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PROCEEDINGS OF THE
2014 EVIAN WORKSHOP
ON LHC BEAM OPERATION

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Edited by
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The principal aims of the workshop are to:

• Suggest operational parameter ranges for re-commissioning and operation in 2015;

• Establish re-commissioning requirements for beam based LHC systems;

• Establish planning for re-commissioning 2015;

• Revisit overall strategy for 2015 (bunch spacing, scrubbing, special runs, MD etc.);

• Provide input to Chamonix 2014.

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EVIAN 2014 - SUMMARY

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Abstract

A terse summary of the workshop is presented in which an attempt is made to highlight issues with direct bearing on post LS1 operation. A preliminary attempt is made to estimate the potential post LS1 performance, outline the commissioning strategy and the potential limitations for Run 2.

INTRODUCTION

The 3 day workshop attempted a survey of the following areas with the emphasis very much on identifying issues pertinent to operations in the post LS1 era. The sessions covered:

- Operations in 2015
- Systems: status and commissioning plans
- Machine Protection
- Availability
- Planning and preparation for 2015

OPERATIONS

Experiments' requirements

Broadly, the experiments clearly recognize 2015 as a commissioning year and an investment for the future. 25 ns bunch spacing is very strongly favoured (even at expense of luminosity in 2015), however they will accept up to 1 fb^{-1} at 50 ns during the ramp-up phase. They request the target energy by the end of summer 2014. 6.5 TeV is the clearly stated target and also the maximum value to be considered for 2015, however this will only be confirmed at end of the powering tests. A peak mean pile-up of around 50 is considered to be acceptable for the high luminosity experiments.

With 25 ns ALICE will required offset levelling. This will require relatively large beam separation and as a halo probe it is a potentially interesting exercise.

Actions identified were:

- Intermediate energy proton-proton reference run is still to be scheduled
- The 2015 special run schedule needs to be established with prioritization as necessary.
- The early scheduling of the LHCf/VdM run needs to be confirmed.

Beam in the injectors

The principle goals for the injectors for the LHC are:

- 25 and 50 ns standard and BCMS beams

- Doublet beam for LHC (and SPS) scrubbing. Here reaching the target intensity (1.6e11 p/doublet) will be challenging.
- 8b+4e beam as low e-cloud option

The foreseen 25 ns performance is summarized in table 1.

Table 1: Foreseen 25 ns beams to be delivered at exit SPS in 2015

Scheme	ppb 10^{11}	emittance exit SPS [μm]
Standard	1.3	2.4
BCMS	1.3	1.3
Design	1.15	3.5

As regards the number of collisions for the various possibilities:

- BCMS with 5 injections from the PS to SPS gives an injection scheme of 25ns_2508b_2496_2108_2204_240bpi12inj
- BCMS with 6 injections from PS to SPS give 2592 colliding pairs in IPs 1 and 5
- For the nominal 25 ns scheme on has 2736 colliding pairs in IPs 1 and 5

As regards private bunches, all 25 ns schemes have 12 initial bunches that do not collide in 1 and 5.

Collimation and β^*

As was well established in Run 1, collimation influences the key operational parameters. In protecting the aperture limits of the machine, collimation hierarchy determines minimum protected aperture and thus sets the limit for β^*. The collimation system's effective cleaning efficiency, together with beam lifetime, sets the limit for the maximum intensity.

For Run 2, many things have changed. We will need to start carefully and push performance later. There was a clear consensus at the workshop to adopt a relaxed approach initially and then step up later in 2015 (as, indeed, we did in 2011). The thinking at Evian was along the lines of:

- Start-up with β^*=65 cm with a crossing angle of 160 microrad. This was based on the assumption of : 2012 collimator settings in mm; 2012 aperture; 2012 orbit stability; 11 sigma long range separation; and standard 25 ns beam sizes.

- During commissioning thoroughly check the stability, aperture etc.
- An even more conservative β^* of around 80 cm was suggested. The acceptable margins for initial β^{**} (aperture, orbit, optics) was subsequently revisited in the LMC and this initial value of β^* was accepted. The around 2 σ additional margin can be utilized in a number of ways: increased crossing angle, enjoying a high minimum aperture; retracting the TCTs reducing the risk of hitting them during an asynchronous dump; retracting the collimators and possibly reducing the two beam effects in the squeeze.
- The ultimate β^* in 2015 was established to be 40 cm. Clearly experience previously in the run will determine the final value.

β^* levelling, collide and squeeze

In 2012 we saw beam instabilities towards, and after, the end of the squeeze. One way of avoiding these would be to perform the squeeze in IPs 1 and 5 with colliding beams, the so-called "collide and squeeze". This is non-trivial because one must guarantee that beams stay in collisions during the process. A robust operational solution will require some effort, testing and commissioning. To complicate start-up with the commissioning of such a scheme would appear not to be such a good idea.

However the more limited scheme of β^* levelling in LHCb looked good to go and seemed appropriate as a first test of principle. Investigation of the need for validation at intermediate optic points is required. (Subsequent analysis showed a, perhaps, prohibitive commissioning time for the collection of optics involved.)

Optics and run configuration

A number of options are ruled out for initial commissioning. These include so-called flat beams; combined ramp and squeeze; tilting of LHCb's crossing angle. The choice of optics is between:

- nominal optics as used in 2012;
- a modified version of this with adjustments in IR4 to optimize the beam sizes for instrumentation;
- an ATS compatible optics.

The decision was made shortly after Evian to have as the baseline the ATS compatible optics including: new collision optics in 1 and 5; new collision optics and squeeze sequence for IR2; new optics in IR4 (at WS, BSRT, BGI, ADT); and a new crossing scheme in IR8.

Subsequent validation reveal some potential issues. Loss map simulations showed some new loss spikes in the arc to the right of IP8. There is loss of protection margin because of the change in phase advance from beam 2's dump kickers to IP5s tertiary collimators. Given this, it was felt prudent to stick with the nominal optics for re-commissioning, and investigate further ATS in MD and perhaps change during a year end stop.

Table 2: Machine parameters at start-up

Parameter	Value
Maximum energy	6.5 TeV
Target bunch spacing	25 ns (but via 50 ns)
Injection tunes	0.28/0.31 – as in 2012
Injection beta*	11,10,11,10 – as in 2012
Optics	nominal with modifications in 4 and 8
Initial β^*	80 cm
Beating	at least as good as 2012
Chromaticity	high – around 15
Ocutpoles	negative detuning
Initial bunch length	1.25 ns

Stability limits

All 25 ns beams should be stable with a negative octupole polarity in the two foreseen collimator scenarios (2012 mm kept and 2 sigma retraction), although the BCMS is only marginally stable in the pushed scenario (2 sigma retraction).

The long-range beam-beam contribution to stability in squeeze and the dependence on octupole polarity was considered. From long-range beam-beam perspective there is a "clear preference for positive polarity". However, the consensus at the workshop was to start-up with negative octupole polarity and high Q (this combination has not yet been tried operationally). It was also recommended to step back in β^* to avoid the most serious long-range beam-beam regime.

Measurements are required during commissioning to establish the single beam instability limits as function of Q', ADT gain and octupole polarity. LRBB measurements of the limits of instability and thresholds as a function of chromaticity and damper gain is essential in 2015. Meaningful LRBB measurements will only be feasible during the intensity ramp-up at the earliest.

Emittance blow-up

There has been some advance in understanding the issues, with important input from optics measurements in the ramp. Looking to 2015, it is essential to perform optics measurements with AC dipole and k-modulation, and ensure calibration of all transverse profile monitors at the start of Run 2. Comparison of wire scanner, luminosity and SMOG during Van der Meer scans should be performed at the beginning of Run 2.

Bunch length

An interesting strategy was presented to reduce bunch length in Stable Beams. An increase in voltage to 16 MV during physics would reduce bunch length by around 20%

from 1.25 ns (2.0 eVs) to 1.0 ns. The instantaneous luminosity increases by 15% in theory. Any reduction of the blow-up target must be done in small steps and with careful monitoring of heating and transverse stability. Subsequent discussion shows the reduction in luminous length seems to be OK with the experiments although LHCb still have reservations.

SYSTEMS

Detailed system talks were presented by the following proponents.

- RF (Philippe Baudrenghien)
- ADT (Daniel Valuch)
- Collimation (Gianluca Valentino)
- Injection (Wolfgang Bartmann)
- Beam Dump System(Nicolas Magnin)
- Cryogenics (Krzysztof Brodzinski)
- Vacuum (Giuseppe Bregliozzi)
- Beam instrumentation and feedbacks (Georges Trad, Thibaut Lefevre, Enrico Bravin)
- Machine protection backbone and QPS (Ivan Romera Ramirez)
- BLMs and thresholds (Mariusz Sapinski)

Major modifications across the board have taken place during LS1. These have addressed: reliability, availability, performance, operations and protection. These modifications translate into a huge amount of changes and upgrades to: hardware all systems; software at all levels; controls at all levels; additional interlocks (hardware and software).

The ensemble represents an impressive range of:

- Maintenance & consolidation & repairs;
- Improvements based on creative thinking and experience;
- Deployed technology: processing speed; noise reduction; temperature control;
- Improved diagnostics: resolution, stability;
- Data, data transfer rates, analysis tools;
- Improved functionality;
- Better fault tracking;
- Enhanced safety.

Theres a lot to be re-commissioned without and with beam. This is going to take some time. The importance of hardware commissioning, dry runs, reliability runs, machine checkout, re-qualification, with and without beam, can not be understated. A full summary would not be useful here, some key points are highlighted.

Transfer and injection

There have been important upgrades to the injection system during LS1. These include: much needed consolidation of the TDI; and full renovation of the injection kickers (conductors, cleaning, NEG etc.). The consolidated TDI are not the final solution and upgraded TDIs (coating, gap measurements) are to be installed Christmas technical stop 2015 to 2016. On the SPS side there have been improvements to the stability of the MSE. The injection septa are now controlled with FGCs with improved interlocks and incorporation into BETS.

The BLM system team have installed "little ionization chambers" (LICs) in the injection region. Here the deployment strategy is to be defined with a important outstanding question being about the need for temporary blinding of the LICs during the injection process.

A number of issues were identified:

- Collimation: cant move scratched TCTs (5th axis) because of integration issues
- ADT: new hw/sw/functionality - team stretched - to be phased with SPS efforts
- LBDS: asynchronous dumps – 1/year/beam to be established during the reliability runs
- LBDS: need post-asynchronous dump procedure
- Strategy for deployment of upgraded orbit feedback system to be established
- Tune feedback versus QPS MP3 – increase of thresholds fro the trim quadrupoles is expected
- SPS BCT to timing telegram would be appreciated by a long list of clients (RF, TFB, BSRT)
- Full current range of the MCOs is required for operations
- Interlocking of fast power aborts for CMS, LHCb and 60A correctors is to be implemented.

Machine protection

"Quite some changes and upgrades to the backbone of the machine protection system. This includes: circuits protection, access interlocks, QPS, 600 A detection thresholds, Safe Machine Parameters, re-triggering, user inputs, FMCM, and SIS. Full and thorough commissioning with and without beam is, of course, necessary.

A proposal for the set-up beam flag (SBF) settings at high energy was proposed.

1. Normal SBF: 1.1e10 for all users.
2. Restricted SBF: 1.25e11 in 2 bunches for special users
3. Relaxed SBF: 1.5e10 in 16 bunches for MDs.

Collimator commissioning would be with 2 nominal bunches at 6.5 TeV i.e. the restricted SBF.

A full list of matters arising from MP workshop in Annecy was presented. A list of high priority issues was enumerated. These issues are being followed up in the appropriate bodies. A detailed analysis of potential BLM performance at 6.5 TeV was given. BLMs are very well adjusted up to 4 TeV. They are not yet validated for for energies greater 4 TeV.

STRATEGY

The last two Evians have seen a baseline commissioning strategy evolve.

Table 3: Approximate breakdown of LHC's 2015 schedule.

Activity	Time assigned
Machine check-out etc.	14
Commissioning with beam	56
Machine development	19
Scrubbing run for 50 ns	9
Scrubbing run 2 for 25 ns	14
Proton physics 50 ns	7 + 21
Proton physics 25 ns phase 1	44
Proton physics 25 ns phase 2	46
Change in β^*	5
Special physics runs	5 + 7
Ion run set-up	4
Ion physics run	24
Technical stops	13
Technical stop recovery	6

- Low intensity commissioning of full cycle - 2 months
- First stable beams with a low number of bunches
- Special physics run early on for LHCf and Van der Meer scans
- Scrubbing for 50 ns (partially with 25 ns)
- Intensity ramp-up with 50 ns
- Commissioning continued in this phase: systems (instrumentation, RF, TFB etc.), injection, machine protection, instrumentation with high intensity. Characterize vacuum, heat load, electron cloud, losses, instabilities, UFOs, impedance.
- Scrubbing for 25 ns with 25 ns and the doublet beam
- 25 ns operation with a relaxed β^*
- Commission lower β^*
- 25 ns operation

It was noted that the intensity ramp-up took all year in 2010, 4 months in 2011, and 2 weeks in 2012. We will certainly be involved in a learning process again in 2015.

Potential performance

Assuming the above schedule and:

- Conservative beta* to start;
- Conservative bunch population;
- Reasonable emittance into collisions;
- Same machine availability as 2012;

the potential performance is shown in table 4.

CONCLUSIONS

The stated goal is 25 ns operation at 6.5 TeV. Concerted scrubbing program required. Despite this, electron cloud could remain an issue. LHC has been pulled apart and put back together plus major system upgrades. Serious testing without and with beam will be required to re-establish the appropriate level of machine protection.

Table 4: Post LS1 performance estimates for GPDs – usual warnings apply

scheme	Nb	ppb 10^{11}	b*	Emit [μm]	Peak lumi	mu	days	Int. lumi fb^{-1}
50 ns	1300	1.15	80	2.5	4.6e33	27	21	$\approx$1
25 ns 1	2496	1.15	80	2.5	7.4e34	22	44	$\approx$5
25 ns 2	2496	1.65	40	2.5	1.3e34	39	46	$\approx$9

A non-aggressive parameter choice/strategy has been proposed as a starting point. More aggressive exploitation could be pursued later in the year, as could a number of novel developments.

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SUMMARY OF SESSION 1: OPERATION IN 2015 - PART 1

V. Kain and R. Tomàs, CERN, Geneva, Switzerland

Abstract

The first session of Evian focused on the operational configuration of LHC for 2015. This paper reports on the discussions held during the session.

PRELIMINARY ASSUMPTIONS,
GIULIA PAPOTTI

B. Goddard stated that BCMS cannot be the baseline yet, as all protection devices in the injection region and dump region need to be validated for BCMS first. J. Uythoven added that the TDI would break during an impact of 6 BCMS batches from the SPS. V. Kain mentioned that the current transfer line collimators would not attenuate BCMS beam enough to protect the downstream equipment. S. Redaelli said that experimental robustness checks with BCMS beams will also have to be carried out with collimators. R. Schmidt asked how one can be sure about the simulations. Simulation of changing material properties due to shock waves and high temperature gradients is not straight forward. S. Redaelli replied that beam tests with CfC and graphite material blocks are planned in HiRadMat. He has planned tests where full jaws are tested against injection failure (that for the moment is considered the same for injection protection and for IR7 collimators, i.e. the hit of a full injection train). S. Redaelli plans to test three full jaws: 2 with advanced materials for future upgrades and one with the present CFC. There is the hope that BCMS beams can be *faked* at HRM by using smaller beta functions to achieve the same beam size. S. Fartoukh commented on the assumed bunch length, which was agreed to be 1.25 ns. W. Hofle remarked with the current length of the MKI waveform, part of the 25 ns batch was already on the rising and falling edges. The assumption so far was that the 8.2 μs for 6 BCMS batches should still be feasible with the MKIs. J. Uythoven said the MKI waveform will be measured during the sector test.

With ATS optics the phase advance between the dump kickers and the triplet at flattop collision optics will be 90 degrees. S. Redaelli mentioned that this fact will have an impact on assumed margins for the collimator setting choice and β^* reach. J. Wenninger replied that so far for all machine protection considerations the worst case (90 degrees) was assumed, as the phase advance can change due to failures. He does not see why now the strategy for collimator settings choice should be changed in view of ATS. S. Redaelli replied that the knowledge that the phase to the triplet was close to zero provided an additional margin: "Can we use the same assumptions if we know for sure that the triplet will be hit?"

S. Fartoukh remarked that this phase advance between dump kickers and triplet changes between injection and collision and that, actually, in 2012 the situation was more critical at injection. S. Redaelli replied that anyway at injection there are other margins and this phase advance is not so relevant.

V. Kain asked B. Gorini whether a pile-up of 56 events in the beginning of the fill would require leveling. B. Gorini replied that this could be tolerated as the luminosity will quickly decay.

EXPERIMENTS' EXPECTATIONS,
BENEDETTO GORINI

P. Collier remarked during B. Gorini's talk that the energy in 2015 will not be larger than 6.5 TeV and that only in December 2014 we will know if energy needs to be lower. The experiments are aware of the risk of having to re-run their Montecarlo simulations at a lower energy.

J. Wenninger requested a clarification of the minimum meaningful energy change. B. Gorini answered that this minimum step is about 250 GeV per beam.

B. Goddard asked for a clarification on the B. Gorini's statement: "It is accepted that running at 25 ns could result in lower delivered luminosity in 2015 compared to a 50 ns scenario". In particular, B. Goddard asked whether a factor 10 lower luminosity would be OK and B. Gorini replied positively.

P. Collier commented that the physics program for 2015 will need prioritization. Many additional physics requests with different β^* and partly different energies have been approved for 2015.

ALICE will take data during p-p separated at 6 sigma. The dump threshold of their BCM is a luminosity of 6×10^{31} cm^{-2}s^{-1}. G. Arduini asked whether bunch-by-bunch luminosity variations due to blown up bunches from instabilities will not be harmful for ALICE. With the emittance variations we saw from run 1, a factor 10 difference in bunch-by-bunch luminosity can be expected. B. Gorini replied this should be OK.

Constant luminous region is important for the experiments according to B. Gorini and R. Jacobsson. S. Fartoukh said that during β^* leveling the crossing angle should also be changed to keep the luminous region as constant as possible. J. Jowett remarked that ALICE would profit from combined β^* and separation leveling.

COLLIMATION AND β^* REACH,
RODERIK BRUCE

B. Goddard asked how Roderik's scenarios would change if we had to assume 10 asynchronous beam dumps per year for 6.5 TeV. Roderik said that this will have a big impact. The number of asynchronous beam dumps per year should be re-evaluated. R. Schmidt wanted to know how one can know that TCTs are damaged in case. S. Redaelli answered that TCT alignment checks would be used and loss maps would be compared to reference loss maps. It was mentioned that moving the TCTs with the fifth axis in case of a scratch to a new collimating surface is not available due to integration issues.

O. Brüning asked how reliable it would be to extrapolate the measured aperture from injection to collision optics knowing that in the past there were discrepancies. R. Bruce replied that discrepancies observed in the past disappeared after a careful analysis and that, anyway, this procedure would only be applicable as a worst case extrapolation.

THE LHC NOMINAL CYCLE, PRECYCLE AND VARIATIONS IN 2015,
JÖRG WENNINGER

J. Wenninger mentioned in his talk that with the current software tools and restrictions coming from the MCS interlock functions of the collimator re-optimizing collide & squeeze might be hampered e.g. if the orbit would have to be re-adjusted to establish collision again. M. Lamont replied that one will have to count on reproducibility. J. Wenninger added that DOROS BPMs with increased resolution will be help a lot to control the orbit at the IP with the implied liability if a single DOROS BPM would fail. M. Lamont commented that maximizing the luminosity should be the ultimate tool to keep beams in collision.

P. Collier commented that IP8 β^* leveling looked dangerous. After this remark he asked about the *structures* that were building-up over time in the IR orbit correctors, probably based on cancellations between the involved correctors. J. Wenninger replied that this was not understood but that did not pose any significant problem.

S. Redaelli said that one should not give up on combined ramp & squeeze. It could bring significant reduction in turnaround time and probably represents an easier manipulation than the other that are considered feasible. J. Wenninger mentioned that the tools are not sufficiently ready to implement ramp & squeeze.

R. Tomás asked whether the $\beta^* = 19$ m optics would be considered a step in the de-squeeze towards the $\beta^* = 90$ m. J. Wenninger replied that this would depend on the final decision for the $\beta^* = 90$ m operation, as H. Burkhardt is proposing to inject directly at $\beta^* = 90$ m.

LEVELING OPTIONS AND STRATEGY,
ARKADIUSZ GORZAWSKI

R. Jacobsson asked in case β^* leveling does not work how long it would take to commission another squeeze. J. Wenninger replied at least 3 or 4 days. He also remarked that it will be faster to revert from collide & squeeze than from IP8 β^*. Collide & squeeze would simply need to re-separate the beams and re-adjust the TCTs. R. Jacobsson also said that even though they offer to try out β^* leveling at point 8 they want efficiency and collect as much data as possible. They offer to try β^* leveling because they believe that the machine will be able to do it and see it as an investment for the future. B. Goddard asked if in case one goes for β^* leveling in point 8 one would have to repeat loss maps at every level β^* point. S. Redaelli agreed. G. Arduini remarked that this would not have to be done for collide & squeeze and also collide & squeeze would not take place during stable beams, hence not exposing the experiments.

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SUMMARY NOTES AND CONSIDERATIONS ON SESSION 2 - OPERATION IN 2015 - PART 2

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Abstract

In this paper the main points emerged from the six presentations given at the Session 2 of the 5th Evian Workshop are reported, together with the main topics discussed.

TRANSVERSE EMITTANCE THROUGH THE CYCLE – UPDATE

M. Kuhn [1] reviewed the current understanding of the emittance evolution during the LHC cycle, including also its variation during the physics fill.

The puzzling situation of transverse emittance shrinking during the ramp has been clarified, thanks to a review of the measured optical parameters.

A better understanding of emittance evolution is heavily relying on a well-functioning instrumentation and on the possibility of performing cross-checks between the data obtained by the various instruments.

It was very difficult to obtain useful BSRT data during Run I. On the other hand the improved optics in IR4 and the installation of the demonstrator BGV are really welcome for Run II.

The emittance obtained from the luminosity measurements is affected by strong assumptions in the derivation (same values for both beams and planes) and on systematics observed during Run I. On the other hand it has been pointed out that very precise beam size measurement from LHCb could be made available during the VdM scans for the sake of cross-calibration studies.

The main source of emittance growth at injection and along the ramp is IBS, while at top energy instabilities and beam-beam, during the physics fill, are the main culprits. Obviously, high brightness beams will suffer severely. While in several cases the numerical simulations of IBS effects are in good agreement with measurements, for the case of the vertical plane no growth is predicted. The observed value cannot be explained by coupling or vertical dispersion and additional studies are needed to clarify this point. Also, during the discussion it turned out that the effect of intensity reduction during the fill is not included in the numerical simulations.

LONGITUDINAL PARAMETERS AND BEAM INDUCED HEATING

J. F. Esteban Müller [2] reviewed the situation of the longitudinal parameters looking at potential instabilities and at the impact of the chosen values of the longitudinal parameters on the machine performance.

A key aspect discussed is the situation in terms of beam induced heating. Thanks to the analysis of the situation during Run I and to the mitigation measures taken during LS1, together with the expected margin in terms of beam stability and IBS, it is possible to re-consider the option of shortening the bunch length from 1.25 ns used during 2012, down to its nominal value of 1 ns. This provides enough lever arm to propose luminosity levelling, bunch length control (radiation damping at 6.5 TeV might lead to bunch length shortening). Furthermore, a boost in peak luminosity of about 15 % could be considered. The proposed strategy is to start with the 2012 values and reduce the bunch length in steps, carefully looking at all the new heating monitoring and diagnostics deployed during LS1.

From the following discussion it emerged that the Experiments might not be too keen on using this additional degree of freedom to improve the machine performance. Basically, more important than the peak luminosity, the luminous region should be kept as much constant as possible. Nevertheless, it has been agreed that this proposal will be seriously considered and feedback will be given in the future months.

Another option that was discussed is the possibility of bunch flattening. Flat bunches could help reducing the beam induced heating in the critical devices and would produce a more uniform pile-up density.

Another point discussed in relation with the control of the bunch length is the possibility of introducing an interlock to avoid any possible damage to equipment in case of too strong heating effects. No conclusion has been achieved, but this item will be probably followed up by MPP.

IMPEDANCE AND INSTABILITIES

N. Mounet [3] reviewed the situation in terms of impedance and single beam instabilities.

New ingredients have been added to the LHC impedance model and its comparison with measurements is at the level of a factor of two.

The new optics in IR4, mainly, is not expected to introduce any sensible change in the LHC impedance, in spite of the increased beta-functions for optimising the performance of the beam instrumentation.

The proposed reduction of bunch length is likely to have a small effect for the range of chromaticity values (positive and large) that are anticipated for the operation in 2015.

The data collected in the year 2012 provided valuable information for estimating beam stability in 2015. Error bars are large and mainly due to the fact that in some cases a perfect control of the beam parameters was not

possible, e.g., in the case of repeated measurements with the same beam.

The analysis confirms what had been already mentioned earlier, namely that negative polarity of the octupoles (LOF < 0) provides the best stability situation, even including the pushed beam parameters discussed in Session 1.

Imperfections in the functioning of the ADT have been considered and the impact is non-negligible on beam stability.

It is stressed that, given the still imprecise knowledge of thresholds, a detailed programme of beam measurements, such as growth rates vs. chromaticity and damper gain, should be part of the 2015 activities.

TWO BEAM EFFECTS

A review of the observations made during Run I and in particular 2012 have been given by T. Pieloni [4].

The first point addressed is the criterion to be used to specify the required crossing angle. It has been proposed to request 11 σ of beam-beam separation for a maximum intensity of $1.3 \cdot 10^{11}$ ppb and nominal emittance of 3.75 μm, which should ensure enough dynamic aperture (about 7 σ) to have a good lifetime, comparable with what was achieved during the first part of 2014, i.e., before the change of octupole polarity.

It is worth stressing that by determining the crossing angle assuming the beam properties of the beam commissioning, i.e., nominal beam parameters, the crossing angle in microrad will be also an upper bound to the value required for more pushed beams. This choice will imply that whenever the machine performance will be pushed in terms of emittances, the crossing angle might be only reduced, which is deemed to be a rather straightforward and quick procedure. On the other hand, higher intensities might require up to 12 sigma separation.

It has been stressed that, based on considerations of beam-beam effects, the preference for the octupole polarity would be LOF > 0 in 2015.

In case of LOF < 0, collide and squeeze is mandatory, unless it is shown that the long-range effects can be mitigated. From recent numerical simulations if the crossing angle is larger than 15 σ then even in case of LOF<0, the complicated collide and squeeze procedure may not be needed.

The β^* value at which the collide and squeeze procedure should start should be clearly defined and the potential issue of non-colliding bunches should be checked in detail already with simulations, if not with beam studies.

It has been made clear that ATLAS and CMS will request for non-colliding bunches to study beam-gas interactions. Such bunches will have a smaller number of long range encounters and hence, no particular issues are expected prior to putting the beams in collision. However, during the physics fill their stability might be at risk due to missing stabilising effects of the head-on interaction and hence should be checked. Furthermore, the fact that

during stable beam periods the mitigation techniques, such as higher chromaticity and high octupoles strength, have to be partially removed to guarantee good beam lifetimes, calls for a carefully check of the dynamics of these special bunches.

It is stressed that, given the complexity of the models in the presence of beam-beam long range interactions, testing the limits of instability and thresholds as a function of chromaticity and damper gain with beam-beam should be an essential part of 2015 activities during beam commissioning. A detailed control and knowledge of the relevant parameters, such as bunch by bunch properties and machine chromaticity, is also a fundamental ingredient to clarify the different contributions to the beam stability.

It has been suggested to check in 2015 also the possibility of levelling luminosity by separation in IR1/5 for the case LOF > 0 with the aim of having a direct and conclusive evidence of the feasibility of this technique, which had been probed already with tests of separation scans, but with single bunches, only.

ELECTRON CLOUD AND SCRUBBING

G. Iadarola [5] presented the situation of the electron cloud and scrubbing run in LHC for the 2015 starting from a review of the observations made during Run I.

Both 50 ns and 25 ns beams, injected in the LHC during scrubbing runs, machine study sessions, and physics production, have been considered. The first observation is that while the scrubbing has been certainly effective in mitigating the electron cloud in the dipoles, at least at 450 GeV, the effect remains quite strong in the quadrupoles.

Another important point is that during LS1 a number of improvements have been implemented: i) the cooling capacity of standalone magnets has been increased by a factor of two; ii) the cooling capacity of sector 3-4 has been restored to its nominal level after the incident; iii) extra thermometers have been added in three half-cells of sector 4-5; iv) high-sensitivity vacuum gauges and pilot vacuum sectors have been installed; v) upgrade of several hardware components (e.g., MKI, TDI) and preparation of software tools for on-line data taking and analysis.

It is worth stressing that, using the presently available SEY models, the achieved SEY in the LHC arc dipoles can be estimated to be around 1.4. Lower values have been obtained in controlled scrubbing experiments in the laboratory, but were never observed in direct measurements on particle accelerator vacuum chambers. Therefore, the possibility to achieve these values, and thereby full scrubbing of the arc dipoles, will have to be proved during the LHC Run II.

The work horse beam for 2015 scrubbing in the LHC is the so-called doublet beam generated at SPS injection by transferring long PS bunches on the longitudinal unstable fixed point, such that the bunches are split in two adjacent 5 ns buckets. Such a novel beam has been already tested at injection in the SPS in 2012-2013, but its injection in

the LHC will require non-negligible efforts on the LHC side (e.g., false readings from the interlocked BPMs in IR6 should be addressed), but also preparation in the SPS.

Simulations show clearly the benefit of the doublet beam with respect to the nominal 25 beam and their predictions were widely benchmarked with SPS measurements in the electron cloud monitors. As opposed to other possible electron cloud enhancing schemes (e.g. 12.5 ns spacing with nominal intensity per bunch), another key advantage of the doublet beam is its compatibility with the RF constraints of the LHC injection chain and its relatively easy production scheme.

Scenarios for the scrubbing run and after it have been presented: the final choice among them will be based on the outcome of the scrubbing run and cannot be anticipated now.

BEAMS IN THE INJECTORS

The complete menu of beams that should be delivered by the LHC injectors' chain has been discussed by H. Bartosik [6].

The list is quite impressive, ranging from single- to multi-bunch beams for commissioning and physics (including both 50 ns and 25 ns variants), as well as special beams for, e.g., scrubbing.

Some of these beams have been already produced and studied, even if not injected into the LHC. Some have been proposed during LS1; hence, a suitable testing time is required. This is the case of the so-called 8 bunches +4 empty beam, which has been proposed at the RLIUP workshop to mitigate electron cloud effects, but also for the acceleration of the doublet scrubbing beam to the SPS flat top, which has not been demonstrated yet.

While the 2014 run can be seen as the ideal moment to prepare the beams in the injectors, prior to the LHC beam commissioning in 2015, it is reminded that the chain of accelerators will have to focus on the re-start after LS1, during which non-negligible changes to several ancillary systems of the injectors have been implemented.

A large number of operational beams will have to be prepared, including also ions for special runs.

In addition, the preparation of the large variety of LHC beams will require huge efforts, not to mention MD time. In this respect it has been mentioned that the time requested for dedicated MDs in the SPS is exceeding by a factor of two the available MD time, thus requiring a delicate prioritisation and a good efficiency in the overall schedule.

ACKNOWLEDGMENT

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5th LHC OPERATIONS WORKSHOP, EVIAN2014
SUMMARY OF SESSION 3: SYSTEMS 1 - HARDWARE STATUS AND COMMISSIONING PLANS

G. Papotti and S. Redaelli, CERN, Geneva, Switzerland

Abstract

This paper summarizes the discussions that followed the presentations of the session 3 "Status and commissionin plans," at the 5th LHC Operations Workshop, Evian2014.

INTRODUCTION

The third session of 5th LHC Operations Workshop, Evian2014, was dedicated to the presentation of status and commissioning plans for some key accelerator systems. The session included the following five talks:

1) **RF system**, by Philippe Baudrenghien;

2) **Transverse beam damper**, by Daniel Valuch;

3) **Collimation system**, by Gianluca Valentino;

4) **Injection systems**, by Wolfgang Bartmann;

5) **Beam dumping system**, by Nicolas Magnin.

For each presentation of the session, summaries of the discussion that followed the presentations are given. A summary of the critical points and open actions is also given.

RF SYSTEM (PH. BAUDRENGHIEN)

J. Jowett recalled that with heavy ions beams synchrotron radiation damping is twice as strong. It is important that controlled blow up is available as it might help reducing the IBS growth in the transverse plane. *P. Baudrenghien* agreed, highlighting that the most difficult part is to figure out which noise distribution to use.

G. Arduini asked if there will be intensity limitations from RF for the doublet beams that can be injected in the LHC and what needs to be monitored at intermediate intensities for the intensity ramp-up of the doublet beam. *P. Baudrenghien* replied that this should not be the case as these beams will not be ramped. The HOM power should be monitored at the different cavities as with the different bunch spacing different harmonics might be intercepted. He also recalled that in Run 1, the HOM measured power was lower than expected.

S. Redaelli asked if the items listed in the MD request page are part of the commissioning or if they can be addressed in MD period after the intensity ramp up. *P. Baudrenghien* replied that the few ramps could come later, but not too late as the experiments would need the information rather early on, and prefer not to have changes on the luminous region length during the run.

J. Wenninger asked to clarify what is meant by "moderate intensity", if that corresponds to few bunches in early commissioning or more, so during intensity ramp-up. *P. Baudrenghien* and *E. Shaposhnikova* replied that it is important to foresee some RF dedicated measurements in the first two months of commissioning with single bunches. Measurements will have to continue during the intensity ramp-up, probably requiring negotiations with the MP panel. They added that the evolution of the bunch length is not yet known during physics, and that it will be interesting to look into what physics processes drive the evolution of the bunch length then.

TRANSVERSE BEAM DAMPER (D. VALUCH)

M. Lamont commented on the resource availability for the full implementation of the new observation features. *W. Höfle* replied that some prioritization will have to be made and reckoned that most of the work relies on support from their controls section (BE-RF-CS).

O. Brüning asked about the interface between the ADT observation box and Timber. *D. Valuch* replied that the two systems are complementary but they do not talk to each other. The new data from the ADT will not be stored in the logging database whereas the previously logged parameters will remain as in Run 1. For the observation box, different users will subscribe to different chunks of data, but buffers will write continuously removing the bottleneck of deadtime.

M. Lamont asked to comment on the FESA 3 migration. *D. Valuch* replied that at present the priority is on the injectors restart and that the teams are working hard on that. For the LHC, commissioning staging will be the way to go. This will start after summer. *A. Butterworth* added that indeed the workload is important. *W. Höfle* added that a choice based on priorities needs to be done. The importance of the SPS scrubbing beam development drove the changes on the SPS damper and made it a priority. Until the new SPS damper is not operational the LHC system will not be switched.

R. Schmidt inquired about the use of the non colliding bunches at IP1/5 to measure the tunes. *D. Valuch* recalled that an active Q measurement was demonstrated by kicking bunches, and that a passive one was demonstrated with massive number crunching to calculate the tune from the noise spectrum. He added that the ideas are alternative solutions to the BBQ. This is not part of the new data that will be made available by the observation box. *R. Jones* com-

mented that the BBQ cannot do bunch-by-bunch, but can do fast measurements e.g. for feedbacks, while the ADT measurements could be bunch-by-bunch but mostly offline. The two systems should be seen as complementary.

COLLIMATION SYSTEM (G. VALENTINO)

O. Brüning asked about the collimator setting problem mentioned by the speaker. Why was it not caught by loss maps? *S. Redaelli* replied that a setting error for the centre of one TCT in IR2 was put in at the beginning of the run so there was no correct reference loss maps to compare against. This case would be immediately caught by the new BPM collimators that measure the beam location inside the jaws.

O. Brüning also asked whether the new BPM feature will lessen the need for validation loss maps. *G. Valentino* replied that the settings validation will still rely on loss maps. The new BPMs feature will however be crucial for online orbit measurements and for faster alignment in the IR's. *S. Redaelli* emphasized that the added value is in the orbit monitoring that will allow online detection of potential setting problems in the collimator centring that is presently not easily validated.

G. Arduini asked to clarify whether the initial alignment will be done as in Run 1, with losses. *S. Redaelli* replied that after initial comparisons between the BLM and the BPM methods, only the BPM method will be used. He however recalled that only a small fraction of the system is equipped with BPMs so the majority of the collimators can only be aligned with the BLM technical. The TCT with BPMs will ensure an efficient setup in case of changes of IR configurations.

M. Pojer asked whether calculations were performed to address the impact on electronics in the RRs from the increased radiation due to the TCL6s. *M. Brugger* replied this is the case: simulations show that the radiation levels to electronics remain in the tolerance budget. *S. Redaelli* commented that we should foresee some measurements at startup to validate the simulations for different TCL configurations.

M. Lamont recalled that the experiments requested splashes on the TCTs and asked if this will remain feasible. *S. Redaelli* replied that they will be ok with the new TCTPs.

INJECTION SYSTEMS (W. BARTMANN)

O. Brüning asked about the 1.4 SEY threshold for the MKI. Is this acceptable for electron cloud? *G. Rumolo* replied that this value is similar to the ones of dipoles and is considered acceptable.

O. Brüning asked about the consequences of not coating the TDI. *B. Salvant* replied that the TDI will be equivalent to before LS1 from the impedance point of view. The coating would have greatly improved the impedance according to calculations performed by *N. Mounet*.

P. Baudrenghien commented that with 25 ns beams, the increased transient beam loading at the SPS is likely to cause more capture losses in the LHC. What are the plans to set the new sunglasses for the LIC BLM's? *W. Bartmann* stated that the sunglasses will in theory be possible after the LS1 upgrade of the system but a follow up with the MP panel is needed. *B. Dehning* clarified that it is a major decision with a potential impact on the whole BLM system (might have an effect on the other monitors also), thus a broader discussion is needed. There is also a manpower issue within the BLM team, but this can be overcome. *V. Kain* commented that at the end of Run 1 the problem had already been mitigated and was not limiting severely the performance. The feature might therefore not be needed anymore. *W. Bartmann* pointed out that the mitigation was primarily coming from the increased operational gaps for the transfer line collimators that were opened from 4.5 to 5 sigma. The final decision on the implementation of the sunglasses depends therefore also on the planned protection settings. *B. Goddard* agreed and re-iterated the need for a wider discussion.

R. Schmidt highlighted that the MSI current interlock is vital and worked well during Run 1. Why was it changed? Was a failure analysis performed concerning the implemented changes? *V. Kain* recalled that the MSI will adopt the LHC-type FGC power converter controls. An interlock on the settings will be needed, which is not there at the moment. *J. Wenninger* explained that the MSI had an SPS converter, which meant it could not be degaussed. The idea came to put it on an FGC, but that implied the loss of the fast interlock. He added that there are other dipoles in the transfer lines that are as dangerous as the MSI but are on SPS interlocks only. *J. Uythoven* stressed that it will be put in the BETS to make sure that it has the right settings. This should make it safer than the SPS interlock.

S. Redaelli asked about the radiation resistance and the robustness to beam impacts of the upgraded TDI featuring optical sensors. Considering the criticality of the device (that is hit a few times per year by important beam losses) is it not worth considering beam tests at HRM to address the robustness of the proposed solution? *R. Losito* replied that the measurement heads will be out of beam trajectories and he excludes problems from beam impacts.

B. Goddard hinted that quite a lot can be done in transfer line tests and sector tests for the commissioning steps proposed by the speaker. *W. Bartmann* agreed, adding that SPS extraction aperture tests should be repeated with proper SPS supercycles. He estimated the amount of time needed to 66 hours, or 4 shifts per transfer line.

BEAM DUMPING SYSTEM (N. MAGNIN)

R. Bruce asked a best guess of the number of asynchronous dumps per year after the LS1 changes. *J. Uythoven* replied that we should keep the assumption of one asynchronous dump per year per beam. Due to the

hardware changes, this is to be confirmed by the reliability run. *B. Goddard* stressed the importance of accumulating a couple months of operational data with the reliability run before confirming the yearly figures.

M. Zerlauth recalled the importance of the UPS powering test, stressing that the study of the LBDS response was one of the main motivations for the first test executed. However, the LBDS was not available for this first test. It will be available in its final configuration for the second UPS test.

B. Goddard asked about the need for beam tests of the direct dump BLMs. *B. Dehning* recalled that the BLM thresholds had to be reduced in previous tests to trigger a dump, and then increased back to the operational values. This procedure will likely have to be repeated.

P. Collier asked about the failure modes of the dilution kickers. Do we need all kickers per plane for a safe dump? *B. Goddard* replied that studies showed that one dilution kicker per plane is sufficient for a safe dump. The present implementation foresees a dump immediately if one of the dilution kicker fails. *N. Magnin* recalled that indeed in case of failure of a kicker, a synchronous beam dump will be pulled. *P. Collier* and *R. Schmidt* argued why to dump the beam in a non-optimal condition instead of trying to recover the kicker. *J. Uythoven* explained that this is better than risking additional failures that could generate unsafe conditions.

SUMMARY OF SESSION 4: SYSTEMS 2 - HARDWARE STATUS AND COMMISSIONING PLANS

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Abstract

This paper summarizes the discussions that followed the presentations of Session 4 "Systems 2 – Hardware Status and Commissioning" of the 2014 Evian workshop.

LIST OF PRSENTATIONS

The session included five presentations, two on beam instrumentation topics, one each on vacuum and cryogenics complemented by a talk on software packages:

- Software Packages (*D. Jacquet*)
- Cryogenics (*K. Brodzinski*)
- Vacuum (*G. Bregliozzi*)
- Transverse Beam Size Measurement (*G. Trad*)
- Status of Tune and Orbit Measurement and Correction, Testing and Strategy (*T. Lefevre*)

SOFTWARE PACKAGES (D. JACQUET)

Delphine summarized the major changes which include the CMW upgrade, the move to FESA 3, LSA "refactoring", timing system upgrade, repopulation of the LHC Alarm screen, an upgrade to Diamon as well as a number of other software packages. She added that the logging using SDDS would no longer be possible and that someone should be given the responsibility to complete the data implementation for the fault tracking project.

To a question by *Mike Lamont* on the aperture model and whether it would be available for the injection tests, *Piotr Skowronski* said that this would be revived in November 2014. *Jorg Wenninger* added that first turn data, such as that from injection tests, has never been used in the model.

Philippe Baudrenghien asked about how the alarms for LHC would be repopulated. *Delphine Jaquet* replied that the decision on which alarms should be reported will be taken by OP in consultation with the equipment groups.

In reply to a question by *Philippe Baudrenghien* concerning automation of the abort gap cleaning during RF blow-up in stable beams, *Jan Uythoven* replied that both an automatic and manual mode was foreseen.

Withold Kozanecki asked when the Van de Meer Scan application will be ready. *Fabio Follin* replied that it was on his to-do list, but would not be started before the SPS was once again fully operational with beam.

Enrico Bravin was worried about the consequences of abandoning SDDS data, in particular the ability of the logging database to cope with the demand for the large quantities of data often associated with these files. *Chris Roderick* stated that this had been fully tested.

CRYOGENICS (K. BRODZINSKI)

During LS1 a number of leaks are being repaired and mitigation work in the framework of the R2E project is also being carried out. The strategy to increase availability and reduce recovery time in case of failure scenarios was explained. Limitations were presented, in particular for the electron cloud expected with 25 ns and the associated scrubbing run.

Bernd Dehning asked about the likelihood of losing Helium following a quench and the expected recovery time. *Krzysztof Brodzinski* explained that no Helium is lost in the event of a quench and that the experience from the high current powering of Sector 5-6 showed that the recovery time was reduced from 15 hours down to 7 hours.

Ruediger Schmidt enquired about a prediction concerning the availability of the cryogenic system for Run II. *Krzysztof Brodzinski* replied that aim is to be at 90% with the hope to increase towards 95%.

VACUUM (G. BREGLIOZZI)

Giuseppe Bregliozzi recalled the design parameters for the LHC vacuum system and explained the ongoing upgrade and repair work during LS1. The expected performance for the scrubbing run was detailed.

Wolfgang Hofle asked whether the requirements have been tightened for Run II. *Miguel Jimenez* replied that the requirements themselves have not changed, but that non-conforming equipment installed before the original LHC start-up are now being addressed and corrected.

TRANSVERSE BEAM SIZE MEASUREMENT (G. TRAD)

Georges Trad summarized the plans for the wire scanners, the BSRT and BGI as well as the new BGV for which a prototype will be installed on beam 2.

To a question by *John Jowett* on the availability of bunch-by-bunch data from the BGI for ions, *Georges Trad* replied that from the camera point of view gating at 50 ns is possible but that the scintillator used may be too slow. *John Jowett* insisted that this would be very useful to have.

On the subject of calibration for all these instruments, *Withold Kozanecki* recommended to coordinate the calibration campaigns with VDM scans. While it may be difficult to correlate the actual beam size in Point 4 with that in the LHCb experiment due to uncertainty on the optics, it would still provide valuable input for relative measurements. *Bernd Dehning* added that collecting more data with the LHCb SMOG detector would also be useful.

Mike Lamont asked about the status of the application for bunch-by-bunch beam size scans. *Verena Kain* commented that this is planned by OP, but would not be available for the start-up. *Georges Trad* explained that the scans should in future run with a cycle time of 20 minutes. To a question by *Gianluigi* on the source of the limitation to 20 minutes *Enrico Bravin* replied that this is limited by software. Faster scans would be possible by using FPGA based acquisitions; however no one is currently assigned to work on this.

Paul Collier enquired about the precision of halo measurements for tuning Alice luminosity at 6σ. *Rhodri Jones* explained that while this is being looked into for HL-LHC no instrument capable of this dynamic range is currently installed. *Gianluigi Arduini* added that tuning Alice would be carried out using their measurement of luminosity.

Stephane Fartoukh asked whether the calibration factors depend on the beam size itself and whether studies should be foreseen with a squeezed optics in IR4. *Frederico Roncarolo* and *Georges Trad* reply that indeed this can be checked in studies, but it is judged to be easier to change the beam size by controlled blow-up using the ADT than by optics changes.

STATUS OF TUNE AND ORBIT MEASUREMENT AND CORRECTION, TESTING AND STRATEGY (T. LEFEVRE)

Thibaut Lefevre summarized the status and modifications foreseen for Run II concerning the Beam Position and the Tune Systems as well as their related feedbacks. The changes for the BPM system include the installation of 48 water cooled racks for improved stability, installation of a number of additional pick-ups and the deployment of a new electronics processing system based on diode detection for improved precision down to the 1 μm level (DOROS). This electronics will initially only be installed on a few pick-ups in the LSS regions in the 4 experimental points.

The tune system continues to rely on the BBQ system, with new pick-ups installed to separate out the continuous, on-demand and bunch-by-bunch measurements. The Schottky monitor is also undergoing a complete overhaul and is complementary to the BBQ system.

The feedback systems for tune and orbit undergo modifications mainly with respect to the computer control and software in order to improve their reliability.

Oliver Bruning asked about the availability of the PLL for beam transfer function measurement. *Thibaut Lefevre* explained that the PLL is not currently a baseline instrument. It was commented that it could be very useful for collimation studies as an exciter.

Concerning the suggested use of the Schottky *Elena Shaposhnikova* explained the complexity of understanding the longitudinal spectrum.

Following a question from *Mike Lamont* about the orbit feedback system, both *Joerg Wenninger* and *Mike Lamont*

expressed their desire to start operation with a new version running on FESA 3. The old version can be kept as a back-up with a decision on which version to run taken in January 2015. *Thibaut Lefevre* explained that a new version is being prepared by *Stephen Jackson*, but as a new team is in place he insisted that starting with the old system looks like the better option. *Mike Lamont* emphasized that a change of version during the run would imply a large overhead. *Rhodri Jones* summarized that the baseline plan is to proceed with a new FESA 3 version incorporating the changes identified by the feedback review in 2013, while maintain the old system as a back-up.

Stephane Fartoukh enquired about the precision of the orbit system around the inner triplet and questioned whether accurate bunch-by-bunch data would be available. *Marek Gasior* explained that the new DOROS system is not bunch-by-bunch. He underlined that while the implementation of gating is possible it would significantly reduce the precision of the DOROS system. *Thibaut Lefevre* clarified that for the LSS pick-ups in question both the new DOROS and the classical system will be available in parallel.

5TH LHC OPERATIONS WORKSHOP, EVIAN 2014 SUMMARY OF SESSION 5 – MACHINE PROTECTION AND AVAILABILITY

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Abstract

This paper summarises the discussion that followed the presentations during session 5 of the 5th LHC Operations Workshop in Evian 2014. Session 5 was designed to provide a synthesis and outlook of machine protection related activities which have been implemented during the long-shutdown 1 and/or which are still in progress in view of the approaching restart of the LHC and its injector complex. While the machine has been operating since the restart in 2009 without major incidents, reaching stored energies beyond the 140 MJ range, numerous consolidations and improvements have been identified and implemented in view of Run 2. Special attention was given to identify a strategy to increase the beam intensities and integrated luminosities to safely reach the new targets in view of the challenges operation at higher energies will bring to the various protection systems, namely for the understanding and protection against beam loss events.

LIST OF PRESENTATIONS

The following six presentations were given in session 5:

- Machine Protection Workshop revisited, D. Wollmann

- Machine protection backbone, I. Romera Ramirez

- BLMs and thresholds for 6.5 / 7 TeV, M. Sapinski

- Beam instruemntation for machine protection, E. Bravin

- Commissioning and operation of machine protection systems, L. Ponce

- Availability, A. Apollonio

For each presentation of the session, summaries of the discussion that followed the presentations are given. A summary of the critical points and open actions is also given.

MACHINE PROTECTION WORKSHOP REVISITED

D. Wollman gave an overview of the status of the various actions and follow-ups defined during the machine protection workshop in Annecy in 2013. With the majority of the actions being well on track for the machine re-start, a few remain to be clarified as a function of the machine and optics configuration used for the 2015 re-start. S. Redaelli enquired what detailed changes were done to the machine protection commissioning procedures with respect to the original version used to prepare run 1. In particular, shall the hardware and beam tests be consistently described for all systems in separate documents? Is there any recommendation from the Machine Protection Panel (MPP)?

D.Wollmann replied that a proposal (which can be found here) has been made and presented at the first MPP meeting in 2014. The changes mainly concern a clean up and clarification of the intensity steps and repetition rates which will be available to conduct the various machine protection tests, based on the experience acquired during Run 1.

R. Schmidt proposed to have a dedicated (small) workshop before the LHC start-up to discuss the updated list of MP tests which need to be performed, in order to guarantee their consistency between the MP subsystems and the machine commissioning strategy.

P. Collier commented that a related session will take place in Chamonix to discuss these issues and that the final updates of the MPP procedures and templates should be presented at the LMC.

MACHINE PROTECTION BACKBONE

Concerning the inputs to the beam interlock system to be made operational for Run 2, R. Alemany Fernandez asked if the input for the LHCf detector has been requested from the experiment side.

I. Romera Ramirez answered that the input has always been foreseen but was not yet enabled due to the absence of the detector during Run 1. If the detector is to be installed for Run 2 and used at unsafe intensity, a position interlock will have to be defined and connected to the foreseen BIS input.

M. Lamont enquired about the status of the QPS protection thresholds for the trim quadrupole circuits (RQTF/D) at 6.5TeV. M. Zerlauth commented that MP3 is currently recalculating the allowable thresholds for all 600A circuits which – if approved - will hopefully allow for the needed margins of the tune feedback system.

T. Lefevre reminded that the BPMs to be integrated in the new collimators are not designed for high availability, nor is the associated electronics. He asked if the collimators could still be used in case of malfunctioning of one BPM.

S. Redaelli explained that in principle a kind of redundancy is provided by the fact that there are two BPMs on each jaw. Still, some operational experience is needed to assess the reliability of the system and define

an appropriate strategy for its use for controlling and interlocking the jaw movement.

BLM'S AND THRESHOLDS FOR 6.5 / 7 TEV

R. Bruce asked what strategy will be chosen to define the BLM thresholds in the Dispersion Suppressor region (DS) downstream of IR7.

M. Sapinski answered that the chosen strategy will depend on whether one wants to favour protection against cleaning induced losses or orbit bumps and/or vacuum leaks. This decision should be taken by the MPP and the collimation experts.

R. Schmidt answered that the thresholds should be defined to protect from the most likely loss scenario, which in this case would be beam cleaning.

S. Redaelli confirmed and commented that this was already done as such in the past when the limits were increased following MD results and operational experience (from losses in the DS corresponding to 200 kW up to 500 kW at the collimators).

J. Jowett reminded that during the heavy ions run considerable luminosity dependent losses may appear in the DS region. These could last for several seconds and the defined BLM thresholds should allow operation under such conditions (while still protecting against quenches). He enquired if there are any plans to use different thresholds for ions and protons.

M. Sapinski answered that at present the same thresholds are used - this topic should also be discussed at the MPP (possibly relaxing for the ion run the margin defined between the predicted quench level and the BLM threshold?)

BEAM INSTRUMENTATION FOR MACHINE PROTECTION

P. Baudrenghien asked if there are any plans to make the Abort Gap Monitor (AGM) data available in the LHC Logging along with calibration factors and units.

E. Bravin explained that the calibration was performed at the beginning of Run 1 and data were then published in protons per ns beam. Many changes were performed during Run 1 to improve the reliability of the system. As it was not always possible to redo the full calibration a "best estimate" factor was applied. There was also the request from the RF team to adapt the dynamic range of the AGM to allow measuring very low intensity. This request is not compatible with the protection function since, in case of fast de-bunching, the photomultiplier could be damaged if set to very high sensitivity. Moreover, in order to use the AGM to automatically start the Abort Gap Cleaning, the sensitivity should be optimized for the range of interest (a few 5E9-1E11).

E. Bravin explained that it is not trivial to add another splitter in combination with an additional channel to perform parallel measurements as the LDM is too slow and does not feature enough dynamic range.

COMMISSIOING AND OPERATION OF MACHINE PROTECTION SYSTEMS

P. Baudrenghien asked if any intensity below the pilot of ~1E10 is foreseen for operation (as this value is important for the definition of the operational dynamic range).

L. Ponce answered that 1E10 is the maximum allowed intensity for the pilot but 5E9 remains the nominal value.

D. Valuch commented that it would be useful to receive information from the SPS about the beam intensity of the next injection in order to use it to automatically set the ADT sensitivity.

R. Schmidt asked if this is mainly done for protection or reliability purposes.

D. Valuch answered that this mainly concerns setup reliability as it would help avoiding unintentional beam dumps.

V. Kain answered that the only thing which is verified/communicated during injection is the filling pattern (right bunch from SPS to be injected into the right LHC bucket) and that looking at the intensity in the SPS and "communicating" it to the LHC is not trivial at all.

Commenting on the proposal for the new Setup Beam Flag values S. Redaelli reminded that the TCT damage limit provided by the collimation team has to be taken with some safety margin; depending on how the machine will behave these values could change (in particular as a function of the orbit stability when moving from 50 ns to 25 ns operation).

B. Goddard commented that the MPP procedures should take into account the option of β^* levelling: at which β^* do the MPP tests have to be repeated and do we have to perform a validation at intermediate optic points as we will remain much longer at intermediate values than if stepping through a nominal squeeze?

AVAILABILITY

O. Bruning asked how sensitive the calculation of the optimum fill length is to a variation of the parameters used in the simulation.

A. Apollonio answered that indeed it is very sensitive and the results depend very much one the confidence one has on the model itself and the correlation between the different parameters. The model has been benchmarked with data from the 2012 run and could predict the delivered luminosity during Run 1 very accurately; hence he is confident that the predications for HL-LHC are realistic.

CONCLUSIONS AND ACKNOWELGEMENTS

Machine Protection and Safety has been a daily concern of MPS experts, operation teams and equipment experts during Run 1 and numerous improvements and additional mitigations have been identified and implemented during LS1. The very good experience during Run 1 will

however not guarantee a start-up in 2015 run free of surprises, as special caution has to be given to a full and rigorous re-commissioning of the MPS subsystems while approaching higher energies and 25ns operation, bearing new challenges for machine protection like beam instabilities, UFOs, reduced quench margins,…

The session conveyers would like to thank all speakers and the MPS/OP teams for their dedication and hard work during the very successful first operational period and for all their input and help in preparing this session in preparation of an efficient LHC startup in 2015.

SUMMARY OF SESSION 6: PLANNING AND PREPARATION FOR 2014-2015

R. Alemany, M. Pojer, CERN, Geneva, Switzerland

Abstract

Session number six focused on the planning and preparation work being carried out during 2014 and that will continue in 2015 in view of beam commissioning. This paper reports on the discussions held during the session.

POWERING TESTS - MACHINE STATUS COMING OUT OF LS1
M. Solfaroli and M. Pojer

Matteo explained that a Free Wheel Thyristor on the output of RB power converters has been installed to reduce the 30 Hz voltage oscillations (ERC 1387235). It will be connected and tested on the first sector that will undergo powering test, and according to the results a decision will be taken in order to use it or not. Wolfgang Hofle asked if there would be any impact on the beam due to this frequency. Matteo said that 30 Hz voltage oscillations only arrive after a fast power abort, and there is no beam in the machine by then.

Jan Uythoven asked if the problem of the feedback tripping the RQTs (tune trim quadrupole circuit) has been solved for RUN 2 (Note: the tune feedback applies only small changes in current but the dV/dt (d2I/dt2) in combination with the parallel resistors creates a voltage rise that QPS cannot distinguish from a real quench). Reiner Denz answered that for RUN 2 the thresholds are being revisited and they will be possibly increased, but if the feedback requires too much, the system, in the end, will not be able to cope with.

Paul Collier asked if time would be dedicated to train the RD3.L4 (single aperture superconducting separation dipole circuit left of IR4) to 7 TeV. Matteo answered that it depends on MP3 but it is believed it can reach nominal values.

Freddy Bordry recalled that the energy in 2015 will not be larger than 6.5 TeV and that only in December 2014 we will know if the energy at which LHC will be operated needs to be lower.

Mike Lamont asked if the 30 A limit on the RCO (octupole spool piece circuit) can be removed. Matteo said that it is possible but needs an intervention that has to be explicitly requested. Mike said that, in this case, he will do the formal request.

Stephan Fartoukh asked if for RCBYHS5.R8B1 (horizontal crossing angle orbit corrector circuit right of IP8 for B1) the dI/dt could be reduced in order to get more Imax, which is the real constraint in order to push the crossing angle. Arjan Verweij replied that it can be done if there is a real need for improving performance, but it is a weak magnet and they prefer to leave a safety margin.

DRY RUNS AND MACHINE CHECKOUT STRATEGY
M. Albert and R. Giachino

A huge amount of work will be, very soon, in the hands of the operation team: they will have to cover shift for powering test, they will have to dry run the complete accelerator control system and perform a thorough cold-checkout of the machine before first beam. Mike asked if BE/OP/LHC has the resources to cover all this work. Markus answered that he is currently preparing the shift plan and seems should be possible. Operations is encouraged to participate in the dry runs since this is a unique opportunity to re-learn how to operate LHC again, which has changed quite a bit.

SECTOR TESTS WITH BEAM, POSSIBLE TRANSFER LINE TESTS WITH BEAM
V. Kain and R. Alemany

Stefano Redaelli asked if it makes sense to do a B2 sector test if it might not be possible to perform a cycle at high energy of sector 78 which seems to be in the critical path in what concerns powering test phase II. Mike answered that many of the tests presented in the slides do not require an accurate knowledge of the higher order multipoles of the magnets. Reyes added that the sector tests would in any case be of crucial importance to detect aperture bottlenecks, establish synchronization with SPS, detect magnet and BPM polarity errors, first setup of the injection and dump region, injection kickers wave form study, etc.

OMC IMPROVEMENTS AND PROSPECTS FOR 2015
A. S. Langner

Andy gave the estimate of the beta beat errors for 2015, before corrections, for both beams: 100% for B1 and 140% for B2. Roderik Bruce asked if Andy could give some estimation on what the beta beat error will be after correction since this is crucial for collimator hierarchy and beta* reach estimation. Andy answered it is very difficult to give such a number, but, of course, should be either the same or better.

Andy gave as well a detailed description of the improvement that can be achieved if MCS, MCO and MCD correctors (sextupole, octupole and decapole spool piece circuits) are used to reduce the higher multipole errors contribution of the arc dipoles. Rudiger asked what the effect on the beam will be if we use them. Rogelio answered that the most important contribution comes from MCO for amplitude detuning at injection since it is a critical parameter for instabilities control.

According to Andy, during the squeeze the field errors in the triplets are the main source of uncertainty in the optics and, naturally, it is the job of the triplet corrector magnets to correct them. Ezio asked if Andy plans to do measurements to correct the optics with the non-linear correctors of the triplets. Andy answered that until 60 cm beta* they do not have any influence, but below that value yes, so measurements will be needed.

Andrzej Siemko asked the status of the understanding of the snapback model and what the strategy will be for RUN 2 taking into account that from 4 to 6.5 TeV there is 40% more snapback contribution. Mike answered that to start with, the same strategy as in RUN 1 will be applied, i.e., chromaticity correction at the start of the ramp will be feed forwarded in the functions based on dedicated measurements during the ramp. Ezio strengthened that all measurements will have to be done for the new energy.

STRATEGY FOR FIRST TWO MONTHS AND KEY EARLY MEASUREMENTS
S. Redaelli

Wolfgang Hofle asked if OP plans to write dedicated procedures for beam commissioning as those which were prepared in 2008. They are very useful for the equipment experts to know exactly when they should be available for commissioning their equipment with beam. Verena Kain replied that OP will prepare soon a detailed plan but not a commissioning document as was done in 2008.

Paul Collier made the remark that we should not put ourselves in a corner being too ambitious in reaching the highest performance possible since the beginning. We should start at a relaxed beta*, prepare the land, and then, in due time, push for more performance.

Stephan Fartoukh asked if besides the asynchronous dump tests, there are other tests related to machine protection that need to be done before we can change the beta*. Stefano replied negatively, but in any case, the asynchronous dump test does not depend on the beta* provided the phase advance between TCTs (tertiary collimators) and TCDQs (mobile diluter that protects the superconducting quadrupole immediately downstream of the extraction as well as the arc at injection energy and the triplet aperture at top energy from bunches with small impact parameters) stays constant. Brennan Goddard said that for validating the ATS-compatible optics proposed by Stephan, where a change in phase advance between the TCTs and TCDQs is foreseen, he would like to test asynchronous dumps with different values of the retraction of the collimators involved.

GLOBAL OVERVIEW OF BASELINE OPERATIONAL PARAMETERS

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Abstract

This paper gives a global overview of the machine and beam parameters most likely to be chosen for the LHC proton beam operation in 2015: beam energy, bunch spacing, optics and β^* reach, preferences for the mitigation of instabilities, etc. The peak instantaneous luminosity performance is sketched, both for a conservative scenario and for a pushed one.

INTRODUCTION

The first period of LHC operation ("LHC Run 1", end of 2009 to beginning of 2013) was characterized by extreme success, and culminated in the discovery of the Higgs boson. It is worth recalling that the few weeks of operation in 2009 and the whole 2010 were dedicated to the first exploitation of the machine, and the target of the year was set in terms of peak luminosity performance. The following years, 2011 and 2012, could then be dedicated to luminosity production, and the yearly targets were set in terms of integrated luminosity. Detailed values are reported in Table 1, and the positive balance between target values and achieved values helps stress the Run 1 success.

Table 1: Yearly targets and achieved results in Run 1.

Year	Target	Achieved
2010	$10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$2.1 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
2011	$1\,\mathrm{fb}^{-1}$	$\approx 6\,\mathrm{fb}^{-1}$
2012	$20\,\mathrm{fb}^{-1}$	$23.3\,\mathrm{fb}^{-1}$

After the end of the first Long Shutdown (LS1, 2013-2014), Run 2 will start and it will be structured similarly to Run 1. The first year, after the major modifications carried out during the shutdown, will be dedicated to establishing proton operation at the higher energy and preparing for physics production. The following years, 2016–18, will be dedicated to physics production.

This paper summarizes the 2015 machine and beam baseline parameters as established for the preparation of this workshop, namely beam energy, bunch-to-bunch spacing, choice of the machine optics and β^* reach, options for the mitigation of instabilities, etc. The beam parameters and their evolution are also sketched, and folded into a projection of the peak luminosity performance.

BEAM ENERGY

The LHC was designed to run at a centre of mass energy of 14 TeV, i.e. 7 TeV per beam [1]. Due to issues with the quality of the main busbar splices, the beam energy was initially reduced to values for which the risk to have a 2008-like incident was evaluated to be negligible: 3.5 TeV/beam in 2010 and 2011, 4 TeV in 2012. During the LS1, a full campaign of splice verification and repair was performed, so to guarantee a splice quality allowing operation up to the design energy.

A campaign of training quenches will be performed during the hardware commissioning period preceding Run 2, in the second half of 2014. Estimates predict that $\approx$15 quenches will be necessary to reach 6 TeV/beam, $\approx$100 quenches for 6.5 TeV/beam and one order of magnitude more will be necessary to reach 7 TeV/beam [2]. The maximum possible beam energy will be known only at the end of the hardware commissioning campaign, foreseen for December 2014.

For 2015, it is decided to run at a maximum beam energy of 6.5 TeV (it is unlikely but possible that the hardware might limit the energy to lower values). This choice is partly determined by the LHC experiments' need to know the energy early on to perform the relative Monte Carlo simulations: a conservative but likely choice is preferred for 2015, while further increases towards the design value are foreseen for the following years.

BUNCH SPACING

The LHC experiments clearly state a preference for 25 ns spaced beams, as planned originally [1]. The alternative, 50 ns spaced beams, results in too high pile-up (μ, number of inelastic events per bunch crossing) for the same luminosity.

The maximum pile-up that the ATLAS and CMS experiments accept for 2015 at the start of a physics fill is $\mu \approx 50$ [3]. Note that if luminosity levelling is required, then the experiments would prefer levelling further down to the more comfortable levels of $\mu \approx 30$–40.

From the machine point of view, 25 ns operation brings along new challenges and possible complications: the formation of electron cloud and the resulting need to scrub [4]; more long-range encounters, resulting in increased beam-beam related problems; the need for a larger crossing angle, also resulting in higher β^* values; higher total beam current and higher intensity per injection, concerns for beam

intercepting devices and Machine Protection in general; increased statistics of Unidentified Falling Objects (UFOs), which additionally worsen with the higher energy [5].

OPTICS

The choice of which optics to use was recently discussed in several occasions [6, 7]. At present, the idea is to restart with an Achromatic Telescopic Squeeze (ATS)-compatible optics, which includes: new collision optics for all experiments (Interaction Region, IR), e.g. to overcome strength limitations of the 2012 optics, and compatible with the full ATS scheme and "flat beam" optics; an exact 90 degree phase advance between the dump kicker (MKD) and the dump protection absorber (TCDQ); increased separation at IR8 (see also [8]); new optics in IR4 to allow the increase of the β function at the transverse emittance instrumentation like wire scanners and synchrotron light telescope (which would otherwise be diffraction limited at the higher energy, due to the operational emittances that are more than a factor two smaller than in [1]).

It is fairly unlikely that innovative options are implemented for the 2015 restart (e.g. flat beams, or the combination of acceleration and squeeze, i.e. "combined ramp and squeeze"). At present there is no request from the LHCb experiment to perform the tilting gymnastics like in 2012 [3].

The full validation of this new optics will be performed in the coming months to prepare for a final choice at the Chamonix LHC Performance Workshop (22–26 Sept. 2014). The items that require follow-up are: the verification of the dynamic aperture, including beam-beam weak-strong simulations and octupoles; the verification of the presence of loss spikes due to a possible local collimation inefficiency; the impact of injection kickers misfires in IR8; the implications of the change of phase between the IR5 tertiary collimator and the dump kickers for ring 2 (the new phase advance is 90 degrees, resulting in the collimator to be directly exposed in case of asynchronous dump: most critical item in this list). The change of phase advance between the MKD and the TCDQ was already verified and approved.

β^* Reach

The configuration at injection is fairly similar to 2012: $\beta^* = 11$ m in IR1/5, $\beta^* = 10$ m in IP2/8, 170 μrad half crossing angles, and 2 mm separation (IR8: 3.5 mm).

Concerning the flat top, it is proposed to start with a fairly conservative scenario in the beginning of 2015, and push further the performance at a later stage (e.g. autumn 2015 or beginning of 2016). For commissioning efficiency, the cycle would be prepared and corrected up to the smallest β^*, while physics production would start at a conservative value and be pushed further after the main questions are resolved (e.g. beam stability and emittance control).

A possible start-up configuration includes [9]: 2012 collimator settings in mm in IR7, 11 σ beam-beam separation, up to 3.75 μm emittance, and results in: $\beta^* = 65$ cm and 160 μrad half crossing angle. This configuration does not require luminosity levelling at IR1/5 and should not pose problems in terms of beam stability. It assumes a 2012-like aperture, which is to be verified at the start of commissioning.

The configuration could later be pushed to the following "ultimate" values [9]: 2012 collimator settings in σ, 10 σ beam-beam separation, up to 2.5 μm emittance, resulting in $\beta^* = 40$ cm and 155 μrad half crossing angle. This configuration requires the beam to be stable and the emittances to be under control, and takes advantage of the full gain from the new tertiary collimators with integrated beam position monitors. This scenario might impose the need for luminosity levelling at IR1/5.

MITIGATION OF INSTABILITIES

At the injection plateau a chromaticity $Q' = 2$ is used. Concerning the Landau octupoles, a starting value could be $K_3L = 12$ m^{-3} that was used during the 2012 scrubbing run (i.e. 26 A in the focusing octupoles), even though further studies are required to prove what the optimum is.

Concerning high energy, the recommendations from collective effects team [10–12] include the use of negative polarity for the focusing Landau octupoles, which is best for single beam stability, and high chromaticity ($Q' = 15$). It is also advised to avoid the long-range regime in the squeeze where instabilities were observed in 2012, either by setting large crossing angles and use small emittances, or by performing the last part of the squeeze with colliding beams to profit from the Landau damping given by the head-on beam-beam encounters ("collide&squeeze", from $\beta^* = 3$ m).

In case of problems, alternative options are the use of collide&squeeze, the opposite octupole polarity or eventually to increase the β^* so to be able to retract the collimators and reduce the impedance. It is important to stress that possible problems or requirements will be probably confirmed only at the start of the intensity ramp-up period, with multi-bunch operation. Nevertheless, a maximum of beam-based experiments should be performed as early as possible, e.g. the measurement of the instability growth rates and octupole strength thresholds with chromaticity and ADT gain should be performed as early as possible to improve the understanding.

In this context it is worth recalling that the request for bunches non-colliding in IP1/5 is still standing [3], in order to allow the experiments to evaluate the beam-gas background.

Collisions and Squeeze

Collide&squeeze [13] was positively tested in three Machine Development sessions in 2012, proving the feasibility and reproducibility of the orbit at an interval of about three weeks. The full operational feasibility is yet to be demonstrated though, the main question being the orbit

Table 2: Beam parameters at injectors, production schemes. Values are at SPS extraction.

Scheme	standard	BCMS
production scheme	$(4+2) \times 3 \times 2 \times 2$	$(4+4) \times 3/2 \times 2 \times 2$
bunches/PS batch	72	48
max number of SPS injections	4	5 / 6
transverse emittance [μrad]	2.4	1.3
N_b [10^{11} p/b]	1.3	1.3
max number of bunches/ring	2748	2604 / 2508
max numebr of colliding pairs in 1/5	2736	2592 / 2496

control and reproducibility (to keep the beams colliding, within some deviation, e.g. $< 1\sigma$).

When performed in "Stable beams", collide&squeeze becomes "β^* Levelling", in which the possibility to change the β^* to modify the luminosity and thus the pile-up is emphasised (as opposed to the use of collisions as a stabilization means). Obviously, this implies a change of optics during "stable beams", with all the complications that derive from this (e.g. collimator movements and loss maps). A set-up overhead is foreseen with respect to the traditional commissioning to allow for finer beta-beating corrections, possibly at every squeeze stop point.

One of the two options might be needed before the end of Run 2 for helping beam stability or for levelling luminosity at ATLAS and CMS if the more pushed scenarios are successful, and β^* levelling is part of the Hi-Lumi LHC upgrade. Consequently, even if not part of the baseline choices at startup, it would be important to perform milestone tests and a basic preparation during commissioning to acquire some experience with these techniques and ease their implementation later. LHCb volunteers for the first tests of β^* levelling, and is supported by the other experiments.

BEAM PARAMETERS

Production

At present, two schemes are foreseen at the LHC injectors to produce 25 ns spaced beams [14, 15]. The main characteristics of the standard scheme [1] and of the newer Batch Compression, bunch Merging and Splitting scheme (BCMS, [16]) are recalled in Table 2.

Notably, the BCMS scheme provides smaller emittances but shorter trains injected into the SPS. The maximum number of injections from the PS into the SPS are presently being looked into: six injections seem feasible from the point of view of kick lengths, but might exceed the damage limits at the TDI [17].

Beam Parameter Evolution in the LHC Cycle

The transverse emittance evolution in the LHC cycle in 2012 is not fully understood. Some causes for the blow-up are known, e.g. Intra-Beam Scattering (IBS), 50 Hz noise,

the end-of-squeeze instabilities, but additional, unknown ones were also present. In this context, it is important to stress the importance of the transverse emittance measurements, which should be operational as soon as possible in Run 2.

We assume a worst case scenario of 3.75 μm emittances at the start of physics, e.g. on selected bunches due to electron cloud. We also assume a best case scenario in which instabilities and transverse emittance blow up are under control, and electron cloud sufficiently scrubbed. In this best case, IBS is still present, and, when simulated for BCMS beams, results in a 20% emittance increase ($<0.3 \mu$m, for 1.3 μm, 1.3×10^{11} p/b, 1.25 ns [18]), mostly due to the injection plateau and energy ramp. For the performance estimates, we take additional margins and consider an overall 30% emittance increase, which can include, together with IBS, also some emittance increase from vertical coupling and other unknown sources. Consequently, 1.3 μm at injection result in 1.7 μm at the start of physics.

Concerning the intensity evolution and losses, we assume 5% losses, i.e. 95% transmission over the whole cycle, which is in agreement with the 2012 experience [19]. Consequently, 1.3×10^{11} p/b at injection results in 1.2×10^{11} p/b at the start of physics.

Concerning the longitudinal parameters, more is available in [20]. The bunch length is 1.2 ns at the injection plateau for 6 MV total voltage. Thanks to the controlled emittance blow-up, the bunch length at the flat top can be controlled, and is set to 1.25 ns, in 12 MV. While longer bunches help reduce machine equipment heating thanks to the narrower spectrum, are favourable for IBS growth rates in the transverse plane, and help reducing the vertex pile-up density, shorter bunches help reduce the losses in collisions (the reduction of off-momentum dynamic aperture is due to the beam-beam interactions). Consequently, in the absence of elements that require bunch lengthening, shorter bunches are favourable from the point of view of losses and integrated luminosity.

PROJECTED PERFORMANCE

The start-up and ultimate scenarios introduced earlier are used to estimate the instantaneous luminosity at the start of physics (Table 3). A range of emittances is used: on one side, the maximum acceptable for that set of settings, on the

other side the BCMS 1.7 μm best case. The BCMS scheme, with five PS-to-SPS injections, is preferred thanks to the low emittances, and the proposed physics filling scheme is defined in [3]. It includes a total of 2508 bunches and 2496 colliding pairs in IP1/5. For comparison, a sixth PS-to-SPS injection would allow having 2592 colliding pairs in IP1/5. The nominal scheme, despite offering less profitable emittances, can provide up to 2736 colliding pairs in IP1/5. It should still be considered a viable alternative in case of problems with the BCMS scheme.

Table 3: Main beam and machine parameters and projected peak performance.

Parameter	start-up	ultimate
bunch spacing	25	25
β^* [m]	0.65	0.40
beam-beam separation [σ]	11	10
half crossing angle [μrad]	160	155
N_b [10^{11} p/b]	1.2	1.2
transverse emittance [μrad]	3.75 - 1.7	2.5 - 1.7
colliding pairs in IP1 and 5	2496	2496
total number of bunches/ring	2508	2508
L [10^{34} cm^{-2}s^{-1}]	0.7 - 1.3	1.4 - 1.9
pile-up μ	22 - 39	43 - 56
stored energy [MJ]	312	312

Even in the start-up scenario, in case the emittance blow-up is under control, the 10^{34} cm^{-2}s^{-1} design luminosity can be reached and even exceeded. In the case of the ultimate scenario and controlled emittances, the pile-up mildly exceeds the experiments' request and the peak luminosity exceeds the triplet cooling limit (1.75×10^{34} cm^{-2}s^{-1} [21]).

CONCLUSIONS

The baseline parameters for the 2015 LHC run are introduced: 6.5 TeV beam energy, 25 ns spaced bunches, produced by the means of the BCMS scheme, which allows reaching up to 1.2×10^{11} p/b and 1.7 μm at the start of collisions. The choice of the ATS compatible new optics is pending validation, and negative focusing octupole strength is suggested together with high chromaticity for the control of instabilities. Two possible scenarios are proposed: a more conservative one that includes $\beta^* = 65$ cm and 160 μrad half crossing angle, and an ultimate one characterized by $\beta^* = 40$ cm and 155 μrad half crossing angle. Both scenarios allow getting beyond design luminosity, if the transverse emittances are under control.

Only the effectiveness of electron-cloud scrubbing and the observation of multi-bunch effects (and UFOs) at the intensity ramp up will give final answers to the questions of emittance blow-up, beam stability, etc. A two stage approach to commissioning is strongly supported: at first, a conservative set of parameters is chosen, with a minimum set of unknowns and risks taken, and then, after a first

period of physics, the performance can be pushed further based on the acquired knowledge. In view of this two-stage approach, it is important to still invest in key early measurements that would allow a faster implementation of new features in the second part.

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EXPERIMENTS EXPECTATIONS

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Abstract

This paper presents the expectations and the constraints of the experiments relatively to the commissioning procedure and the running conditions for the 2015 data taking period. The views about the various beam parameters for the p-p period, like beam energy, maximum pileup, bunch spacing and luminosity limitation in IP2 and IP8, are discussed. The goals and the constraints of the 2015 physics program are also presented, including the heavy ions period as well as the special running conditions.

STANDARD P-P RUNNING CONDITIONS

Before discussing individual parameters it needs to be re-stated that, from the physics point of view, the principle guiding the discussion on beam conditions is to maximize *total integrated* luminosity *usable for physics.*

This means, first of all, that when discussing the 2015 data-taking period one should consider the implications on the integrated luminosity reach of the whole Run 2 period. Moreover, considering machine performance, one should weigh the effect of reaching ultimate peak luminosity against the potential price to be paid in terms of commissioning time or machine availability, as well as any resulting condition, e.g. excessive pileup, that could degrade the data taking or analysis efficiency of the experiments.

Pileup and bunch separation

As always stated the most critical parameter for the high luminosity experiments is the number of interactions per crossing. A higher level of pileup has negative implications on several aspects of the experiments, including the readout capability, due to increase in detector occupancy, the trigger efficiency, affected by the higher rate of fakes, the reconstruction and analysis efficiencies, as well as the systematic uncertainties. All those aspects concur in decreasing the experimental accuracy that can be reached for a given delivered integrated luminosity. The requirements on online and offline computing resources increase as well with higher pileup. Clearly the negative effect of pileup is incremental, as well as analysis and physics dependent, hence one should not take any limit described in this paper as a sharp threshold, below which there is no effect and above which the experiments would stop working, but rather consider pileup as the key parameter to optimize the physics yield of LHC in conjunction with all other relevant machine parameters. ATLAS and CMS have studied carefully several effects and agree that a maximum level of pileup of about 50 would be manageable in Run 2, and would not require luminosity
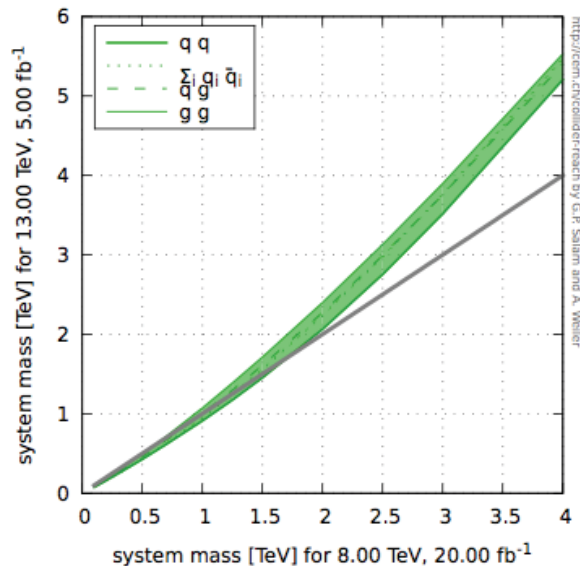

Figure 1: Discovery potential comparison: parton-parton system mass for which one gets the same number of events for 5 fb^{-1} delivered at a center of mass energy of 13 TeV with respect to 20 fb^{-1} delivered at a center of mass energy of 8 TeV. See [1] for more information.

levelling. It must be made clear though that handling such a level of pileup is challenging and it is hence only considered acceptable as an initial fill value, assuming the natural luminosity decay. In a scenario in which the fill luminosity would instead need to be levelled to a constant value, it would be preferable to target a much lower pileup value, ideally between 30 and 40.

As it is obvious that, for the same total peak luminosity, a beam with a larger number of colliding bunches has a lower pileup level, it is considered of paramount importance to aim at running with a bunch spacing of 25 ns, to maximize the ultimate physics reach of the LHC machine. It is understood and accepted by all experiments that running with 25 ns bunch spacing will need a longer commissioning period and could result in lower integrated luminosity delivered in 2015 with respect to an alternative setup with 50 ns, but it is still considered as the supported scenario in view of the longer term scientific goals. It must be otherwise stressed that the increase in beam energy will significantly improve the potential for discovery of new physics even with moderate luminosity (see Fig. 1), hence the 2015 data taking period should not be considered simply as a commissioning campaign. It is also understood that a phase of machine re-commissioning with 50 ns spacing will be needed, but it is expected to be limited to what is

required for establishing the machine conditions without spending time in optimizing performance.

Luminous region and optics

In addition to being affected by the total level of pileup, the experiments are also sensitive to the density of collisions over the luminous region, in particular for the efficiency of the reconstruction of the event's primary vertex in the tracker detectors. Hence, for high total pileup values, the length of the luminous region becomes an important parameter. The experiments would prefer to keep the luminous region at the beginning of the fill to values not significantly shorter than those of Run 1. Decreases of the order of about 10% would be acceptable, while shorter lengths may require further study. There is instead no major concern with adjusting the bunch length or the crossing angle to reduce the luminous region during the fill, in view of moderating the decay of luminosity. It is to be noted that also an excessive lengthening of the luminous region may reduce track reconstruction efficiency in ATLAS and CMS as well as the LHCb VELO acceptance for long-lived B mesons. As a general remark, it would be important for the experiments to know the expected beam parameters as early as possible for MC production.

There are no particular concerns from ATLAS and CMS with respect to the choices of optics at the IP. Injecting at lower β^* would not be a problem as the Van der Meer scan campaign will anyway require ad-hoc optics. Even the possible adoption of flatter optics is not seen as a problem, at least up to a β_x/β_y ratio of 2-3.

Filling schemes

The only constraint with respect to filling schemes for physics data taking is that they should include a few bunches not colliding in IP 1 and IP5, for both beam 1 and beam 2. These bunches have proven to be essential to background studies, as otherwise the experiments would have no direct way to evaluate the level of beam-gas interactions. It is proposed to shift, for one of the two beams only, the initial injection of 12 bunches, required for machine protection checks. Despite the fact that the non-colliding bunches should be as similar as possible to the colliding ones, it would be acceptable to inject lower charge for those ones, to mitigate potential instabilities due to lack of Landau damping.

Levelling and crossing in LHCb

The analysis of LHCb's Run 1 data has not shown a significant improvement of systematic uncertainties due to the tilted crossing angle scheme. This requirement is thus relaxed for Run 2. It is anyhow suggested to aim at minimising differences between the crossing angles for the two experiment's magnet polarities. A regular polarity swap will still be requested about every 100 pb^{-1} delivered to LHCb.

In 2015 LHCb will need the luminosity in IP8 to be levelled to 4-6 10^{32} cm^{-2}s^{-1}. While there is no particular preference for the specific mechanism of levelling, it is suggested by all experiments that a partial implementation of levelling based on modulation of β^* in IP 8 may be useful in view of collecting general experience on the β^* levelling approach, that could prove useful in case such a mechanism should need to be deployed at a later stage in IP1 and IP5.

ALICE conditions during the p-p period

The ALICE experiment needs to collect data in minimum-bias conditions during the whole p-p data taking period. This means that the luminosity in IP 2 should be levelled in a range between 5 10^{29} cm^{-2}s^{-1} and 2 10^{30} cm^{-2}s^{-1}. Assuming a bunch separation of 25 ns, which implies that most bunches collide head-on in IP 2, the required reduction of luminosity must be achieved mostly by beam separation. Looking at beam profiles measured in Run 1 during Van der Meer scan campaigns one can derive that a separation of the order of 5 σ will be needed. Dedicated studies must be carried on early on to assess the feasibility of such conditions. In particular the stability of luminosity conditions at such extreme separations should be addressed as well as the operational procedure to bring ALICE into collisions with a large enough separation, to avoid the risk of frequently triggering a beam dump when removing the separation bump. It is to be reminded in fact that ALICE BCMs have a dump threshold presently estimated to be set at a luminosity of about 6 10^{31} cm^{-2} s^{-1} [2].

ALICE requires to have a few bunches colliding in IP 2 during the 50 ns period. An ad-hoc filling scheme with a few head-on collisions would be preferable given the relative instability of conditions achieved with the main-satellite collisions approach followed in Run 1.

HEAVY IONS CONDITIONS

Four weeks of running have been allocated for Heavy Ions data taking in 2015. It has been decided to run with Pb-Pb collisions at the equivalent nucleon energy of 5.02 TeV. The luminosity reach is expected to exceed the maximum value acceptable by ALICE of 10^{27} cm^{-2} s^{-1} (see [3]), hence a levelling mechanism will have to be setup at least in IP 2. It is suggested to implement levelling as well in IP 1 and IP 5, despite not directly needed by ATLAS and CMS, to limit the performance penalty in ALICE, due to the larger ions burn-off in the other collision points. It is also to be reminded that ATLAS and CMS require a reference sample of p-p collisions at the equivalent proton energy. The actual extent of this data taking period, as well as its detailed schedule are still being discussed in the LPC meetings, but it is required that the necessary commissioning is carried out before the start of the Heavy Ions period.

EARLY COMMISSIONING PERIOD

At this moment the only specific request from the experiments for the initial machine commissioning period is to deliver about 20 beam splashes per beam in both IP1

and IP 5 as well as few TED shots, during the sector tests of sector 78, for LHCb alignment studies. It is also expected that stable beams conditions will be established as soon as possible to allow detectors and triggers commissioning. Some data taking in stable beams conditions will be regularly requested during the phases of intensity ramp up. Dedicated runs with low or very low pileup are not requested at the moment as we expect to collect data in such conditions parasitically during the special run for LHCf.

SPECIAL RUNS

Given the shortness of the 2015 data taking period and the extent of the commissioning campaign, it has been decided to limit the program of special runs to a minimum. The only exceptions foreseen at this moment are special runs for LHCf and a high $\beta*$ period for diffractive physics in ALFA and TOTEM, as well as two Van der Meer scan campaigns.

LHCf run and VdM scans

It is envisaged to combine the first VdM scan and the LHCf data taking periods and to schedule them in the very early days of the 2015 physics period (within about a week of data taking). An early VdM scan is indeed needed for an initial calibration of the luminosity measurements, given the change in beam energy. The LHCf run needs instead to be scheduled before about 500 pb^{-1} of luminosity are delivered to IP 1, to prevent significant degradation of the LHCf detector that suffers from radiation damage even when left in garage position.

LHCf needs to take data with large $\beta*$ as well as with very low pileup ($\mu<0.01$) and large bunch separation ($>2\mu s$). Due to the increased beam energy and the subsequent natural reduction of the beam size, it is established that the VdM scan will need to be performed with un-squeezed optics in order to keep the luminous width significantly larger than the experiments' vertex resolution, to study the non-linear x-y beam correlations that are a dominant source of uncertainty for the luminosity calibration. It is thus suggested to establish ad-hoc optics to accommodate both programs. The requested values of $\beta*$ are 19 m for IP 1 and IP 5, while LHCb would benefit from a larger value, between 30 and 40 m.

The requests in terms of luminosity per bunch are significantly different for the two programs, hence it is suggested to always inject bunches of about 7 10^{10} protons, ideal for the VdM scans, and reduce the pileup in IP 1 by separation when providing data to LHCf.

It is essential to remind that LHCf will need a half crossing angle of 145 μrad. Despite not being ideal, it is accepted that the initial VdM campaign will be performed with the same crossing angle, to allow the commissioning of a single machine setup for both programs.

It is foreseen to start this special run campaign with the VdM scans in the four interaction points and then proceed with the LHCf data taking. LHCf will ideally start collecting data during the scan in IP 5. It is still unclear if a filling scheme can be established to allow LHCf to also take data parasitically during the scans in IP 2 and IP 8 and yet have a total current compatible with operating the DCCT detectors in their preferred range.

A second VdM scan period will need to be scheduled in the second part of the 2015 run, for reaching ultimate precision. This run will need a setup without crossing angle.

Both VdM scans will need a rather large emittance (about 3 μm) as well as special care in the injector chain to deliver beams with nearly-gaussian transverse profile.

High beta runs

Both ALFA and TOTEM have requested data taking with $\beta*$ of 90 m for diffractive physics studies. TOTEM in particular has requested a joint data-taking period with CMS with the target of collecting about 10 pb^{-1} of central diffractive event data. Given the need for low pileup conditions, it is foreseen to inject bunches with a charge of about 7 10^{10} protons. To maximize total luminosity and yet respect the minimal bunch separation requirements of TOTEM, it is suggested to setup a filling scheme with about 1000 bunches and 75 ns of bunch spacing. This requires the development of a machine setup with a crossing angle. It is important to state that even in those ideal conditions one would only reach a luminosity of about 10^{31} cm^{-2}s^{-1}, making the TOTEM statistics goal quite difficult to reach, given 2015 tight schedule. Any degradation of these ideal conditions would immediately put the scientific program in danger.

Since the insertion of the Roman Pots with standard optics is envisaged, it is suggested that end of fill studies be scheduled to test the mechanism during the machine commissioning and intensity ramp-up programs.

ACKNOWLEDGMENTS

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COLLIMATION AND β^* REACH

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Abstract

The reach in β^* of the LHC depends on a number of different parameters, including both the collimation hierarchy and the available aperture, but also on impedance and the needed crossing angle. We investigate different options and make a proposal for the starting configuration of Run II in 2015. The focus is more on feasibility than on performance, and the proposal is based on what is believed can be achieved based on the Run I experience. Furthermore, we discussed different options on how to push the performance later in the run by squeezing β^* to smaller values.

INTRODUCTION

The LHC collimation system [1, 2, 3, 4] influences directly the peak luminosity performance in two ways. Firstly, the cleaning inefficiency (the local losses in a cold element normalized by the total losses on collimators), together with the beam lifetime and the quench limit, defines the maximum acceptable intensity. Secondly, when pushing the β^* to smaller values, the β-function in the inner triplets increases, meaning that the normalized aperture margin between the central orbit and the mechanical aperture decreases. If this margin becomes too small, the aperture can no longer be fully protected by the collimation system. At what aperture this occurs depends on the collimator settings. The loss in aperture is further enhanced by the fact that a larger crossing angle is needed at smaller β^* in order to keep the same normalized beam-beam separation.

The collimation performance has to be evaluated both in terms of cleaning (the removal of unavoidable beam losses during routine operation) and machine protection, in case of failures and abnormal operation. It is based on a multi-stage cleaning hierarchy, where the different collimator families have to be ordered with different distances to the beam [1]. Closest to the beam, in the IR7 betatron cleaning insertion, are primary collimators (TCP7), followed by secondary collimators (TCS7). Further out are absorbers (TCLA). In IR6, at the beam extraction, are special dump protection collimators (TCS6 and TCDQ). They should be positioned outside of the TCS7 aperture. Furthermore, in the experimental IRs, tertiary collimators (TCTs) made of tungsten are installed in order to provide local protection of the triplets and to reduce background. We call the horizontal TCTs TCTH and the vertical ones TCTV. The TCTs are not robust themselves in case of high-intensity impacts

of primary beam and should be positioned outside the aperture of the dump protection in IR6 with adequate margins to avoid the risk of being damaged during a dump failure [1]. The hierarchy is schematically illustrated in Fig. 1.

RUN I EXPERIENCE

The collimator settings used during Run I (2010–2013) for physics operation at top energy, together with the resulting β^*, are shown in Fig. 1. All settings are shown in units of σ, which is the nominal standard deviation of the beam, calculated using the local β-functions at the collimators and a normalized emittance of 3.5 μm.

After the start-up in 2010, a safe and conservative approach was taken. A TCT setting of 15 σ made sure that even in extremely pessimistic running conditions, the TCTs would never be exposed. In 2011, the margins between IR6, TCTs, and aperture were evaluated quantitatively using new models [5] and it was found that they could be significantly reduced without compromising machine protection. As a consequence, β^* could be decreased from 3.5 m in 2010 to 1.5 m in 2011. Later in 2011, aperture measurements at 3.5 TeV with squeezed beams [6] showed evidence of a well-aligned machine with smaller errors than foreseen during the design phase. The measured triplet apertures, close to the mechanical design value, were used to refine the experimental basis of the calculation models for the reach in β^* [7] and allowed β^* to be reduced to 1 m keeping the relaxed collimator settings. The results of the aperture measurements in Run I are summarized in Ref. [8] and the full details can be found in Refs. [6, 9, 10, 11, 12, 13, 14]. This reduction in β^* was made possible also by using some margins in the beam-beam separation, which allowed the crossing angle during the $\beta^* = 1$ m operation to be kept at the same value as in the previous operation at $\beta^* = 1.5$ m.

For the 2012 run, the margins between IR7 collimators were reduced based on experimental studies on the limits of the long-term stability of the collimation hierarchy under drifts of the beam optics and orbit [15, 16, 17, 18]. The same studies showed also that a closer IR7 settings were possible without detrimental effects on beam stability, resulting in the so-called tight collimator settings being put into operation. With these settings, the TCP7 achieved a gap in mm similar to the nominal opening foreseen at 7 TeV. Furthermore, the calculation of margins between IR6, TCTs, and aperture was updated and based on a statistical approach, where the different errors were added in square instead of linearly, in order to have a more realis-
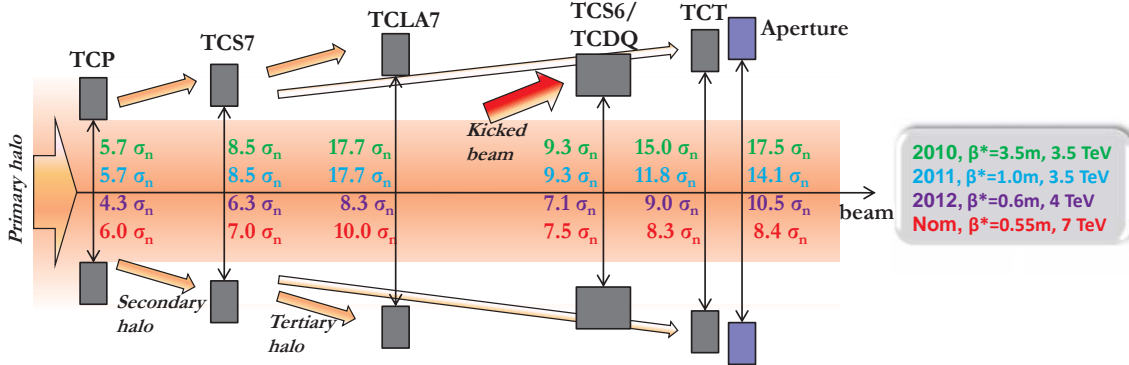
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Figure 1: Schematic illustration (not to scale) of the collimator settings and the minimum aperture that can be protected during the physics runs in 2010 (3.5 TeV), 2011 (3.5 TeV), and 2012 (4 TeV), together with the nominal settings (7 TeV).

tic total error [19]. The combination of tight settings and smaller margins made it possible to squeeze β^* to 60 cm, resulting in a significant gain in luminosity.

RUN II ASSUMPTIONS

At the start of Run II in 2015, many things will have changed compared to Run I. Most notably, the beam energy will be increased to about 6.5 TeV and the baseline filling scheme will be 25 ns instead of 50 ns [20], which imply major changes to the mode of operation. The beams will be more dangerous, the quench limit lower, and there are many uncertainties regarding the loss spikes and instabilities observed in Run I. Therefore, the machine behavior is harder to predict in detail than e.g. before the 2012 run. In view of this, it could be considered wise to start carefully in a configuration that provides some margin for the unknowns. Once sufficient beam experience is gathered, however, the performance could be pushed.

Based on these considerations, the authors would like to propose a strategy where, at the start-up, the focus is put more on feasibility, stability, and ease of commissioning, rather than peak luminosity. It should, however, not be overly pessimistic. The operational achievements in Run I are used, where possible, to deduce what is likely to work.

Different collimator settings have been under consideration for the start-up and the three main scenarios are shown in Table 1. In terms of cleaning, the relaxed settings are close to the limit of preventing a beam dump at a beam lifetime of 12 minutes and full nominal intensity, although significant uncertainties exist [21]. The other two settings have better cleaning efficiency and should suffice, unless the beam lifetime drops significantly below the 12 minute specification. Therefore, if the quench limit and beam lifetime are not worse than expected, we do not expect the cleaning inefficiency to be a limiting factor for the total intensity.

In order to be on the safe side for the cleaning, but without going to the tighter gaps with the 2 σ retraction that are more challenging for impedance, we propose to start Run II with the 2012 setting kept in mm (see middle column in Ta-

ble 1). They also have a well-proven long-term stability in terms of preserving the hierarchy.

The margins in the hierarchy might be reduced even further, using the gain of a better orbit knowledge from the BPM buttons in the newly upgraded TCTs [22, 23], however, before this can be done, more experience is needed in order to understand the limitations. Therefore, we propose to start without using this gain to allow for a learning period, and use it at a later stage to further squeeze β^*.

The impedance and single-beam stability for the different collimator settings are discussed in Ref. [24]. It is shown that for the nominal, large-emittance beam, all proposed collimator settings should provide sufficient stability with both octupole polarities, while stability could be an issue with other beams with smaller emittance. Our assumptions in the rest of this paper is thus a nominal 3.75 μm emittance when considering beam-beam separation and stability[1], which is also compatible with assumptions on electron cloud [25]. The two-beam effects and octupole polarities are discussed in detail in Ref. [26]. Being able to use both octupole polarities introduces more flexibility at the start-up, since there could be a chance to start operation without collide and squeeze, which otherwise requires a significant overhead in terms of commissioning time and complexity [27].

For machine protection, the settings in Tab. 1 fulfill the same demands as used during Run I [19, 28] in terms of the IR6 dump protection shadowing the TCTs and the TCTs shadowing the triplet. However, it is under investigation whether the situation post-LS1 requires additional safety margins because of several factors. Firstly, because of the higher energy, the TCT damage limit in number of protons is also lower. On top of that, the baseline filling scheme is 25 ns instead of 50 ns, which means that there risks to be double the number of bunches within the critical time window during asynchronous dumps when bunches pass the dump kickers and receive intermediate kicks. Now in 2014, more advanced simulation tools are available than during Run I [29, 30, 31], so in order to quantify the im-

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[1] 3.5 μm is still used for collimator settings.

Table 1: Settings, of different collimator families, for different scenarios for 6.5 TeV operation after LS1, where either the 2012 settings are kept in mm, in σ or more open (relaxed).

Settings	Relaxed settings	mm settings kept,	σ settings kept
TCP7 (σ)	6.7	5.5	5.5
TCS7 (σ)	9.9	8.0	7.5
TCLA7 (σ)	12.5	10.6	9.5
TCS6 (σ)	10.7	9.1	8.3
TCDQ6 (σ)	11.2	9.6	8.8
TCT (σ)	13.2	11.5	10.7
protected aperture (σ)	14.8	13.4	12.3

pacts on the TCTs during various accident scenarios, new studies are ongoing to estimate the expected damage risks and if the model to calculate margins are suitable also for Run II.

Furthermore, the collimator margins are calculated based on what was achieved in 2012. If the stability of the optics or orbit correction for post-LS1 would be worse, larger margins are needed. Therefore, one could consider introducing more margins at the startup, before the machine performance is well known, in order to be sure that the TCTs and aperture are protected. If no extra margins are introduced for the machine stability, these parameters have to be monitored very carefully at the startup.

Finally, it is under consideration whether the LHC optics will be changed to ATS [32]. This optics has a fractional phase advance in Beam 2 between IR6 dump kickers and the TCT in IR5 close to 90°, while the phase advance in the nominal optics is close to 180°. Therefore, the IR5 TCTs are much more prone to being hit by primary beam during asynchronous beam dumps with the ATS optics. The introduction of ATS optics may therefore require larger margins in the hierarchy on top of the possible increase mentioned above. Studies to quantify this are ongoing.

In order to estimate the reach in β^*, the aperture margin in the triplet needs to be calculated for different β^*. For that calculation, we assume that the aperture has not become worse during LS1 and, at this stage, do not include additional safety margin there. In any case, it is very important that the aperture is measured with beam very early on during the commissioning, and if it turns out that it is worse than expected, the time loss when stepping back to a larger β^* is very small.

For the aperture calculation, it is also needed to make an assumption on the crossing angle as function of β^*. For this, we use a beam-beam separation of 11 σ, as recommended in Ref. [26] and an emittance of 3.75 μm, corresponding to a half crossing angle of about 170 μrad for β^* =55 cm. This angle is sufficient even if the real emittance would be smaller. This is considered a safe value for the start-up, but could possibly be pushed to smaller values with beam experience. On the other hand, even larger beam-beam separations could be beneficial in order to suppress the long-range effect during the squeeze [26].

INITIAL PERFORMANCE REACH

We use two methods to calculate the aperture: the MAD-X aperture module with the parameters that gave the best agreement with Run I data (see Table 2 in Ref. [8]) and aperture scaling [28], starting from the most pessimistic aperture measurement in Run I. The results are shown in Fig. 2. The MAD-X calculation can for obvious reasons be carried out only at the matched optics points, presently available with a 5 cm granularity below 1 m, while the scaling provides a continuous function. Most calculations were carried out for the 11 σ beam-beam separation mentioned above and for nominal optics, but we show also a result for 12 σ separation and one point with ATS optics (more points are expected to be available in the future). Fig. 2 shows also the minimum aperture that can be protected for the different collimator settings in Table 1.

Several conclusions can be drawn directly from Fig. 2. It is clear that the two aperture calculation methods agree very well, as also demonstrated during Run I [19]. Furthermore, at the β^* value where the ATS optics is available, the achieved aperture with ATS is very similar to the nominal one. In terms of performance, the β^* value compatible with the different collimator settings can be read directly from Fig. 2. Sticking to the matched optics points, β^* =65 cm is the smallest value compatible with the mm kept settings. This is thus our proposed baseline, corresponding to a half crossing angle of 160 μrad.

This leaves also a small aperture margin. One option, if the aperture is well under control and checked with measurements, could be to use this additional margin to increase the beam-beam separation. As can be seen in Fig. 2, the aperture protected by the mm kept settings coincide almost exactly with the predicted required aperture if 12 σ beam-beam separation is used.

It should be pointed out that the proposed configuration relies on several assumptions. For the collimation hierarchy to provide adequate protection of the TCTs and the aperture, the optics and orbit correction has to be at least as good as in Run I. Furthermore, the aperture has to be as close to the ideal one as in the Run I measurements. If any of these prerequisites would not be met, one might have to start at a larger value of β^*. As an example, stepping back from 65 cm to 70 cm would imply a gain of about 0.7 σ
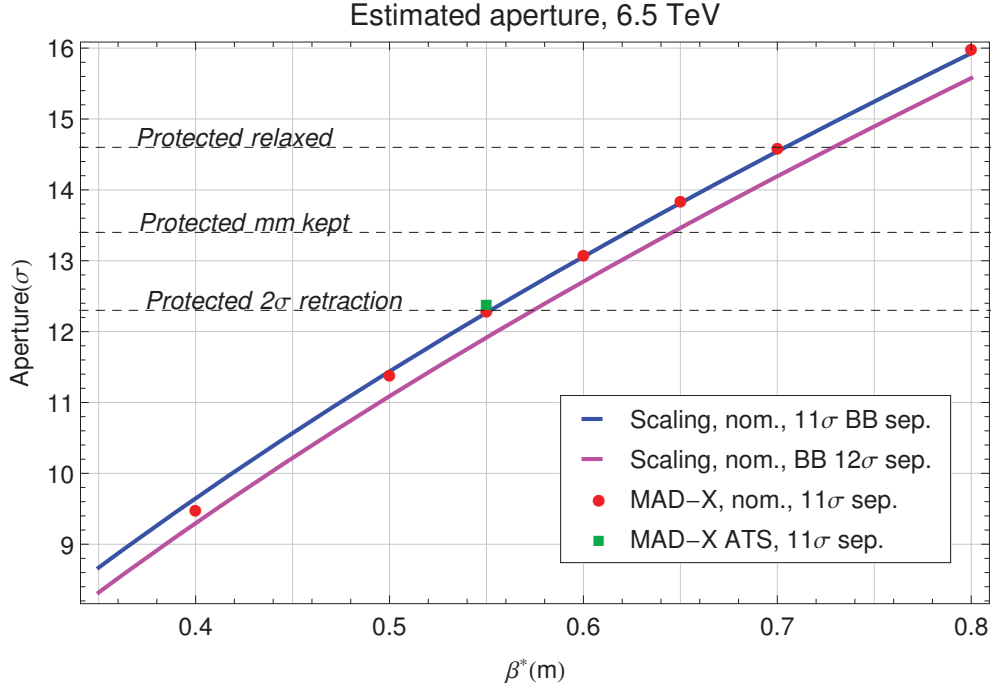
Figure 2: Schematic illustration (not to scale) of the collimator settings and the minimum aperture that can be protected during the physics runs in 2010 (3.5 TeV), 2011 (3.5 TeV), and 2012 (4 TeV), together with the nominal settings (7 TeV).

in aperture, while the gain is about 2.1 σ at 80 cm. The relaxed aperture margin could be used as additional margin between the steps in the collimation hierarchy according to the needs, to retract the whole hierarchy to gain impedance, or to tolerate a larger beam-beam separation and crossing angle if that would be needed.

For completeness, we investigate the reach in β^* also with the other collimator settings. For the 2 σ retraction settings, the protected aperture agrees almost exactly with the required aperture at β^* =55cm. Since there is no margin, it could be that this point does not work, as the aperture can only be predicted with a limited precision. Measurements with beam have to be used to determine if this point is acceptable. With the relaxed settings, β^* =75 cm the smallest compatible value, within 5 cm intervals. Stepping back to this configuration could be an option in order to decrease the impedance, if further studies show that the beam stability is an issue.

POSSIBILITIES TO PUSH β^* LATER IN THE RUN

Once the LHC has been successfully put into operation and a first period of stable beams has been established, the performance limitations and possibilities will be better known [33]. Then, the performance could be increased based on the operational experience and possible MDs. Several machine parameters could be changed to gain in luminosity performance (here we focus on the ones connected to β^*, and mention only briefly the most important

other parameters):

- Collimator settings: If the margins in the hierarchy are reduced, e.g. by establishing the 2 σ retraction settings, a smaller aperture can be protected, and thus a smaller β^* tolerated. However, with tighter settings, the impedance increases. Whether this is tolerable has to be evaluated after some first MDs. Based on further operational experience, the margins between the dump protection and the TCTs, as well as the margin between TCTs and triplets, might be decreased if the integrated BPM buttons can be used to reduce the drift of the orbit from the center of the collimators. The less temperature-sensitive BPM electronics could also be used to determine whether some of the large orbit drifts between TCTs and triplets, observed in Run I, are real or an artefact of the measurement.

- Crossing angle: reducing the crossing angle at a given β^* implies a gain in the required aperture. This reduction can be accommodated either by reducing the beam-beam separation, or operating at a smaller emittance. However, the needed beam-beam separation also increases slightly with decreasing emittance [26]. If the beam-beam separation is decreased, the long-range effect becomes more critical, in particular during the squeeze [26].

- Aperture: unless additional margins are introduced at the start-up, the gain should be rather small. The aperture in Run I was found in measurements to be very

close to the ideal one, and the same assumptions are used for Run II.

- Other parameters independent of β^*: A number of parameters can be used to increase luminosity, most notably the bunch intensity, bunch length, and machine availability. These are not discussed in detail in this paper.

As a realistic example on how to push the performance, we show how the design value of β^* =55 cm can be reached. One way would be to change the collimators to the 2 σ retraction settings. As can be seen in Fig. 2, the required aperture is at the limit of what can be tolerated. If the aperture, after measurements, turns out not to be sufficient, an additional small gain could be obtained by reducing also the margins between IR6 and the TCTs, based on the experience with BPM buttons. Possibly, the change of settings could also be combined with a small reduction of crossing angle.

Alternatively, the main gain could come from the crossing angle. Keeping the mm kept settings, β^* =55 cm and a crossing angle of 130 μrad implies an aperture that fits almost exactly with what can be protected. This configuration corresponds to a beam-beam separation of 8.3 σ for an emittance of 3.75 μm. If the emittance can be reduced to 2.5 μm, the beam-beam separation with this crossing angle is about 10 σ. This configuration is possibly compatible with 6 σ dynamic aperture [26].

In summary, several possibilities are at hand for reaching β^* =55 cm. We consider it rather likely that this should be possible through one, or through a combination, of the mentioned methods.

If we assume that both the collimation hierarchy and the crossing can be pushed to the limits that one can optimistically expect, then β^* could be squeezed significantly below the design value. For this ultimate scenario for Run II we assume the 2 σ retraction settings, with the addition of using the BPM button collimators to their full potential. Furthermore, we assume a beam-beam separation of 10 σ at an emittance of 2.5 μm. These assumptions are considered challenging but possible. They also require significant beam experience and commissioning time.

Using these collimator settings and crossing angle assumption, we obtain β^* =40 cm, together with a half crossing angle of 155 μrad. As an alternative to further increase the integrated luminosity by minimizing the loss from the geometric reduction factor at smaller β^*, flat beams could be considered. A configuration with β^* =40 cm in the separation plane and β^* =50 cm in the crossing plane should be compatible with the same aperture constraints [34]. In this configuration, the present planes for crossing and separation would be switched in order to optimize the usage of the beam screen aperture, which is larger in one plane.

In the future, we still hope to achieve nominal collimator settings in IR7 with a 1 σ retraction between the TCP7 and the TCS7. This would allow to reduce β^* additionally by 5 cm. However, because of the impedance constraints, this is unlikely to be usable during Run II. Installing new TCS7 made of other materials with lower impedance could help to make this possible. Furthermore, integrated BPMs in the TCS7 would help to ensure that the hierarchy is kept in spite of the smaller margin.

CONCLUSIONS AND OUTLOOK

We have given a brief overview of the collimation-driven limits on β^* and the evolution of β^* in Run I. For the 2015 start-up, we propose a configuration with the focus on feasibility and ease of commissioning, rather than peak luminosity, since many important changes have taken place. Based on the Run I experience, the 2012 collimator settings in mm could be used also in 2015. Together with the assumption of 11 σ beam-beam separation [26] and a nominal 3.75 μm emittance, this results in an initial β^* =65 cm and a half crossing angle of 160 μrad. To ensure that all limitations are under control, this could possibly be further relaxed. More aperture margin might be needed e.g. to retract all collimators and reduce impedance, to account for possibly larger drifts in orbit and optics than in 2012, or the higher risk of TCT damage during an asynchronous dump with ATS optics.

Later in the run, based on operational experience and MDs, it is likely that β^* can be squeezed further. The two main methods are to reduce the margins in the collimation hierarchy or reduce the crossing angle by using a smaller beam-beam separation or emittance. It seems realistic to go to the nominal β^* =55 cm, and even smaller β^*-values could be within reach. If we optimistically assume that a 10 σ beam-beam separation is sufficient for a 2.5 μm emittance, that the full theoretical gain in collimation margins from the BPM buttons can be used, and that the 2 σ retraction settings do not cause impedance problems, then β^* =40 cm is within reach. However, it might be that the real limit is higher, and it can be determined only with beam experience.

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THE LHC NOMINAL CYCLE, PRE-CYCLE AND VARIATIONS IN 2015

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Abstract

For beam operation in 2015 a number of changes and improvements are foreseen for the machine cycle. The FIDEL data must be corrected and updated. The different cycle phases will become longer and may require re-optimization. Proposals are made to improve the overall quality of the settings, to collide faster and to remove orbit spikes in the squeeze. Some issues related the collide and squeeze are briefly addressed.

FIDEL

The core of the FIDEL transfer functions (TFs) are already present in the LSA DB. Within the DB the transfer functions and field errors of each magnet or magnet family are modeled by a number of parameters. A dedicated application is used to build the tables of field or field gradient as a function of circuit current as they are used in the LSA trim. With respect to 4 TeV saturation becomes significant at 6.5 and 7 TeV. But the saturation corrections were always part of the FIDEL model, therefore no surprises are expected. Some changes must be made to correct errors in some TFs (for example the MQY magnets) while other TFs must be extended, for example the for triplet. The MB and MQ TFs must be updated to take into account the 18 magnets that were exchanged, even if the expected changes may be negligibly small.

Decay and Snapback

The decay and snapback amplitudes at injection will increase proportionally to the flat top energy, i.e. roughly by 50%, see Table 1. It should be possible to keep the faster PELP at start of ramp (2011 and 2012 ramps), no significant problems are expected. The decay on the flat top is expected to scale $\propto 1/E$.

Table 1: Decay amplitudes (at ∞) for the injection plateau.

Parameter	4 TeV	6.5 TeV
Tune	-0.022	-0.035
b3	0.4	0.5−0.6

The decay at injection and flat top as well as the snapback at the start of the ramp must be remeasured. The measurements will then be used to fit the b2 and b3 component amplitudes and time constants. No changes to the software must be made besides adapting to the new LSA API. The FIDEL server will be reused for the injection plateau. A separate ramp beam process will again be used for the spools to correct the decay at the flat top.

Pre-cycle

No pre-cycle was generated so far for 6.5 TeV, some work is required on the code and some LSA DB tables must be updated. The expected changes:

- The pre-cycle length increases by ≈ 1000 s (dominated by MQs), see Fig. 1. The total pre-cycle duration will be around 4000 s.

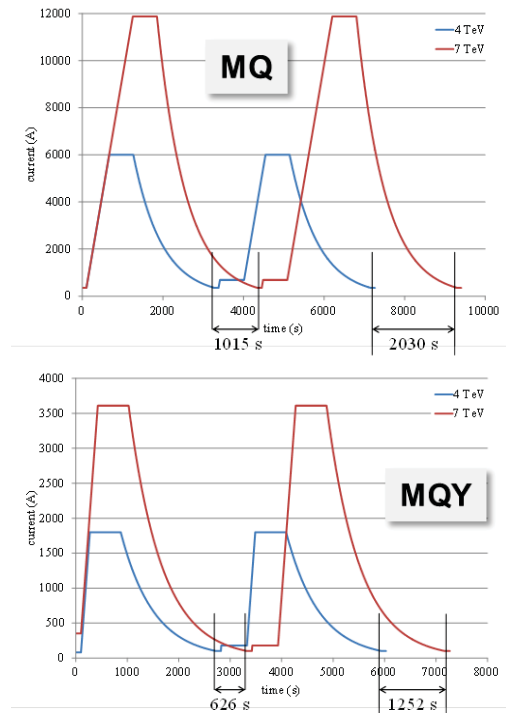- The ramp-down duration increases by ≈ 500 s to a total duration of around 2600 s.

Figure 1: Pre-cycle functions for the MQ an MQY magnets that dominate the duration of the pre-cycle (courtesy N. Aquilina).

COLLISION CONFIGURATIONS

For 2015 we consider the following main collision configurations [1]:

- Low β^* in the range of 0.4 to 0.7 m.

- Medium β^* of 20 m (30-40 m for LHCb) for LHCf runs and vdM scans.

- High β^* of 90 m that will not be discussed here.

Both the medium and low β^* configurations must be prepared during the initial commissioning phase. The expected parameters for the configuration at injection, low and medium β^* are shown in Tables 2 to 4. The parameter θ corresponds to half the total external crossing angle. All numbers and plots presented refer to the classic optics used in 2012 (not the ATS-compatible optics). No significant difference is expected for the ATS-compatible optics. Up to a beam energy of 6.78 TeV there is no need to perform a pre-squeeze in IR2 and IR8 (triplet gradient limit). The injection optics can be scaled up. A combined ramp and squeeze is therefore not mandatory for 6.5 TeV.

Table 2: Injection configuration for 2015. In IR8 a parallel angle of 40 μrad must be added to the increased separation in the vertical plane.

IP	β^* (m)	θ (μrad)	Separation (mm)
1+5	11	± 170	± 2
2	10	± 170	± 2
8	10	− 170	± 3.5

Table 3: Low β^* configurations at 6.5 TeV.

IP	β^* (m)	θ (μrad)	Separation (mm)
1+5	0.65	± 170	± 0.55
1+5	0.4	± 155	± 0.55
2	10	± 120 (?)	± 0.55
8	10−3	− 250	± 0.55

Table 4: Medium β^* configuration at 6.5 TeV.

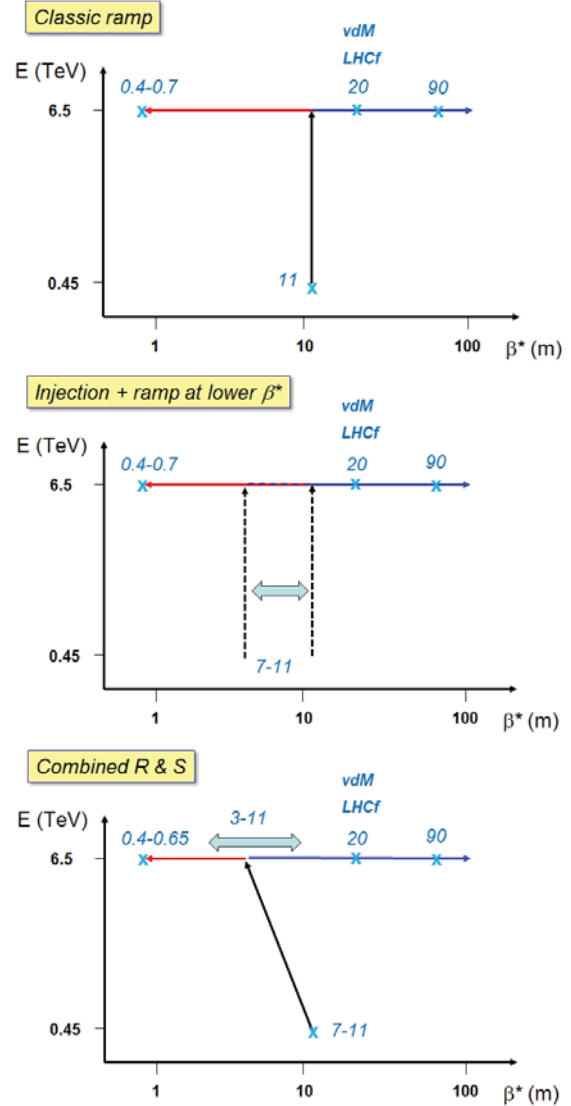| IP	β^* (m)	θ (μrad)	Separation (mm)
1+5	20	0	± 0.55
2	20	0 (?)	± 0.55
8	30−40	0 (?)	± 0.55

Figure 2: Three different possibilities for ramping and squeezing: classic 11 m injection and no optics change in the ramp (top), the same scenarios at lower injection β^* (middle) and finally the combined ramp and squeeze.

Combined Ramp and Squeeze

The duration of the ramp to 6.5 TeV will be 1200 seconds, which leaves of course ample time for potential optics changes. A combined ramp and squeeze beam process (R&S) may gain roughly 10 minutes during every LHC cycle with the reduced length of the squeeze, see Figure 2 for a comparison of different options for 2015. The design of the R&S and the generation of the settings are currently rather "clumsy" because the smoothing of the quadrupole gradients is not applied like in the squeeze, see Fig. 3. The distance between matched points (optics) must be tuned manually until the "kinks" in the functions become tolerable in terms of acceleration for the power converters. To operate seriously with R&S the smoothing that is performed for the squeeze design with parabolic segments must be extended

to the ramp. One can probably use the same principle than for squeeze, and apply the energy ramping on top of it.

Proposal: proceed with standard ramp for the moment, but initiate development and testing of improved R&S software to be ready for future use.

Tunes

For the entire pre-LS1 period, the tune change from injection tunes (0.28/0.31) to collision tunes (0.31/0.32) was made at the start of the squeeze with the matching quadrupoles in IR1 and IR5. Proposal were made already during Run 1 to change the tunes at injection to collision tunes.

Options and possible evolution of the tunes in the cycles are indicated in Fig. 4. With the tune change decoupled from the squeeze, it is easier to evolve and change without impact
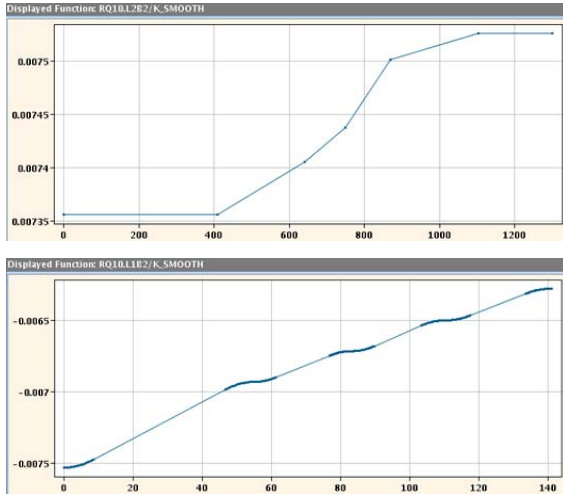
Figure 3: Evolution of the strength for the current ramp and squeeze (with kinks) and for the squeeze where the K's are smoothed (KSMOOTH functions).
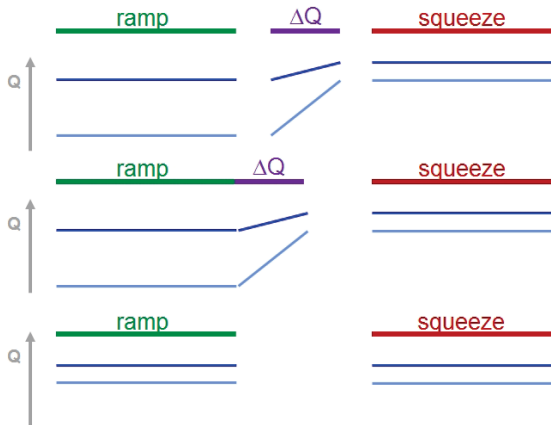

Figure 4: Possible scenarios for the evolution of the tune change between injection and collision tunes.

on the squeeze beam process. Furthermore the tune change should be made with the MQTs instead of the matching quadrupoles in 1+5: the change could be faster and it would lead to smaller orbit perturbations (strength change is more distributed). The induced beta-beating was simulated to be at the level of maximum 1%. This would be also ease switching from one tune working point to another: the tune is trimmed with the standard tune trim knob, and the optics id and name is updated (mainly for beam steering).

There are some practical reasons to use injection tunes instead of collision tunes at 450 GeV. They are mainly related to the tune signal quality and feedback performance. With collisions tunes the peak search windows are tighter and the peak search is more delicate, with a higher risk for the QFB to lock on wrong tune or switch off.

Proposal: start up with injection tunes at 450 GeV and review the choice at a later stage, decouple the

tune change from squeeze, use the MQTs to apply tune change with respect to the collision tunes.

Squeeze

The lengths of the squeeze beam processes at 6.5 TeV for different values of β^* are given in Table 5 for the standard optics. Possible target β^* values are presented in Reference [2]. In all cases the tune change is not included and the initial β^* values are 10 and 11 m. The duration of the squeeze does not change much when the energy is changed from 4 to 6.5 TeV because the duration is determined by the circuits (Q4, Q5 and Q6) that ramp down and where the length is dominated by the decay time constant of the circuit.

Table 5: Squeeze durations at 6.5 TeV.

Type	Energy (TeV)	Target β^* (m)	Duration (s)
2012	4	0.6	906
Squeeze 1+5	6.5	0.6	955
Squeeze 1+5	6.5	0.4	1154
De-squeeze 1+5	6.5	19	453
De-squeeze 1+5	6.5	40	1138
De-squeeze 1+5	6.5	90	2415

BUMPS

There are larger bump shape (separation and crossing angle) changes during the squeeze in IR8 and IR2 than in IR1 and IR5, see Figures 5 and 6. This is due to the injection constraints where the bumps should be closed before the injection point and where the phase advance is constrained for the injection optics. In addition the matched points at the start of the squeeze were too coarsely selected for the IR2 an IR8 bumps: the squeeze was over-optimized with respect to tune and chromaticity without taking sufficiently into account the orbit effects.

Recommendation for the low β^* squeeze: one matched point should be added for IR8 between 10 m and 7.5 m, and another one between 7.5 m and 6 m to smoothen the evolution of the orbit and bumps.

For the ATS-compatible optics a complete analysis and optimization must be performed for tune, chromaticity and orbit once the squeeze becomes available.

Orbit Trim Incorporation

A probable origin of (some of) the orbit spikes near matched points observed in 2012 is the different smoothing methods for orbit correctors [3]. The correctors that were part of the separation and crossing bumps, as well as the MCBX, were incorporated between matched points using the parabolic rounding like for example all the quadrupoles (Fig. 3). All other correctors use a PLP method that did not follow the same shape, but allowed them to be trimmed at any point of the squeeze, even outside matched points. After LS1 all orbit correctors will be smoothed in the squeeze with
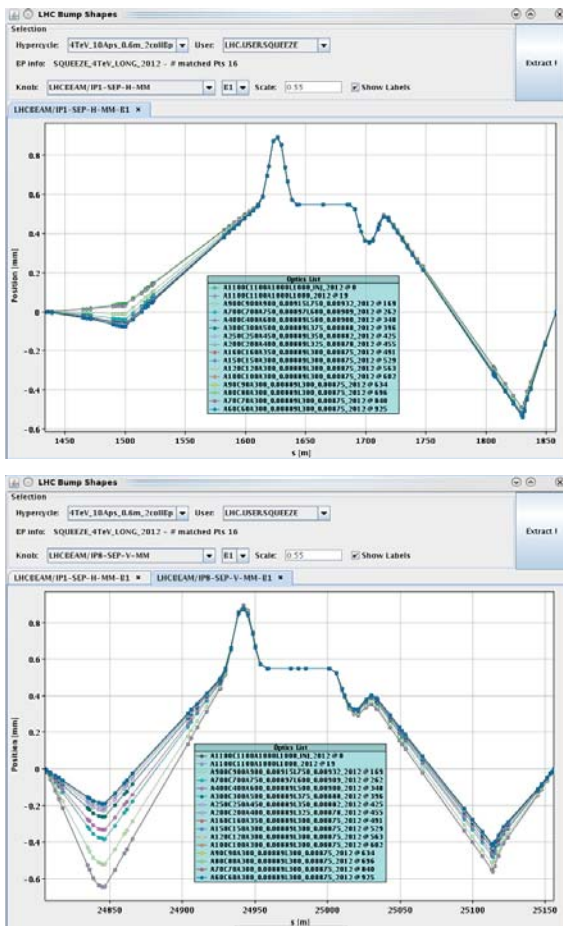
Figure 5: Evolution of the separation bump shapes during the 2012 squeeze in IR1 (top) and IR8 (bottom).

Figure 6: Evolution of the crossing bump shapes during the 2012 squeeze in IR5 (top) and IR8 (bottom).

parabolic rounding. The feed-forward of the real-time trims from the OFB will be applied as correction at the level of the KSMOOTH functions. This will hopefully remove the orbit spikes at the matched points.

COLLISION BEAM PROCESS

Since no problem was ever observed in the past during the IR1/5 separation bump collapse, one can continue to collapse IR1 and IR5 separation bumps together. Since the value of the separation knob is not a "static" part of the optics (it can be adjusted), the design of the collision beam process depends on its target value (and the required margin). For this reason the length of the parabolic sections at both ends and of the linear part are set manually. The required beam process length is adjusted by trial and error (and with time also some experience). Due to lack of diagnostics software, it was difficult so far to judge the efficiency of the collision beam process design. A new application that analyses all orbit corrections functions at the level of current I, ramp rate dI/dt and acceleration provides now diagnostics for the optimization of beam process parameters. An example for the analysis of the 2012 collision beam process is shown in Fig. 7: in that case it is apparent that the acceleration is very

low, less than 0.1 A/s^2, while the maximum acceleration of the circuit is 0.2 A/s^2. The parabolic segments of the beam process were longer than necessary, slowing down the collapse in the critical part when the separation is close to zero.

With the new application it is easy to optimize the beam process. As an example a collision beam process was designed for 6.5 TeV and a β^* of 0.5 m, where the ramp rate in the linear part was pushed to 90% of the maximum rate of the orbit correctors at Q4 and Q5 (those limit the ramp in the linear part), while at the same time the acceleration of the RCBX that is limiting the parabolic segment is also pushed to 90% of its limit. Figure 8 gives the evolution of the separation for that beam process.

As an additional improvement the parabolic part could be shortened further if the kick strength that is currently using a single RCBX would be spread over 2 or 3 MCBX instead of just one magnet. Another gain may come from the powering tests where the acceleration rates will be pushed towards 0.5-1 A/s^2 design values.
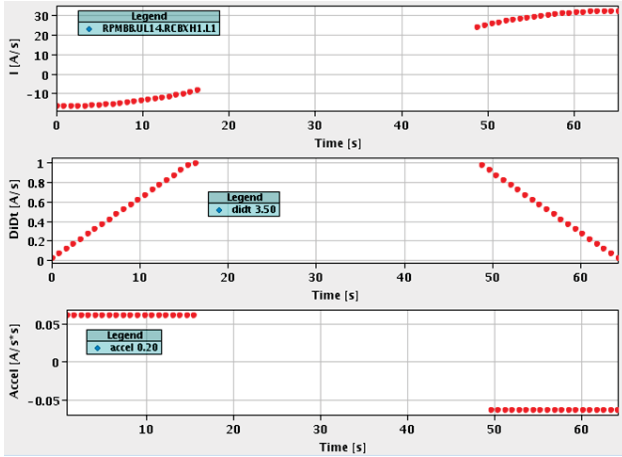
Figure 7: Evolution of the current I (top), the ramp rate dI/dt (middle) and acceleration (bottom) for the RCBXH1.L1 circuit during the 2012 collision beam process. The acceleration is only 0.06 A/s^2 for a limit of 0.2 A/s^2.
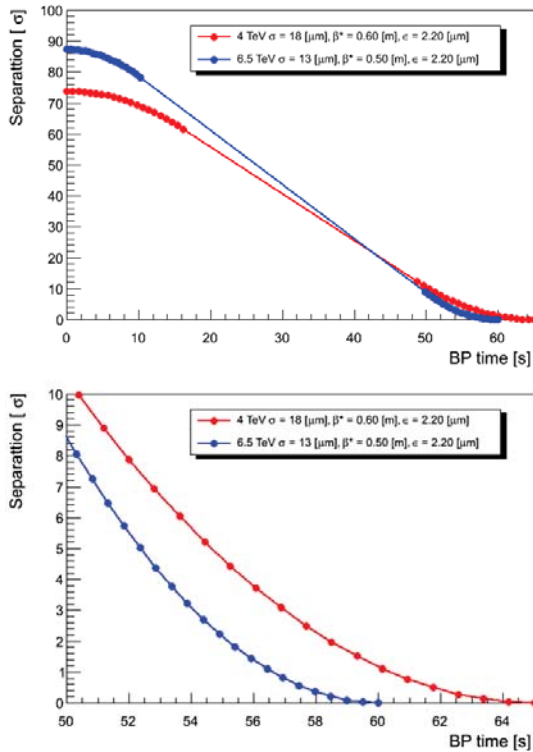

Figure 8: Evolution of the separation in IR1/5 for the optimized collision beam process at 6.5 TeV and the 4 TeV collision beam process used in 2012. The bottom figure is a zoom in the last part of the collapse. Despite the higher energy the 6.5 TeV beam process is shorter, and the collapse in the last parts where the beams approach each other is much faster.

ALICE

Due to the very low target luminosity of ALICE, see Fig. 9, offset leveling must be applied in IR2. The luminosity in ALICE is plotted as a function of the total separation of the two beams at 6.5 TeV for bunch populations of 1.2×10^{11}, β^* of 10 m and emittances of 2 μm and 3.5 μm. The corresponding beam sizes are 54 μm and 71 μm. A separation between 4 and 6 σ will be required, implying that the ALICE luminosity may become very sensitive to tails. It cannot be excluded that the luminosity will exhibits large fluctuations, in fact the luminosity may become an excellent tail diagnostics in the separation plane (i.e. horizontal).
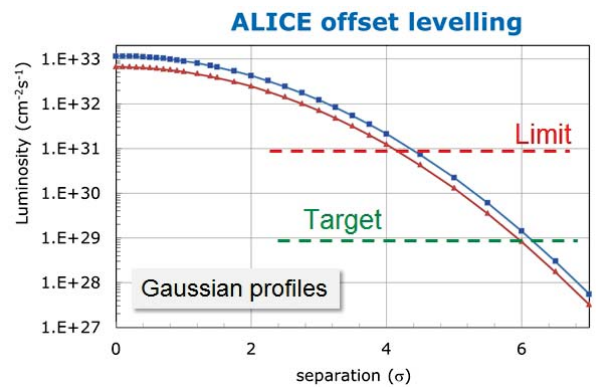

Figure 9: ALICE luminosity as a function of the total beam separation expressed in units of beam size.

Collide and Squeeze

In case the beam have to collide during the squeeze in IR1 an IR5 too ensure beam stability (C&S) [4], there are two options to handle the segment where the separation is collapsed. Either the beam collide at constant β^* and optics (Fig. 10 top) or the squeezes continues in parallel to collapsing the separation bumps (Fig. 10 bottom). For setup and regular (fill-by-fill) checks it must be possible to perform stops along the C&S at key points: before going into collision, at the first point where collisions are established, at the end of the squeeze and after colliding all IPs (yellow points in Fig. 10). In addition it must be possible to stop at intermediate points (pink points in Fig. 10) to establish collisions during commissioning and to re-establish collisions in case the beams no longer collide at a certain moment.

If the beam process is cut into 4 segments, the regular stops can be taken care of. The current implementation of the collimator interlock function does not allow intermediate stops due to the digital signatures associated with MCS. Either one has to split the squeeze into many short beam processes which makes the process rather clumsy, or one will have to revisit the collimator interlock function management (and / or MCS).

Another complexity of the C&S: head-on collisions will probably make life of the tune peak finder for the tune feedback even more difficult, unless non-colliding bunches are
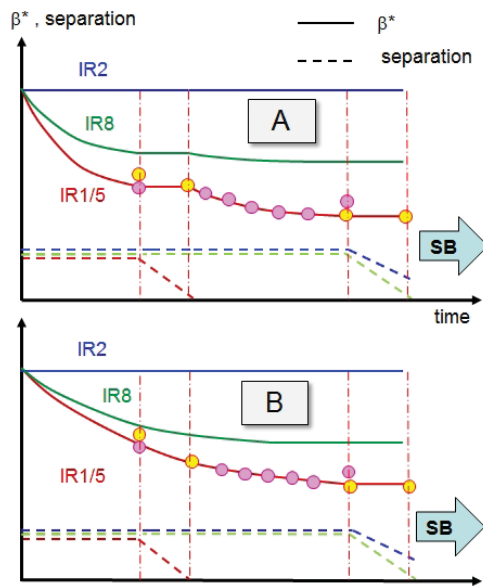
Figure 10: Possible design of a C&S where the squeeze is either stopped (top) or continued (bottom) while the separation is collapsed to bring the beams into collision. Stops points that are required for every fill are indicated in yellow, occasional stop points in pink (fixing the beam process, re-establish clean collisions).

maintained. As a feed-down effect it may also be more complicated to measure chromaticity since the quality depends directly on the tune measurements.

It is clear that an operational C&S requires more design work on the controls (MCS functions) side.

SOFTWARE

The settings generation and FIDEL software will receive some face-lifting. In order to easily switch configurations between pure squeeze, C&S, R&S etc, the setting copy tools must be improved to merge two beam processes, split one beam process into two, lengthen or shorten a beam process.

For the C&S work must be done for the collimator functions / MCS. To enhance the flexibility for switching β^* combinations, it is recommended to maintain corrections (optics, orbit) as local as possible in the future. During commissioning of the squeeze, orbit correctors in the arcs and in IRs that are not squeezed will be de-activated for the OFB and the manual steering. It is recommended to split beta-beating corrections in a similar way, at least as far as reasonably possible.

SUMMARY

First predictions for the length of pre-cycle and of standard beam processes within the operation cycle were presented. The cycle was analysed in view of past issues (orbit stability) and future improvements (C&S, R&S). Recommendations for changes and improvements were presented.

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LEVELING OPTIONS AND STRATEGY

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Abstract

This paper gives an overview of possibilities for luminosity leveling in the LHC Run 2. Different scenarios together with detailed proposals will be presented. Since luminosity leveling by transverse offset was operationally proven part of this paper will describe in detail how leveling of luminosity will be done using β* adjustment on the example of LHCb.

EXPECTED PEAK PERFORMANCE

After the long shutdown the LHC will restart beam operation in 2015 at an energy of 6.5 TeV. The LHC's two high luminosity experiments, ATLAS and CMS can cope with a maximum average pile–up of 50 and a time-averaged pile-up(μ) of 30 to 40. The LHCb experiment on the other hand will operate at a maximum pile-up of $\mu = 1.6$. Assuming two restart scenarios [1], the relaxed parameter set ($\beta^* = 0.65$m and $\varphi = 170\mu$rad) does not require of the luminosity leveling in ATLAS and CMS. However, LHCb, due to it's nature, will always require leveling. With the pushed parameter set ($\beta^* = 0.4$m and $\phi = 155\mu$rad, assumed to be used as from 2016 and onwards) both ATLAS and CMS will require leveling for up to 2.5h at the beginning of each high intensity fill.

A step back to 50ns operation will require the leveling for ATLAS and CMS as from beginning of the high intensity operation due to pile–up values reaching 146. The time needed to level this excess will reach 4h in the most pessimistic case.

For the LHC luminosity upgrade HL-LHC (from 2023) [2] luminosity leveling by β* is part of the operational baseline. Therefore, an extended learning period is required to master the process.

LUMINOSITY LEVELING METHODS

Two main luminosity leveling methods are considered for Run 2, namely leveling by beam offset d and leveling by β*. The range of both methods is limited by practical aspects or by beam dynamics effects. Beam stability is an issue with too large offset while beam control is an issue for β* leveling [3].

Offset Leveling

Offsetting the beams is easily implemented with local orbit bumps around a collision point. This technique was used routinely during LHC Run 1 for the LHCb experiment [4]. The main drawback of the method is related to transverse beam stability. The LHC high intensity beams must be stabilized by a transverse feedback and by Landau damping from octupoles and from head-on (HO) beam-beam collisions. Bunches colliding with offsets have less Landau damping and may suffer from instabilities. Leveling by offset is also a potential source of emittance growth. For these reasons,

offset leveling cannot be applied at all LHC collision points at the same time [5].

β* Leveling

Another way for controlling the pile–up is to change the beam size of the colliding beam through β*. This technique does not affect the beam–beam parameter since the beams remain head-on. Landau damping from HO collisions is therefore preserved [6]. During a change of β* the optics of the entire interaction region and long straight section is affected. The gradient changes in the quadrupoles require adjustments of the crossing angle shapes and lead to orbit changes due to feed-down from the beam offsets in the quadrupoles (due to misalignments). Leveling by β* requires therefore excellent control of the beam orbit in the straight section and at the collision point whenever the optics (β*) is changed to maintain the luminosity. The beam separation d should ideally not exceed 0.5σ during the process. Furthermore the interlocked collimators, located close to the low-beta quadrupoles, must follow the optics changes smoothly.

STRATEGY FOR LEVELING DURING LHC RUN 2

LHCb – Proposal

A base line for the LHC β* leveling implementation consist of directly implementing it in LHCb, using all possible optic points plus 4 additional new points to satisfy luminosity excursion constraint ($\frac{\Delta L}{L} < \pm 0.05 \Rightarrow \frac{\Delta \beta^*}{\beta^*} < 0.10$).
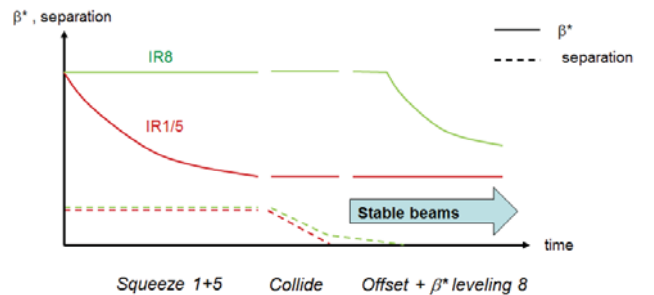

Figure 1: Operation scenario of LHC for 2015 at 6.5 TeV. In a first step the optics is squeezed (β* reduction) in IR1 and IR5 with non-colliding beams. The beams are then brought into collision. At that stage the experiments start data taking ('Stable beams'). The luminosity if IR8 is first leveled by offset before β* leveling takes over after some time.

Due to the large pile up (up to μ=12) and the injection constrains of initial β*= 10m (process of un–squeeze every fill would extend turnaround time of the machine) it is not sufficient to use only β* leveling. Therefore, a mixture with the offset leveling may be considered. It was simulated

that offset leveling time will last up to 6h for each fill (if bright BCMS beams are used). To limit the influence and the possible operation complications of the leveling by $\beta*$ it is considered to squeeze LHCb to 8m before going into collisions. That extends the period of the offset luminosity leveling to maximum of 8h. As the most probable is to restart with is the 25ns beam (n=1.2e11 and $\varepsilon_N = 2.6\mu m$) a respective times are a maximum of 3h (10m) and 5h (8m). Furthermore comparison of these values with an average fill length [9] and the number of the fills that actually were longer that this time, leads to the conclusion that 240 (10m) and respectively 200 (8m) for an average year of the fills would potentially give an experience with $\beta*$ leveling. Performing $\beta*$ leveling in LHCb operation may not remain transparent for the ATLAS and CMS performance. Due to global $\beta*$ change a variation of recorded luminosity is expected to happened. Therefore, the ratio between the recorded luminosity in both experiments may not be constant. All necessary corrections to compensate this effect will be included in the commissioning phase but it is possible that residual errors will remain.

The commissioning implies careful optics and orbit corrections to keep the beams head-on during each step. The optics must be corrected such that it minimizes the perturbation of $\beta*$ in IR1 and IR5. A total of 20 optics points are required to cover the $\beta*$ range of 10 m to 3 m. The time needed for this was estimated to 4 shifts [7].

ATLAS / CMS: Collide and Squeeze

An implementation of a combined *Collide and Squeeze* beam process gives the same experience as $\beta*$ leveling and may be needed in case of increased beam-beam instability observations [8]. However, it doesn't solve the need of leveling in LHCb. Therefore, two sub options are proposed: Direct $\beta*$ leveling implementation or full offset leveling. The *Collide and Squeeze* option requires the heaviest work for beam process preparation (Fig.2). But it also gives the most flexible and the most adaptive configuration including readiness for the 50ns fallback scenario and the ultimate 2016 performance requirements (need of leveling in ATLAS and CMS with pushed scenario reaches max. 3h of each fill).

MDs

Testing $\beta*$leveling during the cyclic Machine Development period (MD) gives the possibility to use any of the LHC IPs. However, this requires a certain time to prepare beam processes in advance. Moreover, this approach does not give a regular experience in the view of possible need of usage: collide and squeeze and/or leveling. Additionally, long time intervals between two MDs will lead to extended time of preparation since quality of the service depends on global reference orbit stability which over so long period of the time, is not given and has to be re–establish. The number of possible experience possibilities is a factor of 50 less then in case of direct implementation in LHCb and almost a factor 100 less if *collide and squeeze* is implemented in ATLAS
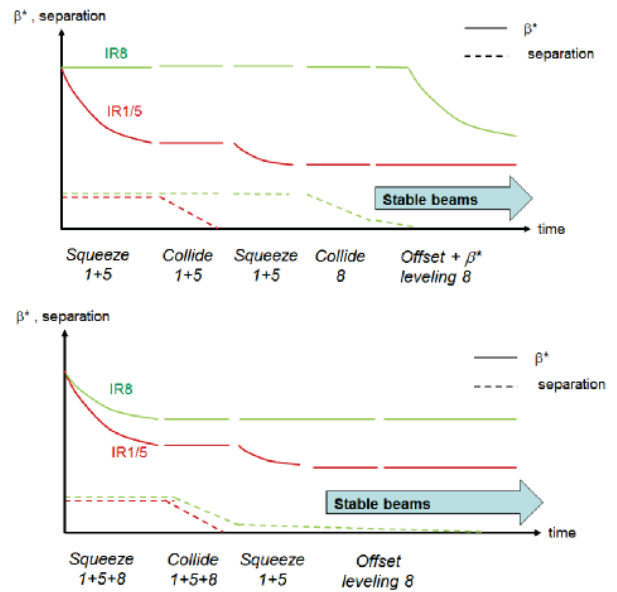

Figure 2: Operation scenario of LHC if Collide and Squeeze will be implemented. In the first step the optics is pre squeezed (β⋆ reduction) in IR1 and IR5 with non-colliding beams, followed by bringing them into collision. After this stage, a continuous reduction of β⋆ is performed down to the minimal value without declaring stable beams (top Fig.). The same but with SB declaration would give a β⋆ leveling when required. The luminosity of IR8 is either leveled via offset (top Fig.) or like on 1 scenario as a mixture of offset and β⋆ leveling (bottom Fig.).

and CMS: it is estimated that in MDs there will be a total of 4 attempts per year.

ALICE

The fourth possible testing solution is a leveling while producing luminosity with heavy ions. It has the same requirements and advantages as $\beta*$ leveling in LHCb but unlike for the protons (leveling in ALICE that would need a range starting form $\beta*$=1km) for heavy ions would be required to start around $\beta*$=4m. The number of the fills that would give the exercise experience is only limited by the length of the heavy ion run.

SELECTED SCENARIO AND DETAILS

A closer look at the process (Fig.3) example of LHCb start-ing from $\beta*$=10m highlights the operation details. The sim-ulation was performed for a standard beam: 25ns, n=1.2e11 and ε_N =2.6μm. To overcome the luminosity peak at the beginning a transverse offset leveling is applied in the first 3h of the fill followed for another 10h by $\beta*$ leveling. This gives a 3h of $\beta*$ leveling, assuming on average fill length of 6h.
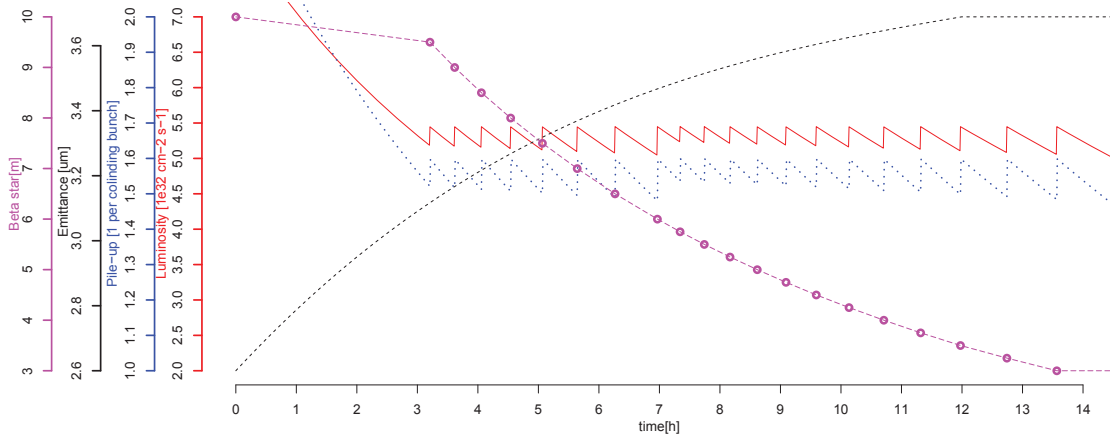
Figure 3: Evolution of several parameters during β^* Leveling at LHCb. The luminosity (red) is leveled to match an average event pile-up (blue) of 1.6. The beam emittance (black) increases during a fill and is based the observed evolution during Run 1. The β^* (magenta) change is made in steps corresponding to predefined matched optics. In the first part of the fill the luminosity is leveled by offset.

β^* implementation in details

A closer look at the β^* change step (one of the peaks in Fig.4 , [10]) leads to the definition of the sequence of the actions.

- A luminosity decay phase due to the intensity decrease and emittance blow up.

- The preparation of the next the step (**A**) when all the currents functions are loaded into the power converter controllers. Position functions are loaded into the control of the collimators. The orbit feedback receives a function to track the reference orbit.

- The step execution (**A** $\mapsto$ **B**) when power converters and collimator execute their pre-defined functions.

- The end of the step (at **B**) when the collimator position thresholds are updated. At that point the luminosity is re-optimized in case the orbit was not corrected perfectly leaving a non-zero residual offset d.
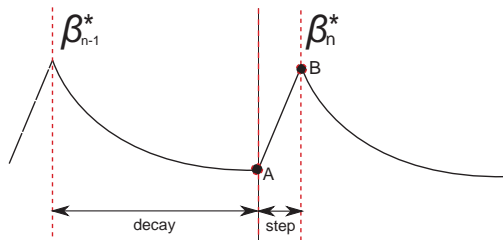

Figure 4: One step in the β^* leveling sequence. Three main phases can be seen on the picture: the luminosity decay phase at constant β^*, the step start, execution and end.

During the leveling step (**A** $\mapsto$ **B**) the beam orbit feedback system must ensure that the beams remain in collision. Since the shape of the crossing angle bumps used to provide

long-rang beam-beam separation changes with β^*, the reference orbit must be dynamically adapted during the step. It is crucial to ensure the traceability of the corrections that are applied at each step, a complete history of the correction applied during all steps must be maintained, including adjustments by the orbit feedback system.

Software challenge

A simple JAVA application is currently controlling luminosity leveling by offset as it was used during LHC Run 1. The application listens to messages from the experiments (leveling requests) and informs the experiments of the leveling status [4]. Due to concurrency problems in case multiple instances of the application run in parallel, a dedicated server will be developed to handle all request related to luminosity optimization and leveling. It will consist of two leveling modules, each dedicated to one method: offset leveling and β^* leveling, business logic of the existing application will be moved into a dedicated module whereas a β^* control module will be developed from scratch.

CONCLUSIONS

Luminosity leveling will be required during the entire life cycle of the LHC. Depending on the machine and beam parameters, it may be already required for all experiments during Run 2. For the HL-LHC upgrade, luminosity leveling is mandatory and must be done by the use of with β^* leveling. Therefore an experience that can be achieved the during upcoming run is crucial.

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TRANSVERSE EMITTANCE THROUGH THE LHC CYCLE - AN UPDATE

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Abstract

During LHC Run 1 about 30 % of the potential peak performance was lost due to transverse emittance blow-up through the LHC cycle. Measurements indicated that the majority of the blow-up occurred during the injection plateau and the energy ramp probably due to Intra Beam Scattering (IBS). IBS Simulation results will be shown and compared to measurements also considering emittance growth during collisions. Requirements for commissioning the LHC with beam in 2015 after Long Shutdown 1 to understand and control emittance blow-up will be listed. A first estimate of emittance measurement accuracy for LHC Run 2 will also be given.

INTRODUCTION

In 2012 the LHC was operated with high brightness beams with beam parameters pushed to their limits for outstanding luminosity production. With a bunch spacing of 50 ns the LHC was filled for physics with 1374 bunches, containing up to 1.7×10^{11} protons per bunch (ppb) with transverse emittances as small as 1.5 μm at injection. However, high brightness could not be preserved during the LHC cycle. Measurement campaigns in 2012 revealed a transverse emittance blow-up of about 0.4 to 0.9 μm from injection into the LHC to the start of collisions, see Fig. 1. The emittance of the first 144 bunch batch in the LHC was measured with wire scanners at injection and compared to the calculated emittance from peak luminosity in ATLAS. Emittances from CMS luminosity show similar results.

EMITTANCE EVOLUTION THROUGH THE LHC CYCLE

Wire scanners are used to measure the emittance through the LHC cycle. Thus only low intensity fills (maximum 24 bunches) could be studied to avoid wire scanner breakage or excessive losses in the downstream superconducting magnets and beam dumps. At the end of the 2012 LHC proton run it was found that wire scanner gain and filters have an influence on the obtained beam sizes. It was not possible to obtain optimum wire scanner settings and thus optimum beam size values during LHC Run 1 [1].

An important ingredient for analysing the wire scanner data are reliable beta function measurements at locations of the profile monitors. The optics had been measured with the turn-by-turn phase advance method at 450 GeV injection energy, four discrete points during the energy ramp (at 1.33, 2.3, 3.0 and 3.8 TeV for beam 1, and at 1.29, 2.01, 2.62 and 3.66 TeV for beam 2) and 4 TeV flattop energy before and after the β^* squeeze [2].
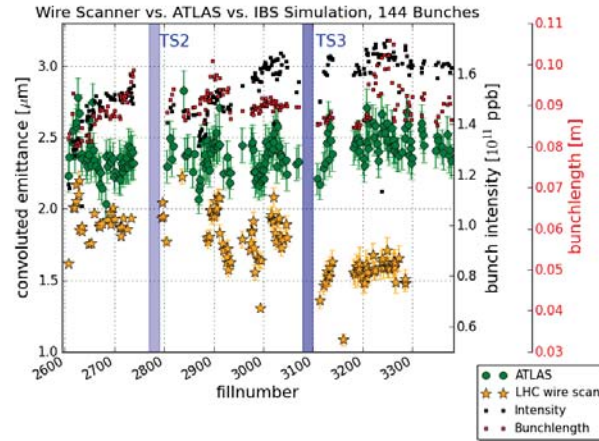

Figure 1: Convoluted average emittance of the first injected 144 bunch batch at injection (orange stars), measured with wire scanners and fitting the entire transverse profile, and at the start of collisions (green dots), calculated from ATLAS bunch luminosity using measured bunch length (red) and intensity (black).

Figure 2 shows the beam 1 horizontal emittance evolution through the cycle of two 6 bunch batches during test Fill 3217 (October 2012). The evolution of the energy and beta functions is also indicated. Linear interpolation is used between the different beta measurement points. The injected bunches had an intensity of 1.6×10^{11} ppb, a bunch length of 1.2 ns and a transverse emittance of 1.3 - 1.6 μm.

The growth during the injection plateau has been studied in detail in [1]. Intra Beam Scattering (IBS) and 50 Hz noise
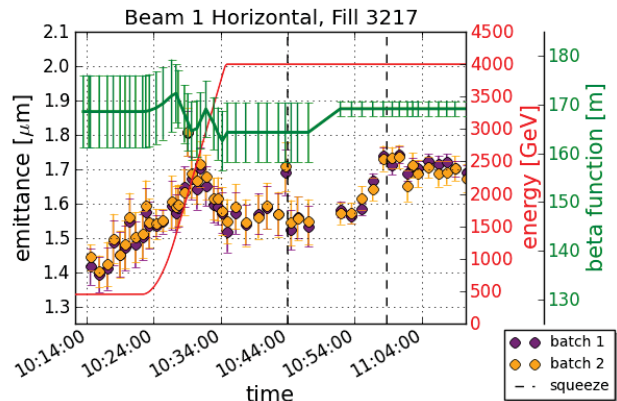

Figure 2: Average beam 1 horizontal emittances of 6 bunches per batch through the LHC cycle for Fill 3217 measured with wire scanner. The core emittance is displayed. Vertical black dashed lines indicate the period of the squeeze.

seem to be the main driver. The non-physical emittance evolution during the ramp is now believed to come from insufficient knowledge of beta function evolution during the ramp. Many more beta measurement points will be needed in the future. The dashed vertical lines in Fig. 2 indicate the period of the β^* squeeze. The emittance blow-up during the squeeze, which manifested itself mainly during the second half of 2012, is believed to be connected to the observed beam instabilities. Their origin is not understood to date.

During injection plateau and ramp, the emittance growth in the horizontal plane dominates. Vertical emittance growth occurs in case of large coupling during injection and ramp or with instabilities during the squeeze.

Non-Physical Emittance Evolution during Ramp

Understanding the emittance blow-up during the LHC ramp was one of the main objectives for emittance growth investigations in 2012, the last year of proton physics of LHC Run 1. Only in 2014, after refined beta calculation algorithms to compute the beta functions at the profile monitors became available, progress in the understanding came. In spite of not changing the design optics between injection plateau and until the end of the ramp, the beta functions do not stay constant during the ramp due to various effects. The measurements of non-physical emittance evolution, e.g. shrinking emittances, can most probably be explained by non-monotonically changing beta functions and not enough beta measurement points during the ramp, see Fig. 3 for beam 1 vertical. The beta functions for beam 2 horizontal grow monotonously during the ramp and linear interpolation between two measurement points is justified, see Fig. 5.

EFFECT OF IBS DURING THE CYCLE

IBS has been found to be the main source of growth in the horizontal plane during the injection plateau. The effect of IBS reduces with increasing energy but is not negligible for the LHC beam parameters during the ramp and flattop en-

Figure 4: Average emittances of 6 bunches per batch during the LHC ramp for Fill 3217 measured with wire scanners and compared to IBS simulations with MADX.

Figure 5: Average emittances of 6 bunches per batch during the LHC cycle for Fill 3217 beam 2 horizontal measured with wire scanner and compared to IBS simulations with MADX. The beta function evolution is also shown.

ergy. Figure 4 compares emittance measurements corrected with the measured and interpolated betas during the ramp and predictions from IBS simulations. The simulations were performed with the IBS module of MADX [3] using the initial measured emittance, bunch length and intensity as input parameters. To take the evolving emittances and therefore evolving IBS growth times into account, simulations were performed in an iterative way using intervals of 10 s. The updated emittances were then used for the next simulation. The total length of the ramp in 2012 was 13 minutes.

For beam 2 the simulated emittance evolution during the ramp fits remarkably well with the measured one for the horizontal and vertical plane, see Fig. 4. Moreover, IBS seems to be the dominant source for emittance growth through the entire cycle for beam 2 horizontal, see Fig. 5.

IBS simulations for physics fills with typical 2012 beam parameters give an estimated total growth of about 0.4 μm in the horizontal plane for the very bright beams towards
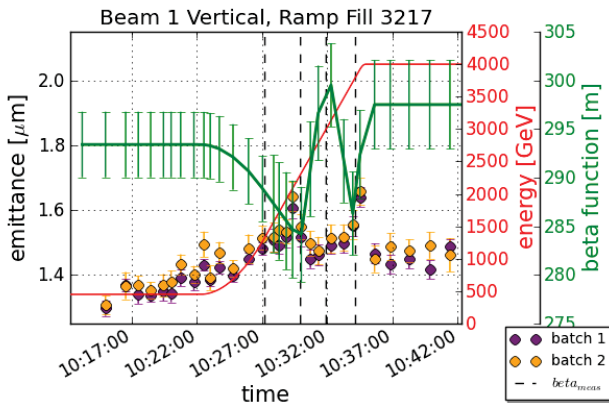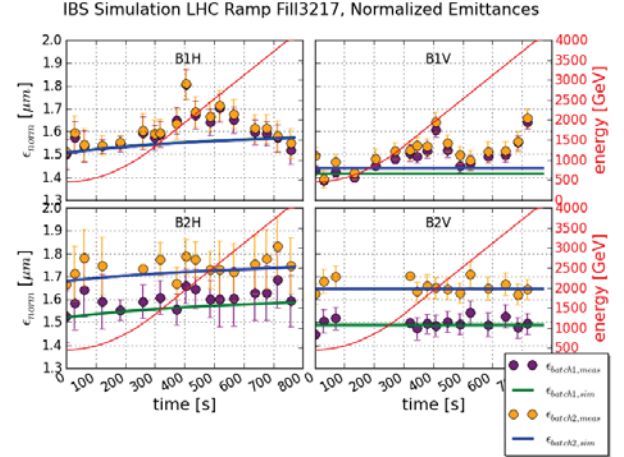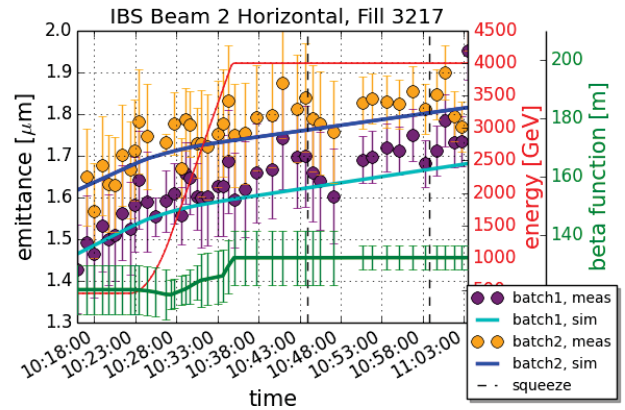

Figure 3: Average beam 1 vertical emittances of 6 bunches per batch during the LHC ramp for Fill 3217 measured with wire scanner and compared to the beta function evolution. Vertical dashed lines indicate a beta measurement.

the end of 2012. However, growth in the order of 1 μm was measured.

EFFECT OF IBS DURING COLLISIONS

To be able to compare emittances of physics beams during collisions calculated from luminosity to IBS simulations one has to assume equal transverse beam sizes. Therefore the real value of the horizontal emittance at the start of collisions is uncertain. To get meaningful simulation results, long, high performance fills from 2011 and 2012 were chosen and data cleaned if necessary (e.g. removal of unstable bunches). A comparison of emittances from luminosity and simulation during collisions in the LHC is shown in Fig. 6. IBS simulations where performed with MADX and the Collider Time Evolution program (CTE) [4] taking the measured bunch intensity and bunch length evolution into account.

Note that for fills later in 2012 the emittance at the start of collisions is larger (~ 2.4 μm) and the slope of emittance evolution is steeper at the beginning of collisions and overall more parabolic than for fills earlier in 2012 and in 2011 (emittance at start of collisions ~ 2.2 μm). The simulated growth, however, looks similar for all fills. The absolute measured emittance growth is about 1 μm in 8 hours for all fills. For fills at the end of 2012 the emittance blow-up calculated from luminosity is almost twice as large as the simulated horizontal emittance growth.

During a low intensity test fill in 2012 emittances were measured with wire scanners while beams were colliding (Fill 3160). Here a direct measurement of the horizontal emittance can be compared to IBS simulations (MADX), see Fig. 7. Measurements were performed only during 2 hours in collisions and the bunches had a very short bunch length and small emittances, thus emittances blew up by ~ 40 %. Yet,

Figure 7: Average relative emittance growth of 6 bunches per batch during LHC collisions for Fill 3160 measured with wire scanners and compared to IBS simulations with MADX. Batch 3 bunches are non colliding. Bunches of batch 4 are colliding in ATLAS and CMS.

the simulation matches the measurement in the horizontal plane.

Figure 7 also shows almost the same measured emittance blow-up in the vertical plane as in the horizontal plane. So far no explanation could be found.

IBS Emittance Growth for Beams In Run 2

At the start of Run 2 the LHC will be running with nominal beams meeting the LHC design parameters (standard scheme [5]). Later in the run the beam parameters can be pushed to higher brightness with a Batch Compression, bunch Merging and Splitting scheme in the LHC injectors (BCMS scheme [6]). Assuming that injection and flattop plateau length are the same as in 2012 and a 20 min ramp to 6.5 TeV, estimates for the horizontal emittance blow-up during the LHC cycle and collisions from IBS can be given, see Table 1 (RF voltage from 6 MV at injection to 12 MV at 6.5 TeV, 1.25 ns bunch length, 1.3×10^{11} ppb at injection and 95 % transmission through the cycle). Based on previous physics fills about 20 % intensity losses during 8 hours in collisions are predicted and included in the simulations. Similar as in 2012, the high brightness beams will suffer severely from IBS.
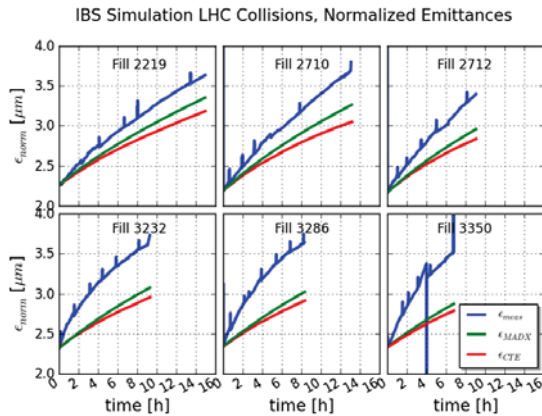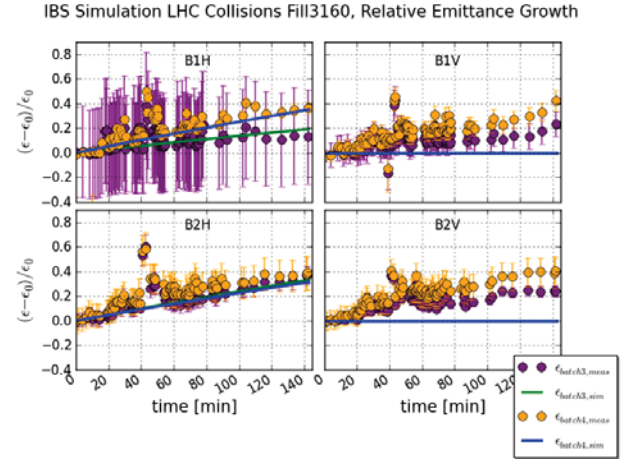

Figure 6: Convoluted emittance evolution during LHC collisions calculated from luminosity (blue) for fills in 2011 (Fill 2219), beginning of 2012 (Fill 2710, 2712) and end of 2012 (Fill 3232, 3286, 3350) and compared to simulated horizontal emittance growth from MADX (green) and CTE (red). The spikes in the blue curve correspond to luminosity optimization scans.

Table 1: Simulated Horizontal Emittance Growth from IBS for LHC Run 2 Beam Parameters.

Scheme	Standard	BCMS
$\varepsilon_{injection}$ [μm]	2.4	1.3
$\Delta \varepsilon_H$ cycle	5 % (≤ 0.15 μm)	20 % (≤ 0.3 μm)
$\varepsilon_{collision}$ [μm]	2.7	1.7
$\Delta \varepsilon_H$ 8 h collisions	13 % (≤ 0.35 μm)	35 % (≤ 0.6 μm)

EMITTANCE MEASUREMENT PUZZLE

The total growth measured through the LHC cycle with wire scanners for low intensity test fills at the end of the year is less than 50 % of what is measured with the emittance from luminosity for physics fills. The first conclusion after this observation was that low intensity fills are not representative for full intensity physics fills in terms of emittance growth. During test fills the beams were also put into collision and luminosity data was taken while wire scans took place. Emittance results from wire scanners and the luminosities of ATLAS and CMS were obtained at exactly the same point in time. For the calculation of the emittance from luminosity all known effects and their uncertainties, such as measured β^*, crossing angle, measured bunch length and intensities, are taken into account. Nevertheless the convoluted emittances from luminosity are always about 30 - 50 % larger than the convoluted emittance from the wire scanners. An example measurement (Fill 3217) is shown in Table 2.

During another test fill (Fill 3160) beam profile data was also taken with the LHCb SMOG detector [7]. Compared to wire scanner results, LHCb delivers smaller or larger emittances, depending on the beam and plane, with a difference of up to 0.6 μm, which is still within the measurement uncertainty. For some cases the wire scanners measure even larger emittances. Mostly for this fill emittance values from LHCb are smaller than ATLAS and CMS values and larger than the wire scanner ones.

The discrepancy between wire scanner emittance values and those from luminosity and LHCb SMOG is not understood. With the results from LHCb we can preliminary conclude that the emittances from luminosity are overestimated. During LHC Run 2 wire scanner measurements and uncertainties on emittance extrapolations from luminosity will have to be characterized in detail.

Table 2: Comparison Convoluted Emittance from Wire Scans and Luminosity for Fill 3217 Batch 2.

	Wire Scan	ATLAS	CMS
$\varepsilon_{injection}[\mu m]$	1.58 ± 0.06	Measurement not possible.	
$\varepsilon_{collison}[\mu m]$	1.84 ± 0.06	2.33 ± 0.12	2.63 ± 0.14
$\Delta\varepsilon[\mu m]$	0.25 ± 0.12	0.75 ± 0.18	1.05 ± 0.20
	(16 %)	(47 %)	(66 %)

NEW LHC POINT 4 OPTICS

In 2015, at 6.5 TeV LHC collision energy, the transverse beam sizes of the high brightness beams will be very small. This affects the measurement accuracy. It will not be possible to get reasonable emittance results for beam sizes smaller than 200 μm. A solution would be to increase the beta function at the transverse profile monitors to increase the local beam size. Table 3 shows the expected beam size improvements with overall new ATS-compatible optics in LHC point 4 [8, 9] assuming 1.7 μm emittance at flattop energy.

Increased beta functions at the wire scanners and BSRT leads to a better beam size measurement accuracy and meaningful emittance results. Also the BGI might be applicable during LHC Run 2 for beam size measurements with the new optics. (It was not possible to calibrate the BGI correctly for the LHC proton run in 2012.)

Table 3: Expected Beam Size Improvements at the Transverse Profile Monitors with New LHC Point 4 Optics (ATS) at 6.5 TeV with 1.7 μm emittance with respect to design optics (nom).

$\sigma[\mu m]$	B1H		B1V		B2H		B2V	
	ATS	nom	ATS	nom	ATS	nom	ATS	nom
Wire Scanner	201	217	266	289	174	213	315	320
D3 (BSRT)	206	222	230	271	177	219	287	297
BGI	277	282	153	229	259	279	228	251

CONCLUSION AND PLANS FOR LHC RUN 2

According to the LHC design parameters less than 10 % emittance growth through the cycle is allowed. During LHC Run 1 more than a factor 3 of this value was observed based on emittance derived from luminosity data. In this paper it was shown that IBS is one of the main sources of growth through the entire cycle including the 4 TeV flattop.

The discrepancy between emittance values from wire scans and luminosity is still not understood and has to be investigated thoroughly in 2015. Luminosity was the only means during LHC Run 1 to get emittance information for physics fills.

The emittance measurement accuracy LHC Run 2 could be improved with new optics in point 4 that increase the beta functions at the transverse profile monitors.

To understand and control emittance blow-up after Long Shutdown 1, early optics measurements with the turn-by-turn phase advance measurement and with k-modulation are essential. All transverse profile monitors need to be calibrated at the start of Run 2. This includes quantifying wire scanner photomultiplier saturation.

Van der Meer scans at the beginning of Run 2 can be used to compare wire scanner measurements to emittance results from ATLAS and CMS luminosity as well as beam sizes from the LHCb SMOG detector. Measurements with few bunches during the entire cycle including collisions are requested to compare emittances measured with wire scanners, BSRT, BGI and BGV if possible. Finally, lumi scans at the end of physics fills might help to understand emittance blow-up during collisions.

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LONGITUDINAL PARAMETERS AND BEAM INDUCED HEATING

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Abstract

The longitudinal beam parameters are proposed for the LHC re-commissioning and operation in 2015, based on the experience obtained from operation and MD results during LHC Run 1. Controlled longitudinal emittance blow-up is necessary during the whole ramp to 6.5 TeV. The value of the longitudinal emittance is defined by beam stability and IBS, and bunch length and RF voltage by particle losses, beam induced heating and experiments requirements. The impact of the longitudinal parameters on luminosity will be also discussed here.

Beam induced heating limitations during LHC run 1 are reviewed and an update on the mitigation measures taken during LS1 is presented. The situation in 2015 is expected to be more favourable due to all improvements made and potential issues would be mainly caused by unexpected non-conformities. In addition, more devices are equipped with temperature sensors that will allow us to monitor beam induced heating and react early to try and prevent damage to the equipment. Since further increase of bunch length leads to beam lifetime degradation, a special controlled emittance blow-up that flattens the bunch profile is also considered for beam induced heating mitigation.

LONGITUDINAL PARAMETERS

The nominal LHC longitudinal parameters were defined in the LHC Design Report [1] and are shown in Table 1.

Table 1: Longitudinal parameters from LHC Design Report.

Energy	RF Voltage [MV]	Bunch length [ns]	Emittance [eVs]
450 GeV	8	1.5	0.8
7 TeV	16	1.05	2.5

At the end of the LHC Run 1, in 2012, the longitudinal emittance of the bunches extracted from the SPS was lower than in the DR, i.e, 0.5 eVs and 0.45 eVs for the Q26 and Q20 optics, respectively. The voltage at injection was 6 MV, which was enough to keep injection losses below 0.5 %. At 4 TeV, however, the bunch length had to be increased to ~ 1.25 ns ($4\,\sigma_t$ calculated from BQM FWHM for a Gaussian distribution) to reduce the beam induced heating. First issues started in 2011 when the beam intensity was pushed [2] (bunch intensity up to 1.6×10^{11}) and then problems continued during 2012 [3].

In this paper we analyse the possible range of the longitudinal parameters after LS1, taking into account the effects on beam stability, particle losses, synchrotron radiation, IBS, and beam induced heating. We also present the strategy to follow during the start up in 2015, a mitigation for the

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beam induced heating in case of problems, and a scheme for luminosity levelling via bunch length.

Landau Damping

The single bunch stability threshold at 6.5 TeV will be similar to that at 4 TeV if the bunch length and the RF voltage V are the same as it follows from the scaling [4]:

$$N_b^{th} \propto \frac{\varepsilon^{5/2}}{E^{5/4}\,V^{1/4}}, \qquad (1)$$

where N_b^{th} is the threshold bunch intensity, ε is the longitudinal emittance, and E is the beam energy.
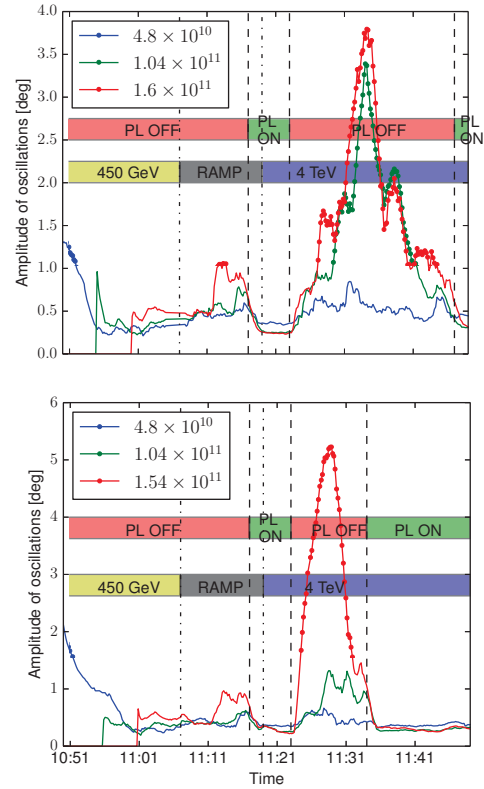

Figure 1: Amplitude of dipole oscillations during a fill with acceleration to 4 TeV for Beam 1 (top) and Beam 2 (bottom). At 4 TeV, all bunches had a longitudinal emittance of 1 eVs. The bunch with intensity of $\sim 1.0 \times 10^{11}$ was unstable in Beam 1 and at the limit of stability in Beam 2. Beam energy and Phase Loop status are indicated in the plots.

From measurements performed during an MD in 2012 and shown in Fig. 1, the threshold at 4 TeV and with 12 MV was found to be around 1 eVs for a bunch intensity of 1×10^{11} [5]. However, only three bunches were measured and therefore measurements with more bunches are needed to obtain more statistics and a more precise threshold. Using Eq. (1), we can scale to the operational parameters of 6.5 TeV and 10 MV

and obtain an intensity threshold of 6×10^{11} for a bunch with 1.25 ns length (same as in 2012), and 2.8×10^{11} for the nominal bunch length of 1.05 ns. In both cases, the threshold is well above the nominal bunch intensity of 1.15×10^{11}. The minimum emittance required for stability for a bunch with nominal intensity is 1.32 eVs (0.85 ns).

The coupled bunch instability has not yet been observed for the operational parameters during Run 1 (50 ns beams, total beam current up to 0.4 A), neither at injection energy nor at 4 TeV. It was not observed either for 25 ns beams during the scrubbing run at 450 GeV, when the total beam current was increased to 0.5 A. The scaling to higher energy is not trivial, but it can be approximated for the case of equally spaced bunches and constant bunch length. In that case, the intensity threshold scales as $I_{th} \propto V^{1/4}$ [4] and therefore the beam would be stable at 6.5 TeV. For shorter bunches, the threshold cannot be estimated as it depends on the resonant frequency of the driving impedance.

Particle Losses

Two particle loss mechanisms that are related to the bunch length were observed during LHC Run 1. The first one is due to particles escaping from the RF bucket. It was proven during an LHC MD in 2011 that the loss rate increases for longer bunches, as it can be seen in Fig. 2 [6].
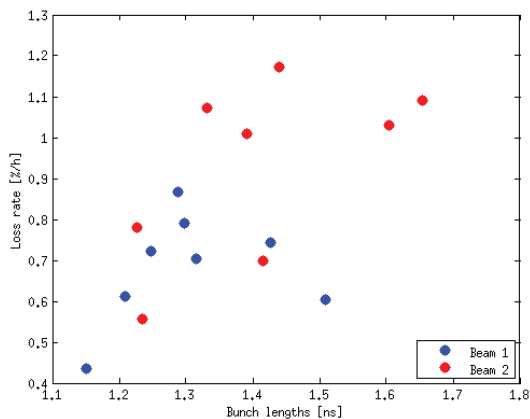

Figure 2: Measured particle loss rate at 3.5 TeV as a function of bunch length for 8 non-colliding bunches in Beam 1 (blue) and Beam 2 (red). Bunch intensity of $(1.15 \pm 0.15) \times 10^{11}$.

The second loss mechanism is caused by the beam-beam interaction and it was observed as a longitudinal shaving. In 2012, this effect was limiting the maximum bunch length to about ~ 1.3 ns, as shown in Fig. 3. At the end of the Run 1, from 29 October 2012, the voltage program was modified to the following: the RF voltage was increased during the ramp to 10 MV instead of 12 MV, and then to 12 MV after 2-3 h of collisions to improve the integrated luminosity. The voltage increase seems to enhance this effect, as the maximum bunch length is reduced. This could mean that the losses are related rather to the energy spread than to the bunch length. If that is the case, lower voltage and smaller emittance would be desirable in operation.
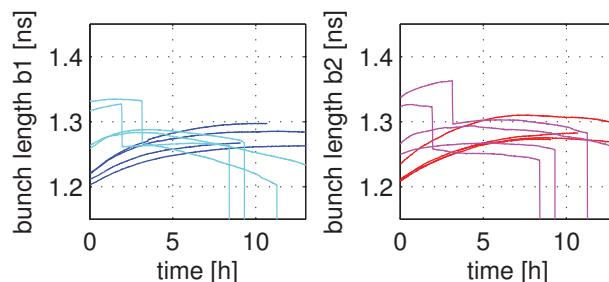

Figure 3: Bunch length evolution for several fills in 2012, for Beam 1 (left) and Beam 2 (right). Two different voltage settings: constant 12 MV (blue and red) and 10 MV increased to 12 MV after 2-3 hours (cyan and pink). Courtesy G. Papotti.

Synchrotron Radiation

Synchrotron radiation will be stronger at 6.5 TeV as compared to 4 TeV, with an increase in the energy loss per particle from 0.7 keV to 5 keV per turn. If synchrotron radiation damping rate were higher than the blow-up from RF noise and IBS, bunches would shrink and if it leads to any problems it should be compensated by controlled longitudinal emittance blow-up [7]. Otherwise this gives a luminosity increase through the geometric factor.

In addition, particles lost from the RF bucket will all move in the same azimuthal direction much faster than at 4 TeV.

Intra Beam Scattering (IBS)

Simulations using MAD-X show no emittance growth in the vertical plane, but a growth in the horizontal plane that increases for shorter bunches and for smaller longitudinal emittances [8], as shown in Fig. 4. Nevertheless, Fig. 5 presents a calculation done for a transverse emittance of 1.7 μm, RF voltage of 12 MV and $\beta^* = 40$ cm that shows that reducing the bunch length from 1.25 ns to 1.0 ns results in a higher integrated luminosity. The approximation was done assuming constant bunch length and emittance growth rate, although the growth rate is strongly dependent on the transverse emittance and it is slower for larger emittances. In practice, the gain in luminosity would be probably higher.

Luminosity Levelling via Bunch Length

Bunch length levelling could be used in case of excessive beam induced heating or too high pile-up density. The acceleration would be done with constant 6 MV or increasing it to 8 MV if needed, and with controlled longitudinal emittance blow-up to get bunches with ~ 1.25 ns at the beginning of physics. Then they will be shrunk slowly by increasing the voltage up to 16 MV. Taking into account that the bunch length τ dependence on voltage V is $\tau \propto V^{1/4}$, a factor 2 increase in voltage translates to a 20% reduction in bunch length. The lower synchrotron frequency could be detrimental for the transverse stability and its effect should be studied as well as the effect of synchrotron radiation.
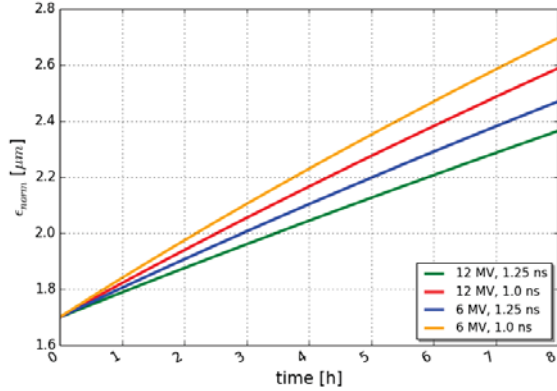
Figure 4: Horizontal emittance growth due to IBS for different voltages and bunch lengths. The growth rate is faster for shorter bunches and for lower voltage [8].
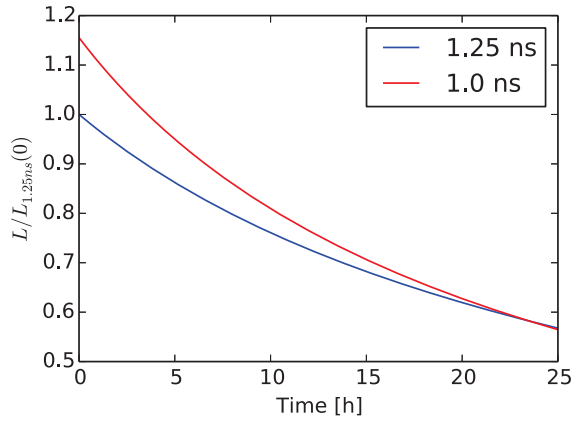

Figure 5: Instantaneous luminosity evolution for 1.25 ns (blue) and 1.0 ns (red) bunch lengths, relative to the initial luminosity with 1.25 ns, taking into account the transverse emittance growth due to IBS.

BEAM INDUCED HEATING

Beam induced heating was one of the main performance limitations in the LHC with 50 ns beams during Run 1. The consequences were damages to equipment, undesired beam dumps, and delays to re-inject. [9]

The power dissipated P in a device with a longitudinal impedance $Z(\omega)$ depends on the single bunch spectrum j_k according to:

$$P = \sum_{k=-\infty}^{\infty} j_k^2 \operatorname{Re} Z(k\,\omega_0) \left[\frac{\sin(M\,k\,\omega_0\,t_{bb}/2)}{\sin(k\,\omega_0\,t_{bb}/2)} \right]^2 , \quad (2)$$

where ω_0 is the revolution frequency, M is the number of bunches, and t_{bb} is the bunch spacing in the train. For a broadband impedance increasing the bunch length usually reduces the beam induced heating. For that reason, the bunch length was increased in few occasions up to 1.25 ns during Run 1.

Several mitigations were put in place by equipment groups before and during LS1 and they are summarized in the following list:

- All the VMTSA double bellows were removed.

- All non-conforming RF fingers were repaired during LS1 and a new design is being developed [10].

- The TDI beam screen was stiffened and more support was installed during LS1. The copper coating on the TDI jaw that was planned had to be abandoned due to technical issues. This means that the beam will deposit the same power in the consolidated TDI compared to the old TDI, but the consolidated TDI is expected to sustain better this heat load. It is important to note that the cooling was simulated to be inefficient but could not be upgraded during LS1 [11].

- The injection kicker MKI screening was significantly improved and the two non-conforming magnets that were causing heating problems were repaired (MKI8C and, in particular, MKI8D) [12].

- The primary collimator that was overheating, TCP.B6L7.B1, was exchanged during LS1 and the non-conformity should have been removed. The cooling system was suspected of being the issue, but investigations will be performed in September, to allow for sufficient radiation cool-down.

- All the 2-beam-collimators TCTVBs were removed, one half in 2012 and the other half during LS1.

- The valves of the standalone quadrupoles were upgraded to allow higher cooling of the beam screen [13].

- A shielding was installed on the ATLAS-ALFA and TOTEM detectors during LS1 to reduce heating, however the TOTEM plans to approach high luminosity beams may increase the heating to their pot [14].

- A new design of the BSRT mirror was installed during LS1 to reduce the heating [15].

In addition to these mitigation measures, an efficient monitoring of the elements with potential heating issues is necessary. Many systems have been requested to be equipped with additional temperature sensors during LS1 and the measurements to be be logged in the logging database. The implementation of a fixed display in the control room CCC is planned, together with alarms for fast reaction to prevent damages.

Figure 6 shows simulations of heating in the ALFA roman pot for the old and the new designs. The dependence on bunch length is very strong. The beam induced heating should be largely reduced with the new design, and less heating than in 2012 is foreseen even for nominal bunch length. The same behaviour is also expected in several other upgraded equipment.
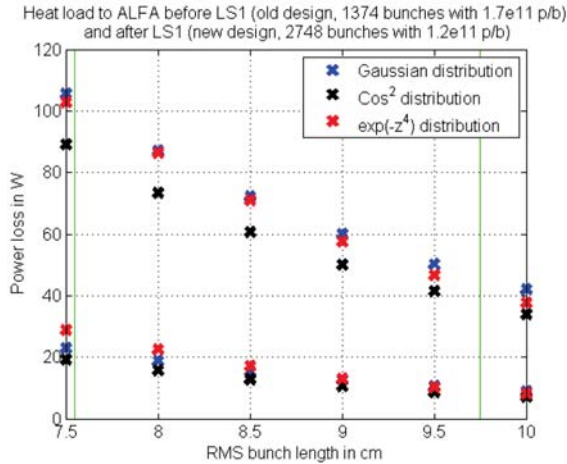
Figure 6: Simulated beam induced heating in the ALFA roman pot as a function of bunch length, for three different particle distributions. The points that have higher heating correspond to the old design, and the ones with lower heating are for the new design.

Flat Bunches

Another option to reduce the beam induced heating is to flatten the bunches [16]. In the absence of a 2nd RF system in the LHC, this can be done by applying a phase modulation close to the synchrotron frequency. This method was already tested in the LHC and Fig. 7 shows that the beam spectrum was considerably reduced for frequencies below 1.2 GHz, but increased above that frequency (for 1.25 ns bunch length). A beneficial effect was observed on the monitored devices, but further tests would be required to check that there are no devices with impedance at a frequency higher than 1.2 GHz that could overheat as a result.

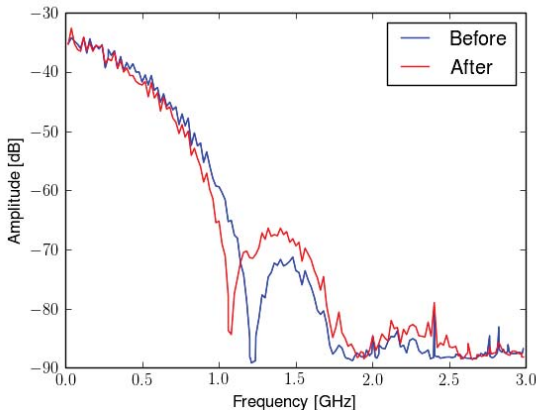Another advantage of using this method is that the pile-up density would be more uniform.

Figure 7: Envelope of the beam spectrum before (blue) and after (red) the RF modulation. The spectrum amplitude is reduced for frequencies below 1.2 GHz, but increased above.

PROPOSED STRATEGY

The LHC will run with 50 ns beams only for a short period during the start-up in 2015 and the same RF parameters as before LS1 will be used. The rest of the run, the LHC will operate with 25 ns beams. Beam induced heating should be carefully monitored as the total beam intensity will be higher (0.55 A).

The SPS can currently deliver the 25 ns beam with a bunch intensity up to 1.35×10^{11} and a longitudinal emittance similar to that obtained with 50 ns beams, i.e 0.47 eVs using Q20 optics.

The RF voltage in the LHC at injection energy is suggested to be set to 6 MV, the same as in 2012, in order to achieve similar transmission and beam stability. Then the beam is accelerated to 6.5 TeV with controlled longitudinal emittance blow-up, with an initial bunch length target of 1.25 ns.

Two options are possible to increase the luminosity at 6.5 TeV. The first one consists in reducing the bunch length to the nominal 1.05 ns, keeping the RF voltage constant to 10 MV or 12 MV. In this case, the reduction of the blow-up target during the ramp must be done in small steps and with careful monitoring of the beam induced heating and the transverse stability. The second option is to reduce the controlled longitudinal emittance blow-up and the RF voltage at 6.5 TeV, which would give the potential for luminosity levelling by increasing the voltage during the physics.

SUMMARY

Lower emittances at 6.5 TeV are tolerable thanks to the expected margin in longitudinal stability. This could have a positive impact on the beam lifetime and luminosity. It would also allow to use luminosity levelling via bunch length variation. The effect of IBS is not predicted to be significant.

The known issues with beam induced heating should be solved during LS1. More temperature monitoring and alarms will be available in 2015, and will help preventing damages if there are any unexpected issues. Flat bunches and bunch length levelling could be used as mitigations if necessary.

ACKNOWLEDGEMENTS

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IMPEDANCE AND INSTABILITIES

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Abstract

In these proceedings we evaluate the impedance of the LHC in 2015 and the corresponding stability situation, up to the beginning of the squeeze, for various beam and machine parameters. As a starting point we use the current knowledge of the machine in terms of observed limits in single-beam operation, or in physics operation up to the beginning of the squeeze, and rescale them thanks to simulations and the impedance model obtained for the possible collimator settings scenarios. We also evaluate the possibility to mitigate instabilities thanks to an optimization of the chromaticity.

INTRODUCTION

During LHC run I and particularly in 2012, transverse coherent instabilities of the beams were observed routinely in normal operation and have become one of the limitations of the machine performance [1–3]. A particular area of concern is the single-beam stability, which must be ensured up to close to the end of the squeeze. Indeed, when beams are at flat top with collimator half-gaps down to their tightest settings of the cycle, the beam-coupling impedance is maximum while the beams still do not see each other so stability cannot benefit from any additional tune spread from beam-beam effects. During that lapse of time of several tens of minutes, one can rely only on chromaticity, trans-verse damper and machine non-linearities (mainly from oc-tupoles) to maintain beam stability.

In 2015, we can quickly and approximately sketch how more critical will be the situation. Assuming a constant impedance and chromaticity with respect to 2012 (we will discuss these assumptions below), the growth rates of instabilities will be reduced by around a factor of 1.6 thanks to the beneficial effect of energy (going from 4 to 6.5 TeV) while the stability area provided by octupoles will shrink by around a factor of 2.6 (1.6 coming from the shrinkage of physical emittances, and another 1.6 from the higher beam rigidity [4]). Even if we take into account the beneficial effect of a slightly higher possible octupole current (570 A instead of 510 at the end of 2012), in the end the situation will be worse by almost 50% if nothing changes fundamentally for the unstable modes, i.e. if everything remains the same in terms of impedance (in particular the collimator half-gaps in mm), chromaticity and damper gain. Given the fact that at flat top it seems in several observations [5] that during normal operation the beams were beyond the

limit of stability even at maximum octupole current and high chromaticity, the situation might become very critical in 2015.

In these proceedings we will try to analyse the situation in more details. First we will summarize the available ob-servations and the recent improvements made to the LHC impedance model. Then we will analyse the impact on the impedance of the localized change in optics foreseen in 2015, and the impact of bunch length on stability. The core of the proceedings will be then an updated analysis of the stability limits for several collimator scenarios. Finally we will give a few perspectives on how we could improve the situation, and our conclusions will then follow.

SUMMARY OF OBSERVATIONS AND UPDATED COMPARISONS WITH THE LHC IMPEDANCE MODEL

Refinement of the LHC impedance model

In 2013 a significant effort was undertaken to improve the LHC impedance model [6]. In particular the following updates or additions to the previous model [7] were performed[1]:

- the geometric impedance of collimators were re-evaluated [8] thanks to the Stupakov formula for flat tapers [9] (this is pessimistic, by up to a factor two),

- the resistive-wall impedance of beam screens and warm vacuum pipe was refined, including the NEG coating for the latter, and the effect of the stainless-steel weld for the former [10],

- the beam screen pumping holes impedance was updated, applying Kurennoy formula [11] with the polarizabilities of rounded slots from Ref. [12], using detailed beam screens dimensions,

- several equipments in the high-beta triplet region were more precisely taken into account, in particular the tapers, using the approach of Yokoya for round tapers [13], and the beam position monitors (BPM), using 3D electromagnetic fields simulations from the CST code [14],

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[1]Recently it was found that in the 2012 model the copper coating on the TCDQ collimators jaws was not taken into account as it should have been (while it is taken into account in the model of the new TCDQs put in place for the restart in 2015 – see below). At the time of the talk associated with these proceedings this was still not known so this modifcation is not implemented in the results shown here. The estimated impact on the total impedance model is estimated to be below 5%.

- the broad-band and high order modes of several cavities were updated: for RF cavities using Ref. [15], for the CMS cavity using Ref. [16], and for ALICE and LHCb experimental chambers using 3D electromagnetic fields simulations from the CST code [14],

- the cutoff frequency of all broad-band resonators was put to a very high value (50 GHz), to simulate better a constant inductive impedance up to arbitrarily large frequencies. This was done to avoid a dip in the wake at ~ 5 cm that was recently found [17], which otherwise had a tendency to reduce (in a non physical way) the instability growth rates at high chromaticity,

- the detailed machine optics was used to sum up the broad-band contributions of the model, in an analogous way to what was done up to now only for the resistive-wall contributions (see Ref. [7])[2].

Many of these improvements were done using the Impedance library (also called PyZBASE) [18] which is a PYTHON tool enabling the computation of lumped impedance models in a relatively flexible way. This li-brary is interfaced with the resistive-wall code Impedance-Wake2D [7] which was also used to compute all the (resistive-)wall impedances of the model, and is available in the IRIS repository [19].

In the end, these updates and additions have an impact mainly on the imaginary part of the impedance (responsible for the real coherent tune shift), at least below a few GHz, as can be seen in Figs. 1 and 2 where the 2012 4 TeV transverse dipolar impedance model is shown. On the other hand, close to 5 GHz, the change in cutoff frequency for the broad-band models affects both the real part and imaginary part of the impedance. The various impedance contribu-tions in the new model are detailed in Figs. 3 to 6.

The effect on the instability growth rate for the most unstable mode of a single-bunch at a high damper gain and with various chromaticities Q', can be seen in Figs. 7 and 8 where we compare results from the DELPHI Vlasov solver [20]) and the HEADTAIL macroparticle tracking code [21]. The two codes are in good agreement despite the fact that they compute the growth rates in a very dif-ferent way, the latter solving an eigenvalue problem and picking the most unstable mode, while the former tracks many macroparticles along many turns, and fit the emerg-ing instability with an exponential. It appears that the ef-fect of the refinement of the model is relatively small on the growth rate except at high chromaticities, in particular close to $Q' = 12$ where the difference is up to 40%, and for $Q' > 20$ where the difference gets even larger. Those
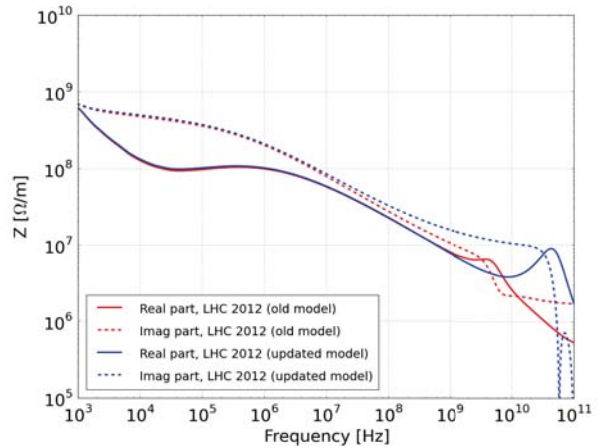

Figure 1: Horizontal dipolar impedances with both the previous and new LHC impedance models (real and imaginary parts), at 4 TeV with typical 2012 collimator settings.

single-bunch results are very similar to those with a full 50 ns beam, since with such a high gain of the transverse damper and assuming it is perfect and acting bunch-by-bunch, the multibunch effect is rather small, as was also found out earlier in Ref. [22].

All these results were obtained for beam 1; for beam 2 the model has only negligible differences with respect to the one of beam 1, as can be seen in Figs. 9 and 10.

Several of the refinements of the LHC impedance model described above were introduced in an attempt to under-stand better the discrepancy between measurements and simulations in terms of tuneshifts (in particular for a sin-gle bunch) that was found out in previous studies [23, 24]. In particular, the refinement of the collimator geomet-ric impedance [8] has an impact on the tuneshifts simu-lated, increasing them by 10 to 20% as shown in Fig. 11, thus decreasing the discrepancy between measurements and model. Another source of discrepancy between mea-surements and simulations is currently investigated [25], as it was found that, depending on the simulation parame-ters, simulations of tuneshifts with HEADTAIL and DEL-PHI may differ by a significant amount [26].

Review of single-beam instabilities observed in 2012

In Fig. 12 we summarize all instabilities observed with single (or separated) beams in 2012 at 4 TeV, for each oc-tupole polarity tested. Note that here and in the rest of the paper, "negative octupole polarity" refers to the polarity that was used in the LHC run I before the change of po-larity in August 2012 (negative current in the focusing oc-tupoles) while the positive polarity corresponds to the one used after that date, with the opposite sign of the currents. We plotted there, as a function of the chromaticity Q', the

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[2]At 4 TeV we use the squeezed optics ($\beta^* = 60$ cm in IP1 & 5, 3 m in IP2 and 8), despite the fact that we are focusing on the flat top situation before or at the beginning of the squeeze (when beams are separated). In terms of impedance alone, the squeeze has a local impact on the β func-tions around the IPs (plus an additional movements of tertiary collimators that anyway contribute little to the impedance), that is mainly detrimen-tal, therefore we are slightly – and most probably unsignificantly – more pessimistic than reality on this aspect.
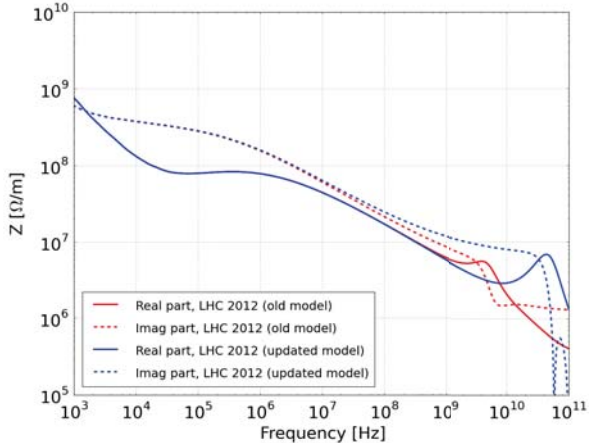
Figure 2: Vertical dipolar impedances with both the previous and new LHC impedance models (real and imaginary parts), at 4 TeV with typical 2012 collimator settings.
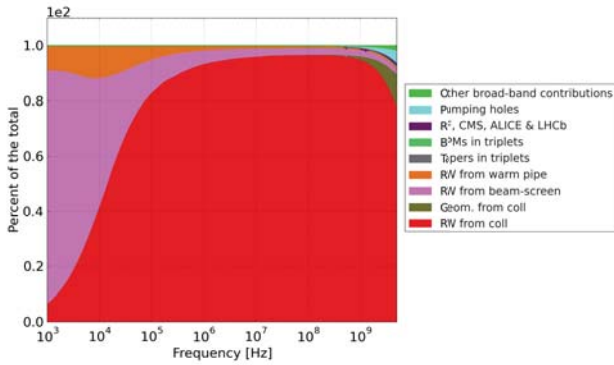

Figure 3: Horizontal dipolar impedance contributions with the new LHC impedance model (real part), at 4 TeV with typical 2012 collimator settings.
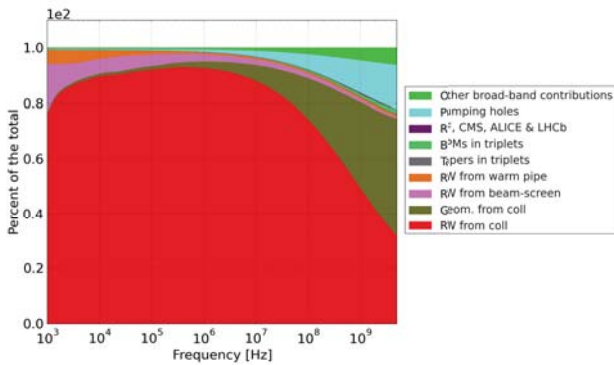

Figure 4: Horizontal dipolar impedance contributions with the new LHC impedance model (imaginary part), at 4 TeV with typical 2012 collimator settings.
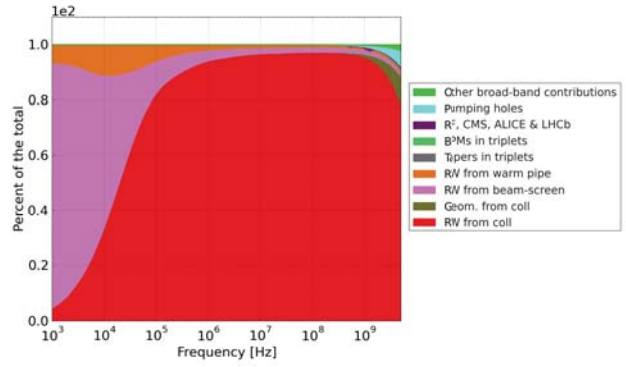

Figure 5: Vertical dipolar impedance contributions with the new LHC impedance model (real part), at 4 TeV with typical 2012 collimator settings.
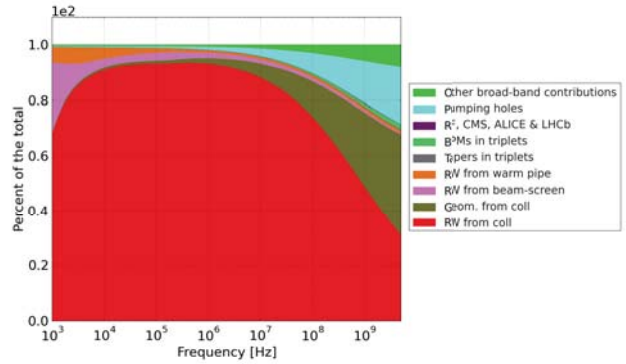

Figure 6: Vertical dipolar impedance contributions with the new LHC impedance model (imaginary part), at 4 TeV with typical 2012 collimator settings.

stability parameter defined as

$$\text{Stability parameter} = \mathcal{C}\frac{|I_{oct}| \cdot \varepsilon}{N_b}, \qquad (1)$$

with I_{oct} the octupole current, ε the normalized emittance, N_b the bunch intensity, and $\mathcal{C}$ a normalization constant set in such a way that the stability parameter is 1 for $|I_{oct}| = 500$ A, $\varepsilon = 2$ mm.mrad and $N_b = 1.5 \cdot 10^{11}$ p$^+$/bunch, which were typical 2012 parameters. The physical meaning of the stability parameter is that the higher it is, the more the beam *should* have been stable, so the more worrisome is the instability that was actually observed at this point.

Most of the data of Fig. 12 actually comes from several machine development studies (MDs) [28, 29]. In addition, three instabilities were also observed during normal operation, while the beams were still separated [5]. These three cases can be identified as the highest point for each octupole polarity for chromaticities between 5 and 10 (actually, two out of the three cases are exactly superimposed – the ones with a negative polarity and $Q' = 7$).

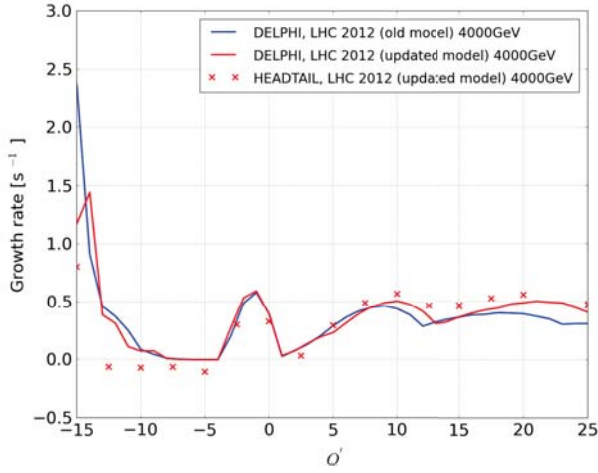The error bars along the vertical axis come from the error

Figure 7: Horizontal growth rates vs chromaticity with both the previous and new LHC impedance models (from dipolar impedance only), at 4 TeV with typical 2012 collimator settings. We assume a perfect bunch-by-bunch damper with a damping time of 50 turns, a single bunch of intensity $1.5 \cdot 10^{11}$ p$^+$/bunch, 1.25 ns total bunch length and no Landau damping. For the updated model we compare results from the Vlasov solver DELPHI and from the HEADTAIL tracking code.
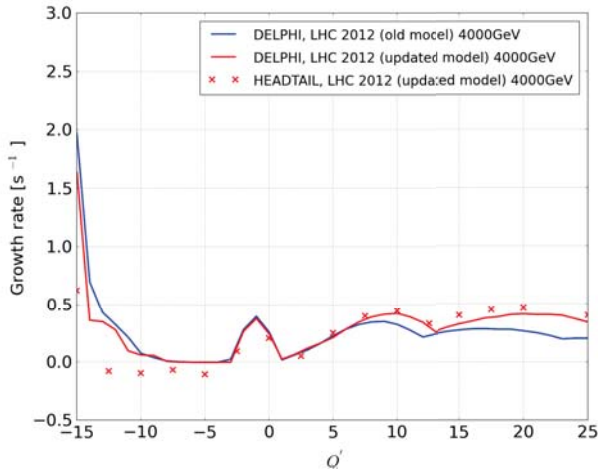

Figure 8: Vertical growth rates vs chromaticity with both the previous and new LHC impedance models (from dipolar impedance only), at 4 TeV with typical 2012 collimator settings. We assume a perfect bunch-by-bunch damper with a damping time of 50 turns, a single bunch of intensity $1.5 \cdot 10^{11}$ p$^+$/bunch, 1.25 ns total bunch length and no Landau damping. For the updated model we compare results from the Vlasov solver DELPHI and from the HEADTAIL tracking code.
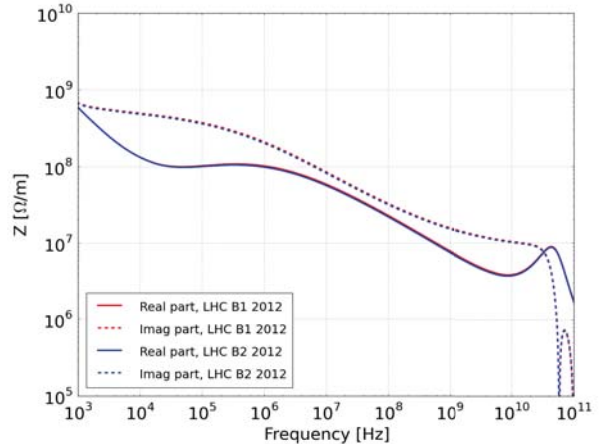

Figure 9: Horizontal dipolar impedances with the new LHC impedance model, for beam 1 and 2 (real and imaginary parts), at 4 TeV with typical 2012 collimator settings.
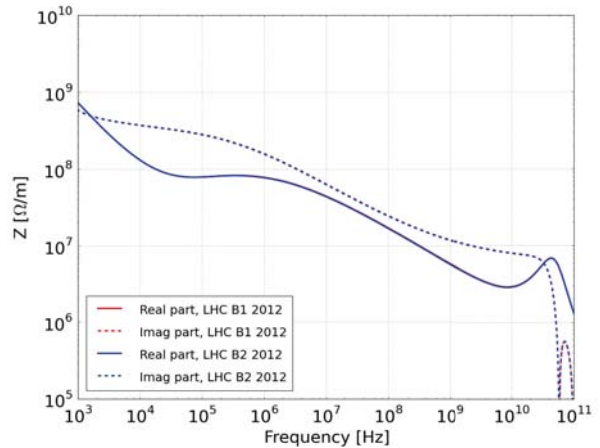

Figure 10: Vertical dipolar impedances with the new LHC impedance model, for beam 1 and 2 (real and imaginary parts), at 4 TeV with typical 2012 collimator settings. In this case the curves for the two beams (red and blue) are hardly distinguishable.

on emittance (estimated to be around 0.5 mm.mrad) and the RMS spread of intensities along the bunch train, while in horizontal the chromaticity is assumed to be known within 2 units. Note that the octupole feed-down effect to the chro-maticity was taken into account in the MD measurements (and the calibration of this effect performed right before or after the MDs).

The transverse damper gain has slightly different values in these measurements (ranging from 50 turns of damping time to 200 turns), which is not expected to have a strong effect at least in the high chromaticity region [26], which is the region that will be used to compute the stability limits (see below). Also, both planes and beams are mixed, which
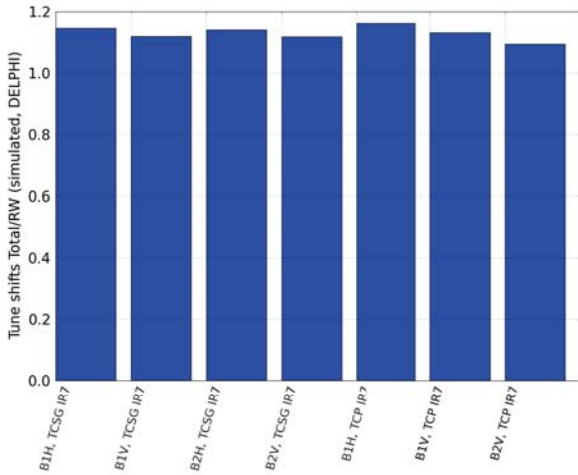
Figure 11: Ratio of the total simulated tuneshifts with the new LHC impedance model, vs. the tuneshifts obtained with the resistive-wall impedance only, for various collimator families under certain conditions (described in Ref. [23]). Simulations were done using the DELPHI Vlasov solver.

is justified by the fact they are all very similar in terms of impedance (see above). Note that for beam 1, only one case is reported here: it is the case with the highest stability parameter at negative octupole polarity and $Q' > 0$ (more precisely the one with $Q' = 7$) observed during normal operation at flat top [5].

The main obvious feature of Fig. 12 is that for positive chromaticity there is a huge spread in the measurements, in particular for the positive octupole polarity, which is nei-ther explained nor correlated with any observed beam prop-erty, and means basically that measurements are not at all reproducible. This will in turn generate enormous uncer-tainties on the stability limits foreseen for 2015, as we will see below.

The main conclusion from this plot is then that the nega-tive octupole polarity seems more favorable than the pos-tive one, as was also expected from the stability diagram theory [27].

EFFECT OF THE OPTICS CHANGE IN IR4 AND IR8

In 2015 a change in optics is foreseen, in particular in IR4 [31]. We show in Figs. 13 and 14 the expected impact on the transverse dipolar impedances, in terms of ratio between the 2015 impedance at injection and that of 2012. Injection energy was chosen because it's the configuration in which the change will have the highest possible effect, as the impedance is then less dominated by collimator contributions (which is not modified by this optics change). Clearly, from these plots we see that the optics change has a negligible impact on impedance.

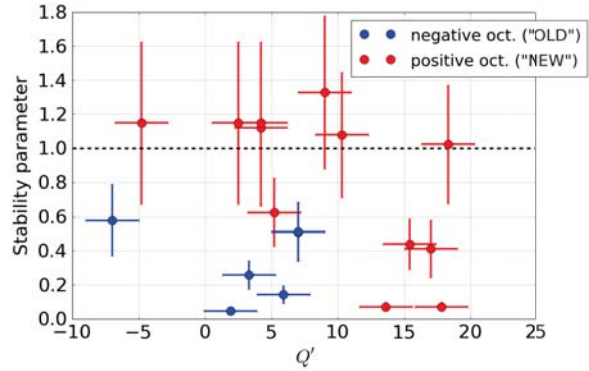Figure 12: Summary of single-beam instabilities observed in 2012 at 4 TeV, for the two octupole polarities.
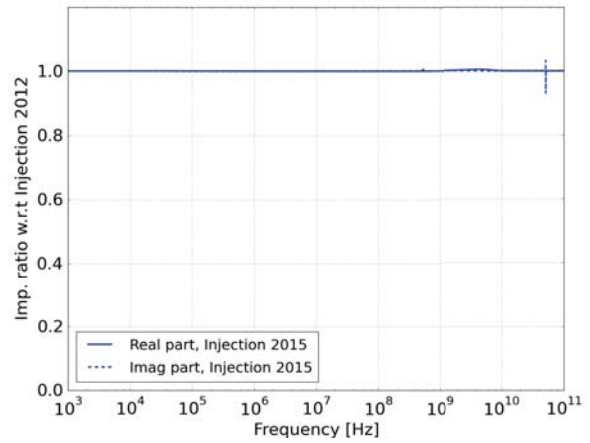

Figure 13: Horizontal dipolar impedance ratio between the 2015 (new optics) and 2012 configurations, at injection with the new LHC impedance model.
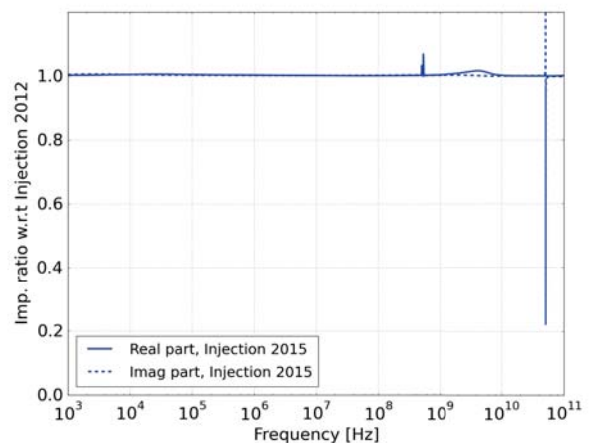

Figure 14: Vertical dipolar impedance ratio between the 2015 (new optics) and 2012 configurations, at injection with the new LHC impedance model.
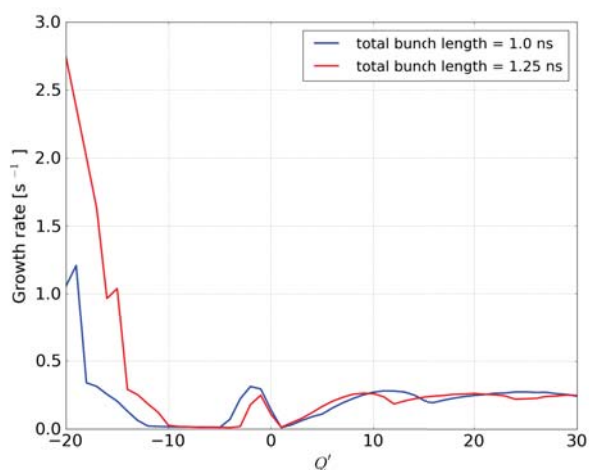
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Figure 15: Horizontal growth rates vs chromaticity with the new LHC impedance model (from dipolar impedance only), at 6.5 TeV with "mm-kept" collimator settings. We assume a perfect bunch-by-bunch damper with a damping time of 50 turns, a 25 ns beam with $1.3 \cdot 10^{11}$ p$^+$/bunch and no Landau damping, for two different bunch lengths.

EFFECT OF THE BUNCH LENGTH

We evaluate here the potential impact of changing the bunch length. In Fig. 15 we plot the horizontal growth rate vs Q' at 6.5 TeV, in a possible collimator scenario ("2012 mm-kept" settings, see next section – the exact collimator scenario does not matter here), when the bunch length is changed from 1 ns to 1.25 ns (total length, i.e. 4 times RMS), with a 25 ns beam (equidistant and equipopulated bunches), $1.3 \cdot 10^{11}$ p$^+$/bunch and 50 turns of damping time (bunch-by-bunch perfect damper). We see that in the high chromaticity region (for $Q' > 10$), the minimum growth rate over the region is not changing much between these bunch lengths, only the exact chromaticity at the minimum is changing. This means that the bunch length has little impact on the stability, provided we choose appropriately the chromaticity for the bunch length chosen.

SINGLE BEAM STABILITY LIMITS FORESEEN FOR SEVERAL COLLIMATOR SCENARIOS

We analyse now the stability situation in 2015 with the new LHC impedance model. Despite the refinements of the model, since it's only partly able to explain quantitatively the observations in the real LHC machine we have to resort to scaling laws to predict stability limits after LS1. The strategy is based on 2012 observations but is slightly more complicated than the one adopted previously [24], and enables the computation of error bars on the stability limits (instead of considering only the most pessimistic cases as was done in e.g. Ref. [24]):

- For each of the highest chromaticity cases in Fig. 12

(i.e. for $Q' > 5$ with negative octupole polarity and $Q' > 9$ with the positive one), the beam is assumed to be at the threshold of instability at 4 TeV with the beam parameters measured at the time of the instability. For each of these cases we can compute the "stability factor" F as

$$F = \frac{|I_{oct}| \cdot \varepsilon}{E^2 \Im(\Delta Q_{coh})}, \qquad (2)$$

with the same notations as for Eq. (1), E the beam energy and $\Im(\Delta Q_{coh})$ the imaginary tune shift of the most critical mode (without Landau damping), computed with the parameters from this particular case (in particular taking into account the chromaticity and the damper gain) with the DELPHI Vlasov solver.

- For each octupole polarity one can then compute the average and standard deviation of all such F for the cases considered.

- Assuming then that in 2015, $E = 6.5$ TeV, $I_{oct} = \pm 570$ A in the octupoles, and that at the threshold of stability we must have the same "stability factor" F as in 2012, reversing Eq. (2) we can get $\Im(\Delta Q_{coh})$ vs normalized emittance ε at the stability limit, that we can translate into a number of particles per bunch N_b through, again, DELPHI simulations where we assume a high chromaticity (as at the end of 2012) $Q' = 15 \pm 1$ and a high bunch-by-bunch damper gain (50 turns).

Note that in the simulations we use the nominal bunch length (1 ns), and the same bunch spacing (25 or 50 ns) as the beam for which we want to compute the stability.

This procedure is very approximate and reflects our lack of reliable and reproducible measurements. Error bars are therefore very large.

We analyse the stability for several kinds of beam parame-ters detailed in Table 1 and several possible collimator sce-narios shown in Table 2, which we can briefly describe as:

- the "mm-kept" scenario, where the collimator settings are very similar to those of 2012 in mm,

- the "2 σ retraction" scenario, where both the IR3 collimators and the secondaries and subsequent collimators of IR7 are closer than in the "mm-kept" scenario,

- the nominal settings, which are those defined in the LHC design report [32] and are put here for reference only.

For the two first collimator scenarios above, we show in Figs. 16 and 17 the average stability limits as the curve $N_b = f(\varepsilon)$ above which the intensity should be too high for the beam to stay stable. We also show there the error bars (in the form of shaded error zones around the average stability curve) related to the uncertainty in the measurements shown in Fig. 12. Clearly, the error zone is very

large and prevents clear quantitative predictions. Nevertheless one can state that even with the safest (in terms of impedance) "mm-kept" collimator settings, only the standard 25 ns beam is almost guaranteed to stay stable at flat top, while the BCMS and 8b+4e 25 ns beams can be stable with the negative octupole polarity but have a high probably to be unstable with the positive polarity. Then for the 2σ retraction scenario the situation is even worse, as the BCMS and 8b+4e 25 ns beams can barely be stabilized even with the negative octupole polarity, while the standard 25 ns beam should remain stable with negative polarity but could already become unstable with positive polarity.

The three collimator scenarios are put together (without the error bars) in Figs. 18 and 19 for respectively the positive and negative octupole polarity, giving essentially the same conclusions as above, with the additional fact that the nom-inal collimator settings should lead to even lower stability limits than the two other scenarios.

Finally, for reference we sketch in Fig. 20 the stability lim-its (with error zones) for the 50 ns beam with typical 2012 parameters (except for the higher energy) and the "mm-kept" settings. It appears that the beam is barely stable even with the negative octupole polarity.

Table 1: Possible beam parameters scenarios for post-LS1 operation, as achievable by the injectors [33]. A tranverse emittance blow-up of 0.6% mm.mrad was assumed in the LHC, except for the standard 25 ns beam where the nominal design report emittance was used [32].

	N_b (p+/bunch)	ε (mm.mrad)
25 ns, standard	$1.3 \cdot 10^{11}$	3.75
25 ns, BCMS	$1.3 \cdot 10^{11}$	1.9
25 ns, standard, 8b+4e	$1.8 \cdot 10^{11}$	2.9
50 ns, standard (2012)	$1.7 \cdot 10^{11}$	2.2

Table 2: Collimator settings (in number of σ) for the three collimator options analysed.

Collimator family	2012 mm-kept	2σ retraction	Nominal
TCP IR3	15	12	12
TCS IR3	18	15.6	15.6
TCLA IR3	20	17.6	17.6
TCP IR7	5.5	5.5	6
TCS IR7	8	7.5	7
TCLA IR7	10.6	9.5	10
TCL IR 1 & 5 (except TCL6)	12	10	10
TCL6 IR 1 & 5	retracted	retracted	10
TCT IR 1 & 5	11.6	10.3	8.3
TCT IR 2 & 8	15	15	15
TCDQ IR6	9.6	8.8	8
TCS IR6	9.1	8.3	7.5
TDI & TCLI	retracted	retracted	retracted

Figure 16: Intensity limit for the 25 ns beam at 6.5 TeV, as a function of transverse normalized emittance, for the "2012 mm-kept" collimator scenario as shown in Table 2 and for both octupole polarities. Beam parameters scenarios as achievable by the injectors have been indicated as well (see Table 1). The shaded areas represent the uncertainty on the stability limit.
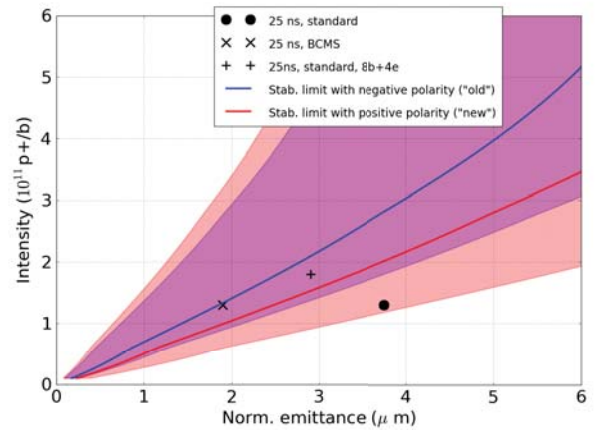
Figure 17: Intensity limit for the 25 ns beam at 6.5 TeV, as a function of transverse normalized emittance, for the "2σ retraction" collimator scenario as shown in Table 2 and for both octupole polarities. Beam parameters scenarios as achievable by the injectors have been indicated as well (see Table 1). The shaded areas represent the uncertainty on the stability limit.
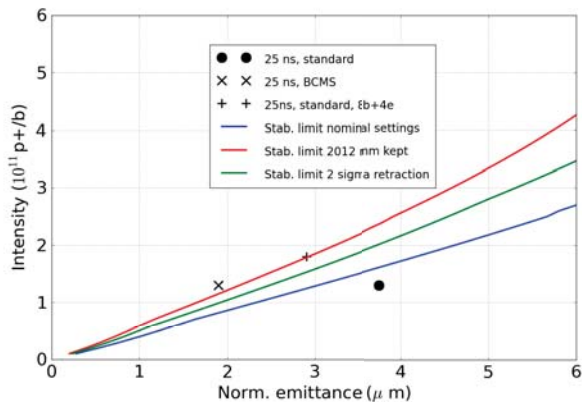
Figure 18: Average intensity limit for the 25 ns beam at 6.5 TeV, as a function of transverse normalized emittance, for all the collimator scenarios shown in Table 2 and for positive octupole polarity. Beam parameters scenarios as achievable by the injectors have been indicated as well (see Table 1).
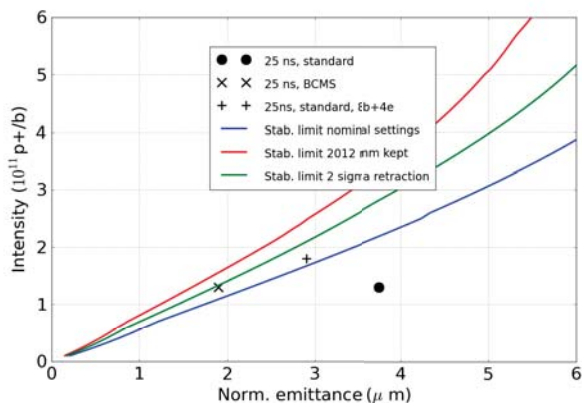
Figure 19: Average intensity limit for the 25 ns beam at 6.5 TeV, as a function of transverse normalized emittance, for all the collimator scenarios of Table 2 and for negative octupole polarity. Beam parameters scenarios as achievable by the injectors have been indicated as well (see Table 1).

PERSPECTIVES OF IMPROVEMENT

To improve the stability situation for a given impedance, several means coud be employed. First, the negative octupole polarity with high chromaticity was never tested in MDs nor on many successive operational fills, therefore its real impact on beam stability is unknown and could well be better that what is foreseen from the above plots (which are based on measurements taken at much lower chromaticities – see Fig. 12).
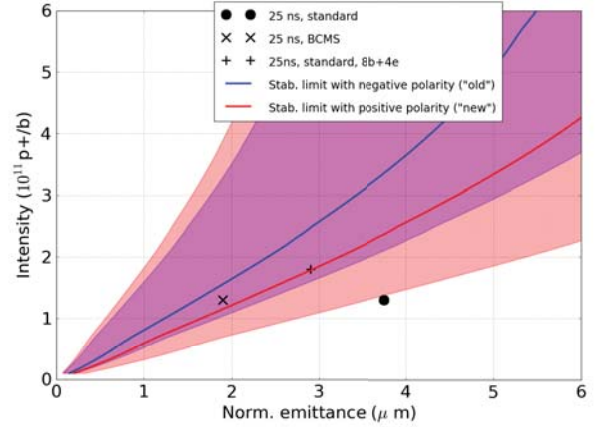

Figure 20: Intensity limit for the 50 ns beam at 6.5 TeV, as a function of transverse normalized emittance, for the "2012 mm-kept" collimator scenario as shown in Table 2 and for both octupole polarities. Beam parameters scenarios as achievable by the injectors have been indicated as well (see Table 1). The shaded areas represens the uncertainty on the stability limit.
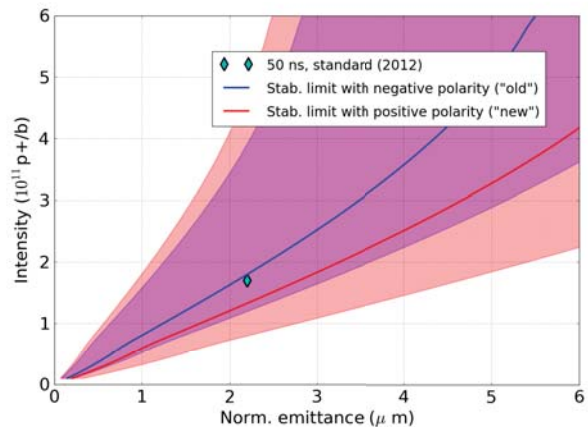
Secondly, it was already seen in e.g. Fig. 15 that the chromaticity could have very strong beneficial impact on stability, especially with a bunch-by-bunch ideal damper: at negative chromaticities and also for Q' close to 1, some regions of high stability (without any need for Landau damping) appear. Therefore one could think that with a fine tuning of chromaticity a much better stability could be achieved.

Nevertheless, recent studies show that taking into account damper imperfections can lead to very different results, as shown in Fig. 21. Clearly, a fine model of the transverse damper is needed, and ultimately the same kind of curve from measurements in the machine.

CONCLUSIONS

The LHC impedance model has been refined, leading mainly to an increase in its imaginary part, and to a significant but limited impact on tuneshifts and growth rates predicted by the model. The impact of bunch length and optics changes that will potentially occur in 2015 were analysed through this new model, showing respectively a small and negligible impact on the instabilities.

The single-beam instabilities observed in 2012 at 4 TeV have been reviewed, and clearly exhibit a lack of reproducibility. Based on the limited statistics that can be obtained from these measurements, scaling laws, and simulations of growth rates from the LHC impedance model together with a bunch-by-bunch damper and a high chromaticity, the single-beam stability limits in 2015 were obtained, for different beam and collimator scenarios. Overall the only safe configuration in terms of instabilities remains the high emittance standard 25 ns beam.
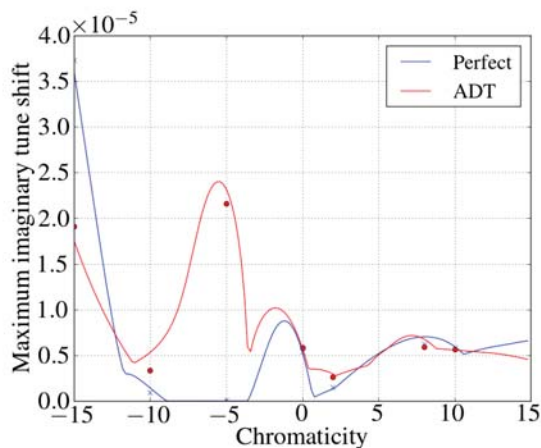
Figure 21: Single-bunch imaginary tune shift (=growth rate/revolution angular frequency) vs. Q' with typical 2012 4 TeV beam (50 turns damper, $1.5 \cdot 10^{11}$ p$^+$/bunch), for a perfect and a more realistic ("ADT") damper model. For this plot we used the old LHC impedance model (not updated). Solid lines are from the linear matrix model from Ref. [34] while the dots are from macroparticle tracking simulations done with the COMBI code [35].

To improve the situation, one might try to perform a fine tuning of the chromaticity, taking into account the damper imperfections. Such a procedure would have to rely on extensive, systematic and reproducible measurements in the real machine, if possible without the octupoles.

ACKNOWLEDGMENTS

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TWO BEAM EFFECTS

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Abstract

In this talk we propose possible scenarios for operation of beams during the betatron squeeze, adjust and stable beam mode at 6.5 TeV energy for the 2015 LHC physics run. The available parameter space in term of intensity, emittances, chromaticity, octupole current, damper gain will be explored for the 25 ns bunch spacing. Conclusions on possible settings for the operation will be based when possible on experimental experience from the LHC 2012 physics run. Limitations and possible countermeasures will be considered in the choices of possible scenarios in order to provide the highest integrated luminosity.

INTRODUCTION

The 2012 run of the Large Hadron Collider (LHC) has shown, despite the great physics discovery of a Higgs-like boson, several instabilities that have perturbed the accelerator performances. To achieve the required integrated luminosity several parameters had been changed and pushed compared to 2011: reduced β^*, from 1 m to 0.6 m, and higher brightness beams (approximately two times larger than nominal). To ensure protection of the triplets collimator gaps have been reduced to tight settings corresponding to apertures close the nominal 7 TeV configuration, leading to larger impedances [2]. Moreover to cure the instabilities several other parameters have been changed experimentally (i.e. chromaticity from approximately 2 units to larger values of 15) and the transverse feedback gain increased from 200 turns up to 50 turns.

The main beam parameters, compared to those of 2010 and 2011, are summarized in Tab. 1.

Table 1: LHC Operational Parameters

Parameter	2010	2011	2012	Nominal
$N_p[10^{11}$ p/b]	1.2	1.45	1.58	1.15
N_b	368	1380	1380	2808
Spacing [ns]	150	75/50	50	25
ϵ_n [μ m rad]	2.4-4	1.9-2.4	2.2-2.5	3.75
β^* (IP1/5) [m]	3.5	1.5-1	0.6	0.55
L [10^{32} cm$^2 s^{-1}$]	2	35	76	100

In this paper we show the impact of all the operational changes on the beam-beam interactions via simulations and try to compare to 2012 observables where possible. Predictions for 2015 operation are also shown and possible limits highlighted. The studies are focused on two main domains:

incoherent beam-beam effects and the role of beam-beam effects during the coherent instabilities observed during the LHC Run1 at the end of the betatron squeeze, the adjust beam process and during stable beams. The origin of these instabilities is still not understood however some observations have led to considerations on the beam stability to help defining the LHC possible future scenarios. Based on the experience from the 2012 Run, we use the predictions for 2015 to define a set of parameters for the start-up of the LHC (i.e. beam-beam separations for different brightness of the beams, chromaticity, octupoles) and propose a possible strategy to ensure the most robust performances.

INCOHERENT BEAM-BEAM

Long range experiments versus simulations

The Beam-Beam Interactions (BBIs), head-on and long range, lead to a detuning with amplitude of the beam particles [3]. In Fig.1 we show the two dimensional detuning with amplitude for particles up to 6σ due to beam-beam interactions head-on and long ranges, the so called tune footprints [3]. The different tune footprints are calculated for bunches with intensities of $1.3 \cdot 10^{11}$ protons per bunch and a long range beam-beam separation of $10\ \sigma$ at the first encounter defined as:

$$d_{sep} = \alpha \cdot \sqrt{\frac{\gamma \cdot \beta^*}{\epsilon_n}} \qquad (1)$$

where α is the crossing angle, γ the relativistic factor, β^* the beta function at the Interaction Point (IP) and ϵ_n the normalized emittance.

The different footprints correspond to different operational scenarios of the LHC: the 2012 Run1 case with 50 ns bunch spacing (blue lines) is compared to the nom-inal LHC design report case with 25 ns bunch spacing with emittances of 3.75 μm (red lines) and with emittance of 1.9 μm (green lines). As one can notice, despite the smaller emittances the wings of the footprint are larger for the transversally smaller bunches (in green) because their head-on contribution to the spread is much larger respect to the case with almost twice the emittances (nominal LHC case in red) even for identical separations at the long range encounter of $10\ \sigma$. This picture is used to illustrate why the choice of the crossing angle α, β^* and or the beam emittances ϵ should be taken together to ensure no surprises when pushing the beam brightness during the physics run. The common idea that reduced emittances are always better has to be compared to the contribution given by the head-on spread to the overall footprint.
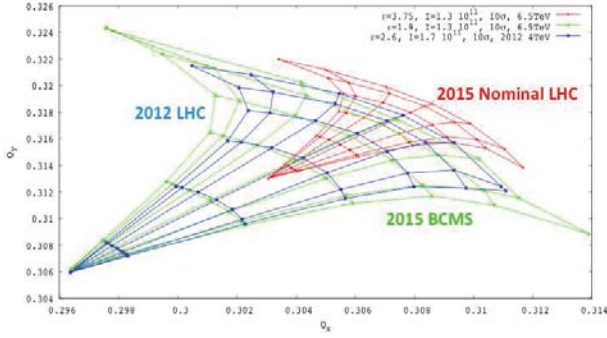
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Figure 1: Beam-beam tune footprints: for the 2012 case at 50 ns bunch spacing (blue lines), for the nominal LHC emittances of 3.75 μm rad (red lines) and for reduced emittances of 1.9 μm rad (green lines) both for 25 bunch spacing.

Figure 2: Bunch by bunch relative intensity losses as a function of time for different crossing angles α. The number of long-ranges interactions per bunch are indicated in the legend.

Several experiments aiming to characterize the long range interactions have been carried during the 2011 and 2012 LHC runs. These experiments were performed to probe our Dynamic Aperture (DA) simulation in order to get confidence in the use of these tools for predicting the performances of future scenarios and for the general understanding of the non-linear dynamics of beam-beam. Details of the experiments could be found in several papers [4, 5, 6]. The experiments were done with trains of bunches so that the full set of long ranges interactions were applied, the crossing angle α, and therefore the beam-beam separation d_{sep}, was reduced in steps till detrimental effects, large losses with impact on beam lifetimes, were observed. An example of such an experiment is shown in Fig. 2 where the relative intensity drop for a train of different bunches experiencing different numbers of long range interactions are shown as a function of time while the crossing angle at the IPs is reduced in steps of approximately 1 σ in beam-beam separation. The onset of losses starts at a beam-beam separation of approximately 6 σ for this specific case with the beam parameters as indicated.

This type of experiment has been repeated for different intensities, β^* and bunch spacing (50 and 25 ns). A summary of the different results is given in Tab. 2. We will call lately this limit at which the deep losses and lifetime drops occur as the limit of chaotic motion, which identifies the limit from which we should define our margins for beam-beam effects to not deteriorate significantly and drastically the beam properties. At these separations particles from the tails are lost and also core particles diffuse, due to beam-beam, to larger amplitudes feeding the tails and therefore reducing the beam lifetimes. We compare then the onset of losses identified by the experiments with our dynamic aperture simulations. The DA is defined as the region, in units of beam size, of phase space where particles are stable. Comparing the experimental point to DA simulation show that the limit of chaotic motion is around a value of DA of $\approx 4\,\sigma$. This means that when we reach this limit particles at 4 σ are not stable and particles at 2 σ start showing chaotic spikes [7].
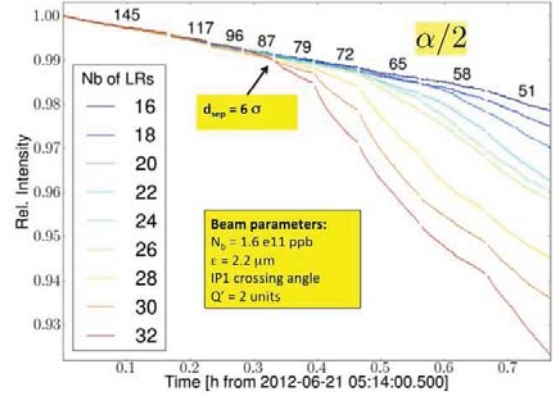
Table 2: Summary of onset of losses measured during long-range beam-beam experiments.

Spacing (ns)	β^*(m)	N_p (10^{11} p/b)	$\alpha(\mu$rad)	$d_{sep}(\sigma)$
50	1.5	1.2	240	5-5.5
50	1.5	1.2	240	5-5.5
50	0.6	1.2	290	5-5.5
50	0.6	1.6	290	6-6.5
25	1.0	1.0	290	6.5-7.5

This is visible in Fig. 3 where the DA calculations for 50 (green line) and 25 (red line) ns bunch spacing are shown for a nominal LHC case ($1.15 \cdot 10^{11}$) while the experimental points (cyan dots) are shown on top of the simulations. A detailed analysis of the different cases have been shown at [8] where simulations of the different experimental conditions have been compared to the experimental data.

From the dedicated experiments we have learned that:

- measurements of the limit of chaotic motion are reproducible and it seems to be settled at a DA of 4-5 σ

- changing β^* does not change the limit (what counts is the normalized separation d_{sep} of Eq.1)

- changing the crossing angle doesn't change the limit (what counts is the normalized separation d_{sep} of Eq.1)

- increasing the intensity from 1.2 to 1.6 10^{11} anticipates the limit by 1σ, the dependency is known to be linear and approximately 1 σ more separation is need to have the same DA

Figure 3: Dynamic Aperture as a function of the first beam-beam long range encounter separation in units of beam size. The red dots are simulations for a 25 ns bunch spacing while the green points are for 50 ns bunch 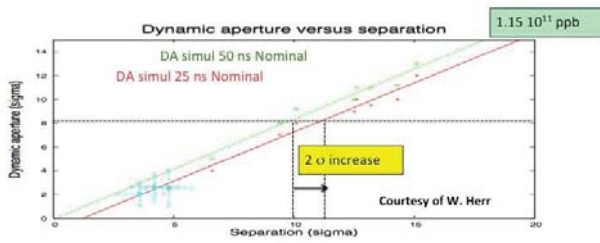spacing. Simulations were performed for IP1 and IP5 interaction regions with head-on and long-range interactions for an intensity of $1.15 \cdot 10^{11}$ ppb and a transverse emittance of $3.75 \mu m$ rad. The blue points corresponds to experimental points collected during dedicated experiments where beam losses were appearing [5].
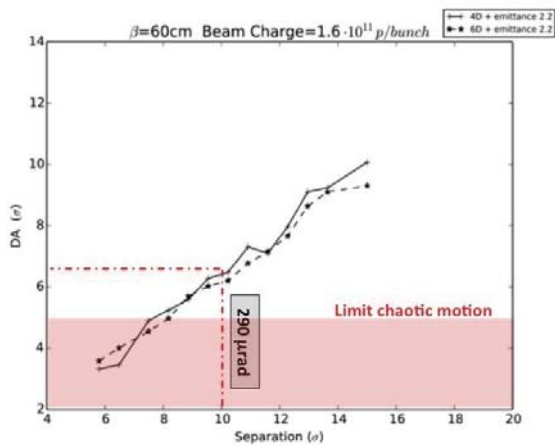

Figure 4: Dynamic Aperture as a functions of the beam-beam separation at first long range encounter for a beam with $1.6 \cdot 10^{11}$ proton per bunch. The red region identifies the chaotic motion region.

- doubling the long range encounters (from 50 to 25 ns) anticipates the limit by approximately 2 σ in simulations, from measurements caused by big uncertainties on the beam emittances it has been measured at 4-6 σ

- the lower limit for 25 ns beams has not been identified yet.

The absolute value of DA simulations is very difficult to relate to a machine observable. On the other hand it is very powerful if used in relative to predict the impact of changes in the machine configurations (i.e. impact of intensity, crossing angle, β^* and bunch spacing). The lower limit, which defines our margins, can be identified only experimentally. However for the 25 ns case the 2012 measurements were not conclusive and therefore an experiment of long range interactions in 2015 will be needed to iden-

tify the limits in order to decide the margins to take from that.

2012 Physics run: impact of chromaticity

Another important change that occurred during the 2012 run was the increase of the machine chromaticity Q' to cure coherent instabilities. Q' was raised from 2 units up to approximately 15 in the August 2012 [9]. In Fig.5 the bunch by bunch emittances, computed from the specific luminosity, is shown as a function of time. One can notice the faster blow up of the high brightness bunches respect to the blown up ones with emittances of around 3.4 μm. The smaller picture shows the bunch by bunch emittances after 30 minutes in stable beams to distinguish between bunches stable (blue dots) during the betatron squeeze and those unstable (green dots). This observation has raised the question if maybe could be beam-beam provoking a blow-up of the bunches [10]. A detailed analysis of the bunch by bunch emittance blow-up and lifetime evolution in stable beams is still on going , however simulations have been carried to characterize the DA for this case.
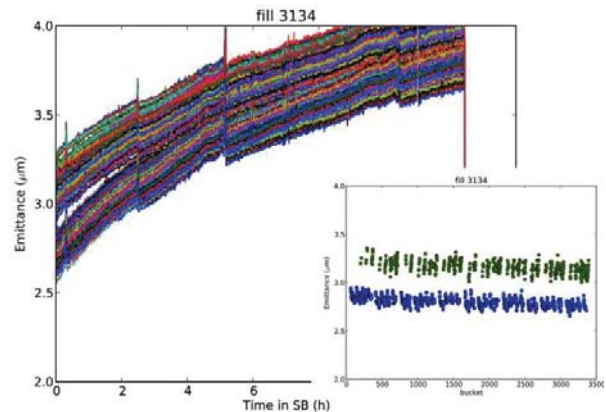
Figure 5: Bunch by bunch luminosity convoluted emittance versus time during physics fill 3134 of the LHC in 2012.

High values of the chromaticity deteriorates significantly the DA. Results of simulations are shown in Fig. 6 where we compare the DA of the first part of the year with Q'= 2 units (black lines, dots) versus the case with Q' = 15 units (blue and red lines). The high chromaticity plots are for two beam emittances: for bunches with 2.5 μm (red lines) and for the bunches with 3.5 μm emittance. This scenario corresponds to the physics fills of 2012 , second part of the year. One can notice that the DA for both cases is reduced and for the bunches with smaller emittance much closer it is on top of the limit of chaotic motion. The chromaticity change during the year might be the explanation for a deprecation of the integrated luminosity per fill due to a stronger blow-up of the emittances and reduced lifetimes.

Stron-strong simulations also confirm the emittance blow-up. In Fig.7 the simulated emittances are shown as
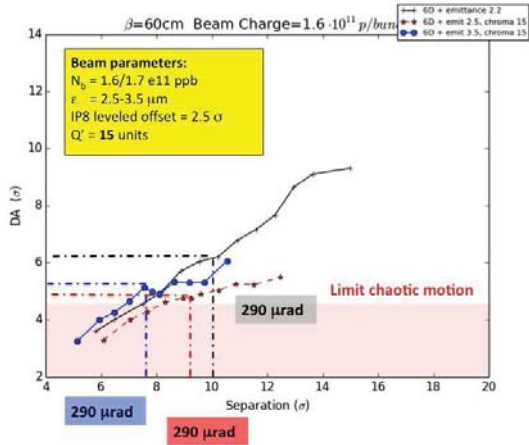
Figure 6: Dynamic aperture simulations for $1.6 \cdot 10^{11}$ proton bunches as a function of the long range beam-beam separation in units of the beams size. Black line correspond to the first part of the 2012 Run with chromaticity of 2 units and a separation of 10 σ while the other two lines are for the second part of the year with Q'=15 units. Red and blue lines correspond to beams with transverse emittances of 2.5 ($d_{sep} = 9.2\,\sigma$) and 3.5 ($d_{sep} = 7.8\,\sigma$) μm rad, respectively.

Figure 7: Emittance blow-up for different values of chromaticity Q'. Simulations are performed with Beam-Beam3D.

Figure 8: Footprints of head-on collision for different values of chromaticity. Upper plot for Q'=0 and lower for Q'=15 units.

a function of the time in collision (two head-on collisions) for different values of chromaticity. One can notice that up to a 20% per hour blow up due to the head-on collisions only is expected. A possible explanation to this phenomenon is that it is due to the crossing of the 10th order resonance (as highlighted in Fig. 8). The beam lifetime deprecation could then be linked to the long range and high chromaticity values and octupole setting during collision which should result in larger detuning for large amplitude particles which are responsible for bad lifetimes. The effect of the emittance blow-up is linked to another observation, the bunch shortening in collision, which was reproduced with this model and therefore gives us confidence that it is a good representation of the machine set-up. The detailed study could be found at [11].

As a result of these studies we can conclude that chromaticity has to be settled as low as possible close to zero (slightly positive) when in collision and head-on beam-beam interactions are granted. If this is not possible due to instabilities on non colliding bunches then these bunches will set the lowest limit, to avoid instabilities, however this highest value of the chromaticity will deteriorate the beam lifetimes and an emittances blow-up should be expected when pushing the beam brightness. An experimental verification of the resonances driving the beams blow-up in collision will help delimiting the available space in tune diagram in within we should keep the footprints to avoid these effects.

2015 Scenario

Simulations of the dynamic aperture expected for the LHC 2015 possible scenarios are shown in Fig.9 for bunches with intensities of maximum $1.3 \cdot 10^{11}$ protons and transverse emittances of 1.9 μm (black lines, dots) and 3.75 μm (red lines and dots) to cover the whole range of possible beam parameters. We have settled the chromaticity to 2 units in all cases.

If one wants to set the dynamic aperture as in 2012 for
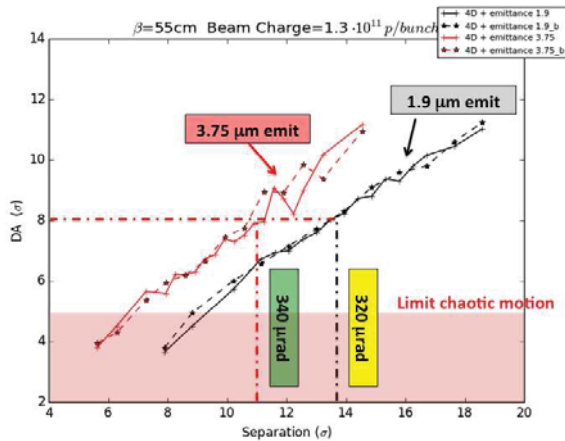
Figure 9: Dynamic aperture simulations as a function of the beam-beam separation d_{sep} for bunches of intensity of maximum $1.3 \cdot 10^{11}$ protons and transverse emittances of 1.9 μm (black lines, dots) and 3.75 μm (red lines and dots). A relaxed dynamic aperture of 8 σ is highlighted red dashed line and the corresponding crossing angle required for two beam emittances.

Figure 10: Dynamic aperture simulations as a function of the beam-beam separation d_{sep} for bunches of intensity of maximum $1.3 \cdot 10^{11}$ protons and transverse emittances of 1.9 μm rad (black lines, dots) and 3.75 μm rad(red lines and dots). A pushed dynamic aperture of 6 σ is highlighted with red dashed line and the corresponding crossing angle required for the two beam emittances.

beams of $1.15 \cdot 10^{11}$ protons per bunch and transverse emittance between 2 and 3.5 σ one should increase simply by 2 σ the beam beam separation to take into account the doubling number of long range encounters. This can be deduced from Fig.3 moving from the 50 to the 25 ns curve to keep the same value of DA one needs to move from 10 to 12 σ beam-beam separation d_{sep}. However the 2015 run should have beams with bunch intensity never exceeding $1.3 \cdot 10^{11}$ protons, therefore a slightly reduced separation could be applied. To start as in the 2012 run we need to guarantee a dynamic aperture value of 8 σ, which corresponds for the larger emittance beams to 11σ beam to beam separation (for 55 cm beta* this corresponds to a crossing angle of 340 μrad). This is visible in Fig.9 where we highlighted the d_{sep} at which one will keep a 8 σ DA. This separation might not be the smallest achievable.

For the 25 ns beams (twice number of long ranges respect to 2012 case) the limit of chaotic motion has not been defined yet. Uncertainties in the emittance measurements and bunch by bunch blow-up due to e-cloud effects put large error bars on the measurements. During a specific MD we measured it between 4-6 σ DA, details can be found in [8]. A reduced d_{sep} could be proposed in a second stage after a dedicated experiment with the goal to identify the limit of chaotic motion when the beam parameters (mainly emittances and intensities at collision) and machine parameters (chromaticity) are settled and under control. This possible step is sketched in Fig.10 where assuming a chaotic limit at 5 σ DA, we could aim, if no lifetime deprecation is visible in experiments, to a beam-beam separation of approximately 8.5 σ.

INSTABILITIES

The LHC beams were accelerated in 2012 from injection energy (450 GeV) to a top energy of 4 TeV. The β* at the different IPs were then lowered (from 10 m to 3 m in IP2 and IP8 and from 11 m to 0.6 m in IP1 and IP5). This process, known as β squeeze, lasted around 15 min. At the beginning of the year at a β* value of $\approx$ 1.5 m during the execution of the β squeeze several bunches were becoming unstable, losing their intensity in a non-reproducible manner. In particular the instability was observed only during a subset of the physics fills. The bunches have become unstable one after the other for several minutes till the head-on collision was established. In some cases, the instabilities generated losses high enough to cause a beam dump. An important parameter for stability is chromaticity that might explain the non reproducibility of the instability when operating with small positive value (LHC was operating at Q' $\approx$ 2 units till the beginning of August 2012). At the beginning of August 2012 the machine configuration has been changed drastically in terms of chromaticity (changed from 2 units to 15 units [9, 12]), the polarity of the Landau octupoles (changed from negative to positive [13]) and the transverse feedback gain (from 200 to 50 turns). The changes have been implemented within a few fills since fill number 2926, making difficult the analysis of the implications of the different parameters. As a result of these changes the instability has significantly changed. It became extremely reproducible, occurring at minute 16 from the start of the betatron squeeze and in the vertical plane only. Many bunches were affected by the instability, causing reduced intensity drops, as opposed to large losses on few bunches in the previous configuration. In Fig.11 we show

the fills with instabilities during the β squeeze (red dots) and fills without instabilities (black dots). In the plot we highlight the middle of the year changes (octupole polarity, chromaticity and feedback gain).

Figure 11: Beam intensity per physics fill of the LHC 2012 run. Red dots correspond to a fill that had an end of squeeze instability while black dots correspond to fills without instabilities during the squeeze.

2012 case and change of polarity

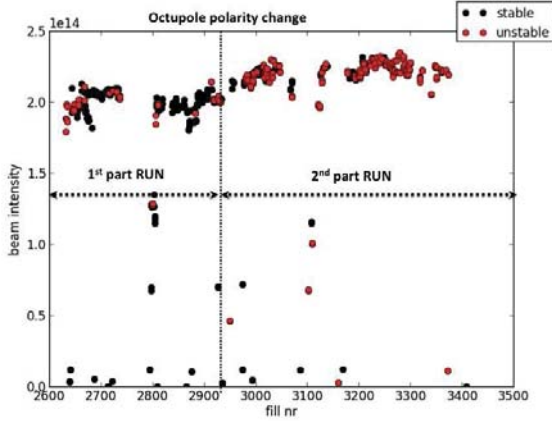The stability of the beams before going through the β squeeze and during the squeeze is given by the Landau octupoles which ensure a given stability diagram, defining a limit under which all impedance driven modes , not stabilized by the transverse feedback, should be dumped. In the LHC the stability diagram at the beginning of the betatron squeeze are illustrated in Fig. 12 (black lines) for both octupoles polarities (left negative and right positive). The negative polarity was preferred before the squeeze since it provides larger area for the expected modes, having negative real tune shift [14]. However, the long-range interactions also contribute to the non-linearities and affect the stability diagram at the end of the β squeeze (red and blue lines in Fig. 12). For the case of negative polarity they reduce the stability area while for the positive polarity they increase it. This was the motivation for inverting the polarity of the Landau octupoles [13].

In Fig.13 we show a comparison of the worst stability diagram for both polarities of the Landua octupoles. The smaller stability diagram at the end of the squeeze is the one where long range are strongest (nominal bunch with full long range encounters) for the negative polarity (red line) and the one of a pacman bunch (least number of long range encounters) for the positive polarity of the octupoles (blue line). The change of polarity of the Landau octupoles have moved reduced stability diagrams from nominal (central bunches of a train) to pacman bunchs (head and tails of a train). The total area is very similar as visible in Fig. 13. This might also be proved with a clear pattern of un-
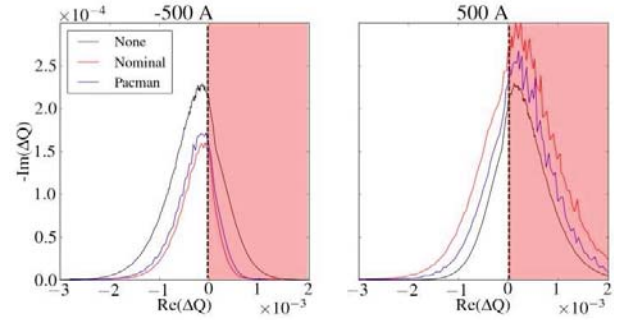
Figure 12: Stability diagrams for negative (left plot) and positive (right plot) polarity of the Landau octupoles (black lines) compared to the stability diagram reduced by long range interactions for a nominal bunch (red lines) and a pacman bunch (blue lines).

stable bunches for the second part of the year with positive polarity in the octupoles where tail bunches were the one unstable [9].
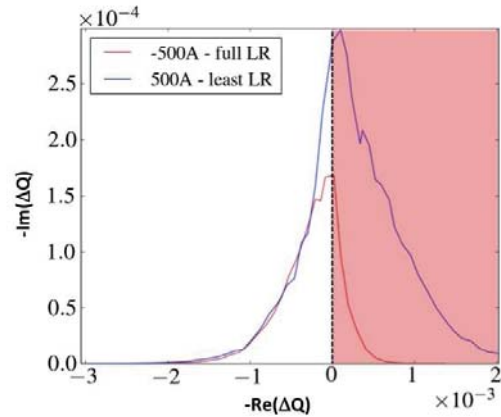
Figure 13: Stability diagram for negative polarity and full long range encounters (red line) and for positive polarity and least number of long range (blue line).

2015 run with twice long range encounters

The 25 ns beams will lead to twice the number of long ranges, moreover the energy increase will lead to less effective Landau octupoles. Depending on the octupole polarity the stability diagrams will be reduced by long range detuning if the polarity is negative and will add up if it will be positive. In Fig.14 we show the stability diagrams ($\mathrm{Re}(\Delta Q)$ and $-\mathrm{Im}(\Delta Q)$) for different beam-beam separation d_{sep}. Stability diagrams are defined by the octupoles when the long range separation is large (from 25 to 15 σ separation) and they are modified by the long ranges when the separation is further reduced to 10 σ. From beam-beam point of view there is a clear preference in this case for the positive polarity of the octupoles.
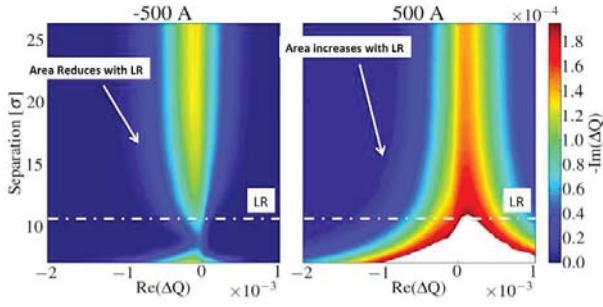
Figure 14: Stability diagrams (Re(ΔQ) and -Im(ΔQ)) as a function of the long range beam-beam separation d$_{sep}$ for negative polarity (left plot) and positive polarity (right plot) of the octupoles.

One can see in details in Fig15 the worse stability diagram a bunch could have for positive (blue lines) and negative (red lines) octupole polarity for the 2012 configuration (left plot) and for the 2015 case (right plot). The 2015 case is characterized by stronger long range interactions which will redude significantly the area with respect to the 2012 case (two red curves). The positive polarity for 2015 will give a stability diagram, which is the largest, and therefore the preferred with beam-beam.
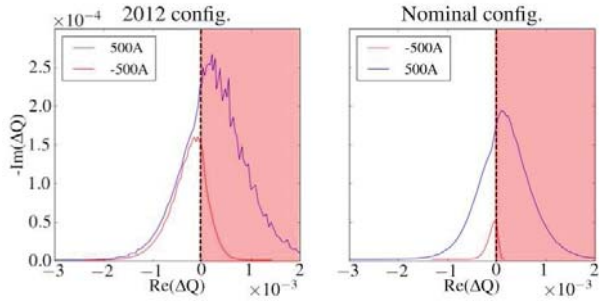
Figure 15: Comparison of the stability diagrams for both polarities of the octupoles at the end of the squeeze with long range effects. The left plot refers to the 2012 case while the right plot to the 2015 possible run at 6.5 TeV. The red lines are the worse stability diagrams for negative polarity while the blue are for the positive polarity.

Positive versus negative polarity

It is clear however from Fig.16 that the negative polarity of the octupoles is preferred to the positive for single beams (larger area for negative than positive polarity: dashed lines). A question raised by S. Fartoukh is: can we push out of the squeeze the long range effects. In Fig.16 we show the reduction of the stability diagram from a pure octupole contribution (largest area with dashed line) to the different reductions while squeezing the β^* (coloured lines). The arrow shows the direction in time during the squeeze. This has been repeated for two crossing angles,

larger than nominal 340 and 400 μrad. As a comparison the stability diagram for the positive polarity is shown (dashed line with smaller area). One can notice that stopping at a β^* of 65 cm with a crossing angle α equal to 340 μrad the stability diagrams will always be larger or equal to the one obtained in case of positive octupole polarity. For the case with crossing angle equal to 400 μrad the $\beta*$ can be reduced to 50 cm. The stability diagrams are smaller than the one with positive polarity for separations below 12 σ.

Since the single beam stability prefers the negative octupole polarity and based on the study of the stability diagram we could accept this choice and relax the long range effects to assume their effects are smaller than going for a positive octupole polarity. The choice of relaxed long range interactions is at around 12 σ. This proposal is also in line with the conclusions made from the DA beam-beam studies.
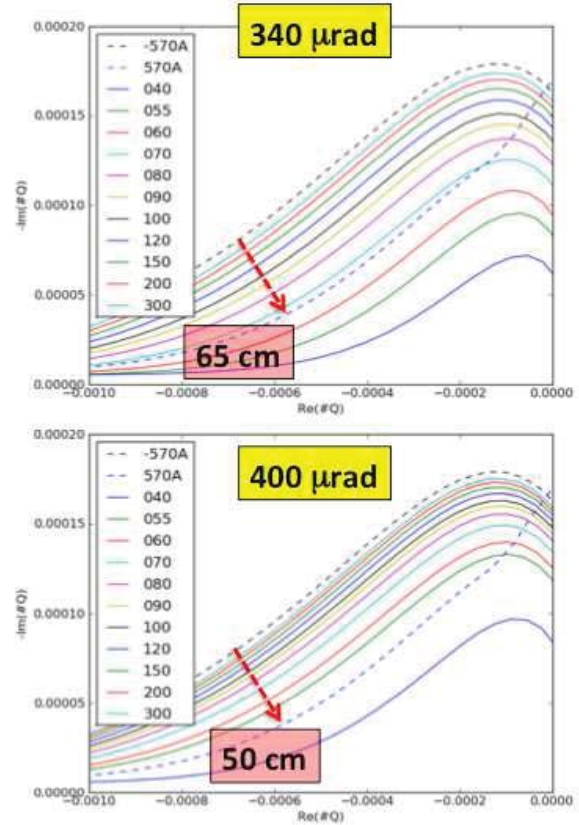
Figure 16: Stability diagrams for nominal bunch during the β squeeze for two different crossing angles for the negative octupole polarity.

Collide and squeeze

While the end of squeeze instability has not been understood yet observations of the LHC 2012 instability have also demonstrated the head-on collision to be the only mean to stabilize the beams. Indeed, the tune spread due to

a head-on collision is much larger than the one due to oc-tupoles or beam-beam long range interactions or any other non-linearity present in the LHC. Moreover, the detuning is more important on the core particles of the beam rather than the tails, which significantly enhances its contribution to the stability diagram. It would be therefore profitable to have the beams colliding during (part of) the squeeze in or-der to avoid the instabilities, details on this possibility are discussed in [15]. An operational effort should be done at the start-up to explore the possibility of making the collide and squeeze procedure operational in order to gain experi-ence in case of real need.

Instabilities and beam dumps during the adjust beam process

The end of squeeze instability, was lasting also during the collision beam process. At the beginning of the year the process was long (≈ 200 s) and was not directly go-ing for head-on collisions in IP1 and IP5 but was slowed down to first collapse a separation in the crossing plane and to allow the tilting of IP8 crossing angle and only at the end optimized for luminosity. Several instabilities were observed while IP1 and IP5 were staying almost steady at an intermediate separation. In more recent analysis (ques-tion raised by G. Arduini) of these instabilities it has been noticed that at the end of the squeeze a separation in the crossing plane was still on during the adjust beam process and was collapsed only in the first part of the adjust beam process. In Fig. 17 we show the beam to beam separations at the long range encounters with parallel separation (at the end of the squeeze blue dots) and without (red dots) for two cases if a separation in the crossing plane is added (bottom plot) or not (top plot). For the 50ns beams this was not giving detrimental effects since the separation at the first encounter was reduced from 11 to 7 σ, however the effect was not negligible. In a configuration at 25 ns bunch spac-ing this would have given a first long range at 5 σ with very detrimental effects. A separation in the crossing plane has to be avoided during operation since it could give re-duced long range separations due to a longitudinal shift of the beam-beam parasitic encounter locations.

In Fig.18 we show the instabilities observed during the adjust beam process as a function of time (middle plot) to be compared to the collapse of the separation bumps in the crossing planes and separation planes (plotted in the top figure). For this configuration the stability diagrams are plotted (bottom figure) as a function of the collapse of the bumps. One can notice that the stability diagram is reduced further when the separation in the crossing planes is col-lapsed then it is stable till the head-on component becomes important which occurs around 1.5 σ. Therefore instabil-ities during the adjust could be counted as end of squeeze instabilities. Studies are on-going to quantify the expected variations in chromaticity due to the collapse of a separa-tion in the crossing plane.
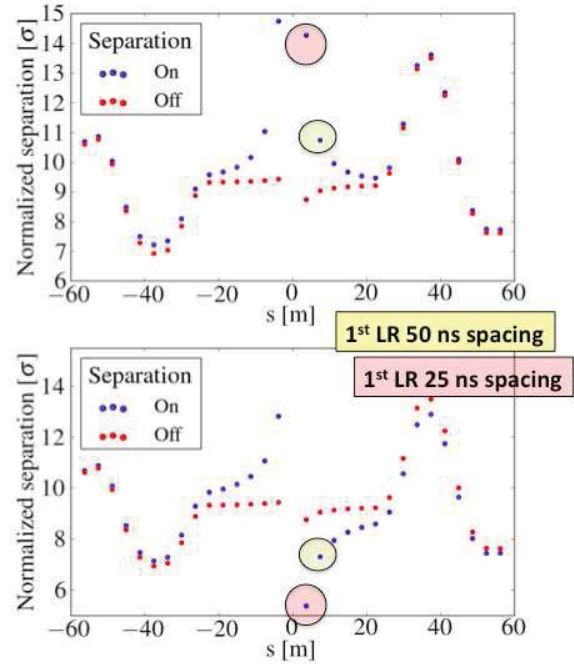
Figure 17: Beam to beam separation in units of the beam size at the end of the squeeze with the parallel separation (blue dots) and without (red dots). Top plot is without a separation in the crossing plane while bottom with a sepa-ration in the crossing plane.

Instabilities during stable beams

Another instability was occurring during stable beams the so called "snowflake" instability [9]. This instability was involving only special bunches colliding head-on only in IP8. The instability was arriving after several hours in stable beams. A more recent analysis [17] has shown that the IP8 special bunches are colliding with a transverse off-set to level the luminosity. The range of the offsets was from approximately 4 σ to zero. The expected stability di-agrams for such a configuration are shown in Fig. 19. As for the case of the adjust beam process a minimum of sta-bility is expected when fully separated above 2.5 σ and at around 1.3 σ separation the picture deviates a bit from a collapse of a separation dump, because of the tilted plane of collision in the LHCb experiment. One can notice that due to the geometry of the collision the minimum is ex-pected in the vertical plane and data analysis shows the in-stability always in this plane. The data analysis also shows a pick of the instabilities occurring at a separation of 2 and 1.3 σ separation. The instabilities have not disappeared af-ter the middle of the year change of 2012 but just became very weak (very small intensity drops) and since the beam lifetimes were very bad, they became very difficult to be detected.
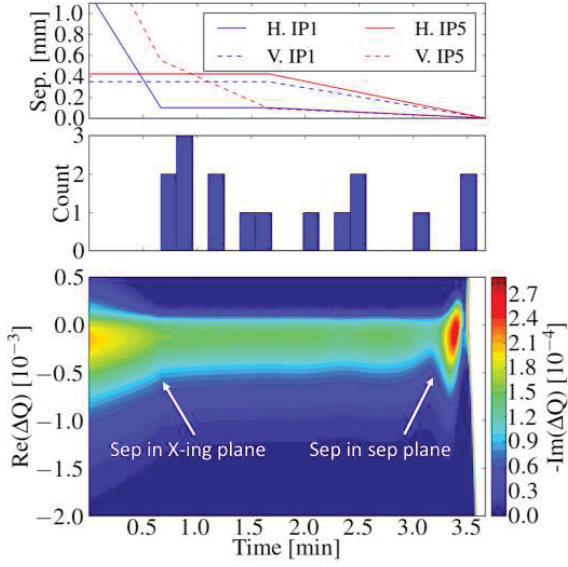
Figure 18: Dumps counting (middle plot) as a function of the time during the adjust beam process compared to the separation bump evolution (top plot) and the corresponding stability diagrams (lower plot).
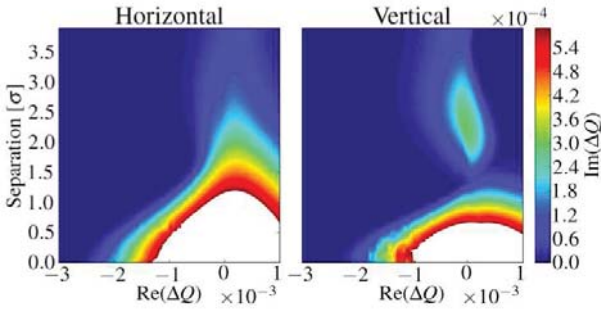
Figure 19: Stability diagrams for bunches colliding in IP8 with a transverse offset as a function of the offset. Left plot is in the horizontal plane while right plot vertical.

TRANSVERSE DAMPER

During 2012 operation, the transverse feedback, the Landau octupoles and the chromaticity have been set to high values to ensure the beams stability. However a deep study of the different contributions is fundamental in the first commissioning period of the LHC in 2015. The feedback modeling is fundamental for our understandings. In Fig. 20 we show simulation results of the growth rate of the most unstable mode (color code) versus chromaticity and feedback gain when the LHC impedance and long range beam-beam effects (settled at a separation of 10σ) are interplaying. The upper plot is for a perfect model of the damper while the lower plot is for a damper with a sensitivity to head-tail motion as shown in [18].

The right plot of Fig. 20 shows how deprecated becomes the zero and negative chromaticity area for high damper gains.
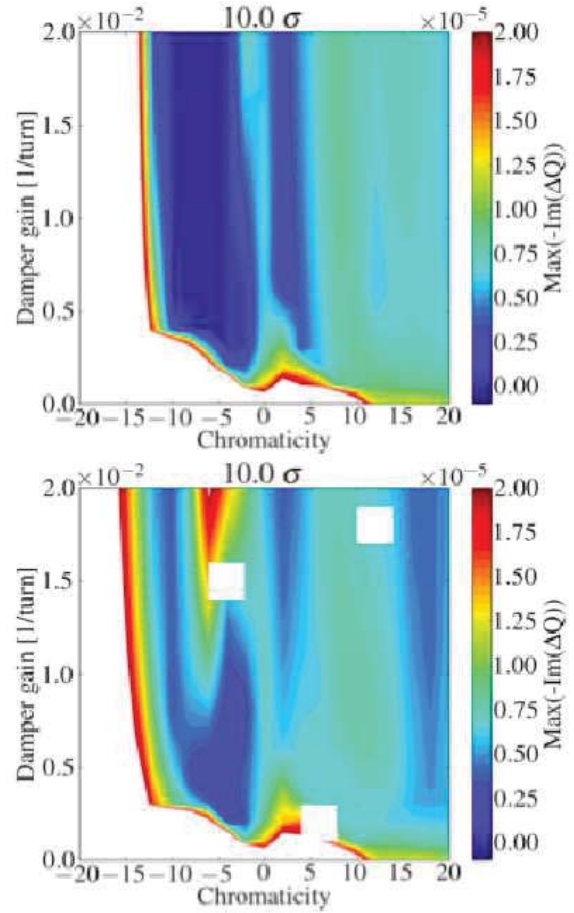
Figure 20: Growth rate of the most unstable mode (color code) versus chromaticity and feedback gain when the LHC impedance and long range beam-beam effects (setted at a separation of 10σ) are interplaying at the end of the squeeze. Upper plot is for a perfect feedback while lower plot is with a non-perfect feedback.

The area with high chromaticity and ADT gain is still the most promising in terms of stability. A deeper knowledge of the feedback dynamics will be fundamental to address the instabilities observations. On top of suppressing the co-herent motion arising from the interplay of beam-beam and impedance driven modes the ADT shows also an impor-tant role in enhancing diffusion of particles. This diffusion mechanism affects strongly the stability diagrams even for small variations of the beam tail profiles of which we have no knowledge.

CONCLUSIONS

There are many unknowns concerning the instabilities observed during the 2012 run of the LHC. Models including the machine impedance, the transverse damper, Landau octupoles and beam-beam interactions have being developed to allow a better understanding of the observations [12, 19]. Nevertheless, some time should be dedicated to the testing of these models with beams after

LS1. In 2012, the time allocated for systematic studies on the effect of the octupoles, as well as on the effect of chromaticity was not sufficient to conclude on possible settings for 2015. An initial period of commissioning should be devoted to study the parameter space in order to properly assess potential stability issues during the run. Nevertheless, the observations described here and in [2] brings us to two possible scenarios.

An up-date of the data analysis of the instabilities led us to some conclusions:

- all instabilities during end of squeeze and adjust can be considered as end of squeeze instabilities due to a separation in the crossing plane collapsed in the first part of the adjust process

- only two dumps occurred during the collapse of the separation bumps in the adjust beam process, during the intensity ramp up.

- the reduction of the stability diagram could not explain the instabilities observed in 2012 the impedance modes should have been stable inside the area even if reduced by long range [2]

- The instabilities in IP8 were present the whole year and seem to be well explained with the minimum of stability diagram due to the missing head-on collision due to the offset leveling

- The beams stability greatly depends on the chromaticity, a good control of this parameter will be required in any event.

- Head-on collision have shown to be the only efficient damping mechanism, therefore the collide and squeeze procedure should be explored in operation to face possible difficulties before a possible need

Single beam prefers the negative polarity since it gives larger margins for pushing the beam brightness [2]. The beam-beam interactions will reduce the stability diagrams however keeping the long range effects relaxed will allow to have a stability diagram always larger or equal to the positive polarity case for single beam. Therefore we are confident that the negative polarity stopping the beam-beam separation at 12 σ will be better in terms of stability diagrams than the positive polarity. High chromaticity should be preferred and high damper gain. In this configuration the machine should be less sensitive to chromaticity variations.

However, no cure for the instabilities at the end of the squeeze have been found in this configuration, at the end of 2012 run. Indeed, the end of squeeze instability was visible during all fills and have shown to be sensitive to a tune split. A study to determine if it is a tune effect of coherent beam-beam mode related should be followed. The stability at the end of the squeeze will, therefore, strongly rely on colliding during the squeeze if the instability will appear again. Testing this procedure during early stages of commissioning would help identifying possible problematics (offsets at the IP) and take countermeasures. The relaxed long range separations will also keep orbit effects from beam-beam much more relax and this will be also beneficial for a possible collide and squeeze procedure.

If the collide and squeeze procedure shows problems then we will need to step back to positive polarity and reduce the beam brightness.

For incoherent beam-beam considerations a minimum separation of 11 σ is mandatory to avoid going to close the limit of chaotic motion. A two stage approach is preferred where relaxed settings 11-12 σ beam to beam separation is requested and lately, only after a long range experiment, one could maybe reduce the separation to smaller values approaching the identified limit.

For the low luminosity experiments (IP2 and IP8) the effect of parasitic encounters should be kept in the shadow of the high luminosity experiments. Therefore a larger separation at the long range encounters is required. These two IPs do not have passive compensation of the tune shifts and chromaticity leading to enhanced pacman effect. In particular, the difference between bunch families, in particular in term of tune and chromaticity, may become significant rendering difficult the optimization of the machine. Over the 2012 year moreover evidence of selective losses on bunches with long range interactions in IP2 were visible and presented in [21]. For these two IPs we therefore suggest separations larger than 13-14 σ in all cases if not limited by hardware constrains.

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ELECTRON CLOUD AND SCRUBBING: PERSPECTIVE AND REQUIREMENTS FOR 25 ns OPERATION IN 2015

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Abstract

In order to routinely operate the LHC with 25 ns bunch spacing during Run 2, electron cloud effects will have to be mitigated through beam induced scrubbing. Therefore, the Run 1 experience with 25 ns beams will be reviewed and used for defining the most effective scrubbing strategy. In particular, the potential of using a dedicated scrubbing scheme based on the "doublet" beam, following the promising SPS tests in 2012, will be described and analysed. The impact of this scheme on the LHC equipments and machine protection will be discussed. The different stages of the scrubbing process, including the high energy tests, will be outlined in terms of beam requirements and expected duration. To conclude, possible alternatives of post-scrubbing scenarios will be also considered, which will depend on the degree of success of the scrubbing run.

BRIEF SUMMARY OF ELECTRON CLOUD OBSERVATIONS IN LHC RUN 1

The electron cloud observations in the LHC during Run 1 are of high importance to define the roadmap after the LHC start up in 2015. Before 2011, while LHC was producing physics with 150 ns spaced beams, electron cloud effects could be mainly seen in the interaction regions when both beams were circulating in the machine. Only when 50 and 75 ns spaced beams were first injected into the LHC, electron cloud effects became visible with single beam. In 2011, the LHC evidently suffered from electron cloud both at the beginning of the 50 ns run and then later, during all the machine study sessions with 25 ns beams. An initial scrubbing run with 50 ns beams, which took place at the beginning of April 2011 [1], could scrub the beam chambers just enough as to allow the LHC to move into physics with 50 ns beam and guarantee safe operation at both 450 GeV and 3.5 TeV. Further scrubbing was later achieved by using trains of 25 ns beams. The first injection attempts of this type of beams were hindered by severe electron cloud effects in terms of heat load in the arc screen, emittance growth of the bunches located at the tails of 24-bunch trains [2] and coherent instabilities at the tails of 48-bunch trains leading to dumps due to fast beam losses or large orbit excursions [3]. As LHC got gradually further scrubbed, 72-bunch trains of 25 ns beams could be injected with high chromaticity settings, reaching 2100 bunches for Beam 1 and 1020 for Beam 2. Though initially these beams suffered heavy degradation from electron cloud, a considerable amount of additional scrubbing could be achieved. The maximum Secondary Electron Yield (SEY or $\delta_{\max}$),

on the screen of the arc dipoles, as estimated from PyECLOUD simulations, decreased from a value of about 2.1 at the end of the 50 ns scrubbing run to 1.5. By the end of 2011, trains of 72 bunches with 25 ns spacing exhibited much reduced degradation with respect to the first injections, although both their lifetime and emittance evolution still indicated the presence of a significant amount of electron cloud in the LHC [4]. The top plot of Fig. 1 shows the calculated electron cloud induced heat load in the arc dipole screen as a function of $\delta_{\max}$ for both 25 and 50 ns beams. From the two curves it is clear that, while a $\delta_{\max}$ value of 2.1 can be sufficient to ensure low electron cloud operation with 50 ns beams, the achieved value of 1.5 is still not enough as to completely suppress the electron cloud in the arc dipoles with 25 ns beams.
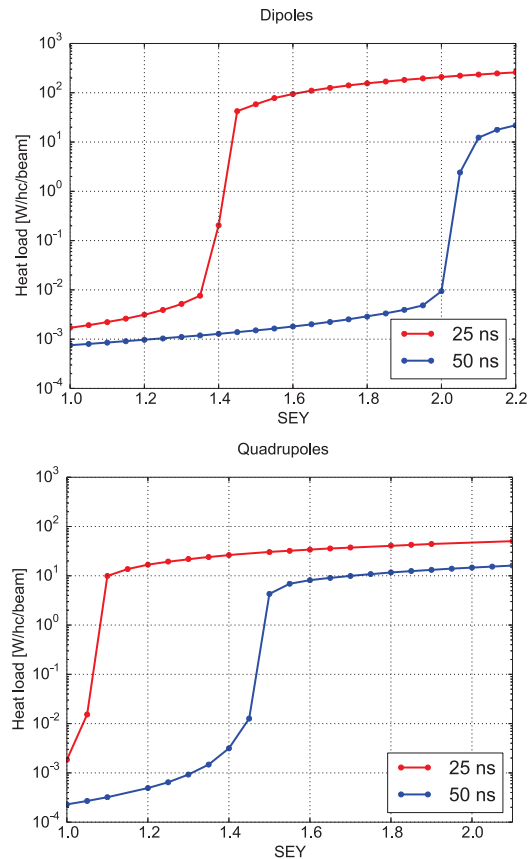
Figure 1: Calculated electron cloud induced heat load on the arc screen (top: dipole, bottom: quadrupole) as a function of $\delta_{\max}$ for both 25 (red)and 50 ns (blue) beams.

The bottom plot of Fig. 1 depicts the calculated electron cloud induced heat load on the arc quadrupole screen as a function of $\delta_{\max}$ for both 25 and 50 ns beams. Due to the length ratio between arc dipoles and quadrupoles ($\approx$15), as

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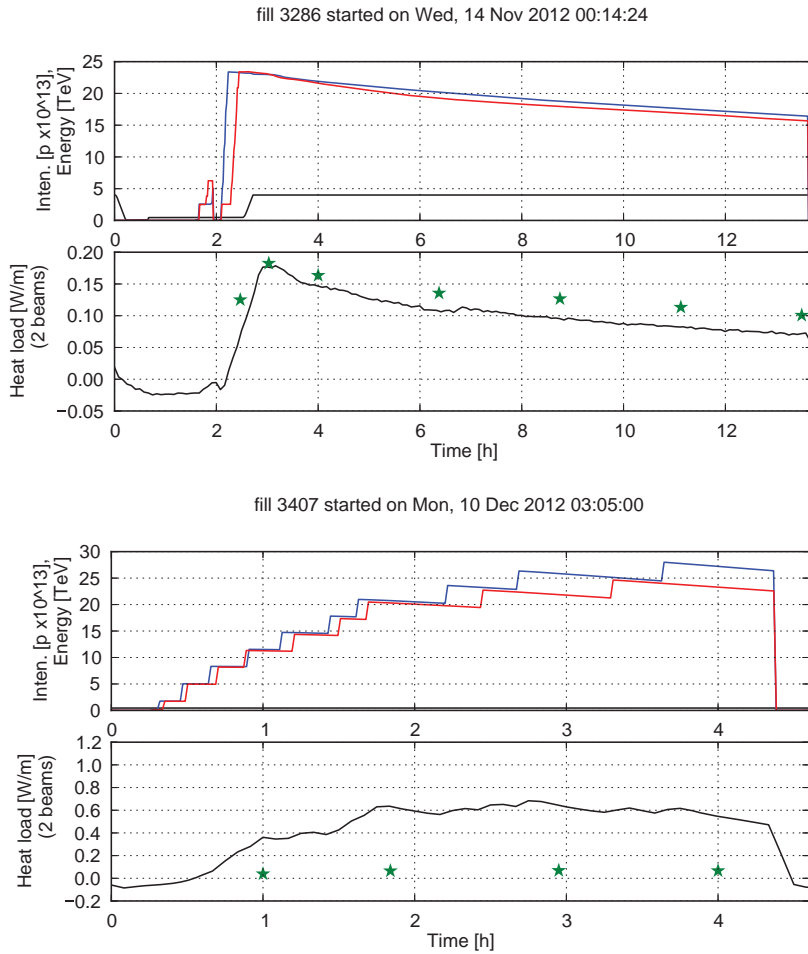
Figure 2: Top plot: Typical 50 ns fill with measured heat load in the arc beam screen and calculated values from the beam screen impedance model (green stars). Bottom plot: Scrubbing fill with 25 ns beam with measured heat load in the arc beam screen and calculated values from the beam screen impedance model (green stars).

long as the electron cloud in the dipoles is strong enough, the dominant contribution seen in the measured heat load comes from the dipoles and no conclusion can be made on the δ_{max} of the quad screens. The quadrupole heat load becomes significant in the balance only when the δ_{max} of the dipole screen has reached down the knee of the heat load curve (i.e. for values below 1.5 with 25 ns beams).

Thanks to the margin gained with the 25 ns beams in 2011, operation with 50 ns in 2012 was smooth and electron cloud free. It was only during the scrubbing run in December 2012, when the LHC was filled with 25 ns beams (up to 2748 bunches per beam) and reached the record intensity of 2.7×10^{14} p stored per beam, that heat load, emittance growth at the tails of the trains and poor beam lifetime indicated again the presence of a strong electron cloud with this mode of operation. However, a clear improvement in the electron cloud indicators over the first 70 hours was observed, followed by a sharp slow-down of the scrubbing process. The emittances of the bunches at the tails of the trains were blown up during the injection process, especially for sufficiently long bunch trains. The elec-

tron cloud continued to be present also during a few test ramps to 4 TeV and the two days of pilot 25 ns physics run and exhibited an important dependence on energy. A detailed summary of the observations and our present degree of understanding is presented in [5] summarized the next sections.

LESSONS LEARNT IN RUN 1

Both the MDs with 25 ns beams in 2011 and a relatively little deconditioning over the 2011-2012 end-of-year technical stop (EYTS) were the basic reasons why the LHC could be operated with 50 ns beams throughout the 2012 proton-proton run without electron cloud in the arcs [6]. This can be concluded from Fig. 2, top plot, which displays the evolution of the heat load in the arc screen measured during a typical 50 ns physics fill (solid black line) together with the calculated values of power loss obtained summing the contribution from impedance and that from synchrotron radiation (green stars). The agreement within less than 10% between calculated and estimated values shows that in this case no additional contribution to the heat load of

the arc beam screen is expected from electron cloud. However, when the 25 ns beam was injected into the LHC in 2012 (notably during the scrubbing run, 6 – 8 December, 2012), the electron cloud returned, which manifested in a heat load in the arcs becoming one order of magnitude larger than the values expected from the theoretical calculation based on impedance and synchrotron radiation. This is depicted in the bottom plot of Fig. 2, in which both the measured and calculated heat loads are plotted for a typical 25 ns scrubbing fill.

Distribution of electron cloud in the LHC arcs

As was mentioned in the introduction, a decreasing trend in the measured heat load as well as an improvement of the beam quality and lifetime were observed in the first part of the 2012 scrubbing run, while any improvement tended to become marginal in the later scrubbing phases [6]. This observation suggested that the process of beam scrubbing was saturating in the arcs, in the sense that any further little improvement would require increasingly longer running times with 25 ns beams.

Based on the simulated heat load curves in dipoles and quadrupoles shown in Fig. 1, an attempt was made to interpret the observed saturation of the scrubbing process and thus envisage possible solutions for Run 2. In particular, assuming the different SEY thresholds in dipoles and quadrupoles discussed above, the behaviour of the electron cloud evolution during the scrubbing run could be compatible with the following scenario:

1. The SEY in the dipole beam screen might be coming asymptotically closer to the threshold value for electron cloud build up leading to indeed much lower electron cloud in the dipole chambers, but not yet full suppression;

2. The SEY in the quadrupole beam screen, though probably scrubbed to a similarly low value as the dipole one, is still high enough to cause strong electron cloud in the quadrupole chambers.

Since in the arc cells it is not possible to disentangle the contribution to the heat load given by the dipole chamber (total length 14.2 m×3 per half cell) from that given by the quadrupole chamber (total length 3 m per half cell), the only way to have an indication on the plausibility of the above scenario is to look into the heat load in the so-called Stand Alone Modules (SAM). These include several matching quadrupoles and separation dipoles situated the Insertion Regions (IRs). Several matching quadrupoles have their own cooling circuits and their heat loads can be independently evaluated. The separation dipoles D3 at left and right of point 4 (D3L4 and D3R4) are the only dipoles to be equipped with independent cooling circuits. Other matching quadrupoles are paired with the close-by separation dipoles in one single cooling circuit. These are called semi-SAMs and their heat load would still come from the

combination of a dipole and a quadrupole (though with different length ratio than in the arcs). A full inventory of SAMs and semi-SAMs in the LHC can be found in [7].

Figure 3 shows the evolution of the heat load per unit length at the beam screen of the matching quads Q5's (taking the average of the values measured in Q5 left and right of points 1 and 5) and that at the beam screen of the separation dipoles D3's (taking the average of the values measured in D3 left and right of point 4) over a 25 ns fill towards the end of the scrubbing run.

Figure 3: Heat load per unit length (W/m) measured in the matching quadrupoles Q5 on both sides of the IRs 1 and 5 (purple, average among the four magnets) and in the separation dipoles D3 of the IR 4 (green, average between the two magnets) over one of the last fills of the 2012 scrubbing run. Beam currents for both beams are shown in the upper plot.

This plot strongly supports the scenario presented above. First of all, the specific heat load in the quadrupole beam screen exceeds by over one order of magnitude that in the dipole beam screen. Considering the factor about 15 difference in length, this would translate in basically equivalent contributions to the heat load from the dipoles and the quadrupole in an arc half cell. Secondly, the heat load in the dipoles exhibits a decay with the beam degradation even despite new injections, while that in the quadrupoles hardly decreases with deteriorating beam conditions. This suggests that, while the SEY of the dipole beam screens could be close to the electron cloud build up threshold value, that of the quadrupole beam screens is still far from it. The scenario of an electron cloud close to suppression in the dipoles at 450 GeV means that an electron cloud enhancing technique could be applied to achieve full scrubbing in the dipoles (see following section on the doublet beam), although a significant amount of electron cloud could still survive in the quadrupoles.
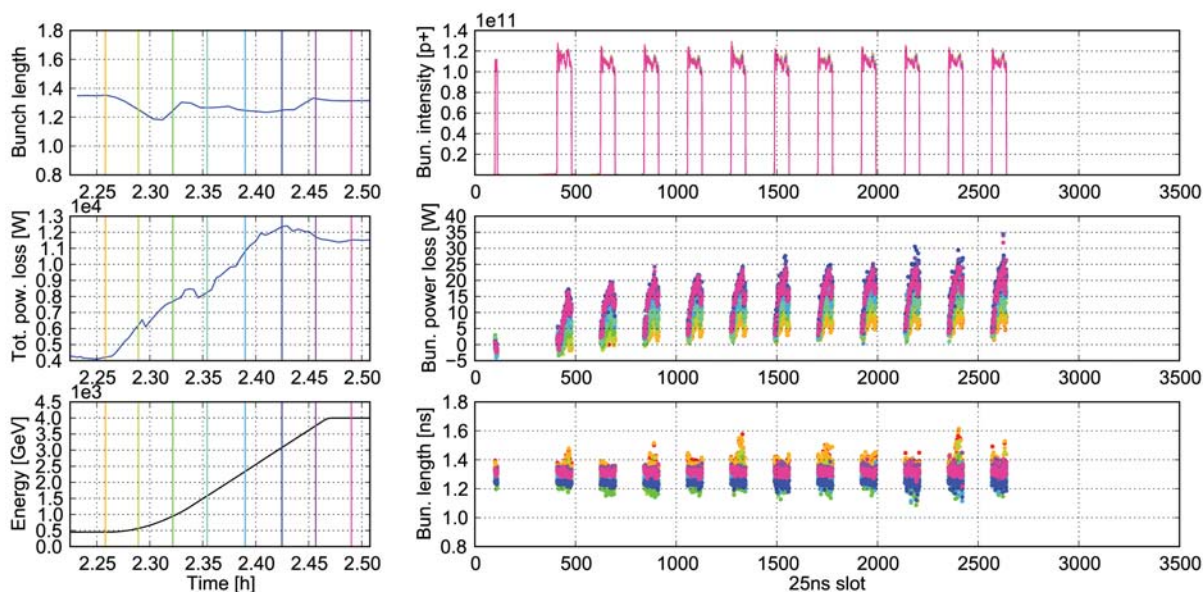
Figure 4: Beam energy and bunch-by-bunch energy loss measurements for beam 1 during the energy ramp of a fill with about 800 bunches with 25 ns spacing. The different traces in the right plot correspond to different times indicated by vertical bars in the left plot.

Energy dependence of the electron cloud in the arcs and effect on the beam

After the 2012 scrubbing run, increasing numbers of bunches of 25 ns beam were ramped to 4 TeV over several subsequent fills. Both heat load in the arcs and beam energy loss measurements from the bunch-by-bunch synchronous phase shift [8] showed a sharp increase over the ramp, which would be consistent with a growing electron cloud with the beam energy. An example of beam energy loss behaviour for an energy ramp with 800 bunches distributed in equally spaced trains of 72 bunches is fully displayed in Fig. 4. The plots on the left side share the same time axis and represent, from bottom to top, the energy ramp, the sum of the bunch-by-bunch energy loss as estimated from the synchronous phase shift and the average bunch length. At the eight time cuts highlighted with coloured vertical bars, on the right hand side the snapshots of the bunch-by-bunch intensity, energy loss and bunch length are depicted from top to bottom using the same colour convention. A steady increase of beam energy loss, which reveals an increasing electron cloud activity, is clearly visible along the energy ramp. One possible explanation of this behaviour is that the electron cloud enhancement is first triggered by the bunch shortening occurring at the beginning of the ramp and is later sustained by the photoelectrons, whose rate of production becomes significantly higher than that due to gas ionisation only at around 2 TeV. The fact that the electron cloud is most likely responsible for this increase is also confirmed by the snapshots of the bunch-by-bunch energy loss along the ramp. The bunches suffering the highest enhancement of energy loss are those located towards the end of each bunch train, while those at the beginning of the trains even at 4 TeV keep losing the same amount of energy as at 450 GeV. The pattern of the energy loss is also reminiscent of an electron cloud build up with the rise over one train to a defined saturation value and basically little memory between trains (only visible in the slower rise of the first train, probably due to the electron cleaning effect of the 12-bunch train). Hardly any sign of beam loss or anomalous lengthening or shortening for selected bunches can be spotted along the ramp, which leads to the encouraging conclusion that the enhanced electron cloud, probably thanks to the increasing beam energy, is not detrimental to the beam (although it is responsible for a fourfold increase of the heat load in the arcs).

One question concerning the electron cloud enhancement over the energy ramp is again whether it is localised in some specific elements of the LHC. In principle, a way to determine its distribution would be applying a similar approach to that shown in the previous section to disentangle the contributions to heat load from dipoles and quadrupoles in the arcs. Figure 5 shows the evolution of the heat load per unit length at the beam screen of the matching Q5's (average of the values measured left and right of points 1 and 5) and that at the beam screen of the separation dipole D3's (average of the values measured left and right of point 4) over the injection and ramp phases of the 25 ns fill already discussed for Fig. 4. It is clear that, while at 450 GeV the heat load in the quads is more than one order of magnitude larger than the one in the dipoles, the ramp causes an enhancement of the heat load only in the dipoles. This is not surprising, because the SEY in the dipoles is close to
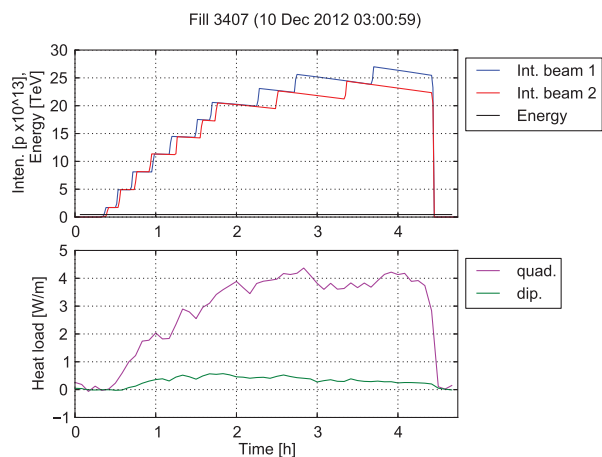
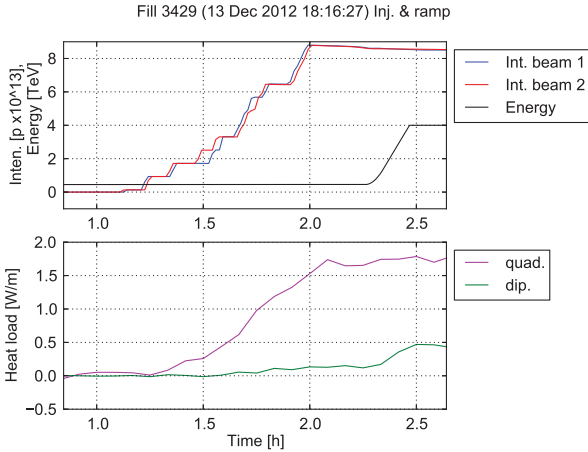Figure 5: Heat load measured in the matching quadrupoles Q5 on both sides of the IRs 1 and 5 (purple, average among the four magnets) and in the separation dipoles D3 of the IR 4 (green, average between the two magnets).

the build up threshold and the electron cloud there is most sensitive to the bunch shortening and/or enriched seeding from photoelectrons, while these effects would play only a marginal role if the SEY had been far above this threshold (e.g. in the quadrupoles). At 4 TeV, the specific heat load measured in D3 becomes only about one third of that measured in the quadrupoles. By merely applying these values to the arc dipoles and quadruples, and scaling by their lengths, one finds that, while at 450 GeV arc dipoles and quadrupoles would contribute about equally to the measured heat load, at 4 TeV the integrated contribution of the dipoles becomes again dominant and at least fivefold that of the quadrupoles. The fact however that this heat load remains then nearly constant over the whole fill duration (8 hours of 4 TeV store) [5, 6] also indicates that the SEY of the dipole screen has entered a region in which the increase of scrubbing flux associated to the electron cloud enhancement is not sufficient to impart a significant acceleration to the scrubbing process.

The beam behaviour at 4 TeV has been analysed through the evolution of the bunch-by-bunch transverse emittance over the stores of 25 ns beams. The store discussed above in this subsection was not a physics fill and the beams were not squeezed nor brought into collision. Therefore, the only emittance measurements available at 4 TeV for this store were those from the Beam Synchrotron Radiation Telescope (BSRT), which unfortunately worked only for Beam 1 at the time of the 2012 scrubbing run. A look at the snapshots taken over the eight hours during which the beam was stored in the LHC reveals that only a small emittance growth can be measured, affecting uniformly all bunches of the train and therefore not ascribable to electron cloud effects [6]. Later on in the 2012 run, three physics fills with 25 ns beams took place. For these fills, the bunch-by-bunch emittance evolution could be reconstructed from

the luminosity in ATLAS and CMS, providing a very reliable measurement all over the whole length of the physics store. A very interesting case was the last physics fill of the 25 ns pilot physics run, with 396 bunches per beam distributed in trains of 2×48 bunches collided for over six hours. Figure 6 shows seven snapshots of the bunch-by-bunch emittances from the moment of declaration of stable beams (time 0h) to six hours later (6h). The emittance pattern over the trains clearly exhibits the imprint of the electron cloud, with typically growing emittances towards the tails of the trains. The zoom on the second train displayed in the picture, however, allows us to spot even more interesting features of the emittance distribution and its evolution. Firstly, the electron cloud patten is present already from the first snapshot (i.e. at time 0h), meaning that the shape was created at injection energy (this could be also confirmed by means of BSRT measurements on Beam 1). Secondly, the emittance growth over the fill duration is such that the electron cloud pattern tends to even out, which suggests a blow up rate that is larger for the first bunches of the trains (with lower initial emittances) and lower for those at the tails (with higher initial emittances). This observation is consistent with an emittance growth mechanism at 4 TeV certainly different from electron cloud and emittance dependent. To summarise, the available 2012 beam observations seem to point to the electron cloud as a fast degrading effect for the beam at 450 GeV but not the main determinant of the beam quality at 4 TeV.
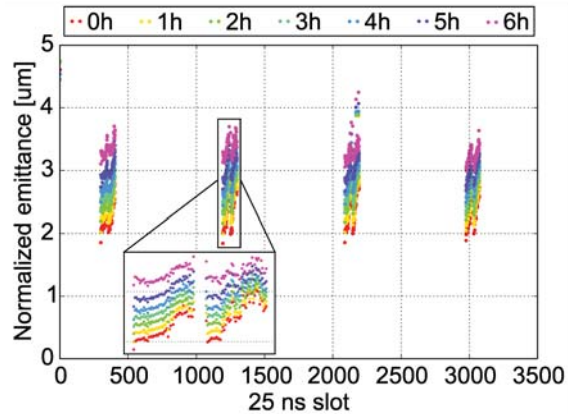
Figure 6: Bunch-by-bunch transverse emittances estimated from luminosity at the ATLAS experiment during a fill with 396 bunches with 25 ns spacing. Different traces correspond to different moments during the store.

Extrapolation to 2015 beam parameters

Before describing the roadmap of the 2015 scrubbing run, which should enable operation of LHC at 6.5 TeV with 25 ns beams, it could be useful to extrapolate the expected heat load in the arcs in 2015 if we run in the same conditions as we had after the 25 ns scrubbing run of December 2012. This exercise is fully summarised in Table 1.

The reference fill for this extrapolation is the one of eight hours with 800 bunches in trains of 72, which was dis-

Table 1: Expected distribution of the heat load in the arc dipoles and quadrupoles for the 25 ns 8 hours store with 800 bunches (reconstructed from 2012 measurements in the first column, rescaled to full machine in the second column, rescaled for the packed filling scheme in the third column and rescaled to 6.5 TeV in the fourth column)

	Measured in 2012 with 800 b. at 4 TeV	Rescaled to 2800 b.	Effect of tighter filling scheme	Effect of higher energy (6.5 TeV)
Dipoles	40 W/hcell	($\times$3.4) 136 W/hcell	($\times$2) 272 W/hcell	($\times$1.6) 435 W/hcell
Quadrupoles	5 W/hcell	($\times$3.4) 17 W/hcell	($\times$1) 17 W/hcell	($\times$1) 17 W/hcell
Total	45 W/hcell	153 W/hcell	289 W/hcell	450 W/hcell

cussed in the previous subsection. Assuming that the measured heat load in the arcs of 10 W/(half cell) after the end of the injection of both Beam 1 and Beam 2 is attributable in equal parts to dipoles and quadrupoles and that the increase to 45 W/(half call) with the ramp only comes from the dipoles, one can conclude that, after the scrubbing of December 2012, the heat load of 800 bunches at 4 TeV would be distributed 11% on the quadrupole beam screen (5 W/(half cell)) and the remaining 89% on the dipole beam screen (40 W/(half cell)). To extrapolate to 2015, we need to first rescale both these numbers by 2800/800 to account for the increased number of bunches (full machine). Then, we can further apply a factor 2 to the value in the dipoles as an effect of the more packed filling pattern and a factor 1.6 as an effect of ramping to 6.5 TeV instead of 4. For the quadrupoles, given the experience of 2012, we would expect neither the filling scheme nor the beam energy to significantly affect the electron cloud build up (heat load scaling factor 1). Table 1 shows that, after applying these scalings and regrouping together the heat load from dipoles and quadrupoles with full machine at 6.5 TeV, we find a value of 450 W/(half cell), which exceeds by almost a factor three the available cooling power of 160 W/(half cell) available in the LHC at 6.5 TeV.

In conclusion, even assuming that we can live with the beam degradation induced by electron cloud at injection, it would be impossible to fill LHC with a standard 25 ns beam, because the cryogenic system would not have enough power to cope with the induced heat load in the arcs. A strategy to achieve more scrubbing of the dipole beam screens (ideally, full suppression of the electron cloud in the dipoles) is therefore necessary to guarantee 25 ns operation for the LHC during Run 2.

SCRUBBING IN 2015

The experience of LHC Run 1 has shown that the electron cloud can potentially limit the achievable performance with 25 ns beams mainly through both beam quality degradation (transverse emittance blow-up, poor lifetime) at low energy and intolerable heat load on the arc beam screens at high energy. To avoid this scenario, a scrubbing program aiming at a significant mitigation (ideally, suppression) of the electron cloud in the dipole beam screens must be envisaged. This would benefit both the heat load at top energy, which would be brought back within the limits of the cooling capacity, and the preservation of the beam quality throughout the 450 GeV injection plateau.

Several improvements implemented during LS1 are expected to have a beneficial impact on our knowledge on the electron cloud in LHC and/or the efficiency of the scrubbing run:

- *Cryogenics* [9]. The cooling capacity of the SAMs, which limited the speed of the injection process in 2012 by delaying the time between successive injections, and leading thereby to beam deterioration, has been increased by about a factor 2. The cooling capacity for Sector 34, which was half in 2012, has been restored to nominal. In terms of diagnostics, three half cells in Sector 45 have been equipped with extra thermometers. This will allow for magnet-by-magnet heat load measurements and disentangling the heat load in the arc dipoles from that in the quadrupole.

- *Vacuum* [10]. In general, pressure rises did not limit the efficiency of the 2012 scrubbing run, but it was not possible to monitor the pressure in the arcs due to the sensitivity of the vacuum gauges. High sensitivity vacuum gauges have been installed in the same Sector 45 half cells equipped with thermometers. Vacuum Pilot Sectors (Q5L8-Q4L8) are being equipped with gauges and e-cloud detectors to study behaviour of NEG coated vs. unbaked Cu beam pipe.

- *Injection kickers* [11]. At the very first stages of the scrubbing run, another limitation for the speed of the injection process was also the outgassing at the injection kickers (MKI). A new design of the beam screen with capacitively coupled ends allows for 24 screen conductors and, consequently, reduced beam induced heating. The by-pass tubes have been NEG coated and a NEG cartridge has been also added at the interconnects, which should result in a much improved vacuum.

- *TDIs* [12]. During the 2012 scrubbing run, heating and outgassing of these injection protection devices could be kept under control by retracting them between subsequent injections. Besides, a few problems with detected misalignment or stuck jaws were
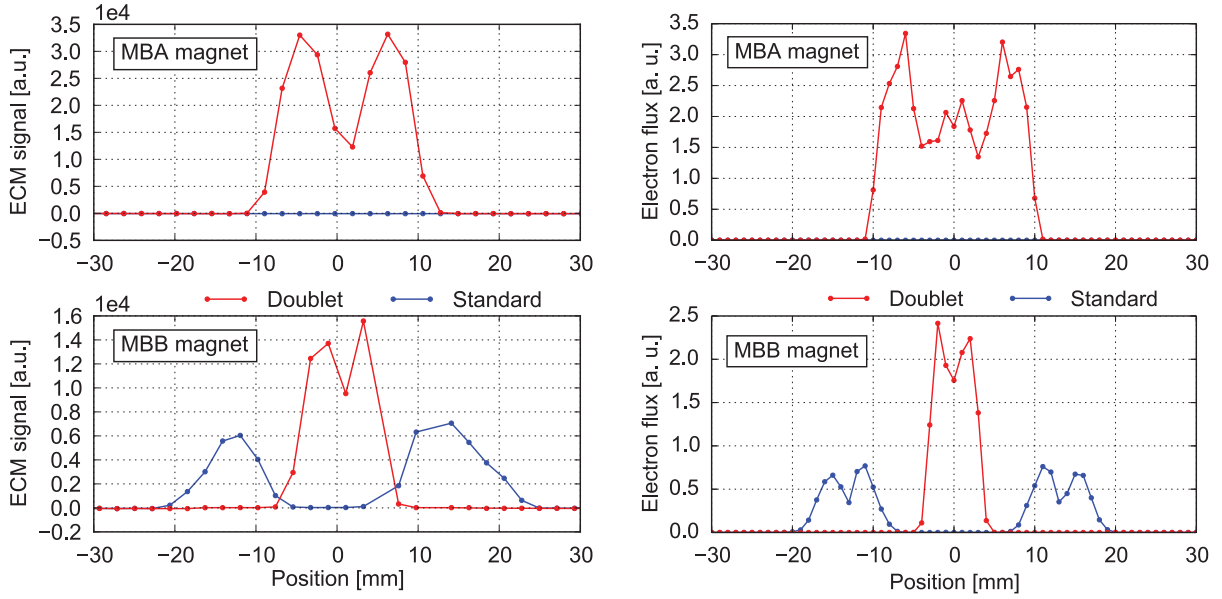
Figure 7: Electron flux to the wall of an MBA-type chamber with SEY=1.5 (top) and an MBB-type chamber with SEY=1.3 (bottom) as a function of the horizontal position for the standard 25 ns beam (1.7×10^{11} p/b, blue trace) and a doublet beam (1.7×10^{11} p/doublet, red trace). In the left column are the measured signals while in the right column are the simulated distributions.

encountered especially toward the end of the scrubbing run. The improvements introduced during LS1 include a reinforced beam screen made of Stainless Steel, a Ti flash to reduce SEY on the Al blocks, the installation of temperature probes that will allow monitoring heating, mechanics disassembled and serviced, which should minimise the risk of alignment problems.

- *On-line electron cloud monitoring.* New software tools for on-line monitoring of the scrubbing process and its steering are being prepared. Virtual variables for the heat load in the beam screen of the arc half cells for all sectors as well as SAMs and triplets have been implemented in the LHC logging database [13]. Furthermore, a specific application for the on line reconstruction of the bunch-by-bunch energy loss data from the RF stable phase is also under development.

Beside the above list, during Run 1 a special beam to enhance electron cloud production with respect to a standard 25 ns beam was developed and successfully produced at the SPS at 26 GeV. If accelerated to 450 GeV and then extracted to the LHC, this beam, called the doublet beam and described in detail in the next subsection, will be shown to have the potential to perform the further scrubbing step needed to run the LHC with 25 ns beams.

The "doublet" scrubbing beam

The idea of facilitating the scrubbing process by enhancing the EC while keeping the beam stable with high chromaticity was already proposed in order to speed up the scrubbing process in the SPS [14]. Exploratory studies in 2011 indicated that a promising technique for EC enhancement consists of creating beams with the hybrid bunch spacings compatible with the 200 MHz main SPS RF system and tighter than the nominal 25 ns. The schemes initially envisioned to produce these beams, i.e. slip stacking in the SPS or RF manipulations in the PS, turned out to be inapplicable due to technical limitations of the RF systems in the two accelerators. However, a novel production scheme was proposed to create a beam with (20+5) ns spacing. The scheme is based on the injection of long bunches in 25 ns spaced trains from the PS on the unstable phase of the 200 MHz SPS RF system, resulting in the capture in two neighbouring buckets and the generation of 5 ns spaced "doublets" out of each incoming PS bunch. Successful tests were conducted in the SPS and further details can be found in [15]. As a highlight, we display in Fig. 7, right column, the signals from the electron cloud detectors (in both the SPS dipole chamber types, i.e. MBA and MBB) during a machine development session with a standard 25 ns beam with 1.7×10^{11} p/b and a doublet beam with the same intensity per doublet. This measurement provided a direct evidence of the stronger electron cloud production and showed that the signals measured in the machine matched the distributions anticipated in simulations to a high degree of ac-

curacy (Fig. 7, left column). So far the doublet beam has been only produced in the SPS and stored at 26 GeV for few seconds. To be used in the LHC, it will be necessary to accelerate it with the desired intensity and preserving the beam quality before extraction to LHC.

The proof-of-principle of the production and efficiency of the doublet beam in the SPS, as well as the validation of our simulation tools for predictions, was an essential milestone to consider this beam as a future option for scrubbing the SPS after LS1. The capability of the doublet beam of further scrubbing the LHC dipole beam screens in order to lower the electron cloud level with 25 ns beams can be fully explained looking at Fig. 8. Here the simulated heat load is plotted as a function of the SEY for the 50 ns beam (1400 bunches), the 25 ns beam (2800 bunches) and the doublet beam (900 doublets in trains of 144 doublets per injection from the SPS, limited by the cryogenic capacity). Simulations were done for an LHC arc dipole at injection energy. As a reference, the line of the cryogenic limit, given by the cooling capacity, is also drawn as a yellow line. Scrubbing first with 50 and 25 ns beam can lead in a reasonable amount of time (4–5 days from previous experience) to the blue point close to the knee of the 25 ns blue curve. At this point, we can inject the doublet beam (red curve) and rely on high chromaticity settings to enhance the electron cloud without triggering instabilities, thus increasing the scrubbing flux on the dipole beam screens up to the available cooling capacity. One of the main challenges for this phase will be to keep an acceptable quality of the doublet beam while scrubbing at 450 GeV. If we succeed in maintaining a large scrubbing flux with the doublet beam (we can also top up with more injections if needed), further scrubbing down the red curve can be accumulated, leading eventually to an SEY point, for which the electron cloud in the dipoles has been completely suppressed with standard 25 ns beams.

Table 2, upper line, shows the values of expected heat load in the arcs for a full machine with 25 ns beam (2800 bunches) and the relative distribution of specific heat loads in dipoles and quadrupoles at the end of the 25 ns scrubbing (blue point at the knee of the heat load curve in Fig. 8). At this stage, the arc heat load with this type of beam is about evenly distributed in the dipoles and quadrupole. Furthermore, as an example, also the power loss in a sensitive element like the TDI is displayed. The lower line of the table shows the same quantities calculated for the fill with 900 doublets, which has been envisaged as the natural step following the saturation of the scrubbing process with 25 ns beams (higher red point in Fig. 8). The total heat load in the arcs increases to the value of the cooling capacity and becomes mainly located in the dipoles. The heating of the TDI is four times less severe than with the full 25 ns beam.

After a general review on the use of doublet beams in LHC [16], the following points have been assessed.

- *Production*. Splitting at SPS injection is the most favourable scheme (compared to splitting at high energy in SPS, or at LHC injection) both for beam qual-

ity and electron cloud enhancement

- *RF*. No major issue has been found. The phase measurement will average over each doublet, for which the Low Pass Filter bandwidth needs to be optimised. If the bunch length from SPS stays below 1.8 ns, the capture losses will be comparable to those for standard 25 ns beam

- *Transverse Damper*. The common mode oscillations of the doublets are damped correctly, but the system will not react to pi-mode oscillations, i.e. when the two bunchlets oscillate in counter phase. This kind of instabilities (if observed) will have to be controlled with chromaticity and/or octupoles

- *Beam Instrumentation*. No problem is anticipated for Beam Loss Monitors (BLMs), DC Current Transformers (DCCTs), Abort Gap Monitors, Longitudinal Density Monitors (LDMs), DOROS and collimator Beam Position Monitors (BPMs). BBQ (gated tune), Fast Beam Current Transformers (FBCTs), Wire Scanners, Beam Synchrotron Radiation Telescopes (BSRTs) will integrate over the two bunchlets. The Beam Quality Monitor (BQM) or LDM will be adapted to monitor the relative bunch intensity information. The BPMs might suffer errors up to 2-4 mm, especially for unbalanced doublets in intensity or position. Orbit measurements could still rely on the synchronous mode and gating on a standard bunch. However, the interlocked BPMs in IR6 will suffer the same issues as the other BPMs, but need to be fully operational on all bunches to protect the aperture of the dump channel. A possible strategy to circumvent this issue could be a reduction of the interlock setting (presently 3.5 mm) according to the results on error studies conducted in the SPS first (2014) and then in LHC with single doublet.

Scrubbing stages and operational scenarios

The different phases of the LHC start up, including all the stages relevant for scrubbing and 25 ns operation with mitigated electron cloud, are detailed in Fig. 9.

After LS1, the situation of the beam screen in the arcs will be likely reset. Upon resuming of the LHC operation in 2015, since most of the machine parts will be either new or exposed to air, it is reasonable to assume that the SEY in the arcs will have returned to values above 2.3, as was before the 2011-2012 machine scrubbing. For this reason, it will be necessary to envisage and schedule a period devoted to machine conditioning in order to get into physics production with 50 ns first, and later on with 25 ns beams. After an initial re-commissioning with low intensity, based on the experience of 2011, five to seven days with increasingly longer trains of 50 ns beams will be needed for vacuum conditioning and first scrubbing of all the machine parts exposed to air during LS1 or never exposed to beam
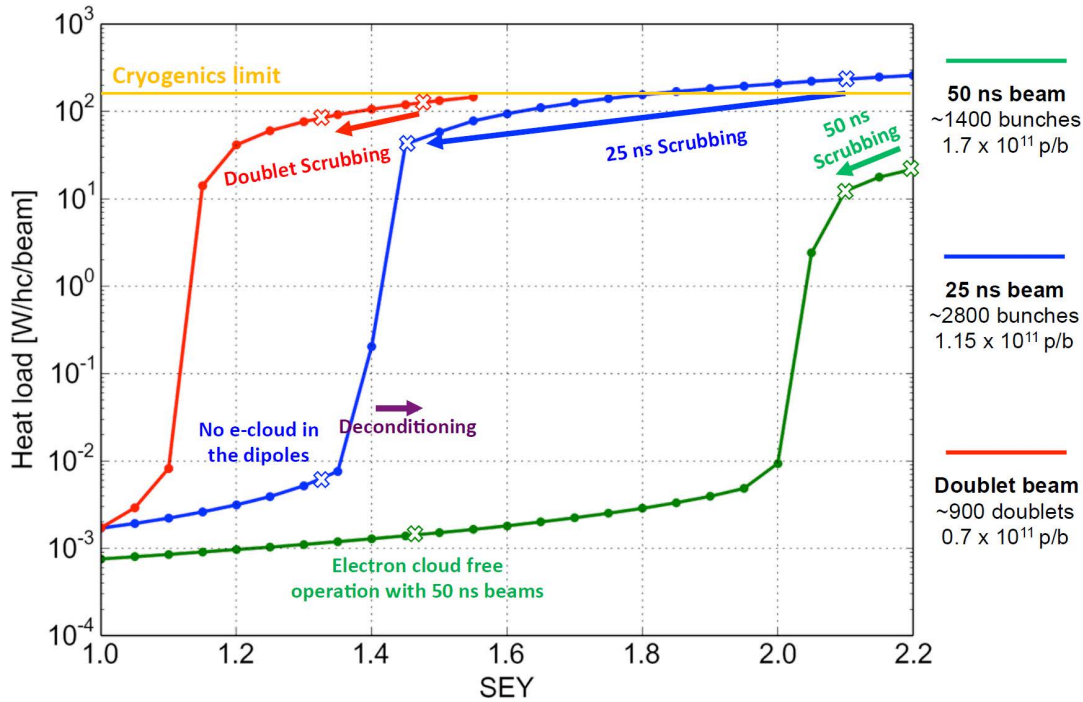
Figure 8: Heat load in the LHC dipole beam screen as a function of the SEY for 50 ns (1400 bunches, green line), 25 ns (2800 bunches, blue line) and doublet beams (900 doublets, red line).

Table 2: LHC beam parameters and heat loads (arc dipoles, arc quadrupoles and TDI) for full machine with a standard 25 ns beam (upper line) and for a fill with 900 doublets (lower line)

	$N_{bunches}$	Bunch intensity	Total intensity	Heat load	P_{dip}	P_{quad}	P_{TDI}
Std. 25 ns beam	$\sim$2800 bunches	1.15×10^{11} p/bunch	3.2×10^{14} p/beam	71 W/hcell/beam	1 W/m	9.2 W/m	415 W
Doublet beam	$\sim$900 doublets	1.4×10^{11} p/doublet	1.2×10^{14} p/beam	125 W/hcell/beam	2.6 W/m	3.2 W/m	107 W

before. This will lead to a general reduction of the desorption yield all over the machine and will also lower the SEY in the arcs to a value close to the threshold for electron cloud build up for 50 ns beams. At this point, to allow LHC to gain enough margin to ensure electron cloud free operation with 50 ns beams, this phase could be ideally ended by one or two days with injections of trains of 25 ns beams aiming at lowering the SEY in the arcs below 2.0. After a short physics production period with 50 ns beams at 6.5 TeV, during which the 6.5 TeV operation will be established with the well mastered 50 ns beams and further surface conditioning will be achieved thanks to the enhanced synchrotron radiation, the switch to 25 ns operation will rely on performing a second scrubbing step with the 25 ns beam and doublet beams. By simply adding up the 50 hours of 25 ns MDs in 2011 and the 60 to 70 hours of efficient scrubbing in 2012, we obtain that a maximum of 5 days of run with increasingly longer trains of 25 ns beams at injection energy should be sufficient to get back

to the same situation we had in December 2012 after the 25 ns scrubbing run. After that, the machine will be ready to receive doublet beams to enhance the electron cloud in the arc dipoles and continue the scrubbing down to values lower than the build up threshold in the dipoles for 25 ns beams. The next step is to ramp the 25 ns beams up to 6.5 TeV, while the number of bunches can be gradually increased.

If all the previous phases have been successful, the LHC will finally be able to move into physics production with 25 ns beams at 6.5 TeV under controlled electron cloud effects. However, it is worth noticing that during the 25 ns operation of the LHC, the electron cloud, though mitigated, will still be present in the quadrupoles (and possibly other machine regions, e.g. the higher order multipoles, the inner triplets) even after scrubbing. This entails the following effects, which shall be taken into consideration:

- The integrated effect of this residual electron cloud
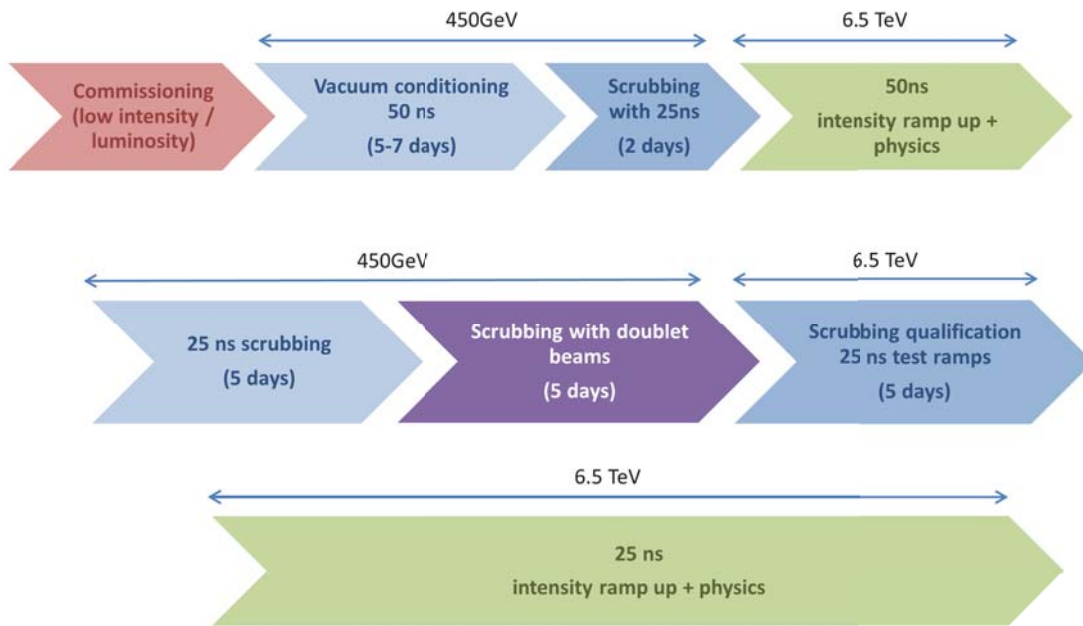
Figure 9: Timeline of the LHC scrubbing in 2015.

might result into a significant emittance blow-up at injection. To limit the luminosity loss due to this effect, the injection speed will be crucial, but also some beam parameters could be better tuned to minimise the amount of electron cloud seen by the beam at 450 GeV (e.g. bunches can be lengthened);

- If there is still a heat load limitation on the ramp or at 6.5 TeV, an optimal configuration in terms of number of bunches, bunch intensity and bunch length might have to be sought and applied;

- It was observed in 2012 that some degree of deconditioning occurs in absence of scrubbing beam for some time. If the extent of the deconditioning is such as to re-awaken the electron cloud with 25 ns beams, a few hours for scrubbing could become necessary after each longer stop (i.e. certainly after every Winter stop, but possibly also after each Technical Stop).

If the scrubbing phases detailed above will not be sufficient to eliminate the electron cloud from the machine dipoles and 25 ns operation will still be hampered by heat load on the ramp and beam quality degradation, the main fallback option foresees the use of the 8b+4b filling scheme [15]. This will allow storing up to 1900 bunches/beam in the LHC with the advantage of having both a higher multipacting threshold compared to the standard 25 ns beam (shown by PyECLOUD simulations) and the potential to accept a higher intensity per bunch (to push up luminosity within the desirable limits of the pile-up). This scheme, although already proven in simulations, still needs to be confirmed experimentally in the injector chain. The gain in

terms of electron cloud build up also needs to be assessed experimentally, once this beam will be available in the SPS. A second option would be to stick to the 50 ns spacing and run the LHC again like in Run 1 (although instabilities at 6.5 TeV could be an important intensity limiting factor for this scenario). In this way we could store up to 1380 bunches in the LHC and rely on a multipacting threshold much larger than for the standard 25 ns beam or the 8b+4e.

CONCLUSIONS

To conclude, the experience from LHC Run 1 has taught that the electron cloud can seriously limit the achievable performance with 25 ns beams mainly through beam degradation (poor lifetime, emittance blow up) at low energy and high heat load at top energy. The scrubbing achieved in 2012 could strongly weaken the electron cloud in the beam screen of the dipoles, but did not fully suppress it. After LS1, to cope with the nominal number of bunches, we need to scrub LHC more efficiently than in 2012 and aim at the total suppression of the electron cloud from the dipole beam screens. To accomplish that, we will benefit from:

- Several hardware and instrumentation improvements, which will allow for better scrubbing efficiency;

- The doublet scrubbing beam based on 5 ns spaced bunchlets separated by 25 ns, which was produced and tested at the SPS, and looks very attractive for LHC scrubbing. The compatibility of this type of beam with the LHC equipment was reviewed and no major showstopper has been found. Presently, the only

pending issue is the possible offset on the interlock BPMs in IR6 and this is being followed up.

A two stage scrubbing strategy is proposed for the LHC start up in 2015. This will rely on: 1) a first scrubbing/conditiong run with 50 ns beams (and possibly one or two days with 25 ns beams) to allow for safe operation with 50 ns beams at 6.5 TeV; 2) A second scrubbing run with 25 ns and doublet beams to allow for operation with 25 ns beams at 6.5 TeV. If scrubbing will turn out to be still insufficient, even with the doublet beam, the 8b+4e scheme could be used for providing a significant electron cloud reduction with 50% more bunches than the 50 ns beam and similar bunch intensities.

ACKNOWLEDGEMENTS

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BEAMS IN THE INJECTORS

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Abstract

For the 2015 LHC start up and operation, the injectors will be requested to provide a large variety of beams. Probes and individual LHC-type bunches will be needed at the early commissioning stage. Later on, standard beams with 50 ns bunch spacing, 25 ns bunch spacing and a special doublet beam for electron cloud enhancement will be used for LHC vacuum conditioning and scrubbing. High brightness variants of the 50 and 25 ns beams (BCMS) will also have to be available for the LHC physics operation. The more exotic 8b⊕4e beam could also be considered in some operational post-scrubbing scenarios and should be made ready for that use. The goal of this paper is to provide a realistic estimation of the beam parameters expected from the injectors in 2015 for the aforementioned beam types. Since this estimation will rely on the full recovery of the 2012 performance and the successful implementation of new or optimized production schemes, we will address: 1) The critical milestones to reestablish the 2012 beam conditions (e.g. the scrubbing run of the SPS after the long shutdown); 2) The roadmap of machine studies for testing or improving the beam production schemes in PSB and PS; 3) The necessary experimental tests needed in the SPS for the production of the doublet scrubbing beam, and related issues.

INTRODUCTION

During the LHC Run 1 in 2011 and 2012, the LHC physics production was based on beams with 50 ns bunch spacing, while beams with 25 ns bunch spacing were injected into LHC on few occasions for injection tests, Machine Development (MD) sessions, an extended scrubbing run and a short pilot physics run [1]. After the startup in 2015 the center-of-mass energy at LHC collision will be raised to 13 TeV. It will be crucial to establish physics operation with the nominal 25 ns bunch spacing in order to maximize the integrated luminosity in Run 2 for the limited event pile-up acceptable for the LHC experiments [2]. The LHC will thus request a large variety of beams for the different stages of the machine scrubbing [1], such as standard beams with 50 ns bunch spacing, 25 ns bunch spacing and a special doublet beam for electron cloud enhancement. High brightness variants of the 50 and 25 ns beams (BCMS scheme [3, 4]) will also have to be available for the LHC physics operation.

In this paper the parameters of the LHC physics beams achieved in the injectors until 2012 and the experience gained during the LHC Run 1 will be reviewed. The possibilities for optimizing the beam production schemes, as identified in the course of the RLIUP workshop in 2013 [5], and the beam parameters that should be available from the injectors in 2015 will be presented. The challenges for the production of the doublet beam for scrubbing of the SPS and in particular of the LHC will be summarized together with the necessary machine studies that remain to be done for demonstrating the acceleration of this beam to the SPS flat top to be ready for the LHC scrubbing in 2015. Also the new 8b+4e beam [6], which should allow for a higher intensity per bunch at the expense of a smaller total number of bunches in the LHC, will be discussed, as it could be interesting for the physics production in case the electron cloud effect in the LHC cannot be alleviated by scrubbing. The milestones for re-establishing the 2012 beam conditions as well as the necessary steps for the implementation of the optimized beam production schemes and the new beam types will be outlined.

SINGLE BUNCH BEAMS

In preparation of the LHC p-Pb run in 2013 a new beam production scheme has been developed [7]. With this new scheme single bunch LHC beams can be generated in the PSB with unprecedented reproducibility and control of both intensity and longitudinal emittance. The intensity is thereby controlled by longitudinal blow up with the C16 cavity during the first part of the PSB cycle, which allows preserving the 6D phase space volume for a wide range of intensities. It is therefore expected that after Long Shutdown 1 (LS1) the injectors will be able to deliver LHCPROBE bunches ($5 \times 10^9 - 2 \times 10^{10}$ p/b) and LHCINDIV bunches ($2 \times 10^{10} - 3 \times 10^{11}$ p/b) to the LHC with smaller intensity fluctuations compared to the operation during Run 1.

In October 2012, the injectors were asked to provide single bunch beams with an intensity of about $7 \times 10^{10} - 9 \times 10^{10}$ p/b and transverse normalized emittances of about $\varepsilon_{x,y} \approx 2.5\,\mu$m for the Van der Meer scans. The LHC experiments requested in particular beams with transverse profiles as close to Gaussian as possible. A special single bunch beam was prepared in the PSB using a combination of transverse and longitudinal shaving in order to obtain large transverse emittance but with tails less populated than Gaussian distributions [8]. Because of diffusion in the PS and SPS, these bunches evolved into almost perfect Gaussian shapes at the exit of the SPS and at collision in the LHC as confirmed by the experiments. This beam will need to be ready for the van der Meer scans at the beginning of the 2015 run. Potentially, the production scheme of this beam can be further optimized by adapting the aforementioned new scheme for single bunches.

LHC PHYSICS BEAMS

LHC operation during Run 1 was mainly based on 50 ns beams produced with the standard scheme of bunch splittings in the PS. Beams with the nominal 25 ns bunch spacing have been used in the LHC mainly for the scrubbing run and machine development studies. With the successful implementation of the Batch Compression bunch Merging and Splitting (BCMS) scheme [3, 4] in the PS in 2012 the injectors were able to provide LHC beams with almost twice the brightness compared to the standard production schemes. While the 50 ns BCMS beam was injected into the LHC only for a study of the emittance preservation of a high brightness beam along the LHC ramp, the 25 ns BCMS beam was used for the 25 ns pilot physics run at the end of 2012. It should be emphasized that all these LHC beams were produced close to the performance limits of the injector chain. Figure 1 shows the beam parameters for the two types of 50 ns and the 25 ns beams as achieved in 2012 after the operational deployment of the Q20 low gamma transition optics in the SPS [9]. The transverse emittances

Table 1: Operational beam parameters in 2012.

Beam type	Intensity	Emittance
Standard (25 ns)	1.20×10^{11} p/b	$2.6 \, \mu m$
BCMS (25 ns)	1.15×10^{11} p/b	$1.4 \, \mu m$
Standard (50 ns)	1.70×10^{11} p/b	$1.7 \, \mu m$
BCMS (50 ns)	1.70×10^{11} p/b	$1.1 \, \mu m$

shown in these plots are deduced from combined wire-scans at the end of the SPS flat bottom and the values were cross-checked with measurements in the LHC. The error bars include the spread over several measurements as well as a systematic uncertainty of 10%. The bunch intensity is measured at the SPS flat top after the scraping of the beam tails, as required prior to extraction into LHC. The solid lines correspond to the PSB brightness curve (i.e. the emittance as a function of intensity measured at PSB extraction) translated into protons per SPS bunch for each beam type assuming intensity loss and emittance growth budgets of 5% in the PS and 10% in the SPS, respectively. All beams were produced within the allocated budgets for beam degradation along the injector chain apart from the standard 25 ns beam, which suffers from slow losses at the SPS flat bottom and maybe also from space charge effects at the PS injection. Nevertheless, the nominal 25 ns beam is well within the original specifications (i.e. 1.15×10^{11} p/b and $3.5 \, \mu m$ transverse emittance [10]). The beam parameters achieved operationally in 2012 are summarized in Table 1.

The first part of the re-commissioning of the LHC beams in the injector chain in 2014 will focus on re-establishing the beam parameters achieved before LS1. This will rely to a large extent on the successful scrubbing of the SPS in order to suppress the electron cloud effect, which is expected to be a performance limitation during the first weeks after the start-up since large parts of the vacuum chambers have been exposed to air. The strategy on the SPS scrubbing run will be addressed in more detail at the end of this paper.

Once the 2012 beam parameters are reproduced, it should be possible to reach slightly higher beam intensity and potentially also higher beam brightness. Already during MDs at the end of 2012 a standard 25 ns beam was accelerated to flat top with an intensity of about 1.3×10^{11} p/b and longitudinal beam parameters compatible with injection into LHC. In addition, high intensity LHC beams will benefit from the upgraded 1-turn delay feedback for the 10 MHz cavities and the upgraded longitudinal coupled-bunch feedback in the PS, which will be commissioned in 2014. It should also be possible to enhance the beam brightness by optimizing the beam production schemes as discussed at the RLIUP workshop [5]: the space charge tune spread in the PS can be reduced by injecting bunches with larger longitudinal emittance, i.e. increasing the bunch length and the momentum spread at PSB extraction. The maximum bunch length at the PSB-to-PS transfer is determined by the recombination kicker rise time. The maxi-
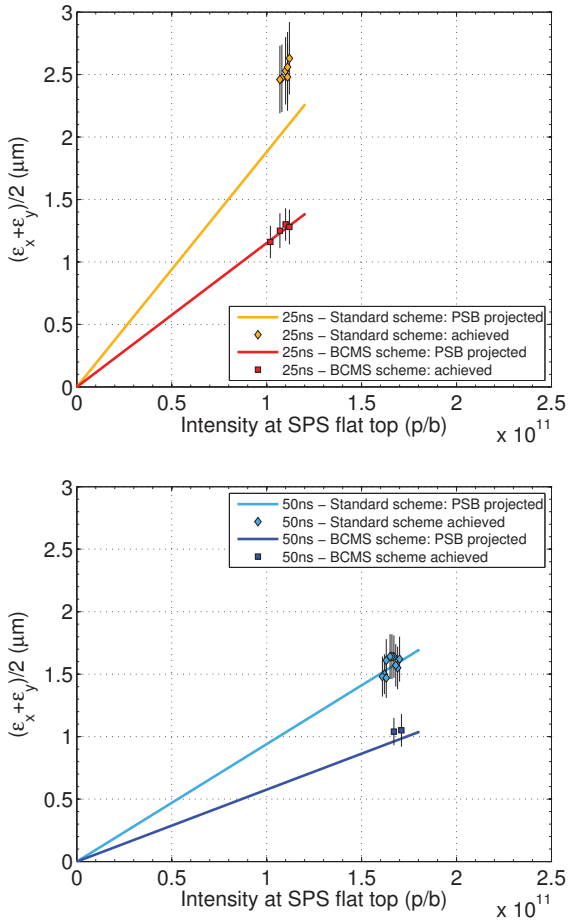

Figure 1: Beam parameters achieved operationally in the SPS in 2012 with the Q20 optics for 50 ns beams (bottom) and 25 ns beams (top) extracted to the LHC.

Table 2: Expected performance limits after LS1.

Beam type	Intensity	Emittance
Standard (25 ns)	1.30×10^{11} p/b	$2.4\,\mu m$
BCMS (25 ns)	1.30×10^{11} p/b	$1.3\,\mu m$
Standard (50 ns)	1.70×10^{11} p/b	$1.6\,\mu m$
BCMS (50 ns)	1.70×10^{11} p/b	$1.1\,\mu m$

mum longitudinal emittance is determined by the RF manipulations and by the momentum acceptance at transition crossing in the PS cycle, but also by the constraint that the final bunches should not exceed 0.35 eVs for injection into the SPS. Optimizing the longitudinal beam parameters at PS injection requires therefore controlled longitudinal blow-up during the PSB cycle with the C16 cavity and the use of the h=1 and h=2 PSB RF harmonics in phase at extraction to keep the larger longitudinal emittance bunches within the recombination kicker gap. Furthermore, the triple splitting in the PS needs to be done at an intermediate plateau of 2.5 GeV instead of the flat bottom for providing sufficient bucket area. Further details are given in Ref. [5]. A summary of the expected performance limits of LHC physics beams for the run in 2015 is given in Table 2.

DOUBLET SCRUBBING BEAM

The doublet beam was originally proposed for enhancing the scrubbing efficiency in the SPS at low energy [11]. This beam is produced by injecting a 25 ns beam with enlarged bunch length ($\tau \approx 10\,\text{ns}$ full length) from the PS onto the unstable phase of the 200 MHz RF system in the SPS. By raising the SPS RF voltage within the first few milliseconds after injection, each bunch is captured in two neighboring RF buckets resulting in a train of 25 ns spaced doublets, i.e. pairs of bunches spaced by 5 ns. Very good capture efficiency (above 90%) for intensities up to 1.7×10^{11} p/doublet could be achieved in first experimental tests in 2012. Figure 2 (top) shows the evolution of the longitudinal profile of the beam during the "splitting" right after the injection in the SPS. Figure 2 (bottom) shows the "final" beam profile, measured one second after injection. It was also verified that it is possible to rapidly lower the RF voltage and inject a second train from the PS without any important degradation of the circulating beam. Observations on the dynamic pressure rise in the SPS arcs confirmed the enhancement of the electron cloud activity as expected from the lower multipacting threshold compared to the standard 25 ns beams predicted by numerical simulations [11]. The experimental studies performed up to now concentrated on SPS injection energy and thus the acceleration of the doublet beam in the SPS has not been tested yet.

Since it is planned to use the doublet beam for the second part of the LHC scrubbing run in 2015 [1], extensive experimental studies in the SPS in 2014 need to be performed for
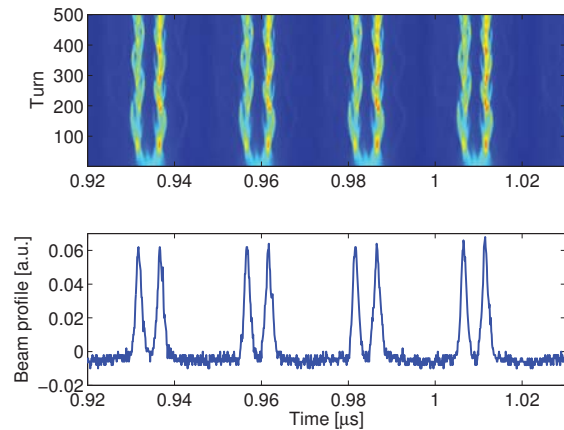
Figure 2: Evolution of the longitudinal beam profile in the SPS during the splitting at injection for the production of the doublet beam (top) and longitudinal bunch profiles of the doublet beam measured 1 s after injection (bottom).

testing and setting up the acceleration of the doublet beam to SPS flat top. The maximum intensity achievable at SPS flat top will be limited by beam loading and the available RF power of the 200 MHz cavities. First MD tests in 2014 will be performed with the normal LHC acceleration cycle, but it is expected that the ramp rate needs to be reduced by up to a factor three in order to reduce the required RF power and thus allow reaching the 1.6×10^{11} p/doublet requested by the LHC [12]. This implies a significant increase of the cycle length in the SPS, even though the flat bottom can be shorter since for the moment a maximum of two batches per SPS extraction are requested for the LHC scrubbing. It should also be mentioned that the doublet beam could suffer from beam quality degradation, such as increased bunch length at SPS extraction, unbalanced doublet intensities and blow-up from e-cloud during the SPS cycle. In the best case the transverse emittance of the doublet beam could be around $3\,\mu m$, but significantly larger beam sizes are to be expected in case of instabilities. On the other hand, after its commissioning, the new SPS transverse feedback system will be able to damp the common oscillation mode of doublets throughout the cycle including the time right after injection where the doublets are created.

8b⊕4e BEAM

Thanks to its micro-batch train structure, the 8b⊕4e beam was considered as an alternative to the standard 25 ns beam in case the electron cloud remains a limitation for the operation of the LHC during the HL-LHC era [6]. A simulation of the production of the 8b⊕4e beam based on the standard scheme is shown in Fig. 3 (top). Starting from 7 bunches from the PSB, the triple splitting in the PS is replaced by a direct h = 7→21 bunch pair splitting, which results in pairs of bunches separated by empty buckets. Each bunch is split in four at PS flat top such that the bunch pat-

Table 3: Expected parameters of the 8b+4e beam.

Beam type	Intensity	Emittance
Standard (8b⊕4e)	1.80×10^{11} p/b	$2.3\,\mu$m
BCMS (8b⊕4e)	1.80×10^{11} p/b	$1.4\,\mu$m

mated around 1.8×10^{11} p/b. The maximum achievable brightness can be calculated from the known brightness and space charge limitations of the injectors. The estimated beam parameter limitations are summarized in Table 3. Finally it should be emphasized that this beam has not been produced in the injectors so far since it was developed during LS1. First tests of this new beam production scheme will be subject of MD studies in 2014 or at latest in the beginning of 2015, depending on the availability of MD time in the injectors.

COMMISSIONING AND STUDIES IN 2014

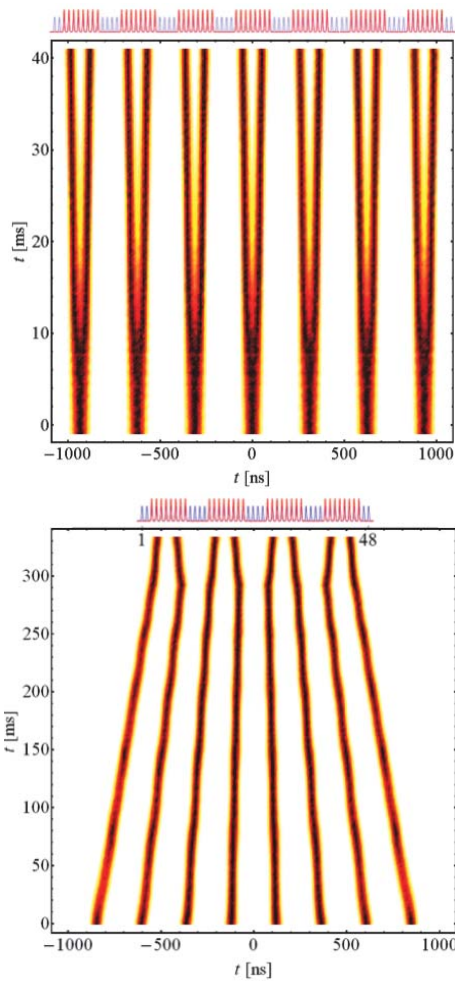The first weeks of the PSB and the PS startup in the middle of 2014 will be devoted to the setup of the beams needed for physics. The setup of the LHC beams in the PS complex will be done in parallel to physics operation, starting from re-establishing the beam conditions from 2012 (but already with the triple splitting in the PS at 2.5 GeV instead of the flat bottom). Only after that, the longitudinal blow-up along the PSB ramp and the use of h=1 and h=2 at PSB extraction for optimizing the longitudinal parameters at PSB-PS transfer will be tested in MDs and eventually commissioned.

The PS complex has to be ready to deliver the LHC beams at the startup of the SPS in September. As large parts of the SPS have been vented and exposed to air in the course of the works performed during LS1, it is expected that the good conditioning state of the SPS will be degraded. Therefore, two weeks of SPS scrubbing are planned for 2014 with the goal of reconditioning the SPS to the state of before LS1. The success of this scrubbing run is the critical milestone for the preparation of the 25 ns LHC beams for physics in 2015.

The setup of the doublet scrubbing beam for the use in the LHC will be the subject of extensive MD studies in the SPS in 2014. Several dedicated MD blocks will be needed for setting up the acceleration cycle with the reduced ramp rate and for pushing the intensity to the requested 1.6×10^{11} p/doublet. During these MDs, also the behavior of the LHC BPMs in the SPS with the doublet beam need to be tested in preparation of the LHC scrubbing, since an offset of the beam position reading depending on the relative bunch intensity and position of the doublets is expected [13].

Besides the preparation of the doublet beam and the optimization of the LHC physics beams, there are many requests for dedicated MD time in the SPS for 2014 [14]. Careful planning and prioritization of studies will be crucial, as the total amount of requested dedicated MD time

Figure 3: Simulations of the 8b⊕4e beam production in the PS based on the standard scheme (top) and based on the BCMS scheme (bottom). *Courtesy of H. Damerau.*

tern 6×(8b⊕4e)⊕8b is obtained. In this case the bunch train out of the PS is longer than the 72 bunches of the standard scheme, but the remaining gap of 4 empty buckets (about 100 ns) is expected to be sufficiently long for the PS ejection kicker. Without optimization of the LHC filling pattern, the total number of bunches per LHC beam is estimated as 1840. A high brightness version of this beam can be produced by the scheme shown in Fig. 3 (bottom), which is similar to the BCMS scheme but the merging and triple splitting is replaced by a regrouping of bunches during the h = 14→21 batch compression. The resulting bunch pattern in this case is 3×(8b⊕4e)⊕8b and the total number of bunches per LHC beam is approximately 1728.

As for all LHC type beams in the SPS, the intensity of the 8b⊕4e will be limited by longitudinal instabilities and the available RF voltage in presence of beam loading. However, as the average line charge density over 300 ns is being reduced to 2/3 compared to the normal 25 ns beams and the filling time of the SPS RF cavities being about 600 ns, the present intensity limit for the 8b⊕4e is esti-

exceeds the MD slots available. Therefore tests of the 8b⊕4e beam production scheme will most likely be done in 2015 (although first studies in the PSB and the PS might be possible already in 2014). In general, it should be stressed that 2014 will be a very busy period for the injectors: Besides the physics operation after the beam commissioning with partially new or upgraded hardware, the setup and commissioning of the different LHC beams including the doublet scrubbing beam, the various dedicated and parallel MD studies, substantial amount of beam time will be needed in the PS and SPS for the first-time setup of the Ar-ion beams in preparation for the physics run beginning of 2015.

Finally, it is worth mentioning that there will be another period of dedicated scrubbing of the SPS in 2015. While with the scrubbing run in 2014 the scrubbing efficiency and the time required for achieving acceptable conditioning after a long shutdown will be qualified, the aim of the scrubbing run in 2015 will be to condition the SPS for high intensity 25 ns beams. The outcome of these scrubbing runs will determine if the SPS vacuum chamber really need to be coated with amorphous Carbon [15] as presently part of the baseline of the LIU project for suppressing the electron cloud for the future high intensity LHC beams [16].

SUMMARY AND CONCLUSIONS

Several optimizations of the beam production schemes will be implemented for the LHC Run after LS1. Single bunch beams will benefit from a better control and better reproducibility of intensity and longitudinal emittance. The longitudinal parameters at PSB-to-PS transfer of the 25 ns and 50 ns physics beams will be optimized for allowing even higher beam brightness and, if requested by the LHC, the intensity of the 25 ns beams can also be slightly pushed compared to the 2012 beam parameters. The first step in the beam commissioning of these LHC beams in 2014 will be however to recover their 2012 performance. In this respect, the critical milestone will be the success of the SPS Scrubbing Run, as it is expected that the good conditioning state of the SPS will be degraded due to the long period without beam operation and the venting of machine sectors related to the interventions during LS1.

The setup of the doublet scrubbing beam with acceleration in the SPS in preparation for the LHC scrubbing in 2015 will be one of the main topics of MDs in 2014. Reaching the challenging target intensity of 1.6×10^{11} p/doublet as requested by the LHC will require a reduced ramp rate in order to overcome RF limitations and thus lots of SPS MD time with a long cycle will be needed. Careful planning and prioritization of the dedicated MDs in the SPS will be crucial due to the limited MD time available. First tests of the 8b⊕4e beam will be performed at latest in 2015.

Besides the various physics users, the commissioning of the LHC beams and the MDs related to the new beams requested by the LHC, lots of beam time will be needed in 2014 for the first-time setup of Ar-ion beams.

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STATUS AND COMMISSIONING PLANS FOR LHC RUN2.
THE RF SYSTEM

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Abstract

The paper presents the work done on the LHC RF system during Long Shutdown 1 (LS1). On the High Level side we have replaced a cryomodule (four cavities, beam 2), which could not operate reliably at the design voltage (2 MV per cavity). The upgrade of klystron collectors has been completed and new crowbar systems have been installed (solid state thyristors replacing the old thyratrons). On the Controls side, all RIO3 CPUs are beeing replaced and the new ones are now using Linux. The new FESA classes are being designed with FESA3. The consequences of the increased beam current (0.55 A DC compared to 0.35 A in 2012), the increased energy (physics planned at 6.5 TeV/c per beam), and the exotic bunch spacing (5-20 ns for the scrubbing beams) will be analyzed from an RF hardware point of view. A tracking code is being developed to understand the effect of coloured phase noise on the longitudinal bunch profile. The expected benefits are the optimization of the blow-up and the possible shaping of bunch profile (flatter bunches) to avoid beam induced heating and improve beam stability. Upgraded longitudinal bunch-by-bunch measurements are being implemented.

UPGRADES DONE DURING LS1

The LHC RF design called for 16 MV total voltage at 7 TeV/c, providing a 7.9 eVs bucket area containing a bunch of 2.5 eVs longitudinal emittance (1.05 ns 4σ bunch length) [1]. At 3.5 TeV (2011) and 4 TeV (2012) we have operated with 12 MV total voltage. For beam 1, the eight cavities were operated at 1.5 MV, but one of the beam 2 cavities (C3B2) could not be operated reliably above 1.2 MV, resulting in uneven cavity voltage settings: 1.2 MV in C3B2 and 1.54 MV in the other beam 2 cavities. This situation is not optimal: unequal voltages result in unequal voltage phase slip caused by transient beam loading, a situation that would be problematic for the future RF phase modulation scheme [2]. Also, a higher voltage may be needed at 6.5 TeV/c. The LHC cavities are housed in cryomodules in groups of four. A complete module has been replaced in the beginning of 2014 (see Fig. 1), hopefully allowing for 16 MV per beam in the future, if needed.

Figure 1: The spare RF cryomodule (four cavities) being lowered down into the UX45 cavern (Feb. 2014).

Every LHC cavity is supplied by an individual 300 kW klystron. Each unit of four klystrons is powered by a power converter (60 kV/40A DC). A fast protection system (crowbar) protects the four klystrons: in case of arcing inside a klystron, the protection system (thyratron) grounds the High Voltage (HV) in less than a few microseconds thereby avoiding damage in the tube [3]. The diversion of the HV energy is achieved by triggering the thyratron, which then becomes conducting and acts as a short circuit of the HV power supply to the ground. The thyratrons in use during the LHC Run1 require very fine adjustment and are very sensitive to noise. Although they proved to be reliable from the point of view of protecting the klystron, from time to time they have suffered from auto-firing that resulted in LHC beam dumps. Figure 2 shows an RF power fault summary for year 2012, with eleven beam dumps triggered by the crowbar (weeks 20 and 28); the majority of these were false alarms.
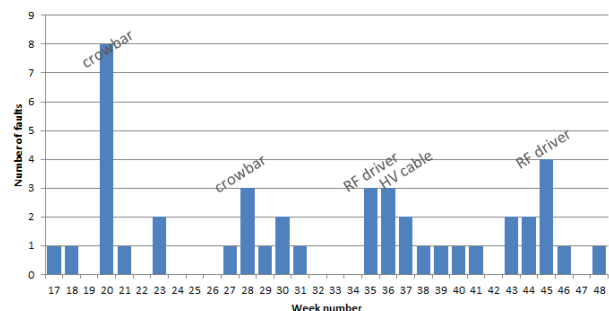

Figure 2: RF power fault summary (2012).

All four thyratron tubes have been replaced with their solid state equivalent (thyristor). One such system had

been installed in Sept. 2012 and performed reliably till the LHC stop in March 2013. Compared to the thyratron, the new system is simpler (little controls electronics), requires no cooling, and is not prone to auto-firing. In addition it is a more modern technology with a large industrial choice. Figure 3 shows both systems.

Figure 3: Thyratron (old system) left and thyristor (new system).

The klystron cathode is raised to a high voltage (50-60 kV) with respect to the klystron body. Electrons are extracted from the cathode filament, resulting in a DC current (8-9 A) from cathode to the anode (collector). As electron emission depends on the cathode's temperature, the filament is heated by an added AC current that is monitored, resulting in klystron trip and beam dump if it deviates from the set value. Several fills were dumped following a "glitch" in the monitoring of the filament heater current. The cause was traced to the poor soldering of the high voltage cables. These have been redone, with new connectors re-weld, using induction welding, without damaging the insulation material (Fig. 4).
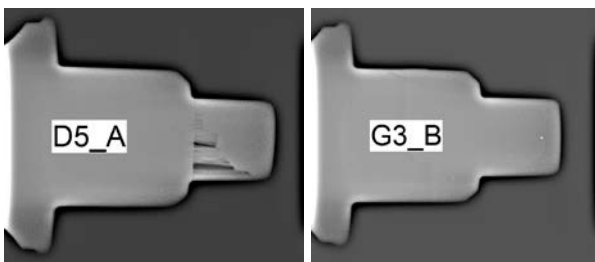
Figure 4: X-ray of the High-Voltage connector before (left) and after replacement.

Photo-diodes are installed inside the RF waveguides to detect possible arcing. They are linked to an interlock that would trip the corresponding klystron and eventually dump the beam. There were many false alarms during LHC Run1, due to photo-diodes detecting radiation instead of a real arc. They have now been replaced with a new design, more resistant to radiation.

The design klystron working point is 58 kV cathode voltage and 9 A beam current, resulting in a DC power of 520 kW, and an RF power of approximately 300 kW. In a klystron, the residual DC power not consumed as RF output power is dissipated in the collector, and with the low RF power required in operation (below 200 kW during Run1), the collector power resulted in overheating (Fig. 5). An upgrade program was launched in 2010, to improve the collector's cooling circuitry and all klystrons are now capable to sustain the full DC power. We have also replaced eight klystrons with spares to make the aging profile more favourable (avoid that all klystrons present aging problem around the same time).

Figure 5: Klystron collector showing traces of overheating (2010).

Several upgrades to the RF Controls are being deployed during LS1: all RIO3 CPUs are being replaced with MEN A20 models, and the Operating System changed from Lynx OS to Linux. Front-End software developments for the new boards are now done with FESA3. Old systems remain on FESA2.10 but will be migrated to FESA3 during 2015.

Tools are being developed as diagnostics in the longitudinal plane. The Low Level RF (LLRF) includes a Beam-Based Phase Loop: for each ring, the phase of each individual bunch is measured, and an average over one turn is computed to correct the phase of the RF drive of the corresponding beam. Originally, the individual bunch phase measurements were not intended as diagnostics, but they have been used to study electron cloud, as they provide useful information on the energy loss per bunch [4][9]. This application will be very useful during the 2015 scrubbing run. Bunch-by-bunch phase acquisition has also been used to estimate longitudinal coupled-bunch instability growth rate [5], a study that will be continued during LHC Run2. Finally, this diagnostic tool will be essential if the LHC will ever suffer from longitudinal instabilities in operation. With careful post-processing to remove systematics and reduce random errors, the measurement accuracy is adequate but the limited storage (73 turns only) was a problem during Run1. In 2015, we will export a stream of single bunch phase measurements at 40 M samples per second (one measurement per bunch at 25 ns spacing), for monitoring and analysis by an application running in the Control Room. The

implementation will be similar to the one developed for the diagnostic of transverse instabilities.

RF noise was a major concern during the design of the LHC, with fears that it would limit the luminosity lifetime. This is not the case, thanks to a careful low-noise design, but on a few occasions in 2011, a malfunctioning LLRF has led to severe RF noise with debunching and populating the abort gap as a consequence. In 2012, a commercial instrument was installed to measure the Phase Noise Power Spectral Density (PSD) of the sum of the eight cavities for each beam. An application displayed plots of the spectrum in the Control Room, compared the measurements with references and generated an audio message in case of excess noise. A better diagnostic is being developed for installation during 2015: it will measure the amplitude and phase noise PSD for each cavity individually, will include an interlock and could trigger the beam dump if needed. It will ease the diagnostic by identifying the faulty cavity directly.

RF PARAMETERS FOR 2015

At injection, the LHC capture voltage was initially set in 2010 to 3.5 MV. With the increased injection current, the injection dump would fire on occasion, triggered by radiation measured by the Beam Loss Monitors (BLM) [6]. To reduce capture losses the voltage was raised to 6 MV at the restart in 2011 [7] and has remained at that value through the rest of Run1. From October 2012 on the SPS was operated with the new Q20 optics. Compared to the classic Q26 optics, the $\Delta p/p$ at SPS extraction was 15% smaller, but the bunch length was slightly longer (Table 1). The capture voltage was therefore not changed.

Table 1: Longitudinal emittance and 4σ bunch length measured in the SPS before transfer to the LHC (mean over the injected batch) with the old SPS optics (Q26) and the new optics (Q20). 7.5 MV 200 MHz and 640 kV 800 MHz SPS RF, 50 ns bunch spacing.

SPS optics	Mean longitudinal emittance	Mean bunch length (4σ)
Q26	0.5 eVs	1.45 ns
Q20	0.45 eVs	1.6 ns

With 25 ns spacing in 2015, the bunch intensity will be lower (1.1E11 p per bunch vs. 1.4E11-1.65E11 p for 50 ns spacing in 2012), but the total current will be higher (0.55A DC vs. 0.35 A DC). So we do not expect lower longitudinal emittance and bunch length from the SPS and propose to restart the LHC with unchanged 6 MV capture voltage.

An important beam parameter is the bunch length at top energy. Since a low pileup density is essential for tracker detectors, it is not desirable to reduce the 4σ length below 1.25 ns in physics [8]. With this constraint, the remaining free parameter is the RF voltage during physics. If we operate with the bunch length used in 2012 (1.25 ns), 10 MV at 6.5 TeV/c will provide the same longitudinal

stability margin as in 2012 (12 MV at 4 TeV/c) [9]. A higher voltage would provide a larger bucket area and allow for a larger longitudinal emittance. This would be beneficial as it reduces the transverse emittance growth caused by Intra Beam Scattering. But it also increases the momentum spread causing a larger betatron tune spread (footprint) due to chromaticity, and therefore potential losses. Final optimization in physics will be done by experimenting.

On the hardware side, the maximum RF voltage is limited by the available klystron power. During the LHC Run2 we will use the same algorithm as in Run1, that is, trying to fully compensate the transient beam loading caused by the no-beam segments[*]. We keep the voltage strictly constant over one turn. After optimizing the cavity coupling (adjustable in the LHC cavities), the required RF power per cavity is [10]

$$P = \frac{V\, I_{rf,pk}}{8} \qquad (1)$$

$I_{rf,pk}$ is the RF component of the beam current during the beam segment. It depends on the DC beam current, the bunch length and the longitudinal distribution. LHC klystrons are designed for a 300 kW RF output. We wish to keep a safe 20% power margin for regulation, therefore limiting the operational RF power at 250 kW. This sets the maximum voltage per cavity as listed in Table 2.

Table 2: Cavity voltage produced by a 250 kW klystron for different beam DC currents, bunch lengths and longitudinal distributions: Gaussian, cosine-square and point-like (Dirac pulse).

I_{DC}	Bunch length	Gaussian		Cosine2		Point-like	
		$I_{rf,pk}$ (A)	V @ 250 kW (MV)	$I_{rf,pk}$ (A)	V @ 250 kW (MV)	$I_{rf,pk}$ (A)	V @ 250 kW (MV)
0.55 A DC	1ns 4σ	1.156	1.73	1.269	1.58	1.41	1.42
	1.25 ns 4σ	1.034	1.93	1.196	1.67	1.41	1.42
0.50 A DC	1ns 4σ	1.04	1.92	1.142	1.75	1.269	1.58
	1.25 ns 4σ	0.931	2.15	1.076	1.86	1.269	1.58

The longitudinal distribution in LHC is determined by the controlled emittance blow-up [14]. The cosine-square shape is a good match. With 1.25 ns bunch length we can operate with 1.67 MV per cavity (13.4 MV total) at nominal beam intensity and with 1.86 MV per cavity (14.9 MV total) at 0.5 A DC. Comparing to the 10 MV lower limit (longitudinal stability margin as in Run1), we have some flexibility in the choice of voltage in physics. We propose to optimize it, by testing a few physics fills with different voltages.

For Run2, we will operate with 25 ns bunch spacing. This was the original specification for the LHC RF and the hardware is fully compatible [1]. To make the e-cloud scrubbing faster, it is proposed to work with 5 ns-20 ns spacing, that is, pairs of bunches spaced by 5 ns, with

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[*] Above nominal LHC beam (0.55 A DC) the klystron power will not be sufficient to compensate the transient beam loading and we will modulate the phase of the RF following the beam gaps [2]. With this scheme the required RF power will be significantly lower than given by equation (1).

25 ns spacing between pairs. The LHC Beam Based Phase Loop has been introduced above: it measures the phase of each bunch, averages over one-turn and updates the phase of the corresponding beam RF. This scheme is classic in Hadron machines. It provides fast damping of the longitudinal oscillation mode zero (all bunches oscillating in phase). When the RF is generated by an oscillator, the phase noise is particularly large at low frequency offset from the carrier. In a large collider the synchrotron frequency is small (just above 20 Hz in the LHC) and the noise will excite coherent longitudinal oscillations. Due to the non-linearity of the RF potential, the oscillations will result in growth of longitudinal emittance and losses as the RF bucket gets full [11]. With 25 ns spacing the electronics measures the phase of each bunch. For 5-20 ns spacing it will give an average over the two paired bunch. As the measurements are then averaged over one turn to generate an update for the RF drive, the performance is expected to be similar with the scrubbing beam [12].

STUDIES ON CONTROLLED RF NOISE

If we apply only adiabatic variations of the RF parameters, the longitudinal emittance (expressed in eVs) remains constant during the acceleration. Since the longitudinal stability threshold decreases with energy, the beam would be unstable at high energy without intentional emittance growth during the ramp [13]. This controlled blow-up is achieved by injecting band-limited RF phase noise in the cavities, while monitoring the mean bunch length [14]. The method has been in operation since summer 2010. Various implementations have been tried: the phase noise can be injected in the LLRF loops or directly in the cavity. It can cover a narrow spectral band around the RF frequency or around a revolution sideband. Blow-up was also tested with and without Beam Phase Loop [15]. In spring 2014 a study was started to explain the observations with blow-up recorded during Run1. The PyHEADTAIL tracking code has been upgraded to allow for injection of colored RF phase noise. With this modelling, we hope to gain better understanding of the blow-up in order to make it more reproducible from ramp to ramp, more uniform among the bunches, and to produce longitudinal profiles that create less machine heating in 2015. It was also proposed to use RF phase modulation to create flat bunches (flat longitudinal distribution) [16]. Such a profile would reduce the beam-induced heating [†] and could be beneficial for transverse stability, and thus luminosity. At 7 TeV/c the synchrotron radiation damping time is 24 hours (for σ_z). Ignoring all other blow-up sources, the bunch length would shrink to 80% of its initial value in 6 h [18]. Although Intra Beam Scattering and, to a lesser extent, RF noise will counter-

act, the net effect may still be shortening that could be compensated by periodically injected bursts of RF phase noise during physics. These manipulations require a better understanding of the effect of controlled RF noise in the LHC.

CONCLUSIONS

The high-power RF equipment underwent a major upgrade during LS1: installation of a spare cryomodule complete with four cavities, new solid-state crowbar systems replacing the old thyratrons, klystrons upgraded for full DC power and improved arc detectors. These should improve the RF availability.

During Run2, we plan to operate initially with 1.25 ns bunch length in physics. Capture voltage will be 6 MV. At 6.5 TeV/c, the RF voltage can be chosen between 10 MV (conservative stability threshold) and 14 MV (RF power limit). The lower value is defined by the loss of Landau damping, scaled from MD results at 4 TeV/c. We plan to measure the stability threshold at 6.5 TeV/c at the beginning of run2. During most of run1[‡], we used 12 MV in physics as C3B2 could not provide more than 1.2 MV. For constant bunch length, a high voltage value is beneficial as it reduces transverse emittance growth caused by Intra Beam Scattering, but it results in a large momentum spread that may reduce lifetime in collision (betatron tune spread caused by chromaticity). Optimization should be done in 2015, in physics. We do not anticipate hardware problems with the 25 ns spacing, neither with the exotic 5-20 ns (scrubbing beams).

New diagnostics are in preparation: bunch-by-bunch phase measurement (hopefully available at start-up) and monitoring of the RF noise (second half of 2015).

The controlled injection of RF phase noise is being implemented in the PyHEADTAIL simulation code. The goal is to improve longitudinal blow-up and design RF manipulations to precisely control bunch profile in physics.

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[‡] We used 10 MV for a few fills towards the end of Run1.

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LHC TRANSVERSE FEEDBACK

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Abstract

The LHC Transverse feedback system (ADT) is undergoing a major upgrade during LS1. In an effort to further reduce the noise floor of the system, the total number of pickups has been doubled. New beam position electronics are being designed using current, state of the art components. An upgrade of the digital signal processing system accommodates all of the extra functionality that had been introduced during the LHC Run I. Use of the most recent FPGAs will allow more sophisticated signal processing algorithms to be deployed for Run II.

The upgraded ADT will also feature multiple, fully dedicated signal paths with independent gain and bandwidth control for treatment of witness bunches, the abort/injection gap cleaning pulses, and for the main feedback. The cleaning process will be fully automated. An additional, alternative data processing algorithm can detect anti-symmetric intra-bunch oscillations. An instability trigger network is being deployed in LHC point 4 to interconnect systems and instruments which can detect instabilities and those which can provide observation buffer data. Feasibility of an external "observation box" to record transverse and longitudinal data from the RF and ADT systems has been demonstrated and work has started on its implementation.

The current status, readiness for restart and beam commissioning plans will also be presented.

ADT PRE-LS1 AND MOTIVATION FOR UPGRADE

Initially conceived for damping injection oscillations and providing stability for coupled bunch dipolar oscillations the LHC transverse feedback system (ADT) [1] has found after initial commissioning [2,3] many applications far beyond what the electronics were designed for [4,5]: Abort gap cleaning [6,7], although originally envisaged [8], has been extended to so called "injection gap" cleaning [9]; beam observation of oscillations with unprecedented precision, bunch by bunch, are complementary to LHC beam instrumentation capabilities; and the injection of noise for the purpose of loss maps [10] have become indispensable for efficient collimation set-up [11]. Moreover, excitation for tune measurement [12] and quench tests [11,13] with the possibility of modulating the excitation strength and feedback gain around the circumference of the LHC have proven to be essential for studies and operation and should be further developed for the case of the tune measurement.

Limitations of the system, both in terms of performance (noise level) and suitability of the hardware and software for the many different applications have also become visible during Run I. A major upgrade program is under way during LS1 which will permit the system to be better adapted to the various applications that the ADT is now used for, to provide more functionality for beam observation, and to reduce the noise floor. The main modifications are:

- Doubling the number of pick-ups to reduce the level of noise; re-cabling of pick-ups with higher performance smooth wall coaxial cables
- Redesign of the analogue and digital signal processing hardware to have independent gain control for feedback, abort gap cleaning, and excitation
- Improved frequency response by new cabling and analogue and digital correction of the frequency response aimed at 25 ns bunch spacing and improved pulse shape for abort gap cleaning
- An external "observation box" for bunch by bunch data collection
- A triggering network linking RF, ADT and BI observation to acquire data synchronized with occurring instabilities on the beam

The new digital hardware is going to be tested in the SPS during the run in 2014. After these successful SPS tests, the new hardware will be deployed in the LHC. The new hardware will also be controlled using the latest FESA 3 middleware.

HARDWARE AND NEW FEATURES POST-LS1 FOR RUN II

Power System

Maintenance on the power system is being carried out with refurbishment of the water cooling system and interlocks as well as the installation of additional vacuum gauges for improved robustness with respect to false interlocks. Careful measurements of the transfer functions of the power system are planned at re-start and these will permit to optimize the signal processing for best phase compensation and bunch-by-bunch operation.

Pick-ups and Cabling

Following an agreement with the Beam Instrumentation Group the number of pick-ups used for the ADT system will be doubled with optimal positions of the pick-ups for the ADT at high beta function values. Table 1 and Table 2 summarize the ADT pick-ups left and right of IP4 together with expected values for the beta functions. The necessary swap of pick-ups with BI is detailed in an ECR [14].

Table 1: ADT pick-ups left of IP4 with beta functions for respective plane used (pick-ups added for run II in *italic*)

Beam/ plane	*Q10L*	Q9L	*Q8L*	Q7L
B1.H		111 m		106 m
B1.V	*175* m		*155* m	
B2.H	*158* m		*96* m	
B2.V		160 m		167 m

Table 2: ADT pick-ups right of IP4 with beta functions for respective plane (pick-ups added for run II in *italic*)

Beam/ plane	Q7R	*Q8R*	Q9R	*Q10R*
B1.H		*133* m		*153* m
B1.V	161 m		142 m	
B2.H	150 m		101 m	
B2.V		*151* m		*180* m

The doubling of the number of pick-ups has already been proposed in the past as one of the options to increase the signal-to-noise (S/N) ratio [15]. Assuming that noise is not correlated from pick-up to pick-up, but signals are, the S/N improvements with respect to a single pick-up, scales with the square root of the number of pick-ups N used. As signals also scale with the square root of the β-function and assuming noise does not scale with β, the improvement of the S/N in dB with respect to the use of a single pick-up with design β=100 m can be expressed as

$$\left(\frac{S}{N}\right)_{improvement} = 20\text{dB} \times \log_{10} \frac{\sum_{n=1}^{N} \sqrt{\beta_n / 100\text{m}}}{\sqrt{N}}$$

Table 3 compares the improvement for Run I (two pick-ups per plane and beam) with respect to a single pick-up and for Run II with four pick-ups per plane foreseen and the relative improvement from Run I to Run II that is expected.

Table 3: Improvements in signal-to-noise ratio with respect to single pick-up at design beta of 100 m.

Beam/ plane	Run I dB	Run II dB	Run I → II dB (relative)
B1.H	3.8	7.0	3.2
B1.V	4.2	8.0	3.8
B2.H	4.4	8.0	3.6
B2.V	4.9	8.2	3.3

The expected improvement from Run I to Run II of more than 3 dB in S/N is also due the overall increased values of the beta functions at the pick-ups, a result of an optimization by the LHC optics team.

The new cabling has been carried out using smooth wall coaxial cables which have less dispersion of group velocity for high frequencies than the previously used corrugated cables. Moreover, careful cable pulling together with rigorous quality control during cabling ensured that reflections due to bends and deformation of the cable during pulling and attachment are minimised. All previously used pick-up cables that were part of the damper system for Run I have also been changed. Consequently at start-up length matching of cables has to be checked as part of a full setting-up procedure.

Signal Processing Hardware

Figure 1 shows the layout of the new digital signal processing. The new digital hardware will be able to treat the complete set of four pick-ups per plane and generate the analogue output signal for one ADT module. Eight such digital cards are needed to drive the eight kicker modules (two per beam and plane).
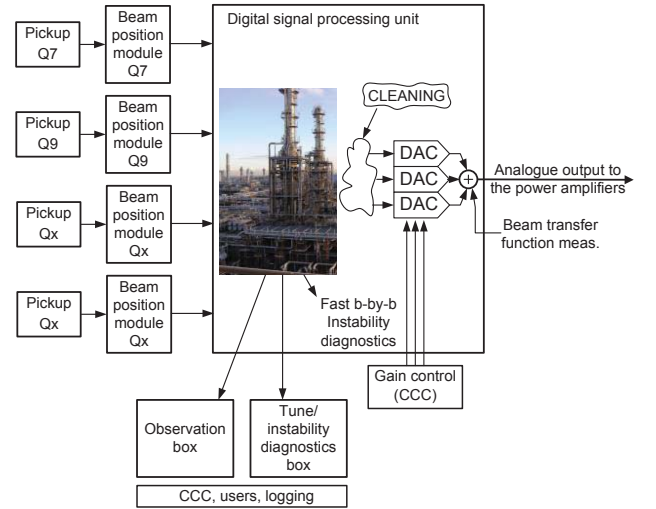
Figure 1: Layout of Signal Processing for ADT hardware after LS1.

The three output DACs permit the combination of the principle feedback control signal and the signals for excitation and abort gap cleaning, each with independent gain control. Fast bunch-by-bunch diagnostics on board is possible and is principally planned to be used for setting-up, RF group internal purposes, and in a limited capacity for fixed displays and logging as in the past. A separate hardware platform based on PCs will receive the digital data streams for storage, and on- or offline processing and is described in more detail below.
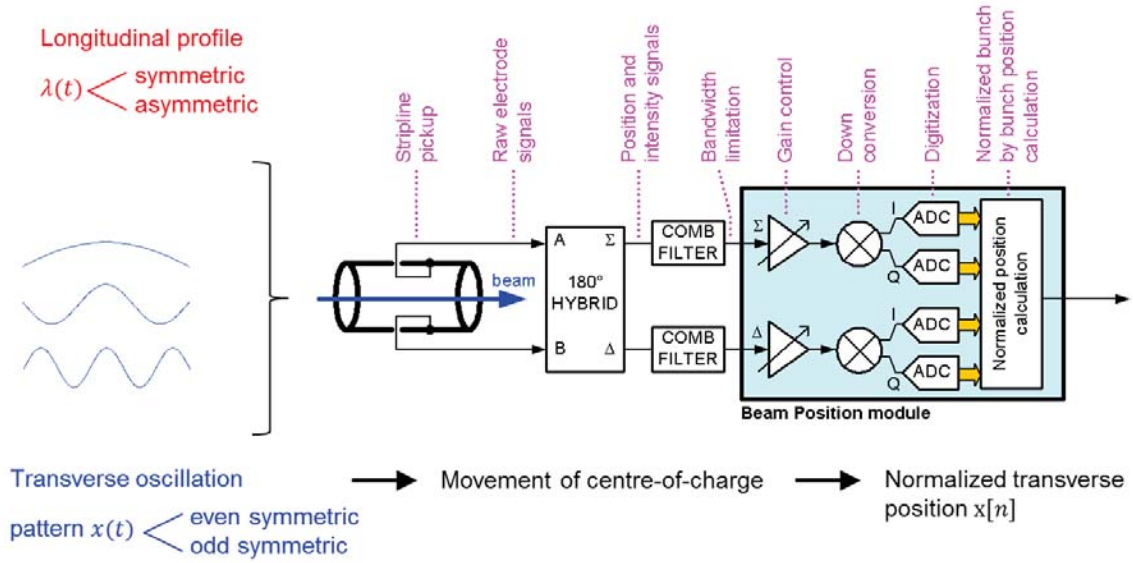
Figure 2: Signal Flow for ADT pick-up electronics frontend. Four signals are digitized, the in-phase (I) and quadrature (Q) components of the Σ and Δ signals with respect to the RF signal at 400.8 MHz.

ADT DATA FOR OBSERVATION AND ANALYSIS

ADT Pick-up Signal Processing and Head-Tail Oscillations

The transverse feedback system is targeted to damp dipole oscillations, i.e. the centre of gravity of the oscillation. Figure 2 shows the signal flow of the analogue part of the pick-up signal treatment electronics up to the digitization [16]. Four signals, the I (in-phase) and Q (quadrature) components of the pick-up sum and difference signals are digitized. The algorithm first rotates vectors of sum and delta (I,Q) pairs to align them (Fig. 3) and then computes the normalised position from [16-18]

$$x_N = \frac{I_\Delta I_\Sigma + Q_\Delta Q_\Sigma}{I_\Sigma^2 + Q_\Sigma^2},$$
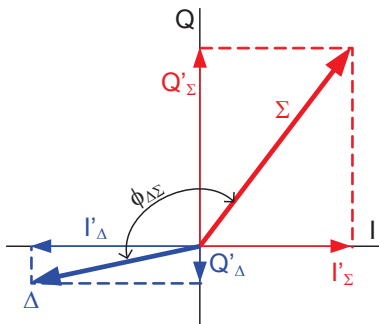
Figure 3: Vector diagram of (I,Q) vectors of Σ and Δ at 400 MHz with respect to RF at 400.8 MHz. During calibration the angle $\phi_{\Sigma\Delta}$ is determined.

whereby the (I,Q) vectors of Σ and Δ have been assumed to have been rotated to align in (I,Q) space beforehand, see [17].

Figure 4: Sensitivity of the computed position to *symmetric* intra bunch motion, mean (red) – weighted with bunch line density, – and actually used (I,Q) algorithm (blue) [18].

Figure 4 shows the sensitivity of the computed position to symmetric intra bunch motion and compares it with the weighted position

$$\bar{x} = \int_{-\infty}^{+\infty} x(t)\lambda(t)\,dt$$

where $\lambda(t)$ is the bunch line density. In Fig. 4 the bunch shape has been assumed to be $\cos^2$ shaped with a length of $4\sigma = 1.2$ ns corresponding to measured profiles at 6 MV RF voltage and zeros in the spectrum at 1.5 GHz [19]. For any *symmetric* bunch profile the algorithm is only sensitive to *symmetric* bunch oscillation patterns within the bunch and perfectly rejects the anti-symmetric part if present (head-tail oscillation). An alternate processing of the (I,Q) samples can be used to quantify the *asymmetric* part assuming a symmetric bunch profile [18]

$$x_N^R = \frac{Q_\Delta I_\Sigma - I_\Delta Q_\Sigma}{I_\Sigma^2 + Q_\Sigma^2}$$

This asymmetric oscillatory part is *rotated* by $\pi/2$ with respected to the longitudinal signal component, i.e. appears in quadrature with the longitudinal signal. It is most sensitive to oscillations just below 1 GHz as shown in Fig. 5 as a result of the combination of bunch shape and frequency used to down convert the signals (400.8 MHz). It can be viewed as a parameter characterising head-tail activity on the bunch and any higher-order asymmetric intra-bunch transverse oscillations.

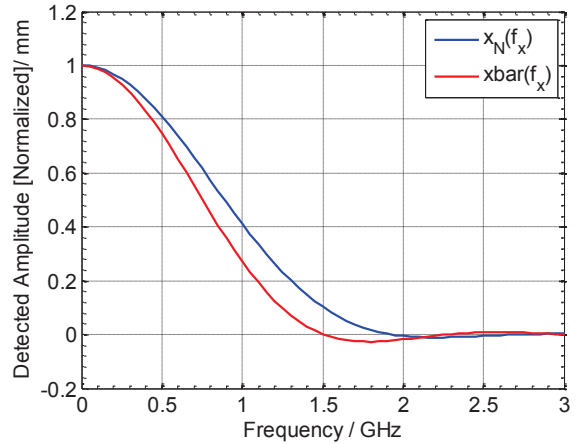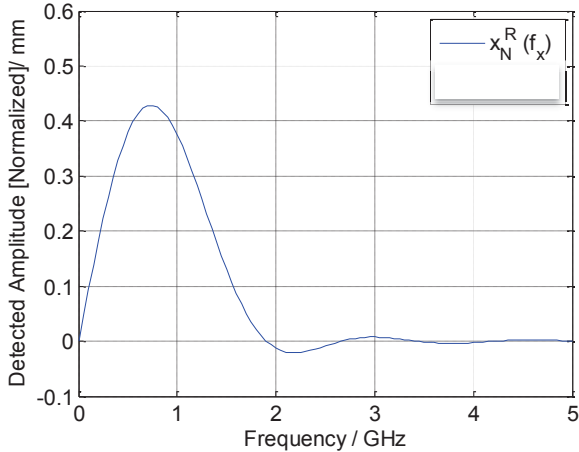Figure 5: Sensitivity of the computed position to *asymmetric* intra-bunch motion using alternate algorithm from (I,Q) samples [18].

This new alternate algorithm has not been explored during the LHC Run I, but for Run II can turn out to be essential in identifying the presence of intra-bunch motion up to 2 GHz. As the information is available bunch-by-bunch recording these signals is complimentary to the planned multi-band instability monitor (MIM) [20] which will not have full bunch-by-bunch capabilities and (I,Q) processing in the initial phase, but with many frequency bands and high sensitivity can better identify the frequency band of any instabilities. In fact the ADT front-end electronics can be viewed as a single band of the MIM with full (I,Q) demodulation and bunch-by-bunch capabilities and as such can demonstrate a way to upgrade the MIM at a later stage.

ADT – RF Observation Box

The "Observation Box" is a PC based gateway to present data from both the ADT and the LLRF system to users. It was launched as a development to overcome the limitations of data transfer in the VME based hardware that is used for both the ADT and LLRF systems in the LHC. The observation box will receive digital bunch-by-bunch data streams from the VME hardware over optical serial links using a proprietary protocol. The observation box will be able to:

- transfer data in blocks using a standard FESA interface, to users or application software
- acquire on demand following the reception of an instability trigger
- process data for tune and instability analysis, issue triggers and present processed data using standard FESA based interfaces
- eventually, store data locally, in the spirit of "take home your MD data on a hard disk"

A total for four operational observation boxes will be deployed for ADT (one per plane) plus one development system.

The wealth of the data available and its usefulness have been previously described. In particular for monitoring injection oscillations with 25 ns bunches there is a need to make bunch-by-bunch oscillations visible at injection. As an example Fig. 6a and Fig. 6b compare the oscillation amplitudes at a vertical ADT pick-up as recorded for a batch of 144 bunches at 50 ns spacing and half of a nominal batch at 25 ns bunch spacing (also 144 bunches) as recorded during MDs in 2012 in the LHC [21]. Such displays will become possible online following the commissioning of the observation boxes and development of the application software needed.
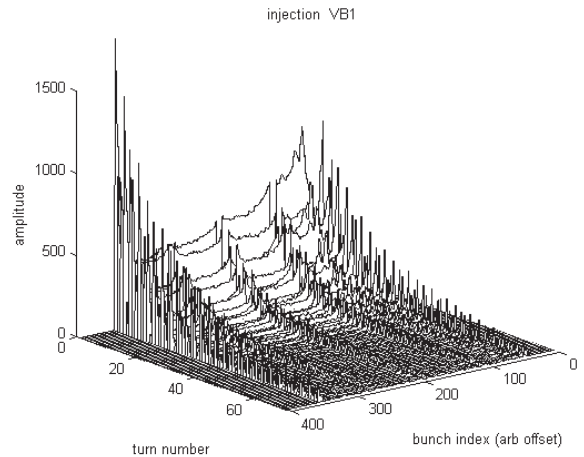
Figure 6a: Injection oscillations in vertical plane for beam 1 (absolute value) for 144 bunches at 50 ns spacing; spikes of large oscillation amplitudes can be seen due to the kicker rising and falling edge (standard ADT bandwidth settings [21]).

Figure 6b: Injection Oscillations (a.u., vertical beam 1) for 144 bunches at 25 ns bunch spacing during 25 ns tests in 2012; spikes visible at the batch limit due to the kicker rise time are rapidly damped thanks to the enhanced bandwidth settings [21].

More sophisticated analysis such as for tune diagnostics, using the ADT can be realised on the same platform but perhaps call for a separat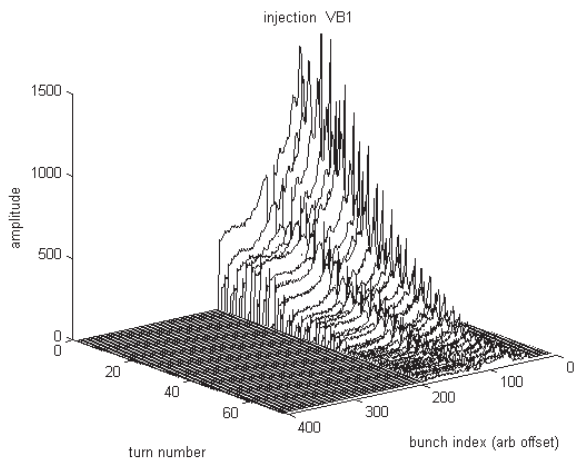e instance of the observation box. Using GPUs for parallel processing of bunch data is foreseen with the observation boxes and has previously been considered for the purpose of tune analysis [12].

Using the ADT data for instability diagnostics will heavily rely on the successful deployment of the instability triggering network described in the next section.

ADT and the Instability Trigger Network

A project has been launched to install an *Instability Trigger Network* [22]. This network is based on *White Rabbit* technology [23] and will link clients via a central hub to permit them to exchange trigger information for data acquisition across different systems and instruments. It addresses the need of synchronised acquisition in case of instabilities across a wide range of devices spread geographically around the LHC. In the first stage RF and BI systems in point 4 of the LHC will be connected to the central node in the CCC. The system can later be extended across the LHC to other users.

Figure 7 shows as an example the signal flow after an instability is detected by the horizontal ADT system. The trigger is time-stamped and sent via the White Rabbit network. Depending on a pre-configured mask all subscribed clients can trigger *synchronously* after a pre-defined delay. In the example of Fig. 7, the configuration leads to triggers being generated for the ADT system for beam 2 (all planes and observation box), the APW, and the MIM. The trigger system is easily scalable so that other instruments can be connected by adding new nodes to the White Rabbit network.
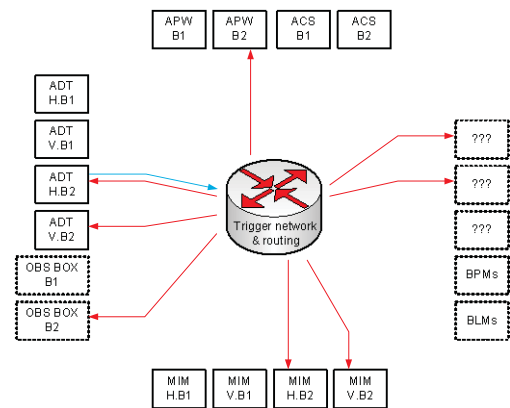
Figure 7: Example of signal flow with the LHC instability trigger network (explanations, see text).

The synchronism in the White Rabbit network ensures that all data is frozen at the same moment and correctly time stamped for later reference. Storage of the data in the Measurement data base or − a clearly defined, limited amount − through the infrastructure of the post mortem system is being considered.

STATUS AND COMMISSIONING PLANS

Status of LS1 Works in Summer 2014

As of summer 2014 the power system modifications have been completed and re-commissioning of the kickers, power converters and power amplifiers is well advanced and on schedule. Infrastructure for the new pick-ups and the instability trigger has been prepared, namely all cabling to the tunnel has been completed. New LLRF electronics for the damper is being designed and fabricated with series production starting after full validation in the SPS, foreseen at the start-up in autumn 2014.

Commissioning Plans

As additional pick-ups will be available and cabling and electronics will have been changed a full re-commissioning and set-up has to be carried out. The commissioning will include preparations for the 25 ns run with improved choices for the flattening of the frequency response and automatic adaptation to bunch intensity and spacing. The redesign of the controls software for FESA3 and new hardware will represent a significant workload for the software team yet to be accomplished.

SUMMARY

Substantial modifications have been undertaken in the ADT during LS1. These comprise doubling the number of pick-ups and a re-design of the electronics to better match the evolved requirements. All modifications are aimed at improving flexibility, reducing noise, and optimizing for the 25 ns bunch spacing, the baseline for LHC Run II. The

instability trigger network and the planned observation system will permit a better use for operations, in MDs and for diagnostics, of all the data available inside the ADT system.

ACKNOWLEDGMENT

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COLLIMATION SYSTEM POST-LS1: STATUS AND COMMISSIONING

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Abstract

The LHC collimation system has undergone an important upgrade during LS1. A total of 32 collimator installations are taking place to consolidate and improve the Run 1 system. This includes 18 new collimators with embedded beam positions monitors (BPMs), additional physics debris collimators, additional passive absorbers and re-installation or displacement of existing collimators. This paper summarizes the post-LS1 collimation layout, highlighting the expected gains from each modification, and the readiness of the new collimation hardware for commissioning without and with beam. Special emphasis is devoted to the new software for the control and configuration of the BPM collimators. A proposal for the necessary beam conditions during collimation alignment and validation with loss maps at 6.5 TeV is also discussed, including a strategy for the machine protection aspects. A list of early machine development studies is proposed.

INTRODUCTION

During Run 1 the LHC collimation system has shown excellent performance at 4 TeV [1]. The cleaning stability in the dispersion suppressor of IR7 was shown to be very good. The cleaning inefficiency was always below $\eta_c = 10^{-4}$ for both beams. No quenches with operational beams were experienced with up to 140 MJ stored energy at 4 TeV.

After Long Shutdown 1 (LS1), the LHC beam energy will increase up to 6.5 TeV. At this energy, the destructive power of the beam is much higher. In particular for metallic collimators, like the tungsten tertiary collimators (TCTs), the onset of plastic damage can occur when single bunches of 5×10^9 p fully impact on the collimator jaw. The limit for fragment ejection is about 2×10^{10} p [2]. In order to monitor the beam orbit at the collimators and perform the collimator alignment without touching the beam at 6.5 TeV, it was proposed to replace the tertiary collimators and the 2 secondary collimators in IR6 by collimators with embedded beam position monitors (BPMs) which will also enhance the operational efficiency of the system.

In addition to the installation of collimators with embedded BPMs other activities are taking place during LS1 that will:

- Improve IR flexibility and configuration.

- Improve physics debris cleaning in IR1 and IR5.

- Improve IR8 layout: replacement of the 2-in-1 beam collimators by single-beam collimators, similar to IR2.

- Increase the protection of the warm magnets in IR3 by adding new passive absorbers in front of them.

Due to the installation of new ventilation doors in IR7, 3 primary collimators in that region were also taken out of the tunnel and re-installed afterwards. In addition to this, a primary collimator was replaced due to heating problems during Run 1. After the changes listed above, the new system post-LS1 will consist of 118 collimators, of which 108 are movable. The collimator hardware changes will be described in detail in the next section.

HARDWARE CHANGES

Embedded BPM collimators

The reasons for installing collimators with embedded BPMs in IR6 and the experimental IRs are:

- **Safer alignment:** With the online measurements of the beam orbit and a software feedback routine the collimator could be aligned without touching the beam [3] thus reducing the risk of jaw damage during alignment.

- **Faster alignment:** At 4 TeV the alignment tool achieved a setup time of few minutes per collimator. With the new setup tool and the input from the BPM measurements, the setup time can be reduced to a few seconds [3]. This allows for more flexibility in the IR configuration, since the new alignment of the 16 collimators could be done in parallel in a couple of minutes.

- **Reduce orbit margin in cleaning hierarchy:** Since the orbit will be more precisely known at the collimators, the margins used for the β^*-reach calculation could potentially be reduced, providing more room to squeeze the β^* [4].

- **TCT and triplet protection:** The BPM signals will be used to generate a beam interlock that dumps the beam if the orbit at the TCT changes by more than a given threshold.

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A total of 16 tungsten TCTs in all IRs and 2 carbon TC-SGs (secondary collimators) in IR6 are being replaced by new collimators with integrated BPMs. The interfaces of these collimators are fully compatible with the infrastructure currently present in the LHC tunnel [5], although new BPM cables were required. The active part of the collimator jaw is still 1 m long. At each side of the jaw, BPM pick-up buttons are installed, as shown in Fig. 1. Figure 2 shows a TCTP collimator ready to be installed in the LHC tunnel.

The 2 TCSPs were internally produced by CERN and the 16 TCTPs are produced by an external company. All collimators have been installed in the LHC as of July 2014. More details on installation can be found in [6, 7].

Figure 1: New TCSP carbon jaw with embedded BPM.
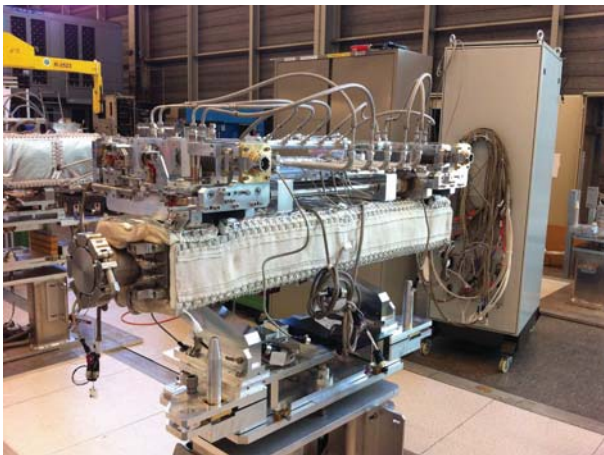
Figure 2: TCTP collimator with embedded BPMs.

Physics debris collimators

Several collimators are installed to protect the equipment in the matching sections of the high-luminosity experimental IRs from physics debris. In Run 1, two copper TCLs were installed per beam, in cell 5 of IR1 and IR5. These TCLs were positioned at 10 σ during stable beams as of 2012. Four other copper TCLs were produced prior to Run 1, and were intended for installation in cell 4 [8]. However, these collimators were not installed, as they are only required at design luminosity. These collimators have been installed during LS1, and will allow for the operation of the forward physics detectors (Roman pots), as the TCL5 can now be opened in high-intensity fills.

In addition, 4 other TCLs, recycled from previously-installed tungsten TCTs, were installed in cell 6 of IR1 and IR5 to complete the system as designed for nominal luminosity. These collimators will reduce the losses in the dispersion suppressor by two orders of magnitude, and also provide flexibility for future upgrades of the forward physics programme. The final settings for these collimators are still under evaluation due to impedance considerations [9].

Passive absorbers

Passive absorbers are fixed collimators which reduce the dose in the warm magnets in the cleaning insertions and increase their lifetime. During Run 1, 3 passive absorbers per beam were added to protect the D3 and Q5 in IR7, while only 1 passive absorber per beam was installed to protect the IR3 D3. The dose measured during 2011 and 2012 showed that the operational flexibility of the collimator settings could be compromised without additional protection of Q5 in IR3. Therefore, the installation of 1 additional absorber per beam in IR3 in front of Q5 to reduce the dose from off-momentum cleaning losses by a factor 2-5 according to simulations [10] was proposed [11]. Two passive absorbers were produced in-house in 2013 (see Fig. 3) and installed in March 2014.
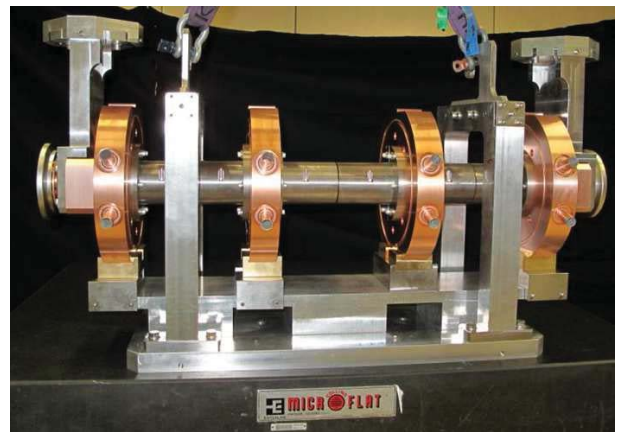
Figure 3: New passive absorber of TCAPD type installed in IR3.

Status of Installation and Production

All collimators have been installed by July 2014 as per the original schedule, after a successful production. Figure 4 shows the status of the installation of all collimators (with and without BPMs) and passive absorbers. Figure 5

shows a snapshot of the LHC collimation system for post-LS1 operation, with the type of LS1 activity for each collimator category in colour. The new system will be composed of 118 collimators, of which 108 are movable. With this new configuration the LHC collimation system is complete and there are no foreseen installations until the upgrades for Hi-Lumi LHC.
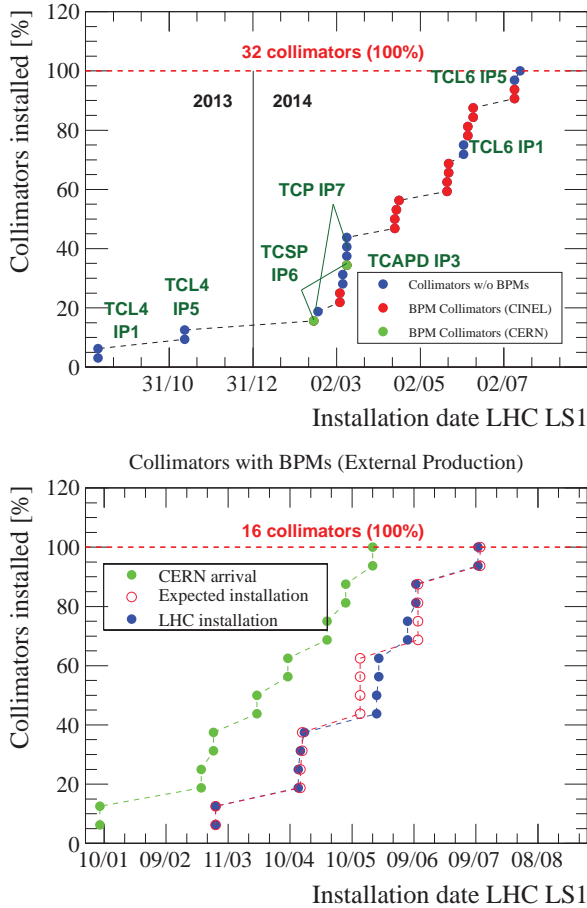
Figure 4: Status of general collimator installation (top) and BPM collimator installation (bottom).

SOFTWARE CHANGES

Several improvements have been done to low-level control system of the LHC collimators. The controls racks have been upgraded with a new PXI high availability chassis, with redundant, easily replaceable fans and a redundant hot swappable power supply, designed specifically for the collimation system. The FESA class was completely rewritten following the move to the new FESA3 framework. Beam-beam separation limits have been added, but as their calculation is difficult, it was decided to rely on the orbit measurements provided by the embedded BPMs in the tertiary collimators. In addition, 12 LVDTs affected by magnetic interference will be replaced by a new design called Ironless Inductive Position Sensor (I2PS) [12].

During Run I, improvements were also made to the software alignment tool application. The alignment of the 100 collimators was done by moving each individual jaw towards the beam until the beam halo was touched. The showers from the protons impacting the collimator jaws were detected by beam loss monitors (BLMs) installed downstream the collimators. The alignment time of a single collimator was initially of the order of 20 minutes. Beam-based collimator alignment is now performed via a feedback loop executed in a Java application. BLM data are received at 12.5 Hz, and the collimator jaws are moved in 5-10 μm steps until the losses exceeded a pre-defined threshold. The resulting spike is analyzed to ensure that the temporal pattern indicates that the is was aligned to the beam. The improvements on the alignment tool decreased the collimation setup time down to few minutes per collimator [13].

For Run 2, 80% of the collimators will still be aligned using the BLM-based technique. The feedback loop is moved to a new FESA class. In addition, this FESA class calculates the jaw gaps for the BPM-equipped collimators and forwards them to another FESA class, which will receive the BPM data and compute the measured beam positions. The alignment FESA class will use this data to align the collimators via a successive approximation algorithm, already tested with beam in the SPS [14].

The BPM-based technique will allow for the jaws to be aligned at large gaps (>50 mm) without touching the beam. The alignment of all BPM-equipped collimators can be performed in parallel in <20 s, which represents a reduction in time by 2 orders of magnitude with respect to the previous BLM-based technique. In addition, it will be possible to align the jaw corners individually. The software architecture is shown in figure 7.

COMMISSIONING

As 80% of the system remains the same as in Run 1, the commissioning plan for 2015 is strongly based on the experience accumulated so far. However, additional tests are foreseen for the commissioning of BPM collimators.

Required intensity for commissioning

Histograms of the beam intensity consumed during alignments in 2010-2013 are shown in figure 6. On average, 7×10^{10} p were consumed during an alignment campaign for all collimators. The minimum intensity required for the embedded BPMs to operate is 5×10^9 p.

On the other hand, the minimum intensity required for qualification loss maps is defined by the minimum BLM signal needed to measure the leakage to the IR7 dispersion suppressor:
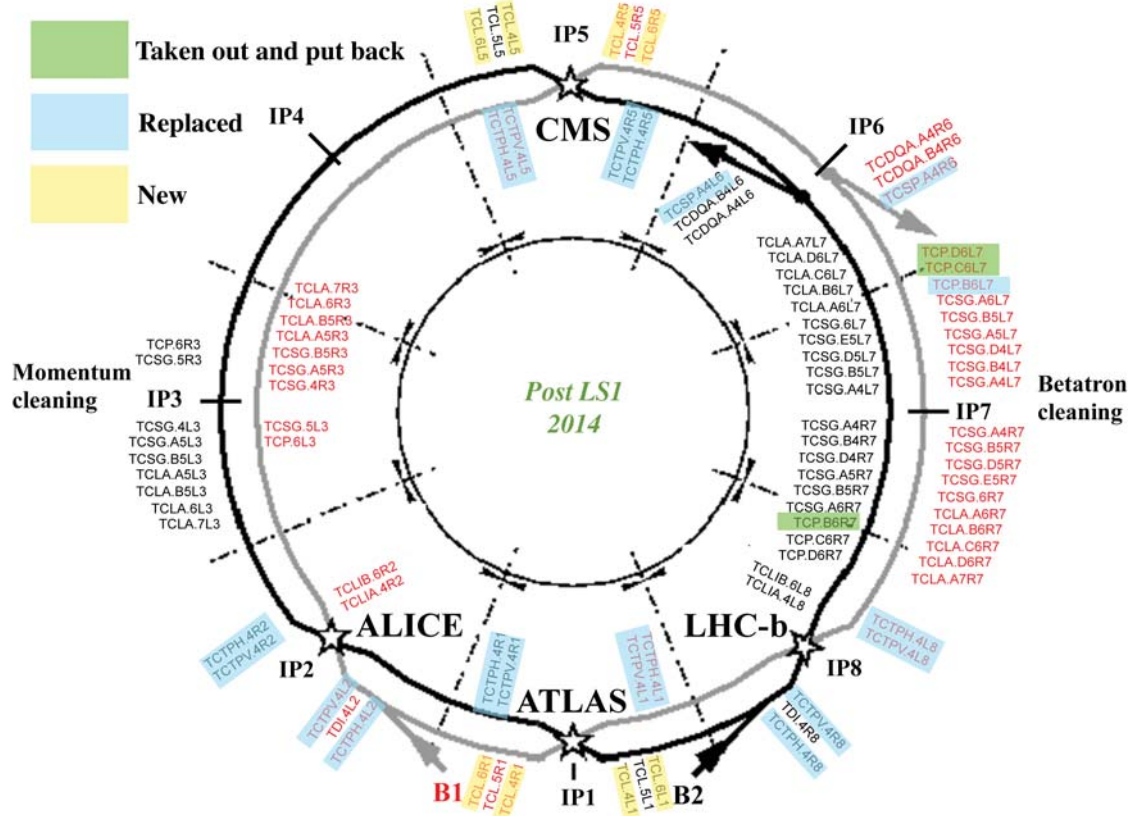
Figure 5: The LHC collimation system layout for post-LS1 operation.
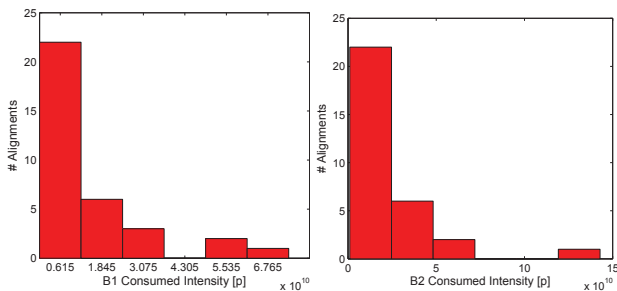
Figure 6: Beam intensity consumed during alignment for B1 (top) and B2 (bottom).

$$\mathrm{BLM}^{\mathrm{Q8}} = \eta_{\mathrm{c}} \times \mathrm{BLM}^{\mathrm{TCP}}_{\mathrm{min}} > \mathrm{BLM}^{\mathrm{noise}} \qquad (1)$$

$$\mathrm{BLM}^{\mathrm{TCP}}_{\mathrm{min}} > \frac{3 \times 10^{-7} [\mathrm{Gy/s}]}{5 \times 10^{-5}}$$

$$= 6 \times 10^{-3} [\mathrm{Gy/s}]$$

This corresponds to at least 8×10^{9} protons at 4 TeV per plane (horizontal and vertical). One would expect the minimum number of protons to be lost to obtain the same BLM signal to be lower at higher energies. During 4 TeV operation in 2012, 3 nominal bunches were safe, so this minimum threshold was never encountered.

However, as a stable orbit is needed during beam-based alignments and loss maps, the operational limitation on the needed minimum intensity becomes the requirement of 2 nominal bunches to establish and optimize collisions. In addition, during collisions, the ADT blow-up cannot be performed on the colliding bunches, as crosstalk is induced in the other beam. Hence, additional non-colliding pilot bunches are required for loss maps in this machine configuration.

The required intensities and bunch configurations for the commissioning of the collimation system at the different machine stages are shown in Table 1. The intensities are below the proposed "restricted" Setup Beam Flag of 2.5×10^{11} p [15]. However, it is important to confirm as soon as possible these approximated figures with 6.5 TeV beams, as there are important uncertainties in the scaling from lower beam energies. Approximately 1 shift is required per alignment and qualification for each of the injection, flat top, squeezed separated and squeezed colliding beam configurations. Once experience is gained with the embedded BPMs, in the event of frequent machine configuration changes, the alignment and qualification after the squeeze and during collisions could be done in the same fill. Additional fills will be required for asynchronous dump qualifications at injection, flat top and during collisions in the event that the beams are dumped when per-
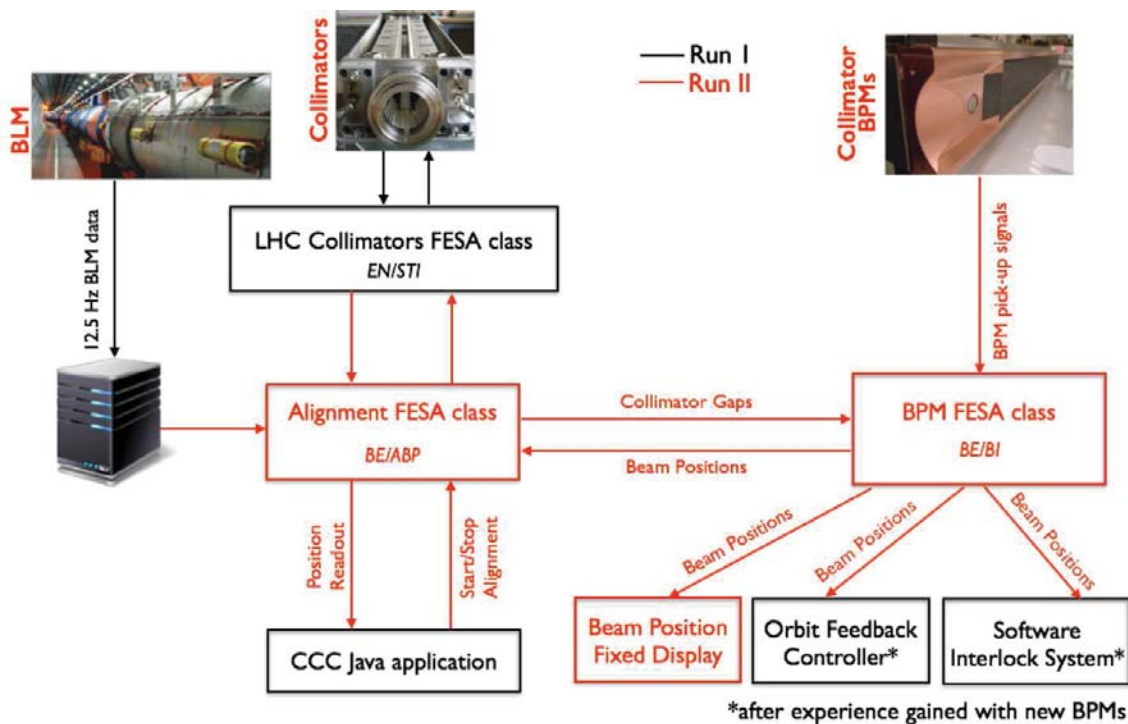
Figure 7: Software architecture for operation of the embedded BPM collimators.

Table 1: Intensity ($\times 10^{11}$ p) and bunch configuration per beam required to commission each machine stage.

Machine Mode	Alignment		Betatron Loss Maps		Off-momentum Loss Maps	
	Intensity	Bunch config	Intensity	Bunch config	Intensity	Bunch config
Injection	2	2 nominal	2	2 nominal	2	2 nominal
Flat Top	2	2 nominal	2	2 nominal	2	2 nominal
After Squeeze	2	2 nominal	2	2 nominal	2	2 nominal
Collisions	2.4	2 nominal + 2 pilot	2.4	2 nominal + 2 pilot	2.4	2 nominal + 2 pilot

forming the off-momentum loss maps.

Early measurements

The collimators will be used in the sector tests [16]. The jaws of several collimators in IR3, IR6 and IR7 will be positioned at the anti-collision switches at gaps of ∼0.5 mm and tilted to leave no clearance. In this configuration, the jaws will be at a 5 mm overshoot across the nominal beam orbit.

Beam position measurements with embedded collimator BPMs will be made parasitically from the very first fill. Collimator scans will need to be made to measure the BPM non-linearity correction coefficients, as was done in the SPS. Finally, the beam positions measured with BLM-based and BPM-based alignments need to be compared.

In order to perform more controlled off-momentum loss maps, the minimal RF trim for the right trade-off between the loss map quality and the operational efficiency (in terms of number of fills required) needs to be evaluated.

The simulations done for cleaning, impedance and R2E studies for different Roman pot and TCL collimator settings need to be validated by measurements. In addition,

the proposed collimator settings for the full system need to be tested. This would be done via beam loss maps, as done in the collimation quench tests.

CONCLUSIONS

The LHC collimation system has performed very well during Run 1. No quenches were observed, and the cleaning efficiency of the system was close to the design value. Several hardware and software consolidation and upgrades are ongoing during LS1 to prepare the system for Run 2, as the the machine approaches the nominal parameters. The work is on track, and the system will be ready in time for the sector test to be held in November.

ACKNOWLEDGMENT

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LHC TRANSFER LINES AND INJECTION SYSTEMS

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Abstract

The status and commissioning plans of the transfer line and injection hardware are presented with focus on the injection dump and kickers. Modifications of the beam loss monitoring in the injection region, its readiness for the start- up and commissioning strategy are shown. A new interlock strategy for the injection protection elements and the injection septum is introduced. The expected transfer line stability and possibilities to improve the turnaround with optimized SPS supercycles for LHC injection are discussed.

TRAJECTORY STABILITY

The trajectory stability in the transfer lines TI 2 and TI 8 is dominated by the stability of the SPS extraction septum (MSE) power converters. The low MSE inductance of 80 μH is the cause of having almost no filtering effect from the load side on the current.

Three main frequency ranges of voltage instabilities can be distinguished for the MSE:

- Asymmetries in the power converter: 100 -200 Hz

- Measurements, stray fields: 50 Hz

- Regulation: few Hz

For the MSE power converter in BA6 the filter was further improved in LS1 which allowed to reduce the voltage ripple for the higher frequency ranges mentioned above. A reduction of the peak-to-peak ripple from 9 to 3.5 A is expected which has to be compared to the overall aim of having a ripple below 4 A.

The MSE power converter in BB4 has a better topology than the one in BA6 but an asymmetric 18 kV ac distribution network which is considered to partly cause the ripple. The other contribution came from a problem in the DC current transformer (DCCT) which showed a 5 A peak-to-peak oscillation when the power converter had been switched off, Fig 1. This caused the closed feedback loop to correct for this non-existing oscillation and therefore disturbing the power converter performance. The DCCTs in BB4 were repaired, Fig. 2, and the ones in BA6 tested without detecting this problem.

The filters in BB4 were improved, too. A total of 200 capacitors will be exchanged during LS1.

FINAL TDI HARDWARE

The main upgrades of the TDI during LS1 concerned the beam screen. The old copper screen was replaced by a reinforced 6 mm stainless steel screen on a new supporting
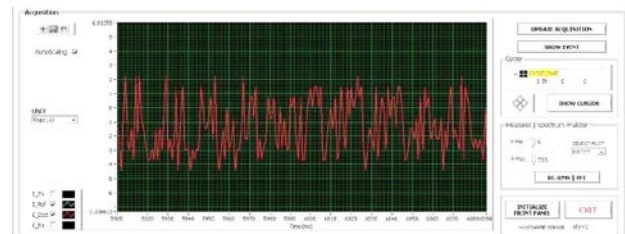
Figure 1: DCCT in BB4 before the repair. A 5 A peak- to- peak current oscillation is visible (PC switched off).
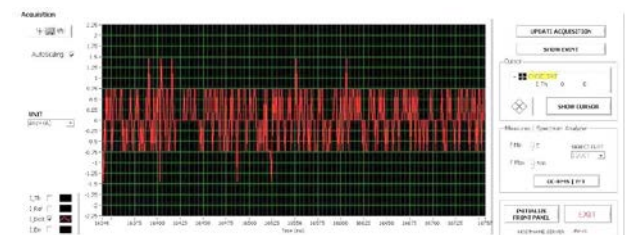
Figure 2: DCCT in BB4 after the repair. Note the scale. A ±0.75 A peak-to-peak current oscillation is visible which corresponds to the expected noise level.

frame. The sliding system was upgraded, the central RF fingers were replaced by mechanical connections and the RF extremities bolted instead of electron beam welded. In total 8 temperature sensors were installed. The gearboxes were replaced by new greased ones. The cooling circuits were not in the initial TDI design but added later. Even though measurements of the cooling water temperature gradients had shown that the cooling circuits are not very efficient the same design will be kept for after LS1. The coating of the different TDI blocks was tested during bake-out. As a result NEG coating is not compatible with hexagonal boron nitrite (hBN) outgassing after baking at 300ºC, Figs. 3 and 4.

In Table 1 the original proposal of coatings is compared with the final solution. The adjacent chambers to the TDI will be NEG-coated and baked to improve the vacuum level and thus reduce the background for the experiments.

Table 1: TDI coating.

	Original proposal	Final coating
BN blocks	Ti + NEG + Cu + NEG	Ti coating
Al blocks	NEG	Ti coating
CuBe blocks	NEG	No coating
Beam screens	Cu + NEG	No coating

Figure 3: Boron nitrite blocks with coating of 5 µ*m* Ti, NEG, 2µ*m* Cu and NEG before the bake-out.

Figure 4: Coated boron nitrite blocks after bake-out at 300ºC.

The spare TDI units could be installed during the end of year stop 2015/16 if the time needed for bake-out is compatible with the planning. For these units it is foreseen to add Cu on top of Ti for the hBN blocks to reduce the beam impedance. This additional coating needs to be validated by tests.

NEW INTERLOCKS

Two new interlocks for the injection septum current and the injection dump gap were put in place during LS1 and are described in the following paragraphs. The interlock on the gap of the transfer line collimators (TCDIs) is described in [1].

TDI Gap Interlock

During the LHC Run 1 the TDI jaws suffered from elastic deformations due to beam induced heating. The jaw position measurement with linear variable differential transformers (LVDT) was compromised because of the flexible junction between jaw and its mount, Fig. 5. This caused reduced machine availability due to the interlocked tight TDI jaw position tolerances. The criticality of the TDI as injection protection element

gave rise to add a redundant measure- ment of the gap between the jaws based on interferometry, Fig. 6. The angular acceptance of the interferometric sys- tem is increased by using reflecting tubes instead of mirrors. Also the position measurement shall be kept at all times, from beam position to parking with all possible jaw angles to avoid a re-initialisation of the position. All elements have undergone radiation tests up to 10 MGy. The feedthroughs will be tested for vacuum tightness on a spare for a duration
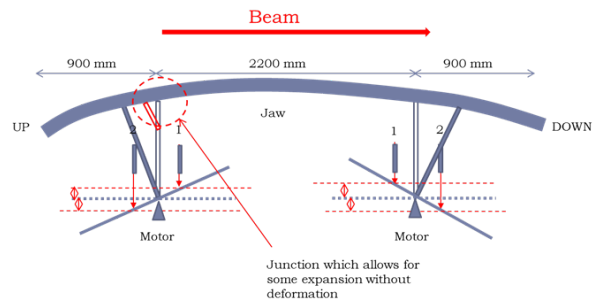
Figure 5: Deformation of the TDI jaw due to beam induced heating.
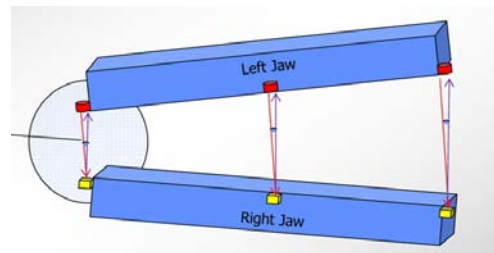
Figure 6: Position of interferometric sensors on the TDI jaw.

of 6 months. The spare TDI should be ready for installation in the end of year stop 2015/2016. As a difference compared to Run 1, this gap measurement will be connected to the Beam Energy Tracking System (BETS). The BETS will allow for 3 positions:

- *Injection:* 10 mm gap for normal injection operation; the interlock is triggered only if the gap is outside the tolerance or an BETS internal failure occurs.

- *Dump:* In case the TDI is positioned such that the injected beam is stopped, the BETS will be put on a maskable input to allow for the setup of injection system and the TDI itself.

- *Parking:* After injection the TDI is retracted to its parking position of ±50 mm to reduce the impedance, beam induced heating and the background for the experiments. In this case the BETS interlocks the SPS extraction.

Until the interferometric measurement is ready, the value for the gap calculated from the LVDTs will be used as BETS input. The change from the LVDT gap calculation to the interferometric gap measurement as input is transparent for the BETS.

MSI Current Interlock

The current in the injection septa (MSI) are presently protected against fast changes by the Fast Magnet Current Change Monitors (FMCM) interlock. The current value itself is protected by the SPS power converter hardware interlock (FEI) which is based on the measured current and calibration tables. Due to the lack of passive protection elements downstream the MSI it was deemed important to monitor and interlock the MSI current by the BETS. To keep modifications on the BETS side to a minimum, the present MSI power converter electronics will be replaced by an FGC LHC power converter electronics. This also allows to easily synchronise foreseen de-gaussing cycles of the MSI with the LHC ramp. The MSI power converter will be linked via fiber optics to the BETS. The BETS transfer function translates the current into an energy value; on the BETS side it is checked if the current stays within its limits corresponding to a 1-σ trajectory oscillation and the energy within 450±1 GeV.

The same argument of missing horizontal passive protection elements holds for the strong bending magnets at the end of the transfer lines downstream of the TCDI collimators. Extending the BETS interlock on these magnets shall be envisaged.

MKI UPGRADES

Prior to LS1 only 15 out of 24 screen conductors were installed, in the LHC injection kicker magnets (MKIs), to avoid flashovers. The 15 conductors were arranged such that the ferrite is screened and - in order to reduce the flashover probability - the lower part of the chamber close to the high voltage bus bar was left without screen conductors. In this configuration most of the MKI magnets had a power deposition of 70 W/m; a value which - known from operation in 2012 - does not limit injection. However, the MKI8D magnet had a power deposition of 160 W/m which limited injection between high-luminosity fills due to extended waiting times to let the ferrite yoke cool down. The increased heating in the MKI8D originated from twisted conductors. The beam screens of all 8 MKIs have been upgraded during LS1. The outside metallization has been removed from the ceramic tube starting about 20 mm before the open-circuit end of the screen conductors. A conducting metal cylinder with a vacuum gap of 1 – 3 mm to the ceramic tube has been added. These modifications allow all 24 screen conductors to be installed: in addition

the predicted maximum electrical field, on the surface of the ceramic tube, with 24 screen conductors installed is 40% less than was the situation for the 15 screen conductors pre-LS1.

Figure 7: Improved MKI beam screen with 24 graded length conductors and a conducting metal cylinder with a vacuum gap of between 1 to 3 mm to the ceramic tube.

Figure 8: Ceramic tube with 24 screen conductors in slots.

Figure 9: Longitudinal beam coupling impedance for different numbers of screen conductors in the MKI. Courtesy H. Day.

The 90º twist of the conductor slots, in the old MKI8D, along the length of the ceramic chamber, orientated the 9 screen conductor gap, at the downstream end of the MKI8D, from the high voltage bus 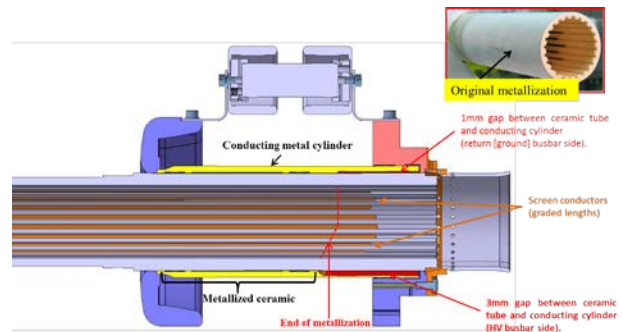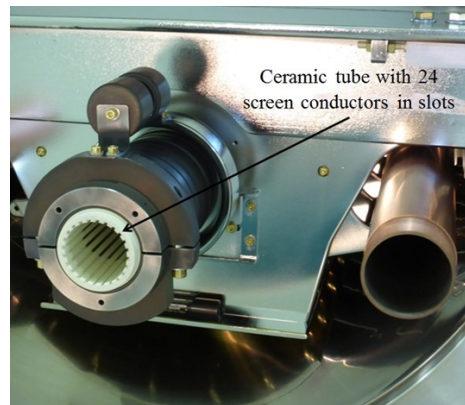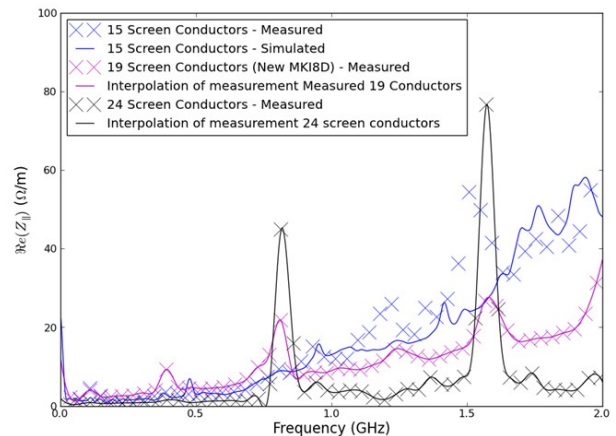bar to the ferrites, and therefore caused increased heating of the magnet yoke, especially at the downstream end. The newly manufactured ceramic tubes are carefully inspected to ensure that they do not have a twist: however a twist of the conductor slots, with the now installed full complement of 24 screen conductors, would not have a significant effect upon yoke heating. The expected power deposition after LS1 is approximately 50 W/m, thus, heating of the MKI ferrite yoke is not expected to limit injection.

In order to increase the emissivity of each MKI vacuum tank ion bombardment of the tank, in an atmosphere of argon and oxygen, has been performed, Fig 10. However the initially very promising results of samples could not be repeated for the actual tank due to limitations on the treatment temperature. Hence the emissivity in the range of wavelengths of interest was not improved. However, even without increased emissivity of the MKI vacuum tanks, the power deposition after LS1 (approximately 50 W/m), is not expected to limit injection. For the future, indirect cooling of the ferrite yoke by adding cooling channels is very difficult due to the brittleness of the ferrite: in addition water cooling is not compatible with the high voltage and vacuum demands.
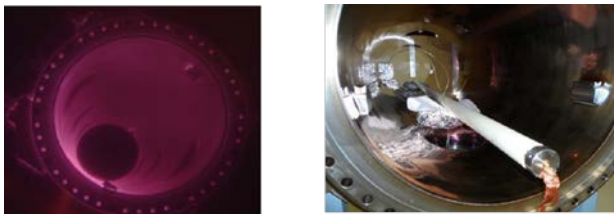
Figure 10: MKI tank during ion bombardement in Argon and Oxygen atmosphere (left) and after the bombardment (right).

Another option under investigation is to significantly reduce the surface area of a plate below the ferrite yoke to improve radiative heat transfer between the ferrite yoke and tank.

In order to validate the high voltage performance of the MKI magnet with the full complement of screen conductors the magnets have been tested up to 56.4 kV pulse forming network (PFN) voltage (nominal at Point 8 is 51.3 kV): as expected from predictions the flashover performance is even better than for the originally installed screen with 15 conductors. Tests of the beam screen have also been carried out outside the magnet, with background pressure of neutral hydrogen in the

range of $1 \cdot 10^{-9}$ to $1 \cdot 10^{-7}$ mbar. The test setup will be modified such that the injected hydrogen gas can be ionized during the tests, to better represent the effect of the beam in the LHC.

Other upgrades to the MKIs during LS1 include increased emissivity of clamps and corona shields for the damping resistor of toroidal ferrites. V2b RF fingers were installed and the by-pass tubes NEG coated. In view of dust particles creating beam loss (UFOs), improved cleaning of the ceramic tube has given a substantial reduction of dust particles relative to the MKI8D installed during the technical stop 3 (TS) –, 2012 – which itself was a lot better than the pre-TS3 MKI8D; During the LS1 upgrades, the ceramic chambers have been flushed with high pressure nitrogen and the dust particles captured in a filter: subsequently the number of dust particles in the filter has been estimated by the CERN material and metrology section (EN-MME-MM). The MKI8D installed during TS3 in 2012 resulted in $390 \pm 47 \cdot 10^6$ particles after flushing and this unit showed low UFO occurrence in beam based measurements; with the new cleaning procedure the number of particles is reduced by another factor of 20 – 40, thus, the occurrence of UFOs in the MKI magnets should be significantly reduced after LS1.

Further upgrades nearby the MKIs during LS1 include NEG coating of beam position screens and timing modules (BTVSI and BPTX) and installation of NEG cartridges on the cold-warm transitions and MKI interconnects.

There are ongoing studies of chromium (III) oxide (Cr_2O_3) and amorphous carbon coating of the ceramic tubes. Cr_2O_3 coated samples from industry were obtained and some of these were measured to have a peak secondary electron yield (SEY) of less than 1.4, after some conditioning, which is the critical value for the electron cloud build-up for the MKI geometry, Fig 11. For comparison the naked ceramic of the tube has a peak SEY of 6-10. A contract has recently been placed in industry to develop the application procedure of the Cr_2O_3 coating for a 3 m long ceramic tube.

A 50 cm long ceramic tube has been coated with a thin layer (200 nm) of amorphous carbon and resulted in an SEY of 1.25 – 1.5; this increased value compared to the expected SEY of 1 originated from uncoated parts in the measurement area, e.g. the sample holder. The tube will be high voltage tested in the near future.
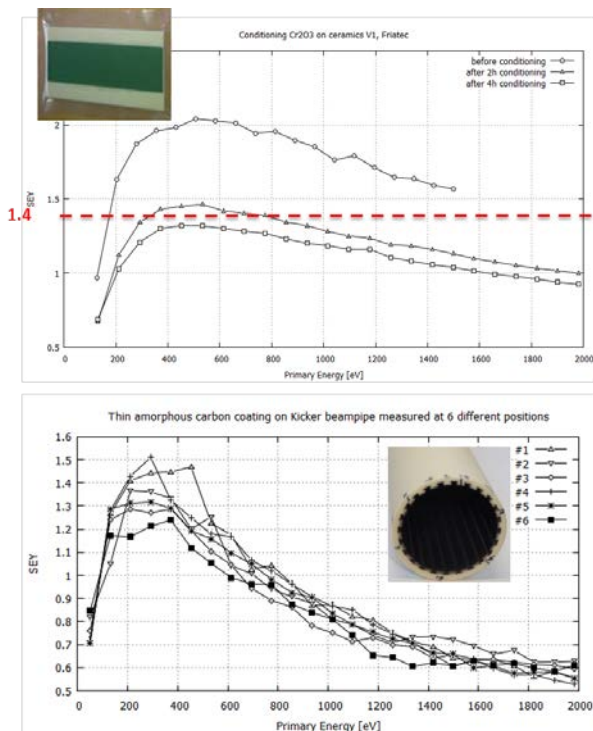
Figure 11: Secondary electron yield of Cr_2O_3 coating (top) and amorphous carbon coating (bottom). Courtesy M. Mensi.

MODIFICATIONS OF THE BLM SYSTEM

The motivation to modify the beam loss monitoring (BLM) system in the injection region originates from avoid- able beam dumps at injection. Loss showers from the transfer line collimators (TCDI) hit from the outside of the cryostat the sensitive LHC loss monitors where the tunnels of the transfer lines TI 2 and TI 8 merge with the ring tunnel. Even if higher dump thresholds were acceptable in this region at injection energy, the saturation level of the ionization chambers presents a limit. To overcome this dynamic range limitation, little ionization chambers (LIC) were tested and after validation installed. They allow to move the upper dynamic range limit by a factor 10 compared to the standard ionization chambers (IC). For the new monitors the threshold limit can be overcome if the higher thresholds are accepted during the time the machine is at 450 GeV injection energy. The new monitors are installed such that redundancy between the well tested ICs and the new LICs is kept. The ICs where higher thresholds would be required to keep machine availability at injection, are connected to blindable crates. These crates will have the possibility to receive a timing signal and accordingly blind out the interlock input at the moment of injection. The criterion to select monitors which shall have the blind out possibility is a factor 5 margin between the operational loss level and the dump thresholds. Also, the expected loss levels should be within a reasonable signal to noise ratio. The loss levels which entered the analysis considered operation with TCDI half gap openings of 4.5 σ. Since the measured LHC aperture was larger than expected, the TCDIs were opened by 0.5 σ to reduce the number of unnecessary dumps at injection. The future TCDI opening depends on the available aperture after LS1. During LS1 two new processing crates were installed, one per injection point, and the cabling was modified to route all blindable monitors to those crates. The next steps are the FPGA development, the setting up of a test bench, the verificaton of the system in the laboratory, and eventually machine protection tests with beam in the machine when the new firmware will be deployed. The machine protection commissioning of the new firmware requires several pilot beam injections per beam validation two functionalities:

- Interlock inhibit:

    - Close injection protection collimator
    - Inject pilot
    - Check that the interlock of dedicated crates is inhibited and only that

- Energy check:

    - Disconnect timing cable from CISV on BLM crates of P2 and P8 surface (i.e. energy level fall to 7 TeV)
    - Inject again pilot
    - Check that dedicated crates' interlock request is not inhibited

If the new firmware will be ready for tests in the machine right at the startup or after a technical stop will be addressed in the LHC machine protection panel (MPP).

DEDICATED LHC FILLING

The LHC filling time could be reduced by optimising the supercycle composition [2]. Presently the supercycle has a length of 43200 ms of which 21600 ms are used by the LHC cycle. To the time of the LHC cycle one has to add 5 basic periods for beam production in the injectors and the LHC Injection Quality Check (IQC) wich corresponds to 6000 ms. This results in a minimum dedicated LHC filling supercycle length of 27600 ms and a potential reduction of 15600 ms. This difference will be smaller in 2015 due to the stop of CNGS. A shorter supercycle of about 36000 ms is expected, so the possible supercycle length reduction is 8400 ms. A drawback of a dedicated LHC filling is the uncertainty in the effective filling time which can vary between one to several hours. This could be a problem for injector experiments with a rigidly scheduled beam time.

SPECIFIC COMMISSIONING TESTS

During the long shutdown several machine components were exchanged or adjusted and require specific testing. The SPS and parts of the transfer lines were realigned and therefore the SPS extraction channel aperture will be scanned to check for obvious aperture limitations already during the sector test. A proper scan of the extraction bump and available apertures for the extracted and circulating beam will be done as soon as the same cycle is available as for operation during beam commissioning. The SPS extraction kicker (MKE) waveforms will be scanned carefully to find a representative position to place the intermediate intensity bunch trains which are used for steering the transfer line trajectories. A kick response measurement is foreseen for both transfer lines and their adjacent LHC sectors to identify wrong polarities of correctors and beam position monitors and to verify the dispersion matching from the transfer lines into the ring. Similarly to the SPS the injection apertures will be scanned coarsely during the sector test together with orthogonal steering tests in the injection region. The above mentioned modifications of the MKI magnets together with adjustments of the damping resistor require to re-measure the MKI waveforms. Also the two new BETS interlocks for the MSI current and the TDI gap interlock will be tested in addition to the standard commissioning procedures. All tests mentioned in this section can be largely covered during the sector tests depending on beam availability. The commissioning of the blindable crates for BLMs can be done the earliest during beam commissioning.

CONCLUSION

The trajectory stability of TI 2 and TI 8 was dominated during run 1 by the voltage ripple of the SPS extraction septum power converter. After LS1 gentle improvements can be expected for the TI 2 stability due to an optimised filter gain and in TI 8 due to a repaired DCCT.

Major changes to the beam screen of the TDI shall mitigate the experienced issue due to beam induced heating. Foreseen coatings need further investigation, the presently installed jaws have either Ti or no coating. Installation of a TDI spare in the 2015/16 end of the year stop could be envisaged if the bake-out time is compatible with the planning.

A redundant TDI gap interlock based on interferometry which is connected to the BETS is being developed and should be ready after a six month testing period on the spare TDI. Presently the existing LVDT measurement will be used as input for the BETS.

Also the MSI current measurement will be connected to the BETS since no passive protection is in place in the horizontal plane. Extending this interlock

upgrade shall be envisaged also for the strong bending magnets at the end of the transfer lines right downstream the transfer line collimation.

The MKI8D heating problem is solved; many upgrades concern better heat transfer, reduction of dust particles and improved vacuum levels. Studies on improved tank emissivity, indirect ferrite cooling and coating of the ceramic chamber are ongoing.

The necessary hardware to route selected BLMs to blind- able crates is installed. Tests in the lab and with beam are defined while the deployment strategy remains to be clarified.

Dedicated LHC filling would allow to reduce the super-cycle length from 36 to 28 s. It could have a negative effect on injector physics scheduling.

Realignments of big parts of the machines and many upgrades of the hardware require several additional measurements for the startup. A big part of these measurements can be done during the sector tests.

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LHC BEAM DUMPING SYSTEM
STATUS AND READINESS FOR LHC RUN II

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Abstract

The hardware status of the LHC Beam Dumping System (LBDS) after the many announced system improvements performed during Long Shutdown 1 (LS1) will be presented. The latest estimates of expected availability and reliability of the LBDS after LS1 will be summarized. The readiness of LBDS for LHC start-up, including the progress of the reliability runs, as well as the commissioning plan will be discussed. A list of the tests with beam required to validate the system after LS1 will be proposed.

INTRODUCTION

During past operation of the LHC, all requested beam dumps were executed correctly and no damage to the accelerator related to the LHC Beam Dumping System (LBDS) occurred [1, 2]. But the repairs to the interconnections of the LHC main dipoles, taking place during the present Long Shutdown 1 (LS1), will allow increasing the beam energy of the LHC from 4.0 TeV to approximately 6.5 TeV from 2015 onwards. This increased energy means higher operational voltages of the LBDS generators and could have a negative effect on the operational availability and safety. Modifications applied to the LBDS, with the aim of maintaining the good results mentioned above, are detailed in the following sections along with the re-commissioning plan to assess the good shape of the system after the many upgrades performed.

STATUS OF UPGRADES PLANNED FOR LS1

Addition of MKBV E&F kicker magnets

Two vertical dilution magnet (MKBV) tanks were not installed for LHC Run 1 in a manner to spread the costs as well as the preparation and installation time, the vertical dilution being strong enough with four tanks per beam for the operation limited to 4 TeV.

During LS1 the remaining two vertical dilution magnets and their high-voltage (HV) generators were installed, so we will have the nominal dilution for LHC Run 2.

All the dilution kicker magnets (MKB) tanks are now being slowly conditioned up to their nominal current.

Vacuum reading problems

During LHC Run 1, a lot of problems with the reading of MKB tanks vacuum occurred, so we had to mask the analog interlocks during almost the whole run. Vacuum team is taking this problem seriously: MKB vacuum gauges were replaced, and then investigation for regular vacuum spikes problem was started. The problem seems to be a real vacuum spike and not a control noise issue. As the problem is not visible anymore during LS1, investigations will have to continue at LHC startup, if the problem reappears.

TE-ABT anyway made the decision to definitively remove the redundant analog interlocks, and so to rely only on the digital interlocks from the vacuum systems, as it was initially planned.

MKD HV generator FHCT switch renovation

The HV generators, that power the extraction (MKD) and the dilution (MKB) kicker magnets, use HV Fast High Current Thyristors (FHCT), semiconductor switches assembled in stacks of ten to sustain the high voltage.

Before the start of LS1 was discovered a problem of electrostatic discharge on the two switches installed inside each MKD HV generator. This electrostatic discharge regularly yields to a self triggering of the switch, which would result into asynchronous beam dump. The operation of the LBDS was therefore limited to 5 TeV.

The adopted solutions consisted in the use of new materials with increased radius for insulating pieces, and the insertion of new insulators between every FHCT of the stack and the return current rods [3].

Moreover, these switches are sensitive to Single Event Burnout (SEB), due to the presence of high energy hadrons (HEH) leaking from the tunnel into the service galleries. A SEB could also provoke a self-triggering of the switch, and so could result in an asynchronous beam dump.

After several measurements of SEB cross-sections of the two FHCT families used in operation were made, a significant sensitivity difference of a factor larger than 50 was observed, and the family of switch the most sensitive to radiations was replaced during LS1 [3]. This should reduce the probability of a SEB-related dump to less than one per year (for an HEH fluence of 10^5 HEH/cm^2/year).

The huge work for the renovation of the 80 sacks in operation already started during LHC Run 1, and one or two generators were exchanged during every technical stop. The work was finished during the first months of LS1.

Increase of PTU voltage

Modifications were made to the Power Trigger Units (PTU) that trigger the FHCT switches, with the aim of increasing the trigger current, as well as reducing the SEB probability of the PTU HV switches [4]. The PTU HV

power supply was upgraded from 3 kV to 4 kV, and the PTU HV switches were replaced accordingly.

During Run 1, the use of two FHCT families and the low trigger current forced us to use a variable PTU voltage vs. energy specific to each generator. This resulted in a long switch synchronisation procedure, and a complicated management of the PTU voltage reference tables. The tests with an increased PTU voltage and a single FHCT family resulted in a lower dispersion of switching times, which would make possible the use of a unique constant PTU voltage of 3500V for all generators.

The 80 PTU crates in operation have been reworked during the first months of LS1 and are now operational.

TCDQ – Absorber reinforcement

At the beginning of LS1, the previously installed TCDQ systems were removed from the LHC. Subsequently, additional space was made available upstream of the original location for the installation of the upgraded TCDQ absorbers [5]. The new TCDQ was extended from 6 m to 9 m, and the absorber material changed for a sandwich of graphite and Carbon Fibre reinforced Carbon (CFC) to be compatible with future HL-LHC beams. A 10.6 m movable girder was installed, upon which are located the three vacuum vessels that contains the absorbing elements. New 'large displacement' vacuum bellows connect each movable TCDQ system to the LHC beam pipe.

At present, both TCDQs (for beam 1 and beam 2) are installed, aligned and under vacuum.

TCDQ – Control consolidation

As a result of the study held in 2009 [6], that identified a common mode failure of the PLC CPU which provides both position control and supervision, the TCDQ control system will be consolidated. The main change is the dissociation of the Motor Drive and Control (MDC) and Position Readout and Survey (PRS) modules into two separate functional entities, each one based on an independent PLC, see Fig. 1.

The LVDTs used for the position measurements were replaced by potentiometers. Two potentiometers were installed above each other, attached to the girder at the same longitudinal position at the entrance and exit of the absorber blocks, to avoid the introduction of errors between the read-outs. These potentiometers are used for the remote displacement system (one for regulation and the second one for the verification).

The hardware is ready, and is being installed in the LHC. The remote displacement tests are planned later in 2014.
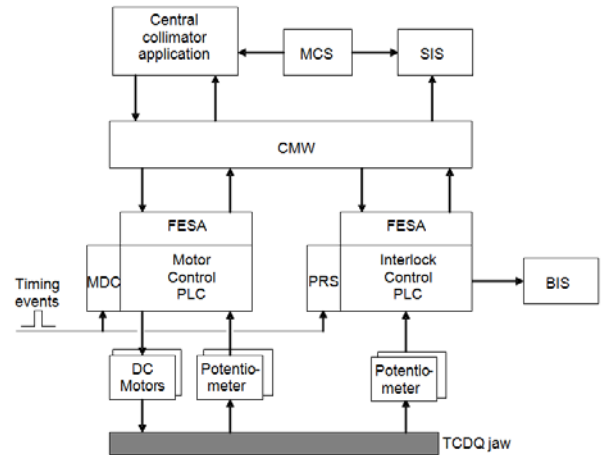
Figure 1: New TCDQ software architecture: separation of MDC & PRS functions

TCDQ – Beam Energy Tracking System

To add redundancy to the PRS, a Beam Energy Tracking System (BETS) [7] is being implemented for the surveillance of the correct position of the TCDQ jaw w.r.t. the beam energy. The jaw positions are measured thanks to two potentiometers installed on each side of the girder.

This BETS will be connected to the LHC Beam Interlock System as an additional maskable channel and will request a beam dump in the case an incorrect TCDQ position is detected.

Shielding of cable ducts between UA and RA

Now only the cable ducts in front of TCDQ are filled with iron rods. During LS1, all the cable ducts between UA and RA in front of MKD and TCDQ systems will be filled with iron rods to diminish then radiation level in UA, mainly due to TCDQ scattering.

This work has not been planned yet.

Improvement of Power Distribution Architecture

Following the LBDS powering review held in 2012 [8], lots of improvements will be perform on the LBDS power distribution. The LBDS was directly connected to a second UPS located in US65, and every crate Power Supply Unit (PSU) is powered through an individual circuit breaker. The monitoring of the state of all the redundant PSUs of LBDS crates is now performed, and the Software Interlock System (SIS) will request a dump in case a failure is detected in a PSU.

A Power-Cut test is still to be performed, with F3 and F4 circuits OFF simultaneously. The test is not planed yet. To be noted that the same test was already performed successfully in September 2013, after LHC Run 1.

TSU v3 Development

Following the operational experience gained during Run 1 of the LHC, the external review of the Trigger Synchronisation Unit (TSU) card design performed in 2010 [9], the internal review of LBDS Powering

(2012) [8] and the identification of a possible common mode failure scenario at the level of the distribution of the +12V inside the unique crate containing the two TSU cards, a new design of the TSU card has been carried out, and the new hardware will be installed within the LBDS during LS1.

In order to avoid the +12V common mode failure, the two TSU cards are now deployed over two separate VME crates. A third VME crate will contain the shared RF and BI hardware. A surveillance of all internal voltages was added to the TSU card itself, hence the redundant card will trigger in case the first one loses one of its power supplies. Additionally, an internal continuous surveillance of the CRC of all the TSU programmable logic circuits (FPGA) has been implemented. In case of a Single Event Upset (SEU) corruption of one of the programmable circuits, an incorrect CRC will be detected and a dump request will be issued to the redundant TSU through a dedicated channel. The on-board diagnosis functionalities have been significantly improved, such as the surveillance of the output current of the synchronous beam dump trigger signals, and many additional TSU internal signals will be acquired and analysed by the Internal Post Operational Check (IPOC) system [10], such as all the redundant dump requests from all the various clients.

The hardware prototypes were validated and a production of twelve cards was done.

The firmware development is still in progress. It is foreseen to have two main development steps: A first one limited to porting the TSU v2 firmware on the TSU v3 hardware, the second step would support the new TSU v3 hardware capabilities and diagnosis features.

If the first firmware is not operational in July, we might have to fall back to the TSU v2 version, but deployed over two crates anyway, which implies the development of a new VME backplane to interconnect the two TSU cards.

Direct connection from the BIS to the LBDS Retrigger-lines

It was noted that the beam dumping system is very sensitive to any unidentified failure mode of the Trigger Synchronisation and Distribution System (TSDS) [11]. In case of failure of the TSU, and despite the large redundancy within it, any external beam dump request of the Beam Interlock System (BIS) would not be executed. To reduce this sensitivity, a direct link is established between the BIS and re-triggering system of the LBDS [12]. The new link between BIS and LBDS consists of an electronic board (CIBDS) that follows the same principle as the board mounted on the TSU (CIBO): It is included in the optical loops, and generates a dump request when it fails to detect the Beam Permit.

In normal operation, the dump trigger is issued by the TSU synchronously with the beam abort gap. To cover a possible failure of this synchronous trigger, an asynchronous dump request is also systematically generated by the TSU. As up to 90 µs (one beam revolution) can be necessary to trigger a synchronous dump, the asynchronous dump request is delayed by 200 µs using a Trigger Delay Unit (TDU). The CIBDS generates an additional asynchronous dump request, delayed by 250 µs, using a TDU of 250 µs (TDU250).

The 2 CIBDS cards, along with the 4 TDU250, were installed in the LHC and connected respectively to the BIS and the LBDS re-trigger lines.

Software upgrades

During LS1, BE/CO performs major upgrades to the control software systems. The most important change is the new Front-End Software Architecture v3 (FESA3), using a new communication layer Remote Device Access v3 (RDA3). As a consequence we have to adapt most of our control software to these new frameworks. The development of FESA3 and RDA3 was being delayed a lot, so our migrations are not going as fast as expected.

The only fully migrated system in operation at LBDS is the State Control and Surveillance System [13]. Some systems are under test in the laboratory, such as the TSU-VME diagnosis and the IPOC system. But the migration of the BETS and the development of the new control system of the TCDQ MDS&PRS, are still to be done.

Moreover the addition of MKBV E&F and the increase of operational energy above 5 TeV imply numerous changes in the PLC software, the LBDS Analysis & Calibration tools [2], and the eXternal Post Operation Check (XPOC) analysis system [14].

All software upgrades are planed to be finished by the end of summer.

AVAILABILITY & SAFETY ESTIMATES

LBDS Safety & Availability Study Projects

Before the start of LHC, a Ph.D. thesis was conducted at CERN on the LBDS dependability analysis [15]. This study predicted the LBDS to be SIL 4, and a number of 8 ± 2 false beam dumps and 2 asynchronous beam dumps per year. It was based on Time-To-Failure (TTF) data from manufacturer or military handbooks.
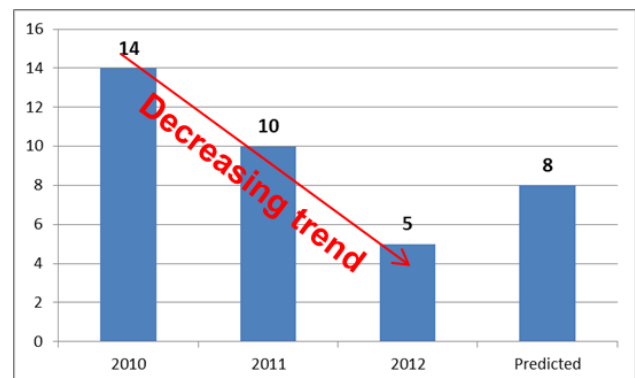

Figure 2: Number of false beam dumps observed vs. predicted

After LHC Run 1, a mandate was given to the same expert to update the model, based on operational fault statistics [16]. 139 failure events, of which 90 were internal to LBDS, were collected from LHC-OP and TE-ABT logbooks for the period 2010 – 2012. They were then classified and identified to a failure mode.

The updated LBDS safety model predicts a **SIL3** safety level at least, which is more conservative than predicted in 2006, because of the contribution of new failure modes, but nevertheless still acceptable. Predicted rate of asynchronous and false beam dump are not changed. All statistics, including availability and safety, show a positive trend, which attests an improvement in operation, see Fig. 2.

Safety Margin & Safety Gauge

The absence of any major catastrophic event is a necessary but not sufficient condition to assess that the LBDS meets SIL3 at least. A new approach consisting of the computation of a safety margin value after every beam dump is proposed: How far from a single point of failure were we during the last dump execution? A new metric, based on the reliability model, must be defined to estimate the distance to a single point of failure after every dump.

This new metric could also help to balance safety and availability: Is the system protected or over-protected?

In case of nominal beam dump, the system is expected to be fully available or in an acceptable degraded state.

In case of false beam dump, the internal dump must be justified so the safety margin is expected about to be eroded, otherwise the LBDS is certainly overprotected.

It was suggested that the quantification of the safety margins is be performed after every beam dump, and displayed using the safety gauge on LBDS Fixed Display, see shown on Fig. 3. This would give system experts and EIC valuable information to take decisions on the LHC operational conditions to accept.
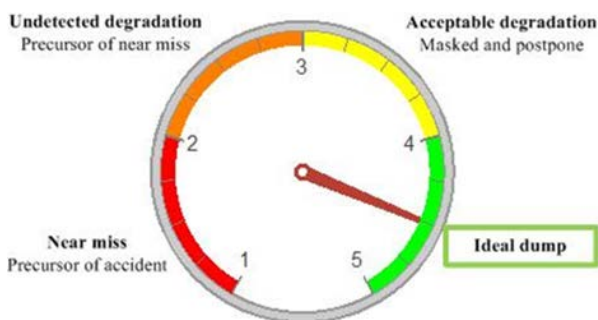
Figure 3: The Safety Gauge shows the safety margin for an normal dump

Direct Connectionfrom BIS to LBDS Retrigger-Lines

A detailed reliability analysis of the CIBDS card and the TDU250 box was performed in order to ensure the LHC safety increase, without significantly reducing its availability [17].

The specification was to not add more than 1 asynchronous dump per beam over 10 years, and no more than two synchronous dumps per beam per year.

The study predicts about 0.025 asynchronous dump for both beams over 10 years and 0.01 false synchronous dump for both beams per year. So the impact of the new direct connection from BIS to LBDS Retrigger-Lines on LHC safety and availability is negligible.

FIRST RELIABILITY RUN RESULTS

Spontaneous Triggering of MKD HV Generators

After the MKD HV generator FHCT switch renovation discussed above, we started the first LBDS reliability run with the aim of validating their sustaining to a voltage corresponding to 6.5 TeV for long periods (> 8h).

We discovered that some generators where still experiencing erratic triggering: 2 generators on LBDS beam 1 (08.2013) and 6 on LBDS beam2 (11.2013).

After month of investigations, we found a workaround consisting of the addition of resistors on the trigger path of FHCT stacks, reducing their sensibility to electrostatic discharges.

One source for the electrostatic discharge was traced back to be insulating tubes in the upper part of the HV generator that get charged slowly due to their geometry and surface properties, and eventually discharges through the top FHCT A-G capacitance.

A new production of insulating tubes was launched, and 20% of the tube will be tested in laboratory before their installation into all LBDS generators, planned for end of July.

We will continue to explore the limits of electrostatic discharges due to the geometry of insulating parts using a 'dummy' generator (where all sensitive electronic parts are remove), operated under a much higher voltage to increase the rate of spike events.

MKB Conditioning

The conditioning of MKB magnets has started. MKB Beam 2 is conditioned up to 7.1 TeV. The vacuum is in good shape (< 4e-7 mbar). MKB Beam 1 recovered well from aluminum foil pollution, and is presently at 6.6 TeV, also to be conditioned up to 7.1 TeV.

LBDS is ready for operation above 6.5 TeV during upcoming dry runs.

FIRST DRY RUN RESULTS

LBDS Armed in REMOTE

The LBDS was configured for operation in REMOTE: The local BIS loops were installed at LHC Point 6, the BETS was connected to a signal generator to simulate the LHC bending magnet currents (BETS-Simulator), and the Beam Revolution Frequency (BRF) was generated locally using a timing card.

The LBDS was successfully armed at 450 GeV. As the MKBs were not yet conditioned, we could not go above.

After updating the LHC sequencer logic, we successfully controlled the LBDS remotely, and executed arm & dump sequence in loop.

The LBDS will be ready for remote dry runs, as soon as the MKBs conditioning will be finished.

Direct Connection from BIS to LBDS Retrigger-Lines

The CIBDS cards were installed at LBDS, along with their TDU250 connected to the retrigger lines between the MKDs and MKBs.

An Internal Post Operation Check (IPOC) system acquires the retrigger pulse from the BIS on the retrigger lines after every dump, and will assess of its presence.

The first measures of this pulse showed that it is attenuated a lot by passing through the 15 MKD retrigger boxes, and fall from 24V at the output of TDU250 to less than 5V at the input of the IPOC. But this level is enough to be properly detected by the digital acquisition cards of the IPOC system, as Fig. 4 shows.
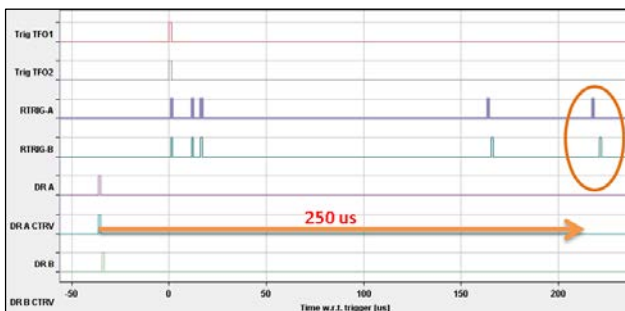
Figure 4: BIS-Retrigger pulses captured by the IPOC system, 250 us after the dump request from the BIS

We verified that, despite their low level, the pulses from TDU250 successfully trigger an asynchronous beam dump, thanks to the domino effect. This attenuation problem has to be further investigated.

UPDATED PLANNING

Six weeks of tests operated from the Central Control Room will start next week, with the BETS-Simulator and a local BIS loop, to test the new link between the BIS loop and re-triggering system, and the stability of the HV generators during many ramps and dumps.

Then 4 weeks of consolidation work on the LBDS generators are planned, to exchange all the HV insulating tubes and revalidate the generators afterward. The new TSU cards v3 will be installed in the LBDS during this period.

The LBDS will be switched to REMOTE again, for a period of minimum 4 weeks, to test the new TSU v3 cards, the HV holding of the generators for long periods, and the many renovated software components.

When the local BIS loops will have to be removed, at a date to be defined by OP and MPE, we will continue with reliability tests in LOCAL, to validate further more the system, until the beginning of the first sector test, planned for November 2014. To be noted that we would like to keep LBDS in REMOTE with the LOCAL BIS loops as long as possible.

COMMISSIONING

Considering the important changes being performed on the LBDS described above, a complete re-commissioning of the system is mandatory. In addition to the updated Machine Protection Procedures for LBDS [18, 19], the requested tests, with and without beam, described below should be performed.

Commissioning without beam

We request 2 days with the LBDS armed in REMOTE, with the BIS loops closed, to re-validate the hardware and all the software layers, re-check the arming sequences and the Injection Permit signals, test the Inject and Dump test modes, etc.

Commissioning with beam

We will need some time of LHC with pilot beams to re-synchronise the MKD rising edge with the abort gap of circulating beam, and the Beam Abort Gap Keeper (BAGK) with the injected beam, by adjusting respectively the TRIGGER and the BAGK delays on the TSU cards.

A scan of the MKD rising edge is requested as well, as it was never done before. The procedure for such a measurement is still to be approved. One complete run will be needed.

Also the BLMDD client of the TSU cards has to be activated. The procedure does not exist, and has to be defined and approved.

CONCLUSION

Although the LHC beam dumping system performed as expected during the LHC Run 1, an important list of system improvements are being implemented during the present long shutdown.

Unforeseen complicated problems of spontaneous triggering of high voltage generators were encountered, and long investigations were needed to identify a possible source. Consequently we are late on the original schedule, but fortunately we foresaw margin.

The LBDS will be in REMOTE, ready for dry runs, after the MKBs conditioning, estimated for next week.

A lot of changes have been performed on LBDS during LS1 so careful re-commissioning is mandatory.

All these modifications should allow the safe operation of the beam dumping system at higher beam energies.

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SOFTWARE PACKAGES:
STATUS AND COMMISSIONING PLANS

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Abstract

The many modifications of the software packages that have been done during LS1 will be reported. Based on the issues and requirements that have been presented in the 2012 Evian workshop [1], the solutions implemented and their impact on operation will be explained, the status of these different upgrade projects will be presented. Without doing a complete inventory of the control room applications, those with important functional modifications or presenting issues will be covered.

INTRODUCTION

During the three years of LHC operation, several issues and limitations have been discovered concerning the control system [1]. With the operational experience, new requirements have come out to optimize the operational procedures and improve the LHC performance. The LHC operation's schedule includes short technical stops during which such issues and requests are addressed. But due to the time constraint, the implementation has to be done fast, and only backward compatible changes are allowed. As a consequence, the new developments are not always implemented in the cleanest way.

The technology used by the LHC control system is frozen during the accelerator run, while outside the software world is moving fast, with new performant hardware replacing obsolete product, new libraries version with less bugs and new features, etc…

LS1 is the opportunity for all control systems to be refactored and cleaned. It is time to integrate the latest version of the third party libraries and implement the new requirements. The users have time to adapt to the non-backward compatible changes, and a testing period is allocated.

COMMON MIDDLEWARE [2]

The common middleware is composed of several modules that ensure and secure the communication from the control system to the hardware devices.

The communication layer Corba is facing technical limitations: this was a solution chosen 15 years ago and the software is not actively maintained anymore, this is a big risk for the project. In addition much better products

exist now on the market. After a careful evaluation, ZeroMq was chosen for Corba replacement.

Several issues were highlighted during beam operation with the RDA layer, in particular

- Insufficient protection against bad or slow clients: the subscription reliability affected, i.e. issue with the software interlock system subscriptions that lead to several spurious beam dumps.
- Poor client number scalability: stability issues when client number was above 200.

The new RDA3 layer, based on zeroMq, will provide a new subscription mechanism and a priority system for the clients. It also supports new data structures requested by the users like multi-dimensional arrays.

RAD3 has been integrated with the middleware libraries: new extension of JAPC and new CMW proxy for RDA3 server.

The JAPC core library has been improved both for RDA2 and RDA3 extension to solve the stability and performance problems.

Status

RDA3 is ready and deployed in operation for FGCD gateway in PSB and Linac2, the next deployment will be for the FGCD in CPS. In June FESA will have a new version based on RDA3. During the summer and until the LHC start-up, several equipment classes will migrate to this new version, and RDA3 should be deployed massively for the LHC operation. Nevertheless RDA2 will be maintained until LS2.

FESA3

The Front-End Software Architecture (FESA) framework is a comprehensive environment for equipment specialists to design, develop, test and deploy real-time control software for front-end computer. FESA 3 is the latest evolution of the tool and brings new features that will optimize the classes' development and maintenance. The major technical improvement is that the new version can handle the multicore CPUs.

Many critical LHC systems are planned to restart with FESA3 like QPS, cryogenic, power converters, kickers and collimators [3]. The equipment's responsible have already started the migration from FESA2 to FESA3.

Some systems like Beam Interlock System, RF and beam instrumentation will migrate later. FESA2 will be supported until the end of 2015.

LSA [4]

Core software

The LSA platform consists of a server, a database and an application suite used to operate particle accelerator and transfer lines. The development of LSA started ten years ago, based on SPS and LHC requirements. With operational experience, many requirements and fixes have been implemented on top of the first design. In addition LSA has been extended to the PS complex to renovate their control system, with necessary adaptations and additional functionality. The software modifications were applied in the context of running machines, with quick fixes and new features deployed during the short stops. The complexity of the API and design increased in such a way that it was difficult to stay flexible and add new functionality to the system.

During LS1 it was then mandatory to operate a major refactoring of LSA that would make it easier to maintain and extend:

- The software structure has been simplified with a reduction of the number of modules and a simpler package hierarchy.
- The services responsibility has been reorganised in a more coherent way, with less exposed methods.
- Common concepts have been factored out of LSA to a generic package for re-use by any software package (timber, applications…).

LSA Database

The LSA database had known performance problems in 2012 with the access of the settings. This was explained by the rapidly growing number of settings that doubled during 2012. The number of clients increased with the extension of LSA to PS complex, and some application needed frequent access to a lot of settings. Actions were immediately taken to optimize the data access, but their efficiency was limited by the huge amount of data and the hardware performance.

During LS1, the hardware has been replaced by a new CPU, a new disk and a bigger data cache that will provide a much faster access to the data. A data cleaning campaign has been started, only the last operational settings for each type of LHC operation will be kept (Pb/Pb, Pb/p,p/p), the rest will be deleted. A back-up database with data frozen on April 2013 is kept and will be accessible via 2012 LSA version in case old settings needs to be retrieved.

Status

LSA version has been released as pro in March 2014. All software using LSA needs to be adapted to the new API. This is not simple and trivial and can be time consuming, a web site is provided by the LSA support team to help the user. Today most of the operational applications have been adapted. Most of LSA software is being tested and debugged with the start-up of the injectors, and the dry-runs organized for the LHC.

Controls configuration database

With the migration to FESA3 and the upgrade of equipment, the device-types, the properties and fields and sometime device names are updated in the controls configuration database (CCDB). The LSA database configuration needs to be synchronised with the CCDB. In case of backward compatible changes or addition of new devices, this is trivial and the task will be automated soon. In cases of non-backward compatible modification on existing devices, this is more complicated when the settings need to be kept. A migration map that give the mapping between old and new configuration need to be given to the database responsible, and according to the complexity several iteration may be needed, this is not an immediate process.

RENOVATION OF CENTRAL TIMING [5]

The LHC central timing will be renovated during LS1. The front-end design will be simplified, only one front-end will be used instead of three. LynxOS will be replaced by Linux SLC5, and the FESA classes upgraded to FESA3 to handle the multi-core CPU.

A new communication protocol with the CBCM (central timing for the injector) will be designed for the injection request. It will be simpler, more flexible and robust. The limitation of 1.2s for the injection time in the SPS cycle will disappear. This will solve the dynamic destination issue encountered in 2012.

The protocol has been already implemented in the CBCM side. The new LHC central timing with the new protocol and new hardware will be deployed at the end of October 2014.

LOGGING

SDDS eradication [4]

Until LS1, the logging service offered two options: logging of data in the measurement and logging database

(Oracle) or logging of data in SDDS files. For maintainability and simplification reason, the SDDS logging will be eradicated. It is replaced by a full parameter logging that stores the same data in the measurement database instead of SDDS files. Parameter logging is ready and already configured for more than 8000 devices.

The SDDS logging is now disabled and no more SDDS files are generated by the logging process. Old data can be transferred in the logging database on demand.

Logging Data extraction API renovation

The logging data extraction API is the API used by timber application and more than one hundred other custom applications to extract the data from the measurement and logging database.

The actual API started to be developed 10 years ago, and has evolved a lot. Refactoring and cleaning was necessary to improve the flexibility and efficiency of the code and allow the addition of new functionality. The new API is under development and will include new features, particularly in the data analysis domain:

- Extraction of data from multiple sources, not only from the logging database but also from the LSA settings, the logbook, the post-mortem or new PVSS database.
- Possibility to store analysis results related to events in the past.
- Increase data aggregation and alignment options.
- Extracting data based on other signals
- Data value distribution analysis and histograms
- Extraction of vector elements over time as time series

DIAMON AND CONNECTION VIEWER

There is a recurrent complaint that the Diamon application doesn't always give the correct status of a process or a front-end. Most of the time, this is the consequence of a configuration problem. During LS1, Diamon software has been refactored and improved to facilitate the configuration of the front-ends, i.e. the limits for temperature, CPU load or memory can now be adjusted directly from the application. Nevertheless an effort is required from operation team and equipment owners to adjust the configuration to get reliable information on Diamon: the equipment owner has to be informed by operation team in case the process or front-end status is not right and act on the limits and detection points to solve the issue. The cold check out is the period to make sure that everything is well configured before the start-up.

To help with the front-end and process diagnostics and complete diamond information, a new application called "connection viewer" has been created. It retrieves and displays all the connections between CO processes.

ALARMS

The alarm screen has never been fully used in LHC operation, because with the actual alarms configuration it was permanently overloaded with yellow or red alarms with no direct meaning for LHC operation. A complete review of the alarms configuration would require a huge and time consuming effort from OP and equipment's group that one can't afford.

To improve the situation anyway, it was decided to remove all the alarms from the laser configuration for LHC-OP. Once the laser screen is empty, OP in collaboration with the equipment group and laser team will decide on the alarms that are useful for operation and add them to the LHC-OP configuration.

OTHER OPERATIONAL TOOLS

QPS software tools

The QPS software will be widely renovated after LS1, with a new set of java applications (QPS Swiss knife) for piquet and operation teams to perform basic and safe operations on the QPS. For example the power cycling of a QPS crate will be done by this tool, replacing the Labview application used during run 1.

The QPS settings management will be migrated to LSA, using standard LSA functionalities for storing and loading/cross-checking of parameters and settings in the QPS cards. That will allow improving the security by using RBAC and a systematic settings consistency check will be performed from the sequencer.

Accelerator test framework (ACCTEST)

The accelerator test framework is the software used for hardware commissioning tests and it is envisaged to be used in the future as well for machine checkout and machine protection system commissioning. In view of the large campaign of tests that have to be done after LS1, the software was reviewed and improved for better tests and analysis efficiency.

New analysis modules have been integrated directly in the Java framework. All sequences and analysis steps for the commissioning of the 60A and 120A circuits will be fully automated; the expert will be needed only in case of doubts or problems. Gradually the automated analysis will be extended to more complex circuits. This will represent a consequent gain of time and mean fewer dependability on the expert presence during the commissioning campaigns.

The new Java analysis modules are conceived in a generic way such that they can be run after any circuit failure and not only after predefined current cycles. This will allow a regular check of the circuits during beam operation, increasing the chance to discover problems early on.

Accelerator Statistics and Data Analysis

The accelerator statistics and data analysis project will provide a coherent and maintainable solution for accelerator statistics. The implementation will be common for all accelerators. New interactive web interface will replace the current statistic web pages for LHC, SPS and PS complex.

The project is well on track for the statistic part; already the PSB data is being collected. For the other machines the data specifications are on-going. The development of the web interface will start in July.

For the data analysis, the requirements have been gathered and will be integrated in the new logging extraction API. Further input and requests are welcome.

Accelerator Fault Tracking

The actual system for fault tracking is based on the logbook and the post mortem database. The tools tracks only partially the faults: as only the faults that triggered a beam dump are recorded, but not necessary the parallel problems that could be source of more downtime. Furthermore, there is no consensual rule defined between operation and equipment team. The fault analysis was then difficult and incomplete.[6]

The new Accelerator Fault Tracking project should provide better tools. It will be a common solution for all accelerators, it will automate the fault tracking as much as possible thanks to links with logbook, post mortem and logging databases. It will provide functionalities to highlight inconsistency or missing information and will greatly facilitate the follow-up, update and analysis of a fault.

A prototype database is already in place with the data from previous years uploaded from the logbook. The persistence API is under development. User interfaces mock-ups have been created and the use-cases definition is on-going.

Interlocks

The Beam Interlock System (BIS) has been refactored and cleaned. The fast cycling machines will get a new GUI with cycle related information. The BIS GUI will be extended to include the views developed aside by Jorg Wenninger and all their functionality like group masking, display of hidden interlocks etc…

The software interlock system (SIS) will be upgraded mainly to facilitate the interlocks configuration. There will be a new easier language for the configuration (DSL), but xml can still be used, and effort will be made on user documentation.

More powerful hardware will replace the existing for LHC and SPS instances.

Power Converter Interlock

The power convertor interlock is an application that checks the current of the LHC correctors and compares it to a reference. If the difference is greater than the tolerance, a software interlock is generated and the beam is dumped.

The actual system provides a fixed tolerance for each corrector that is not flexible enough. The tolerance ideally should be a function of time and be calculated as a function of the beam energy. LSA parameter will be created with makerules and value generators for these tolerances management.

Later, the PC interlock will be extended to other circuits than only the correctors.

Reference Orbit Management

In the actual system, a reference orbit for the steering the addition of:

- the base reference orbit obtained by orbit measurements and corrections with all the separation and crossing bumps at zero
- the overlays obtained by calculation with MAD of the theoretical beam positions for given optic and crossing and separation bump values

The overlays have to be calculated manually for each optic and bump values of each beam processes. This is a time consuming process that will become quite laborious if we run with combined ramp and squeeze or collide and squeeze beam processes. For the start up a new orbit management system will be developed that will automate the creation of the references using LSA information.

Console Manager

A new tool for the menus configuration will be implemented to replace the databases views, it will be easier to use. An automatic update of the CCM on each console will be put in place for the end of 2014,

On OP request a mechanism to show or hide applications according to the beam mode will be created. It will improve the operational consoles ergonomic.

Sequencer

During LS1, a huge campaign of tasks and sequences cleaning has been performed. The sequencer has been updated to give the possibility to assign external arguments to a sequence, i.e. a sequence to reset and restart a power converter will have the power converter name given online by the operator.

Online model project

The online project model has been taken over by ABP. The aperture measurement application will be reviewed for November 2014.

There are many ideas of tools using online model that could be useful for machine set-up and model improvements. The requirements need to be listed an prioritized and the resources gathered before concrete work can be started.

The knob and optic upload that are part of the online model project had been taken over by OP. A new GUI has been developed to facilitate the upload of new optics and the management of elements in LSA. It replaces old Perl script by a java API for the upload into LSA database, and has facility to compare MADX and LSA information.

Heat load display

The heat load will be a major concern for 25ns beam operation and its monitoring will be crucial to maximize the scrubbing efficiency.

A new display of the heat load is under development [7]: data are extracted from the logging database to compute the heat load. Timber is for the moment used for the display, but should be replaced by a proper fixed display in the control room before the start-up.

In parallel another display will be created, heat load will be computed using the bunch by bunch energy loss measurement from the RF phase.

CONCLUSION

During LS1, developers have been very busy to upgrade, refactor, renovate and add functionalities to the accelerator control software. At every software layer, LS1 was the opportunity for major modifications, and software engineers are still struggling to come back to a stable situation before the start-up of the accelerators. The injectors' start-up will be a major test of the new control system and most of the issues will be caught and solved. On the LHC side, dry-runs have already started, it will allow solving as much as bugs and issues as possible well before the start-up of the LHC.

As the long shut down is over for the injectors, LHC beam is not foreseen before 2015 and there is still a lot to do for the LHC control in the coming months, but no major problem is anticipated.

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LHC CRYOGENICS – PERSPECTIVES FOR RUN2 OPERATION

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Abstract

The first period of LHC cryogenic operation between 2008 and 2013 allowed gaining practical knowledge about the machine operational behaviour. The cryogenic system operation scenario for Run1 was defined and set regarding minimization of potential failures and energy consumption. Tuning of the cooling power in local cooling loops was adjusted according to the requirements for the heat extraction.

The Long Shutdown 1 (LS1), started on the beginning of 2013, allowed for maintenance, upgrade and necessary repairs on the LHC cryogenic installation focusing on preparation for post LS1 accelerator run.

In order to provide required cooling power, configuration of the cryoplants for Run2 will be set differently than for Run1, the available margins will change. The constraints imposed by beam-induced heating during scrubbing run or normal Run2 have been analyzed.

In case of installation failures, the critical spare components management will allow for direct replacement of faulty elements of the installation in most adapted time. The mitigation of failures can be also done by cryogenic plants reconfiguration, in some cases with impact on LHC beam operation scenarios.

INTRODUCTION

The cryogenic infrastructure built around LHC ring is composed of 8 cryogenic plants supplying 8 related LHC sectors. Four of the plants were upgraded from LEP cryogenic system and are supplying low load sectors, and four of them have been installed as new for LHC and are supplying high load sectors [1] (see Fig 1).
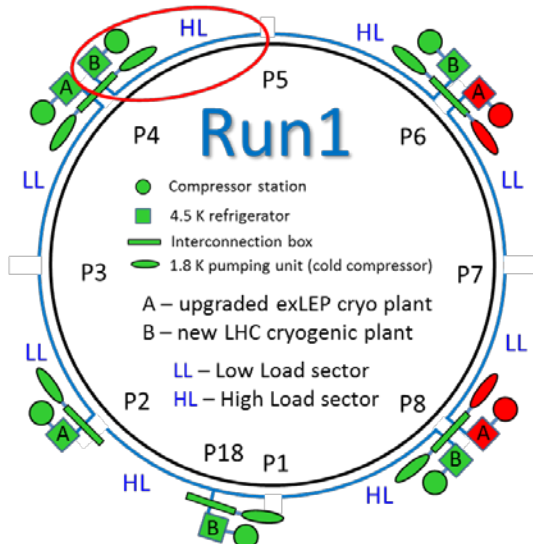
Figure 1: LHC cryogenic infrastructure.

The helium refrigeration process is ensured by considerable number of rotary machines (64 screw compressors, 74 expansion turbines and 28 cold compressors). The system provides cooling power for the magnets, RF cavities and DFBs with their 1258 current leads. The related control system drives ~4000 PID loops and consists of nearly 60000 I/O signals.

LHC RUN1 SUMMARY

The LHC Run1 allowed gaining operational knowledge about performance and requirements related to the cryogenic system. The Run1, with beam parameters lower than nominal, allowed for LHC operation with disabled cryoplants A at P6 and P8 (see Fig.1). The cooling power for both related sectors was provided by plants B. This configuration allowed for electrical power savings over all 3 years of operation between 10 and 20% with relation to the installed power (see Fig.2). The negative aspect of the configuration was longer recovery time at P6 and P8 after the failures. Such configuration was not applied nor at P4 because of additional heat load coming from RF modules neither at P18 because of non-standard configuration of the plants.
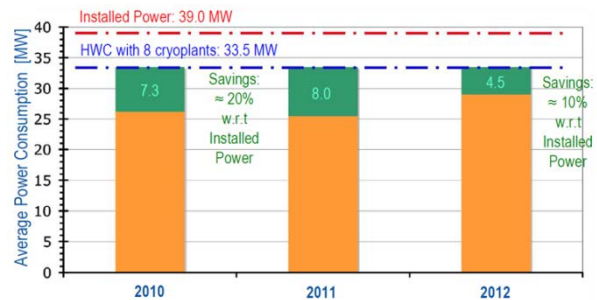
Figure 2: Power consumption and savings during Run1.

Thanks to collective effort in the cryogenic team the helium loses were reduced by factor of ~2 during 3 years of operation (see Fig. 3).
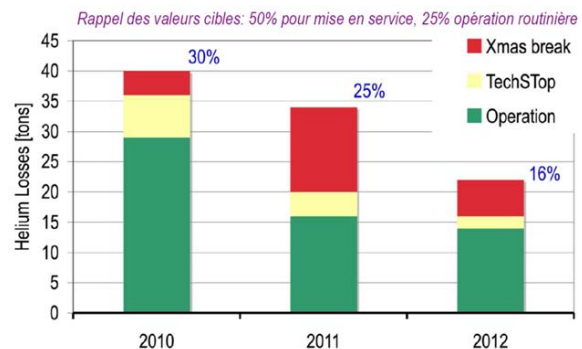
Figure 3: Helium losses reduction during Run1.

The cryogenic global availability for first 2 years of Run1 was equal to about 90% (see Fig 4). The significant impact of single event upset (SEU) was noted during increase of beam parameters in 2011. The problem of SEU and utilitiy failures were treated for last year of Run1 alowing to raise up the global availability to ~95%.
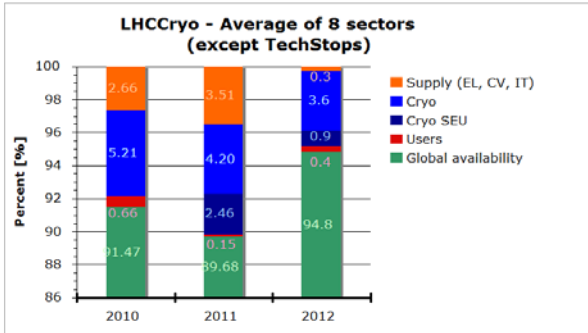
Figure 4: Cryogenic availability – Run1 summary.

MAIN LS1 ACTIVITIES

During LS1 multiple activities were performed on the cryogenic system. The main of them are listed below (see Fig. 5):

- The maintenance work was done on all helium compressor stations (major overhaul of the compressors and electrical motors),
- 4 leaks were repaired on 4.5 K refrigerators, the leaks have been declared during Run1 and warm up before LS1,
- 16 leaky QRL bellows were replaced, the leaks have been declared during the warm up before LS1,
- 2 DFB's gimbal bellows were replaced, the bellows were found deformed during the LS1 inspection,
- R2E campaign was performed in 4 LHC places to avoid excessive radiation to electronics during future LHC runs.

Also many other smaller activities, not visible on the large scale, were performed during LS1 with aim to higher the machine reliability.
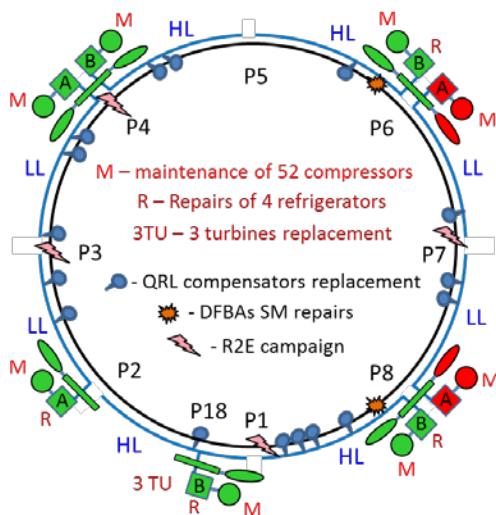
Figure 5: Main activities on cryogenic system during LS1.

RUN2 OPERATION SCENARIOS AND POSSIBLE REDUNDANCY

In order to guarantee required heat extraction from LHC during Run2 the baseline for cryogenic system operation scenario is to run all cryogenic plants (see Fig. 6).
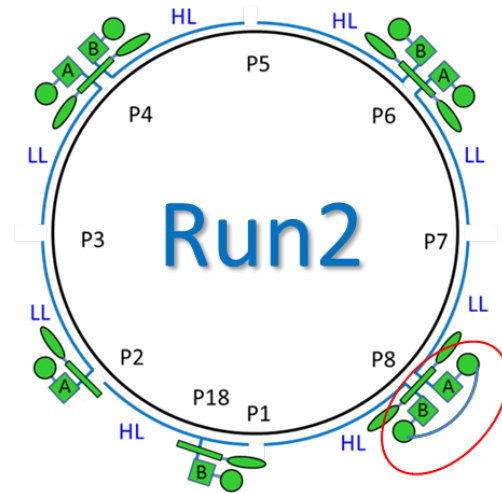
Figure 6: Baseline for LHC Run2 operation scenario.

Compressor station possible redundancy

Thanks to installed inter-piping connections between the cryogenic plants, the compressor stations A and B at P4, 6 and 8 can be linked together to profit from the existing helium flow global margin in case of any compressor failure (see P8 on Fig. 6 and Fig 7).
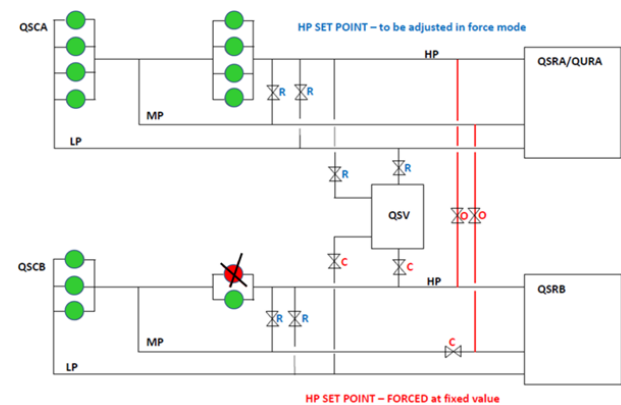
Figure 7: Configuration of linked compressor stations.

More difficult situation is at P18 and P2 where replacement of the faulty compressor has to be considered (except P2 low pressure stage). The available flow margins on low pressure stage (LP) and high pressure stage (HP), considering the biggest compressor lost, are presented in Fig. 8 (the analysis is done for the case of nominal cold box refrigeration capacity). The spares for each type of the compressors and related electrical motors are available at CERN storage and are ready to replace the faulty machines when needed.
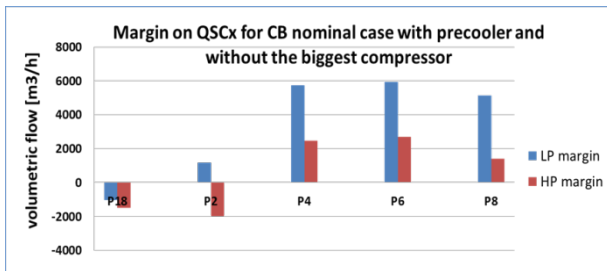
Figure 8: Helium flow margins for compressor stations.

Main LHC 4.5K refrigerators

The most fragile parts in the main LHC cryogenic refrigerators are the rotary machines – turbines. The analysis of possible redundancy and spare parts management lead to identify 3 categories of the turbines regarding associated criticality in case of failure. An example of the analysis for AirLiquide refrigerator is presented in Fig. 9.
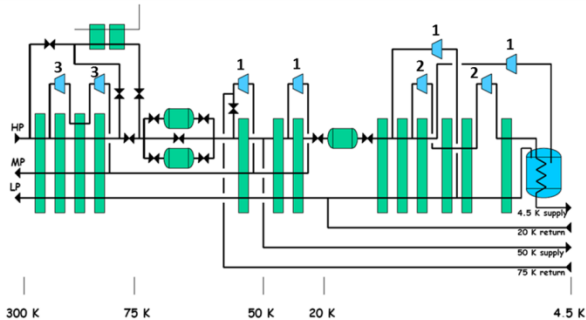
Figure 9: Air Liquide QSRB – turbines criticality.

- Category 1 (high criticality): Operation without the turbine results in a considerable loss in refrigeration power. All types of this turbines category are covered with available spares in CERN storage.
- Category 2 (moderate criticality): Operation without the turbine is possible with a moderate loss in refrigeration power. All types of this turbine category are covered with available spares in CERN storage.
- Category 3 (low criticality): Operation without this turbine is possible with nearly no loss in refrigeration power as the refrigeration power loss can be compensated with LN2. The special contracts signed with the suppliers allow for this turbine category repairs within 4 weeks while normal repair delay can take up to a few months.

Cold compressors – 1.8K pumping units

There are two types of 1.8 K pumping units installed on LHC. One of them is equipped with 3 and other with 4 cold compressors. The cold compressor is the most fragile part of the unit. The run of the unit without even one compressor is not possible, so in case of failure the faulty compressor has to be replaced to allow further operation.

All types of the compressors are covered by a spare available in CERN storage.

However, behaviour of the LHC machine shows lower than expected thermal load at 1.8 K. This fact let to presume that operation of two sectors with one pumping unit running together with two 4.5 K refrigerators should be possible during Run2 (see Fig. 10). The proposed scenario was never set up for operation and is to be tested before Run2. The operation in such configuration will require longer recovery times in case of failures but could be considered as a redundancy if needed.
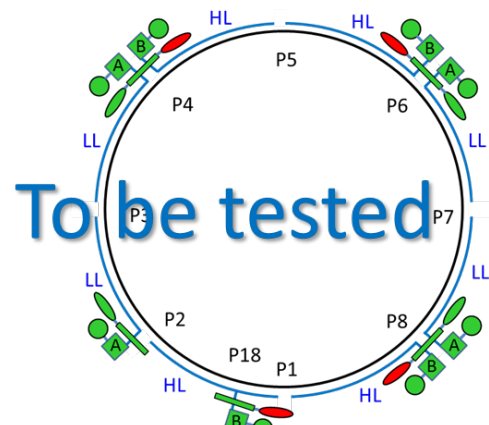
Figure 10: Run2 optional scenario with one pumping unit for 2 sectors.

Cryogenic plant major failure

In case of the major failure of a cryogenic plant at P6 or P8 the operation of the LHC will be possible with reduced beam parameters setting configuration from Run1 (see Fig. 11). Loss of cryoplant A has less impact on the cryogenic power than loss of cryoplant B.
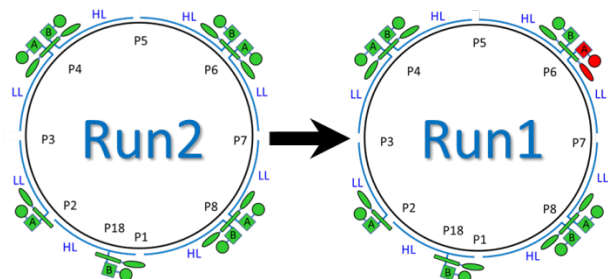
Figure 11: Example of operation scenario in case of cryoplant A loss at P6.

NON CONFORMITIES

There are currently two known non conformities present in the cryogenic system. Both concerns helium leaks specified below:

- Sector 8-1, internal leak on QRL header D, rate of 1.6 E-6 mbarl/s @ 10 bar, 1.4 E-7 mbarl/s @ 1 bar, localization at Q24R8 at dcum 24455 m,
- Sector 1-2, internal leak on QRL header C, rate of 1.7 E-5 mbarl/s @ 10 bara, pre-localized at ~Q13L2

QUENCHES AND RECOVERY

Until now experience for quenches recovery with current above 6.5 kA comes from before Run1 quench training campaign (already 5-6 years ago). The LHC Run1 experienced some "easy quenches" without opening of the quench valves (QV), with pressure rise in the cold mass below 15 bars. The analysis of the recovery after quenches was presented during Chamonix Workshop in 2009. The updated analysis combined with presented in Chamonix graph is shown in Fig. 12.
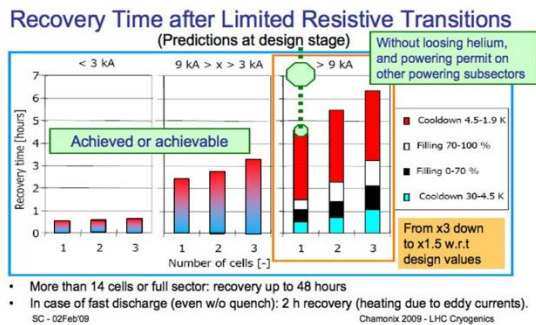
Figure 12: Recovery after quenches

Any quench occurred up to now on the LHC installation did not cause helium loss from the cryogenic installation. In case of opening of the QVs (quenches above 6.5 kA) the helium lost from the cold mass volume was recovered as foreseen in the system. New learning with quenches and recovery will be the subject of future experience for Run2 during the magnets training.

RUN2 BEAM PARAMETERS – CRYOGENIC MARGINS AND LIMITS

The detailed analysis of the beam induced heating was presented during Evian Workshop in December 2012 [2]. This chapter will summarize the work done during LS1 to upgrade the system and will present key values for margins and limits for the refrigeration power.

ARC, SAMs and ITs beam screen circuit

The analysis of scrubbing runs (December 2012) shown e-cloud heat deposition measured on beam screen circuits (BS). The curves in Fig. 13 show topology of the heat deposition with existed before LS1 limitations on specific BS cooling loops.
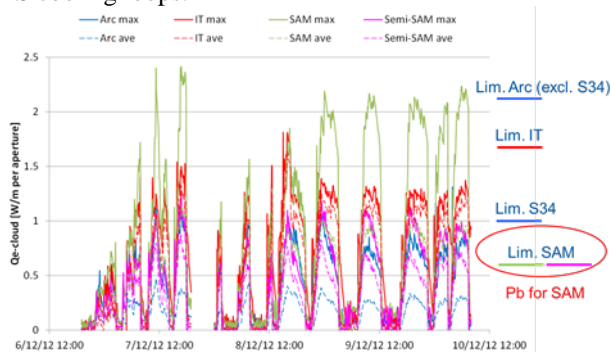
Figure 13: Scrubbing run heat deposition.

The hydraulic limitations on local cooling loops of the beam screen had to be upgraded on SAM and semi-SAM magnets over the accelerator length (38 valve poppets were replaced during LS1). The upgrade was applied also on arc section in sector 3-4 where the cryogenic valve poppets were replaced to go back to the level of cooling capacity equal to the other sectors. The present local limitation for beam scrubbing on all BS cooling loops is about 2 W/m per aperture (see Table 1).

Table 1: Old and new local limitation on BS circuits.

Inventory		Length [m]	CV kvmax [m3/h]		Qbs max [W/m per aperture]		Qbs 25 ns 2015 [W/m per aperture]	Remaining for beam scrubbing [W/m per aperture]	
			Old	New	Old	New		Old	New
SAM Type 1	Q5R1 Q6R1 Q6L5 Q5L5 Q6R5 Q6R5 Q5L1 Q5L1	8.2	0.02	0.05	1.0	2.4	0.4	0.6	2.1
SAM Type 2	Q6L4 Q6R4 C5L6 Q4L5 Q4R6 Q5R6	6.9	0.03	0.06	2.3	3.9	0.5	1.8	3.4
	D3L4 D3R4	11.2	0.03	0.06	1.5	2.4	0.3	1.1	2.1
	Q6L2 Q5R2 Q6L3 Q5R3 Q6L7 Q5R7 Q5L8 Q5R8	12.0	0.03	0.06	1.4	2.3	0.3	1.1	2.0
	Q5L2 Q5R2 C5L8 Q5R8	13.0	0.03	0.05	1.3	2.1	0.3	1.0	1.8
Semi-SAM	Q5D4L4 D4Q5R4	16.7	0.05	0.1	1.6	3.2	0.5	1.1	2.8
	D2Q4R1 Q4D2L5 D2Q4R5 Q4D2L1	19.4	0.05	0.1	1.4	2.8	0.4	1.0	2.4
	Q4D2L2 D2Q4R2 Q4D2L8 D2Q4R8	22.8	0.05	0.1	1.2	2.4	0.4	0.8	2.0
IT	TL1 ITR1 ITL5 ITR5	36.0	0.26		5.7		3.3	2.4	
	TL2 ITR2 ITL8 ITR8	45.0	0.26		4.4		2.5	1.9	
Arc half cell	S12 S23 S45 S56 S67 S78 S81	53.5	0.39		2.4		0.3	2.1	
	S34	53.5	0.22	0.39	1.3	2.4	0.3	1.0	2.1

The upgrade allows for full distribution of available refrigeration power moving the limits from local cooling loops to the limit on global refrigeration power. Taking into account equal distribution of the available refrigeration power the new limitation for beam scrubbing will be 1.6 W/m per aperture (see Table 2).

Table 2: Old and new local limitation on BS circuits.

	Global limitation (Cryoplant) 25ns 2015		
	Qbs max	Qbs 25 ns 2015	Remaining for beam scrubbing
kW per sector	14.8	5.3	9.5
Average W/m per aperture	2.4	0.9	1.6

The distribution of the heat load on the BS and available cooling power for all sectors is presented in Fig. 14 (Qs – static heat load, Qsr – synchrotron radiation, Qic – image current, Qec – electron cloud).
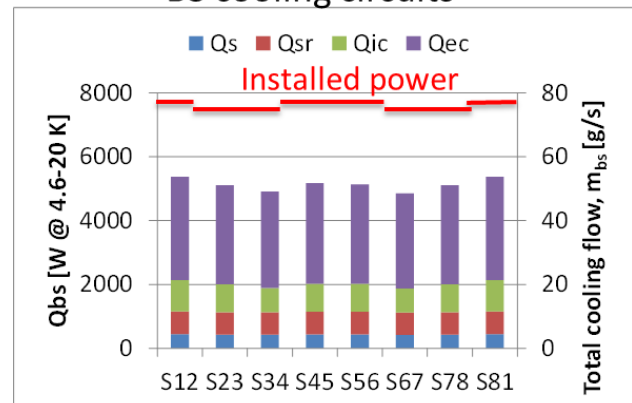
Figure 14: BS heat load and available cooling power.

Heat deposition on the cold mass

The LS1 allowed also for relocation of the braids on all concerned ITs which were wrongly installed before Run1. The local margin on refrigeration power with relation to the luminosity of 1.00E+34 is equal to 1.75 (for details see Table 3).

Table 3: Limitations on ITs cold masses.

	Run 3134				25 ns 2015	50 ns 2015		Lmax compatible with local margin: 1.75E34	
Nb [p per bunch]	1.52E11				1.15E+11	1.60E+11			
nb [-]	1374				2760	1380			
E [TeV]	4				6.5	6.5			
L [Hz/cm2]	6.70E+33				1.00E+34	1.00E+34			
	Qs [W]	Qrh [W]	Qbgs [W]	Qsec [W]	Total [W]	Total scaled [W]	Total scaled [W]	Locally installed [W]	Local margin [W] 25 ns 2015	50 ns 2015
Arc cell	18	2.3	2	0.0	23	27	26	90(1)	63	64
DS cell	25	1.9	2	0.0	29	33	32	140(1)	107	108
ITL1	60	0.6	0.6	60	121	208	208	320(2)	112*	112*
ITR1	52	0.6	0.6	60	113	200	200	320(2)	120	120
ITL2	110	0.6	0.8	0.0	111	113	113	140(1)	27*	27*
ITR2	50	0.6	0.8	0.0	51	53	53	140(1)	87*	87*
ITL5	50	0.6	0.6	60	111	198	198	320(2)	122	122
ITR5	47	0.6	0.6	60	108	195	195	320(2)	125*	125*
ITL8	80	0.6	0.8	3.6	85	86	86	140(1)	54*	54*
ITR8	46	0.6	0.8	3.6	51	52	52	140(1)	88*	88*

(1): limited by sub-cooling heat exchanger
(2): limited by bayonet heat exchanger (IT)
*: could be jeopardized by NC braid

The distribution of the heat load on the whole sector cold mass and available cooling power for all sectors is presented in Fig. 15 (Qs – static heat load, Qrh – resistive heating, Qbgs – beam gas scattering, Qsec – secondary particles).
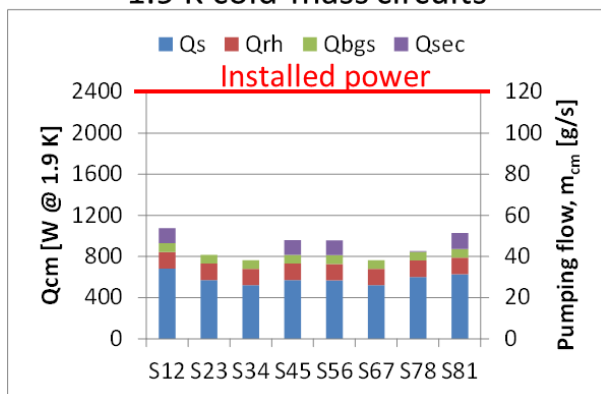
Figure 15: cold mass heat load and available cooling power.

Regarding global heat load coming from the BS circuit and cold mass circuit the available margin is either 1800 W for additional cold mass cooling or 9000 W for additional BS heat load. The representation of global margin for each sector is shown in Fig. 16 combining loads coming from BS and cold mass presented in Figs. 14 and 15.
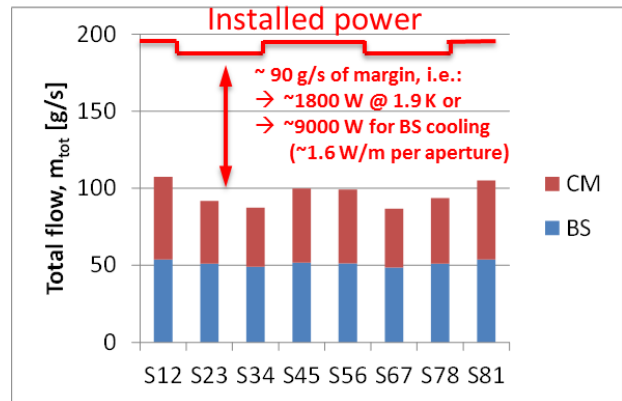
Figure 16: Global cooling margin

CONCLUSIONS

Gained great experience during Run1 allowed operating cryogenic system nearly to 95% of availability during last year of operation. The helium losses were reduced by factor of 2, down to ~22 tons/year. Large LS1 campaign is underway for maintenance, upgrade, repairs and consolidation of different subsystems and components of the LHC cryogenics. Applied study on spare parts and possible redundancies gives good sense of efficient machines operation during Run2 minimizing potential down time. The introduced upgrades on the BS local cooling loops allows for full and more flexible distribution of available global refrigeration power. The existing margin on installed cooling capacity can be used to cover excessive heat load on the LHC cooling loops.

ACKNOWLEDGMENT

Many thanks to all support teams for planned and urgent interventions during Run1 as well as their effort for preparation of Run2 operation.

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LHC VACUUM SYSTEM UPGRADE DURING LONG SHUTDOWN 1 AND VACUUM EXPECTATION FOR THE 2015 OPERATION RESTART

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Abstract

At the beginning of 2013 the LHC accelerator stopped for the Long Shutdown (LS1) by the need to consolidate the magnets interconnects. During this period of time, despite the very good performances of the beam vacuum system during the 2010-2012 physic run, different activities were held in parallel by the VSC group so as to consolidate, improve and upgrades some dedicated area of the LHC accelerator. As example a campaign aiming the consolidation of some RF bridges was conducted, NEG coated inserts were installed as a permanent electron cloud multipacting suppressor in critical locations and boosting of pumping speed by the introduction of compact NEG cartridges were performed in special devices. In addition consolidation of different beam equipment such as collimators, BGI, BSRT, BQS, installation of news TCDQ and MKB to name some, were carried out.

In this paper a review of the main consolidations carried out during the LS1 in the beam vacuum system of the LHC are presented and discussed. Their impacts for the future operation are presented and finally a restart expected scenario for the LHC beam vacuum system is described.

INTRODUCTION

During Run 1, after a successful scrubbing period held during the beginning of 2011, the LHC beam vacuum system operated with a life time due to nuclear scattering of more than 2000 h reaching 75 % of the design proton luminosity at 8 TeV in the centre mass with 2 x 1378 bunches, spaced by 50 ns, each populated by $1.7 \cdot 10^{11}$ protons and a total beam current of 2 x 420 mA. Among other great performances achieved, the total pressure inside the high luminosity experiments where kept below $3 \cdot 10^{-11}$ mbar with such beam parameters. These achieved performances, within specifications, could be reached thanks to the detailed studies, design and procurement of the systems together with dedicated vacuum validation tests prior installation and commissioning in the LHC tunnel. However, in order to prepare Run 2, several repairs, consolidation and upgrade are implemented during LS1. This paper will introduce these activities and the LHC restart.

LHC ARCS

During LS1, all the LHC arcs were warmed up to room temperature (RT) to allow the consolidation of the magnet bus bars located at each magnet interconnects. In agreement with the recommendations of the tasks force following the sector 34 incident, all the LHC Plug-In-Modules (PIM) are protected by half shells to mitigate the impact onto the beam vacuum system of potential arcing. Moreover, ~ 850 rupture disks were installed at each arc's quadruple to mitigate the bellows buckling along the beam line in case of He inrush. These rupture disks are equipped with an innovative non-return valve which protects the cold beam vacuum system from air in leaks due to degradation with time of the rupture disks. Penning gauges were also installed into the arcs at specific quadrupoles magnets, Q12 and Q13. These vacuum gauges will reduce the detection limit from 10^{-9} mbar to 10^{-11} mbar and, together with and upgraded cryogenic instrumentation, will allow a better monitoring of the electron cloud at cryogenic temperature.

Beside these consolidations, regular activities were done. RF ball test after warm up and before cool down were conducted to identify any buckled PIM. Identified critical non-conform PIM located mainly in the dispersion areas were also repaired together with others repaired during magnet exchanges. Helium leak tightness of the beam screen cooling capillary after several years of operation at cryogenic temperature was confirmed by monitoring the absence of He signal during warm up. Finally, all the cryogenic vacuum systems *i.e.* arcs and standalone magnets (SAM), were evacuated during at least 5 weeks to maximise the removal of residual gas (mainly water vapour) prior cool down.

LONG STRAIGHT SECTIONS

Despite the cumulated length of the long straight section (LSS) represents only 14 % of the storage ring, the systems contains 88 vacuum sectors held at cryogenic temperature for a cumulated length of 1.4 km and 174 vacuum sectors held at room temperature (RT) for a cumulated length of 5.8 km.
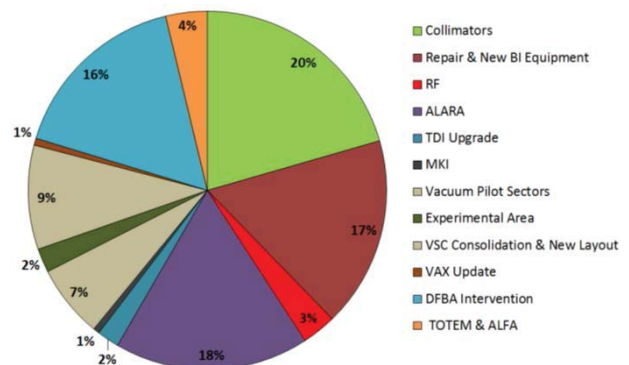

Figure 1: Percentage of all the LSS intervention as a function of beam pipe length.

The RT vacuum system relies on NEG coating technology and it is fully bake-able.

During LS1, 143 RT vacuum sectors were opened and then re-commissioned (*i.e.* ≈5 km) by NEG vacuum activation. Figure 1 shows a summary of the activities performed in the LSS as a function of the different activities. About 1/3 of this activity is due to vacuum system repair, consolidation and upgrade and 2/3 are due to other systems activities. The total cost for the industrial support manpower is ~ 3 MCHF.

Vacuum system

During the intensity increase in 2011, some RF bridges induced pressure spikes during physics fills as typically shown in Fig. 2. These pressure spikes are due to beam induce sparking at RF bridges of the vacuum modules. As a consequence of these observations, a systematic X-ray analysis campaign of all the 1800 vacuum modules was conducted during 2 years. The result of this campaign showed that 96 RF bridges were non-conform and spread over a total of 52 RT vacuum sectors. The systematic repair decided for LS1 requested the opening of 29 RT vacuum sectors.
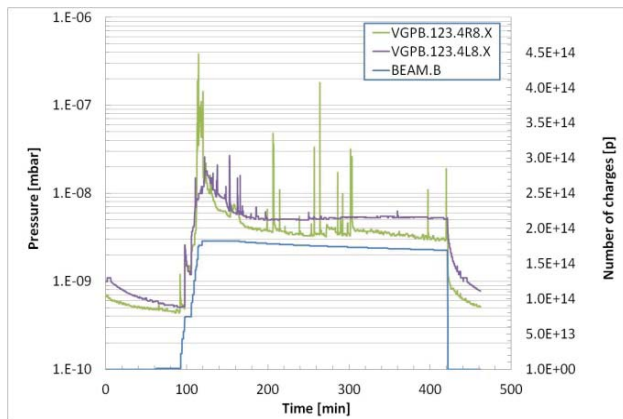
Figure 2: Typical pressure spikes observed in LSS 2 and LSS8 induced by sparking inside VAMTF modules.

Figure 3 shows typical RF bridges non-conformities (NC). On the left side, the NC implies a reduction of aperture with lose of RF contact. Its origin is due to a compression of the vacuum bellow VMAAF after installation, probably during bake-out. On the right side, the origin of the NC is due to beam induced heating as demonstrated by an X-ray image taken a couple of months before and showing a conform module. A detailed analysis revealed a weak design which cannot tolerate misalignment in the vertical plane larger than one mm. This particular module type, VAMTF, has been removed from the vacuum layout.

During Run 1 while increasing the beam performances reducing the bunch spacing by 150 ns, 75 ns, 50 ns and 25 ns, the electron cloud showed up as expected. It built up in weaker areas of the machine *i.e.* unbaked RT location of common pipes, then unbaked RT location of single pipes then baked RT locations. In order to minimise the impact on the experiment's background of the pressure

increase due to electron stimulated molecular desorption, it was decided to install solenoids in these location during the winter technical stop 2010-11 *i.e.* 20 km of cables were wound around the vacuum chambers.
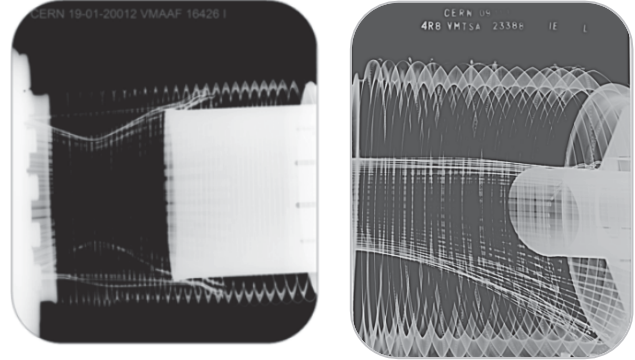
Figure 3: Typical RF bridges non-conformities.

These solenoids were powered ON during physics fill and powered OFF during machine development to allow scrubbing of the vacuum chamber walls. In 2012, most of the solenoids were switched OFF with the exception of the injection kickers (MKI) areas. During LS1, in order to minimise the background to the experiment, the solenoids located in the RT areas are replaced by upgraded RF bridges made of NEG coated transition tubes and the local pumping speed is increased with a 400 l/s NEG cartridge complementing the 30 l/s ion pumps. Figure 4 shows a RF bridge with and without the NEG coating before vacuum validation test in the VSC laboratory. Figure 5 shows a schematic of the upgrade done on the cold-warm transition with NEG cartridge, NEG coated RF bridge and solenoids still installed in the cryogenic area.
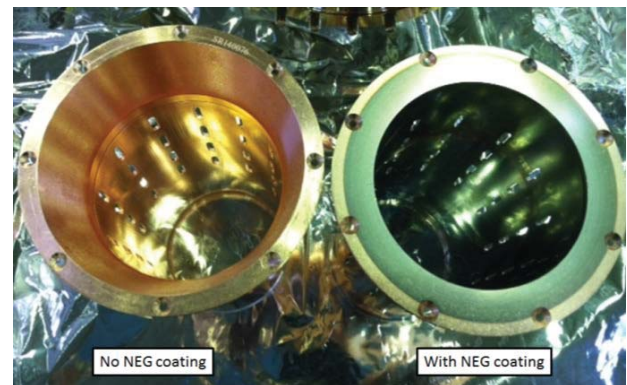
Figure 4: Comparison of the copper and NEG coated RF bridges before vacuum validation in VSC laboratory.

NEG cartridges were also installed in the cryogenic vacuum sectors of the SAM in order to pump the released gas during a magnet quench.

Finally, 88 x 400 l/s NEG cartridges were installed in the collimation areas (LSS3 and 7). According to the ALARA principle, this upgrade will avoid potential human intervention to re-activate the NEG films during future physic runs. The NEG cartridges are inserted into modified standard ion pumps and placed at each collimator extremity. The possibility to remotely re-activate the NEG cartridges allows maintaining a

sufficient pumping speed in case of large saturation of NEG coated beam pipes.

On the instrumentation side, dedicated vacuum pilot sectors for NEG ageing, synchrotron radiation and electron cloud monitoring were also installed in several vacuum sectors located in LSS 2, 7 and 8 [1].
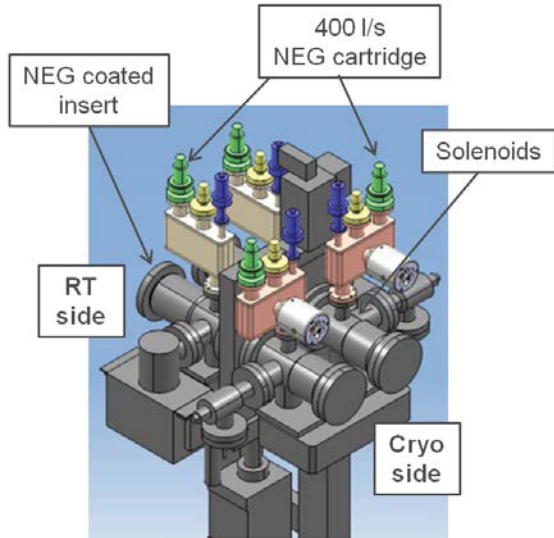
Figure 5: Schematic of the upgrade done on the cold-warm transitions.

Other systems

Many types of equipment of other systems were repaired, consolidated and upgraded during LS1. In order to guarantee the vacuum performances, each of this equipment was previously validated in VSC laboratory before installation into the tunnel. The validation consists in a bake-out cycle followed by leak detection, outgassing rate measurement and residual gas analysis to identify the presence of possible virtual leaks and contaminants. A total of ~ 400 components were tested, see Table 1 for the distribution vs clients [2].

Table 1: Client's distribution of tested components

	Collimation	BI	ABT	Alfa+ Totem
Total	210	80	65	20

The LHC collimation system is made of 3 stages. The part of the second collimation stage located in LS6, TCSP and all the third collimation stage located in LSS 1, 2, 5 and 8, TCTP, was upgraded during LS1. These TCSP with carbon fibre jaws and TCTP with tungsten jaws have embedded beam position monitors (BPM) to allow a faster and more accurate positioning during beam operation [3].

The LHC beam injection system was also upgraded. In particular the 8 MKI located in LSS 2 and 8, had their non-kicked Cu beam tube getter coated and the impedance of the ceramic beam tube was further reduced by a modified beam screen [4]. In particular, 400 l/s NEG cartridges with NEG coated transition tube were installed between each MKI tanks. Moreover, the BTV and BPM beam instrumentation (BI) equipments located upstream and downstream to the kicker magnets were NEG coated too, to reduce further possible pressure increase during beam operation due to electron cloud effects.

In LSS 6, the LHC dilution system was completed by adding a 5th diluter on the extraction line (MKB) and the cold mass protection was upgraded by adding on the beam line a third TCDQ mask.

In LSS2 and 8, the injection mask, TDI was upgraded following beam induced heating during Run 1 [5]. The Cu beam screen was replaced by a stainless steel one and the sliding point mechanism upgraded with ZrO_2 ball bearings. The boron nitride blocks were coated by Ti and the Al masks were Cu coated which allows reduction of the secondary electron yield during beam scrubbing. The 2 x 400 l/s ion pumping system was consolidated with 2 x 2000 l/s NEG cartridge. Finally, the TDI was sectorised with DN 250 gate valves in order to decouple the TDI from its surrounding allowing longer bake-out duration and opening the possibility of its exchange during beam operation if needed.

In LSS4, a RF module was exchanged by a new one. Several BI equipments such as beam position monitors (BPM), TV screens (BTV), beam gas injection systems (BGI), synchrotron light monitors (BSRT), wire scanners (BWS), Schottky monitors (BQS), were also repaired and consolidated following virtual leaks, mechanical and beam induced heating issues [5]. The pumping scheme was also upgraded with 12x 400 l/s NEG cartridge placed along the uncoated dampers beam tube, ADT.

Finally, 2 machine experiments were installed. A beam gas vertexing system, BGV, was installed in LSS 4 to monitor transverse beam profile and a crystal channelling experiments, LUA9, was installed in LSS7 to study future collimation schemes [6].

LHC EXPERIMENTS

All the vacuum chambers to be installed for LS1 into the cavern were vacuum validated at the surface [7]. The main activity during LS1 was to exchange the Be beam pipe at the interaction point of ATLAS and CMS. The new pipes, with reduced aperture (47 mm instead of 54 mm in Atlas and 43.4 mm instead of 58 mm in CMS), allow to accommodate more room for detectors close to the vertex. To minimised the radioactivity of beam pipes, all the stainless steel chambers in ATLAS were replaced by Al ones. In both experiments, the NC RF contact of the vacuum chambers at the TAS position were exchanged and upgraded by the addition of a NEG coated transition tube and a NEG cartridge.

In LHCb, a leaking Be chamber was replaced providing, in the meantime room in the cavern to allows the detector maintenance. To avoid a complete dismounting of the vertex locator (VELO), the vacuum system was vent to neon. For this purpose, a special opening and closing procedures, which did not required a bake out of the VELO, were defined.

During Run 1, ALICE an experiment dedicated to ion physics, suffered from background coming from LSS 2 during proton physics. For this reason, NEG coated liners were inserted into 800 mm vacuum chambers to mitigate the electron stimulated gas desorption induced by the 2 counter circulating beams triggering an electron cloud despite the very large aperture. Figure 6a shows the pressure variation during fills number 2490-3090 in the ID800 and TDI area with indicated also the beam current variation. The integration of NEG coated liner (Fig. 6b) into the 30m long ID800 vacuum chambers will produce, in addition with the upgrade already described for the TDI, a further decrease of the pressure profile with an important decrease of the background in the ALICE experiments.

Finally, NEG cartridges and NEG coated transition tubes where also installed from the VAX area in front of Q1 to the TAN/recombination areas of the LSS 1, 2, 5 and 8 to minimise background to the experiments.
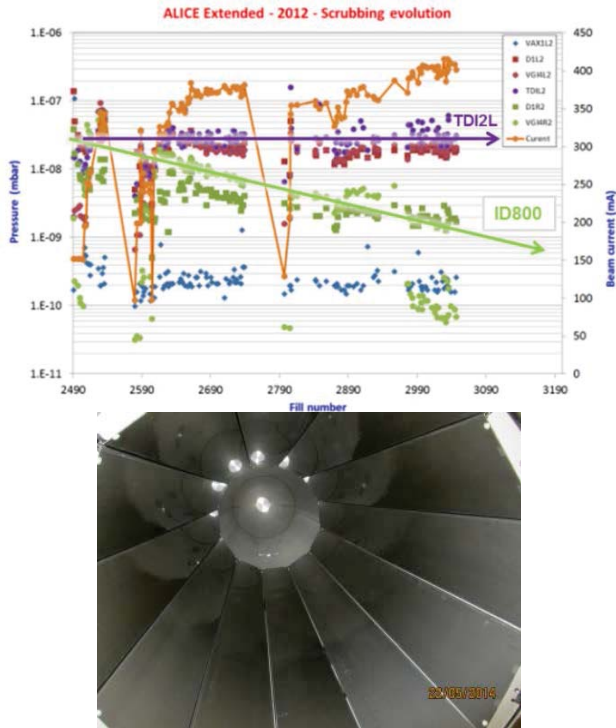
Figure 6: a) Beam current and pressure evolution in the ID800 and TDI during fill numbers 2490-3090 b) Picture of the NEG coated liner inside the ID800 vacuum beam pipe.

RESTART OF LHC OPERATION

More than 90% of the beam pipes of the LHC were open to air during the LS1 and, as a consequence, the secondary electron yield (SEY) and the electron stimulated gas desorption (η) will be reset for almost the entire machine. Experience form Run1 showed that the electron cloud can limit the achievable performance with 25 ns beams mainly through beam degradation at low energy and high heat load at high energy. For the vacuum point of view, the reset η could limit the beam intensity

and consequently the performances of the beam scrubbing. The expectation for the restart of the LHC, as shown in Fig. 7, is that the previously scrubbed and then air exposed surface scrubs between 5-10 times faster (function of the needed SEY) than the "as-received" surface. For this reason it is estimated that all the new components installed during the LS1 (MKB, TCDQ, new dipoles and quadrupoles, etc.) will need a complete conditioning and will probably represent the limiting factor for beam intensity and bunch number increase during the first days of the planned scrubbing run during 2015.
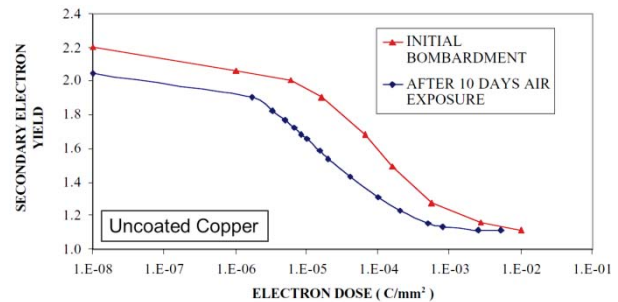
Figure 7: Secondary electron yield vs. electron dose for copper surface as received and for copper surface scrubbed and then exposed to air for 10 days [8].

Furthermore, as depicted in Fig. 8, independently if the new surfaces are held at room temperature or kept at cryogenic temperature will behave the same, meaning that if the electron cloud activities is kept constant all along the beam pipes, both surfaces will reach the same SEY for the same electron dose bombarding the surface.
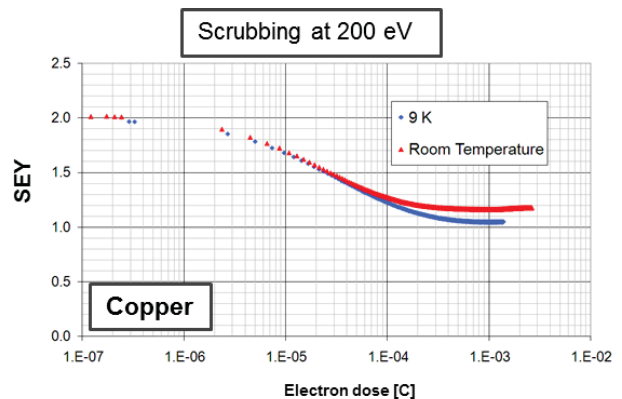
Figure 8: Secondary electron yield vs. electron dose for copper surface at room temperature and at 9K.

For all the room temperature areas with NEG coating a SEY lower than 1.2 is expected already at the beginning of the operation after bake-out at 180°C for 24h (Fig. 9). This SEY will allow a comfortable operation even with 25 ns bunch spacing without activating any electron cloud effects being below the multipacting threshold [9].

Summarizing, during the scrubbing run foresee at the beginning of April 2015 from the vacuum point of view are expected just some localized pressure increase. If necessary, temporary increase of the interlock levels of sector valves are put in place so as to do not interrupt

abruptly the scrubbing period by dumping the beam and if necessary by suppressing the electron cloud effects with the installed solenoid in the cold-warm transition of the SAM. Scrubbing periods with 25 ns will be even more efficient to reduce η allowing a smooth physics run at 50 ns. As shown in Fig. 10 a decrease of one order of magnitude on the dynamic pressure is expected after about 24h of accumulated beam time.

All the upgrades performed in the experimental area of ATLAS and CMS will assure an even further decrease of the background level. Moreover, the efforts for the new NEG coated liners installed in the ID800 chambers should allow ALICE to have a much lower background during the protons physics.

Operation at 25 ns beams will stimulate further gas desorption from the beam screens: pressure could increase again in the range 10^{-7} mbar. A run at 25 ns above the threshold or with "doublets" is needed for further scrubbing and analysis [10].
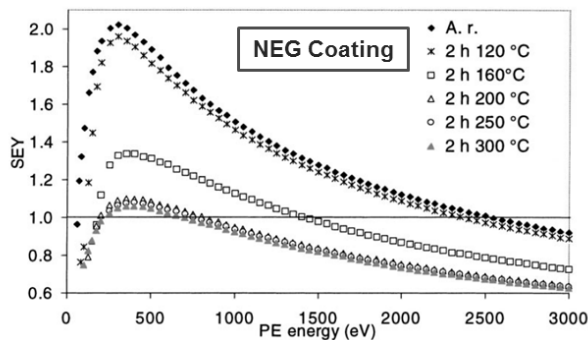
Figure 9: Secondary electron yield vs. electron energy for NEG coating after bake-out at different temperatures.
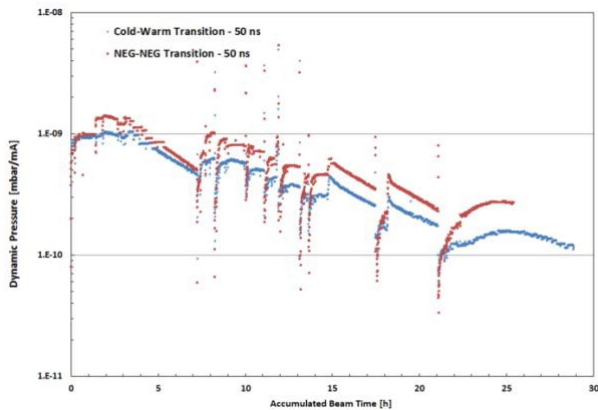
Figure 10: dynamic pressure increase in the Cold-Warm (CW) transition area and in the NEG-NEG area as a function of the beam accumulated time during scrubbing run in 2011 with 50ns bunch spacing.

Finally, after the LS1, the beam energy will approach its nominal value, leading to an increase of the synchrotron radiation critical energy that is proportional to the photon stimulated desorption yield, and the augmentation of the photon flux. The expected desorption due to synchrotron radiation is one order of magnitude higher than the one experienced in 2012. This source of gas will decrease too with the beam pipe conditioning.

CONCLUSION

Following a successful Run 1, the LHC stopped during about 2 years to allow repair, consolidation and upgrade of systems. All the LHC arcs and ≈80 % of the LSS were vented to allow these activities. During Run 1, the LHC vacuum system base line was proven to be valuable. Thus, the vacuum system was simply upgraded by adding more NEG coated surface and more pumping speed at identified weak positions. Dedicated instrumented areas were also implemented in order to provide a better monitoring of the LHC vacuum system performances. In 2015, the vacuum system will be subjected to electron stimulated gas desorption enhanced by beam induced multipacting at 25 ns and subjected also to synchrotron radiation induced gas desorption enhanced by the beam energy increase. Pressure rises will be observed along the ring due to conditioning of newly installed devices and reconditioning of the rest of the ring. After conditioning, the vacuum levels with nominal beams are expected to be within the design values.

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TRANSVERSE BEAM SIZE MEASUREMENT

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Abstract

During the CERN long shutdown (LS1), most of the profile monitors in the LHC went through a consolidation or refurbishment programme to cope with the increase of the machine top energy to 6.5 (and later 7 TeV). In fact the resulting adiabatic reduction of the transverse geometric beam emittance combined with the increased brightness delivered by the injectors will bring most of the beam size monitors close or even beyond their resolution limits. In this paper we will summarize the upgrades/improvements carried out on the Wire Scanners (WS), Beam Gas Ionization (BGI) and the Synchrotron Radiation (BSRT) monitors, focusing on the expected performances and limits of the beam size measurements at top energy.

WIRE SCANNERS

Wire scanners are the reference devices for transverse beam size and emittance measurements in the LHC. They are also used for calibrating other instruments, such as the BGI and BSR monitors. The WS working principle, shown in Fig.1, consists of a thin carbon wire moved across the beam at the speed of about 1 m/s; the radiation produced by the interaction of the protons with the wire is observed by means of downstream scintillators coupled to Photo Multiplier Tubes (PMT). This charge deposition is proportional to the local density of the beam and is used to measure a beam density profile.

The LHC is equipped with eight WS systems. Four are kept operational (one per plane per beam) while four spares can be connected remotely without interventions in the machine.
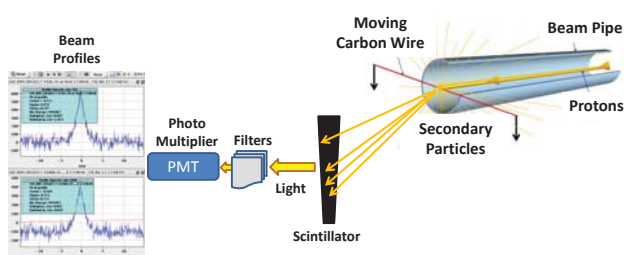
Figure 1: Schematics of the WS chain, presenting its working principle.

During LS1, mainly maintenance tasks were carried out on the WS.

On the hardware level, after evidence of aging due to the sublimation process, the wires were replaced by the same type of Carbon wires (diameter: 30 μm). In addition, following the failure of one of the systems after 10200 scans, related to bellow vacuum leaks causing a 24 h stop of the

LHC operation, the old WS bellows designed to withstand about 10000 scans were replaced by a new design of a higher lifetime (40000 cycles). The number of scans per device are continuously logged and monitored through automated software reports.

The low level software of the WS also went into a consolidation program, mostly aiming to avoid dangerous situations that caused the wire breakage during Run 1 operation: the crash of the FESA server driving the wire movement following operator requests of scanning both beams contemporaneously lead to wires remaining stuck in the "IN" position with circulating beam. Furthermore, the WS user application was completely renovated , getting simpler and more powerful. The GUI will :

- allow an automatic selection for all the bunches circulating in the machine,

- allow automatic scans for both planes and both beams,

- allow repetitive scans per beam,

- feature one gain setting combining the PMT gain and the light Neutral Density (ND) filters,

- feature different fit options on users request (fitting only the bunch core or including tails),

- allow importing custom machine optics for the emittance calculations.

Moreover, studies showed a working point (PMT gain, ND filters) dependence on the measured beam size and intensity. Therefore, a new PMT is under test to mitigate measurements error due to the saturation effect. The option of a particle shielding is also investigated to solve possible non-linearity due to parasitic signal generated in the PMT. Beam studies in the coming machine development time will be needed to study the PMT saturation and implement a corresponding software warning to alert the user.

Following the 2013 beam-induced quench tests with 4 TeV protons, it was found that the maximum intensity limits measurable by the WS is defined by the Carbon wire breakage due to sublimation and not by the beam dump due to downstream BLM interlocks set to minimize the possibility of a superconducting magnet quench. The wire damage is not immediate above the new defined thresholds but scanning such high intensity beams would speed up the wire deterioration. Table 1 presents the found threshold for both beams at injection and 6.5 TeV for two beam emittances. To be noted that the different thresholds per beam and per plane is due to the optical function β value at the scanner location, hence eventual change of optics in IR4 would imply the modification of these thresholds.

Table 1: Maximum beam intensity limits for WS measure-ments (in 10^{11} protons).

	ε (μm)	BEAM 1		BEAM 2	
		H	V	H	V
450 GeV	2	164	118	204	106
	3.5	217	156	269	141
7 TeV	2	53.1	51.5	51.6	26.9
	3.5	70.3	68.1	68.2	35.6

BEAM-GAS IONIZATION MONITOR

The Beam Gas Ionization monitors (BGI) are conceived to infer the LHC beam size from the measurement of the electrons distribution produced by the ionization of Neon gas injected into the vacuum chamber. The schematics in Fig.2 show the working principle of this monitor where the charged beam passes between two ceramic electrodes with a potential difference of 4 KV, over a distance of 85 mm. This potential brings the produced electrons to a Micro-Channel Plate (MCP), where the signal is amplified, before reaching a phosphor screen producing a photon distribution imaged by a complex optical system on a CCD intensified camera. In order to minimize the transverse spread of the electrons, external magnetic field of 0.2 T, directed along electric field lines, is applied.
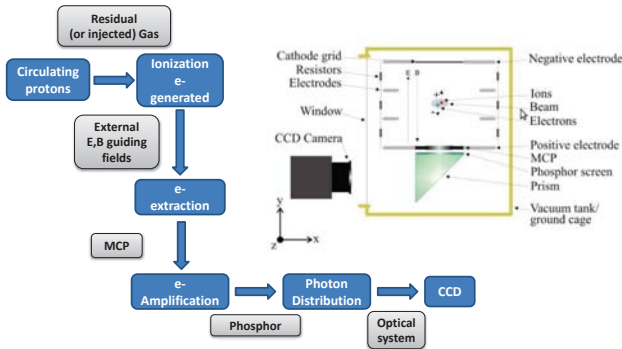
Figure 2: Schematics of the BGI chain, presenting its working principle.

The BGI monitors went through a maintenance program during LS1. On the hardware level, after clear signs of aging, the MCP and the adjacent phosphor screens where replaced by new ones of the same type. In order to avoid radiation damage to the CCD, a new radiation hard assembly is installed, where the camera chip is relocated in a separate shielded box provided by the manufacturer. Finally, in vacuum temperature probes were installed on two out of four monitors to study eventual beam induced heating issues in the detector.

Moreover, extensive simulations targeted the performance of the instrument and it was found that the electrons liberated in the ionization process strongly interact with the

beam charges, affecting electron trajectories and the overall beam profile. The simulated profile broadening was more pronounced in the case of the expected 50 ns beam parameters, as shown in Fig.3, where the resulting beam profile is not gaussian anymore, but highly dominated by the space charge effect. The same simulations predict for the expected 25 ns beam parameters a smaller broadening than 7 TeV 50 ns beams mainly due to the reduced bunch charge and the larger emittances expected. However, this will not allow correct direct measurements of proton beams. It is important to note that the correction algorithm under development depends on the bunch length and intensity, so for the moment it is not foreseen to be done on-line. However, for the ion beams, the space charge effect is negligible and BGI shall be functional.
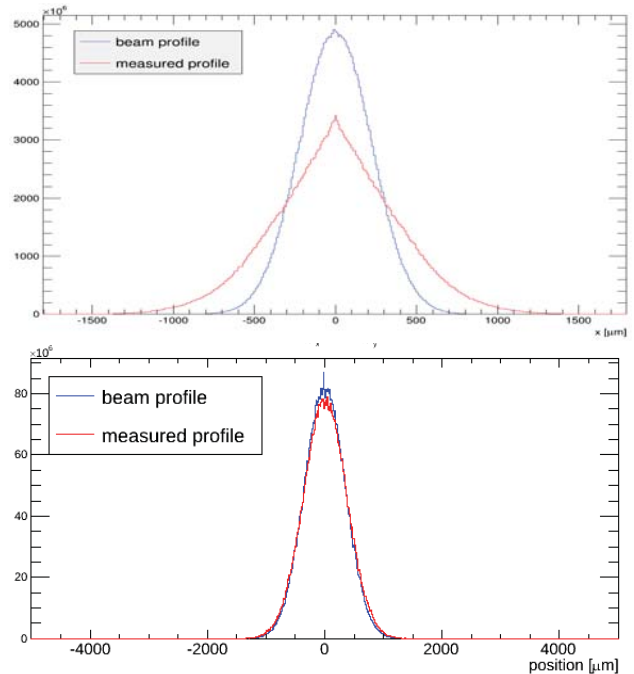
Figure 3: Profile broadening due to space charge effects, for protons (top) and ions (bottom), at flattop energy.

After LS1, for protons, the BGI will continue providing a beam size measurement resulting from the integration of the signal from the whole beam over many turns (10-100 ms integration time). On the other hand, due to the higher output signals from ions beams, a bunch-by-bunch measurement could be implemented exploiting the 50 ns gating possibilities of the camera. In case the software infrastructure will be available, these studies will take place in machine development periods.

SYNCHROTRON LIGHT MONITOR

The BSRT monitor images the synchrotron light generated by beam particles traversing a dedicated superconducting undulator and a D3 type dipole located in IR4. From the LHC injection energy (450 GeV) to about 1.5 TeV, the radiation generated by the undulator is in the visible

range, and shifts to the X-rays along the energy ramp. From 1.2 TeV onward the dominant component of the visible SR is emitted by particles traversing the D3.

At a distance of 26 m from the D3 entrance, the protons are sufficiently separated from the photons to provide room for a mirror that extracts the light, directing it downward through a fused-silica view port to an imaging optic system in a shielded enclave below the beam line.
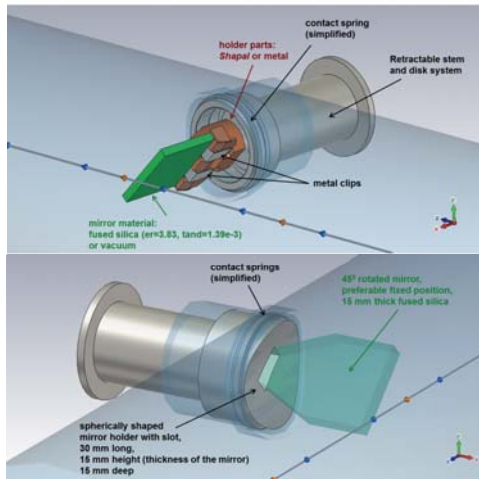
Figure 4: OLD (top) vs NEW (bottom) BSRT extraction mirror and its holder.

During the LHC operation in Run 1, the overall performance of the SR imaging system was dominated by the gradual deterioration and heating of the extraction mirror that lead to its mechanical failure. As pointed out by the available temperature probes, a strong correlation was found between the mirror support heating and the longitudinal bunch length, shape and the total beam intensity. These observations trace back the heating origin to electromagnetic coupling between the beam and the structure. Therefore, with the constraint of keeping the light extraction tank unchanged, a new design of the extraction mirror and its holder was implemented as shown in Fig.4. A longer glass bulk, dielectric coated mirror is inserted through a slit in the beam-pipe replacing the original silicon bulk mirror dielectric coated one. This geometric modification hides the mirror holder and shaft completely, showing no dominant resonance effects in the wake impedance simulation, thus avoiding the need for resonance damping materials, e.g. ferrites. It is worth noting that a very good agreement (within 10%) was found between the EM simulations and laboratory measurements based on the stretched wire method using a spare BSRT tank.

In addition to the in-vacuum temperature probes monitoring eventual heating in the structure, a movable Shack-Hartman mask will be installed just after the view port to monitor the quality of the light extraction mirror. This light-destructive measurement consists of an opaque plate with a regular holes matrix (1 mm diameter each) to be inserted just after the extraction mirror; its projection, illuminated by the SR, will be observed by a CCD camera on a screen located several meters after the mask. Each hole samples a small area of the mirror, and in case of a flat "non-deformed" mirror, a regular spacing pattern is measured on the camera; contrarily, if the extraction mirror is deformed by the heating, by analysing the arrangement of the matrix projection and by calculating the separations between the holes, the distortion of the mirror can be calculated and its surface can be reconstructed.

In addition, only for Beam 1, a new external alignment line was installed, consisting in a modified $BTVSI$ tank replacing the $BSRTA$ (periscope) to allow both imaging calibration and alignment via the same optical line that includes the extraction mirror as well. Therefore the bulky 26 m calibration line will be removed freeing half of the optical bench.

The extracted visible SR light is shared on the optical table among the imaging system measuring the transverse profile of the beam, the Abort Gap Monitor (AGM) and the Longitudinal Density Monitor (LDM) used to characterize the longitudinal distributions of the LHC beam. The AGM verifies continuously that there are no particles within the rise time gap (3 μs) of the dump extraction kicker (MKD); Particles in this gap would indeed not receive the proper kick when the dump system is fired and would damage machine components. In order to not compromise the stability and reliability of this monitor, needed for machine protection, a light wedged splitter was installed immediately after the extraction mirror to completely decouple longitudinal and transverse diagnostics.

Extensive simulations were carried out targeting the imaging system and dedicated tools were developed to assess its performance. With the increasing LHC flat top energy to 6.5 TeV, due to the adiabatic emittance shrinking, the beam size at the SR source will be reduced by 30% getting smaller than the monitor resolution itself. Hence, at high energy, to reduce the Line Spread Function (LSF) of the BSRT, dominated mostly by diffraction smearing, the working wavelength had to be shifted from 400 nm to 250 nm. Clear benefits in terms of resolution are shown in Fig.5. Consequently, as shown in Fig.8 interchangeable focusing lenses will be used to monitor red light at injection energy (green lens A) and near UV at flattop (blue lens B).

However, due to the inevitable small source size, reaching the required precision on the emittance measurement (< 10%) remains a difficult task. The measured beam size by SR imaging corresponds to the real proton beam size broadened by diffraction and lens aberrations and eventual distorted surfaces causing the wavefront deformation; hence the beam size from the BSRT is obtained by subtracting in quadrature a correction factor σ_{corr} from the measured

Figure 5: Deposited SR intensity emitted by a zero emittance beam at 7 TeV on the BSRT extraction mirror (left) and a comparison of its image (Line Spread Function) through the BSRT lens system for 250 nm vs 400 nm.

value:

$$\sigma_{beam_{BSRT}} = \sqrt{\sigma^2_{meas_{BSRT}} - \sigma^2_{corr}} \qquad (1)$$

where the correction factor is retrieved by calibrating the BSRT measurements to the WS measurements:
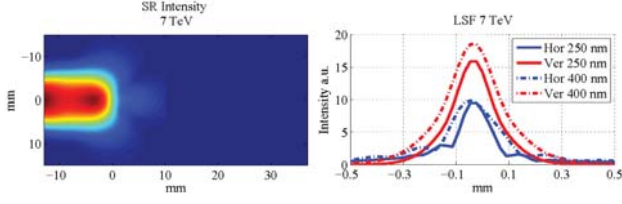
$$\sigma^2_{corr} = \sigma^2_{meas_{BSRT}} - \beta_{ratio} \cdot \sigma^2_{meas_{WS}} \qquad (2)$$

with β_{ratio} being the ratio of the β at the D3 and the WS location. Due to the relative errors on the measurements in the WS, the BSRT and the knowledge of the β_{ratio} respectively: $\epsilon_{\sigma_{meas_{WS}}}$, $\epsilon_{\sigma_{beam_{BSRT}}}$ and $\epsilon_{\beta_{ratio}}$, the resulting relative error on the beam size determination using the BSRT can be expressed by:

$$\epsilon_{\sigma_{beam_{BSRT}}} = \frac{1}{2}\left\{ 8\epsilon^2_{\sigma_{meas_{BSRT}}} \cdot \left(1 + \left(\frac{\sigma_{corr}}{\sigma_{real}}^2\right)\right)^2 + \right.$$
$$\left. \epsilon^2_{\beta_{ratio}} + 4 \cdot \epsilon^2_{\sigma_{meas_{WS}}} \right\}^{0.5} \qquad (3)$$

The amplification factor in the error expression, $\frac{\sigma_{corr}}{\sigma_{real}}$ can be reduced by increasing the beam size at the dipole D3 by increasing β_{BSRT}. Figure 6 shows the effect of increasing the beta function on the overall BSRT beam size determination accuracy, for an optimistic situation where $\sigma_{corr} = 250\,\mu m$, $\epsilon_{\sigma_{meas_{WS}}} = 1\%$, $\epsilon_{\sigma_{beam_{BSRT}}} = 1\%$ and $\epsilon_{\beta_{ratio}} = 2\%$.

The two vertical black dashed lines in Fig.6 represent the nominal minimum value of $\beta_{BSRT} = 127$ m (Beam 2 Hori-zontal plane) and the increased value proposed in the mod-ified IR4 optics $\beta_{BSRT} = 200$ m (feasibility of the optics change is still under investigation).

To overcome this intrinsic limitation of the visible SR imaging, a new beam size monitor, visible SR double-slit Interferometry (SRI), will be tested and implemented in the free space on the optical table for Beam 1. This monitor is a wavefront-division type two-beam interferometer using polarized quasi-monochromatic SR light.

The method, first applied by Michelson for measuring angular dimensions of stars, allows the determination of the size of a spatially incoherent source by measuring the spatial distribution of the degree of coherence after
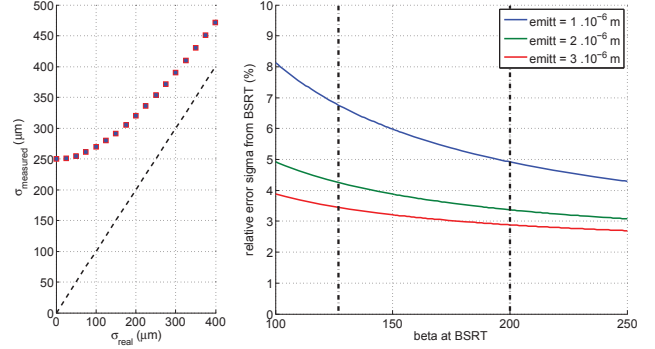
Figure 6: Given a $\sigma_{corr} = 250\,\mu m$, the broadening effect is shown in the left plot where the effective beam size measured (red) is compared to the real beam size (dashed). At the varying bsrt beam size measurement error function of beta.

propagation and is based on the Van Cittert–Zernike (VCZ) theorem, which states that there is a Fourier transform relation between the intensity distribution of an incoherent object and the complex degree of coherence measured in the far field. Its application to synchrotron radiation beam profiling was first proposed and demonstrated by Mitsuhashi as shown in Fig.7 and nowadays is widely diffused in most of the SR storage rings.

A feasibility study of the SRI for the LHC beams was carried out starting from the validity of VCZ: its application is not straightforward due to the small beam size and divergence with respect to the big opening light cone angle. Such beam parameters result in a big coherence area of the propagated wavefront for visible wavelengths. Moreover, due to the big bending radius of D3 ($\rho \sim 6\,Km$), an important component of the fringes visibility reduction is not determined by the beam size but by the incoherent depth of field. In addition, since the main part of the visible SR intercepted by the extraction mirror is emitted in the rising magnetic edge of the D3, strong intensity imbalance can be found on the slits (horizontal separation) that further decreases the fringes visibility. All the aforementioned phenomenas and the distorted surfaces of the mirrors and the lens aberrations lead to the development of a dedicated simulation suite that realistically describes the SRI optical system and its source. A resulting mapping of the measurable fringe visibility to the beam size is presented in Fig.7.

With the fully automated double slit (slit separation and slit width) system under development, interferometry tests are planned to be done at injection energy and at flattop, thus measuring beam sizes ranging from 150 μm to 1.3 mm, in both planes, individually or simultaneously. However, retracting completely the slits will allow to perform SR imaging using the high frame rate intensified sCMOS camera, which has been chosen for the interferometer line. With a frame rate close to 1000 fps, beam tomography could be tested as well for Beam 1.
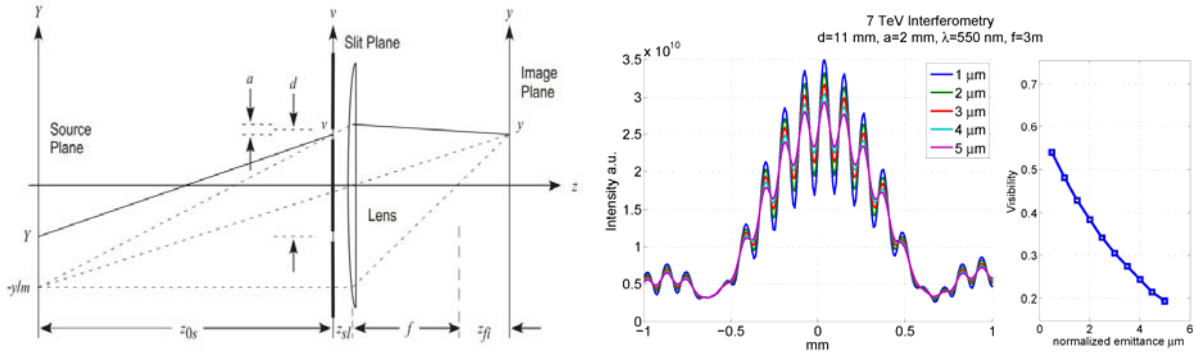
Figure 7: Interferometry working principle (left) and visibility mapped to beam size as a result of the simulations (right).
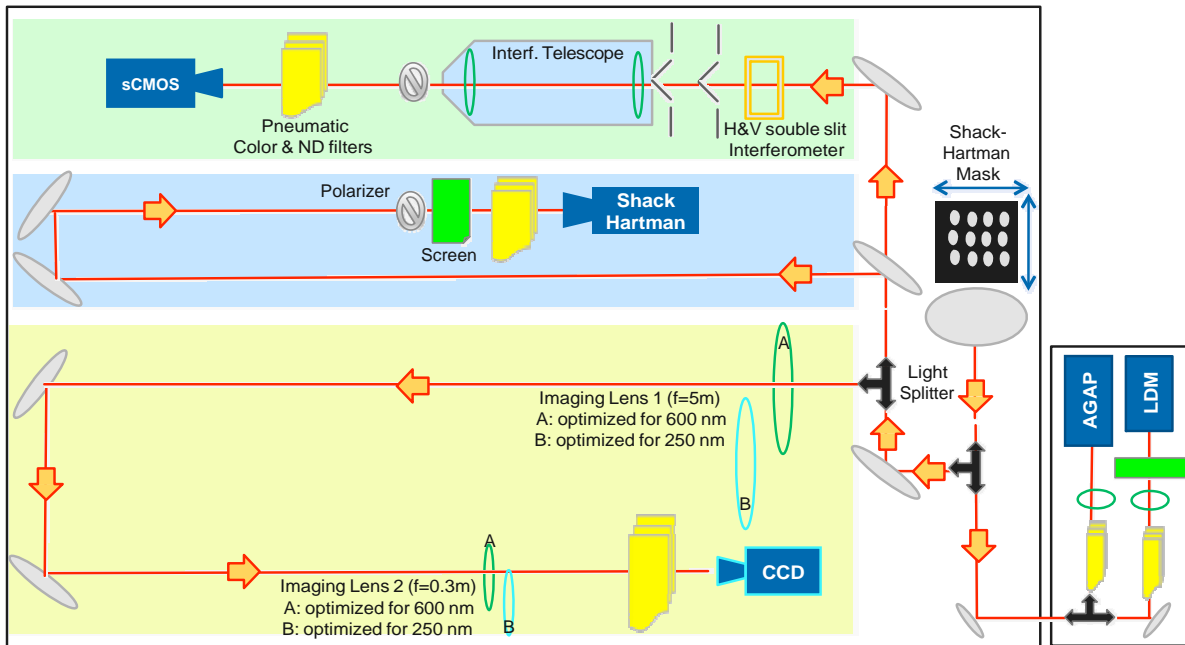
Figure 8: Beam 1 optical table layout after LS1.

Finally, the low level control server will be upgraded, mainly for consolidation of the automated feedbacks and for coping with the HW changes on the optical table equipment (e.g. pneumatic filter system instead of motorized wheels and double slits control). Operationally, the BSRT imaging system will continue providing beam size measurement at 450 GeV and 6.5 TeV at ~ 25Hz, thus measuring the full beam in ~20 minutes. Tests are planned for measurements through the energy ramp, during MD.

CONCLUSIONS

An overview of the status of the main beam size monitors in the LHC pointed out the consolidation, maintenance and upgrades tasks carried out during LS1. Important modification, both at hardware and software level, were presented, giving a summary of the expected performance with the new beam conditions expected in LHC Run 2.

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STATUS OF THE TUNE AND ORBIT MEASUREMENTS AND CORRECTIONS, AND TESTING STRATEGY

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Abstract

An upgrade of LHC beam instrumentation has been performed during the Long Shutdown 1. In this context both the beam position and tune monitoring systems, as well as their respective feedback systems have been reviewed and modified. This contribution presents an overview of the major hardware and software modifications performed during LS1 and the expected performance with 6.5TeV beams in 2015.

INTRODUCTION

With 1070 monitors, the LHC Beam Position Monitor (BPM) system [1] is the largest BPM system worldwide. Based on the Wide Band Time Normalizer (WBTN) [2], it provides bunch-by-bunch beam position with a resolution better than 150μm in bunch/bunch mode and 10μm in averaged orbit mode [3]. During LS1, the main activity on the BPM system was to install the VME acquisition crates in water-cooled racks to reduce the ambient temperature-related drifts.

In addition, 18 new collimators with embedded BPMs [4] are being installed during LS1. These BPMs are used to position the collimator jaws around the beam with a resolution better than 1μm. Their read-out system is based on a compensated diode detector scheme [5], named DOROS, which has already demonstrated to be robust, simple and to provide an excellent position resolution.

The LHC tune monitoring system is based on the direct diode detection technique, also known as BBQ, [6] allowing operation with minute beam oscillation amplitudes. The incompatibility between the transverse damper operating at high gain and the tune monitor has however been a serious limitation during beam operations. A solution was found in summer 2012 based on the development of a new tune front-end, which enables gating on bunches for which the damper operates at lower gain. During LS1, two additional strip-lines have been installed to extend the current operational system, providing tune measurements in parallel in order to fulfil the different functionalities as required by standard operational scenarios, i.e. pilot and high intensity bunches, gated BBQ and coupling measurement.

In addition, an overhaul of the LHC Schottky monitors has been initiated. Supported by simulation efforts, the pick-ups and their electronic were modified and improved.

A review [7] on the LHC Orbit and Tune feedback systems was organised in May 2013. The architecture of the system was presented and discussed. Recommendations were made to improve the functionality and the reliability of the existing system. The current strategy for their implementation is presented in this paper.

STATUS OF BEAM POSITION MONITOR

Test and installation of thermalized racks

48 water-cooled racks have been installed in the LHC surface buildings to house the BPM and BLM digital electronic systems. For each rack a temperature controller module regulates the incoming water flow depending on the cabinet temperature and monitors the functioning of the thermalized racks. 3 measurements have been implemented in order to monitor the inlet water and cabinet temperatures as well as the status of the rack fan. In case of too high temperature in the cabinet, the rack's door will open automatically. All signals and corresponding alarms available in one surface building are daisy chained and sent to the Technical Infrastructure Monitoring (TIM) system where an alarm will be created.

As an example, the evolution over 20 hours of the temperature and the BPM ADC raw values are shown in Fig. 1 for a BPM located in Point 1.
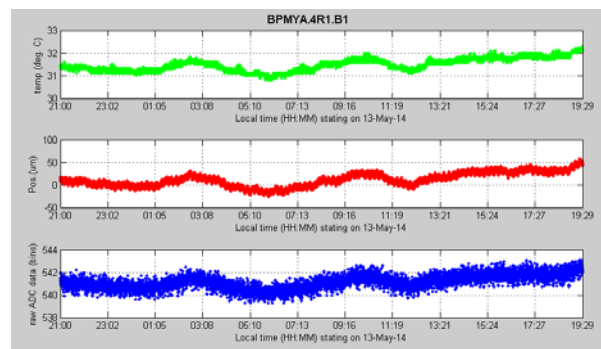
Figure 1: Evolution of the temperature measured on the DAQ (green/top) and the beam position measured in μm (red/middle) and in ADC bins (blue/bottom) for BPMYA.4R1.B1

The temperature variations were seen to be kept within 1°C peak to peak over 22h. The BPM reading

using a calibration signal is still linearly correlated to the temperature however, using a correction algorithm; the RMS noise on the BPM reading is measured to be smaller than 5μm. At this level, the noise could also be linked to the stability of the calibration source. More investigations are required to better understand the limitations of the upgraded system.

Hardware and Software modifications

Two new button-type BPMs were installed in Point 4 close to the BGI monitors and several BPMs were modified and repaired. For example the strip-lines BPM for ALFA, initially short-circuited, have been modified and are now terminated with 50Ohms loads. This will reduce the signal reflections in the system and improve the dynamic range. A survey campaign was also conducted on a few BPMs, which were marked by operation with possibly large mechanical offsets, e.g. BPMD. It turned out that BPMs at Q1 locations could only be aligned with an accuracy of ±1mm due to difficulties in accessing the BPM detector and visualising its survey target.

In the BPM VME crates, all CPUs are being upgraded to MEN A20. The BPM FESA class is also being upgraded in order to correct for the BPM geometrical non-linearity using a new 2-D polynomial fit calibration, which includes x-y cross-terms [8].

Orbit measurement with diode detector

The final version of the diode orbit system, DOROS [9], is presently under development. A sketch of the present system is shown on Fig. 2.
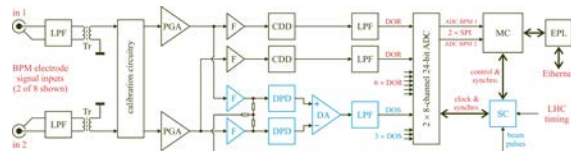
Figure 2: Architecture of the LHC DOROS electronic: LPF: Low Pass Filter, PGA: Programmable Gain Amplifier, F: Follower, DA: Differential Amplifier, MC: Main Controller, SC: Synchronisation Circuitry, EPL: Ethernet Physical Layer

DOROS includes a high-resolution (1μm) beam orbit measurement system based on compensated diode detectors (CDD) as well as a beam oscillation measurement using diode peak detector (DPD). The latter can be seen as an evolution of the electronic originally developed for the tune measurement system. The system processes beam signals using a 24-bit analogue to digital converter. The orbit data is locally processed in an FPGA (MC) and sent out to the control system through an Ethernet link using UDP frames. DOROS is using a standalone architecture that fits in a standard 19" rack. Each box will process 8 orbit and 4 oscillation channels that could monitor either 2 collimators equipped with 4 buttons each or 2 regular BPMs having 4-electrodes.

DOROS will be deployed on 18 TCTPs and TCSPs collimators currently installed on LHC during LS1. Providing a closed-orbit BPM resolution considerably better than the default LHC BPM system, DOROS will also be deployed on several BPMs in parallel to the existing system. All Q1 BPMs in point 1, 2, 5 and 8 will be equipped with DOROS in order to provide the best position resolution close to the LHC experiment. In addition 4 striplines on Q7 quadrupoles in point 7 will be equipped with DOROS to allow better coupling measurements. This is also the case for the BPMs used by the TOTEM experiments.

TUNE MONITOR

Two additional strip-line pick-ups have been installed during LS1 to complement the Tune monitoring system, as presented on Fig. 3.
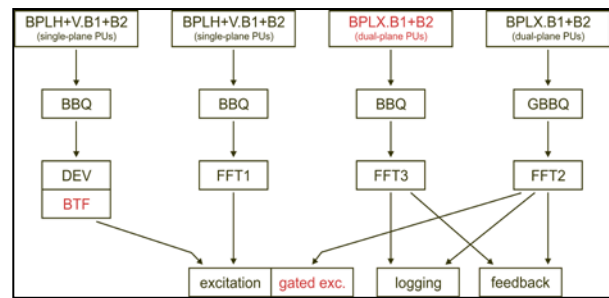
Figure 3: Layout of the LHC Tune Monitoring System

The new features are highlighted in red in Fig. 3.

- FFT1 is the on-demand system typically used to perform measurements requiring changes in acquisition settings and/or beam excitation as needed for chromaticity measurements.

- FFT2 and FFT3 are using gated BBQ (GBBQ) and standard BBQ electronic systems respectively. They provide the continuous tune and coupling measurements that are currently used by the feedback system. As the standard BBQ system observes all bunches, the gated BBQ electronic allows to measure just the selected bunches for which the transverse damper operates at a reduced gain.

- DEV is a development tune system kept for beam studies. The Beam Transfer Function (BTF) measurements will be implemented as an MD tool first on the DEV system.

Some operational software development is required to exploit the full functionality of standard and gated BBQs, with a GUI for bunch selection and bunch scans display.

Status of Schottky monitor

During the LHC Run 1, the LHC Schottky monitors [10] were able to provide high-level Schottky signals of good quality during all ion fills, for B1H, B1V and

B2H, providing reliable single bunch measurements for the tune [11]. However, with protons only the B1H Schottky system gave acceptable Schottky signals, the signals of the other systems were below the noise floor.

During LS1, the Schottky pick-ups have been modified and, basically, four new pick-ups have been designed, manufactured and assembled as depicted on Fig. 4. New waveguides and beam pipe bars made out of copper instead of aluminium were produced to keep any possible thermal expansion matched to the slotted CuBe coupling foils. This will avoid the warping of the foils during bake-out cycles, which was observed on the previous design when the monitors were dismounted. Canted coil-springs are now implemented to guarantee a good RF contact between all parts of this sandwich construction.
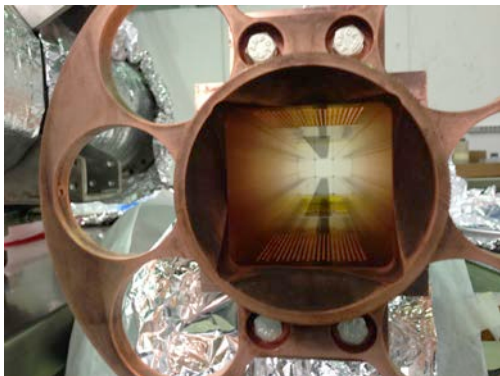
Figure 4: Picture of the new Schottky pick-up made out of copper bars and slotted CuBe foils.

A new coaxial-to-waveguide launcher was designed using CST microwave studio. In order to minimise reflections and standing waves, its return-loss was improved over a frequency range from 4.6 to 5.0GHz frequency range.

The RF front-end electronics will also be modified before the LHC restart. The current system, based on consecutive down-mixing stages, will be modified to operate with a tuneable input frequency in the 4.6-5.0GHz range. This will allow locating the optimal frequency, for which coherent signals are minimised. It requires a tuneable local oscillator for the first down-mixing stage and a tuneable narrow-band input filter (YIG). In addition, a fast, high isolation gate switch will be implemented in front of the first amplifiers to improve the S/N for gated bunch operation. Remote control for all RF attenuators and phase shifters will also be implemented for increased flexibility.

STATUS OF FEEDBACK SYSTEMS

Both hardware and software modifications and improvements are currently implemented on the LHC feedback system.

The machines running the Orbit Feedback Controller (OFC) and the Orbit Feedback Service Unit (OFSU) have been upgraded to new Gen8 computers. They can

run up to 24 threads in parallel with 32GB memory. This has to be compared with the previous G5s machines limited to 4 threads and 12GB. The system is now composed of 4 identical units, 2 being the operational ones and 2 for development work.

While the existing pre-LS1 will be kept as backup, the base-line means starting with newly implemented software described below for the feedback and service-unit. This has implications for operational applications that will require modifications. Regular meetings with OP will allow detailing these changes and agree on short and medium-term milestones.

Additional beam position data from collimator BPMs and normal pick-ups based on the DOROS electronics will be integrated in parallel to the standard LHC BPM acquisition system allowing the steering program to visualize them however it is presently not foreseen to close the feedback based on the data.

The OFC will run in 64bit mode. The introduction of a standard timing module to the server will make the OFSU less critical to operation as it was now required to update the beam energy regularly. The splitting of the OFSU into 2 different FESA servers will be studied to facilitate the maintenance. One server will be dedicated to the OFSU proxy providing orbit and tune data to the control system while the second will handle the beam optic calculation and settings management. With the aim to suppress the 'private' Ethernet link between OFC and OFSU, the possibility to run them on the same machine will be studied exploiting the increase in thread performance.

The deployment of new software versions needs to be looked into carefully. Changes and upgrades on the OFC may be done without any impact on beam operation during technical stops or 'quiet' periods. Modifications to the OFSU may be more critical with possibly some functionalities unavailable during a certain time.

CONCLUSIONS AND PERSPECTIVES

The installation of water-cooled racks performed during LS1 aims at an improved stability and reproducibility of the orbit BPM reading (<10um) over long time period. The use of the synchronous orbit for common beam-pipe BPMs should be tested and deployed operationally in order to limit the cross-talk between the two beams and to improve the accuracy of the position measurements at these locations. The implementation of a better correction of BPM geometrical non-linearity should also provide more accurate measurements.

The new DOROS high-resolution orbit measurement system is being installed on 18 collimator BPMs as well on the 16 BPMs located close to Q1. It is expected to provide a better control of the beam position to optimise collision at IPs and integrated luminosity.

The tune measurement system has two additional pick-ups to fully deploy the gated BBQ operationally and provide better coupling measurements. The measurement of the Beam Transfer Function (BTF) will be made operational responding to a direct request from MD users. A complete overhaul of the LHC Schottky monitors is currently being performed, with new pick-ups and electronics. It is expected to provide bunch-by-bunch tune measurements and chromaticity measurements at injection and flat top energy.

The architecture of the orbit and tune feedback system has been reviewed during LS1. Its computing capability has been increased considerably with more powerful machines and many software modifications have been launched aiming for better reliability in agreement with OP-LHC.

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MACHINE PROTECTION WORKSHOP REVISITED
OPEN ISSUES, PROGRESS AND DECISIONS ON MAJOR TOPICS

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Abstract

At the Machine Protection Workshop, held in March 2013, the upgrades / changes in the machine protection systems planned for LS1 were discussed. Furthermore it gave an outlook on challenges and possible solutions for future LHC upgrades. This paper summarizes the status and progress in the machine protection and related systems relevant for the restart of the LHC with beam. Furthermore, issues that still have to be addressed will be discussed. The follow-ups from the Machine Protection workshop cover the topics material damage and failure scenarios, moveable devices, injection and LHC beam dumping system (LBDS), circuit related protection and electrical distribution, beam instrumentation, operation and software tools, commissioning of MP systems and MPP.

INTRODUCTION

The machine protection workshop in March 2013 addressed the planned and required changes during LS1 in the LHC machine protection systems. The major items of each session of the workshop can be found in the session summaries of the workshop proceedings [1]. Since March 2013 the work on these changes and upgrades has well progressed in the different teams. The detailed changes are described in the different papers of these proceedings. This paper summarizes the status and progress in the machine protection and related systems relevant for the restart of the LHC with beam.

MATERIAL DAMAGE AND FAILURE SCENARIOS

The detailed understanding of failure scenarios causing sudden beam losses is essential to guarantee a safe operation of the LHC. In combination with material damage limits these give the input to set interlock limits, which protect the machine and at the same time allow for efficient operation.

- Review the parameters of the setup beam flag (SBF) in view of onset of damage (beam emittance, impact distribution, operational scenarios, collimation):

A proposal for the updated SBF equations has been compiled for proton-proton operation and are discussed in more details here [2].

- Review and update the single kicker asynchronous beam dump failure scenario and its consequences:

Studies are ongoing and intermediate results on beam impacting on tertiary collimators were presented by L. Lari and R. Bruce to the 83rd/85th [3] and 95th MPP [4].

- Understand protection level of triplet with presently allocated margins between TCT and triplet apertures:

A new method to check the margins between TCT and triplet aperture with circulating beam is currently studied by MPE-PE and will be presented to MPP in autumn 2014.

- Update damage limits for tungsten collimators (TCT, TCL) with realistic impact distributions:

Work ongoing in Collimation team, FLUKA team and EN-MME. Results are expected by the end of 2014.

MOVEABLE DEVICES

The LHC collimation system together with the injection and dump protection devices play an important role for passive machine protection of the cold LHC aperture against fast beam losses (injection failures, dump failures, powering failures in normal conducting magnets, instabilities...). Although the central parts of the LHC collimation system (IR3, IR7) remained in principle unchanged, a few movable devices like tertiary collimators, secondary collimators in IR6, dump (TCDQ) and injection protection (TDI) devices have been either replaced or experienced a substantial overhaul.

- How will collimators with jaw-integrated beam position monitors be used in beam operation (interlocking, linking of LVDT-gap and BPM measurement...)?

A functional specification has been prepared and is under discussion [5]. The hardware changes in the collimation system for Run 2 are discussed in detail here [6].

- Define and optimize the qualification strategy of the collimation system for Run 2:

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A first proposal has been prepared and was implemented into the re-commissioning procedure for the Collimation system (EDMS889345). More details can be found in [6].

- Upgrade of the position measurements and controls of the TCDQ (separation of position control and interlocking, redundant interlocking of *gap* in the beam energy tracking system (BETS)):

  Controls and interlock logic have been separated. The LVDTs for jaw position measurements were replaced by potentiometers. The third potentiometer has been implemented in the BETS and will be interlocked there. More details can be found in [7].

- Interlock the tertiary collimator position as function of the beam-beam separation:

  This functionality has been prepared in the firmware. It will, though, not be implemented for the start-up with beam. As the tertiary collimators will have jaw-integrated BPM buttons it is expected that the interlocking of the beam offset in the collimator can be done more precisely and reliably with these devices. This needs to be shown with beam during the commissioning at the beginning of Run 2.

- Review the hardware changes in the Roman pots (XRP) and their impact on interlocking and re-commissioning:

  The changes in the hardware of the XRPs were presented to the 86th MPP [8]. This topic will be further followed up by the machine protection panel (MPP) in collaboration with the Collimation Working Group (ColWG).

- Improve verification of collimator settings by implementing plausibility checks:

  An application to verify the collimator settings has been developed by the Collimation team. To be deployed in the CCC.

INJECTION AND LBDS

Following to the experience in Run 1, important up-grades of the injection protection devices and the LHC beam dumping system were proposed for LS1. The ma-jor changes affecting machine protection and their status are listed below.

- Implement a redundant link from the LHC Beam Interlock System (BIS) to the re-triggering lines of the LHC Beam Dumping System (LBDS). Due to this link a beam dump can be initiated directly from the BIS without going through the trigger synchronization units (TSUs) of the LBDS:

  The new link has been designed to fulfil strict requirements for reliability (less than 1 additional asynchronous beam dump within ten years, less than 1

additional synchronous beam dump per year). The so-called CIBDS-cards (two per beam) have been installed in the LHC tunnel. Their functionality will be tested during the reliability runs of the LBDS. More details can be found in [7].

- Interlock the transfer line optics via virtual beta* limits of the transfer line collimators (TCDIs):

  The necessary functionalities have been implemented in the low-level software of the collimators. A timing telegram to transmit the optics information has been reserved. The final implementation and tests will be performed in autumn 2014.

- Interlocking of SPS-LHC beam transfer against timing issues, which cause injection into the wrong LHC beam, as experienced during 2012:

  These issues will be mitigated with the new LHC central timing, which will be deployed in October 2014.

- Consolidate issues in the redundant powering of the LBDS, which were discovered during Run 1:

  A new configuration of the trigger synchronisation units (TSUs) of the LBDS has been implemented. The mitigations will be fully validated during the reliability runs of the LBDS and the UPS powering test campaign in autumn 2014. More details can be found in [7].

- Interlock of MSI currents and TDI gaps in Beam Energy Tracking System (BETS):

  All cables necessary for the implementation are pulled and the implementation is progressing. Note that for 2015 only the TDI gaps calculated from the LVDTs at the extremities of the jaws will be interlocked. A redundant interferometric gap measurement is under development (see below). More details can be found in [9].

- Following several weaknesses discovered during Run 1, the injection protection absorbers (TDI) have un-dergone significant refurbishment during LS1 (rein-forcement of beam screen, additional temperature sensors, gearbox, RF fingers, ...). The above mentioned interferometric gap measurement system will be installed on spare TDIs, which could be installed into the LHC during a Christmas stop (e.g. 2015/16). More details can be found in [9].

- TDE dump block:

  Repeated dumps at 6.5/7TeV could cause a rise of the pressure above the venting levels. The effect has been studied and it was concluded that this is not critical for Run 2, as there is enough reserve in the N_2 bottle in case of limited venting.

- The upgrades of the MKI have been executed as planned:

Reduction of impedance by adding strips, improved cleaning to reduce UFOs, NEG coating of by-pass tubes, etc. More details can be found in [9].

- Scan the MKD waveform with beam and test the dump via the direct BLMs at injection energy:

  These tests are planned for the commissioning with beam beginning of 2015.

- Improve transparency in case of operating the LBDS in *degraded* mode with reduced redundancy:

  New procedures have been put in place for the replacement of power converters in the LBDS to avoid enlarging of tracking and interlock windows.

- Interlock the beam position in the TCSG (IR6) through the BIS instead of the SIS:

  A decision will be taken after first experience with beam in 2015.

- Mitigate the problem with the MKB vacuum interlock:

  The vacuum gauges and pumps have been replaced. Studies are ongoing to identify, if the required improvement was achieved through this measure.

- Review the number and necessity of (test-)pulses of MKDs in local mode:

  The upcoming reliability runs of the LBDS have been defined taking this in consideration.

CIRCUIT RELATED PROTECTION AND ELECTRICAL DISTRIBUTION

The LHC quench protection system (QPS) has experienced a major renovation during LS1. Besides that, mitigations have been implemented in several other systems, which are responsible for the protection of electrical circuits.

- Perform a complete revalidation of the LHC quench protection system (QPS):

  The QPS has been completely dismantled and experienced an overhaul during LS1. Therefore a full revalidation of the system is necessary to ensure the required protection levels before the magnet system can be powered. This process is currently ongoing.

- During Run 1 fast power aborts in the CMS and LHCb solenoids caused orbit distortions, which fi-nally caused a protection dump due to beam losses. To mitigate this, MPP requested to interlock a fast ramp down of these magnets:

  The magnet safety system (MSS) for the experimental magnets has been re-designed during LS1. The CMS

and LHCb solenoids will be interlocked by this system. Discussions are currently ongoing if the interlocking strategy of the experimental magnets in ATLAS and ALICE has also to be revised.

- The simultaneous trip of the 60A orbit correctors in one sector caused orbit distortions which finally caused a protection dump due to beam losses:

  The logic implemented in PVSS for the 60A correctors has been found to have been erroneously implemented and was corrected during LS1. This will prevent the simultaneous trip of many orbit correctors in the future. Furthermore, it is planned to change the PP60A timing telegram, which will give an additional protection against this type of event. Detailed information to the implemented changes can be found here [10].

- QPS: ease the implementation of critical upgrades by integrating the possibility to download the firmware remotely.

  This functionality was not implemented during LS1 and will only be implemented in a future QPS2 system (LS2 or later).

- Decrease system vulnerability of QPS by sanity checks, dependable configuration tools, enhanced automatic analysis, enforced validation of changes etc.:

  Improved supervision of parameter management and remote configuration has been implemented in the QPS hardware. Software tools to fully exploit these functionalities are currently under development.

- Improve rejection of electrical network disturbances by thyristor power converters to avoid triggering the Fast Magnet Current Change Monitors (FMCM):

  Following studies by TE-EPC the D1 power converters will be replaced in the Xmas break 2015/16. A replacement of the power converters of the warm D3s and D4s is pending due to budget constraints.

- Extend power converter interlock to other non-orbit corrector (COD) power converters:

  As a first step the tolerances in the existing COD will be improved by optimization of the functions. In a second step the quadrupole magnet currents will be added to the COD. This activity is planned for autumn 2014. The interlocking of the COD currents will be removed from the SIS, as the power converter interlock is sufficient.

- Review and unify strategy for circuits classification (maskable / non-maskable/ transparent):

  The circuit classification has been reviewed for the PIC in collaboration with BE-ABP (see [11]). It still needs to be clarified if this strategy should also be applied to the circuit classification in the cryogenic system and OP.

- Perform a full-scale test of redundant powering for the Machine Protection Systems after the UPS consolidation during LS1:

  The preparations for this test are ongoing. Pre-tests have been performed and the full-scale test has been scheduled.

- Check interference of new UPS switching frequency with ADT:

  The switching frequency of the UPS has changed from 8kHz to 7kHz and the noise level has been reduced by a factor of 5. Therefore no interference with the ADT is expected by the experts. Nevertheless a final test will be performed in autumn.

BEAM INSTRUMENTATION

The beam instrumentation systems in the LHC play an important role for machine protections (BLMs, BPMs) and for diagnostics. A significant number of improvements in these systems have been performed during LS1.

- A full implementation of a Fast Beam Current Change Monitor (FBCCM) was requested by Machine Protection to improve the redundancy in beam loss detection after LS1:

  The hardware for such a system is under test in the lab. The final performance has to be validated with beam in 2015. Only then can the decision be taken to interlock on the FBCCM or not. More details can be found in [12].

- Improve dynamic range for the interlocked BPMs in IR6 to enhance availability and machine safety:

  The required mitigations in the hardware have been performed. The sensitivity threshold between high and low intensity range is expected to be $\sim$ 2e10p/bunch. More details can be found in [12].

- The data from the interlocked BPMs in IR6 should be sent to the XPOC:

  The XPOC data, which are sent to the post mortem are already used in the TCDQ module. This will be optimized during Run 2.

- Ensure a reliable monitoring of the abort gap population with an improved BSRA and foresee automatically initiated cleaning and dumps:

  Together with the BSRT the BSRA has been completely re-designed during LS1 to solve the problem with heating mirrors and improve the reliability. The specification of the BSRA calibration procedure can be found in the document EDMS1337184. More details can be found in [12].

- Beam loss monitors:

  - A full revalidation of BLM system after LS1 is required as the system was completely dismantled and removed from the tunnel:
    The re-validation of the BLM system is ongoing.

  - Install small ionisation chambers (LICs) in the injection region to increase the dynamic range of the BLM system in case of injection losses:
    The LICs have been implemented. More details can be found in [13].

  - Implement a mechanism to inhibit the beam interlock for BLMs in the injection region during injection:
    The BLMs in the injection region have been regrouped and connected to two special crates per injection region. The interlock request from these crates could be inhibited, without influencing the rest of the BLM system. The mechanism to implement this interlock inhibit is currently under discussion. The agreement for the implementation method and the deployment strategy is expected for October 2014. More details can be found in [9].

  - Review the BLM thresholds with the experience from Run 1 and the performed quench tests with beam:
    A first proposal for the BLM thresholds for the magnets in the superconducting arcs has been presented by the *BLM threshold working group (BLMTWG)* and is currently under discussion. Furthermore, in the future the BLM thresholds will be generated directly in LSA. Therefore the algorithms will be implemented there. More details can be found in [13].

  - Displace one out of three BLMs from the arc quadrupoles to the interconnects of the neighbouring dipoles to increase the detection sensitivity in case of UFO losses:
    The change of the BLM configuration in the superconducting arcs has been approved and the installation has been performed. The post LS1 configuration is described in EDMS1307356. More details can be found in [13].

  - Send separated buffers with BLM data for B1 and B2 to XPOC:
    The implementation of this request is subject to a hardware test and can only be confirmed thereafter. More details can be found in [13].

- Will the interference between tune feedback and QPS thresholds reappear after LS1?

  The magnets used by the Q-feedback will run with low operational currents at 6.5TeV, thus, the QPS thresholds can be increased. Therefore, no problems are expected for Run 2.

- Improve reliability of OFB:

  The work in this direction has started. Significant improvements can only be expected during Run 2 but not from the start-up. More details can be found in [14]

- Perform a sanity check to verify the BPM functionality before every fill: to be discussed.

OPERATION AND SOFTWARE TOOLS

- Implement a tool for tracking of changes (exchange of hardware, expert masking, ...) in machine protection systems:

  For the long term this is planned within the AC-CTESTing framework. For the short and medium term we will still rely on procedures.

- Review SIS interlocks - which are obsolete, which should be replaced by hardware interlocks, which are newly required:

  A proposal concerning the SIS interlocks was presented to the 85th MPP [15].

- Propose a strategy to track beam induced heating after during start-up and routine operation:

  A first proposal of the strategy for the follow-up on beam induced heating in the LHC during Run 2 was presented to the 91st MPP [16].

- Improve the injection quality check (IQC) to require fewer resets: Improvements could be achieved by adjusting the warning and latching levels: To be discussed.

- Implement tools to facilitate loss-map checks by the operations crew: To be discussed.

COMMISSIONING, REVALIDATION OF MP SYSTEMS AND RMPP

- Review and update commissioning procedures for the machine protection systems. Update existing commissioning procedures, define non-negotiable re-validation tests in case of system changes as function of risk:

  The discussion of the revised commissioning procedures in the MPP is ongoing. The re-validation tests are specified in the commissioning procedures of the respective machine protection system.

- Update membership of rMPP after LS1 and define an rMPP contact person, who coordinates the dump analysis and functions as rMPP contact to operations and machine coordinators:

  To be discussed by MPP and proposed to LMC.

- Implementation of a fault tracking system, to improve consistency and quality of fault data:

  The Accelerator Fault Tracker (AFT) has been kicked off and will be available in the LHC at the start-up with beam to ease and standardize the tracking of faults by OP. The closer inclusion of equipment in the AFT will come during Run 2.

CONCLUSION

An impressive amount of work has already been performed to improve the different machine protection systems following the experience from Run 1. Many changes still need to be finalized, but the vast majority of defined actions and mitigations is on track for the commissioning and restart with beam. The re-commissioning procedures for the machine protection systems are currently being updated as vital input to update the follow-up and tracking of commissioning steps in the different systems and their correct order. Additional work has been identified in operational and software tools. For some systems - e.g. collimator with jaw-integrated BPMs or interlock inhibit for BLMs in the injection region during injection - the experience with beam will have the final word on how they will be used.

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MACHINE PROTECTION BACKBONE

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Abstract

The LHC Machine Protection System needs to adapt to the Run 2 operational requirements. In addition, important upgrades and consolidations have been implemented on the MPS backbone during the first long shutdown. This paper summarizes the changes affecting Beam Interlock System (BIS), Powering Interlock System (PIC), Fast Magnet Current Change Monitors (FMCM), Quench Protection System (QPS) and Software Interlock System (SIS).

MAGNET POWERING INTERLOCKS

Electrical circuit definitions

Failures in the electrical circuits can have different consequences on the operation with beam. They depend on the operation mode of the accelerator and therefore on the magnet operating currents. The criticality of electrical circuits is defined in the PIC as:

- Essential: If circuits are required under any condition for beam operation, including safe beams (e.g. circuits defining the geometry of the machine). The PIC will send a beam dump request to the BIS in case of powering failures.
- Auxiliary: If circuits do not necessarily impact the beam in case of failures (e.g. orbit correctors that can be compensated by other circuits). In case of powering failures, the PIC sends a beam dump request to the BIS which will decide whether to dump or not the beam depending on the operation mode of the machine.

During the first LHC run some changes have been done to the list of auxiliary circuits. The eight skew quadrupole correctors RQSX3 located in the inner triplet regions had to be included in the list of auxiliary circuits of the PIC following an unexpected dump [1].

Run 2 operation means new powering requirements and circuits which were operating at low currents during Run 1 will become more critical for operation and therefore will need to be included in the PIC configuration [2]. The list of proposed changes agreed with BE-ABP is the following:

- ROD/ROF: They will be defined as auxiliary to avoid EMC coupling on neighbouring circuits.
- RCBCHS5.L8B1: This circuit was replaced by a normal conducting circuit during Run 1 due to a non-conformity and repaired during LS1. It will be defined as auxiliary for Run 2.
- RQS: Skew quadrupoles used to correct beam coupling will be included in the list of auxiliary circuits.
- RQT: Corrector quadrupoles defining machine optics will be configured as auxiliary.

Access restrictions while powering

After the incident occurred on September 2008, new rules were defined to access the LHC underground areas during periods of magnet powering. In order to avoid relying purely on procedures, two mechanisms have been put in place to limit the current on the power converters and to interlock powering if magnet currents exceed a safe limit when access is allowed. The latter relies on an interlock logic programmed on the SIS which receives the access status from the LHC Access Safety System (LASS). Since the link between the LASS and the SIS is currently based on the Technical Infrastructure Monitoring (TIM), it has been suggested to improve it by a more dependable solution.

During LS1 a new PLC has been installed in the CCR. It will be in charge of getting the access conditions through eight safety relays from the LASS and then will publish the access status to the controls middleware, including the SIS (Fig 1). This new mechanism will increase the availability of the longest and weakest link in the existing interlock chain [3].

Figure 1: Layout of the Access Powering Interlocks

FAST MAGNET CURRENT CHANGE MONITORS

It is well known that one of the main root causes of beam dumps coming from magnet systems in the LHC is the electrical glitches affecting the CERN electrical network distribution. In 2012, a total of 24 events provoked FMCM triggers which lead to preventive dumps in order to avoid dangerous beam excursions. In most cases, these disturbances were only seen by FMCMs and no other equipment trip was recorded. An internal review of the system carried out in 2012 concluded with a set of recommendations, amongst them the replacement of the most sensitive RPTG thyristor-based power converters

(RD1 and RD34) [4]. During LS1, the design of the new switch mode converter, cabling and cooling infrastructure is being prepared. The installation of the two RD1 power converters will be carried out during the 2015-2016 Christmas break, while the two last RD34 power converters will be replaced during the 2016-2017 Christmas break.

BEAM INTERLOCK SYSTEM

LBDS retriggering link

Following a review on the UPS power distribution of the LHC Beam Dumping System (LBDS), it has been decided to implement an additional redundant triggering path directly from the BIS to the LBDS Retriggering System (RTS). This link is aimed at increasing the dependability of the LBDS and is based on two new boards (CIBDS) connected to the beam permit loops. The new hardware will trigger systematically a 250 us-delayed asynchronous beam dump request upon detection of the beam permit loop opening (see Fig 2). This link will be available from the beginning of Run 2.

The impact of the new retriggering channel on the machine safety and availability has been analysed through dedicated dependability studies [5]. Results show that the expected rate of both asynchronous and synchronous dumps can be considered as negligible for the overall MPS (see Table 1).

Table 1: Dependability of the LBDS retriggering line

Failure mode	Requirements	Dependability
Asynchronous	2 per 10 years	0.025 per 10 years
Synchronous	2 per year	0.011 per year

User systems

The existing user channel connections have been reviewed and new channels are foreseen [6]:
- LHCf detector: User channel remains disabled since 2010. If the detector is to be installed and used at unsafe intensity, the input has to be enabled on the BIS side.
- Fast Beam Current Change Monitors (FBCCM): A new interlock system will be operational from

the beginning of 2015. However, the input will remain initially masked until we gain some experience.
- CMS magnet: Detector input has been updated to trigger in case of fast power aborts of the magnet solenoid.
- CIBDS: The two new boards will be connected to the unmaskable inputs of the BIS and will trigger upon requesting an asynchronous dump to the LBDS.
- TCDQ Beam 1&2: A maskable beam dump request will be triggered if the relative position of the jaw is above the interlock limits.
- Crystal collimator experiment: It will only be moved in safe conditions and included to the maskable inputs.

QUENCH PROTECTION

During LS1 the protection system for the superconducting circuits has been upgraded with the aim to improve the immunity to ionizing radiation and to extend its diagnostic capabilities. In the frame of the R2E campaign, the equipment in charge of the inner triplet protection has been relocated to low radiation areas (UL14/16 and UL557). In addition, new radiation tolerant hardware has been installed in exposed underground areas (i.e. RR13, RR17, RR53, RR57, RR73 and RR77) where relocation was not possible during the long shutdown.

Main circuit protection

Main circuits are equipped with quench heater strips to dissipate the stored energy within the magnets. Since quench heater faults can be dangerous for the protection of the magnet, an enhanced monitoring system has been developed to identify faulty heater circuits and to detect precursor states of potential failures. The new system acquires both discharge voltage and current using a sample rate of 192 kHz and 16 bits resolution. The implementation of the new hardware requires new protection crates which have been adapted to the new redundant UPS powering scheme. These crates are equipped with two external radiation tolerant 230V AC-DC converters which will be monitored by the DAQ systems.
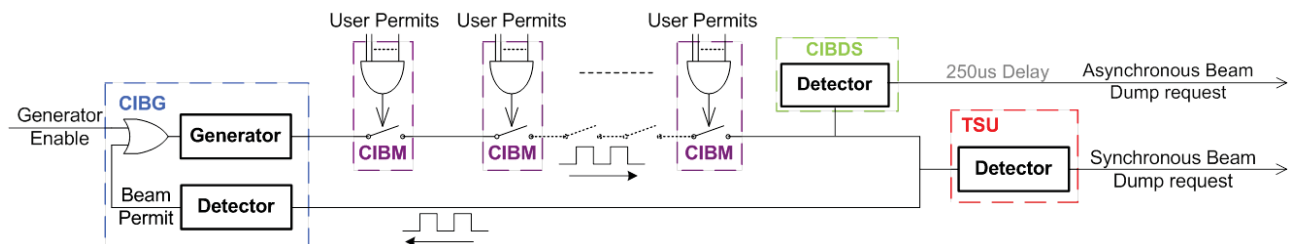

Figure 2: Layout of the Beam Permit Loop with the new CIBDS board to trigger an asynchronous beam dump request

In order to monitor the electrical insulation strength during fast power aborts, main dipoles and quadrupoles will be equipped with voltage feelers. Per sector a maximum of 54 feelers for the main dipole circuit and 55 for each of the main quad circuits will be installed with the goal to detect earth faults in the main circuits. In addition, all data will be logged in the logging database for data analysis.

With regard to the energy extraction (EE) systems, new arc chambers will be installed in the RQD and RQF circuits, which will allow increasing the maximum operational voltage of these circuits. In addition, the installation of snubber capacitor banks will be required to suppress voltage transients in the main quads. Furthermore, the EE resistors for the main circuits will be reconfigured for 7 TeV operation in order to reduce the maximum voltage across the switches and to avoid quench back [7]. Recommended values are represented in Table 2.

Table 2: EE characteristics of main circuits after LS1

Circuit family	R_{EE} (mΩ)	τ (s)	V_{EE},max(V)	dI/dtmax (A/s)
RB	2x83	103	900	-117
RQ	7.8	34	94	356

600A circuit protection

During Run 1 several 600A circuit families exhibited coupling-current induced quenches (quench back) during fast power aborts. In the end-of-run powering tests a reduction of the energy extraction resistor value was successfully tested in a RQTD circuit in order to increase the discharge time and to avoid quench back [8]. Based on this test and numerical modelling it was proposed to reduce the resistor value of the RQTL9 circuits to 0.4 Ω.

Operational improvements

Significant efforts have been done to improve operational software tools with the aim of facilitating the most common QPS tasks. The so called "QPS swiss knife" will provide remote power cycling capabilities. QPS settings and thresholds will be now stored in LSA database and the correct configuration of the protection systems will be guaranteed through the systematic execution of consistency checks.

SOFTWARE INTERLOCK SYSTEM

By the end of the Run 1, there were 52 interlock types implemented on the SIS. Due to the non-negligible number of changes applied to the different systems and to the new operational requirements a full revision of the interlocks will be required [9]. Three new interlocks will be added for:
- Embedded BPM collimators: Interlock on the beam offset with respect to the collimator centre.
- Abort gap monitoring: Interlock in case of excessive particle density in the 3us abort gap.

- Virtual beta* for transfer lines: Similar concept as for ring collimators. The SIS will publish the virtual beta* value associated with the optics.

In addition, some of the existing interlocks need to be updated, such as:
- Access Powering Interlocks: A new more dependable system has been put in place during LS1 and is ready for the restart of the powering tests.
- Particle type interlock: It avoids that protons are sent into a ring setup for ions and vice-versa. Particle type to be identified from SPS timing telegram.

SUMMARY

LS1 has served to implement quite some changes and upgrades to the MPS backbone which aim at increasing the machine dependability and to adapt to the new operational requirements. Consolidations will hopefully reduce machine downtime; especially from magnet powering systems mainly due to the reduced number of radiation induced spurious trips and electrical network perturbations.

Changes to the MPS will be validated following dedicated MPS procedures already reviewed by the Machine Protection Panel (MPP).

ACKNOWLEDGEMENTS

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BLMs AND THRESHOLDS AT 6.5/7 TeV

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Abstract

During Long Shutdown 1 the Beam Loss Monitoring system went through several hardware upgrades and general maintenance. Many elements of the system, starting from the tunnel detectors to the threshold-comparator cards were brought from their locations to the lab and refurbished. Almost 30% of the detectors will be reinstalled in new positions, optimizing system sensitivity to so called UFO losses. In order to tune the thresholds on cold magnets a series of quench tests has been performed during Run 1. An extensive analysis of these tests has been done leading to suggestions of a new sets of beam abort thresholds. The threshold setting strategy has been proposed. New tool to generate and set thresholds is being developed.

INTRODUCTION

The Beam Loss Monitoring system (BLM) performed very well during LHC Run 1, dumping the beam in cases of losses due to beam instabilities and providing terabytes of diagnostic data. The beam-abort thresholds have been tuned during the 3-year run and allowed a safe and efficient machine operation. Nevertheless, a series of hardware upgrades and refurbishments were performed during LS1. A campaign to recalculate the BLM thresholds has started in view of Run 2. These two main aspects of the preparation of the system for the next run are discussed in this paper.

HARDWARE CHANGES

Relocation of detectors - One of the most important change in the BLM system is the relocation of about 30% of the detectors on the cold magnets. Motivation for this relocation was the observation of losses all along the ring and not only in short straight sections where beam size reaches its maximum. This change is discussed in detail in [1].

High-voltage issues - In case of very high and prolonged losses the High Voltage (HV) power distribution network was unable to support the detectors leading to a decrease or disappearance of their output signal. The voltage drop is monitored and interlocked by the Software Interlock System. During Run 1 the HV drops lead to unnecessary beam dumps as well as non-reliable measurement of extensive losses. Two mitigations to the this problem have been applied [2]. The first one is the installation of suppressor diodes and resistors in some of the HV distribution boxes. This allows to limit the voltage drop to 220 V. The second mitigation is an exchange of resistors in BLECF tunnel cards what decreases the voltage at which the card

issues the HV beam dump interlock signal from 1370 V to 950 V.

Maintenance and upgrade of the system - The following changes to the BLM system hardware have been agreed:

- Installation of temperature-regulated racks.
- Exchange of signal cables to better isolated cables for 240 detectors with the largest noise.
- Refurbishment and re-check of all electronics cards.
- Improvement of the system sanity checks.

At the same time, a series of changes in the firmware is planned as well as the replacement of the front-end computers in the processing crates with newer and faster Linux CPUs. They will allow faster data transfer rates, that will be utilized, for instance, to increase the length of the transmitted post-mortem and UFO buster data to the full 43690 samples. This change is discussed in detail in [3].

New measurement techniques - Although the backbone of the BLM system are standard, 50-cm long ionization chambers (IC), other types of detectors are also used.

The maximum current which can be measured by the BLM electronics is limited to 1.27 mA, what limits the maximum radiation level which can be monitored using standard IC to about 23 Gy/s. In some cases, for instance during the injection process, the losses can be much higher, therefore a less sensitive detector was needed. A scaled-down version of the IC is called Little Ionization Chamber (LIC). Those detectors are about 10 times less sensitive then the original ICs and their maximum measurement range extends to about 230 Gy/s. They have been installed in IR6 (dump losses observation), IR2 and IR8 (injection losses) and discussion about installation in IR3 and IR7 is ongoing. In many cases they replace Secondary Emission Monitors (SEM) which have a sensitivity about $7 \cdot 10^4$ smaller then standard detectors and were found not sensitive enough to observe the majority of LHC beam losses.

Diamond detectors were tested during Run 1 for high temporal resolution measurements of beam losses. They were used by the machine systems as well as by the experiments (cf. CMS Beam Condition Monitors). During LS1 a total of 12 diamond detectors will be installed in IR2, 4, 5, 7 and 8 and connected to machine beam observation systems. They will be used to observe the bunch structure of the losses.

BLM IC location outside of the magnet cryostat leads to relatively low sensitivity to the loss pattern. As a consequence in some cases it is difficult to distinguish between normal losses (eg. due to luminosity production) and potentially quench-provoking abnormal losses [4]. In order to
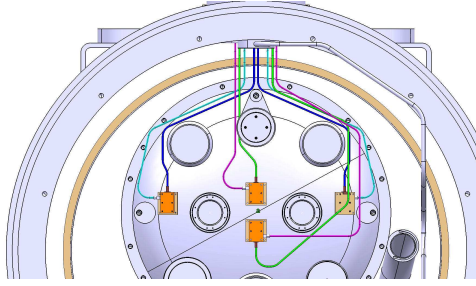

Figure 1: Installation of Cryogenic BLMs on the front face of main dipole cold mass.

restore the ability the BLM system to prevent quenches the radiation sensors should be installed closer to the superconducting coil, improving the correspondence between BLM signal and energy deposition in the coil.

While the final cryogenic BLMs will be installed only during LS2 and LS3, a test installation on the cold masses of two main dipoles (MB) has been performed. Figure 1 presents the location of the four detectors on the MB end cup. The installation is described in [5].

QUENCH TEST RESULTS

Numerous quench tests have been performed during the Run 1 [6]. The last, most advance series of experiments took place in February 2013. The analysis started afterwards and is being finalized now. The quench tests allow not only to assess limits of the machine performance but also allow to fine-tune quench-preventing BLM thresholds, study particle shower beam loss simulations and validate models of heat transfer inside the superconducting coils.

The main loss types threatening LHC operation after LS1 are expected to be steady state losses in cleaning and luminosity insertions and so called UFO losses everywhere in the cold sections. Both loss types produce different temporal and spatial patterns and both were investigated.

The complete analysis procedure of the quench test is schematically illustrated in Fig. 2. It consists of the following steps:
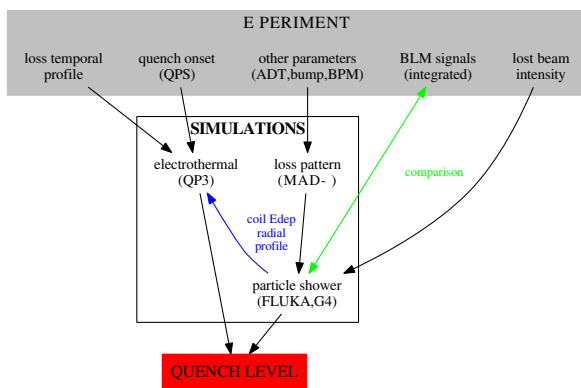

Figure 2: Schematics of quench test analysis procedure.

- Perform experiment assuring a good confinement of the losses and a good measurement of beam intensity decay and BLM signals; other parameters are measured depending on experiment.
- Based on knowledge of the beam trajectory, aperture and the beam excitation mode, simulate the loss pattern.
- Use the loss pattern together with FLUKA/Geant4 geometry of the sector of the accelerator involved in the test to run particle shower simulations.
- Scale the simulation results: BLM signals and energy deposit in the coil (E_{dep}), with number of lost protons measured during the experiment.
- Compare obtained BLM signals with the ones measured during the experiment; a good agreement gives a confidence in accuracy of E_{dep} estimation.
- The energy density in the coil is the first main result of the test.
- The radial profile of the E_{dep} is an input to electro-thermal simulations (usually QP3 code).
- Second input is the temporal behaviour of the beam loss (from measurement).
- Output of the electro-thermal code is the second result of the test.

The above analysis scheme is complex. The two quench level values obtained at the end are not independent as the electro-thermal simulation uses the radial shape of the energy deposition in the coil obtained with particle shower simulation.

The outcome of the quench test experiments is a better understanding of electro-thermal properties of the coils and the loss patterns generated by various beam excitation mechanisms. These studies were reported in numerous Quench Test Analysis Working Group meetings [7], conference papers and ATS notes. A journal publication summarizing the results is prepared and a Workshop on Beam Induced Quenches will take place in September 2014. The most important quench level values obtained are shown in Table 1. In both cases the quench levels are higher then assumed for the initial settings of BLM thresholds. Particularly in the millisecond timescale the difference is factor 5 to 10. In addition, for this timescale, the discrepancy between electro-thermal and particle shower analyses is the largest.

Table 1: The main results of the quench tests.

Loss duration	Experiment + FLUKA	QP3	Run1 value
5 ms	$198 - 400$ $[\mathrm{mJ/cm^3}]$	$58 - 80$ $[\mathrm{mJ/cm^3}]$	40 $[\mathrm{mJ/cm^3}]$
20 s	$41 - 69$ $[\mathrm{mW/cm^3}]$	$74 - 92$ $[\mathrm{mW/cm^3}]$	20 $[\mathrm{mW/cm^3}]$

BLM THRESHOLDS FOR STARTUP

Thresholds settings at the beginning of Run 1 were based on a limited number of simulations which were available at that time and an algorithm from [9]. During the Run 1 the thresholds were tuned, what is documented in numerous ECRs and presentations of the BLM threshold working group [8]. Clearly, this experience is a solid base for defining the new thresholds for LHC startup in 2015.

On the other hand, the thresholds were verified up to the beam energy of 4 TeV and the extrapolation to 7 TeV, at which the quench levels are 2-3 times lower, represents a serious challenge. Therefore, an effort to recalculate the BLM thresholds has started.

The values of the BLM thresholds depend on the assumed loss scenario. For instance, a localized loss typically gives lower values of the BLM thresholds than spread loss. Moreover, many of the loss scenarios used to calculate BLM thresholds for Run 1 turned out to be not relevant and others - like the UFO losses - were not initially considered. Therefore, a **review of the loss scenarios** is being performed.

The BLMs are grouped in families which have identical beam-abort master threshold tables, usually because they protect the same elements from the same beam loss scenarios. The number of independent families is more than 150, but many of them have identical thresholds. In order to reduce system complexity the **BLM families will be reviewed** and their number will be reduced.

One of the main tasks is also **reviewing the models** used by the threshold calculation procedure. On the cold magnets the thresholds are calculated following Equation 1:

$$T(t_{loss}, E_b) = f \cdot \frac{S_{BLM}(t_{loss}, E_b)}{E_{dep}(t_{loss}, E_b)} \cdot QL(t_{loss}, E_b) \quad (1)$$

where:

- $S_{BLM}(t_{loss}, E_b)$ is a BLM signal as a function of beam energy, for a given loss scenario, obtained from particle shower simulations and checked with experiments.

- $E_{dep}(t_{loss}, E_b)$ is energy density in the coil; it is obtained from particle shower simulations and it is a function of beam energy but also the loss duration/scenario.

- $QL(t_{loss}, E_b)$ is the quench level, obtained from electro-thermal simulations and from measurement; it is a function of magnet current (which in case of dipoles is proportional to E_b) and the loss duration.

- f represents empirical corrections to the threshold values, for instance the discrepancy between electro-thermal simulations and quench test results.

The new particle shower simulations give more accurate parametrizations of $S_{BLM}(t_{loss}, E_b)$ and $E_{dep}(t_{loss}, E_b)$.

To prepare the thresholds the extensive simulation program has started.

It must be noted that the tools used during Run 1 did not allow for generation or threshold based on more then one loss scenario for a given BLM family. The tool developed for startup will contain this functionality.

Another action foreseen before the startup is a check of minimum thresholds against loss fluctuations appearing in various moments of the accelerator cycle, as done in [10].

Despite of all the experience collected during the Run 1 and quench tests it is crucial to be ready to introduce empirical corrections to the BLM thresholds during the Run 2.

New threshold generation approach

The current thresholds generation application (called `thrc++`) is a standalone C++ application making use of `root` classes for visualization and interpolation. The program was compiled and all the parameters defining BLM thresholds were stored in card-files in svn directory, providing history of changes.

In the new approach the algorithm to generate thresholds as well as values of parameters characteristic for each BLM family is stored within the LSA database [11]. The security of the data, the algorithm and the whole application is improved not only by Oracle mechanisms but also by the RBAC mechanisms.

CONCLUSIONS

During LS1 the BLM system went through a hardware maintenance and upgrades which will increase its reliability, availability and diagnostic potential. As one of the main tasks of the system is quench prevention, a series of quench tests have been performed and analyzed. As a result new, more realistic estimations of quench levels have been established and the code which will be used for BLM threshold settings has been validated. The thresholds need to be recalculated as new simulations and measurements are available now. The structure of the BLM families will be reviewed, reducing unnecessary complexity. A new, safer implementation of the threshold calculation algorithm will be used.

ACKNOWLEDGMENT

The authors would like to thank the numerous colleagues who worked on the BLM system in recent years and who assisted in performing quench tests.

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BEAM INSTRUMENTATION FOR MACHINE PROTECTION

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Abstract

This paper will focus on three instruments with implications for machine protection, namely: the abort gap monitor, the fast beam current change monitor and the interlocked BPMs in IR6. For each of these instruments a brief description of the issues observed during Run 1* will be given and the improvements done during the long shutdown (LS1) presented, with particular focus on the performance and reliability aspects.

INTRODUCTION

In order to guarantee the safe functioning of the LHC it is important to monitor certain beam parameters with sufficient accuracy and reliability. In particular in this paper the focus will be set on three devices: the interlocked beam position monitors in IR6 (beam extraction), the fast beam current change monitor (FBCCM aka dI/dt) and the abort gap monitor (BSRA).

The interlocked BPMs in IR6 are used to avoid large orbit offsets at the beam extraction septum which could lead to the beam scraping the septum or the absorber (TCDS) that protects the septum in case the dump kicker (MKD) misfires. A schematic of the extraction channel is depicted in Fig. 1. The orbit reading of these special Beam Position Monitors (BPMs) is directly linked to the beam dump, meaning that both the measurement accuracy and the presence of measurement glitches are important, the later leading to undesired beam dumps and the consequent loss of physics time.

The FBCCM monitor is based on the fast current transformer and is used to detect fast AC (bunched) current changes which could arise from beam losses or debunching. In fact beam losses are already monitored by the beam loss monitors and indirectly also by the quench protection system. The FBCCM is thus primarily used to protect from fast beam debunching (RF issues).

Finally, the BSRA is used to monitor the population of particles in the 3 μs long abort gap. Particles that are present in the abort gap are swept over the machine elements at the moment the dump kickers fire. Hence, it is necessary to assure that the number of particles in the abort gap remains below a safe limit. The BSRA is based on the detection of synchrotron light and during Run 1 it was not connected to the beam dump system due to its limited reliability.

During Run 1 several issues affected the reliability of these devices [1]. Actions have been taken during LS1 to address these problems.

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*With Run 1 we refer to the LHC running period 2009-2013.
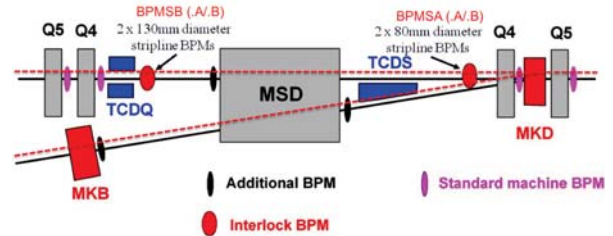

Figure 1: Layout of the beam dump channel.

INTERLOCKED BPMS IN IR6

The BPMs consist of strip-line pick-ups installed after the Q4 quadrupole (originally named BPMSA and renamed to BPMSX after LS1) and just before the TCDQ absorber (BPMSB, renamed to BPMSI after LS1) [2]. Each monitor is doubled for redundancy and is referred to as system A or system B. The signal acquisition is based on the standard LHC normaliser design [3][4], but with a custom firmware adding the interlocking features. The whole interlock logic is made in hardware (and firmware) and is connected to a maskable input of the beam interlock controller (BIC).

The interlock logic requires that either 70 bunch readings out of the last 100 turns are out of limits (protecting against single bunches with large excursions) or that 250 readings in the last 10 turns are out of limits (protecting against fast orbit excursions). The limits are set at 3 mm [5].

The normaliser triggers a position acquisition every time a signal pulse larger than a given threshold is detected at its input (asynchronous acquisition). Unfortunately, if the pulse amplitude is close to the threshold the read position is quite inaccurate and can trigger the interlock. Moreover, the use of shorted strip-line detectors as pick-ups implies the presence of re-reflections in case of not perfect matching at the electronics end. In the initial design two remotely selectable detection thresholds had been included, one for the pilot bunch and one for the nominal bunches. In real operation, however, the intensity distribution of the bunches is far from uniform and it was impossible to find threshold levels accommodating all the possible signal amplitudes and the corresponding reflections.

The situation was further complicated by the need to use the same threshold values for both the proton and the heavy ion runs where the bunch intensities are quite different.

The software tools available to the operators to study the interlock events was insufficient, making it difficult to understand whether the interlock fired due to real beam oscillations or just the aforementioned quirks.

Actions on BPM interlock during LS1

During LS1 several actions have been carried out on the BPM interlock system, in particular the shorted strip-lines have been modified and now have proper 50 Ω terminations reducing the re-reflections (Fig. 3). For the same purpose absorptive low-pass filters, with a cut-off frequency of 100 MHz, have also been added at the pick-up output. The orbit and interlock functions have been separated and are now handled by two different acquisition boards. This action frees resources for the post-mortem data of the interlock function, allowing a history buffer of 3564 bunch slots over 294 turns. The FESA server will be adapted to this new structure and to the new firmware (also the ppc VME CPUs have been replaced with x86 modules). A GUI for the analysis of the BPM interlock post-mortem data is now under development in BI with the collaboration of OP. Figure 2 shows the main modifications to the BPM interlock system during LS1.

All the BPM DAB acquisition cards are now installed inside thermal controlled racks since rather large temperature drifts perturbed Run 1. However, this change is more important for the orbit system than for the BPM interlock.
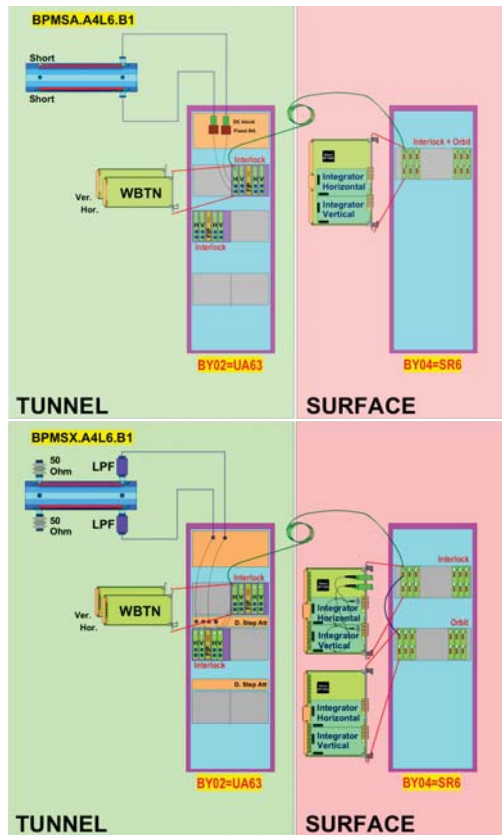

Figure 2: Changes made to the interlocked BPM system during LS1. The top picture shows the situation during Run 1 while the bottom picture shows the situation after LS1.
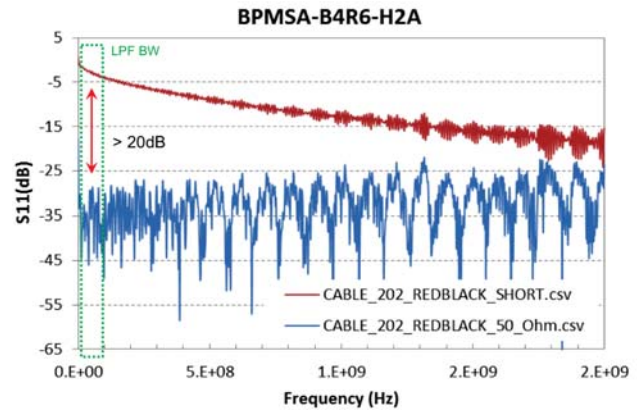

Figure 3: Reflection amplitudes for the shorted strip-lines (red curve) and for the 50 Ω terminated ones (blue curve). By matching the downstream ports of the strip-line and limiting the bandwidth to 100 MHz, reflections amplitudes (S11) are reduced by 20 dB.

BPM interlock after LS1

The modifications of the pick-ups allow the extension of the operational range of the normaliser card for each sensitivity mode by about 10-15 dB as shown in Fig. 4. Nevertheless, since the pilot bunches are usually lost during the proton physics cycle, it is necessary to keep the two sensitivity modes and to set the detection threshold of the low sensitivity mode above the intensity of the pilots (values to be defined with OP and the machine protection team). This means that for the proton physics there will be little change compared to Run 1. The main advantages will be in the post mortem analysis and in the heavy ion physics (like Pb-Pb and Pb-p) where the high sensitivity mode can now cover easily the required range.
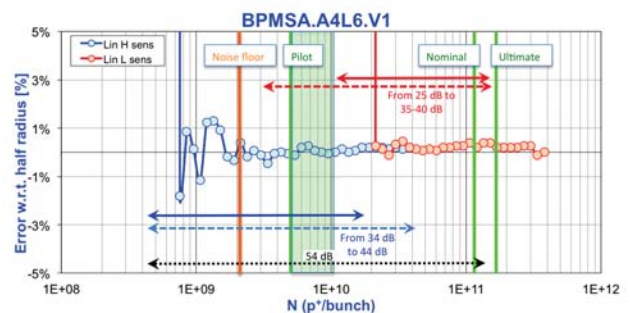

Figure 4: Position error vs. signal amplitude for the post LS1 situation. The red curve shows the low sensitivity response, while the blue curve shows the high sensitivity case.

BPMs and scrubbing dublets

The electron cloud phenomena, caused by secondary electrons released from the beam pipe surface, may induce

instabilities in the closely spaced proton bunches and constitute an excessive thermal load for the cryogenic system. Beam scrubbing is an effective way of reducing the secondary emission coefficient of the beam pipe surface and thus reducing the e-cloud effect. Unfortunately, the effectiveness of the scrubbing decreases as the secondary emission yields decreases, meaning that it takes a very long time before the emission coefficient is reduced below the e-cloud threshold. The effectiveness of the scrubbing can be increased by reducing the bunch spacing. This is one of the reasons why in Run 1 the scrubbing was done with 25 ns beams and the subsequent physics with 50 ns bunch spacing. Although the emission coefficient obtained after scrubbing was not below the threshold for 25 ns operation, it was for 50 ns. After LS1, running at 50 ns will have neg-ative implications due to the large pile-up in the experi-ment. In order to efficiently scrub the LHC for 25 ns op-eration, it has been proposed to use the so called *doublets*, i.e. sequences of bunches with 5 and 20 ns spacing. This is obtained by capturing trains of 25 ns bunches across two RF buckets in the SPS [6]. In order to use this new scrub-bing scheme it is important that the various LHC devices can cope with the doublets beam. In particular it is im-portant that the orbit and BPM interlock systems can give reliable information. Computer simulations and laboratory tests have been performed to study the response of the BPM system to the doublets pattern. Figure 5 shows the results of these simulations. For the arc BPMs the largest error is 0.4 mm and stays below 0.2 mm for high intensity bunches, while for the interlocked BPMs the error can be as large as 1 mm, reduced to 0.5 mm for high intensity bunches. In both cases the error shows a maximum exactly at 5 ns spac-ing which is the spacing of the doublets. Nevertheless, if these values are confirmed with beam it should not prevent from scrubbing the LHC with doublets.

FBCCM

The fast current change monitor is a device that detects rapid changes of the bunch currents. The system, as already mentioned, is based on the current measurements provided by the fast beam current transformers (FBCT aka BCTFR). Figure 6 shows the schematics of the FBCCM signal processing.

The signal from the FBCT is first digitised, then a narrow-band band-pass-filter (FIR) and an IQ-demodulator are used to extract only the 40 MHz component of the signal. The variations over time of each 25 ns bin are computed using six different integration windows (running sums) corresponding to: 1, 4, 16, 64, 256 and 1024 turns and compared with energy dependent threshold values.

If any of the computed delta is above the corresponding threshold, the interlock output is fired pulling the BIC channel (initially masked during the commissioning phase). The thresholds are stored in a lookup table which is addressed using the beam energy from the LHC timing tele-gram (MTG).
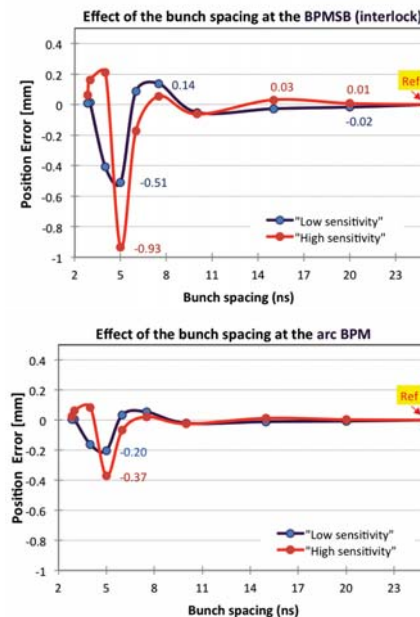

Figure 5: Measurement error as function of the *doublets* bunch spacing. The top plot refers to the strip-lines of the interlocked BPMs, while the bottom plot refers to the arc button BPMs.
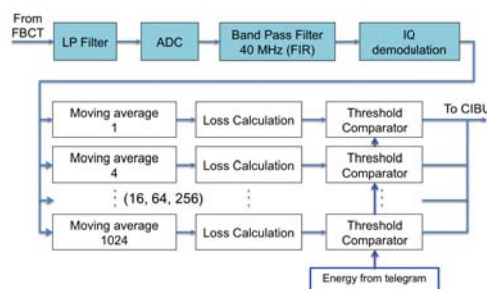

Figure 6: Schematic diagram of the signal processing inside the FBCCM monitor.

The system is contained in a box to which the bunch clock, the Master Timing Generator (MTG) and the FBCT signals are fed. The control of the parameters and the read-out of the data takes place over a TCP connection (ethernet).

FBCCM modifications during LS1

Two similar firmware implementations of the FBCCM have been tested during Run 1. One of the two designs has been retained without significant modifications. The electronics cards on the other hand have been consolidated with the replacement of development boards by custom made boards. The FBCCM boxes have also been split with only one channel per box in the new version in order to eliminate the observed crosstalk. The hardware modifications have also reduced the noise, mainly by better separating the analogue and digital parts. A picture of the new FBCCM box can be observed in Fig. 7.

Figure 7: Picture of the operational FBCCM electronics box.

Another limitation of the FBCCM observed in 2011 was the position dependency of the fast beam current transformers. This issue resulted in orbit oscillations mistakenly identified as fast current variations. This problem has also been studied during LS1 and two possible solutions have been identified: a CERN developed wall current monitor (BCTW) and a CERN/BERGOZ integrating transformer (BCTI). Both solutions can potentially solve the issue and will be tested in parallel after LS1.

FBCCM after LS1

Six FBCCM acquisition boxes have been produced. Four will be installed in LHC and two kept in the lab for tests and spare. Of the four installed devices, two will be the operational devices (one per beam, identified as system A) with stable hardware and firmware and will be connected to the LHC FBCT monitors. The other two (system B) will be used for debugging and development and will be connected to the alternative fast current monitors under development, the BCTW and the FBCTI respectively. Similarly, for the fast current transformers the Run 1 devices will remain the operational devices (system A), while the BCTW and FBCTI will be used on system B for devel-opment. The FBTCI will be installed on beam 1, while the BCTW on beam 2. The devices are installed in a way that allows switching between FBCTI and BCTW without breaking vacuum.

A FESA class and the relative expert GUI have been produced, while the post mortem analysis tool is still being worked on in collaboration with OP.

As already mentioned, the FBCCMs will be connected to the beam interlock system (BIS), but the relative BIC channels will be initially masked allowing the collection of trigger statistics. After the commissioning and validation phase the mask will be removed and the FBCCM will become part of the machine protection system.

Some beam time will be needed for the commissioning of the FBCCM, mainly for repeating and validating the tests performed in the lab, requiring controlled losses, beam scraping etc. Most of the debugging and setting up can be carried out in parallel with the normal operation of LHC. The possibility of carrying out realistic beam simulations in the lab is also under investigation.

ABORT GAP MONITOR

The abort gap monitor is based on an MCP-gated-photomultiplier-tube measuring the intensity of synchrotron light (SL) emitted by the beam during the abort gap [8]. The abort gap itself is a $3\,\mu$s long gap in the longitudinal distribution of the particles in LHC that has to be kept "empty" in order to allow the safe firing of the extraction kickers. Any particle inside the abort gap is, due to the rising edge of the dump kicker, only partially deflected and will be lost somewhere around the ring instead of being sent to the dump. If the number of these particles is too high damage can be caused to the accelerator components or to the experiments.

The initial specifications of the instrument did not demand high grade reliability since the device was foreseen only as a monitor not connected to the beam dump system. Only an alarm had to be generated for the control room operators, if the level of particles in the gap exceeds a certain threshold.

The abort gap population is published and logged at 1 Hz. The measurement accuracy depends on the SL intensity and thus on the beam energy ($I_{\rm SL} \propto E^4$). For protons the sensitivity is better than 10% of the quench level for all energies (fulfilling the specifications). For lead ions, however, the specifications can only be fulfilled above 1.5 TeV, since the amount of light at lower energies is too low and a new undulator would be needed to improve on this [9]. If properly calibrated the accuracy of this monitor is much better than the 50% requested in the specifications.

Reliability of the BSRA

The main source of error is the stability of the various calibration factors. These factors are influenced by: the alignment of the optical elements in the telescope, the attenuation of light in the different components, the gain-voltage curve of the PMT, the stability of the HV generator, the ageing of the photocathode of the PMT and finally the electromagnetic noise in the signal.

The BSRA is part of the synchrotron light telescope and there are a few compatibility issues that reduce its reliability. The Beam Synchrotron Radiation Telescope (BSRT) consists of a rather complex optics system in order to measure the transverse beam size precisely and is still in constant evolution. In 2012 an RF heating problem on the extraction mirrors has been discovered. This problem has become very serious with the increase of the beam intensity during the run, requiring the replacement of the damaged in-vacuum mirrors. The mirror heating problem has been carefully addressed during LS1 with extensive RF computer simulations, test bench measurement and mechanical redesign. A completely new extraction mirror layout

has been developed and installed. According to the simulations and the test bench measurements no heating issues are expected after LS1, it has however to be noticed that the confidence level of the RF simulations is not very high, due to, among other reasons, the difficulty of simulating the thin multilayer reflecting coating of the mirrors.

The optical system of the BSRT has been completely redesigned during LS1 in order to move the working point to lower wavelengths as compared to Run 1. This modification is necessary to cope with the higher beam energy and the resulting smaller beam size. In the redesign particular care has been given to the abort gap and longitudinal density monitors (BSRL, better known as LDM) integration, reducing the interferences between the different systems to the minimum.

BSRA after LS1

Concerning the BSRA, the most important change during LS1 is represented by the redesign of the BSRT extraction mirror and of the optical telescope setup. Another important action has been the review of all the calibration and verification procedures of the BSRA. A document describing these actions and the way these should be implemented in the FESA server, with particular emphasis on the reliability aspect, has been produced and will constitute the base for a refurbishing of the software layer [10]. The new FESA server will include several automated calibration and self-test procedures as well as a dedicated interlock property. It is foreseen to trigger self checks from the LHC sequencer and verify the health of the system at the start of every cycle. The interlock property will be used by the SIS to trigger the cleaning of the abort gap or to trigger the beam dump. Figure 8 shows the logic that will be implemented in the interlock property.

Another action during LS1 has been the redesign of the electronic acquisition chain of the BSRA. The fast linear amplifier and the DAB integrator will be replaced by a custom integrating amplifier and a 100 MHz ADC FMC module. This change should allow a reduction of the noise level and thus an increase in sensitivity of the BSRA. The new electronics will probably not be deployed for the LHC startup as it looks difficult to completely validate the hardware and the software in time.

CONCLUSIONS

The limitations observed during Run 1 and the actionstaken during LS1 for the interlocked BPMs in IR6, the FBCCM monitor, and the abort gap monitor have been presented together with the expected performances after LS1. The BPMs should not be a performance limit after LS1.

The detection threshold level of the low sensitivity mode has to be defined together by BI and OP.

A full set of FBCCM monitors will be available after LS1. The prototypes gave encouraging results. Some debugging and fine tuning will be needed during the commis- sioning phase requiring dedicated beam time.
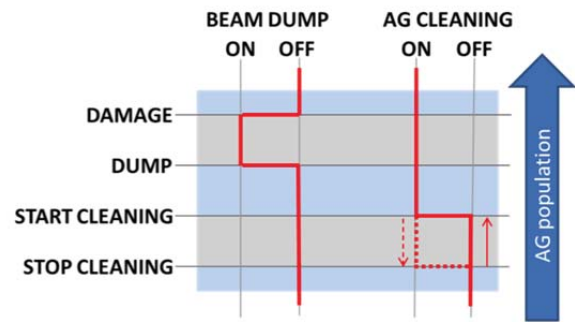

Figure 8: Abort gap cleaning and beam dump logic implemented in the BSRA FESA server. The four thresholds will be defined by the machine protection team.

The reliability of the BSRA will be improved as well as the sensitivity. The system will include self-diagnostic and calibration procedures and will be connected to the SIS for triggering the abort gap cleaning and eventually the beam dump if needed.

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COMMISSIONING AND OPERATION OF THE MACHINE PROTECTION SYSTEM

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Abstract

The presentation is reviewing the MPS commissioning strategy we used during Run1 for the initial setup of the machine and the intensity ramp-up. Based on operational experience, new strategy for the Set-Up Beam Flag definition is proposed to cope with the new beam parameters for Run 2.

MPS COMMISSIONING PROCEDURES

Before the first start-up, in order to properly commission the systems belonging to the machine protection For Run 1, series of detailed commissioning procedures defined in 2009 were used to coordinate the tests related to machine protection during the machine check-out and the beam commissioning. The EDMS reference of these procedures and the concerned systems are listed below:

LHC-OP-MPS-002	Collimation System Commissioning
LHC-OP-MPS-003	Injection Protection System Commissioning
LHC-OP-MPS-004	Beam Interlock System Commissioning
LHC-OP-MPS-005	Powering Interlock System Commissioning
LHC-OP-MPS-006	Vacuum System Commissioning
LHC-OP-MPS-007	Beam Dump System Commissioning
LHC-OP-MPS-008	FMCM System Commissioning
LHC-OP-MPS-009	BLM System Commissioning
LHC-OP-MPS-010	Warm Magnet Interlock System Commissioning
LHC-OP-MPS-014	Software Interlock System Commissioning

These procedures need to be revisited and updated as most of the system have been modified during LS1. New procedures will be added (for example for FBCCM system) and the table of contents will be modified to follow the actual intensity steps and ramp-up that will be done. The tests with beam will specify what needs to be validated at injection energy or top energy, with pilot or with bunch trains, and if tests are needed when beam parameters are changed (crossing angle, β^*,...).

A revision of the periodicity of the tests is also needed and each test will be noted in one of the following category:

MPS test follow-up

All along Run 1, the progress of the MPS commissioning was tracked by the usage of a simple SharePoint site. During the MPS review in 2013, it was proposed [1] to extend the AccTeststing framework used for hardware commissioning in order to replace the SharePoint site. The

N:	Not to be repeated (eventually only executed at beginning of run but not after Christmas stops)
S:	To be repeated only after longer shutdowns during a run (e.g. Christmas stops)
T:	To be repeated after Technical Stop (including longer shutdowns during a run)
P:	Periodical repetition required, like 1 x per month; details to be defined in th text
O:	To be repeated when LHC optics crossing scheme is changed

implementation of the new features required for the migration of the information is progressing, (barriers, dependent/composed tests) but the framework will not be fully ready for the start-up. Few type-tests are implemented, for example the source test of the BLM system or the MKD exchange.

The SharePoint site will still be used for post-LS1 tracking of MPS tests. The site is driven by few individuals (MPP experts) in parallel of the machine coordination. The period of restart will be used to capture sequence and dependencies in view of modeling the info to be first used after Technical or Christmas stops in 2015.

SETUP FROM PILOT TO FIRST COLLISIONS

Initial set-up strategy

The Beam commissioning period starts with establishing the operational cycle with "safe" beam conditions. The main step are the 450 GeV commissioning (both beams capture, closed orbit), optics checks and aperture measurements, ramp and squeeze commissioning (both orbit establishing and optics correction) and finally collisions process.

The MPS commissioning and validation are interleaved with operation during this first phase to prepare the intensity ramp-up:

- Collimator setup and validation (so-called loss maps) at injection, flat top, end of squeeze and in collisions.

- LHC Beam Dump System (LBDS) validation (so-called asynchronous beam dump test)

- Injection protection system set-up and validation

The intensity ramp-up starts when the operational cycle is well establishing meaning the sequence of operation to be done is validated and all the MPS tests are signed by MPP for the next steps. It is also divided in 2 main steps:

first operation with nominal bunch intensity and then the bunch trains operation.

Beam Setup in 2012

Beginning of 2012, the whole process of initial beam commissioning has been done in 22 days. The details are reported in Table [1].

Table 1: planning of the main milestones of the beam commissioning in 2012. The steps in italic are done with pilots intensity, the steps in bold are done with nominal bunch intensity.

Date	Time	Milestone
14.03	23:30	*Beam 1 injected*
15.03	01:00	*Both Beams captured, orbit and Q adjusted*
	11:00	*Optics measured and corrected at injection*
	20:00	**Reference orbit for flat machine**
16.03	22:44	*Both beams 4 TeV*
17.03	16:30	*Beam 1 at 0.6 m β^**
18.03	11:15	*Squeeze at 0.6 m β^**
18.03	11:15	*Separation and crossing at injection*
	18:00	**Collimators set up @injection**
22.03	20:58	*Squeeze with nominal Xing and separation*
25.03	15:00	*Injection protection setup*
27.03	06:40	*Pilot through all cycle*
30.03	18:30	**Collisions, All IPs optimized**
29-30 03	15:00 22:00	**Collimators aligned @4 TeV, end of squeeze and collisions**
05.04	00:38	**First STABLE BEAMS @4 TeV**

During these 22 days, 43 MPS tests are flagged and signed in the Post Mortem database, loss maps not included.

Figure 1: Examples of the MPS tests done during first phase of beam commissioning.

NEW SETUP BEAM FLAG DEFINITION

Setup Beam Flag concept

The Setup Beam Flag (SBF) is defined as the intensity limit to allow masking some pre-defined interlocks: BLM, IR6 interlocked BPM, Collimator movements, RF, AC dipole mode, PIC and Software Interlock System (SIS) Interlocks.

Based on controlled experiments with 450 GeV beam performed in 2005, beam intensity of 10^{12} protons was considered to be safe . A factor 2 was applied to this intensity value to take into account the lower emittance used during operation, so the Set-up Beam Flag was set at 5.10^{11} for 450 GeV. This limit was used to allow masking during the collimators alignment, for loss maps and asynchronous Beam Dump test, for optics and chromaticity measurement and during the ramp/squeeze process commissioning.

After experience gained during the first year of operation, in 2012, 3 different limits were used for the SBF:

- NORMAL: considered to be safe

- RELAXED: was established to allow masking with 1 nominal bunch at 4 TeV

- VERY RELAXED : was established to allow masking with 3 nominal bunches at 4 TeV

The value of the limits used during Run 1 are summarized in Table [2].

Table 2: SBF intensities for injection and top energy energy in protons per bunch.

	450 GeV	4 TeV
NORMAL	5×10^{11}	2.4×10^{10}
RELAXED	5×10^{11}	1.2×10^{11}
VERY RELAXED	5×10^{11}	3.2×10^{11}
IONS	5×10^{11}	6.1×10^{10}

Inputs and limitation for the beam set-up

The different phases of the beam commissioning have been done, using the possibility to mask some interlocks, with a minimum intensity. This gives some needs for a new value of the SBF for 6.5 TeV. Minimum requirement for orbit measurements, already presented at Machine Protection Meeting [2], are the following:

- Efficient set-up of collisions in the 4 IPs : 2 nominal bunches

- New sensitivity after LS1 for the IR6 BPM (interlock limit): around 2×10^{10} p/bunch

- BPM sensitivity for orbit measurement : 5×10^{10} p/bunch

- BPM sensitivity limit for collimator set-up : 5×10^{9} p/bunch

The strategy for the Collimators setup and validation is based on a minimum intensity per beam. The needed limits have been presented by the collimation team [3] and can be summarized as $7x10^{10}$ protons are consumed during the set-up and about $1x10^{10}$ protons are consumed per transverse loss maps with transverse damper excitation. If 1 nominal bunch could be used for alignment at flat top or after the squeeze, 2 nominal bunches are needed at injection and especially in collisions. For the validation loss maps, again in collisions, 2 nominal bunches plus 2 non-colliding probe bunches are needed. These beams intensity are above the SFB when extrapolated at 6.5 TeV.

New values proposed for SBF

In order to allow keeping the same strategy for orbit measurements and collimators setting-up, new values are proposed for the SFB for Run 2. The proposition from MPP is to keep 2 values of intensity limits for 3 bunches configuration:

- Normal SBF: $1.1x10^{10}$ for ALL users

- Relaxed SBF: $1.25x10^{11}$ x 2 bunches for Special users (for orbit and collimator set-up)

- Restricted SBF: $1.5x10^{10}$ x 16 bunches for Machine Development

The bunch configuration for the restricted and relaxed SBF will be enforce with a SIS interlock. The proposed values for SBF for the different top energies are summarized in Table [3]

Table 3: New proposed SBF values for injection and top energy energy in protons per bunch.

	450 GeV	6.5 GeV	7 TeV
NORMAL	$5x10^{11}$	$1.1x10^{10}$	$9.4x10^9$
RELAXED/ RESTRICTED	$5x10^{11}$	$2.5x10^{11}$	$2.2x10^{11}$

INTENSITY RAMP-UP

Moving towards unsafe beams

In order to operate with "unsafe" beam, the operational cycle must be well established, all the MPS tests and the global protection tests detailed in the MPS procedures should be completed and the collimators and absorbers must be in place and validated.

The ramping-up strategy proposed is the same as in 2011 and 2012. A step up of a factor 2 to 4 maximum in bunch number (factor decreasing with increasing bunch number), 3 fills making it to STABLE BEAM per step and 20 hours of STABLE BEAMS per step. For each new bunch configuration, IR6 BPM test must be repeated and MPP experts should sign off the intensity cruise checklist before each new step up.

Intensity ramp-up in 2011 and 2012

In 2011, the intensity ramp-up spread over several month, figure , driven mainly by the machine availability up to 768 bunches: MTG, Tune feedback, FGC current reading, arc detectors... But the time lost due to machine availability allowed to discover and clean-up many teething problems. The initial steps to 912 and 1092 bunches set off UFOs, vacuum activities and SEU effect. When everything goes well, with a very good machine availability, the intensity ramp up can go very fast, as in 2012 when it took only 2 weeks. The ramp-up was reduced in 6 steps:

- 3 bunches for MPS validation

- 2-3 fills and 4-6 hours of STABLE BEAMS with 264 and 624 bunches (in parallel of cycle validation)

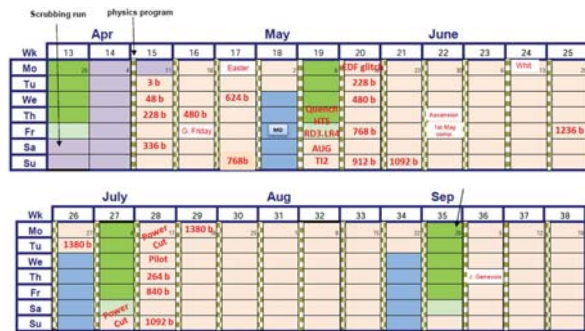- 3 fills and 20 hours of STABLE BEAMS with 840, 1092 and 1380 bunches.

Figure 2: Intensity ramp-up in 2011.

STRATEGY FOR 25 NS BEAM

End of 2012, after the scrubbing run, the re-commissioning to move to 20 ns spacing beam was done in 10 days. The nominal cycle with a new $\beta*$ has been established with 3 nominal bunches in few days. The new tests needed were the transverse dampers set-up and the validation loss maps due to new collimators settings in collisions. The detailed planning is shown in Table 4.

SUMMARY

During Run I, we already experienced MPS commissioning for new beam parameters, we changed the energy to 4 TeV in 2012, new bunch spacing (75 ns, 50 ns and 25 ns) and we also increased the bunch number till 1380. The procedures and the reference body to follow the intensity ramp-up and the MPS commissioning are well established and will be the same for post LS1. In order to keep the same strategy, the Setup Beam Flag should be adapted to the new beam energy. The proposed values to accommodate machine safety and efficient set-up are:

Table 4: Milestones of the 25 ns setup end of 2012.

Date	Time	Milestone
06.12	11:30	ADT setting
	20:00	228b injected, scrubbing
11.12	3:30	Collisions@1m with 3 nominal b
	5:00	Cycle with 3 nominal for collimators set-up
	18:00	Loss maps
12.12	16:00	TDI alignment checks
13.12	06:15	STABLE BEAMS with 72 bunches
	8:30	Loss maps at flat top
14.12	12:30	Loss maps end of squeeze and in collision
15.12	15:00	STABLE BEAMS with 12+2x48 b
	20:00	STABLE BEAMS with 12+4x48 b
16.12	09:00	STABLE BEAMS with 396 b

Normal:	1.1×10^{10}p	ALL users
Relaxed:	1.25×10^{11}p x 2 bunches	Special users
Restricted:	1.5×10^{10}p x 16 bunches	MDs

Being optimistic, the intensity ramp-up will look like in 2012 but with a lot of hardware and software modifications experienced during LS1, exploring the new territory of 25 ns beam at higher top energy may recall the 2011 commissioning.

ACKNOWLEDGMENTS

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AVAILABILITY FOR POST-LS1 OPERATION

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Abstract

Availability is one of the key factors to be taken into account to improve the LHC performance after LS1 and for future LHC upgrades. A comprehensive view of LHC availability in 2012 is given in this paper, based on the analyses of the Availability Working Group. The main contributions to LHC un-availability for Post-LS1 operation are highlighted following the outcomes of the Dependability Workshop, held in November 2013. Goals and foreseen project stages of the Accelerator Fault Tracking (AFT) are presented. Integrated luminosity predictions and sensitivity analyses to relevant operational parameters are shown, as a function of possible future availability scenarios.

2012 LHC AVAILABILITY

A summary of the studies [1] carried out by the Availability Working Group (AWG, [2]) in 2012 is presented in this paragraph and is the base for the extrapolation of future availability scenarios.

The distribution of beam aborts in 2012 is shown in Fig. 1, according to the dump cause classification in the post-mortem database. A classification of beam aborts is proposed, differentiating between aborts caused by experiments, beam-related effects, equipment failures, causes outside CERN's control (external) or initiated by operators. Dumps classified as 'end of fill' (EOF) are generally those executed by operators for luminosity optimization and amount to 30% of the total.
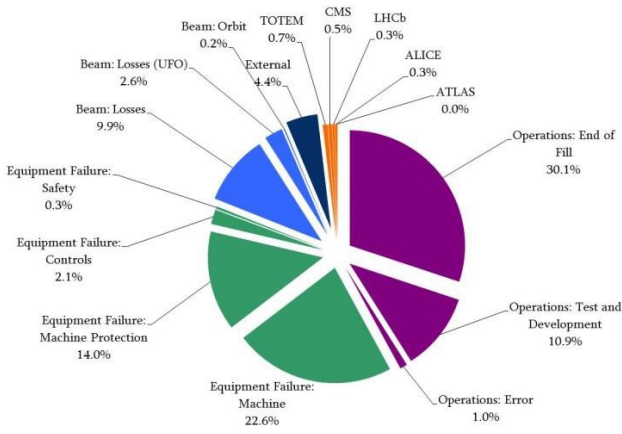

Figure 1: Distribution of beam aborts in 2012.

Figure 2 shows the LHC integrated downtime caused by each system in 2012, based on the data taken from the operational eLogbook (manual entries). The largest contributions to LHC unavailability for beam operation are the cryogenic system, the lack of beam from the SPS and the RF and damper systems.

Following a beam dump, a minimum time of about 3h is necessary again before reaching stable beams with a new fill, when no faults occur (so-called 'turnaround time'). The average time in stable beams for fills terminated by EOF amounts to ~9h and the corresponding time for fills terminated for failures amounts to ~ 4.5h. Luminosity production is then significantly limited by faults occurring after only few hours of stable beams. In this case the unavailability for physics production should not only take into account the fault time associated to the system causing the beam dump, but also the necessary time to go back to stable beams ('lost physics' time). In Fig. 3 a penalty of up to 3h (i.e. the turnaround time) is assigned to systems causing a premature beam dump (<9 h in stable beams), on top of the integrated fault time shown in Fig. 2. Considering this additional factor, which gives an indirect estimate of the failure frequency, the biggest contributions to LHC unavailability come from the cryogenic system, the power converter system and the Quench Protection System (QPS).
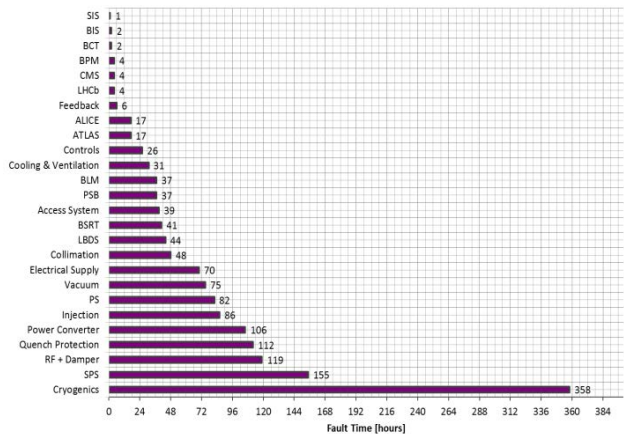

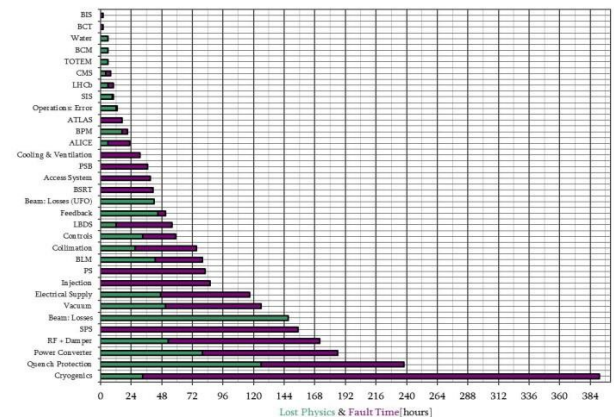Figure 2: Fault time classification from 2012 observations.

Figure 3: Fault time classification, including 'lost physics' time.
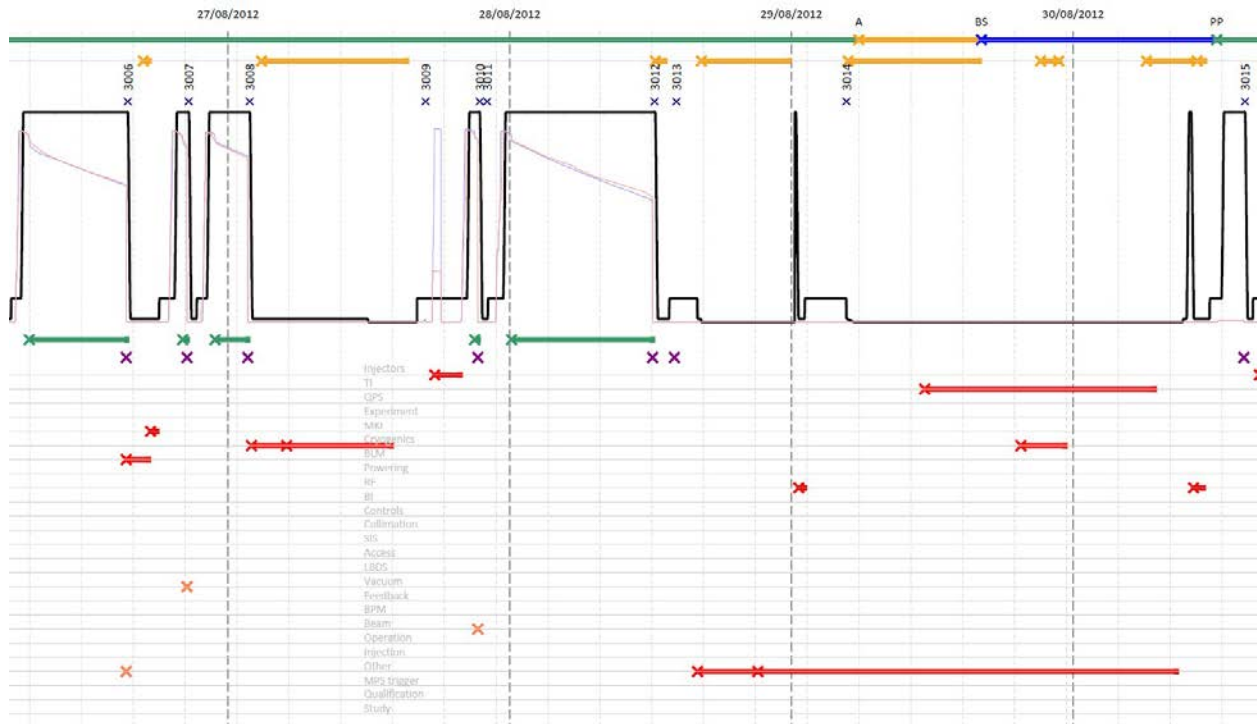
Figure 4: 'Cardiogram' of LHC operation. Few days of the LHC run in August 2012 are reported here as an example.

Figure 4 shows a visual representation of the relevant quantities for availability tracking, besides the fault times, in the so-called 'cardiogram' of LHC operation. The horizontal axis is the LHC run time. The accelerator mode (green: proton physics, orange: access, blue: beam setup), the BIS input indicating machine access (orange: taken from the CCC BIC "Access System" input), energy (black) and intensities (blue and red lines) are shown in the top part of the picture. The green lines indicate stable beams and purple crosses post-mortem events. Red lines indicate equipment faults by system, according to the classification shown in Fig. 2. This representation is based on data coming from different sources (eLogbook, post-mortem database, TIMBER, etc.) and is very useful to spot data inconsistencies for proper availability tracking.

Figures 2, 3 and 4 only give a partial view of the LHC failures, i.e. the ones directly impacting on availability. There are many other faults that are transparent for LHC operation (e.g. due to internal system redundancies), but still need to be taken into account for reliability analyses of individual systems. Tracking failures and failure modes of individual systems is therefore an important element to be considered.

LHC AVAILABILITY FOR POST-LS1 OPERATION

As shown in Fig. 1, the cryogenic system had the largest contribution to LHC downtime, though the absolute number of failure events has been lower than for other systems. Cryogenic stops have long recovery times, ranging from some hours to few days with an average of 9.6 h. After LS1, the higher energy of 6.5

TeV will increase the resistive heat load by a factor 4, resulting in an operating point closer to design values. Failures of rotating machinery will hence have a higher impact on availability; it will take longer time to recover operating conditions after magnet quenches. Mitigation strategies for the cryogenic system consist in major overhauls of rotating machinery, reinforcement of magnetic bearing controllers in the cold compressors against electromagnetic coupling and implementation of mitigations against single event upsets in points 2, 4 and 6 of the LHC [3].

A significant contribution to LHC downtime is caused by failures of the power converter systems. Recovery times are shorter than for cryogenics (the average fault time amounts to 1.6 h), but failures are more frequent. Known failure modes are being addressed during LS1 with dedicated solutions: in particular voltage sources and auxiliary power supplies are being consolidated to be more reliable than during Run 1. A project for the replacement of the current power converter controllers (FGC2) was launched with the scope of deploying a more radiation-tolerant system in the future (FGClite). This system will not be in place for the restart of the LHC in 2015 but will be progressively deployed in exposed areas during Run 2. When first deployed, care must be given to reduce failures caused by 'infant mortalities' of the new system, such that the machine availability will not be affected significantly [3].

Similarly as for the power converters, the Quench Protection System (QPS) caused in 2012 a high number of relatively short stops (with an average fault

time of 2.2 h). These were mainly due to sensitivity of electronic components to radiation in exposed areas and to bad connections leading to spurious triggers of the quench detection electronics and the energy extraction systems. A campaign was launched to mitigate such effects: the relocation of electronics, in combination with the use of radiation-tolerant electronics, is expected to mitigate 30% of radiation-induced faults; cabling will be carefully checked before the restart. In addition a remote-reset functionality has been implemented to mitigation lost communication with quench detection electronics without requiring machine access. These measures will improve the recovery time from QPS faults [3].

For all other LHC systems, consolidation measures of failure modes identified during Run 1 are currently being carried out. In this respect, the philosophy being followed is to first improve safety and then availability. Some of the consolidation measures could potentially reduce availability in order to ensure higher safety. An example is the LHC Beam Dumping System (LBDS) retriggering line via the BIS, which will provide an independent means of triggering a beam dump in case of a complete failure of the LBDS redundant triggering [4]. A dedicated study was performed to quantify the impact of such implementation on reliability and availability, showing that the overall impact on availability will be negligible. Another example is the implementation of additional interlocking channels in the Software Interlock Systems (SIS), which were not present during Run 1, as e.g. the interlock linked to the monitoring of the abort gap population. This interlock will ensure a clean abort gap avoiding large particle losses during the rise time of the LBDS kicker pulse.

Considering beam-related events, the extrapolation of observed Unidentified Falling Objects (UFOs) to 6.5-7 TeV forecasts up to 100 dumps per year after LS1 [5] if the BLM thresholds used for the 4TeV run are maintained. UFOs have shown a clear conditioning trend during LHC run 1, however deconditioning is expected following the consolidations in many of the machine vacuum segments. Relocation of BLMs to better protect against UFO events will ensure maintaining the high level of protection while allowing increasing BLM thresholds at the quadrupole locations. The redefinition of BLM thresholds, according to recent studies on quench limits [6], should allow the right balance between detection of dangerous events versus unnecessary LHC stops to be found.

ACCELERATOR FAULT TRACKING PROJECT

Following the conclusions of the Workshop on Machine protection [7], the Availability Workshop held in November 2013 [3] and previous Evian Workshops, an Accelerator Fault Tracking project (AFT) for the LHC was launched in February 2014 [8]. The main goals of this project are:

- Know when machines are not in use when they should be.
- Know what are the causes of unplanned downtime.
- Look for patterns, relations between systems, operational modes, etc.

The initial focus of the project will be on the LHC, but the infrastructure should be able to handle data from any CERN accelerator. The project timeline currently foresees three project stages:

1. Fault tracking infrastructure to capture LHC fault data from an operational perspective (to be ready for the restart of LHC in 2015)
2. Focus on equipment group fault data capture
3. Integration with other CERN data management systems.

INTEGRATED LUMINOSITY: ASSUMPTIONS AND TARGETS

The basic assumption for all luminosity predictions in this paper is to have 160 days of physics operation per year. The BCMS option is considered as a baseline for the luminosity predictions [9]. Considering the exploitation of luminosity levelling at $1.54*10^{34}$ [cm^{-2}s^{-1}] from a virtual peak luminosity of $2.2*10^{34}$ [cm^{-2}s^{-1}] at 6.5 TeV, a maximum luminosity levelling time of 2.1 h can be achieved. This implies that fills longer than 2.1 h will experience the typical luminosity exponential decay observed without levelling. These calculations refer to stable and reproducible BCMS operation (nominal parameters) and are therefore not to be intended for 2015, when a transition period to recover 2012-like operating conditions is expected.

Given the assumptions introduced above and to set availability targets for the new LHC run, the expected integrated luminosity per year has been calculated as a function of fill length and number of fills, adding constraints in terms of turnaround time, machine failure rate and average fault time. The machine failure rate is defined as the number of fills with failures over the total number of physics fills.

Six scenarios were defined:

1. Optimized luminosity without machine faults, i.e. maximum achievable luminosity; (machine failure rate = 0%, turnaround time =4 h)
2. Optimized luminosity including external faults, i.e. faults out of CERN's control (machine failure rate = 0.08%, turnaround time =4 h, fault time = 2.7 h)
3. Optimized luminosity with figures from 2012 (machine failure rate = 70%, turnaround time = 6.2 h, fault time = 7 h)
4. Optimized luminosity in case all machine faults would require no access in the tunnel to be solved (machine failure rate = 70%, turnaround time = 6.2 h, fault time = 1 h)
5. Optimized luminosity in case all machine faults

would require one access (machine failure rate = 70%, turnaround time =6.2 h, fault time = 4 h)

6. Optimized luminosity in case all machine faults would require major interventions (machine failurerate = 70%, turnaround time =6.2 h, fault time = 12 h)

The results for the six scenarios described above are summarized in Table 1 and show the maximum achievable integrated luminosity for optimized fill lengths (levelling time / luminosity exponential decay, only for fills not terminated by failures) and number of fills.

These results exhibit purely theoretical values, as such optimization (e.g. for scenario 3) can be performed only after measuring fault distributions that occurred during the run. Every time a fault occurs during operation, the optimum working point in terms of ideal fill length would change. The fill length becomes longer with increasing fault times, as could be assumed intuitively.

Table 1: Optimized Luminosity and operational parameters for different availability scenarios.

Scenario	Stable Beams [h]	Number of fills	Integrated luminosity
1	2.1 / 3.4	405	100.5 [fb^{-1}]
2	2.1 / 3.5	396	98.3 [fb^{-1}]
3	2.1 / 5.9	229	56.4 [fb^{-1}]
4	2.1 / 4.7	316	75.9 [fb^{-1}]
5	2.1 / 5.4	266	64.5 [fb^{-1}]
6	2.1 / 6.3	211	52.3 [fb^{-1}]

INTEGRATED LUMINOSITY PREDICTIONS

A Monte Carlo model [10] for LHC Availability was used to make predictions of integrated luminosity based on statistics and distributions from 2012 for fault time, turnaround time, machine failure rate and intensity ramp- up. A sensitivity analysis to the average fault time and machine failure rate was carried out and results are presented in Fig. 5.
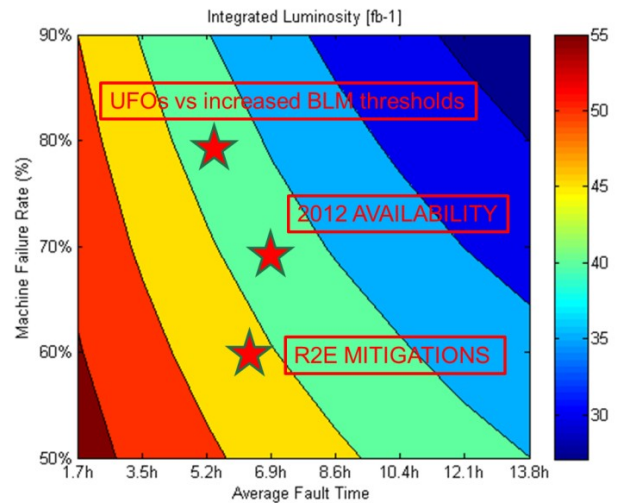

Figure 5: Sensitivity analysis to the average fault time and machine failure rate for BCMS operation.

This analysis shows that for 2012 like operation ~ 40 fb^{-1} could be reached. As mentioned in the previous paragraphs, UFOs could significantly worsen the machine failure rate, even with increased BLM thresholds. In the picture a preliminary estimate of the impact of UFOs at 6.5 TeV in case of a factor 3 higher BLM thresholds is presented. This shows that a less conservative choice of the thresholds, even tolerating few beam-induced quenches per year, would allow keeping the same integrated luminosity target which was obtained with the 2012 distributions. By keeping the BLM thresholds used in 2012, a reduction of ~ 15% integrated luminosity would be expected instead.

Mitigations of radiation-induced effects will have a positive impact on the machine failure rate, which will be reduced by ~10%, allowing up to ~45 fb^{-1} to be produced.

CONCLUSIONS

In this paper the main factors driving LHC availability in 2012 were reviewed based on the studies carried out by the Availability Working Group. The expected availability in the LHC Run 2 has been discussed, taking into account the major consolidation works carried out during LS1 and the impact of future operational scenarios.

The Accelerator Fault Tracking project, allowing for more consistent availability tracking was presented, as well as the foreseen project stages.

Yearly luminosity targets for Run 2 have been calculated, assuming BCMS as a baseline, as a function of optimum fill length and number of fills and depending on various assumptions on fault times and turnaround times.

A sensitivity analysis to the average fault time was carried out to identify the recovery times and acceptable number of machine faults to be achieved during future operation.

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DRY RUNS AND MACHINE CHECK-OUT STRATEGY

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Abstract

The paper describes the structure, organisation and strategies which will be applied to prepare the LHC for beam commissioning in early 2015 after its first long shutdown. Equipment dry runs, sector test preparation and final machine checkout, which constitute the ingredients for a smooth start of beam commissioning, will be explained.

INTRODUCTION

Since March 2013 the LHC is in shutdown mode and most of its systems are undergoing major upgrades in order to improve their reliability, availability and performance for Run II, which is scheduled to start with the beam commissioning phase in February 2015. Although the tunnel work and equipment modifications are still ongoing, the preparations for beam operation have already started in parallel. Because of the huge number of modifications which have been applied to the various LHC systems during the course of LS1, two injection tests, one for each beam, have been scheduled for November 2014 in order to test the beam injection (1 pilot bunch per beam) and perform first measurements with a single pass bunch. Beam 1 will be stopped by a collimator in point 3 whereas beam 2 will go as far as the beam dump in point 6. As a considerable amount of systems has to be operational for those two injection tests, the preparation phase in the form of machine check-out tests and dry runs has already started. The combination of standard machine check-out tests and dry runs has proven to be a successful recipe to prepare the initial accelerator start-up of the LHC in September 2008 and its restart in November 2009. Therefore it will again be used to prepare the machine for its upcoming second run.

MACHINE CHECK-OUT

The transition phase between shutdown and beam commissioning during which a CERN accelerator is prepared for beam operation is commonly called machine check-out. It consists of testing equipment that has passed all individual system tests (IST) remotely from the CCC (Cern Control Center) by operations in collaboration with equipment experts. Those tests comprise interlock tests without beam, equipment tests without beam as during normal beam operation and tests of the associated controls infrastructure by driving the equipment via the standard application programs. It is a vital ingredient for a smooth start of the beam commissioning phase as meticulous and exhaustive equipment testing generally guarantees high machine availability during the beam setup period.

As it was decided to perform two injection tests (one for each beam), scheduled for November 2014 before starting the general beam commissioning in February 2015, the whole machine checkout phase can be divided into three phases.

Phase I – Information collection and planning

The initial phase which precedes any machine checkout period consists in collecting information about the status of each equipment system and the planned handover dates to operations after the individual system tests have been terminated. The operations coordination team organises meetings with the equipment representatives of all accelerator systems in order to establish a planning, which includes all readiness dates and planned system tests. This planning serves as the basis for the subsequent test phases. During this equipment status inventory phase it may occur that a first coordination takes place in case overlaps or interferences between the scheduled dates of two or more equipment groups are identified.

Phase II – Equipment checks for sector tests

Once an accelerator system, like for example the RF acceleration system, has been released for operational checks, the operations group in collaboration with the equipment experts perform a well-defined and complete set of test sequences in order to make sure the equipment behaves as expected for the various operational scenarios. For the machine checkout exercise in 2014/2015 there will be two test periods due to the scheduled beam injection tests which are organised 3 months before the general beam commissioning period during the month of November. The tests which will be performed follow the machine check-out test planning which is established in the previous phase. As there will be an overlap between equipment testing and testing of the electrical circuits of the superconducting magnets (also known as "hardware commissioning", HWC), certain equipment verifications can only be performed once all electrical circuit tests on a whole sector have been successfully passed.

As the injection tests are performed with beam, although only with a single bunch pilot beam, the personnel protection system of the LHC, also known as access system, will have to be fully functioning and will have to be certified for beam operation by the departmental safety officer (DSO). The test which provides this certificate is generally known as DSO test. It is scheduled to take place during the weekend of 11th/12th October.

Phase III – General machine check-out

The final phase of the machine check-out is scheduled just before the beam commissioning period and will take place during the month of January 2015. During this phase all superconducting circuits will be fully qualified and released to operations to be extensively cycled together. In this final phase the aim is to perform tests of:

- The Beam Interlock System (BIS) verifying all hardware interlocks without beam.
- The Software Interlock System (SIS) checking the logic of all software interlocks without beam. •
The beam dump energy tracking system (BETS) under real conditions using the four energy defining sectors and the additional magnets (extraction septa & Q4 quadrupoles).
- The LHC beam dump system (LBDS). The test consists in arming and firing the LBDS, once the following conditions have been fulfilled:
  - o LHC machine closed, access key in position "beam mode".
  - o BIS loop closed.
  - o BETS operational.
  - o Injection BIS enabled.
- The beam vacuum valves and their interlock logic.
- The injection, tune and aperture kickers and the AC dipole.
- Heat runs of all warm magnets.
- Testing the full operational LHC cycle (injection, ramp-up, squeeze, collision, ramp down and pre-cycle) driving all equipment.
- All beam instrumentation and their associated applications.

During this phase a daily 8:30 meeting in the CCC will:

- review the test results of the previous day •
define the test plan of the day
- negotiate access requests

DRY RUNS

In addition to standard machine checkout tests there will also be a series of dry runs in order to optimally prepare the various systems for beam operation and test the interplay of the various accelerator systems in conjunction with the high level control room applications. The emphasis of these tests is on the communication and controls chain, between low level equipment access and high level application software. Past experience, in particular the initial preparation for beam operation in 2008 and the preparation for the LHC restart in 2009, has shown, that the combination of general machine check-out and dry runs constitutes an ideal recipe to prepare the LHC for beam operation.

Dry runs are conducted by the operations group from the CCC in collaboration with the experts of the equipment being tested. First dry runs on the machine timing system, the B1 beam injection system and the B2 beam dump system have already started in May and shown good overall results. The dry runs will continue until the end of 2014 with a frequency of about one per month. The following table shows the list of scheduled dry runs.

Table 1: LHC Dry Runs in 2014

Date	Program
May, W19	Timing, TI2 BI upstream, BPM concentrators, experiments handshake, beam mode changes, experiments frequency ramps, LHC RF re-synchronisation
May, W21	LBDS arming of B2, new arming sequence, new CIBDS board
W24-W29	LBDS reliability run (B1 & B2)
Jun, W25	LHC re-synchronisation (Linux FECs), LHC mastership (dynamic destination in test mode), TI2 – BI with IQC (possibly also TI8), SDDS, AC dipole, tune & aperture kicker, MCS checks, SMP for beta* and energy
Jul, W29	PM and XPOC
Parallel to HWC	Sequence to reset circuits, arm switches, LSA (trim, incorporation, etc.)
Aug, W33	Collimators (+ similar devices), RF beam control, ADT settings, injection cleaning, abort gap cleaning, etc.
Sep, W38	"old" implementation of feedbacks , BLM continuous, global permit loop + LBDS arming + XPOC, experiment interlocks & injection permits, BI sequencer tasks, ALICE frequency ramp, BQM, LHC BTVs, BRANs Start checking EVERY task in nominal sequence
Oct, W42	Vacuum, BIS checks, BCTs, MKI, BLM triggered buffers, new timing system, sector test preparation (injection requests, inject & dump, set machine to injection…)
until end of 2014	profile measurement systems (BSRT, WS), RF cavity control, ADT, new feedbacks

CONCLUSION

During the long shutdown 1 and nearly two years without beam in the LHC, there have been many modifications on the different accelerator systems. All groups have profited from the long stop to apply changes to their equipment in order to improve the reliability, availability and performance of their equipment for the upcoming Run II of the LHC. In order to cope with the

challenges related to restart that modified machine, it was decided to perform two injection tests in order to have a first validation of the equipment around the injection regions, three sectors of the machine and the beam dump system for B2. It was also decided to start the machine check-out test campaign early in 2014 to have time for a detailed preparation of all accelerator systems before the start of beam commissioning which will coincide with an increase of the maximum beam energy from 4TeV to 6.5TeV. The way to prepare the LHC for operation with beam will be a combination of general machine check-out tests and dry runs, as this recipe has already successfully worked during past preparation periods.

ACKNOWLEDGEMENTS

POWERING TESTS

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Abstract

During the first, planned LHC Long Shutdown (LS1), several interventions have been carried out on the machine technical systems, besides the superconducting circuit consolidation, with the goal of increasing the system performance and availability, while raising the energy to its design value. In particular the cryogenic system, the power converters and the quench protection system undertook a series of modifications that have to be tested and might impact beam operation. These modifications are presented together with the plan and status of the system re-commissioning and the readiness of the superconducting circuit powering tests.

THE LS1 MODIFICATIONS

Besides the Superconducting Magnet And Circuit Consolidation (SMACC) project, many other interventions have been carried out during the LS1. A big maintenance campaign was performed with the scope of increasing the availability of the machine and various special modifications have been carried out to increase the performance and modify the functionality of different systems; all these changes might impact the machine efficiency thus they have to be carefully tested to ensure a safe re-start of the accelerator.

Power Converter - interventions

During LS1 many activities have been performed on the Power Converters, both to maintain and consolidate their functionality and to improve their performance:

- General maintenance (cleaning, connection tightening, water leak check)
- Water cooling circuits consolidation:
  - Change of all flexible on internal water cooling circuits of IPQ and IPD.
  - Change of defective 600 A PCs to water cooling connections.
- Change of electrolytic capacitor in the power supply feeding the 60 A electronics.
- Change of rectifier diodes in the output modules of 1-quadrant PCs (RQs, IPD, IPQ).
- Software updates.
- Calibration campaign which could potentially have an implication on the re-

start of the machine as, although not expected, some PCs could have drifted away; nevertheless if any wrong calibration is found, the effect can be anticipated and compensated.

- Consolidation of 600 A power supply units to stand high radiation.
- Change of the DCCT on RD4.L4 and RD4.R4 to increase the maximum current, in order to cope with the optics change [1].
- Installation of an additional DC cable for RQ4.L5 and RQ4.R5 to cancel the limitation of the PC [2].
- Replacement of the water-cooled cables of RQX.L5 circuit with higher cross- section cables to increase the di/dt.
- PCs relocation in IP1, IP5 and IP7 (warm magnets) in the frame of Radiation To Electronics (R2E) project.
- Installation of a Free Wheel Thyristor on the output of RB PCs to reduce the 30 Hz voltage oscillations (ERC 1387235).

Almost all these activities should be transparent, but the power converters will be fully re-tested during the short circuit test campaign and the subsequent powering tests.

Quench Protection System – modification

Many modifications were also carried out on the Quench Protection System (QPS):

- R2E consolidation:
  - Relocation (re-cabling) of IT quench protection racks in IP1 and IP5.
  - Upgrade of the 600 A protection system in IP1, IP5 and IP7 to cure Single Event Upset (SEU).
  - Upgrade of the IPQ/D protection system.
- Addition of automatic check of the LSA parameters (with a SET possibility).
- Connection of nQPS to the Post Mortem system.
- Additional post mortem functionality to record both A and B cards from the magnets protection system.
- Migration of the system to FESA3.

- Enhanced supervision of the quench heater discharge.
- Implementation of full redundancy of powering of the detector units.
- Enhanced functionality for remote crate power cycle.
- Installation of earth voltage measurement system on nQPS.

Three additional special cases about QPS have to be discussed in details.

First of all, no change has been implemented on the 600 A IT correctors (RCBXs circuits) to avoid simultaneous powering. This remains a weak point and the implementation of a software protection is being studied.

For what concerns the RQTD/F, their protection system is sensitive to inputs sent on the real time channel by the tune feedback system to the power converter. The stability problem could become an issue at higher current, as the design thresholds for the protection system have to be re-assessed. Different possibilities have been studied (also in the light of what is implemented in similar systems in other laboratories), but there seems not to be an easy solution.

The last case is the one of the RU.R4: due to a missing voltage tap, it was used in Run I at a reduced ramp rate (the ramp to 400 A takes 1.5h), to avoid tripping the QPS. No change was done on this circuit during LS1. Nevertheless, tests have been performed on a spare magnet and an upgrade of the protection electronic was done. As a result, the drift on the reading should become negligible, strongly reducing the impact on machine availability.

Overall the QPS system undertook major modifications and has to be considered as brand-new. Its commissioning will be crucial for the powering tests and the beam operation.

Other Systems – modification

A maintenance campaign was also carried out on all energy extraction systems, by cleaning of the circuit breaker contacts and addition of new relays. The snubber capacitors have been also installed on the main quadrupole circuits. The time constant of the 13 kA circuits have been set back to the design values (104 s for RBs and 29 s for RQs).

In order to increase stability and performance of the cryogenic system, a major campaign was also performed, including:

- Major overhauling of compressors and motors.
- R2E consolidation at IP4.
- DFBA consolidations.
- Repairs of QRL compensator bellows.
- Installation of additional T sensors to disentangle heat load in the dipoles and in the quadrupoles, in order to follow more precisely the scrubbing evolution.
- Dedicated electronics for current lead temperature control.
- Installation of a DFBX current lead cooling control system.

The powering interlock system was also affected by the relocation of the rack within the R2E project. In addition, a new PLC was installed in the CCR to improve dependability in the transmission of the access status to the software interlock system for the powering to access protection.

Finally, new water-cooled cables were pulled in some points and the sheath was changed in many locations.

Superconducting circuits – status

After the modifications applied during LS1, the status of many superconducting circuits changed:

- RCBH31.R7B1 condemned due to its resistive coil.
- RCOSX3.L1 is open, condemned.
- RCOSX3.L2, RCOX3.L2 and RCSSX3.L2 are open and condemned after impact with beam. They are a potential limitation for ions operation at very low beta*.
- RCBYH4.R8B1, RCBYV5.L4B2, RCBYHS4.L5B1: I_{PNO} is limited at 50 A if they are used at 0.67 A/s.
- RCSSX3.L1: maximum current reduced to 60 A (nominal 100 A).
- RCBYHS5.R8B1: I_{PNO} limited at 20 A if used at 0.6 A/s.
- RQTF.A81B1: after the bypass of 4 magnets, the circuit is now working.
- RCO.A78B2 and RCO.A81B2: after the bypass of 2 magnets, these circuits are now working.
- RQ5.R2: maximum current reduced to 4100 A (nominal 4300 A) due to slow training.
- RD3.L4: maximum current reduced to 5600 A (nominal 5850 A) due to slow training. The present current value allows energy of 6.74 TeV.

A full detailed list can be found in [3].

THE SHORT CIRCUIT TESTS

During LS1, a campaign of short circuit tests is being performed in the LHC, in order to validate the warm part of the superconducting circuits and spot potential problems early enough to implement necessary corrections. For these tests, a short circuit block is installed at the end of the water-cooled cables. The current then flows from the power converter through the cables and (if present) into the Energy Extraction system. These tests allow verifying the cooling system for the different circuits, the current sharing into the EE, the quality of the conical connections and the global ventilation in the area where the power converters are located. After a long preparation phase that started in October 2012, these tests are being done in different configurations according to the modifications done during LS1) in all points of the machine. Some problems (i.e. wrong interlock cabling, several lose conical connections and few cable damages) have been already spotted and the necessary corrective actions taken. At the end of the campaign a document with the results will be issued.

POWERING TESTS

A large campaign of powering tests has also to be carried out between mid-August and the end of the year, on the superconducting circuits to ensure their correct performance and functionality, and, above all, to push the main circuits close to the design energy. A total of more than 10.000 powering steps have to be performed and analyzed in less than four months. In 2009 the LHC was commissioned with a completely new QPS system in a similar amount of time. Nevertheless, the other systems had not undertaken massive changes (3 sectors were not even warmed up) and the main circuits were only commissioned for energy of 3.5 TeV. To cope with this challenge the powering tests campaign has to be carefully planned and the tools optimized. The usual separation of powering phases [4] implying different access restrictions will be used.

A team in charge of the "organization and coordination" will coordinate the powering tests campaign, while the "automation" team is in charge of ensuring the correct functionality of the software infrastructure; finally a renewed MP3 (Magnet circuits, Protection and Performance Panel) is entitle to assess the magnet and circuit protection and performance.

In order to reach the goal energy of 6.5 TeV, a training campaign has to be performed on the main dipole circuits; a strategy with a maximum acceptable number of training quenches per sector (after which the situation will have to be assessed) is under definition.

All tools for the automated execution and analysis of the powering tests have been updated with enhanced functionality. The procedures to power the different circuits and the related software sequences have also been updated in order to check the new functionalities of the protection system. In order to verify all these changes, a test bench (short circuited power converter with simulated or strapped interlocks) has been prepared to execute dry runs and ensure full debug phase.

CONCLUSIONS

The LHC superconducting circuit requalification has been carefully studied and its planning started already in October 2012.

Besides the general maintenance, many changes have been applied with the goal of increasing availability, reliability and performance of the different systems. These modifications will have an impact on the time needed to re-start the LHC and on the machine efficiency. To limit this effect and to ensure a safe re-start, various test campaigns are planned. In particular, the ongoing preparation of powering tests campaign is crucial for its success thus for a quick re-start of beam operation; a close coordination and problem follow-up is needed to ensure readiness of all systems.

ACKNOWLEDGMENT

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LHC TRANSFER LINES AND SECTOR TESTS IN 2014

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Abstract

Sector tests in the past were undoubtedly invaluable and fully met their goals. They resolved a long list of problems, debugged and tested the control system, the beam instrumentation, timing and synchronization, software, etc. Measurements with beam allowed detailed optics and apertures checks to be performed, discovering aperture bottlenecks and polarity issues that could be solved.

Being sector tests an essential precursor and a high profile milestone in preparation for full beam commissioning, two sector tests are proposed for 2014. This paper summarizes the proposed dates, the pre-requisites, how to stop the beam with collimators, the proposal for beam measurements, and gives a first detailed plan of the tests as a base for discussion.

MOTIVATION

During LS1 most of the accelerator subsystems and the control system underwent important changes in view of improving availability and reliability. Most of the magnet interconnections have been opened and the machine has been exposed to air. Some magnets and other equipment have even been changed. The accelerator control system was upgraded with effects on most of the accelerator equipment. A complete summary of all the interventions made in all the accelerator subsystems can be found in these proceedings.

The proposed transfer line and sector tests will provide the unique opportunity to debug and test the accelerator subsystems involved, resolve possible problems at an early phase, carry out the first commissioning of the most critical systems, injection and dump, and perform the first measurements with beam, assessing the performance of the beam instrumentation and, in general, of the accelerator subsystems after the Long Shutdown One (LS1).

Several sector tests have been performed in the past always in preparation for final beam commissioning. TI8 transfer line was commissioned for the first time with beam in 2004 [1, 2]. In 2005 the TI8 test was repeated with high intensity beams. TI2 saw beam for the first time in 2007 [3]. In preparation for first circulating beam in 2008, five sector tests were performed [4]. Finally, after the 2009 shutdown, following the sector 34 incident, two injection tests were accomplished, together with the first ion injection in the LHC.

In all occasions the tests were undoubtedly an essential precursor to the successful start of LHC Beam Commissioning.

STRATEGY

Three weekends have been proposed and approved at the LMC 176 to perform the transfer lines and sector tests in 2014:

- ST1: 1-2 Nov 2014 ➜ TI2 and TI8 transfer line tests and beam through sector 23.
- ST2: 22-23 Nov 2014 ➜ TI8 transfer line tests and beam through sectors 78 and 67 up to the beam 2 dump block.
- ST3: 13-14 Dec 2014 ➜ contingency

ST3 is a contingency date and it will only be used in case ST1 and/or ST2 fail.

The tests are scheduled weekends to minimize the impact on the experiments and hardware commissioning.

Single pilot bunches of $2\text{-}5\times10^9$ protons will be used for the test in order to reduce the ambient radiation and therefore have less or no impact on post-test tunnel activities.

The setting up of TT60/TT40 extraction will be done before the sector test. The date is still to be defined.

During the first sector test, beam will be sent down TI2 and TI8 and time will be dedicated to commission both transfer lines. Then the beam will be sent to the TDI with the injection kickers (MKI) of beam 1 off. After the required setup time in this configuration, the same exercise will be done with the MKI on. Once the injection region is properly set up, the TDI will be retracted and the beam will be sent to the insertion region 3 where the momentum collimators are located. From then onwards a series of measurements will be performed as detailed in the following sections.

The same steps will be carried out during the second sector test, except that the TI8 transfer line will have been commissioned before. In addition, beam 2 dump line and the associated systems will be commissioned this time.

PREREQUISITIES

The success of the sector tests relies heavily on the success of the preparation activities carried out during the year like: hardware commissioning, individual system tests, powering tests, dry runs, access system commissioning, Departmental Safety Officer (DSO) acceptance test and machine checkout. A detail review of those activities can be found in these proceedings.

Those activities will exercise all the required systems and debug their integration, which is crucial to narrow down the problems or solve them before the beam comes.

HOW TO STOP THE BEAM

The same strategy as used in 2008 and 2009 for stopping the beams safely and reliably with collimators will be used. The technique is called overshoot:

- Place collimators with the minimum possible gap between jaws on anti-collision switches ➜ 0.5 mm gap.
- Move the collimator gap 5 mm aside from the reference orbit to assure the beam impacts on the jaw.
- If required, the collimator can be tilted in addition.

Table 1 lists the collimators used during the injection tests in 2008. Open settings means the collimator is fully retracted to let the beam go through. Intermediate settings correspond to gaps of the order of +/-10 and +/-12 mm depending on the collimator.

BEAM INTERLOCK CONFIGURATION

Two configurations have been prepared, one for the beam 1 sector test and the other for the beam 2 sector test. The configurations are summarized in Table 2 and 3.Only the inputs relevant for the sector tests will be enabled. To avoid modifying the hard wired Power Interlock Controller (PIC) arrangement, the interlocking of the magnet circuits will be done with the Software Interlock System (SIS). The PIC input to the Beam Interlock System (BIS) will be disabled.

ENERGY INFORMATION

The Beam Energy Tracking System (BETS) for the Beam Dump System will get the energy from the BETS simulator. The main dipoles of the four sectors that provide the energy measurement under normal circumstances will not be available. Those sectors are 45, 56, 67 and 78.

EXPERIMENTS SHIELDING

During the sector tests the experiments involved in the tests, i.e. ALICE and LHCb, should have their full shielding in place. This will be the case for LHCb but not for ALICE. ALICE foresees to install the shielding at the end of December only. A scenario has, however, been worked out by the ALICE Technical Coordination office that would allow closing the shaft shielding without major impact on the ALICE schedule. The PX24 shielding plug is made of two distinct layers, the "beams" (2 m thick material) on the bottom, and the "blocks" (0.8 m thick) on the top. ALICE will install the beams the night between Thursday 30 and Friday 31, and they will be removed the night between Monday 3 and Tuesday 4.

Table 1: Summary of collimators used for the different injection tests in 2008 with the corresponding type of settings. The arrows indicate the direction of the beam.

Beam 1 stopped at LEFT of IR3	Collimator Name	s pos [m]	angle	settings
	TCP.6L3.B1	6487.6713	H	OPEN
	TCSG.5L3.B1	6520.9928	H	OVERSHOOT
	TCSG.4R3.B1	6707.5758	H	OVERSHOOT
	TCSG.A5R3.B1	6718.9208	S	OVERSHOOT
	TCSG.B5R3.B1	6724.7408	S	INTERMEDIATE
	TCLA.A5R3.B1	6755.2208	V	OVERSHOOT
	TCLA.B5R3.B1	6757.2208	H	OVERSHOOT
	TCLA.6R3.B1	6843.7703	H	OVERSHOOT
	TCLA.7R3.B1	6915.1758	H	OVERSHOOT

Beam 1 stopped at RIGHT of IR3	Collimator Name	s pos [m]	angle	settings
	TCP.6L3.B1	6487.6713	H	OPEN
	TCSG.5L3.B1	6520.9928	H	INTERMEDIATE
	TCSG.4R3.B1	6707.5758	H	INTERMEDIATE
	TCSG.A5R3.B1	6718.9208	S	INTERMEDIATE
	TCSG.B5R3.B1	6724.7408	S	INTERMEDIATE
	TCLA.A5R3.B1	6755.2208	V	OVERSHOOT
	TCLA.B5R3.B1	6757.2208	H	OVERSHOOT
	TCLA.6R3.B1	6843.7703	H	OVERSHOOT
	TCLA.7R3.B1	6915.1758	H	OVERSHOOT

Beam 2 stopped at RIGHT of IR7	All IR7 collimators closed with overshoot technique

Beam 2 stopped at LEFT of IR7	TCLA.A6L7 (W collimator) overshoot

Beam 2 dumped in IR6	Collimator Name	s pos [m]	angle	settings
	TCSP.4L6.B2	16507.62818	H	OVERSHOOT
	TCDQA.B4L6.B2	16511.53818	H	CLOSE

Radiation protection made the corresponding dose calculations for this configuration. It has to be pointed out that during LS1 (including the sector test), the ALICE cavern and counting room (CR) are considered *Non Designated Areas* with a dose per hour limited to 2.5 μSv/h. During normal operation ALICE CR and cavern are classified as a *Supervised Radiation Areas* with a dose limited to 15 μSv/h.

The dose calculation concluded that with 2 m shielding in place at PX24, two to four shots (for 5.0×10^9 to 10.0×10^9 particles per bunch (max), respectively), would be enough to reach the dose limit per hour at the counting room if the beam is lost at the unshielded beam pipe region. Therefore, the requirement is to lock the access to the CR during the sector test.

Table 2: User permits needed for the first sector test.

INJ1	CIB.SR2.INJ1.1	CIB.SR2.INJ1.2
	LHC Beam 1 Permit	Nothing needed
	Operator switch	
	MKI2 status	
	Vacuum	
	MKI2 erratic	
IR2 (B1)	CIB.UA27.R2.B1	L2.B1
	MKI	BLM
	Vacuum	Vacuum
	ALICE detector	
IR3 (B1)	CIB.UJ33.U3.B1	CIB.SR3.S3.B1
	ACCESS_SB	BLM
	WIC	

Table 3: User permits needed for the second sector test.

INJ2	CIB.SR8.INJ2.1	CIB.SR8.INJ2.2
	LHC Beam 2 Permit	LBDS.B2
	Operator switch	
	MKI8 status	
	Vacuum	
	MKI8 erratic	
IR6 (B2)	CIB.UA67.R6.B2	CIB.UA63.L6.B2
	Vacuum	Vacuum
	LBDS (TSU)	WIC (septa)
	LBDS (PLC)	BLM
	CIBDS B2	
IR7 (B2)	CIB.SR7.S7.B2	CIB.TZ76.U7.B2
	BLM	Vacuum
		WIC
IR8 (B2)	CIB.UA87.R8.B2	L8.B2
	Vacuum	Vacuum
	MKI	BLM
	LHCb detector	
	LHCb movable	

The situation at the "top of the pit" is more relaxed since up to twenty shots at the unshielded beam pipe would be needed to reach the dose limit. At 1 m distance from this position, 100 shots would be needed. The radiation monitors in those areas will all be operational. Injection will be stopped before the radiation limit is reached. More details on the dose calculation can be found in [5].

BEAM MEASUREMENTS

The beam measurements to be done during the sector tests are the following:

- Transfer line optics and aperture checks and matching between the transfer lines and LHC injection.
- Establish injection:

  - o kicker synchronization
  - o wave form study
  - o kicker control
  - o SPS-LHC RF synchronization
  - o pre-pulse transmission
  - o timing system functionality
  - o injection sequencer commissioning
  - o aperture checks
- Beam Position Monitor system commissioning:
  - o response
  - o acquisition
  - o concentrator
- Threading:
  - o establish first trajectory and first orbit correction
  - o application software commissioning
- Kick response:
  - o check BPM and orbit corrector polarities
  - o linear optics checks
  - o other circuits polarity checks
- Aperture measurement
- Beam Loss Monitors commissioning
- Collimators:
  - o BLM response
  - o Control system commissioning
  - o BPM collimators first commissioning

Reference [4] compiles all the details of the tests performed in 2008 together with the beam measurements.

PRELIMINARY PLAN

Figure 1 and 2 show the preliminary measurement plan for the two proposed sector tests. They will account for 63 hours and 66 hours, respectively, corresponding to around 8 full shifts. The plan takes into account the request from the experiments, ALICE and LHCb, which would like to have shots on TED and TDI. Note that the final plan for the second sector test will depend on the outcome of the first one.

CONCLUSIONS

Sector tests are essential precursor and a high profile milestone in preparation for full beam commissioning.

Two sector tests are proposed for 2014:

- ST1: 1-2 Nov 2014 ➔ TI2 and TI8 transfer line tests and beam through sector 23.
- ST2: 22-23 Nov 2014 ➔ TI8 transfer line tests and beam through sectors 78 and 67 up to the beam 2 dump block.
- ST3: 13-14 Dec 2014 ➔ contingency

A draft measurement plan is circulating for comments and optimization.

	Time	SECTOR TEST 1: TI8, TI2 & S23	Δt (h)
Friday	12	Patrol and closure of LHC and Experiments. Magnets pre-cycle. Last interlock checks/tests. TT40/TT60 extraction (TEDs in)	3
	15	Beam down to TI2 TED, establish rough trajectory. LHC mastership. MSI & MKI pulsing. First TL BI commissioning. Timing of beam and	4
	19	TI2 TED out, MKI off/on, beam to TDI. Thread last part of TI2 and MSI. Set TDI, TCLI	2
	21	TDI out, beam to IR3 right. First BI commissioning (BLM, BPM, BTV). Threading	3
Saturday	0	BPMs and orbit corrector polarity checks TI2 & Ring, Linear optics & dispersion TI2 & Ring	8
	8	Beam down to TI8 TED, establish rough trajectory. LHC mastership. MSI & MKI pulsing. First TL BI commissioning. Timing of beam and	4
	12	Screen matching TI2 + injection	2
	14	TDI in, physical aperture measurements in TI2 and the injection region. ALICE BCM+BLM calibration in parallel	8
	22	MKI2 waveform scan	2
Sunday	0	TL trajectory stability TI2 - beam on TED. More TL BI commissioning	3
	3	MKE waveform scan LLS4/LLS6	4
	7	BLM latency check	1
	8	BLM response (collimator splashes)	2
	10	Aperture IR2 and S23	8
	18	Magnet polarity (skew quads, sample of MQT, MQTL)	3
	21	BMPs and orbit corrector polarity checks TI8	2
	23	Set TCDI, automatic application TI2	3
Monday	2	Rough LSS4 extraction region aperture scan	1
	3	Pre-cycle - effects	3
	6	End of TI2/TI8/S23 test. RP survey	2

Figure 1: Sector test 1 schedule. The total test duration is 63 hours, which corresponds, to 8 full shifts.

	Time	SECTOR TEST 2: TI8, S78-S67, LBDS B2	Δt (h)
Friday	12	Patrol and closure of LHC and Experiments. Magnets pre-cycle. Last interlock checks/tests. TT60 extraction (TEDs in)	3
	15	Beam down to TI8 TED, establish trajectory. LHC mastership. MSI & MKI pulsing. LHCb TED shots in parallel.	2
	17	TI8 TED out, MKI off/on, beam to TDI. Thread last part of TI8 and MSI. Set TDI, TCLI. More TL BI commissioning	2
	19	TDI out, beam to IR7 right. First BI commissioning (BLM, BPM, BTV). Threading	3
	22	Beam to IR6 LBDS B2 with orbit correctors (TCDQ & TCSG in beam and interlocked). Steering. Beam dump line BI commissioning. Synchronization. Rough check of extraction channel aperture.	3
Saturday	1	Beam to IR6 LBDS B2 with "inject and dump" (TCDQ & TCSG in beam and interlocked). Steering. More check BI. Synchronization. Rough check of extraction channel. MKD knob test. MKB	6
	7	BPMs and orbit corrector polarity checks TI8 & S78-S67, Linear optics & dispersion TI8 & S78-S67	9
	16	Screen matching TI8 + injection	2
	18	TDI in, physical aperture measurements in TI8 and the injection region. LHCb BCM+BLM calibration in parallel	8
Sunday	2	MKI8 waveform scan	2
	4	TL trajectory stability TI8 - beam on TED. More TL BI commissioning. LHCb TED shots in parallel	3
	7	Rough LSS6 extraction region aperture scan. LHCb TED shots in parallel	1
	8	BLM latency check	1
	9	BLM response (collimator splashes)	2
	11	Aperture IR8 and S78S67	9
	20	Magnet polarity (RCO.A78B2, Q5L8, skew quads, sample of MQT, MQTL)	4
Monday	0	Set TCDI, automatic application TI8 (if not done in ST1)	3
	3	Pre-cycle - effects	3
	6	End of TI8/S78S67/LBDS B2 test. RP survey	2

Figure 2: Sector test 2 schedule. The total test duration is 66 hours, which corresponds, to about 8 full shifts.

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OMC IMPROVEMENTS AND PROSPECTS FOR 2015

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Abstract

LHC 2015 operation requires more precise and more efficient optics measurements and corrections. Improvements in these directions are presented including a potential coupling feedback based on DOROS. Furthermore β-beating estimates for 2015 are given and the optics commissioning is described for the non-linear circuits MCO, MCD, MCS and MSS.

IMPROVED OPTICS MEASUREMENT RESOLUTION

A large effort has been put over the past decade in achieving the high precision optics needed for the safe and efficient operation of the LHC [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. A new phase will start in 2015 where the higher energy and the new modes of operation will further challenge the LHC optics measurements tools and algorithms. Soon after the start of the LHC first Long Shutdown (LS1) a review was organized [11] to identify the required improvements in the LHC Optics Measurement and Correction (OMC) techniques to guarantee a high optics quality at 6.5 TeV in 2015. This review is the second of its kind [12]. A summary of the 2013 review [13] collected the highlights and the actions to face the challenges of operating LHC at its highest energy.

Improvements in the β function measurements

The optics resolution in 2012 was insufficient to understand beam size measurements [14] and determine β^* from beam position monitor (BPM) turn-by-turn measurements. Recent improvements to the measurement of β functions follow: (i) a new algorithm, the 7-BPM method, takes more BPM combinations into account and selects the ones which are best suited for the measurement, (ii) the cleaning of measurement data using a singular value decomposition (SVD) technique, (iii) improvements of the optics model including the use of the dipole quadrupole errors and a new more accurate calibration of MQY magnets. The resulting improvements on the β-function uncertainties are shown in Fig. 1.

Measurements from the 2012 run have been re-analyzed [15, 16] with a significant higher accuracy, which allowed the calculation of β values and demonstrated to be critical in the understanding of emittance evolution.

Improvements in the error bar

When deriving the β-function, two phase advances between BPMs are used ($\phi_{i,j}$, $\phi_{i,k}$) in which the BPM at s_i appears twice. This introduces a correlation which must
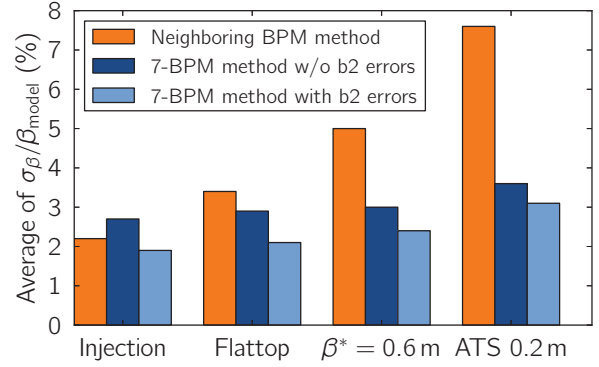
Figure 1: Improvements in the measured β-function uncertainties thanks to the 7-BPM algorithm and the model improvement with the dipole quadrupolar components (b_2).

be regarded in the error propagation. Furthermore the β-function at one position is calculated by combining three β-functions that are obtained from using different BPM combinations, which increases the contribution of correlations, because the same BPMs might be used more often. The error of the measured phase advance can be derived from the standard deviation

$$\sigma_{\phi_{i,j}} = t(n)\sqrt{\frac{1}{n-1}\sum_{k=1}^{n}\left(\overline{\phi_{i,j}} - \phi_{i,j,(k)}\right)^2} \qquad (1)$$

where $t(n)$ is the t value correction from the Student's t distribution, which compensates the underestimation of the uncertainty for a small sample size. During the LHC Run I the error was calculated from a normal standard deviation without the t correction and by dividing the sum by n instead of (n-1). This has been changed since the mean value of the phase advance is also obtained from the measurements, and there are only (n-1) degrees of freedom left for the calculation of the standard deviation. Table 1 shows $t(n)$ for different number of measurements, which shows that this correction is needed since due to limits in the beam time, the amount of measurements is always limited. The correlation between two phase advances which have one BPM in common, $\phi_{i,j}$ and $\phi_{i,k}$, depends on the uncertainty of the single phase ϕ_i at the common BPM. The error of the single phase ϕ_i is not known, because it cannot be compared among the measurement files since its value is arbitrary and may vary. However simulations show that the uncertainty of the phase measurement depends on the β-function at this position, $\sigma_\phi \sim \beta^{-\frac{1}{2}}$ cf. Fig. 2. Therefore
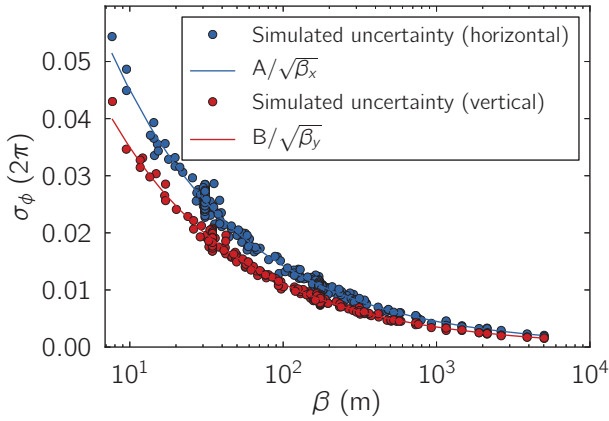
Figure 2: Simulated single phase uncertainties depending on the β-function. The error has been derived from the variation of the phase when a Gaussian noise of 300μm was added to the BPM turn-by-turn data which was obtained from tracking with MAD-X [17].

the error of the single phase can be approximated by

$$\sigma_{\phi_i} = \sigma_{\phi_{i,j}} \left(1 + \frac{\beta_i}{\beta_j}\right)^{-\frac{1}{2}}. \tag{2}$$

The correlation between two phase advances is then

$$\rho(\phi_{i,j}, \phi_{i,k}) = \frac{\sigma_{\phi_i}^2}{\sigma_{\phi_{i,j}}^2 \sigma_{\phi_{i,k}}^2}. \tag{3}$$

Let the phase at the probed BPM be ϕ_1, all other phase advances can be calculated with respect to this BPM. The elements of the correlation matrix for the different phase advances $\phi_{1,2}$ to $\phi_{1,n}$ are defined by

$$C_{i-1,j-1} = \frac{\partial \phi_{1,i}}{\partial \phi_1} \frac{\partial \phi_{1,j}}{\partial \phi_1} \rho(\phi_{1,i}, \phi_{1,j}) \sigma_{\phi_{1,i}}^2 \sigma_{\phi_{1,j}}^2, \tag{4}$$

which is $\sigma_{\phi_{1,i}}^2$ on the diagonal axis and $\sigma_{\phi_1}^2$ elsewhere. Using the transformation matrix

$$T = \begin{pmatrix} \frac{\partial \beta_1}{\partial \phi_{1,2}} & \cdots & \frac{\partial \beta_3}{\partial \phi_{1,2}} \\ \vdots & \ddots & \vdots \\ \frac{\partial \beta_1}{\partial \phi_{1,n}} & \cdots & \frac{\partial \beta_3}{\partial \phi_{1,n}} \end{pmatrix}, \tag{5}$$

the correlation matrix for the phases can be transformed to a correlation matrix for the three β-functions which are

calculated from using different BPM combinations,

$$V = T^T C T. \tag{6}$$

The final β-function is then a weighted average of the three β_i

$$\beta = \sum_{i=1}^{3} w_i \beta_i \tag{7}$$

where the weights can be calculated from the inverse correlation matrix

$$w_i = \frac{\sum_{k=1}^{3} V_{ik}^{-1}}{\sum_{k=1}^{3} \sum_{j=1}^{3} V_{jk}^{-1}} \tag{8}$$

This equation replaces the simple average introduced in [4]. The uncertainty for this measurement is

$$\sigma_\beta^2 = \sum_{k=1}^{3} \sum_{j=1}^{3} w_j w_k V_{jk} \tag{9}$$

Simulation of the uncertainties

In order to determine the requirements on the number of measurements for a reasonable error bar, simulations of the optics measurement have been performed. These simulations are furthermore a test of the correct implementation of the equations in the optics analysis code. Particles were tracked for 2000 turns using MAD-X, while at the beginning a kick with an amplitude of 1 mm was applied to the particle. The oscillations of the orbit at the BPM positions were recorded and afterwards a Gaussian noise of $300\,\mu$m was added. This has been done to create 500 sets of BPM turn-by-turn data, which correspond to 500 measurements.

Since in contrast to a real measurement, in this simulation the phase at each BPM is comparable, it is possible to derive the uncertainty of the phase for each BPM position from its variation. As the uncertainties of the single phases and also of the phase advances are known, they were used directly in Eq. (3) to create the correlation matrix. The afore described error propagation was applied and the β-function derived according to Eq. (7), with its uncertainty according to Eq. (9).

The distribution of the β-function in these 500 data sets has been fitted to a Gaussian for each BPM. The value of the σ from the fit was then compared to calculated uncertainties of the β-function, cf. Fig. 3. The calculated values of the uncertainty fit well to the expected value from the variations of the β-function, which is not the case for the old equations for the error calculation. In this plot one can furthermore see that most of the points are located at two levels. This is due to the fact that the BPMs in the arcs, which are most of the BPMs, are alternating between two β values, and the larger β-function can be measured with a higher relative precision.

Hardware improvements

The accuracy of the phase measurements can be increased by recording the turn-by-turn data for more turns.
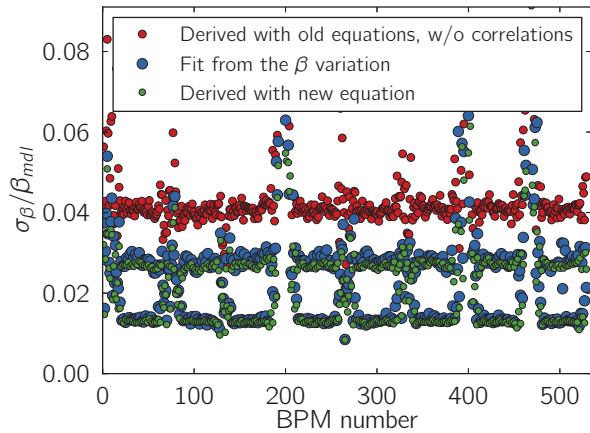
Figure 3: Relative uncertainty of the β-function derived in the error propagation compared to a fit of the variation of calculated β-functions.

Figure 4: Screenshot of the implementation of the automatic local correction tool in the GUI.

This is limited by the AC dipole excitation time and the BPM acquisition software. It is foreseen to increase the maximum number of measured turns by a factor of three. This will allow for a more precise phase measurement and a better time efficiency during the measurements. Furthermore improved non-linear calibrations for BPMs are expected [18].

β-beat estimates for 2015 at $\beta^* = 40\,cm$

Simulations show that the β-beating due to the dipole b_2 errors for injection optics at 6.5 TeV is around 5% and may reach up to 7% for squeezed optics at $\beta^* = 0.4$ m. Due to a broken MQT magnet, four MQT magnets of the same circuit will be switched off in order to minimize the β-beat and dispersion-beat and they will be compensated by increasing the strength of other MQT magnets in the same arc. For a tune shift of 0.08 this will lead to a peak β-beat in arc81 of around 2% for injection optics or 4% for ATS $\beta^* = 0.2$ m optics at 7 TeV. The β-beat due to this is negligible in the other arcs.

In 2012 the local corrections for $\beta^* = 0.6$ m accounted for a β-beat of 80% for Beam 1 and 100% for Beam 2. Extrapolating this to a $\beta^* = 0.4$ m this number increases to 100% for Beam 1 and 130% for Beam 2.

Another source for β-beating is the uncertainty of the saturation component of quadrupole magnets [19]. The impact of this uncertainty is studied by creating 60 different lattices where the saturation component is changed by a Gaussian distributed random value within its uncertainty. The resulting β-beat shows a peak β-beat of around 1% in the worst case.

The distribution of the resulting β-beat if the b_2 errors, hysteresis error, saturation uncertainty and the extrapolation from local corrections in 2012 are regarded together has a maximum for a peak β-beat of 100% for Beam 1 and 140% for Beam 2. It should be noted that this estimate is
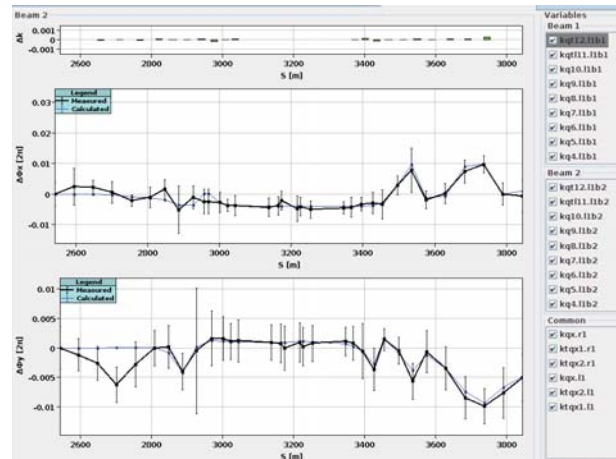
for the $\beta^* = 0.4$ m optics and it is not clear if this optics will be used in 2015. This simulation covers the worse cases, since optics with a larger β^* will have a smaller β-beating.

TOWARDS A COUPLING FEEDBACK

The control of the betatron coupling is fundamental for the safe operation of the tune feedback. Recent advancements in methods and algorithms for the coupling measurement and correction follow [20]: (i) a more precise formula relating the Resonance Driving Term (RDT) f_{1001} to the ΔQ_{min}, (ii) the quality of the coupling measurements is increased, with about a factor 3, by selecting BPM pairs with phase advances close to $\pi/2$ and through data cleaning using Singular Value Decomposition (SVD) with an optimal number of singular values. These improvements are beneficial for the implemented automatic coupling correction, which is based on injection oscillations. Furthermore, a coupling feedback for the LHC is under development. The system will rely on a new BPM electronics system, Diode ORbit and OScillation (DOROS) [21], which will be operational when LHC restarts in 2015. The feedback will combine the coupling measurements from the available DOROS BPMs in order to calculate the best correction.

AUTOMATIC LOCAL CORRECTIONS

During Run I all local corrections have been computed manually by optics experts usually off-line. During LS1 automatic routines for the computation of corrections have been developed using the MADX matching module [22]. These routines are being incorporated to the OMC Graphical User Interface (GUI) for a flexible selection of correcting quadrupoles and constraints from measurements. Figure 4 shows the implementation in the GUI.
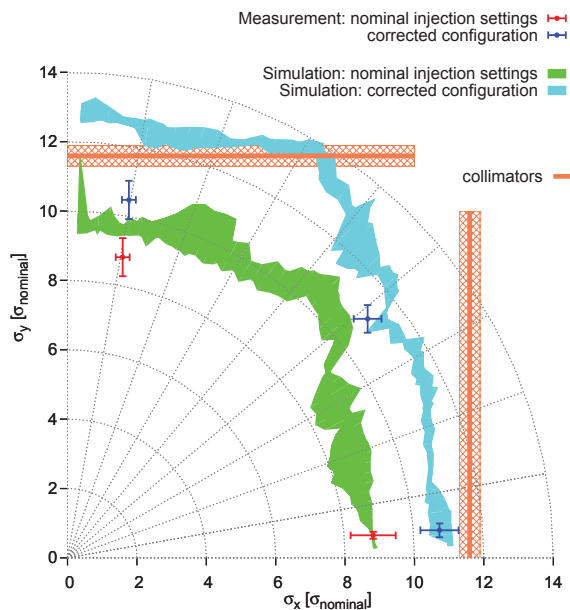
Figure 5: Measured and modeled dynamic aperture before and after correction at injection for Beam 2.

SETTING OF MSS, MCS, MCO AND MCD

MCS correctors are used for the compensation of b_3 errors in arc dipoles, but no beam based checks have been performed so far. The π orbit bump method introduced in [23] can be used to assess the correction quality, and its implementation is recommended for the commissioning of Run II.

Dynamic aperture and amplitude detuning

In [24] it was demonstrated that non-linear chromaticity, amplitude detuning and dynamic aperture could be corrected simultaneously at injection, see Fig. 5. It is desired that such corrections are implemented during the commissioning at low intensity to provide an obstacle free playground for finding optimum settings of Landau octupoles with higher intensities.

In 2012 amplitude detuning was measured for the first time via forced adiabatic betatron oscillations using AC dipoles [8]. This functionality has been added to the OMC GUI to allow fast measurements and corrections during commissioning. Corrections are proposed especially for injection, using the MCO correctors. At flattop the measured amplitude detuning in 2012 with depowered landau octupoles was negligible.

Chromatic coupling

Beam-based techniques were applied for the first time in 2012 to correct chromatic coupling [9] in the LHC. The resulting corrections turned out as efficient as previously computed corrections based on magnetic measurements but requiring significantly weaker correctors. However these corrections were not used in nominal operation. The OMC

Table 2: Results of cleaning and improving OMC software (C/Fortran, Python and Java (GUI)).

	2013-01	2014-02
Lines of code	331,312	141,195
Static analysis issues	479,680	165,531
GUI Critical bugs	7	0
GUI Time startup to corrections	25 min	2 min
GUI Memory usage per shot	100 MB	12 MB
GUI Units test coverage	0	43%

GUI has been equipped with the required algorithms to allow for the chromatic coupling corrections to be set during commissioning. These corrections using the MSS magnets should be implemented in Run II.

Inner triplet high order corrections

Higher order triplet errors were studied via their feeddown to both tune and linear coupling. These measurements were compared with model predictions incorporating magnetic measurements of the non-linear errors in the IR magnets. Where observation and simulation agree, or deviations are well understood, the model may be used to calculate corrections for the non-linear errors. This is the case for IR2 and certain multipoles in IR1, however discrepancies were particularly notable in IR5. Further studies in Run II are needed to allow identification of the sources, their incorporation into the model, and eventual correction.

SOFTWARE IMPROVEMENTS

Since 2012 computer scientists are cleaning, refactoring, optimizing and parallelizing the OMC software [10, 25]. The refactoring of the main programs (Python/C/FORTRAN/Java) and removing of obsolete source code led to a clean software base and a robust execution. The removal reduced lines of code and static analysis issues significantly. Cleaner code facilitates further changes and corrections to the algorithms. Moreover professional software development techniques, like using static analysis tools, version control software, an integrated development environment, a bug tracker and automated tests, were applied to improve software quality. Table 2 shows a comparison of metrics between the old and the current software base.

Software development is one of the fundamental pillars for improved optics measurements and corrections in the LHC. In 2015, the implementation of new techniques and further optimizations will be faster and safer than ever.

ACKNOWLEDGMENT

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STRATEGY FOR THE FIRST TWO MONTHS OF THE LHC BEAM COMMISSIONING AND KEY EARLY MEASUREMENTS

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Abstract

The LHC beam commissioning in 2015 will be based on the experience accumulated during Run 1 and on scenarios further developed during LS1. On the other hand, the operation at higher energies and with different bunch spacing will pose new challenges and will require additional measurements to be carried out in earlier commissioning phases. The commissioning plans for the first months of operation, until the establishment of first stable collisions, are discussed and the required key measurements with beam are presented. The additional requirements for systems that underwent significant upgrades or changes during LS1 are also taken into account.

INTRODUCTION

At the start-up of the Large Hadron Collider (LHC) in 2015 after the Long Shutdown 1 (LS1) the setup of the first "stable beams" at energies close to 7 TeV will represent an important beam commissioning milestone. This is the machine mode when the LHC experiments are allowed to be fully switched ON and to acquire data from collisions. This condition is met when, amongst others, the machine protection validation is completed for all configurations of the operational cycle. Indicatively, two months of beam time are allocated in the 2015 LHC schedule until first stable beams [1].

The validation of a machine configuration entails a lengthy series of measurements that culminate with the complete set of loss maps and asynchronous dump tests to demonstrate that the machine elements, as well as the experiments, are protected for the relevant loss and failure cases. If this validation is successful, the following commissioning step consists in the beam intensity ramp-up until the maximum number of bunches is achieved. Otherwise, key parameters such as aperture and β^*, collimator settings, crossing angles for an assumed emittance, have to be reviewed.

It is crucial that these key parameters are finalized in the first commissioning phase, before proceeding with the intensity ramp-up: later adjustment of beam and machine parameters would be very costly in terms of commissioning time and should be avoided. Thus, one important goal of the initial commissioning is to make the necessary measurements to ensure that, within the given uncertainties, an adequate set of key parameters is chosen. An optimum trade off between peak performance and commissioning risk must be found, taking into proper account the opera-
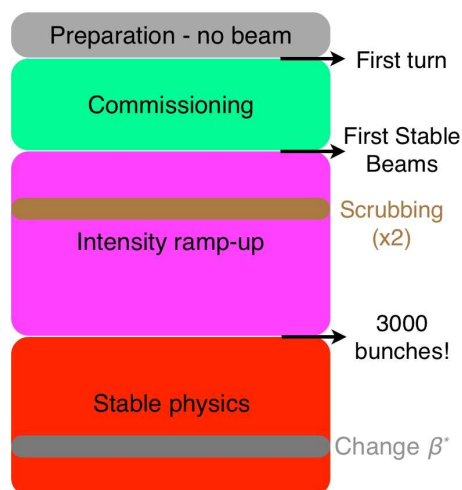
Figure 1: Illustrative view of the 2015 commissioning strategy. Beam commissioning with individual bunches is followed by an intensity ramp-up before achieving a period of stable physics operation without further modifications of the number of bunches. The proposal of changing β^* after a period in physics is envisaged.

tion experience of the LHC Run 1 and the uncertainties for the post LS1 conditions (e.g., beam energy, 25 ns spacing, electron cloud, etc.). While it is clear that some limitations can only become apparent at high intensity, we propose a set of measurements that can provide feedback on the choice of β^* for physics early on.

In this paper, a first look at plans and measurements of the initial commissioning phase until the first stable beams is presented. Rather than outlining the detailed commissioning steps as established in previous operational runs, focus is given to the new commissioning requirements that are consider necessary in order to face the challenges of the operation at higher beam energies and intensities. After recalling the baseline commissioning strategy and the relevant input from the experience in Run 1, important system changes affecting the commissioning plans are presented. First ideas of commissioning requirements are then collected.

Two extreme commissioning approaches might be envisaged: (1) achieve the smallest β^*, computed as ultimate limit under the assumption that the LHC works as well as at the end of 2012 or (2) relax the beam parameters to minimize the risk of instabilities and machine protection constraints, at the expenses of β^*, e.g. opening collimation hierarchy and increasing β^*. Detailed scenarios are worked

out in [2], where a proposal is made for the β^* value of 65 cm at 6.5 TeV in the high luminosity points. This is assumed as baseline.

OVERALL COMMISSIONING STRATEGY

A very simplified view of the 2015 proton run commissioning outline is illustrated in Fig. 1. The detailed LHC schedule taken as a baseline at the time of this workshop was presented in [1]. The start of beam commissioning is foreseen at the beginning of February 2015 and about two months are allocated to produce the first stable beams. Following a hardware commissioning and cold checkout period, the initial phase aims at establishing the first stable beams with a few colliding bunches at 6.5 TeV. This is followed by an intensity ramp-up period aiming at setting up the maximum number of bunches at 25 ns bunch spacing (with the option of switching to a possible fall-back scenario at 50 ns in case of severe issues with the 25 ns spacing). Two beam scrubbing periods are planned in this phase to prepare the machine for the 25 ns operation [4]. The initial ramp-up of intensity, by means of increasing the number of bunches, will be done at 50 ns, before continuing at 25 ns. Stable beams will be regularly declared in the ramp-up phase, while gaining experience in handling larger and larger stored beam energies. The machine will then enter a period of stable physics runs at high intensity. Adiabatic improvement of parameters like bunch intensity, bunch length and emittance will take place with the maximum number of bunches, without major changes of machine configuration.

The possibility to consider a re-adjustment of β^* after an appropriate time of stable physics is also proposed. A similar approach was adopted during the 2011 operation, when the β^* was squeezed from 1.5 m to 1 m in September [3]. This proposal is being evaluated, taking into account the experiments' requests [5]. The advantage of this approach is that one could start with relaxed parameters until sufficient operational experience is accumulated on machine and optics stability, available aperture, beam losses, impedance and beam-beam instabilities etc. The * would then be squeezed further by precisely targeting a more performance-oriented parameter set. Such an approach would have to be prepared early on, e.g., with optics preparation in the first commissioning phase, to minimize the impact on the duration of the recommissioning period (see below).

The detailed discussion of the initial commissioning steps is not reviewed in this paper. The operational experience of Run 1 provides a mature baseline that makes us confident that the standard phases [6] (first threading, beam capture, beam diagnostics commissioning, initial orbit and optics checks, polarity checks; setup of feedback systems, collimation, RF, injection, LBDS, BI, etc.; detailed optics measurement and correction, aperture, ramp and squeeze, collisions, etc.) can be addressed successfully. Adequate commissioning time will have to be allocated to cope with
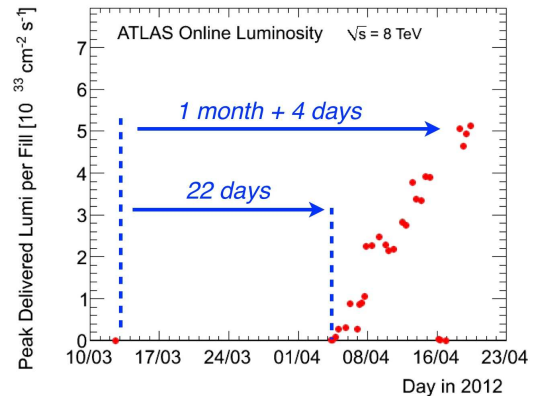
Figure 2: Luminosity versus time as recorded in ATLAS in the first weeks of the 2012 run. Courtesy of the ATLAS collaboration.

the system changes and upgrades that occurred in LS1 and new requirements for the commissioning at a higher beam energy, as discussed below.

RELEVANT INPUT FROM RUN I COMMISSIONING EXPERIENCE

The key milestones of the first weeks of operation in 2012 are illustrated in the diagram of Fig. 3. The first stable beams were achieved only 22 days after the beginning of beam commissioning. A record intensity ramp-up took then place, completing the increase in number of bunches – 1380 at a 50 ns spacing – eleven days after. This is also illustrated by the graph of peak luminosity recorded in ATLAS, see Fig. 2, which reached 80 % of the typical operational values in 2012 only about one month after the start of the beam operation.

In the attempt to identify key ingredients for this outstanding operational achievement, one could point out that, amongst others:

- The commissioning effort was focused on high-intensity proton operation. Set up of special runs was left for later phases.

- A minimum number of hardware changes to the key accelerator systems had occurred compared to the 2011 run.

- Up to 3 nominal bunches at top energy were within the safe limit for machine protection. This eased and made more efficient several commissioning procedures.

These aspects come in addition to the excellent performance of the accelerator systems, which were very efficiently commissioned thanks to the experience accumulated until 2011. This will likely not be the case at the start-up in 2015 due to the LS1 activities.

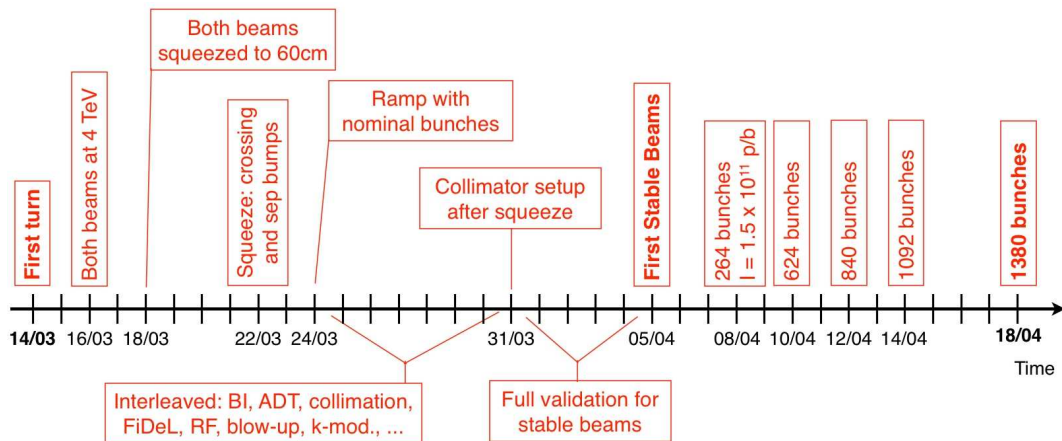The careful choice of 2012 machine parameters was based on a solid knowledge of the LHC and of the accel-

Figure 3: Dates of the main commissioning milestones that led to the first stable beams in 2012 and to record intensity ramp-up from a few bunches to the maximum 1380 bunches for the high-intensity proton operation.

erator systems. For example, the triplet aperture was predicted [7] within 0.5 beam sigmas and the beta-beating errors were kept below 10 % [8]. For 2015, the machine has to be considered as brand new under several aspects due to the long stop of about 2 years. Other uncertainties also apply, like the reproducibility of the machine aperture after having opened the vacuum and the behaviour of magnets at 6.5 TeV and of beam losses and beam instabilities at higher energies.

The machine protection aspects pointed out in the list above should not be underestimated. At 4 TeV, 3 nominal bunches were still below the safe limit. This allowed an efficient setup of the collisions in all interaction points and in some cases allowed speeding up the validation (transverse loss maps followed by asynchronous dump tests in the same fill). At higher energy, operational efficiency might in some cases be reduced if validations have to be split over several fills.

SYSTEM CHANGES AND REQUIREMENTS

The hardware changes that have taken place during LS1 and the corresponding new system requirements were the subject of two sessions at this workshop that addressed status and commissioning plans of various key systems, see for example [9, 10, 11, 12, 19]. It was pointed out that important upgrade of the systems will need adequate recommissioning time. Some key points are recalled, leaving the details for the quoted references.

– Injection and dump systems [12]: new hardware will be used for the TDI and TCDQ protection blocks; new interlocks on the TDI and TCDQ, based on hardware implementations into the BETS, will be deployed; dedicated beam measurements are requested for the TDI heating; measurements done at the beginning of Run 1, such as wave form scans and kick response, are planned to be repeated.

– Collimation [11]: 18 new devices with in-jaw BPMs have been installed and 8 new IR collimators will need to be commissioned. The new BPM functionality will need dedicated time from the collimation and BI teams.

– Beam instrumentation [14, 15]: there will be new beam size measurements, new BLM layout (note in particular the addition of LIC's in the injection regions [12]).

– The FiDeL model will have to be assessed for the new pre-cycle. Saturation effects in the magnet yoke will become relevant for the first time and should be take into account.

– RF: several hardware and software changes occurred for the main RF system as well as for the transverse damper, see [9, 10, 16].

This list is not exhaustive but reflects a selection of topics that were discussed at this workshop. Note that the LBOC and LMC panels are in the process of reviewing in detail each accelerator system. A complete list of system requirements will be re-assessed and put into a coherent beam commissioning plan.

The experiments presented their views and wishes for the start-up [5]. One important requirement is to prepare early on various special physics runs such as the ones for Van Der Meer scans and for the LHCf data taking. Contrary to the case of Run 1, these activities now require different optics with respect to the physics and flat-top optics of the standard operation cycle. The impact of this requirement on the commissioning time should not be underestimated as it will add new constraints and requirements, like additional optics measurements and machine configuration validations, in a phase when the operational experience will still be limited.

Other important scenarios under discussion are the luminosity levelling with β^* and the squeeze with colliding

beams [17]. Both have important impact on the commissioning strategy. This topic is not addressed in this paper as at the time of the workshop a decision on these scenarios was not yet reached.

It is assumed that the operational cycle in 2015 will be as the one in Run 1: the squeeze is performed at constant energy with separated beams; collimators in cleaning (IR3/7) and dump (IR6) insertions are closed to their final settings during the ramp, then only collimators in the experimental regions are moved during squeeze and collision setup; luminosity levelling in IR8 is performed with beam-beam offsets. Impact on commissioning strategy will have to be quantified.

2015 BEAM MEASUREMENTS AND "DECISION POINTS"

In addition to dedicated commissioning time for hardware changes and for fulfilling new requirements, additional measurements are proposed. These are measurements that were not part so far of the initial beam commissioning but are now considered crucial to validate early on the choice of machine configuration parameters. It is proposed to define several "decision points" in the commissioning plan when the choice of parameters is re-assessed before moving to the next step.

◇ **IR aperture at injection**: the Run 1 experience has shown that IR aperture measurements at injection can already provide solid extrapolations for the β^* reach [18]. The IR aperture at injection was only measured systematically in the 2009 pilot run. This should be now part of the commissioning and take place as soon as the reference orbit at injection is established (corrected orbit and optics with nominal bunch intensities).

◇ **Dedicated local orbit and optics correction in the IRs**: Dedicated time to establish local corrections of orbit and optics around the experiments are essential to provide feedback on the feasibility of various scenarios like β^* levelling. Comapred to what was done in the past, addition care should be taken to ensure that non-local transients are minimized (e.g., orbit leakage around the ring while changing IR8 β).

◇ **Collimator impedance with single bunch**: One important question that could not be solved during Run 1 is the role of collimation impedance on the instability observed in 2012 [19, 20]. Early measurements with nominal single bunches should be carried out with high priority to identify potential impedance issues for different collimator settings [2]. It should also be mentioned that there are proposals for collimator settings for reduced impedance with acceptable losses of cleaning [21]. These configurations should also be addressed. Additional monitoring of the system cleaning performance should also be envisaged.

◇ **Stability of orbit and BPM signals**: reproducibility and stability of the machine are crucial inputs for the tolerance margins used to define the achievable β^* and should thus be monitored regularly. This include dedicated orbit measurements with the new DOROS acquisition system.

Additional decision points that can only be addressed during the intensity ramp-up phase are: multi-bunch impedance and beam-beam effects (for possible iteration on crossing angle values), two-beam effects and octupoles, monitoring of machine stability and UFOs. The topic of electron cloud effects is discussed in other contributions to this workshop [16]. Nevertheless it is clear that the outcome of scrubbing runs will be also crucial input in the decision-making process.

In addition, new measurements requirements are

▷ **Chromaticity measurements in different conditions**: Regular chromaticity measurements should be performed to assess the accuracy of the measurement and the reproducibility of the chromaticity along the cycle. These measurements should be repeated in case settings are changed that are expected to affect chromaticity (e.g. octupole settings).

▷ **De-tuning versus amplitude and MCO/MCD settings**: Dedicated tests with octupole and decapole correctors are considered mandatory in order to establish clean conditions for the later setup of Landau octupoles. Although in principle the set values should compensate the predicted errors in the main dipoles. the models of de-tuning with amplitude at 450 GeV were not fully understood in Run 1. The deployed settings might have played against the Landau octupoles.

▷ **Optics measurements and corrections down to 40 cm**: As discussed above, a recommissioning of the optics after a period of stable physics conditions can only be deployed efficiently if the optics measurements and correction of the target β^* are prepared earlier on. Commissioning down to 40 cm represents a small overhead in time if done during the squeeze setup.

▷ **Aperture verification with squeezed beams** should be performed for all β^* values reached in the commissioning in order to have all required information.

There is a proposal to use from start-up the pre-squeeze optics of the Achromatic Telescopic Squeeze (ATS) [22]. This optics changes the phase difference between beam dump kicker in IR6 and super-conducting triplet in IR5. In particular, the case of B2 is unfavorable because a phase difference close to 90 deg between dump and the right IR5 triplet is foreseen. This optics, which is being validated under different aspects [23], will require dedicated loss maps and validation tests to probe the triplet protection.

CONCLUSIONS

Initial thoughts on the first commissioning plans for the LHC Run 2 were presented, addressing the requirements for the first weeks of beam commissioning until the setup of first stable beams is accomplished. In the presence of various uncertainties on the expected performance of the LHC at energies larger than in Run 1, we considered that important goals of the first beam commissioning will be to validate the proposed machine configuration and ensure that the choice of parameters is adequate for the intensity ramp-up in 2015. While several key validations will only be possible later on, during the commissioning of the 25 ns beams, we proposed a number of measurements that can already provide important feedback in earlier commissioning phases, when changes are still possible without major overheads. Other than these additional "decision points", the commissioning will follow the very mature experience of Run 1. Clearly, changes occurred in LS1 must be taken into proper account.

Taking all these constraints into account, and the additional requirements from the experiments that require early on the preparation of various special runs, we consider that the two months scheduled to achieve the first stable beams in 2015 are probably feasible but certainly challenging, even if the LHC will work equally well as in 2012.

A possible way to achieve an efficient commissioning while ensuring a good yearly luminosity performance might be to foresee since the beginning a recommissioning period to squeeze further β^* later on in 2015. Ideally, this would take place after an adequate period of stable physics at the maximum intensity, similarly to what was done in 2011. If well prepared, this approach could ease the initial commissioning phase and allow a finer tuning of machine parameters close to the ultimate performance at 6.5 TeV.

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