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Annecy 11th to 13th March 2013

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Abstract

This report contains the proceedings of the MPP Workshop on LHC Machine Protection, held in Annecy from 11th to 13th March 2013. This MPP Workshop on LHC Machine Protection focusses on the upgrade work in LHC during the Long Shutdown 1 (LS1) for mid-and longer-term improvements of the LHC MP systems.

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MPP Workshop

Annecy 11-13 March 2013

The principle aims of the workshop are to discuss mid-and longer-term improvements of the MP systems:

- Review of the current operational experience with MP systems during the first running period (2010-2012).
- Understanding the planned changes of MP equipment during LS1 and the consequences for operation after LS1.
- Identifying areas where improvements are required.
- Ensuring coherence between the different MP systems.
- Identifying misses.

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The authors are thanked for their high quality contributions, written during a very busy period.

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Session 6: Operation after LS1

Presentations can be accessed from: http://indico.cern.ch/event/227895/timetable/

MACHINE PROTECTION WORKSHOP 2013 SUMMARY OF SESSION 1 MPS OPERATIONAL EXPERIENCE (2008-2012) AND OUTLOOK

T. Baer and D. Wollmann*, CERN, Geneva, Switzerland

Abstract

This paper summarizes the presentations and the discussions of session 1 - *MPS Operational Experience (2008 - 2012) and Outlook* - of the Machine Protection Workshop held from 11th to 13th March 2013 in Annecy, France. It gives an overview of the issues addressed in this session which need a follow-up. The four presentations made in session 1 are listed below:

- MPS issues and MP approach concerning operation and MDs (M. Zerlauth).
- Performance and availability of MPS 2008-2012 (B. Todd).
- OP view on handling of MP issues (G. Papotti).
- Global vision of MPS after LS1 and beyond (R. Schmidt).

MPS ISSUES AND MP APPROACH CONCERNING OPERATION AND MD

This presentation gave an overview of the major machine protection issues observed during the first running period (2010-2012). The handling of these issues was analysed from a machine protection expert viewpoint. Furthermore the handling of machine developments and other non-standard operation modes was critically reviewed and improvements for the future were proposed.

The main MP issues observed in the running period 2010-2012 are listed below:

- LHC Beam Dumping System (LBDS): common mode failure in 12V powering.
- Quench detection issues on IPQ and 600A Energy Extraction.
- HTS instrumentation cable on RB.A45.
- Wrong settings of transfer line collimators after the implementation of the new Q20 in SPS.
- Injecting timing issues due to test with high brightness beams in CERN-PS (H9).
- False collimator settings at the beginning of the 2012 run (TCTV 2x .IR2, 2x .IR3).

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- Roman Pot Controls issues.
- BLM High Voltage Cable not connected.
- OFSU reference problems.
- BSRT Mirror degradation due to RF heating.
- MKI flashovers.
- QFB not usable in squeeze due to poor signal.
- Instrumentation problem in triplet L8 after TS2.
- Loss of redundant protection (60A power permits, LHCb dipole , CMS solenoid,).
- Tertiary collimators in IR2 not moving during squeeze.

Follow-ups

- Dependable tracking of relevant changes in MP systems.
- Assure more coherent approach for follow-up of magnet and beam related MPS issues (MPP, MP3).
- Define and enforce minimum validation of changes through the use of automatic tools and dependency models.
- Introduce the role of a Machine Protection Piquet to follow-up commissioning of machine protection systems, operational changes including the necessary revalidation, analysis and documentation of operational runs and beam dumps, as well as contact person (representing rMPP) to operations.
- Machine Developement: Mandatory note with detailed program and required changes to machine set-up needs to be prepared and approved for all MDs, to enhance safety and improve the efficient use of allocated beam time.
- The use of the three levels (normal, relaxed, very relaxed) of the setup beam flag (SFB) has not been very distinctively, i.e. in most cases either the normal or the very relaxed version has been applied (even during MDs). This needs to be reviewed and the use cases of the different levels need to be more clearly defined and re-enforced.

Discussion

- A. Siemko asks if there is an overlap between MPP and other working groups. Is there a need for re-organization? Any suggestions? M. Zerlauth replies that he does not think that any changes are needed. It works fine to discuss the aspects in different forums. The collaboration with the new MP3 panel will be intensified to guarantee a coherent approach for follow-up of magnet and beam related MPS issues.

- R. Jacobsson asks how the MP responsible would be integrated? M. Zerlauth replies that in certain situations fast reaction was needed and there is a certain conflict for the machine coordinator between luminosity production and MP. J. Uythoven comments that normally the EIC comes to the coordinator in case of issues. For the coordinator it would be useful to have a MP coordinator available to discuss. M. Zerlauth adds that there is a second facet: the follow up of MP issues. R. Jacobsson comments that this would be definitely a very good idea during MDs and commissioning. B. Goddard remarks that this would be helpful also during production runs.

- S. Redaelli mentions that there was not very much distinction between levels of safe intensities (Setup Beam Flag). R. Schmidt responds that we started 3 years ago very cautiously and gained more confidence with operation. But the large variety of levels is not transparent.

- D. Wollmann asks if the Acctesting framwork could be also a solution for revalidation after MDs, etc? M. Zerlauth responds that this will be addressed in K. Fuchsberger's presentation on Wednesday.

MACHINE PROTECTION SYSTEM: AVAILABILITY & PERFORMANCE 2010-2012

This presentation showed the results of an in depth study of the failures recorded in 2012 for the seven Machine Protection Systems and deduced recommendations following from this analysis.

More than 250 faults have been recorded in 2012 for these systems, with a total repair time of over 360 hours. With the help of an availability matrix the five most prominent failure modes have been identified: QPS: Radiation Induced Faults; QPS: Internal Communication Faults; QPS: Spurious Signal; BLM: Optical Link Failure - Surface; BLM: Optical Link Failure - Tunnel.

Follow-ups

- Changes in the different Machine Protection Systems should address prominent failure modes, as mentioned above, to improve the availability of the LHC.

- Planned changes to systems during LS1 should be studied to predict their influence on the availability of post-LS1 operation.

- A fault tracking system should be considered to improve data collection and analysis post - LS1.

- Post Mortem Events labelled as SIS should be further classified by the root cause.

- Infrequently activated inputs to interlock systems should be periodically tested to reduce the risk of dormant unsafe failures. About 50% of the BIS inputs never triggered since 2010.

- The origin of MPS abort events triggered by beam loss interlocks should be investigated to identify possible new hazard chains.

Discussion

- Dumps due to beam losses (BLMs):
  - R. Schmidt mentions that BLM dumps were often caused by losses e.g. during squeeze, etc. Any idea for other events, why and what could be done? B. Todd responds it would definitely be good to look in detail. J. Wenninger points out that many dumps occurred during the squeeze, due to instabilities, and those are very difficult to catch before by other detection mechanism.

- Post Mortem and improved fault tracking:
  - J. Wenninger mentions that PM comments from the EIC and MPS expert are typically very similar and could probably be merged. But some differentiations are needed.
  - S. Redaelli points out that problems in the shadow of other interventions need better tracking.
  - S. Redaelli states that very few cases of false dumps were caused by collimation.
  - A. MacPherson underlines that better fault tracking is needed.
  - W. Hofle asks if the goal of an improved fault tracking would be to increase availability or safety?
  - R. Schmidt points out that we can build available and reliable systems that improve safety without risking to loose availability.
  - B. Todd mentions that performance needs to be watched very closely, as from the number of false positives also the safety of the system can be inferred.
  - B. Goddard asks for the number of occurrences where a fill was not dumped despite a dangerous failure. B. Todd replies that he believes that this is zero.

OPERATION'S POINT OF VIEW ON HANDLING MACHINE PROTECTION ISSUES

This presentation focused on the operational experience with Machine Protection issues. Therefore, the major observed Machine Protection issues were classified into three categories:

- Failures that only experts can detect:
  - Common mode failure in LBDS 12V powering.
  - False settings of transfer line collimators, after shifting from Q20 to Q26 optics in the SPS.
  - Non connected BLM High Voltage Cable.
  - False collimator settings (2 x TCTV IR2, 2x IR3).
- Failures that shift crews can detect after a beam dump:
  - MKI flashovers.
  - Loss of redundant protection (60A power permits, LHCb dipole, CMS solenoid,).
  - Synchronization problem between SPS and LHC during injection (SPS in local).
  - Injecting timing issues in the SPS during tests with BCMS (Batch Compression, bunch Merging and Splittings) beams.
- Failures that shift crews can detect with beam stored in the machine:
  - RF feedback crate down, compromising the control of the whole RF line.
  - Beam Position Monitor readings unavailable during the ramp.
  - Tertiary Collimators in point 2 not moving during squeeze.
  - TCDQ not moving during the ramp.
  - Missing abort gap monitoring due to BSRT mirror failure.
- Dumps that could have been avoided:
  - Dump due to orbit excursion while setting up for 6σ Van der Meer scans at 1.38 GeV/c.
  - Dump due to wrong TCT settings, when exceeding the beam intensity limit defined by the Setup Beam Flag.
  - Dumps due to the weak instrumentation of the interlocked BPMs in IR6.

Follow-ups

- Implement software tools to help shift crew identify and notice the existance of unsafe machine states before the last dumps.
  - BLM reference/example readings for each beam mode.
- Revise Post Mortem (PM) analysis frame and possibly add missing PM checks (FMCM, PIC, BIC, IPOC). For example
  - Verification of collimation hierarchy.
  - Improve power loss module to identify losses higher than normal.
  - Revise Injection Quality Check as it currently latches too often, which weakens its protection functionality.
  - Revise LBDS XPOC checks to reduce the number of latches in non-critical modules (filling pattern, missing beam intensity and BLM data).
- Introduce a sequencer task to remove all masks during ramp down and preparation for injection. This will help to reduce the number of unnecessary dumps especially during Machine Development runs.
- Enforce thorough step-by-step procedures with lists of required setting changes and masks for special runs and MDs.
- Prepare more procedures to deal with possible failures, especially if they can avoid dumping the beam:
  - Orbit out of tolerance in point 6.
  - Increasing abort gap population well above the dump threshold: add values for the ADT to blow the beam out in a smooth and controlled way.
- Implement a training of shift crews on executing emergency procedures.

Discussion

- G. Arduini states that a better analysis of warning events would help (do not stress interlocks). G. Papotti refers to K. Fuchsberger's presentation.
- B. Dehning mentions that for the BLMs an automated failure detection is run about once per week. Also a tool for verification of loss profiles in the field of collimation is available (with need of optimization).
- M. Albert pointed out that the shift crew is not part of the machine protection system and has a significant reaction time.
- B. Goddard asks if there is a procedure for abort gap population. J. Uythoven responds there is a procedure in EDMS and thresholds are visible in an application which is running in the CCC.

- G. Papotti adds that often the problems are the details, e.g. in case of a not working dump, which ADT blow-up settings should be used?
- A. MacPherson proposes to add an EIC on rotation bases as member to rMPP.
- A. Siemko asks about wrong settings and if there exists an idea how these could be interlocked? G. Papotti responds that different hyper cycles are used e.g. for MDs, which include already a different set of settings including limits (collimators, power converters, etc). J. Wenninger adds that other systems like RF and ADT are not fully integrated into LSA and setting reversion relies on experts. G. Papotti comments that special runs have clearly been more critical concerning wrong settings. W. Hofle mentions that some of the settings are relying on certain information (like intensity going to be injected), which is currently not available with the required reliability.
- P. Baudrenghien asks if there is a redundant approach for abort gap monitoring foreseen for after LS1? J. Uythoven responds that there is a strong request to BI to make abort gap monitoring more reliable.
- S. Redaelli comments that the state machine was build e.g. to check for allowed actions, which would help for settings that depend on additional beam information.
- B. Dehning mentions that for the BLM system the settings are checked against values in the logging database. This approach could also be applied by other systems.

GLOBAL VISION OF MPS AFTER LS1 AND BEYOND

This presentation focused strongly on so called *catastrophic* failure scenarios like *beam deflected with non-nominal angle during a dump request* or *beam dump not working*. Their consequences were discussed in the view of recent simulations and damage experiments. Up to now their damage potential cannot be fully quantified, but the presented studies and experiments on hydrodynamic tunnelling should allow a better qualification of the expected damage in the future.

The second part of the presentation addressed possible new fast failure scenarios, which maybe introduced by future upgrades of the LHC (HL-LHC), like crab-cavities. Possible mitigation methods were qualitatively discussed.

Follow-ups

- Further study the consequences of so called *catastrophic* failure scenarios like *beam deflected with non-nominal angle during a dump request* or *beam dump not working*. In addition evaluate mitigation methods such as additional (wast-able) absorbers / internal beam dumps, redundant kickers with absorber blocks and check whether this could limit the potential damage to an acceptable level.
- HL-LHC: Study, if crab cavities will introduce a new type of very fast failures and investigate how to protect against these failures (LLRF, particle free gap between beam and collimators, ...).
- Study the impact of missing beam halo on the current protection strategy (redundancy, reaction time, etc.) and propose required changes.
- Study possible damage and collateral damage due to the use of non robust collimators in view of a possible gain in integrated luminosity.

Discussion

- B. Goddard points out that an internal beam dump would be very complicated and would imply a high redundancy of interlocking. R. Schmidt adds that additional kickers always would fire after the LBDS. But this needs to be evaluated.
- R. Bruce mentions, concerning the example of crab cavity failure, that the collimators will be at about 5.7 real beam sigma most likely after LS1.
- S. Redaelli asks if tests for some of the serious failure cases can be performed?
- A. MacPherson suggests concerning the fast failures in crab cavities, to look into mitigation methods on sub-turn level, like fast coupled feed-backs.
- P. Baudrenghien mentions that with 90deg phase change, the crab cavities could also be used for deflection.

SESSION 2: INJECTION, EXTRACTION AND BEAM DUMP

J. Uythoven, Andrea Apollonio, CERN, Geneva, Switzerland

Abstract

This paper summarises the main conclusions from the second workshop session on Injection, Extraction and Beam Dump.

The four presentations made in session 2 are:

- LBDS kickers (Nicolas Magnin)
- Dump System Protections (Brennan Goddard)
- LHC Injection Systems Modification in Long Shutdown 1 (Wolfgang Bartmann)
- Changes in SPS interlocking (Jorg Wenninger)

MAIN CONCLUSIONS AND DISCUSSION

LHC Beam dumping System

Although all beam dump request were correctly executed during the LHC Run I, and the LBDS showed a good availability, some lessons are to be learned.

Considering the operational statistics, the wearing out of the system is more likely to happen from testing and reliability runs than from normal operation. This will have its effect on dependability numbers and maintenance and one might have to reconsider the justification of all these (test) pulses in local mode.

A study has been launched to assign all system failures to the different failure modes. During operation some failures have been masked while operation continued. Clear expert procedures should be put in place for these circumstances and masking of (redundant) signals should be made more visible so everybody is aware of running in a 'degraded mode'.

Too many false eXternal Post Operational Checks (XPOC) results leading to beam inhibits occurred, generally coming from those modules which can be reset by the operations team. Solutions for overcoming this are being implemented in LS1.

The MKB vacuum interlock due to noisy signals resulted in 13 false dumps in 2011 and 2012. It is not clear if a solution has been found by the vacuum group.

Some serious and unexpected failures of the beam dumping system occurred. As counter measures the powering of the LBDS will be modified, the TSU configuration changed and there will be a direct connection from the BIS to the LBDS re-trigger system. This last change allows for an asynchronous beam dump without the use of the TSU.

The LS1 LBDS commissioning is already starting in 2013. A full system re-commissioning is required. The new BIS – LBDS connection will be tested as part of the reliability run foreseen in 2014. A scan of the MKD waveform with beam and a testing of the direct BLM with beam are foreseen at start-up.

No asynchronous beam dump with a full machine at top energy has yet occurred. With repeated beam dumps at 6.5 TeV beam energy the venting of the TDE dump block, under nitrogen overpressure, could become an issues and should be verified.

The TCDQ absorber will be upgraded in LS1 from 2 to 3 absorber blocks. It is also foreseen that the TCDQ position will be surveyed by the Beam Energy Tracking System (BETS). The BPMS used for the interlocking at point 6 will also be improved in LS1, as improving their availability will also improve the machine safety. The abort gap monitoring will be made more reliable so it can be used automatically for abort gap cleaning and dumping the beam when required.

It was proposed to keep the system tolerances as used by IPOC, XPOC and the BETS 'tight'. This will detect any anomalies as early as possible. Standardisation is required to define when asynchronous beam dump tests should be performed. Also more detailed procedures in case of interventions or non-conformities are required. In this context, the continuation of the rMPP as active 'online' body was strongly supported.

Injection System

The LS1 upgrade of the LHC injection kickers MKI should reduce the temperature increase, due to beam induced heating by a factor 3 – 4 for the same beam currents. This should be sufficient for future operation. NEG coating of the bypass tubes is foreseen to counteract e-cloud effects. Improved cleaning procedures have already proven to be effective against UFOs.

The injection absorber TDI will receive a more rigid beam screen during LS1 and a general revision of its moving parts. This is an intermediate solution before the complete LHC Intensity Upgrade (LIU) compatible change foreseen for LS2. Connection of the TDI gap and the MSI current to a BETS are also under study for LS1.

The settings of the transfer line collimators TCDI will in the future be checked against the applied optics of the transfer line. A solution for correctly measuring the injection losses and not dumping the beams by the BLMs when reaching the measurement range is being studied. A combination of Little Ionisation Chambers (LICs) and temporarily blinding out the BLM interlocks will most likely be used. Improvements of the Injection Quality Check (IQC) are also foreseen. IQC resets should become rare after LS1, and as such will contribute actively to the machine safety.

Changes of the SPS Interlock System

It was pointed out that the Software Interlock System (SIS) was initially designed for the SPS where it is heavily used. For the SPS the BIS and the SIS need to be cycle dependent. Up to LS2 no major improvements of the present systems are expected.

The SPS will possibly have new extractions towards the proposed facilities AWAKE and SBLNF. These should be confirmed before 2016. The different beams are identified by the different extraction energies (dipole field), a system which works very well. The interlocking of the beam position at the extraction points is under-performing for LHC beams.

CNGS beams have been a success story for the SPS with Peta Joules of integrated beam energy on target and activation levels of only a few μSv/h in the transfer lines.

The diagnostics of timing problems for the LHC beams remains rather tricky. This resulted once in sending the wrong beam to the LHC.

In LS1 the SPS power converters FEC will move from the actual ROCS to FCG. A proto-type crab cavity is foreseen to be installed in LSS4. This is a movable device and the interlocking needs to be studied in detail.

ACKNOWLEDGMENTS

The authors of the contributions in this session are acknowledged for their excellent presentations. The lively discussions and contributions from the workshop participants formed the base of this summary.

BEAM DIAGNOSTICS SESSION SUMMARY

B. Dehning, CERN, Geneva, Switzerland

HARDWARE CHANGES IN THE LHC BLM SYSTEM DURING LS1

Fast automatic beam based alignment of collimators has been commissioned. It is based on a new dedicated capture buffer with 80 us integration time and 4396 values, implemented together with a real time client process. The process freezes the buffer, if thresholds are exceeded to allow high time resolution recordings for loss events.

BLM recorded system faults are mainly due to optical link failures, sanity checks and the controls middleware.

The LS1 splice repair requires the dismounting of most of the ionization chambers. A relocation of monitors (about 800) from their location at the quadrupole magnets to the interconnection of the bending magnets is ongoing to allow higher threshold settings in case of losses occurring in the bending magnets (in detail discussed in the next chapter). To reduce the optical fibre transmission errors, temperature controlled racks will be installed at the surface. To increase the data treatment performance the power PC CPUs will be replaced by Linux CPUs, allowing an increase of the data capture and post mortem buffer by a factor 10. Some FPGA changes are needed to exploit the features of the new CPUs and other small changes should overcome limitations in system.

BEAM LOSSES AND THRESHOLDS

Loss measurements in cell 19R2 showed a uniform distribution of dust particle initiated losses (UFO) along the cell, therefore a redistribution of the ionization chambers is proposed. The middle quadrupole ionization chamber for both beams will be relocated and placed in top of the MB.A-MB.B and MB.B-MB.C interconnections. These measurement locations ensure an equal loss detection potential (losses initiated in either of the 3 bending magnets or the quadrupole) for UFO initiated losses.

At the end of the running period in 2013 several quench tests were done to explore the superconducting magnet coil limits. The millisecond duration quench test showed that abort thresholds could be increased by a factor 2 to 8. This result concerns all superconducting magnets and in consequence larger UFO initiated losses could be tolerated.

The collimation quench test resulted in a possible increase of some dispersion suppressor magnet abort thresholds. It revealed that the thresholds for direct proton impact and secondary shower particle impact are different.

The transient quench test of the Q6 quadrupole magnet indicated that the abort thresholds for the shortest integration time could likely be increased for the secondary particle loss scenario.

A new threshold calculation procedure aims to keep the flexibility and reliability of the current calculation procedure. Moreover, functionality for a safe and automatic book-keeping of the different thresholds, as well as inputs for their calculation, will be provided. An improvement on the performance for the threshold deployment procedure is foreseen, because some of its verification steps will become part of the designed tools. The proposed system is based on the migration from C++ stand-alone threshold generation to an implementation of the algorithms in Procedural Language/Structured Query Language (PL/SQL) to be executed in the LSA database. In order to call specific algorithms, visualize parameters, generate thresholds and execute tests and make comparisons a Graphical User Interface is foreseen.

THE FEEDBACK SYSTEM

The system depends strongly on the UDP network latencies, middleware communication, technical network latencies and the timing infrastructure. These services are monitored by the orbit feedback controller but not further exploited.

The majority of the feedback associated dumps in 2011 were related to the QPS and noise in the tune feedback trims. The QPS limits were raised for the 2012/13 run and these beam abort causes disappeared. In 2012/13 the main causes of feedback related aborts were measurement quality related (BPM and BBQ) causing losses and finally aborts, front-end and infrastructure software related and insufficient loop stability.

Foreseen mitigations are the temperature control of the BPM front-end racks to minimize position drifts and of the deployment of the redundant diode based orbit measurement system in the straight sections. Two other improvements are envisaged, the search for several peaks in the BBQ based tune spectrum with some logic to identify the most likely tune value, and the use of the ADP system as a redundant tune measurements system.

Further recommendations are the review of the UDP, middleware, FESA and technical network infrastructure to increase the loop stability. To avoid congestions it is planned to separate the real time traffic from the operation traffic by using options in the technical infrastructure. The benefits of these changes need to be quantified. It is proposed to track and use the active machine optics in the feedback systems. Another proposal is to commission the gain scheduling option. For the test of the BPM functionality a short duration measurement procedure could be implementing to automate this test and execute it regularly before every fill (BLM like sanity test). The implemented feed forward, based on an average orbit measurement could be commissioned. A last recommendation concerns the design of a full feedback test bed.

After the workshop a feedback review took place and requested that the feedback service units need to be split and newly modular design is needed. In addition new features should only be implemented when a test bed exists.

EXPERIENCES WITH MPS RELATED SYSTEMS AND FORESEEN IMPROVEMENTS FOR LS1

The interlocked BPMs in IR6 were equipped in 2012 with attenuators for the proton operation to increase the reliability of the system. For the Pb–proton run the attenuation was again somewhat reduced to increase the minimum measurable bunch intensity to 3~4 10^9.

Changes in LS1 are foreseen to mitigate electrical signal limitations; the 50 Ohm termination scheme will be improved. Another improvement could be made by implementing remotely controllable thresholds.

For the DIDT system (the name comes from dI/dt) it is planned to produce a single PCB. The transformers themselves will be improved during LS1 with the aim of reducing the dependency on the beam position. Two different solutions are investigated: BERGOZ ICT and the CERN inductive pick-up. It is foreseen to have a complete and operational system, including software ready for the start-up.

The abort gap monitor (AGM) is based on a MCP-fast-gate-photomultiplier-tube measuring the intensity of synchrotron light emitted by the beam during the abort gap.

The main task for LS1 is to solve the problem of the heating mirrors. Other changes concern software improvements. It is foreseen to reduce to minimum manual interventions by adding automated calibration features, watch dogs, self tests, proper recovery from unexpected situations and the management of alarms.

SUMMARY OF SESSION 4 OF MPP WORKSHOP 2013: LHC COLLIMATORS AND MOVABLE DEVICES

V. Chetvertkova (scientific secretary) and S. Redaelli (Chairman), CERN, Switzerland

Abstract

This paper summarizes the discussions that followed the presentations of the “Collimators and movable devices” session at the LHC Machine Protection Workshop. The session summary, as presented at the workshop, and the identified action items are also given.

INTRODUCTION

The fourth session of LHC Machine Protection workshop was dedicated to the LHC collimators and movable devices and included five presentations:

1) **LHC Movable Devices**, by Stefano Redaelli;
2) **Settings generation, management and verification**, by Gianluca Valentino;
3) **Beam-based validation of settings**, by Belen Salvachua;
4) **Collimator hierarchy limits: assumptions and impact on machine protection and performance**, by Roderik Bruce;
5) **Updated robustness limits for collimator materials**, by Alessandro Bertarelli.

For each presentation of the session a summary of the discussion that followed the presentations is given, followed by a summary of the critical points and open actions.

LHC MOVABLE DEVICES (S. REDAELLI)

Discussion

K. Fuchsberger asked if one could use for determining the beam separation versus time (for collimator interlock purposes) a similar mechanisms as for orbit correctors setting checks (with a new tool). S. Redaelli replied that this should be possible. On the other hand, he stressed that the implementation should check the values based on the energy and beta* information that is distributed as safe machine parameters in the timing.

R. Jacobsson asked if there are principle objections to move collimators during beta* levelling. S. Redaelli replied that this is not the case. Only, one has to be very careful if this is done in stable beams mode, as transient losses at the TCTs that could cause a beam dump cannot be excluded. Although the TCTs will not directly touch the beams, if there are losses in IR7 (e.g. due to orbit drifts) the leakage to the TCTs might be seen by the experiments.

R. Schmidt asked whether we should consider passing the responsibility of the loss maps analysis for the collimator settings validation to the OP shift crew. S. Redaelli replied that this is in principle possible. However, the detailed analysis done for the final validation is not trivial and he does not see that this can be done by everybody in operation: people in the collimation team need several weeks of training before getting “qualified”' for the loss map validation. Is this something that we want to have for all the OP team? A common strategy should be established, covering similar problems for other systems' validation (injection, dump, orbit, ...).

Summary

- No major changes of movable devices that require reviewing interlock strategy are foreseen during LS1. One single outstanding issue concerns new fast vacuum valves in IP4. This is being addressed by the MP team.
- One main hardware change affects the collimators: a new design with integrated BPM will be adopted for 18 collimators in the ring, in IP6 and all experiments. This has a great potential to improve the interlocking strategy. A learning period will be required, so at start-up this feature will be used for collimator alignment only.
- Clearly, the verification of settings remains a very hot topic for movable devices. Isolated but potentially very critical problems did occur. It was pointed out that LSA has some weaknesses related to setting management. The change of a resident beam process is not adequately protected and this affects in particular injection protection settings. The safety conditions still rely in some cases on manual interventions!
- A possible improvement for the TCT interlocking might come from a new implementation of dump limits versus beam-beam separation. The collimation team will come with a proposal for a possible implementation during LS1. In parallel, this requires the development of a reliable calculation and distribution of a new parameter to be added as SMP in the timing.
- It was pointed out that the conditions for critical settings preparation/validation were not always ideal. People were often handling critical settings manipulations under pressure from the machine side. Enforcing improvements for the operation at 7 TeV (e.g. authorizing the change of critical settings during day time only), should be considered.
- For possible operation of beta* levelling, one should look into the scaling of TCT losses at 7 TeV versus thresholds of the beam loss at the detectors.

- Should we consider giving more responsibility to the shift crew in the validation of systems critical for machine safety?

SETTINGS GENERATION, MANAGEMENT AND VERIFICATION (G. VALENTINO)

Discussion

A. Siemko asked how the beam separation was taken into account for the settings generation of tertiary collimators. G. Valentino replied that the change of collimator centres follows the linear variation of beam separation versus time, as defined by the orbit correctors.

R. Schmidt asked about the use of the aperture meter and of the colour coding. S. Redaelli pointed out that this tool was unfortunately mainly used during commissioning and MDs (aperture measurements) and not in standard operation. He also pointed out that the colour coding is indicative - the system is anyway not connected to the beam interlock.

S. Claudet commented that, based on his experience with fixed displays for the cryogenic system; one should aim at very simple displays and colour coding. The collimator displays seemed to be too complicated. R. Giachino commented that, in his opinion, one should not see red boxes, which would mean that everything is under control. S. Redaelli replied that the system is intrinsically rather complicated: for example, red boxed in stable beams are associated to injection interlocks caused by injection protection devices in “out” position. S. Redaelli suggested to get a clear statement from OP about preferences for the display design (some prefer to have more expert-like displays to understand better the systems, others prefer simpler displays that just indicate problems).

Summary

- The new software for setting checks seems adequate to address problems encountered in 2012. Some further improvements are in the pipeline. We should consider how it could be extended to the injection protection settings.
- The discussion was animated by very lively debates about operational displays. The present tools are adequate for expert usage but could be improved for shift crew operation. It was proposed to improve the collimator fixed display with a machine-mode-dependent status (ok / not-ok). At the same time, it was agreed that a mini-team should be formed in OP to agree on fixed display design, to provide feedback to the system experts. On the same line, OP was also encouraged to use the ALARM system more often.
- The aperture meter within the online model packages has a great potential and should be developed further. Appropriate software support should be made available.

BEAM-BASED VALIDATION OF SETTINGS (B. SALVACHUA)

Discussion

B.E. Holzer asked if one can distinguish horizontal and vertical losses during standard operation. This could open the possibility to use operational losses instead of or alternatively to standard loss maps. B. Salvachua commented that it’s possible to compare with reference cases. S. Redaelli added that in any case it would be hard to avoid dedicated loss maps: we cannot guarantee that in standard operation we have regularly horizontal and vertical losses in the phases of the cycle that require validation. On the other hand, he acknowledged that monitoring of losses during the fill can provide an early detection of possible problems.

Concerning the excitation of non-colliding bunches with the ADT during standard fills, J. Uythoven commented that we should be careful in having intentionally very high losses when the machine is full. This option must be evaluated in detail.

Summary

- There was a great improvement for betatron loss maps thanks to the ADT excitation. On the other hand, the asynchronous dump validation and off-momentum loss maps determine the minimum required number of validation fills. The strategy for this type of tests in the future (how many do we really need?) and possible improvements (like using controlled RF trims) must be addressed.
- The possibility to perform individual bunch excitations with machine being full (loss maps at the end of each physics fill?) should be evaluated.
- Online monitoring of losses should continue. It was however pointed out that clean-loss-maps conditions cannot be entirely avoided. Also note that in 2012 we almost never repeated loss map measurements for regular validation: the loss maps validations were triggered by the many requests of machine configuration changes.

COLLIMATOR HIERARCHY LIMITS: ASSUMPTIONS AND IMPACT ON MACHINE PROTECTION AND PERFORMANCE (R. BRUCE)

Discussion

B. Dehning asked if the uncertainty on the orbit is included in the simulations. R. Bruce replied that the simulations assume a pessimistic scenario, based on the analysis of the fill-to-fill orbit measurements. J. Wenninger commented that part of the orbit changes is an artefact of measurements, but it is not easy to quantify this.

A. Siemko asked about the long-term stability of the collimators. How often do we need to re-align them?

S. Redaelli commented that the stability is very good, to the extent that only one alignment per year is sufficient to ensure an adequate performance. Collimators in the IRs have to be aligned when the machine configuration changes.

R. Schmidt suggested that one could identify most critical collimators likely to be affected by large losses. One could think of addressing these critical cases first. S. Redaelli replied that it is foreseen to build prototypes based on new collimator material and one could indeed envisage to intervene first at the locations that are more exposed.

Summary

- The models for understanding beam losses in case of fast failures, based on semi-analytical analysis and complete particle tracking, are very well advanced. We are confident in the validity of the results. The simulation results might be used to relax some of the pessimistic design assumptions.
- Even in case of asynchronous dumps, the settings are chosen in a way that makes severe damage improbable. On the other hand, we have to be very careful during the collimator alignment when fragile collimators will be close to the beam with few bunches in the machine.
- The beta* reach based on old assumptions is between 31 cm and 60 cm. We will not rely on the full potential from the new BPM design before we are confident that it can be used as expected.
- We should understand in detail the protection level of the triplet magnet with the presently allocated margins between TCT and triplet apertures.
- There are some ideas to use the phase advance as a free parameter to relax machine protection constrains.
- The collimation project is considering with high priority the possibility to build few collimators using new materials to improve the machine performance.

UPDATED ROBUSTNESS LIMITS FOR COLLIMATOR MATERIALS (A. BERTARELLI)

Discussion

B. Goddard asked if the damage limits depend on the beam emittance. A. Bertarelli replied that in case of large impact parameters and high intensity (as addressed in his talk) the dependence on emittance is limited. This parameter can be important for the precise onset of damage, though.

B. Goddard also asked about the confidence in the scaling to high energy. A. Bertarelli replied that the results depend on the energy profile in the material volume. The errors in the scaling should not be very significant: they depend on the scaling of cross section for various interactions in FLUKA.

R. Schmidt asked about availability of equation of state. A. Bertarelli replied that it is very difficult to get them from outside, as they are often protected as military secrets. We are trying to build here the relevant parameters, thanks to the available data from beam tests.

Summary

- The results on real collimators and material samples from HiRadMat are impressive.
- The simulations are - unfortunately - in the good ballpark. The extrapolated safe limits for metallic collimators at top energy are below a nominal bunch. This will have an impact on the commissioning strategy.
- The damage onset dependence on the beam emittance should be addressed in more detail.
- A panel of new materials for future collimators and targets is being built, including the information to define appropriate equations of state.
- A working group attached to the collimation working group will be formed to come up with an executive summary of the HRM test, to prepare new tests after LS1 and to identify new materials for future collimators.
- A rich program on the effects of radiation is ongoing in collaboration with Kurchatov Institute and BNL.

SUMMARY OF SESSION 5 ELECTRICAL CIRCUIT RELATED PROTECTION

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Abstract

This paper summarizes the presentations and discussions during session 5 of the Machine Protection Workshop held on March 11-13th 2013 in Annecy. This session was dedicated to protection of the LHC magnet powering system and its related equipment and infrastructure. The following presentations were made:

- Powering issues (Scott Rowan)
- Changes in QPS (Reiner Denz)
- Changes in powering interlocks (Ivan Romera Ramirez)
- Electrical distribution: How to ensure depend- able and redundant powering of systems? (Vincent Chareyre)

POWERING ISSUES

Powering Systems

With almost half of the premature beam dumps originating in equipment systems related to the LHC magnet powering system, the powering system and dependability of associated protection systems will remain an area of particular importance for LHC machine protection. For power converters and interlock systems a reduction of premature beam dumps could be observed in 2012 with respect to previous years for all different phases of the operational cycle, confirming the effectiveness of mitigations and preventive maintenance performed during the past LHC run. At the same time the sensitivity of parts of the quench protection system to radiation effects was confirmed with a slight increase of dumps during stable beams (despite a first series of mitigations implemented). This was particularly visible for the QPS equipment in the caverns adjacent to the ATLAS and CMS experiments where radiation is mainly caused by the luminosity debris.

While the above is mostly a concern for availability, a few near misses have highlighted a certain vulnerability of the systems following human mistakes in operation/maintenance of the system or being caused by systems not being fully up-to-date. Examples are the non-openings of a main dipole energy extraction (EE) switch in sector 34 and of a 600 A EE switch in sector 12. The failures were due to erroneous interventions or due to the lack of detection of a quench caused by a stalled QPS controller. In view of these observations the following actions should be followed up:

- Revisit dependability studies including the relevant interfaces for the highest risk circuits (i.e. the main dipole circuits).
- Organization and follow-up of specific powering tests (CSCM, tests with nominal parameters…) to have an early assessment of potential limitations for post LS1 operation.

CHANGES IN QPS

While no major change of the protection functionality is considered necessary for post LS1 operation of the LHC, numerous consolidations (in the form of relocations and firmware upgrades) will take place to decrease the sensitivity of QPS equipment to radiation as well as to considerably enhance the supervision and diagnostic capabilities of the system. With almost the entire system being modified during LS1, emphasis has to be given to assure a full and thorough re-validation of the system at the end of the shutdown, including the verification of the related QPS instrumentation cabling.

Major upgrades of hardware and more importantly the firmware of the detection cards can presently only be smoothly implemented during the long shutdowns of the machine. This turned out to have a detrimental effect on the safety of the overall system as on some occasions mitigations in the form of a firmware upgrade could not be fully implemented during an operational year in the entire machine. This resulted in some of the near-misses described in the previous chapter.

Hence the following actions have been identified for detailed follow-up:

- Investigate possibilities for a remote download of firmware via QPS supervision.
- Based on enhanced diagnostic possibilities, implement additional mitigations to decrease the vulnerability of systems (e.g. additional sanity checks at start of each fill, dependable configuration tools, enhanced automated analysis, and enforcement of validations following changes).

CHANGES IN POWERING INTERLOCKS

The three interlock systems related to LHC magnet powering are triggering between one third and one half of the premature beam dumps and hence their performance is of particular importance for both machine safety and availability. The Fast Magnet Current Change Monitors have not been at the source of any spurious dump last year; however the particular sensitivity of the related thyristor power converters (namely RD1 and RD34) to electric network perturbations has been detrimental for machine availability. A full replacement of the power converter by a less sensitive type is currently not planned for LS1, but kept as a final means of mitigation. Current efforts focus on a collaboration with EPFL to improve the regulation characteristics of the converter, which, according to the TE-EPC group allows for sufficient rejection of such perturbations.

A few dumps originating in trips of experiment magnets have highlighted the need to decrease the reaction time of the experiment Magnet Safety System (MSS) which will be done by replacing the current programmable FPGA cards by a NI cRIO FPGA based platform.

Likewise a few failures in the inner triplet circuits require follow-up to reduce interlock thresholds within the power converter and the removal of a watch-dog.

Following a recommendation of the Complex Safety Advisory Panels (CSAP), the powering interlock system will be extended to implement a hardware based link to the LHC Access system, replacing the current software implementation which has the task to limit the allowable current in LHC magnet circuits during special access conditions. The following actions will have to be followed up:

- Study improvements of converter regulation to improve rejection of network perturbations.
- Study cases of 'late' interlocks (EXP, 60APP and IT) and implement mitigations to restore redundant protection.
- Strategy for defining a certain circuit maskable/non-maskable/transparent for operation should be spread to all teams involved (OP, CRYO...) in order to apply this strategy coherently.

ELECTRICAL DISTRIBUTION: HOW TO ENSURE DEPENDABLE AND REDUNDANT POWERING OF SYSTEMS

In order to re-establish fully redundant powering for critical machine equipment, the UPS systems present in the LHC will be completely replaced by a new delta conversion model. This will allow redundant powering of the previously separated F3 and F4 lines, which – while powered from the alcoves - were not backed up by a second UPS and hence induced downtime in case of failure. The new delta conversion UPS systems in addition operate at different switching frequencies of 4 and 7 kHz (as opposed to the previous 7 kHz), imposing the following actions to be followed up:

- The new switching frequencies should be looked at in view of a possible implication on the tune measurement and damper systems.
- The extend of changes imply full-scale tests of the redundant powering of equipment related to machine protection (LBDS, BIS, QPS,…) which needs to be integrated into the LS1 planning.

APPENDIX – DISCUSSIONS

Powering Issues

R. Schmidt: What will we gain changing the parallel resistance (in order to avoid quench back)? **S. Rowan:** we will improve availability. **A. Verweij** commented on this: Such kind of change would be transparent for the magnet but the more quenches one can avoid the better for the magnet.

M. Zerlauth: What would be the feasibility of introducing an additional, direct link of the power converter with the EE system to increase diverse redundancy for its triggering? **S. Rowan:** Reiner's talk will address this in more detail.

Changes in QPS

E. Todesco: Will changing the thresholds for post LS1 operation mean mostly increasing them? **R. Denz:** It depends on the detector. Current lead detectors will have their thresholds lowered (from 3 mV to 1 mV), main dipole and quad will remain mainly unchanged while some IPQ's and 600 A (almost all of them) will have increased values accordingly to the type.

A. Siemko: What will be the situation for data acquisition of the Board B after LS1? **R. Denz:** After LS1 the operators and experts will have the possibility to access data from both monitoring boards simultaneously and retrieve both PM buffers (with some additional time delay).

M. Zerlauth: How to best mitigate human mistakes? **R. Denz:** More analysis tools that are integrated in the nominal cycle (e.g. the sequencer, PM analysis...) will have a large benefit. Not only after an event, but as well on long injection plateaus the consistency of signals can be checked. **R. Schmidt:** It is to be defined within the MP3 body how we go with mitigation of those human errors.

A. Verweij: Will timing corruptions (mainly inside PM files) still be an issue? **R. Denz:** No, due to massive firmware fixes and updates planned and performed during LS1 the situation is expected to be largely resolved, some single outliers cannot be excluded however.

Changes in Powering Interlocks

R. Schmidt: How to ensure that any masks (global subsector off, CRYO signals…) are removed when transiting from hardware commissioning into beam operation? **I. Romera:** The Beam Presence Flag is detected in the PIC SCADA system. If present, it could automatically disable any safety critical masking from the PIC supervision. **S. Claudet** proposed that the strategy for defining a circuit maskable/non-maskable/transparent for operation should be propagated to all teams involved in order to apply this strategy coherently.

M. Zerlauth commented on SPS renovation: With new hardware installed it will be possible to have some hardware interlocks for power converters & magnets instead of using SIS.

Electrical Distribution: How to ensure dependable and redundant powering of systems

G. Arduini: What will be the main switching frequency of the new UPS type? **V. Chareyre:** The two main modes will be 4 kHz and 7 kHz. **R. Steinhagen** asked if the frequency can be adjusted in case of need as 4 kHz is close to the tune frequency? **V. Chareyre** answered that this is an internal UPS property and possibly can be adjusted within slight margins. **W. Hofle** added that the same issue needs to be verified for the transverse damper (ADT).

R. Schmidt: Can we identify equipment that is in sensible areas for LHC (according to slide 24? plot). **V. Chareyre:** Yes, action is taken and to be continued.

M. Zerlauth: The two Fast Magnet Current Monitors (FMCM) in IR1 and R5 are giving very different readings in case of global network perturbations, despite the fact they should be fed from the same 18 kV source (hence see the same perturbation in terms of duration and amplitude). Is this understood? **V. Chareyre:** Still needs to be investigated.

SUMMARY OF SESSION 6 - OPERATIONAL ASPECTS

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Abstract

This paper summarizes session 6 of the Machine Protection Workshop dedicated to operational aspects related to Machine Protection.

The five presentations made in session 6 are:

- Post LS1 Operation (Gianluigi Arduini)
- Update on beam failure scenarios (Jan Uythoven)
- Post LS1 Operational Envelope & MPS implications (Matteo Solfaroli Camillocci)
- Software tools for MPS (Kajetan Fuchsberger)
- Interlock strategy versus availability (Laurette Ponce)

OPERATION AFTER LS1

Summary

In order to ’discover’ the LHC at 6.5 TeV a short running period with 50 ns beams is desirable after a short scrubbing run. In this short period the pileup could be limited to around 40 events per crossing with a β* of 50 cm, close to nominal bunch intensity and low emittances (≈ 2 µm).

This initial period would be followed by an extended period of scrubbing (≈ 10 days) to prepare for operation at 25 ns. Operation with 25 ns beams would begin with a progressive intensity ramp up. Some form of β* levelling is very likely to be used in some IRs. For beam stability reasons it may be necessary to collide during the squeeze.

Other changes to LHC Run 1 standard operation involve lower (also higher) β* at injection and combined 'ramp and squeeze'. The baseline scenario must be defined in 2013 since we cannot implement all scenarios. The implications of the various scenarios and options for operation, collimation and machine protection should be studied.

The 25 ns and 50 ns BCMS beams (Batch Compression and Merging Scheme) are very attractive for machine performance but:

- the average energy density at 450 GeV for 50 ns and 25 ns beams is 35% and 70% higher than ultimate at injection,
- the average energy density at 6.5 TeV for 50 ns and 25 ns beams is 2% and 25% higher than ultimate at 7 TeV.

The consequences on the limits for the Setup Beam Flag (SBF) will have to be carefully evaluated.

The experience of 2012 shows that a working group that follows up on beam induced heating issues is required. Issues should be identified at an early stage to put in place countermeasures before damaging equipment. This beam-heating group could work in close collaboration to the Machine Protection Panel (MPP).

Discussion

F. Bordry: Should we scrub at an intermediate energy? **G. Arduini:** The higher the energy the more we profit from photoelectrons. An advantage to stay lower is the faster turnaround and possibly less UFOs. Nevertheless I propose to go directly up to 6.5 TeV because the aim is to condition the machine – unless we encounter problems. However, we have to be careful with the tuning of the ramp (cryogenic transients). The critical part is the start of the ramp.

R. Jacobsson: Do you expect any problems with heating of the TCTs? **S. Redaelli:** One TCP and two TCTs will be removed. So far only isolated issues have been observed.

R. Schmidt: Heating of components due to the impedance was traditionally not treated in MPP. Should this now also be made an MPP topic? It would be good to have a forum to address this. **J. Uythoven:** As long as issues arise on individual components the problem should be treated by the equipment owners, unless individual equipment failure may cause global machine damage, in which case it becomes a global MPS issue. **G. Arduini:** A follow-up to try to anticipate real problems is desirable, especially in view of higher beam intensity. Impedance related heating should be monitored continuously to avoid cases like the BSRT. **J. Wenninger:** There is some overlap with MPP but there are also other bodies who may address possible issues, but catching heating related problems at an early stage or at least being prepared at an early stage is crucial. **G. Arduini:** A weekly follow up on impedance issues as part of machine protection is necessary.

S. Redaelli: We should define a baseline (combined Ramp and Squeeze, β* levelling etc.) at some point because most of the things have important implications for example to controls, and not all possible paths can be implemented. **J. Wenninger:** It is planned to have a closer look at the different paths starting in April and discuss later in the year also with the experiments to weight all risks (complicated β* levelling may take weeks to be commissioned properly and in the end may not even be needed). A staged approach could be useful but it needs to be discussed.

G. Arduini: For going into collision already during the squeeze, we have to envisage a scenario to first close the primary collimators (to minimise the impedance) and then the secondary collimators to avoid situations were all collimators move in at once. In 2012 collimators have been closed smoothly during the ramp. **J. Wenninger:** This could be done at a later stage. It is important though to prepare a combined Ramp and Squeeze and if it is proven to work efficiently and experience is gained with it, further steps to optimise it can be taken.

BEAM FAILURE SCENARIOS

Summary

All the 'Big Three' failure scenarios (powering failure of the D1 separation recombination dipole, injection kicker failure, asynchronous beam dump) occurred in the period 2009 – 2013, but with some modifications! Equipment weaknesses were detected for 2 out of 3 'Big Three' failure modes:

- The injection protection device TDI suffered from deformations due to heating by the beams,
- The LBDS had issues with the trigger synchronization unit TSU and with crate powering.

Unexpected failure scenarios occurred as expected. They were related to the timing system, beam heating, orbit bumps, UFOs, abort gap, quench protection. Improvements of our protection and additional surveillance had to be put in place rapidly in some cases.

The LHC MPS is relying more and more on SIS to cover subtle or across systems failures.

An important aspect of MPS after Long Shutdown 1 is to continue to understand each beam dump (post mortem) before continuing operation.

Discussion

E. Todesco: Why do you only quote the normal conducting D1 and not also the other super conducting? **J. Uythoven:** For the warm D1 the field decay is faster. Within a few turns one may get a significant change of the orbit. The SC-D1 reacts slower and the BLMs would have enough time to trigger.

S. Redaelli: Did you check if FMCM dumps could have been avoided? **M. Zerlauth:** I. Romera showed that all FMCM triggered dumps were justified, although there were situations where the associated converter didn't trip, but real current perturbations had been provoked, so there is nothing to gain. The only place where gains could be made is to apply modifications to the PC to improve the rejection of these current perturbations. TE-EPC is looking into this. First the PC regulation will be optimised and if that is not enough, then the converter would be exchanged.

R. Schmidt: It would make sense to quantify the SIL level of the FMCM although behind it there is still the redundancy of BLM and QPS. **J. Uythoven:** Even if it is not critical, it might still be interesting to investigate what the reliability of the FMCM is.

J. Wenninger: A test was already successfully performed to mask the D1-FMCM in order to see if the BLMs trigger correctly and demonstrate their protection role. **M. Zerlauth:** For the LHC the knowledge on the FMCM reliability is not so much an issue as there are 12 devices and therefore redundancy is guaranteed in case of a power cut; however, the FMCM exist also in the transfer lines where the redundancy is not existent. **J. Wenninger:** In the transfer lines there are, however, the current interlocks, which protect for drifts and trigger after a few ms.

SETUP BEAM FLAG

Post LS1 Operational Envelope & MPS implications

Summary

After LS1 the LHC will be operated at an energy close to 7 TeV. The value of the normal setup beam flag (SBF) would in this case allow an intensity of only one probe beam (10^{10} charges), which is likely to be a strong limitation for certain setup conditions.

The concept and limits for relaxed and very relaxed SBF must be reviewed, including the requirements for commissioning and MD needs as well as the risks.

Discussion

Ph. Baudrenghien: Off-momentum loss maps should not be considered as a big problem. Instead of moving the whole beam with a frequency trim one could selectively excite the synchrotron oscillation of single bunches. This could provide a much smoother measurement mechanism than what we have done so far. It should be looked at during LS1. **M. Solfaroli:** But this wouldn't remove the problem of beam dumps initiated by the interlocked BPMS in IR6. The beams would still be dumped. **J. Wenninger:** This opens up a protection issue as there is a frequency interlock because of the aperture of the dump channel. **B. Salvachua Ferrando:** It could be that we don't need to trim the frequency by 150Hz, probably less could be sufficient. We would need to perform tests at 7TeV.

M. Zerlauth: The situations when we use the safe beam flag need to be re-discussed, not only the levels and curves associated to its limits. The risk we take is not only related to the absolute values, but also the time spent in these modes. In the past the VERY RELAXED SFB sometimes has been misused (in MDs and other situations when it was not always necessary). Changing the limit curves will have an impact on the implementation side as the SMP is a very critical system. The question to SMP is at what point in time is it necessary to know the new values to make sure that the SMP is qualified to the level of dependencies we have today. **B. Todd:** A decision should be taken as early as possible. One should not forget that the SMP also controls the extraction from the SPS and that any change on the LHC side also affects the SPS extraction evaluations. A complete revalidation on the SPS extractions to LHC would be necessary.

R. Jacobsson: β* levelling should be kept as flexible as possible (decoupling of IP1/5 from IP8)?

J. Wenninger: Limits for β* will have to be widened and levelling will only be performed in Stable Beam mode, with a smooth and transparent transition between the different values. A step by step commissioning for one IP or a group of IPs would be preferable to applying it to all IPs at the same time. β* levelling rations in IP1/5 will certainly be fixed.

SOFTWARE FOR RE-COMMISSIONING

Summary

There are currently new ideas and concepts to move the MPS commissioning and tracking information from the SharePoint WEB site to the ACCTEST software framework developed for Hardware Commissioning. In parallel the commissioning procedures must be updated to take into account the major changes that were applied between 2009 and 2013 to the actual procedures. The updated procedures must then be modelled in the ACCTEST database. Even without automating the tests, the ACCTEST framework could be used to track commissioning, take into account dependencies etc.

Finally it will be necessary to define projects and priorities for the aperture meter and online model.

Discussion

G. Kruk: Will operation continue to use the quite dangerous applications “EquipState” and “FESA Navigator” after LS1? **J. Wenninger:** The FESA navigator is usually not used except when there is no other application allowing communication with a new device. It is not evident to supress both applications from the CCC.

J. Uythoven: Concerning MPS tests with a new software tool, one should block on safe beam. **K. Fuchsberger:** The exact boundaries need to be defined by MPP.

R. Schmidt: After the development and usage of several generations of hardware control software tools we should ask ourselves of how to proceed with the next proposed tool. Should we define a new project? What are the next steps to proceed with it? **K. Fuchsberger:** The best would be that MPP answers these questions and takes them up to define the way to go. **M. Zerlauth:** The first part which should be defined and implemented is the sequencing of MPS tests together with a revision of the commissioning procedures, so that they could be fed into that new framework. The automation part of the steps could be treated then at a later stage. **K. Fuchsberger:** The majority of the work is done if there is a ported version of the current SharePoint site. **R. Schmidt**: A close collaboration between CO, OP and MP is absolutely necessary in order to define the boundary conditions for the advancement of this work. Questions concerning resources need to be addressed by the group leader. **V. Baggiolini:** The work done by Kajetan and CO in general is that the core package or framework is developed by CO experts in a way to allow system experts and/or other developers to provide plugins or modules to extend and complement that core system. This implies a close collaboration between CO and the individual system experts.

R. Jacobsson: We have repeatedly heard that there are many BIS inputs which have never pulled a beam abort and we said it would be necessary to verify that also those channels function correctly. Is there some sort of test-mode which would allow performing those BIS channel verifications? **J. Wenninger:** Yes, for some systems (PIC, WIC, BLM, vacuum) this exists, but it has not been followed up to extend it to all possible inputs. The concept is available and it could be envisaged to use it for all systems. A typical example of rarely used channels is the experiments. The injection permits are very often solicited but not the beam dump channels. **A. MacPherson:** During machine checkout a systematic verification of all input channels at the level of the BIS is performed. **S. Redaelli:** The proposal to automate MP checks is very good; however, it needs to be structured for commissioning. If we decide to change things, we need also to find the resources to implement them. We have many new projects coming up but not necessarily the manpower to do additional work, unless there is one central team which does the work and to whom specifications can be given for implementation. **K. Fuchsberger:** A first approach could be to include this into a sort of checklist and keep everything as it is now, so that no equipment tests would need to be modified, but at least an order in the execution of MPS tests is enforced. **A. Siemko:** There is definitely a need for improved software tools because this undoubtedly will improve the efficiency of many processes. A lot of good ideas have been presented (a sort of shopping list) and the next step should be to make a project proposal. Once we have this, we can discuss about resources, priorities etc. **J. Wenninger:** In the end we have to collect all ideas and decide amongst us which are the ones that deserve being followed up and possibly implemented. **J. Uythoven:** We should nevertheless keep in mind that a fast decision is necessary as the BIS commissioning will start in one year’s time. If we miss this point, the project will be dead because people will be busy.

R. Jacobsson: When do you need the BIC inputs available from the experiments? **J. Wenninger:** Probably sometime during quarter-4 of 2014, when hardware commissioning will transit into machine checkout mode.

SIS AND/VERSUS BIS

Interlock strategy versus availability

Summary

The SIS is heavily used at LHC, with around 2700 subscriptions to equipment devices. While the SIS core is very reliable, it is of course sensitive to communication errors and network related issues. SIS was used to implement fast protection solutions to many problems that were discovered during operation.

The following points, that mainly concern the GUI and not the SIS core, could be improved after LS1:

- GUI layout,
- Post-mortem information,
- Parameter and value monitoring (including the subscription GUI),
- Masking.

The following interlocks could be moved from the SIS to the BIS in the future:

- The beam position interlocks at the TCSG collimator in IR6 and at the TCTs around the four experiments,
- The TDI gap interlocks.

The remaining orbit correctors interlocks that are implemented in SIS should be moved to the PC-interlock server written by K. Fuchsberger, while the beam position interlocks will remain inside SIS (for the start-up).

Based on the discussions during the workshop, one has to expect that new SIS interlocks will arrive after LS1.

Discussion

Ph. Baudrenghien: The FESA subscription problem is also critical for the RF and a degradation has been observed towards the end of the run. **L. Ponce:** This was also observed on the SIS. By looking at the timestamps of the SIS dumps, a concentration can be seen at the end of the run. **P. Charrue:** The problem has been identified as a problem in the interface of CORBA. A change is foreseen and hopefully by June 2013 we will have a new version and all related problems should disappear. Tests will of course be needed to validate it.

R. Jacobsson: The interlocks can be divided into two classes, on one side the consistency checks with hardware interlocks securing the machine and on the other side the time critical interlocks. For the latter I've always been puzzled that the general network, which doesn't allow for priority treatment of packages, is used to communicate. **R. Steinhagen:** The current infrastructure doesn't support ways to split servers providing general purpose information on one network and specialised information for particular clients on another network. **J. Wenninger:** It's mostly a problem with servers and not so much with the network itself. On the outgoing side of the SIS everything worked fine. A beam dump is initiated if the BIS doesn't receive the SIS data within a 20s timeout, however, this never happened. This confirms that the network worked fine. The problem was rather observed on the incoming side, which includes servers publishing their respective data.

Ph. Baudrenghien: The increased SIS timeout could be reduced again once the new CORBA version will have been successfully deployed. **J. Wenninger:** Yes, we should try to reduce the timeout again to its initial value.

V. Baggiolini: As the SIS proved to be very reliable over the past, is there any place where you are abusing this reliability when software is used as a last line of defence for machine protection. **J. Wenninger:** Maybe we could formulate it differently. Because of SIS working so well, there is no strong pressure to move interlocks from SIS to BIS. So in some sense you're partly right. **J. Uythoven:** Systems which are safety critical should not go into SIS, even though at first glance it looks very reliable.

L. Ponce: Probably the BLM-HV interlock as a rather safety critical interlock should be moved out of SIS and be implemented as a hardware interlock. All the other SIS interlocks form more an extra layer to prevent a system failure. **E. Holzer:** The BLM-HV SIS interlock was added to protect from the fact that a cable was cut. Before a fill, the cabling is checked as part of the BLM sanity checks but after that, there is no monitoring anymore. This was the reason to introduce the interlock.

B. Goddard: The 'beam position at TCDQ' interlock could be implemented in hardware as well. **J. Wenninger:** We have at least the beam position at the TCSG as hardware interlock. **R. Steinhagen:** It will be difficult to implement it as hardware interlock as it can't be done by surveillance of a single BPM neither by monitoring a single PC. It's a protection against closed orbit bumps for which one needs combined information.

J. Wenninger: In principle the BLMs provide the ultimate protection. It's just a way to avoid stressing systems unnecessarily. **J. Uythoven:** The BLM-HV interlock should be implemented as HW interlock.

MACHINE PROTECTION SYSTEM: AVAILABILITY & PERFORMANCE 2010-2012

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Abstract

This paper presents the results of studies into the availability and performance of the LHC Machine Protection System (**MPS**) from 2010 to 2012.

The first section outlines the availability and performance as recorded from the operations viewpoint for all three years of LHC operation.

For 2012, a more detailed examination of MPS equipment is introduced, with failure rates, failure modes, and Mean Time To Repair (**MTTR**) identified for the MPS equipment having the biggest impact on LHC availability.

Conclusions are drawn and proposals made using an availability matrix, which directly compares and contrasts failure modes, failure rates and MTTR of MPS equipment. This work results in four suggestions (**S1-4**) and one recommendation (**R1**) to be considered by MPS experts.

OPERATIONAL VIEWPOINT 2010-2012

The operations viewpoint considers availability as the impact on the LHC's ability to produce physics. Therefore the causes of beam aborts are a key indicator of availability. Every abort leads to the creation of a post-mortem event and corresponding post-mortem database entry. Analysis of these events reveals most of the impact the MPS has on the LHC availability as seen from the operations viewpoint. This is not an exhaustive analysis, as other events, such as parallel faults involving MPS, are not considered.

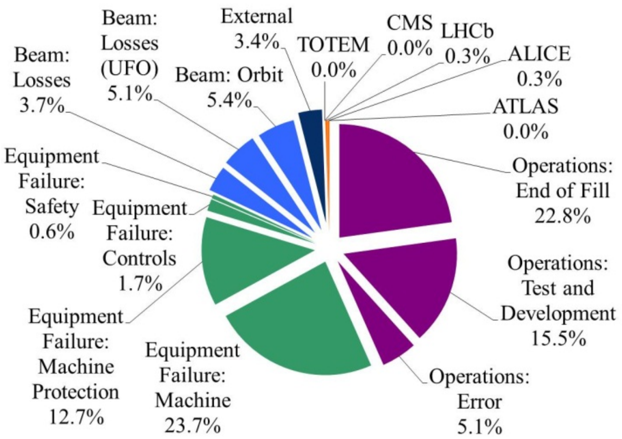

Figure 1: Distribution of Beam Aborts in 2010 (total 355)

Post-Mortem Dump Cause Evolution 2010-2012

Considering only beam aborts that took place above injection energy, between March and November, then classifying dump cause into five categories (external, beam, equipment, operations or experiment) leads to the following distribution of beam aborts for 2010 [1]:

The same analysis for 2012 [2]:

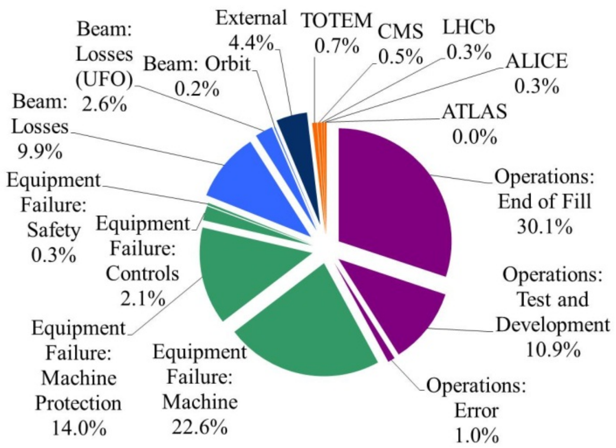

Figure 2: Distribution of Beam Aborts in 2012 (total 585)

Details of MPS Dump Causes

The analysis shown in figures 1 and 2 has been carried out for 2011 [3], leading to the following table of physics fills, and dump cause counts due to "Equipment Failure: Machine Protection" e.g. MPS Failure [4]:

Table 1: Beam Aborts Induced by MPS Failure 2010-2012

	2010	2011	2012	Total
Qualifying Fills [#]	355	503	585	**1443**
MPS Failure [#]	43	71	82	**196**
MPS Failure [%]	12.7	14.1	14.0	**13.6**
Quench Protection	24	48	56	**128**
Beam Loss Monitors	4	4	18	**26**
Beam Dump	9	11	4	**24**
Software Interlocks	4	2	4	**10**
Powering Interlocks	-	5	-	**5**
Beam Interlocks	2	1	-	**3**

This table indicates that between 2010 and 2012, from the operational viewpoint:

- There has been a slight increase in the ratio of beam aborts due to failures of the MPS from 12.7% to 14.0%.
- Only six sub-systems of the MPS have been responsible for beam aborts.
- The largest contribution of beam aborts has been the Quench Protection System (**QPS**)

For the year 2012, only four MPS sub-systems contributed to loss of LHC availability as seen from the operation viewpoint.

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EQUIPMENT VIEWPOINT 2012

In contrast to the operation viewpoint, the equipment viewpoint is not restricted by beam aborts or by machine fill, rather all system faults for the whole year are considered, in order to determine sub-system reliabilities.

Failure modes, failure rates, Total Time To Repair (**TTTR**) and MTTR were considered for seven sub-systems of the MPS. Failures have been categorised as follows:

- External – failure due to a system dependency.
- Random Hardware – failure due to a random in time failure of hardware.
- Radiation Hardware – failure due to radiation induced effects on hardware.
- Exploitation – failure due to the manner in which the system was setup, or being operated.

*Software Interlock System (**SIS**)*

The post-mortem database indicated **4 beam aborts** due to the SIS. However, in 2012 the SIS did not fail. All actions carried out by the system were due to real conditions requiring an interlock. Table 2 shows records for typical causes and ratios for interlocks generated by the SIS [5].

Table 2: SIS Dump Causes and Ratios

Cause	Ratio [%]
CMW Failure	20
Orbit Feedback Crash	20
Power Converter Fault	15
Beam Position Measurement	10
Beam Loss Monitor High Voltage	10
Others…	25

*Fast Magnet Current Change (**FMCM**)*

The post-mortem database indicated **0 beam aborts** due to the FMCM, with equipment experts indicating **one failure**, which occurred four times while being diagnosed, as shown in Table 3 [6]:

Table 3: FMCM Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
Earth Cable Intermittent	1	5.8	5.8
combined	**1**	**5.8**	**5.8**

*Powering Interlock Controllers (**PIC**)*

The post-mortem database indicated **0 beam aborts** due to the PIC, with equipment experts indicating **one failure**, as shown in Table 4 [7]:

Table 4: PIC Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
Ethernet Switch Fault	1	1	1
combined	**1**	**1**	**1**

*Warm Magnet Interlock Controllers (**WIC**)*

The post-mortem database indicated **0 beam aborts** due to the WIC, with equipment experts indicating **one failure mode**, occurring twice, as shown in Table 5 [8]:

Table 5: WIC Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
Power Converter Trigger	2	11	5.5
combined	**2**	**11**	**5.5**

*Beam Interlock System (**BIS**)*

The post-mortem database indicated **0 beam aborts** due to the BIS, with equipment experts indicating several failure modes as shown in Table 6 [9]:

Table 6: BIS Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
User Side Powering	3	6	2
User Side Infrastructure	2	40	20
User Interface Powering	2	4	2
Monitoring Corruption	1	1	1
Power PC Failure	1	1	1
Reference Database Fault	1	1	1
combined	**10**	**53**	**5.3**

The User Side Infrastructure failure mode was an intermittent failure being complex to diagnose. The input to the BIS was disabled whilst system experts from both sides investigated. This prevented the failure from having an impact on LHC availability.

*LHC Beam Dumping System (**LBDS**)*

The post-mortem database indicated **4 beam aborts** due to the LBDS. However, for the same period, equipment experts identified **9** such events. The total system characteristics are shown in Table 7 [10]:

Table 7: LBDS Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
Slow Surveillance Fault	10	4	0.4
Vacuum Fault	5	3	0.6
Power Electronics Fault	4	8	2
PM / Arming Problem	4	0.5	0.1
Beam Interlocks Failure	4	3.5	0.9
Control Hardware Error	4	1	0.3
Energy Tracking Hardware	1	1	1
combined	**33**	**27**	**0.8**

*Beam Loss Monitors (**BLM**)*

The post-mortem database indicated **18 beam aborts** due to the BLM. The overall system characteristics are shown in Table 8 [11]:

Table 8: BLM Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
Optical Link – Surface	15	45	3
CMW	14	14	1
SEM Connectivity	10	20	2
Optical Link – Tunnel	6	30	5
LIC Connectivity	5	10	2
High Voltage Droop	4	12	3
IC Connectivity	3	9	3
VME Power Supply	1	3	3
Programmable Logic	1	1	1
combined	**59**	**146**	**2.5**

Middleware (**CMW**) faults are approximately 50% due to failure of the Management of Critical Settings (**MCS**) and 50% due to failure of communication with front-end computers. Some of the failures listed are designed to allow the current mission to complete, but then inhibit the next mission to force correction of the faulty state.

As BE/BI has no dedicated piquet service, a best-effort system is in place, this may cause an increase in the MTTR.

Quench Protection System (QPS)

The post-mortem database indicated **56 beam aborts** due to the QPS. The overall system characteristics are shown in Table 9 [12]:

Table 9: QPS Failure Modes, Rates, TTTR and MTTR

Failure Mode	#	TTTR [h]	MTTR [h]
Radiation Induced	39	35	0.9
Internal Communications	25	15.5	0.6
Spurious Signal	23	23	1.0
Power Converter	13	13	1.0
WorldFIP Fault	12	17	1.4
DFB / Current Lead	9	18	2.0
Mains Perturbation	8	9	1.1
600A Energy Extraction	7	13	1.9
13kA Energy Extraction	6	11	1.8
EM Interference	2	3	1.5
CMW	1	0.5	0.5
13kA Power Supply Fault	1	2.5	2.5
Others	9	6	0.7
combined	**155**	**166.5**	**1.1**

The QPS system will be significantly consolidated and upgraded during the LS1 period.

CONCLUSIONS

On Availability

Combining the information from the previous section allows failure rates, modes and repair times to be compared. In total, for the seven sub-systems, there were over **250 faults** identified, split into around **36 failure modes**, having a total repair time of over **360 hours**. An *availability matrix* has been created, with impact on the y-axis, and repair time on the x-axis. Failure Modes are plotted as coordinate points. Three options can be exploited to improve LHC availability:

1. Move a failure mode left on the x-axis, by **decreasing the MTTR**. This can be done by improving maintenance plans, or moving equipment to areas that are accessed more quickly.
2. Move a failure mode lower on the y-axis, by **decreasing the failure rate**. This can be done by building systems out of more reliable components, or by more advanced techniques such as redundancy.
3. **Removing a failure mode** altogether. This can be done by redesigning or redeploying systems.

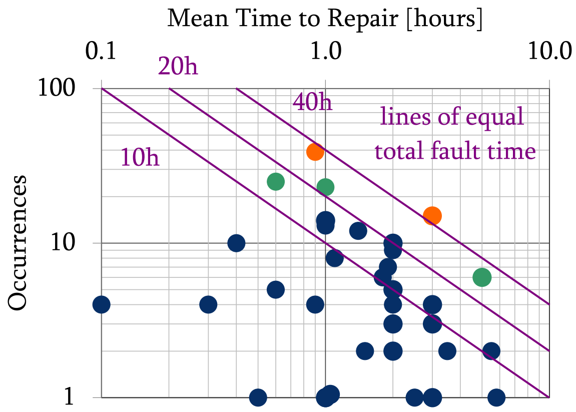

Figure 3: 2012 Availability Matrix

For the systems studied, there are five failure modes which stand out: (frequency, MTTR)

1. BLM: Optical Link Failure – Surface (15, 3.0)
2. QPS: Radiation Induced Fault (39, 0.9)
3. QPS: Internal Communications Fault (25, 0.6)
4. QPS: Spurious Signal (23, 1.0)
5. BLM: Optical Link Failure – Tunnel (6, 5.0)

Changes should be made during LS1 to address failure modes such as these, leading to an improved availability post-LS1.

S1. Study planned changes to systems in LS1 to predict the expected availability post-LS1.

On Fault Tracking

The information presented in the paper has been the result of many days work data mining the various log books and sources throughout the various equipment and operations groups. More robust conclusions require a more robust collection of raw failure rate information.

R1. Consider a fault tracker to improve data collection and analysis post LS1.

On the SIS

The SIS has been identified as a source of several premature beam aborts in 2012. In each case the beam abort was justified, but the root cause of the beam abort beyond the SIS was not recorded in the PM database.

S2. PM Events that are labelled as SIS should be expanded to include root cause information.

Potential Dormant Failures

In studying the behaviour of the BIS, it was revealed that several of the input channels have not been activated since the beginning of LHC operation in 2010. Internal test modes have been used to verify functionality internal to the BIS but not beyond that to the user system.

S3. Infrequently activated inputs to interlock systems should be periodically tested to reduce the risk of dormant unsafe failures.

Defence in Depth and Hazard Chains

The MPS ensures that the LHC operates with an acceptable risk, based on a two-step approach: *prevent* hazardous situations from occurring, *protect* the machine if they do. A significant proportion of activations of the MPS are occurring in the *protect* phase, indicating that hazardous situations are occurring, as evidenced by the dump events labelled with a root cause of “Beam Losses”.

S4. MPS abort events which are triggered by Beam Loss interlocks should be investigated to try and identify new hazard chains.

ACKNOWLEDGMENTS

This work is a combination of information from many different sources, which took a considerable effort to consolidate, in particular the authors wish to express their gratitude for the input from the Availability Working Group (**AWG**), P. Dahlen, K. Dahlerup-Petersen, R. Denz, R. Filippini, S. Gunther, C. Martin, V. Montabonnet, L. Ponce, I. Romera and J. Wenninger in the completion of this work.

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[1] PM database. Extracted from 23rd March to 6th December 2010, only for fills >450.1 GeV, ignoring entries marked as “no input change”.

[2] PM database. Extracted from 1st March to 6th December 2012, only for fills >450.1 GeV, ignoring entries marked as “no input change”.

[3] PM database. Extracted from 17th February to 13th December 2011, only for fills >450.1 GeV, ignoring entries marked as “no input change”.

[4] Sort [3] by MPS Dump Cause, Discarding EOF, MD and MPS Test. Identify only those events caused by “MPS Equipment Failure”

[5] Courtesy L. Ponce, J. Wenninger. PM database, filter by SIS, extract labelled events and generalise.

[6] Courtesy S. Gunther, I. Romera. Extracted from TE-MPE-COMS “FMCM” Issue Tracker

[7] Courtesy S. Gunther, I. Romera. Extracted from TE-MPE-COMS “PIC” Issue Tracker

[8] Courtesy P. Dahlen, S. Gunther, I. Romera. Extracted from TE-MPE-COMS “WIC” Issue Tracker, ignoring “SPS/TL” events

[9] Courtesy C. Martin. Extracted from personal records, and TE-MPE-COMS “BIS” Issue Tracker.

[10] Courtesy R. Filippini. Extracted from TE-ABT logbook, LHC-OP logbook, and expert personal records

[11] Courtesy C. Zamantzas. Extracted from BI-BLMS Issue Tracker and expert personal records

[12] Courtesy K. Dahlerup-Petersen, R. Denz, S. Gunther & I. Romera. Extracted from TE-MPE-COMS “QPS” Issue Tracker

MPS issues and MP approach concerning operation and MDs

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Abstract

The performance of the machine protection system with a focus on safety has been studied for the first 3 years of LHC operation. An overview of the remaining limitations, major issues, periods of non-standard operation and the functioning of machine protection organisation as seen by machine protection experts will be presented in this paper and the procedures and processes to handle these will be discussed.

Inferring from the experience gained, proposals to improve said processes and the support to the operation crews during intensity ramp-ups, MDs, and other non-nominal modes of operation will be made for the re-start of the machines after LS1 and the operational period thereafter.

INTRODUCTION

With close to 30 fb^{-1} of integrated luminosity been delivered to ATLAS and CMS during the first 3 years of operation, the LHC machine has surpassed many of the expectations during this first run, despite still operating with 50 ns of bunch spacing and being limited in energy to 4 TeV. At the end of 2012 the machine was routinely operated with bunch currents reaching $2{\cdot}10^{14}$ protons per beam, representing stored beam energies of more than 140 MJ. This was only possible due to the expertise and confidence gained in the two previous years, where the intensity was progressively increased to safely reach the ultimate intensity target. During this first three years of running, the LHC machine protection systems have safely removed circulating beams from the machine 3500 times, whereas for almost half of these dumps (namely 1582) the energy was above injection energy. Even while routinely operating with stored beam energies well above 100 MJ, no unintentional beam induced quenches have been observed with circulating beam, emphasising the dependable protection provided by the different layers of the machine protection system. Likewise no severe equipment damage was recorded during the entire run, apart from some damage recorded in the SDD calibration unit of ALICE [1], a few corrector coils of the inner triplet L2 following kicker erratic's during beam injection and some issues related to beam induced heating of components during 2012.

All beam dump events above injection energy, be it a programmed dump or a premature beam dump request, have been meticulously analysed and validated by the operation crews and Machine Protection System (MPS) experts and have been used to build a knowledge database to assess possible long-term improvements of the LHC machine protection and equipment systems [2]. This database has proven a useful asset in the efforts to understand and improve machine performance throughout the different operational phases as shown at the example of dumps occurred during the operational year 2012 (Figure 1).

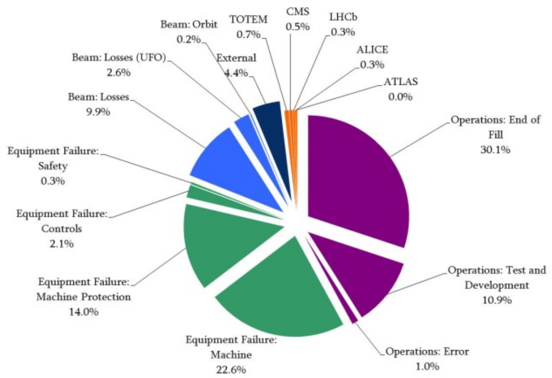

Figure 1: Causes of beam dumps above injection energy of 450 GeV during the operational year 2012

MACHINE PROTECTION ISSUES

The aforementioned database is also extensively used by machine protection experts and rMPP members to assure that potentially dangerous situations are recognised, documented and published as well as concordant actions are being followed up throughout commissioning and operation.

Despite the absence of severe damage to equipment during the first three years of operating the LHC, a number of issues and near-misses have probed the thoroughness of the machine protection architecture and the way the system is used during operation, a selection of which is listed in the following:

- Common cause failure mode of 12V supply in LHC Beam Dumping System (LBDS)
- Quench detection issues on IPQ, 600A EE
- Wrong setup of TL collimators for SPS Q20 optics
- Timing issues when injecting H9 beams
- Wrong collimator settings (2 x TCTV IR2, 2x IR3)
- Roman Pot Controls issues
- BLM High Voltage Cable interruption
- Orbit Feedback System Utility (OFSU) reference problems
- Beam Synchrotron Radiation Telescope (BSRT) beam induced heating
- MDs and other non-standard machine operation
- MKI flashovers
- Tune Feedback System (QFB) not usable in squeeze due to poor signal
- Instrumentation problems in triplet L8 after TS2

- Loss of redundant protection (60A power permits, LHCb dipole, CMS solenoid…)

In the following the top five machine protection issues in 2012 and their consequences for the operation of the LHC, listed in the sequence of their appearance, are critically reviewed along with describing the actions taken and mitigations put in place [3].

Reference problem in the orbit feedback system

During the intensity ramp up it was observed that the reference used by the orbit feedback system was suddenly set to zero along the whole LHC ring at 4 TeV/c (see Fig. 2). This lead to orbit offsets of up to 4 mm in some of the LHC insertion regions, where the orbit feedback removed the separation bumps due to the wrong reference orbit. The beams were finally dumped due to particle losses in the vertical beam 2 tertiary collimator in IR2. Because of this problem the next step of intensity increase was postponed and a new software interlock was introduced, to dump the beam in case of an orbit reference problem. Due to this measure and additional checks in the LHC sequencer and by the operators the problem was reduced to an availability issue.

Powering of the LHC beam dumping system

Two major problems were discovered in the LHC beam dumping system (LBDS) during 2012. On the 13th of April a fault in one of the two redundant power supplies caused a loss of power in the whole set of general purpose beam dump crates. This would have caused an asynchronous beam dump if beam would have been present in the LHC at this time. As a short term measure one of the triggering synchronization units was connect to a second independent UPS and fast fuses were introduced.

During lab tests a common mode failure in the 12 V DC powering of the triggering synchronization units was discovered. In the LHC this failure would have inhibited the beam dump. This is considered to be the worst case failure scenario, as any other problem could then lead to a fatal damage of the LHC. Due to the severity of the discovered problem the operation of the LHC was stopped until a short-term mitigation in form of a watchdog to supervise the 12 V supply voltage was implemented. This will dump the beams in case of a problem. A fail safe and fault tolerant solution to mitigate the two problems will be implemented during LS1.

Mirror support degradation in synchrotron radiation monitor

Besides other critical beam parameters the LHC Synchrotron Radiation Monitor Light Extraction System delivers information about the population of the abort gap.

This is of importance for machine protection, as a too high particle population in the abort gap may lead to high losses, magnet quenches and possibly damage of accelerator equipment in case of a beam dump. A gradual deterioration of the two devices due to beam induced heating was observed in 2012 [4]. On the 27th of August the deterioration suddenly increased in beam 2 and the optical mirror, threatened to drop from its support, damage the view port and fall through the beam. Therefore, fill 3012 was dumped to allow to un-install the device and avoid any risk of collateral damage due to this problem.

False settings of Transfer Line collimators

End of September 2012 the so-called Q20 optics has been implemented in the CERN-SPS for the injection of beam into the LHC. The optics, i.e. the quadrupole strengths, in the two transfer lines to the LHC were adjusted accordingly. On the 19th of November it was discovered that the settings of the transfer line collimators, which protect the aperture of the LHC against too big injection oscillations, had not been adjusted to the new β-functions.

This caused deviations from the required gap openings ($5\,\sigma$) of up to $1.3\,\sigma$, which resulted in a reduced protection. When the problem was discovered LHC physics operation was stopped to re-setup the transfer line collimators and validate their settings with beam.

Injection Issues due to Timing Problems

Tests with high brightness beams from the CERN-PS led to a problem with the timing in the SPS. This caused the injection of beam into beam 1 instead of beam 2. Thus, the injection kickers in beam1 did not fire and 20 bunches were therefore injected onto the LHC injection beam stopper (TDI). Therefore these tests were stopped until the reason for this problem could be identified and mitigated. Shortly afterwards, a second problem appeared during injection, when the SPS RF-clock was not synchronized with the LHC, i.e. running in local mode. This caused a mismatch between SPS extraction and LHC injection. Therefore, twice 48 bunches hit the beam 2 TDI.

These issues were a reminder that currently there exists no active protection against timing issues during injection. The passive protection for injection problems, i.e. the correctly positioned TDI, worked as foreseen.

MACHINE PROTECTION ORGANISATION AFTER LS1

Experience over these past three years has shown that a majority of the issues detected where 'dormant' failures. Despite the fact that appropriate actions where always taken immediately, the mid-term lessons should be learned and commissioning and operational procedures accordingly modified and tightened up. A few of the issues were allowed to persist for longer periods in time, as the reaction to a certain event varies as a function of the individuals knowledgeable about it. In retrospect it may not always have been easy for the operation crews and Machine Coordinators to assume the double role of optimizing performance of the machine as well as to assure its safety. To increase and facilitate the support to the operation crews the role of a 'Machine Protection piquet' is proposed as of the start of commissioning the LHC after LS1. This role could alternate between selected rMPP members on a weekly or bi-weekly basis and would include the follow-up of the commissioning of machine protection systems, operational changes and the necessary revalidations, analysis and documentation of operational runs and beam dumps as well as serving as the contact person (representing rMPP) to operations.

This recommendation results from the experience that, while the initial MPS commissioning phase was prepared and carried out with the required rigor and necessary time available [5], we did not manage to maintain this commissioning mind-set throughout the full running period. Due to various factors such as scheduling pressure, routine, relatively smooth operation of the machine, fatigue and others the initially commissioned safety level certainly degraded towards the end of the running period. Hence possibilities to counter-act such phenomena should be investigated, e.g. to

- Dependably track (relevant) system changes
- Assure a more coherent approach for follow-up of magnet & beam related MPS issues
- Define and enforce a minimum validation cost of changes (following previously defined and agreed procedures) through the use of automatic tools and dependency models
- Introduce the role of a Machine Protection Piquet for non-standard cases

These considerations are particularly important for phases of non-nominal operation of the machine such as special runs or machine development periods, which by definition explore new machine and machine protection territory, often requiring numerous changes to the machine and machine protection systems to allow for the MDs to be performed. In general MD requestors have demonstrated a high level of responsibility by proactively providing the required MP documents, towards the end of 2012 MDs where however planned on shorter notice which sometimes did not allow for an equally thorough preparation of the MDs.

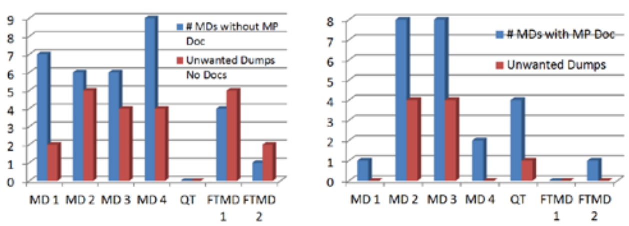

Figure 2: Number of Machine Developments (blue) and unintentional dumps (red) during the different MD blocks in 2012. For MDs without a detailed MP document (left) and where a detailed MP document has been prepared (right).

While an MP document is mandatory when using unsafe beam or a non-operational setup of the machine, Figure 2 shows that in general the preparation of an MD (through a mode detailed document) is beneficial even for the efficiency of the MD (if measured through the number of unintentional losses of beams during the MD). As shown in the figure the likelihood of losing the beam – often because of forgotten interlock conditions, masking of certain system inputs… - is roughly twice as high in absence of an MD document. To further enhance the safety as well as making an optimum use of machine time allocated to MDs, the preparation and approval of a short MD note [6], detailing the program and required changes to the machine setup will become mandatory for the allocation of an MD slot.

CONCLUSIONS AND OUTLOOK

The LHC Machine Protection and Equipment Systems have been working extremely well during the first three years of operating the LHC thanks to a lot of commitment and rigor of operation crews and equipment and machine protection experts. There is no evidence of a major loophole or uncovered risks within the MPS architecture, however a few near-misses have revealed shortcomings in designs, commissioning procedures and operation of the MPS systems which will have to be addressed and mitigated during LS1. The organization and response of coordinators, operation crews, (r)MPP and equipment experts in case of such near-misses was adequate, however the issue of decreasing attention and rigor towards the end of a running period remains to be addressed. Despite the high dependability of the machine protection systems during the past operational years we have to remain vigilant also in the years to come when more emphasis will be given to increase the overall machine availability and when it will become increasingly challenging to maintain the systems at their required level of dependability due to questions of resources and additional operational challenges in the post LS1 era.

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Operation's point of view on handling Machine Protection issues

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Abstract

LHC Machine Protection has worked extremely well in these first years of LHC operation, but in a few isolated cases issues presented themselves. Failures like design faults, software bugs or manual mistakes pointed out weaknesses in the protection mechanisms. This paper recalls a number of these issues, as experienced by operations, highlighting which follow-up actions were devised and identifying which actions might still be missing (e.g. new interlocks or new procedures).

INTRODUCTION

It is widely recognized that the LHC Machine Protection (MP) dependability has been excellent during operation in the years 2009–2013 [1] and only a few cases over the years can be defined as MP issues.

In MP issues, MP systems do not respond as foreseen and this could result in the machine being in an unsafe state. The exceptionality of these situations arises from them not having been thought of before, or them being a first occurrence, and is exacerbated by the fact that the next steps might be unclear and procedures might be missing. As a result, the actions to be taken are often left to the shift crew's experience, feeling or intuition. While in some occasions time to think might be available, in others it is imperative to act promptly.

After a short discussion on MP redundancy and combined system failures, in this paper we recall the main examples of these issues or failures and separate them into categories: failures that only experts can detect; failures that shift crews can detect, after beam dumps or with beam still in; dumps that could have been avoided. We also highlight measures that were put in place to solve them, or are possibly still missing (e.g. interlocks or procedures). Some open questions and conclusions close the paper. The failure examples discussed here are taken from the 2012 operational period, unless otherwise noted.

FAILURES AND REDUNDANCY

It is important to point out that the failure of a single system is generally not an issue as MP has abundant built-in redundancy. E.g. cases of "late" interlocks from magnet powering (i.e. through the Power Interlock Controller, PIC) were safely caught by the detection of beam losses by the Beam Loss Monitors (BLMs). This happened a few times over 2012, e.g.: for power converter faults in the inner triplet, for the LHCb dipole, for 60 A orbit correctors. More generally, the BLM and the Quench Protection Systems (QPS) are considered to be the "last line of defence" of MP as failures in other systems are eventually caught by beam losses or at the time of magnet quenches. Note also that the BLM system is redundant in itself, having three detectors per main quadrupole. Furthermore most failure cases will produce observable beam losses in several locations around the LHC ring.

Combined failures, instead, are a main worry. The typical example is an asynchronous beam dump happening while certain collimators are not in the desired position. In this case, that fortunately has not been experienced so far, the combined failures of the beam dump and of the collimation systems put the machine in an unsafe state and the protection of the hardware is not guaranteed, possibly resulting in magnet quenches or more important damage. As a general rule, if weaknesses are detected in one system, the beams should be immediately removed to allow for the necessary repairs before a second failure occurs which could expose the machine to serious damage. Unfortunately there are a few cases in which dumping might not be the best solution, namely when the dump could be dangerous in itself (e.g. impaired dump protection due to TCDQ with reduced efficiency or subject to overload, i.e. due to bad orbit at point 6 or too many particles in the abort gap).

FAILURES THAT ONLY EXPERTS CAN DETECT

Major events belong to this category, e.g. design faults and wrong reference settings in a MP system. In these cases the system expert detected the problem, often required the stop of beam operation to fix it, and decided when it was safe to restart. Little is in the hands of the operation shift crews as these faults could not have been detected by others than the experts themselves.

Examples are: the 12 V power supply failure that would have resulted in preventing the beam dump to fire; wrong settings defined for the transfer line collimators when shifting from SPS Q20 to Q26 optics and for ring collimators defined at the commissioning phase in the beginning of the year; the interrupted BLM High Voltage (HV) cable that would have prevented the BLMs from triggering the dump on heavy losses (2011, covered since by a Software Interlock).

FAILURES THAT SHIFT CREWS CAN DETECT, AFTER DUMP

Anomalous situations that led to the beam dump belong to this section. The shift crew might be able to identify them for example based on a careful analysis of the

Post Mortem data. E.g. during a physics fill, an internal trip of the Inner Triplet power converters (RTQX2.L2) was caught by beam losses due to a drift in orbit, while the PIC interlock came after the beam had already been dumped ($\approx$70 ms later). In this example one layer of MP redundancy was bypassed as the beam perceived the orbit perturbation caused by the Power Converter (PC) trip. The shift crew promptly informed the MP experts and the PC experts, and waited for their approval before resuming operations. The event was then followed up at the Machine Protection Panel and it was decided to reduce the over current protection thresholds of the PC [2].

A few other examples happened at injection energy: Injection Kicker (MKI) flashovers; lack of SPS-LHC synchronization due to the SPS being on local frequency or timing issues at the first Batch Compression, bunch Merging and Splitting (BCMS) tests (while SPS beam was extracted in TI2 the injection kicker MKI8 was pulsed). Already in 2010 it was pointed out that: "Beam dumps above injection are rigorously analyzed, we can do better at injection, avoiding repetitive trials without identifying the cause" [3].

For events that belong to this category (i.e. with the beam being dumped), the machine is in a safe state. However, the machine might have been in an unsafe state prior to the dump. Because of this, and in order to verify that the anomaly does not get repeated, the shift crews or often the system expert need to verify the correct behaviour of the systems and possibly take action to improve it.

Software tools can help the shift crew to spot these anomalous situations. Some of these checks are already included in the PM expert acknowledge (e.g. FMCM, PIC and BIC Internal Post Operational Checks (IPOCs)), but more checks can be added to the PM analysis frame: e.g. verification of collimation hierarchy, use of the power loss module to identify losses that are higher than normal.

FAILURES THAT SHIFT CREWS CAN DETECT, WITH BEAM STILL IN

In this case the system failure did not lead to a beam dump, resulting in a situation with the beam still in the machine but with at least one MP system that is impaired or partly impaired. At that point, it is up to the shift crew to judge and possibly decide to dump the beam manually if deemed necessary. In many occasions, after the first occurrence of such failure, an appropriate interlock was put in place so to increase protection. Examples are:

- during a physics fill, an RF feedback crate went down impairing the control of the whole RF line; taking into account that similar situations are interlocked and dump the beam to avoid putting excessive load on the collector, the shift crew dumped manually in agreement with the RF piquet; this event possibly highlighted a configuration to be added to the RF interlock connections to the Beam Interlock System (BIS);

- at a start of the energy ramp, all Beam Position Monitor (BPM) readings became unavailable, which meant no control or measurement on the beam orbit and no real-time corrections to it; the shift crew tried rebooting a few crates and then promptly dumped after realizing that the situation could not be recovered in a short time; such lack of BPM readings is now covered by a Software Interlock System (SIS);

- the tertiary collimators (TCTs) in point 2 did not respond to the timing event at the start of the collision beam process for a physics fill; consequently, at the end of the beam process, the orbit had changed but the collimators had the wrong centre (despite having the correct gap between the jaws); the state machine change to "Stable Beams" would have been prevented, but there is no interlock that dumps the beams automatically in such case (note that the LHC was not properly protected if an asynchronous beam dump had happened then); the suggested recipe in similar cases is to dump as soon as possible, as long as there is no strange orbit excursion in point 6; future improvements may come through the use of TCTs with integrated BPMs.

For failures in this category, the shift crew is faced with the choice of dumping manually or not: on the one hand there is cautiousness and MP, on the other hand there is operational efficiency (which gets degraded in case the situation could have been recovered by other means). In either case the support of both the machine and physics coordination would be appreciated. It is important, especially in the context of the restart after the first long shutdown, to define clear guidelines to alleviate the crews' choices during shifts.

It is also worth stressing that the time criticality of the manual dump changes from case to case: in the case of the RF collector heating for example the rapidity in the response is less important than in the case of missing BPM data during the ramp.

In fact, many interlocks are built on the experience from previously encountered situations and provide both a timely response and a coherent action across the shift crews. It should not be forgotten that at times, manual checks and dumps became the short term procedure: examples are the TCDQ not moving during a ramp in 2010 and the abort gap monitoring that was missing due to the BSRT mirror failure in 2012. The SIS provides the flexibility to add new interlocked conditions on very short notice and cover holes in the MP found once in the past (e.g. BLM HV verification missing interlock condition), software bugs (e.g. zeroed orbit feedback references during the squeeze), operational mistakes (e.g. incorrect settings on the main quadrupoles at injection in 2010).

Given these observations it is also unlikely that all failure scenarios have happened already. For this reason shift crews should be vigilant about unusual situations. Software tools can be designed to help the crews, e.g. BLM "reference" readings per beam mode.

DUMPS THAT COULD HAVE BEEN AVOIDED

This category collects all the cases in which the machine safety was not in danger, but the impact was rather on machine efficiency as the beam was unnecessarily dumped. Some examples are: a beam dump due to orbit excursion while setting up $6\,\sigma$ Van der Meer scans in the 1.38 GeV/c run; a dump at the transition of the Setup Beam Flag (SBF) from true to false (intensity surpassed $5 \cdot 10^{11}$ppb) as a masked interlock from the collimators was active (the TCTs were at coarse settings for collisions at injection); the dumps from the interlocked BPMs in point 6 due to reflections or low intensity bunches, especially during the proton-lead runs in 2013.

Many of these dumps could have been avoided had the procedures been prepared more thoroughly. This is especially true for special runs and Machine Developments (MDs), in which the machine operates in a different regime for a short period of time, and at the transition from these special regimes back into physics operation.

The masking in the BIS is automatically not taken into account when the beam intensity is above the SBF threshold. In this sense, masks that are set, but should not be, impair efficiency more than safety. A task that clears all masks during the preparation for injection sequence (to be run in the shadow of the magnet rampdown) will mediate this problem.

Some masks in the SIS are also dependent on the SBF and some others are non-maskable, but there are also many for which more flexibility is allowed. Forgetting to set appropriate masks or interlock settings has sometimes impaired the efficiency for special runs and MDs (e.g. orbit references for 90 m optics runs), as most are tweaked around nominal physics operation. Forgetting to unmask at the end of the special runs, i.e. when going back to nominal physics operation, has an impact on safety.

One straightforward solution is the preparation of very thorough procedures for special runs and MDs, including detailed step-by-step plans, settings change list, masks list. This helps to achieve results and to improve efficiency. The preparation of the document itself even helps to avoid misunderstandings within the teams. The document can be circulated beforehand to the shift crews for information and helps to minimize surprises and the need to adapt the plans during machine time. The impact is also positive on the definition of responsibilities and the document can function as a checklist to remember all reversions to be carried out at the end of the special run. In this frame, the request for a written MP document for MDs of type C and D (which foresee changes to MP systems and non-negligible intensity beams) will be extended to require at least a detailed plan for all MDs, to be handed in a few weeks before the MD is scheduled to take place.

Successful examples of MD document preparation are the ones for the quench tests carried out in February 2013. These documents were handed in well in advance allowing proper discussion and comments by all the experts involved. Even then, the documents could have been even more thorough and include e.g. masking the SIS TCSG/TCDQ retraction interlock that has caused the unnecessary loss of a fill.

It is worth recalling that also settings for other MP systems should be verified regularly, e.g. interlocked BPMs in point 6, BLM Monitoring Factors (which is already carried out by the experts on a weekly basis).

MISCELLANEA

Interlocks that latch or are masked too often loose effectiveness. It is important to define clearly what is really critical and what is not, to avoid the risk of overlooking or ignoring what should not be. In this perspective, the philosophy of the Injection Quality Check (IQC) latches should be revised [4].

The beam dump external Post Operational Checks (LBDS XPOC, see also [5]) is divided into several individual modules, the results of which can fail independently. Only experts can reset the critical modules (e.g. concerning dump kicker waveforms or synchronization units), while shift crews can only reset non-critical modules (e.g. latches from filling pattern, missing intensity or BLM data). At present, latches on non-critical modules are abundant (also due to weaknesses in other systems), but this mainly affects efficiency, rather than safety.

Concerning dumps coming from magnet protection (i.e. QPS and MP3), the answer that the shift crew gets from the on-call service often sounds like: "I am not sure why the QPS triggered, but the magnet protection worked as it should have: so you can carry on with operation, and the analysis will follow offline". This is "safe" even though it does not satisfy the shift crew's curiosity. Finally, it has to be recalled that operation was always stopped when needed. One representative example, is the case of impaired redundancy which was revealed by the coexistence of a bad temperature sensor and a bad cabling of a QPS detection board. As a result a Distribution Feed Box (DFB) High Temperature Superconductor (HTS) was protected only by the other QPS board (which was correctly connected). With two redundant protection systems defunct out of three, no redundancy was left in the quench protection of the DFB HTS (2011).

OPEN QUESTIONS

As stated earlier, not all unforeseen failures have happened yet and some time should be invested in devising other procedures for possible failures, before they are actually needed on shift. For example it might be useful to develop further on the cases where it is better not to dump, e.g. in the unlikely case in which the orbit is out of tolerance in point 6 or when the abort gap population is well above dump thresholds and keeps on increasing. A procedure is in place for high abort gap population [6], but it might be useful to include more details coming from the experience gained in 2012 (e.g. on transverse damper blow-up settings).

Another point concerns the confidence of the shift crews in executing the existing emergency procedures, it might be beneficial training them.

CONCLUSIONS

Machine Protection has worked remarkably well in these past few years of LHC operation and this success is the base for the success of the LHC. A catalogue of MP issues from 3 years of operation was presented though: cases of missing interlocks, design faults, weaknesses. The experience so far has helped to strengthen MP, but the long shutdown gives us the pause for thought to learn further from previous mistakes.

Shift crews can spot abnormal situations and act in case of need, but they should be assisted as often as possible with software and procedures so to align the decisions in stressful situations, and more importantly to shorten the decision time there where the human reaction time becomes too long for many beam-related failure scenarios.

ACKNOWLEDGEMENTS

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GLOBAL VISION OF MPS AFTER LS1 AND BEYOND

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Abstract

The most critical failures in machine protection systems will be revisited, in particular failures discussed in [1]. This paper takes into account recent work on hydrodynamic tunneling by high intensity beam and studies of the consequences of an asynchronous beam dump for the magnet system. An outlook to failure scenarios during the next (few) years will be given and the consequences on machine protection systems will be discussed.

INTRODUCTION

The LHC Machine Protection Systems are designed for very high reliability. Possible causes and consequences of serious failures of the LHC Machine Protection Systems were addressed in [1] [2], some of the failure scenarios are discussed below:

1. The beam dumping system deflects the beam with non-nominal strength, e.g. due to a wrong evaluation of the energy e.g. 450 GeV instead of 6.5 or 7 TeV.
2. Spontaneous firing of one (or more) kicker magnets and a failure of the retriggering system.
3. After a failure when the beams should be dumped, the beam dumping kickers are not triggered due to a failure in the protection systems.

An asynchronous beam dump is not considered a serious failure since the machine protection systems were designed to cope with such events without risking equipment damage.

The failure of a quenching superconducting dipole magnet and the energy extraction not activated is also considered as a serious failure due to the large energy stored in the RB circuit of one GJ per sector. Other magnet powering circuits are also critical, in particular for the triplet magnets MQXA/B (large stored energy, critical situation of spare magnets, difficult to replace). Protection related to the magnet powering systems is addressed in session 5 of this workshop.

CASE I

Several failures could lead to the beam deflected with non-nominal angle, e.g. if one (out of 15) kicker magnets fires and the retriggering does not work, or the LHC operates at 7 TeV and the kicker extract the beams with an angle corresponding to 450 GeV. In both cases, the beam will be deflected with an amplitude of about 15 σ into the TCDQ / TCSG absorber assembly (about 10 m of graphite). Qualitatively, the first bunches will be absorbed by the absorbers and heat the graphite. Part of the protons will be re-scattered into the LHC ring. Several 10 bunches are sufficient to melt and then vaporize the graphite. Bunches arriving later will therefore not be absorbed, travel through the absorbers further into the ring and are likely to hit the next aperture limitation, either collimators in IR7 or collimators in another insertion. Two studies help to understand what could happen:

- The energy deposition of protons and their showers scattered from the TCDQ / TCSG absorber into the magnets downstream in case of an asynchronous beam dump was calculated [3]. This allows understanding if magnets could be damaged by the energy deposition from the full beam hitting the TCDQ / TCSG.
- Calculations were performed during the last 10 years on the impact of a full 7 TeV beam on graphite and copper targets [4], and recently an experiment was performed at HiRadMat to validate the simulation method [5]. These studies allow to predict the number of bunches impacting on a long absorber before hydrodynamic tunneling will have created a channel for the beam to pass through the absorber.

For the studies of beam impact on TCDQ / TCSG in case of an asynchronous beam dump, a 7 TeV beam with 50 ns bunch spacing was assumed. About 42 bunches with 4.8×10^{12} protons are hitting the TCDQ. The maximum coil temperature of the MQ4 and MQ5 in such an event, will be of the order of 220 K, assuming a peak energy deposition of 200 J/cm^3 (for a failure scenario that is more likely the energy deposition will be a factor of 5-10 less). The energy deposition into the superconducting magnets in the adjacent arc 6-7 is shown in Fig 1.

The energy deposition into the adjacent magnets in the arc is considered if the TCDQ and TCSG absorber remain intact during the full beam pulse. The energy deposition would be a factor of 50-80 higher compared to the results presented in [3]. MQ4 and MQ5 are likely to be damaged for such event. The maximum energy deposition for the arc magnets is less than 50 J/cm^3, therefore no damage is expected.

Hydrodynamic tunneling of beam through the target becomes important after the impact of some 10 bunches. The first bunches arrive, deposit their energy, and lead to a reduction of the target material density. Bunches arriving later travel further into the target since the material density is reduced. This effect has been already predicted for SSC [6]. The calculation of hydrodynamic tunneling is complex and performed in several steps. Firstly, the 3D energy deposition in the target for a few bunches is calculated with FLUKA. The hydrodynamic code BIG2 [4] uses the energy deposition to calculate temperature, pressure and material density in the target. The density changes and the energy deposition by the following bunches needs to be recalculated with the modified density distribution by FLUKA. The programs are run iteratively in several steps. Typical parameters for the simulation are: 2808 bunches with 1.1×10^{11} protons,

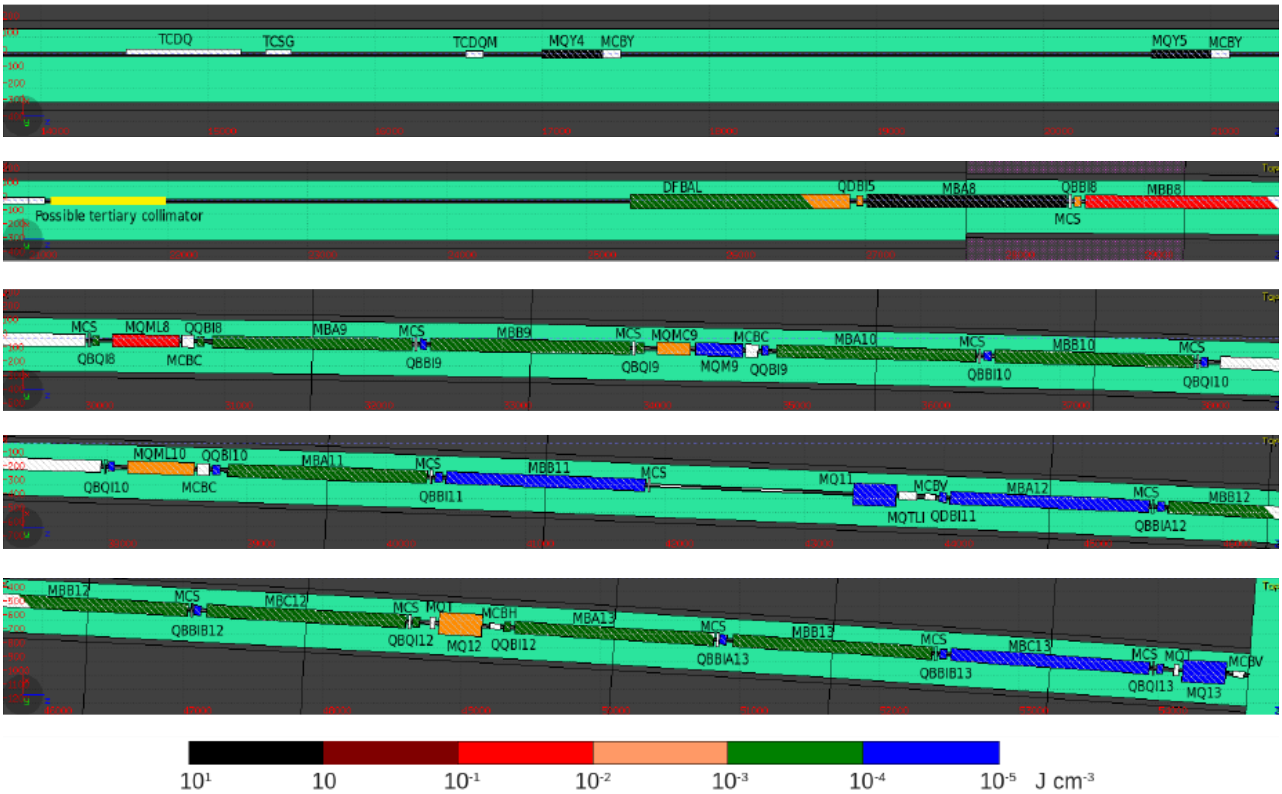

Figure 1: Energy deposition of an asynchronous beam dump for a 7 TeV beam with 50 ns bunch distance with beam impact on the TCDQ / TCSG assembly.

σ = 0.5 mm and 25 ns bunch distance. The solid cylindrical target has a length of 6 m, a radius of 5 cm, and a density of 2.3 g/cm3 in case of graphite.

In Fig. 2 the target density for three different time steps is shown in 2D. Fig. 3 shows the change of density along the axis of a graphite block by more than a factor of 10. The new TCDQ/TCSG assembly of 10 m length will not absorb bunches arriving after about 25-30 μs, but these bunches will travel further from IR6 to IR7 or IR5. A number of other collimators will be damaged but a precise estimation of the damage is not yet possible. A long additional absorber in IR6 could reduce the damage for this failure mode.

For a validation of the code an experiment was performed at the SPS HiRadMat facility by irradiating three copper targets with the following SPS 440 GeV beams (see the target assembly in Fig. 4 [7]):

- Target 1: 144 bunches about 1.9×10^{11}, 50ns, σ=2.0 mm – no tunneling expected
- Target 2: 108 bunches about 1.9×10^{11}, 50ns, σ=0.2 mm – tunneling expected
- Target 3: 144 bunches about 1.9×10^{11}, 50ns, σ=0.2 mm – tunneling expected.

Each target consists of copper blocks with a length of 10 cm and a slit between the blocks. When the copper melts or vaporizes, material escapes through the slits and is projected against the cover of the targets. This allowed us to estimate the depth of the damaged zone and therefore provide and idea of hydrodynamic tunneling. The traces on the cover are shown in Fig. 5. The range of the beam in target 3 is larger than in target 1 and 2. Although a detailed analysis is not yet completed, this gives already a clear indication for tunneling. After radiological cool down of the setup, it is considered to examine the blocks to establish a more precise measure of the depth.

CASE II

The second failure case considered is the beam dumping system not working. If this happens following a request from an operator to dump the beams, then there is still the option of forcing a beam dump trigger, and if this does not work of reducing the intensity by slowly scraping the protons away (see [8]).

If the beams are not extracted after a failure affecting the particle trajectories (e.g. after a quench of a magnet, a failure of a power converter, an object moving into the beam) there is no time for scraping. The orbit will move and possibly the beam emittance will blow up. Initially, particle losses are captured by collimators. It is likely that superconducting magnets will quench after a short time. Depending on the time constant of the failure, collimators will be damaged first, or superconducting magnets will quench. In case of a collimator being damaged the cleaning efficiency is reduced, which also leads to a superconducting magnet quench shortly later.

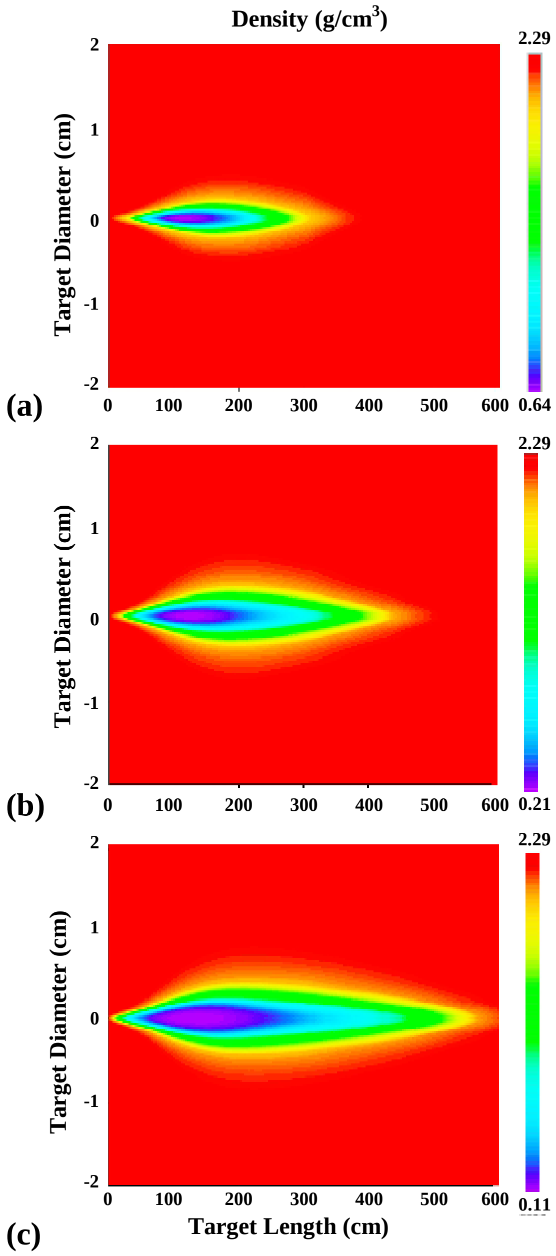

Figure 2: Density distribution calculated in BIG2 in the carbon cylinder, r = 5 cm, L = 6 m, irradiated by a 7 TeV LHC beam, at the left face; (a) at t = 5 μs; (b) at t = 10 μs; (c) at t = 15 μs.

If we assume a quench in a dipole magnet, the orbit will change even further. After about 10-20 ms the beam will hit one of the collimators. The collimator will be destroyed within a few ms, the beam will continue to move further out and more collimators will be destroyed. It is not clear if the beam will reach the vacuum chamber aperture, but the computational tools to study hydro-dynamic tunneling and the results from HiRadMat should allow a better quantification of the damage to be expected.

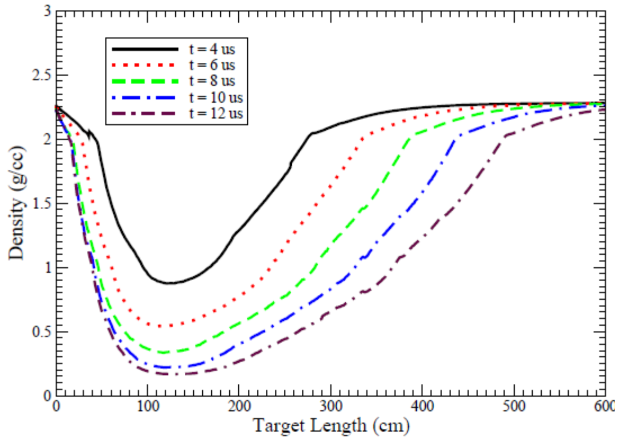

Figure 3: Target density reduction as a function of time.

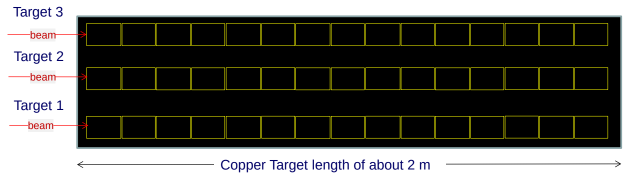

Figure 4: Layout of the copper targets.

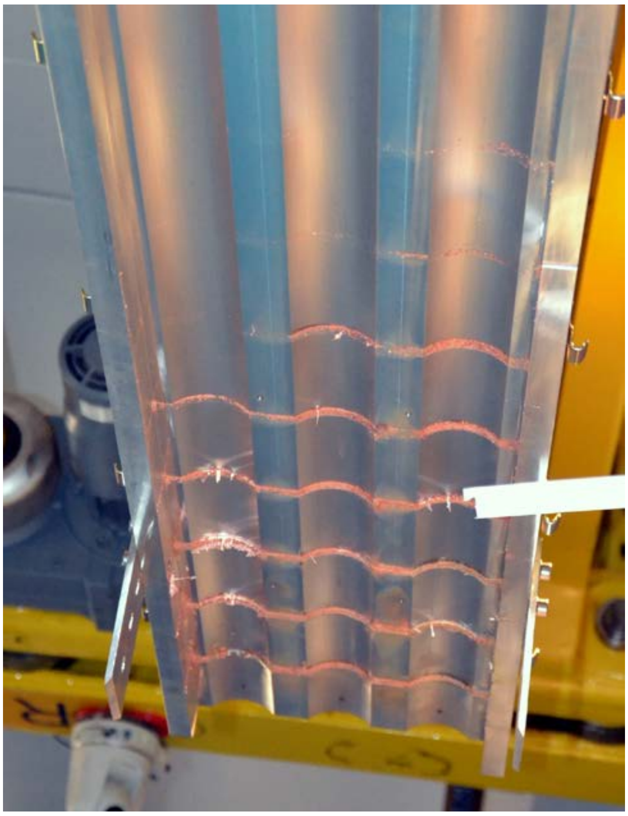

Figure 5: Target cover with the projected copper.

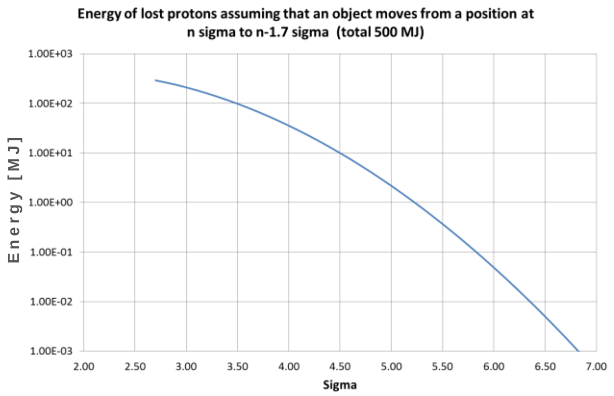

Figure 6: Energy loss assuming that an object cuts into the beam tail by 1.7 σ.

POSSIBLE MITIGATION

To mitigate against failure of the LBDS kicker magnets not firing, one option would be the installation of one (or two) kicker magnets that deflect the beam by an angle of about 30 μrad into internal absorbers. These absorbers should have a length of at least about 20 m and will be destroyed if such event occurs. The kicker magnets should never fire before triggering the kicker magnets of the LBDS and would therefore be delayed by about 1 ms. Considering recent experience, a delay of 1 ms is acceptable for all failures that have been observed. There should be no charged elements in the kicker power supply to prevent any spontaneous pre-firing. This mitigation does not help if an LBDS kicker pre-fires and the retriggering fails. For this case, massive absorbers at an aperture further out than the secondary collimators, but closer than the tertiary collimators, could reduce the damage. If such absorbers would be installed in IR6 they would capture most of the beam energy. It might be possible to install such devices behind the TCDQ / TCSG assembly.

Are such absorbers beneficial for all scenarios where the beam is not extracted after a failure? To some extent yes, massive absorbers close to the beam are likely to capture part of the beam energy, but it is not yet possible to quantify this effect.

KNOWN FAILURE SCENARIOS REVISITED

During the design of the LHC machine protection systems, no failure leading to massive beam losses faster than about one ms was identified. A change of the closed orbit after a powering failure of the normal conducting D1 magnet is still considered to be the most critical failure for operation with circulating beams. During the three years of experience, this assumption proved to be correct (except UFOs that lead to beam losses in less than one ms but are not threatening to damage equipment).

The transverse beam intensity distribution has tails. It had always been assumed that the distribution is Gaussian, but several measurements show overpopulated tails with respect to a Gaussian distribution. If the beam tails touch the collimators when the beam moves, say, by one sigma in one ms, the BLMs detect the losses and there is enough time to dump the beam before any damage occurs.

For the future, new failure scenarios need to be considered:

- Crab cavities that are discussed for HL-LHC might lead to a deflection of the beam within a very short time in the order of μs by 1.7 σ in case of a single crab cavity failure.
- Long range beam-beam interactions change the orbit of both beams. When one beam is dumped, the orbit of the other beam changes in a very short time.
- Fast vacuum valves: for the protection of critical equipment (such as the SC-RF cavities in IR4) in case of a major vacuum leak it had been proposed to install vacuum valves that close much faster than the valves installed today.

In the following paragraphs, only issues related to the installation of crab cavities are discussed.

For the transverse planes, a Gaussian distribution for the intensity is assumed and a collimator at a position corresponding to 4 σ. In case of a crab cavity trip and a fast displacement of the beam by 1.7 σ, all particles above an amplitude of 2.3 σ would be scraped away. If the energy stored in the beam corresponds to about 500 MJ, the energy loss would correspond to 35 MJ. For a collimator at 5 σ the energy loss is 2.2 MJ and for a collimator at 6 σ the energy loss is less than 0.1 MJ. The energy loss as a function of collimator setting in case of such failure is shown in Fig. 6.

It is not yet clear if crab cavities can generate such beam movements. Mitigation methods are being discussed, such as a passive increase of the time constant τ for critical failures through LLRF and cavity design (available power, Qext, ...). If this is not possible and such failures need to be anticipated, a particle free aperture between collimators and beam of, say, two sigma might be required (or at least a strongly reduced particle population that still allows the early detection of beam displacement with beam loss monitors). Such gap could be produced by hollow electron lenses or other halo cleaning techniques. A dependable measurement and interlocks on the particle population in the transverse tail and possibly on the longitudinal head-tail oscillations would be needed.

Ideas for upgrade of protection systems:

- Dependable and fast detection of failures at/close to cavities (in about one μs).
- Direct links between the crab cavities and the beam dumping system to reduce the delay for a beam dump, between IR1/5 and IR6. In addition, asynchronous beam dumps might have to be accepted for limited failure cases to further reduce the delay time.
- Additional abort gaps.

- Position of collimators further outside (between 5.5 σ and 6.0 σ).

Future work: understand details of loss scenario, extract beam as fast as possible, possibly accept some limited damage to collimators if the probability for such event is low and if collateral damage can be minimized to an acceptable level.

QUESTIONS

Instead of a conclusion, it is suggested to address several questions:

- Do we have the tools for a credible estimation of consequences of “catastrophic” failures? How far should such consequences be further investigated?
- How to evaluate mitigation methods such as absorber blocks, or redundant kicker plus absorber blocks?
- Are crab cavities introducing a new type of very fast failures and can we protect the LHC efficiently if such failures occur?
- Should we continue using only robust collimators, or reconsider the materials if possible damage is understood and limited, if we gain in overall integrated luminosity?
- Do we have to reconsider our protection strategy in case of missing beam halo?
- What other changes are expected that can have an impact on machine protection?

ACKNOWLEDGMENT

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LBDS KICKERS OPERATIONAL EXPERIENCE DURING LHC RUN 1 AND PLANNED CHANGES DURING LHC LONG SHUTDOWN 1

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Abstract

The LHC Beam Dump System (LBDS) operational experience acquired during LHC Run 1 is presented. The major problems encountered during this period, along with the actions taken as a consequence, are summarized. The various changes foreseen for LS1 are explained, in particular the implementation of a redundant triggering path by the BIS, the release of the card TSU-v3, the upgrade of the PTU, the consolidation of the high voltage generators and the modification of the UPS powering to a full redundant architecture. The interlocking policy in place is discussed, and the foreseen improvements in post-mortem analysis systems are shown. The strategy for the reliability run and the re-commissioning of LBDS is presented.

OPERATIONAL EXPERIENCE

LBDS usage analysis

Analyses on the usage of the LBDS during LHC Run 1 were performed, based on the data extracted from the logging of the Internal Post Operation Check (IPOC) system and the eXternal Post Operational Check (XPOC) system [1]. They show that the system has been much more solicited than what was expected. For instance, for LBDS beam 1, during 3 years of operation more than 40000 pulses were executed in LOCAL mode (i.e. the LBDS is controlled locally from the tunnel), and more than 12000 pulses in REMOTE mode (i.e. the LBDS is controlled remotely from the CCC). This is much more than the 400 physics fills per year initially foreseen [2].

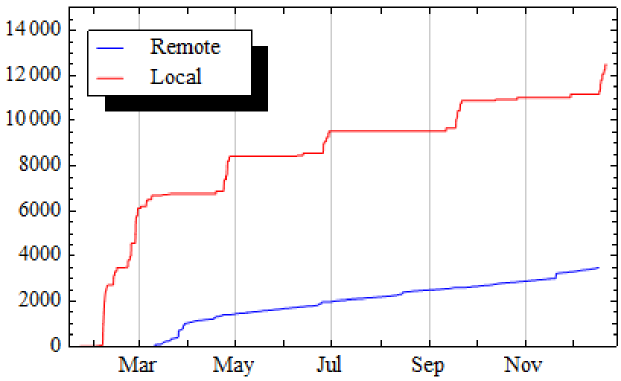

Figure 1: Cumulative number of pulses for LBDS beam 1 during 2012.

Figure 1 shows the cumulative number of pulses recorded during year 2012. We see that the many pulses in LOCAL mode correspond to the end of the Winter Shutdown (WS) and the various Technical Stops (TS), during each of which one or two MKD HV generators were upgraded (see section 'Changes to HV generators'), and subsequently many pulses were performed to recalculate and revalidate the numerous LBDS parameters. The number of pulses in REMOTE mode also includes the commissioning and the Machine Development (MD) periods, which explains why it is much larger than the 585 physics fills dumped during 2012 [3].

From the logging of the Beam Energy Tracking System (BETS), an analysis of the LBDS operational energy during LHC Run 1 was performed. Figure 2 shows that during 2012 most of the time (~110 days) was spend at full energy (4 TeV), and roughly equal time (~85 days) at injection energy (450 GeV) and in standby (400 GeV). The time spent during energy ramps is small (~15 days), and the system has been turned OFF mostly during the WS (~50 days).

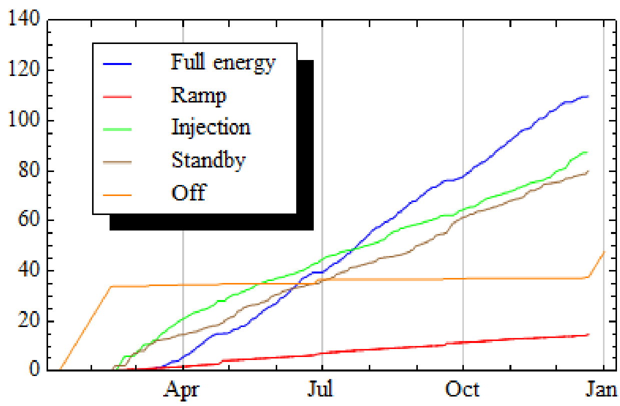

Figure 2: Cumulative number of days spent at each energy for LBDS beam 1 during 2012.

Of course this LBDS utilisation depends entirely on the LHC operation. It is nevertheless interesting information as it shows the periods of stress on the LBDS high voltage equipment. At the beginning of the year we spent more time in standby or at injection energy, but around May the trend is inverted and we spent most of the time at full energy until the end of the year.

LBDS failure events analysis

The list of failure events that occurred on the many devices composing the LBDS during LHC Run 1 has been extracted from the TE-ABT and the OP logbooks [4]. These numerous failure events have then been classified w.r.t. various criteria such as the control mode (LOCAL/REMOTE), the beam mode (No beam, Injection, Beam in, Stable beam, etc.), the type of failure (detected or silent) and the type of intervention needed to solve the problem.

Figure 3 shows the cumulative number of failure events that occurred during the year 2012. Over a total of 33 recorded failure events (blue curve), 16 occurred with beam in the machine, called 'false dumps' (red curve). Almost half of the failure events occurred without beam. They correspond mainly to problems that occurred during the WS when upgrades were performed on the LBDS, or to problems in arming the LBDS that were caused by faults in external systems such as Vacuum, RF or Beam Interlock System (BIS).

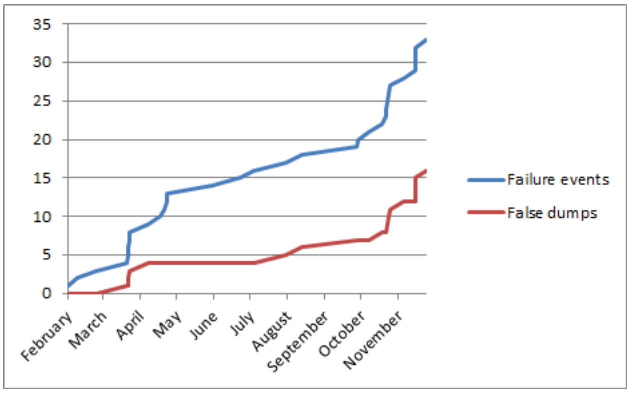

Figure 3: Cumulative number of LBDS failure events during 2012 (LOCAL & REMOTE).

Figure 3 also shows an increase of the number of 'false dumps' at the end of 2012, corresponding to various recurrent failures that needed many interventions before the problem could be identified and fixed. This concerns for instance AS-i bus or Anybus industrial components.

To be noted that all of these failure events resulted in a beam dump properly executed.

Of the 28 failure events that were catalogued for 2012 operation in REMOTE mode (with or without beam), 25 were detected and 3 were silent.

Detected faults are related to fail-safe parts of the LBDS, where surveillance guarantees the detection of the fault, and the execution of a beam dump before the situation degrades.

Silent failures are those occurring in fault-tolerant parts of the LBDS, where redundancy guarantees a correct execution of the dump, even with a redundant path that is not working. The problem is then detected during Post-Operation Checks, and will be corrected before the next beam injection.

Only 5 failure events occurred in LOCAL mode during 2012, corresponding mainly to various power supply failures during WS and TS.

Failure follow-up interventions

The interventions executed after a failure event are classified in four categories:

- **Remote**: A reset using an expert application is enough to solve the problem, no access is needed.
- **Masked & Postponed**: The problem is not critical in the current operational conditions, and it is decided to mask the error and to proceed with the LHC operation.
- **Postponed**: The access is needed but is postponed, for instance to wait for the end of operation with the other beam during an MD.
- **Immediate access**: The problem is critical and needs an access before beam is allowed in the machine.

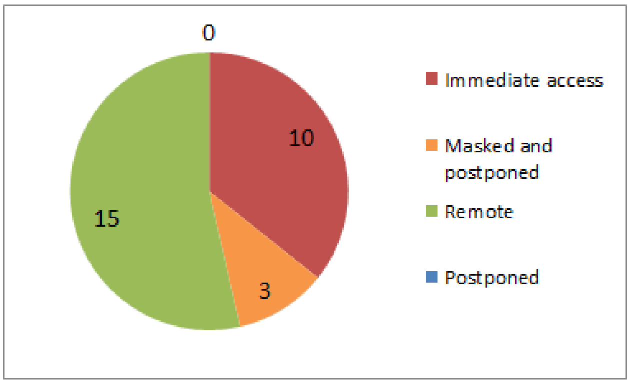

Figure 4: Statistic on the interventions performed during 2012.

Over 28 recorded interventions during 2012, more than 50% were performed remotely, and only 30% needed an immediate access, as shown in Fig. 4.

XPOC errors

After every beam dump execution, the XPOC server [5] performs a number of checks on the LBDS behaviour, using data coming from the various LBDS surveillance and diagnosis systems. Depending on the XPOC module that fails, an LBDS expert has to be called to analyse the situation and reset the XPOC error.

During the operation in 2012-2013, a large number of 'false XPOC errors' occurred, i.e. errors that are not due to a bad behaviour of the LBDS but to a bad execution of an XPOC analysis session. These errors are often related to missing data.

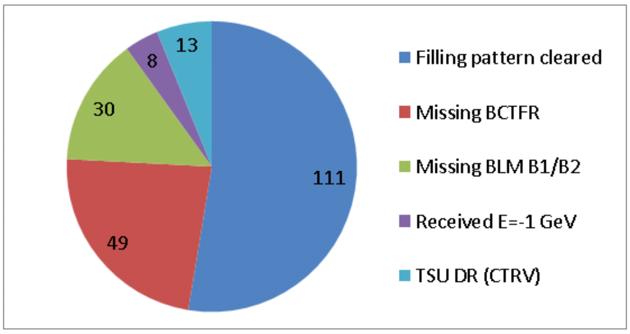

Figure 5: Statistics on the false XPOC errors during 2012.

Over a total of 430 errors detected by XPOC in 2012-2013, 211 were 'false errors', due to 5 recurrent problems as shown in Fig. 5.

The identified problems are:

- **Filling pattern cleared (111):** The filling pattern has been cleared by the LHC operator before performing the 'over injection' of a bunch over the circulating pilot. The dump occurred between the clearing of the filling pattern and the injection of the bunch, so an error is issued by XPOC because the measured intensity does not correspond to the filling pattern content.
- **Missing BCTFR (49):** The fast BCT ring (BCTFR) failed and did not publish the circulating beam intensity. As many check limits depend on the beam intensity, XPOC generates an error when this information is missing.
- **Missing BLM B1/B2 (30):** The BLM hardware contains only one XPOC buffer for both beams (200 ms). When the two beams are dumped within a short time interval, data related to both dump events will be included in the BLM buffers. But when beams are dumped more than 100 ms after each other, the XPOC doesn't find data regarding the second dump in the BLM buffers, and issues an error.
- **TSU DR (CTRV) (13):** The two dump requests and the synchronous trigger generated by the two Trigger Synchronisation Unit (TSU) cards are captured by two CERN Timing Receiver for VME (CTRV) cards to precisely timestamp them. Due to a problem not yet clearly identified in the driver of the CTRV card, sometime a dump request is not recorded by the CTRV card. In this case the XPOC generates an error because apparently one TSU did not generate its dump request.
- **Received E=-1 GeV (8):** The XPOC needs timing telegram data such as beam energy to compute many check limits. Sometime the beam energy is not saved properly by the XPOC server at the time of dump, and an invalid value of -1 GeV is send to the XPOC analyses, resulting in an error.

For most errors a reset by the LHC operator is possible. But for the following errors, an LBDS expert had to be called:

- Received energy E=-1 GeV;
- TSU DR not detected (CTRV).

There were far too many 'false XPOC errors' during LHC Run 1 (almost 50% of total XPOC errors) and LHC operators spend way too much time to address them. An LBDS Expert had to be called for 10% of the cases.

All these problems have to be solved during LS1. Discussions have already started with the concerned groups and we are confident that solutions will be found.

LBDS self-trigger with beam

The statistics of MPS show that only 4 physics beams were dumped by an internal fault in the LBDS [3]. However, it should be noted that only beam dumped at energies higher that 450 GeV were accounted. (At 450 GeV, the beams were lost 40 times due to an LBDS self-trigger).

Table 1 shows that these four physics beams were dumped due to two recurrent hardware problems:

- AS-i bus error: SIEMENS AS-i bus power supply was delivering unstable voltage;
- BEM Anybus error: Anybus communication module on Beam Energy Meter (BEM) card, part of the BETS, was not functioning properly.

Table 1: Physics Beams Dumped in 2012 by LBDS Self-Trigger

Date	*Energy*	*Cause*
02-OCT-12 16.17.38	3310	AS-i bus error
27-OCT-12 07.58.38	4000	AS-i bus error
28-OCT-12 11.11.05	494	BEM Anybus error
29-OCT-12 19.50.47	458	BEM Anybus error

These errors were also responsible for many dump events at the end of 2012, as shown in Fig. 3, and needed many interventions until the source of the problem was identified and definitely solved.

Industrial component failures

Many failure events were due to design problems with off-the-shelf industrial component, i.e. the component did not meet the announced performances in terms of MTBF. A list of hardware problems encountered during LHC Run 1 is shown in Table 2. These components had all to be sent back to their manufacturer for repair or upgrade, or had to be repaired at CERN.

Table 2: Industrial Component Redundant Failures

Component	*Items in operation*	*Problem description*
National Instruments PXI-5122	61	Weak fuse.
VERO PK55 PSU	50	Bad electrolytic capacitor.
Heinzinger 3kV HVPS	80	Bad electrolytic capacitor.
Heinzinger 35kV HVPS	40	HV transformer sparking.
SIEMENS AS-i bus PS	4	Bad electrolytic capacitor.

Electrolytic capacitors are the most predominant source of failure, and many bad quality capacitors were replaced by more reliable ones in many power supplies units.

Potentially dangerous failures

Four failure events were identified to be potentially dangerous, i.e. if they had occurred in other operational conditions they could have yield to significant machine down time. These four events are described below:

- **TFOT Driver IC burned:** The Trigger Fan-Out Transmitter (TFOT) cards are responsible for driving the 60 redundant synchronous triggers to the 15 MKD generators. A line driver IC burned in one of the TFOT cards, generating a pulse at its outputs. The way the redundant triggers are cabled between the output of the TFOT and the input of the generators lead to two generators receiving the bad trigger. As a result two generators triggered erratically, and then the 13 others were triggered ~800 ns later by the retrigger lines.
  Following this incident, the TFOT were re-cabled in a way that, if the same line driver problem occurs, only one generator would be triggered erratically, which is acceptable. A review of the design of the TFOT card was conducted, and concluded that no design problem could account for this event [6].
- **WIENER Power Supply Failure:** The power supply of a WIENER cPCI crate failed during a TS with its main power input in short circuit (failure of the Power Factor Correction circuit). This provoked the trip of the main circuit breaker of the UPS, leading to 8 racks of LBDS control electronics being out of power simultaneously. As a consequence only asynchronous triggers were issued.
  This problem of selectivity in the UPS electrical distribution was not expected, and a review of the whole LBDS powering was conducted [7]. As an outcome the power distribution of the LBDS has been upgraded: a second UPS source was provided (from QPS), and individual fuses were installed on every LBDS control crate.
  During LS1, the LBDS power distribution will be consolidated by adding a second independent UPS (from US65) and an individual circuit breaker for every crate.
- **+12V Power Supply loss on TSU crate:** During analyses performed for the preparation of the LBDS powering review, we identified a scenario that could yield to a potentially catastrophic situation. In this scenario the +12V power supply fails in the crate that contains the two Trigger Synchronisation Unit (TSU) cards. In this case no triggers, neither synchronous nor asynchronous, are generated and so any dump requests will be discarded. This scenario never occurred. When the problem was discovered an immediate beam dump was requested, and the LHC operation was stopped. A temporary solution that monitors the +12V power supply in the TSU crate and generates an asynchronous beam dump in case a failure is detected was implemented.
  This fix was consolidated during the following TS, and to definitively avoid this problem in the future, a new TSU card is designed and will be deployed on two separate crates during LS1.
- **MKD generator HV sparking above 6 TeV:** As the MKD generator GTO switches are very sensitive to temperature change, we added a Peltier cell inside each generator to maintain the switches at a constant temperature. These modifications were made after the LBDS reliability run that took place during 2009.
  After the addition of the Peltier cells, we realised that the MKD generators could not handle the full operational voltage anymore. For a voltage corresponding to an energy higher than 6 TeV, sparking occurred in the generators, causing a self-trigger of the GTO switches. An explanation for this complex phenomena could be that the air is dried by the Peltier cells, and becomes so insulating that the charges produced on the surface of the Plexiglass insulators cannot flow away anymore so they accumulate and after a certain voltage is reach, they eventually discharge on the GTO deflectors, sometimes igniting a self-trigger of the GTO stack.
  As the operational energy foreseen for LHC Run 1 was 3500 - 4000 GeV, it was decided to limit the LBDS operational energy to 5000 GeV.
  Studies for the upgrade of the GTO stacks were immediately initiated and insulating pieces avoiding sparking will be installed during LS1.

Missing procedures

Operational procedures are also needed to help experts to take decisions based on risk evaluation, and to limit the LHC operation with beam when the LBDS is used in degraded mode (masking of switch ratio, enlarging of XPOC tolerances, etc.). Moreover, the fact that the LBDS is in degraded mode is not clearly visible in the CCC and, at least, a warning indication should be added on the LBDS fixed display.

Operational procedures to be followed after hardware changes in the LBDS are needed, to enforce the revalidation of the system by performing standard tests.

PLANNED CHANGES DURING LS1

Additional re-trigger from BIS

The LBDS comprises a complex Trigger Synchronisation and Distribution System (TSDS) [8], which includes two re-trigger lines that connect every MKD and MKB generators with each other, shown in red and blue in Fig. 6. In the case an MKD generator self-triggers, the re-trigger lines will propagate a trigger to all the other generators, resulting in an asynchronous dump with the 15 generators pulsing.

Each time a dump request is sent to the TSDS, the TSU cards generate synchronous triggers that will be distributed to the 15 generators, plus redundant asynchronous triggers 200 μs later that will be sent over the re-trigger lines to cover the case were the synchronous dump has not been executed properly.

To cover the case where a dump request is not handled by the TSDS and no dump triggers are issued at all, such as the +12V power supply problem discussed previously, a direct connection from the BIS to the LBDS re-trigger lines is recommended.

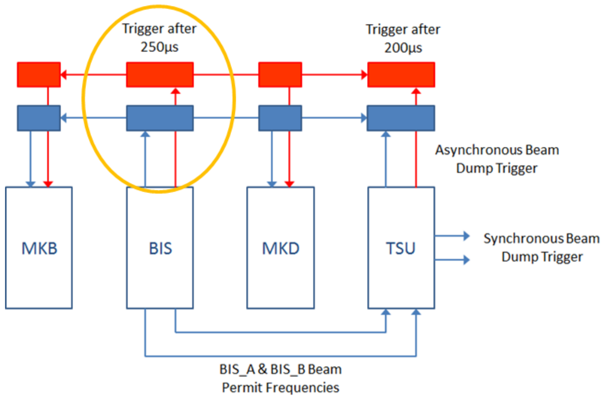

Figure 6: BIS connection to the LBDS re-trigger lines.

Each time the BIS loops open, a pulse would be sent over the re-trigger lines 250 µs later. This would guarantee at least an asynchronous beam dump in the case the TSDS does not react to a dump request.

The presence of this pulse on the re-trigger lines will be checked after every beam dump by the TSDS IPOC system.

The drawback of such a solution could be an increase of the asynchronous beam dump rate, due to a malfunctioning of the hardware added between the BIS and the re-trigger lines.

During LS1, functional and engineering specifications of the connection between BIS and LBDS re-trigger lines will be written [9], and a reliability analysis of the new hardware will be conducted [10].

Upgrade of TSU card

Following an external review of TSU card design [11], the problems foreseen regarding the loss of +12V power supply on the TSU crate and the review of LBDS powering [7], a new hardware design of the TSU card will be implemented during LS1. The new TSU cards will be deployed over two separate crates, and a surveillance of all the power supplies will be added on the TSU card itself, hence the redundant TSU will trigger in case the first one loses one of its power supplies. The diagnostics will be improved as well, as many additional TSU internal signals will be acquired and analysed by the IPOC system, such as all the redundant dump requests from all the clients.

LBDS powering modifications

Following the LBDS powering review [7], a separated connection to a second UPS (in US65) will be installed for LBDS and an individual circuit breaker will be installed on every crate Power Supply Unit (PSU). Moreover a monitoring of the state of all the redundant PSU of LBDS crates will be performed, and the Software Interlock System (SIS) will request a dump in case a failure is detected in a PSU.

MKB vacuum interlocking problems

The dilution kicker magnets (MKB) are installed in a vacuum tank. They can be operated only under defined vacuum conditions to avoid sparking. During LHC Run 1 we experienced many problems due to noise present on the vacuum probe signals. The analogue vacuum signal is very noisy and was always masked since the beginning of LHC Run 1. The digital interlock signal is very noisy as well (spikes and glitches) and is at the origin of more than 13 beam dumps during 2011-2012 operation.

Discussions with TE-VSC have started, and a solution to all these vacuum probe problems must be provided during LS1.

Changes to HV generators

As explained in the section “Potentially dangerous failures” above, the operation of the LBDS has been limited to 5 TeV during LHC Run 1, due to electrostatic discharge occurring inside the MKD generators for energies above 6 TeV.

The sparks appear between the GTO HV deflectors and the Plexiglass insulated return current rods [12].

To avoid the electrical breakdown for voltages corresponding to an energy higher than 6 TeV, insulators between the GTO HV deflectors and the return current rods will be added to all generators during LS1, as shown in Fig. 7.

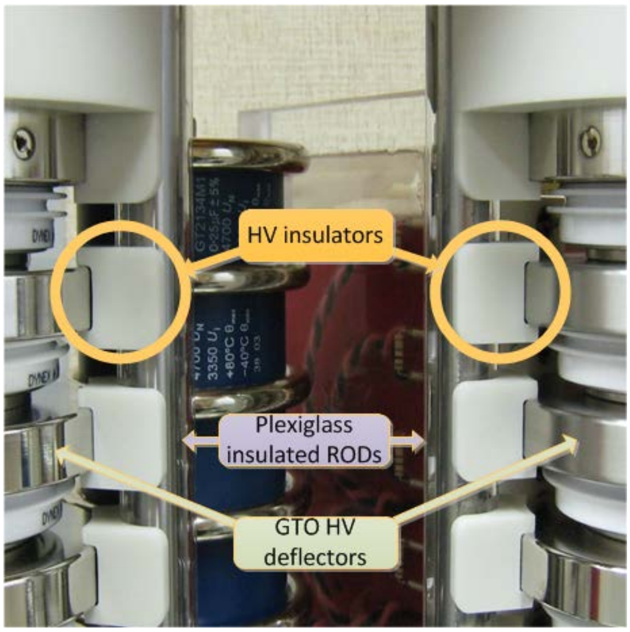

Figure 7: Details of two GTO stacks in an MKD generator showing the added HV insulators.

During Run 1 the GTO stacks were provided by two different manufacturers. After LS1, only ABB GTO will be used as they have better Single Event Breakdown (SEB) test results and have a more stable turn-on delay [12]. Nevertheless, a common mode failure could appear due to this choice of a unique technology and will be evaluated.

Upgrade of Power Trigger Units

The GTO stacks in the HV generators are triggered by Power Trigger Units (PTUs) that deliver the current in the GTO gates. These PTUs are composed of a High Voltage Power Supply (HVPS) that charges a capacitor, which is then discharged into the GTO gates using IGBT switches.

During Run 1 the PTU HVPS voltage was continuously adjusted w.r.t. the beam energy varying roughly from 600 V to 3000 V. These adjustments, which were specific for each generator, were made to maintain the rising edge of every kicker magnet currents within a window of 2.7 μs at all energies [12].

During LS1 the 3kV HVPS will be replaced with a 4kV one, and the 1.2kV IGBTs will be replaced by 1.7kV ones. SEB tests show that the new 1.7kV IGBT is substantially less sensitive to SEB than the previous one [13].

With this increased PTU voltage, the GTO gate currents are higher, leading to lower GTO turn-on delays. Moreover the GTO turn-on delays becomes less dependent on the GTO anode-cathode voltage, so the adjustment of the PTU voltage w.r.t. the beam energy would not be necessary anymore.

After LS1 we plan to use the PTUs with a constant voltage of ~3300 V, and we expect that no increase of the beam abort gap duration would be needed when operating the LBDS under these conditions.

Other changes…

Many other changes will be performed in the LBDS during LS1. The main changes are:

- **Upgrade of the 30 MKD generator IPOC systems**: Four digitizer channels will be added on each MKD generator to capture and analyse the PTU current waveforms.
- **Upgrade of the 30 MKD -300V DCPS**: One operational amplifier will be replaced in the compensation DCPS (-300V) of all MKD generators, to solve a problem with its offset. This will facilitate the replacement of a defective DCPS.
- **Upgrade of the 30 MKD generator temperature probes**: Absolute temperature measurements, used to maintain the GTO stacks at a constant temperature using the Peltier cells, are not precise enough. We will replace the temperature probes by more precise ones (± 0.1 ^{O}C instead of ± 0.3 ^{O}C), and connect them using 4 wires instead of 3 to reduce the sensitivity to cable length and contact resistances.
- **Improve shielding in MKD&MKB cable ducts between UA and RA**: Presently only ducts in front of TCDQ are filled with rods made of lead. All the cable ducts between UA and RA will be filled.
- **Add 2 MKB magnets (1 tank) per beam**: During Run 1 only 4 vertical dilution magnets were installed per beam instead of the 6 initially planned. This was sufficient to dilute the beam up to 4 TeV. During LS1 the two remaining vertical dilution magnets will be installed.

FULL RE-COMMISSIONING

After all the changes that will be performed on the LBDS during Run 1, a full re-commissioning of the LBDS is mandatory.

After a first revalidation period, a reliability run will be conducted for approximately 3 months. It will consist in running the LBDS in LOCAL mode and performing pulses at various energies, keeping the LBDS at full energy for long periods, simulating ramp-up and ramp-down, etc…

This will be followed by the re-commissioning of the LBDS in REMOTE mode without beam, so called ‘dry-run’. The LBDS will be controlled from the CCC to validate the various control software interfaces, and a local BIS loop will be installed to check the functionality of the new link between BIS and LBDS with sufficient operational statistics.

This is followed by a commissioning with beam which allows validating all the LBDS parameters by checking the position of the beam on the Beam TV Direct Dump (BTVDD) screen, located 30 meters upstream of the beam dump absorber block.

Additional tests have to be conducted after the commissioning, such as the measurement with beam of the effective rise time of MKD extraction kicker magnets. The procedure for this test is still to be defined, but it will certainly rely on a scan of the MKD ‘threshold’ and ‘start’ points with a pilot, and the measure of the effect on the beam using BTVDD and BPMs.

Another obligatory test will be to provoke a beam dump triggered from the Beam Loss Monitor Direct Dump (BLMDD), which is a BLM located at point 6 and directly connected to the TSU cards. This TSU client has never been activated up to now during operation.

All the existing commissioning procedures [14] will be reviewed and updated, in the light of the LBDS operational experience during LHC Run 1.

Procedures for a non-working LBDS trigger

A procedure has been established to cover the case where the various dump triggers are not generated on request and so the beam dump is not executed [15].

This procedure must be updated taking into account all the changes performed on the LBDS during LS1, such as the new TSU cards deployment over three separate crates, or the changes in the LBDS power distribution including the addition of a UPS. The new procedure must be carefully validated.

Safety and Reliability analyses

An expert has been mandated during LS1 to analyse and classify all the failure events that occurred in the LBDS during the LHC Run 1, in a manner to validate the safety and reliability analyses of the LBDS performed in 2003-2006 [16]. The first statistics on failure events are presented at the beginning of this paper. The results of this study confirm the agreement of the calculated statistics with the predicted estimates, in terms of impact on the LHC operation and safety [2].

Another part of the safety analysis was to model the TSDS in the light of all the changes that will be performed during LS1. This modelling was not included in the analysis before. The analysis showed the TSDS to be largely SIL4, thanks to the changes performed during LS1 such as improvements in power distribution and surveillance, and a different routing of synchronous trigger signals [17].

SUMMARY

Operation of the LBDS during the LHC Run 1 was completely satisfactory as all dump requests were correctly executed and the availability of the LBDS was good. However, there were some negative surprises, which did not affect operation directly but could have led to dangerous situations. Many changes to the LBDS are foreseen for LS1, which will mitigate all the potential problems identified. An extensive re-commissioning of the LBDS, including a reliability run, a dry run and beam tests will be required at the start-up of LHC Run 2.

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DUMP SYSTEM PROTECTIONS

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Abstract

The protection functionalities of the various systems connected to, and associated with, the LHC Beam Dump System (LBDS) are covered in this talk, in particular the dump channel protection (TCDQ), Beam Position Monitors (BPMs) and Abort Gap Monitoring (AGM). System changes planned for Long Shutdown 1 (LS1) are described, and the machine protection implications are detailed in terms of the improvements in the system safety and also in terms of changes to the operational procedures and expected performance. Run 1 (LHC operational period 2009-2012) experience is reviewed concerning aperture and tolerances with an outlook to 7 TeV. Some other ideas to improve operational availability without compromising safety are explored, together with possible improvements to the validation procedures for the dump protection.

TDE THERMAL RESPONSE

In LHC Run 1 the maximum beam energy deposited in the dump block TDE was around 140 MJ. The TDE thermal response has been inferred from the pressure data, where the pressure of the N_2 gas containment was logged throughout the year. The temperature change is estimated from the logged pressure P through the ideal gas law. The results are shown in Fig. 1 and give a 10 K peak average temperature rise for a single dump, which is reasonably consistent with the expected average temperature rise of the dump block plus steel jacket (we would expect about 22 K if all the energy were absorbed and instantaneously spread out).

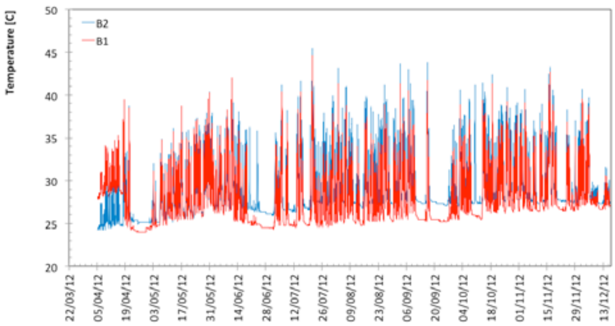

Figure 1: Calculated TDE temperature rise in 2012.

The thermal time constants of the TDE could also be derived from the data, Fig. 2, and these are about 4.5 hours for both dump blocks.

Repeated dumping of the full intensity beam was seen to push the temperature rise to about 20 K. Further analysis of these results was used to extrapolate to Run 2 and High Luminosity (HL)-LHC performance expectations – the main concern is the N_2 pressure, which may exceed the 1.3 bar limit and thus require an active gas handling system. The maximum delta T was ~5 K per 10^{14} protons, which for 6.5 TeV will increase to ~8 K per 10^{14} protons. We would expect about 27 K delta T for a full nominal intensity 25 ns beam, with maybe 55 K for repeated dumps corresponding to a delta P of 233 mbar, to around 1.45 bar. This already indicates that in Run 2 some N_2 may be vented in case of repeated dumps.

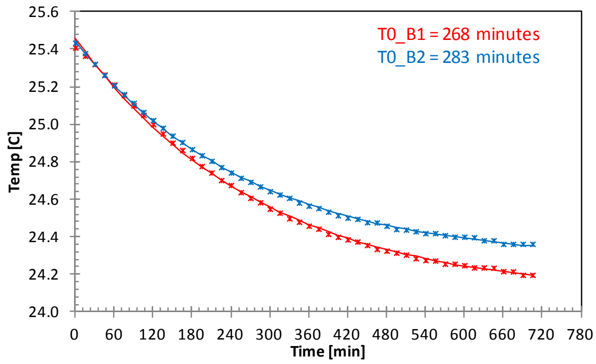

Figure 2: Thermal cool-down for TDE blocks.

CHANGES IN LS1

The changes which are foreseen for LS1 are listed below, with a discussion of their implications.

TCDQ Upgrade

The existing 6 m long graphite TCDQ (in 2 tanks) are being replaced by 9 m long CfC diluters (3 tanks), Fig. 3. The upgraded version [1] is designed to be robust to $2.5 \cdot 10^{11}$ p^+ per bunch with 2808 bunches at 25 ns spacing, corresponding to the HL-LHC maximum. Other improvements include the replacement of LVDTs with potentiometers, and a modification of the motorisation to increase the stroke and angle range to ±1.1 mrad.

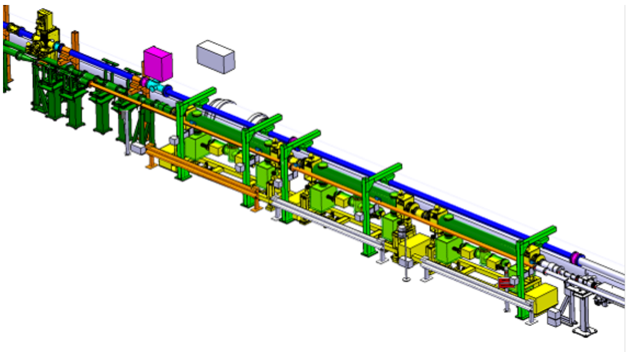

Figure 3: Layout of upgraded TCDQ with 3 tanks.

Additional TCLAs (not for LS1)

Space has been left in the lattice between the collimators TCDQM and TCSG for additional horizontal and vertical TCLA type absorbers. These are intended to reduce cleaning losses on Q4, and to reduce the peak load on Q4 after an asynchronous dump. The energy deposition in Q4 was simulated [2] with the new TCDQ and the HL-LHC beam parameters. The maximum energy density was 20 J/cm^3 in the Q4 coil, Fig. 4, and 40 J/cm^3 in the Q5 coil, leading to the conclusion that these additional absorbers are "not needed for the operation after LS1 from the magnet protection point of view". Their installation has therefore been postponed pending further study.

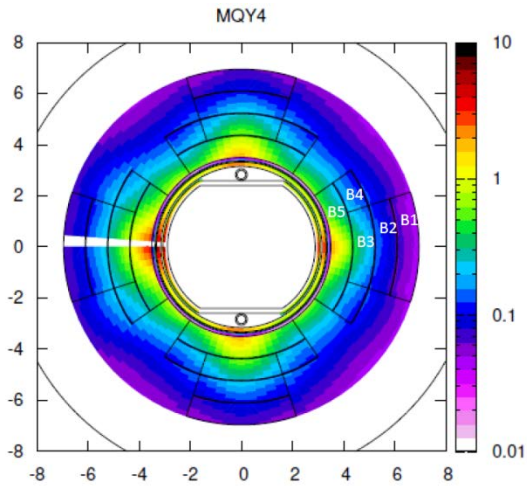

Figure 4: Energy deposition (in J/cm^3) in Q4 coil with new TCDQ.

TCSGP in IR6

New TCSGP (secondary collimators with button pickups in the jaws) will be installed in IR6L/R, replacing the existing TCSGs. The jaw BPMs will allow more accurate setting-up of the TCSG without touching the beam.

Presently a tolerance of 1.5 sigma is needed between TCSG and TCT collimators for the asynchronous dumps, which limits the minimum beta*, although the main contribution is orbit instability and not setting-up accuracy. It will be difficult to immediately 'use' the tolerance gained to improve the beta* reach as TCSGP and TCDQ would need to dynamically follow the orbit.

The present Software Interlock System (SIS) interlock on the beam position at the TCDQ can be moved to TCSGP to improve the accuracy. It should be investigated whether a hardware implementation could be possible to avoid any software or communication related issue.

The main gain from the TSCGP will be in setting up time and accuracy, and in interlock accuracy. As time is needed to gain experience with the new system, there are no immediate plans to have the collimator jaw positions dynamically follow the orbit, even though this would give the most benefit.

TCDQ in the BETS

A major change for the Beam Energy Tracking System (BETS), Fig. 5, is the addition of the TCDQ jaw positioning, to generate a dump via a hardware interlock when the jaw position is out of tolerance. The system will demand a synchronous dump if the position reading goes out of (an energy dependent) tolerance.

New electronics are needed to allow masking this input to the BETS when the Setup Beam Flag is TRUE, otherwise it is not possible to set up the TCDQ with low intensity beam. Alternatively, this can be achieved by connecting the BETS to the BIS, instead of directly to the Timing Synchronisation Unit (TSU). This option has already been suggested for the TDI.

The implementation details (electronics, fibres, …) remain to be worked out after the MPP workshop.

Interlock Beam Position Monitors

The interlock BPMs in IR6 (BPMS) were a frequent source of dump triggers – for good reasons. The system has a simple logic for dumping the beam, with N wrong counts in a window of M turns, where N includes also bunches with bad readings. There were many "correct" dumps when the beam was unstable, but the reading also suffered when the bunch intensity dropped below threshold.

Several interventions were made to adapt the attenuators to increase the dynamic range – in each case a beam measurement was needed to scrape beam and check the response. The single channel limits (N) were relaxed on a few occasions with ions.

The changes foreseen for LS1 are to improve the Post-Mortem diagnostics, to be able to trace the origin of the dump (bad bunch reading, position out tolerance, …) and to add this into the External Post Operational Check (XPOC) system. Improvements on the system to increase the dynamic range will also be tested. Another suggestion is to make a calibration every fill – at present this is only done when the Front-End Computer (FEC) is rebooted.

POSSIBLE AREAS TO IMPROVE AVAILABILITY AND/OR SAFETY

BPMS tolerances and settings

The BPMS trigger level is set to allow ±4 mm maximum orbit excursion at the septum protection TCDS and the septum MSD, to ensure a clean dump with low transverse losses. This was checked during the initial LBDS commissioning at injection, and indeed was found to be an acceptable range. The beam also needs to be extracted cleanly with only 14 of the 15 kickers MKD available – this was tested in 2010 commissioning, but not in combination with a 4 mm orbit offset as these failures are considered to be independent.

The BPMS thresholds are now set to about ±3.0 mm around the measured orbit, allowing ±1 mm for fast dynamic orbit changes plus the initial uncertainly on the BPMS reading.

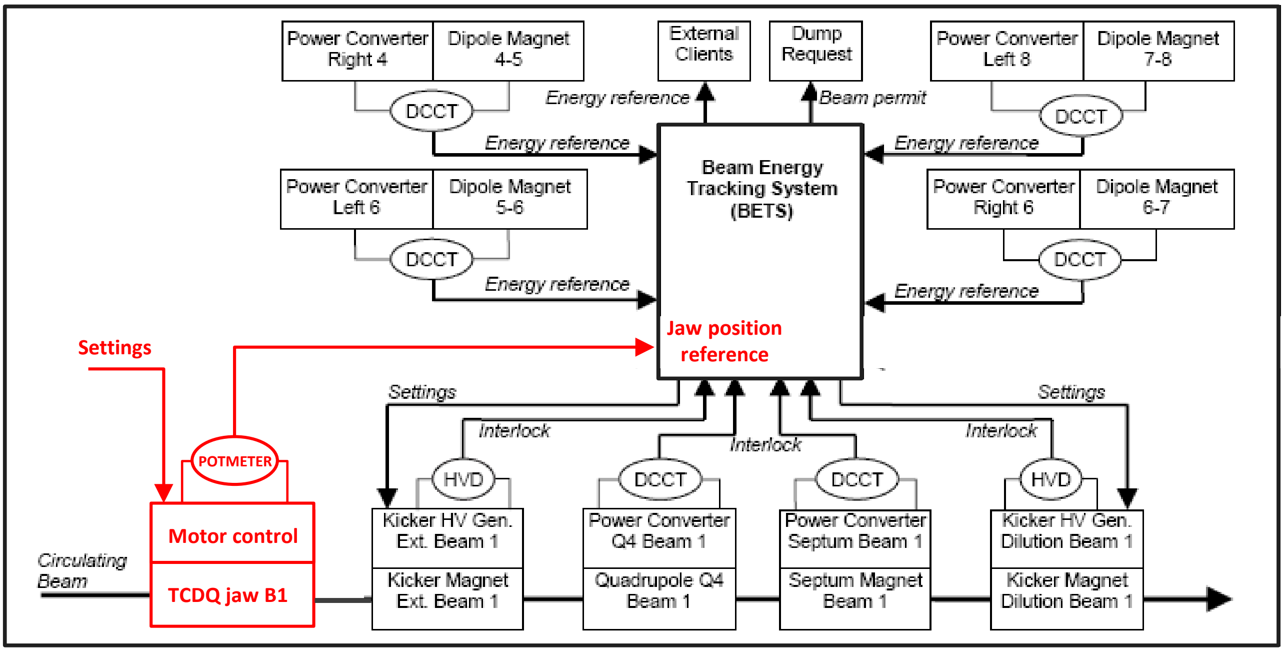

Figure 5: LBDS BETS showing the additional TCDQ functionality.

The question arises whether we still need the full ±1 mm for the orbit. Post-mortem data of positions at the BPMS at dump would help to decide.

Opening the thresholds to the maximum would give a larger margin for bad bunches, and assuming 2 µm emittance we might gain ±2 mm. But we would need to then 'interlock' on beam emittance (or rely on the losses at TCPs). Furthermore the TCDS protection of the MSD also depends on the maximum local orbit excursion [3]. Finally, the BPMS response is very non-linear, so that we would only gain a small fraction in dynamic range.

Improving the beam centring in BPMS or updating more frequently the threshold centre w.r.t. the measured orbit would both bring only marginal gains.

Overall, not much can be gained by changing the thresholds, and the best solution is to directly address the issue of the BPMS dynamic range.

MKD tolerances

As mentioned, the dump channel aperture was designed for ±4 mm orbit margin, assuming 3.75 µm emittance at 450 GeV, 0.27 mrad MKD total kick, and either 14 or 15 MKD firing. The aperture was validated under these conditions, including the missing MKD case.

Much effort has been made in stabilising the temperatures of the MKD switches (including a full Peltier cooling system) to reach the specified current stability of ±0.5 – 1.0% (depending on which point on the waveform is measured). This requires a very close control of actuators and sensors (power supplies, voltage dividers, …), but also brings additional operational issues, including either full 24h recalibration, or adjustments of calibration factors in the FEC after an equipment exchange.

Experience from Run 1 shows smaller emittance and a more stable orbit than foreseen in the LHC design. Also there has not been a dump with a missing MKD (yet).

The margin for the MKD/B current error could potentially be increased safely (e.g. by small reduction in BPMS thresholds), and we could conceivably use this margin to stop cooling the switches, and to stop fudging the FEC calibration factors when components are changed.

This would need wider IPOC and XPOC tolerances, and we would then be less sensitive to gradual degradations of switches/connections. The TE-ABT group equipment experts also prefer to keep the constant operating switch temperature, for high voltage reasons.

Overall it is not recommended to stop cooling, despite the need to keep the complex system running.

The question of how to deal with the calibration factors needs to be discussed in more detail – this is a compromise between minimising risky manual updates, and having nice tight thresholds for operational tolerances to spot degradation.

Abort gap monitoring and cleaning

Presently the CCC operators are using the Abort Gap Monitoring (AGM) from the Beam Synchrotron Radiation Abort-gab (BSRA) signal with a "wetware" [4] connection to the Beam Interlock System (BIS), i.e. via the LHC Announcer and the EiC, to launch the Abort Gap Cleaning (AGC) or to dump the beam.

The concept is working well (clean dumps, problems are spotted), but issues include the reliability of this approach (which is very likely SIL0, for example one must not mask/turn down the announcer, and the EiC must be within earshot); no backup system in case of BSRA issues (encountered in 2012 after Beam

Synchrotron Radiation Telescope (BSRT) failure with compensatory measures including periodic AGC); the dependence on BSRT steering.

Possible improvements include automatic calibration of AGM, to improve availability to a level where a software connection to AGC and/or BIS could be foreseen, and the development of a complementary abort gap population measurement, from diamond BLMs in the collimation region or/and from experiments.

The optimum overall approach and the BSRA HW upgrades still need definition – this should be followed up in a coordinated way, and specifications should be discussed and formulated.

For the cleaning, the negative impact on the luminosity remains to be understood and cured [5] – this would allow AGC to be ‘always on’, which would solve the issues of the AGM availability.

Finally, we need to quantify how important AGM/AGC is for safety – e.g. assumptions on the frequency of asynchronous dumps (in coincidence with non-empty abort gaps) which enter into the calculation of the TCT settings.

Dump protection validation

Presently asynchronous dump loss maps, Fig. 6, are made periodically and analysed ‘by hand’. The maps are normally acquired during commissioning, after configuration/collimator changes, and periodically when collimation loss maps are also acquired.

On the loss map measurement frequency, we should standardise when/which asynchronous loss maps are needed, before the run starts, and then stick to the plan.

There is always some beam in abort gap which gives measurable losses on TCDS/TCDQ. This opens the possibility to produce loss maps in collision, although without the 1.2 mm offset at the TCDQ. We should consider updating the XPOC module to check TCDQ/TCT loss ratios, and possible make trending analyses.

More sophisticated tools could also be conceived using Diamond detectors, although development is needed.

Operational procedures

Operational procedures were very complete for the LHC commissioning phase in 2008/9, as there was lots of time to prepare, but were less well defined for regular running, where it was clearly impossible to foresee all combinations of problems, faults and configurations.

The most important aspects are that a) potentially dangerous situations are recognised and communicated and b) that time is taken to discuss before allowing operation to proceed.

This paradigm requires open communication and the availability of experts. It also requires Machine Coordination and Management to take warnings seriously – it is not easy for a potentially junior colleague to insist that “we need to stop the machine while we think”, but time thinking is much better than exposing the machine to potential damage. The restricted Machine Protection Panel (rMPP) should continue as an ‘online’ reactive body, able to provide a consensus on possible issues and to support such warning – reinforcement of the present aging body is important!

Finally, a better definition is needed of the actions to take in terms of requalification for different types of equipment intervention (for example, power supply or switch exchange, protection device sensor exchange, …).

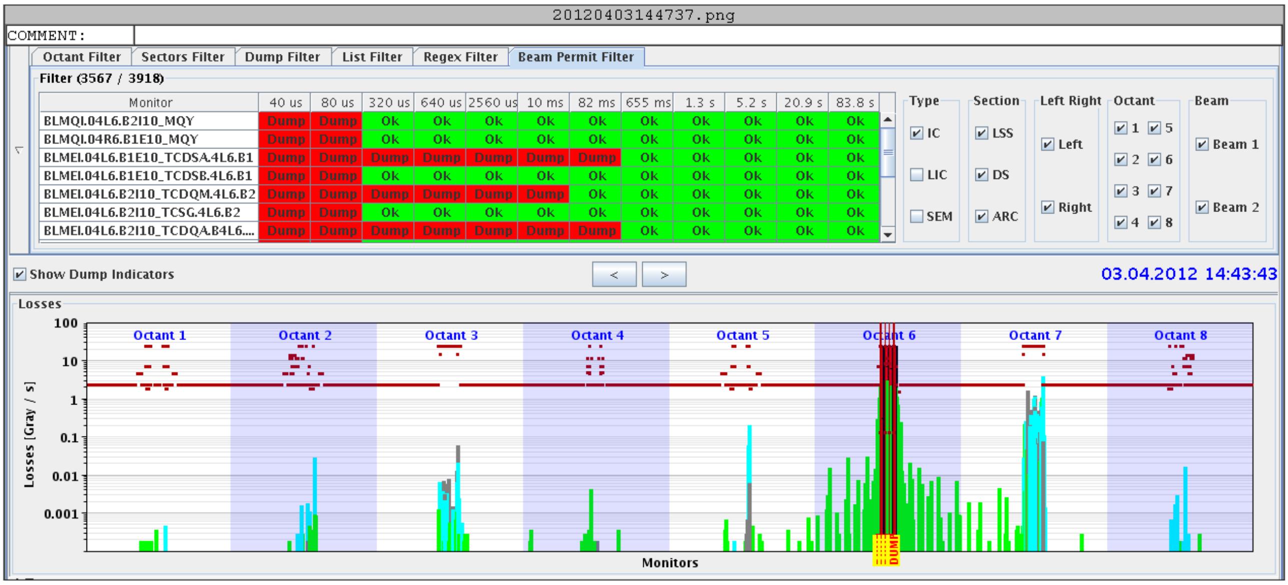

Figure 6: Asynchronous dump validation loss map.

CONCLUSIONS

LHC is still waiting for its first asynchronous dump with a full machine at high energy. However, we must continue to maintain, and even improve the associated protection. Changes to some systems connected to the LBDS will take place in LS1, designed to increase the robustness, safety or availability. These are the new TCDQ absorber, TCDQ input of the BETS, new TCSGP, improved AGM, improved BPMS, and the XPOC module for dump protection validation. Work is needed now on finalising specifications and requirements.

Associated changes in commissioning and validation procedures also need to be considered and documented – the forum for this is not evident – should it be the LHC-wide commissioning team, the MPP or the LHC Injection and Beam Dump (LIBD) team?

Relaxing the tolerances for the MKD current by removing temperature control or to ease recalibration needs could be possible, but may then mask onset of other issues and is not recommended.

SUMMARY OF ITEMS FOR FOLLOW-UP

- When and if TCLAs are needed in IP6;
- Maximum TCDQ-TCSGP6 retraction, and MP issues of orbit 'tracking' ;
- Connecting BETS to BIS, rather than TSU;
- BPMS dynamic range, procedures for threshold changes and calibration improvement;
- Relax some MKD waveform tolerances to gain simplicity in revalidation (but lose some trending 'trigger' ?);
- BSRA availability, and automatic triggering of cleaning and/or dump;
- Alternative abort gap monitoring methods;
- Abort gap cleaning transparency for luminosity;
- XPOC modules to review (asynchronous dump checks, abort gap population, TCDQ/TCSG retraction/setting, …);
- Review of procedures for revalidation after component exchange.

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LHC INJECTION SYSTEMS MODIFICATIONS IN LONG SHUTDOWN 1

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Abstract

Hardware changes of the injection and injection protection systems, foreseen in LS1, are presented. Proposals for improving the protection logic of the abort gap keeper, ensuring correct TDI and TCDI settings and its validation, avoiding SPS-LHC timing issues and the need for BLM 'sunglasses' after LS1 are discussed. Suggestions for safely steering the transfer line trajectories and improving the role of the Injection Quality Check (IQC) as an operational tool are presented.

MKI UPGRADES

Due to high voltage breakdown reasons, most of the presently installed injection kicker magnets MKI have 15 screen conductors to reduce the beam impedance, rather than the initially planned full complement of 24. For the upgrade after the Long Shutdown One (LS1) it is foreseen to equip all magnets with 24 screen conductors which shall reduce the beam induced heating by a factor of approximately 3-4. To achieve this, several modifications are being made to the beam screen. Some part of the metallization at the end of the ceramic tube will be replaced by a conducting cylinder which is spaced from the ceramic, Fig. 1. Preliminary test results indicate that this modification in-

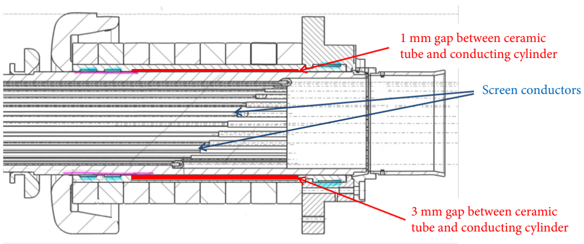

Figure 1: Upgrade of the MKI screen conductors.

creased the PFN voltage at which surface flashover occurs by at least 50%. The copper bypass tubes for the counter-rotating beam will be NEG-coated in order to suppress electron cloud build-up, Fig. 2. Increased tank emissivity shall lead to better thermal radiation of the heat generated in the ferrites. The vacuum system for the cold-warm transitions in the MKI areas shall be upgraded with NEG-coating of the copper insert, installation of new domes on both sides of the sector valves with a D400 NEG cartridge and 2 ion pumps. All Beam Position Screens (BTVSI) and Beam Position Timing modules (BPTX) will be NEG coated. For the MKI interconnects, the ion pump shall be exchanged to a version including a NEG cartridge, and the copper insert of the warm bellow module will be NEG coated. In order to reduce dust particles (UFOs) which can lead to beam losses and hence beam dumps, the ceramic tubes will be even better cleaned, as already performed on the MKI8D unit (installed during the technical stop TS3 in 2012) with promising results. There are ongoing stud-

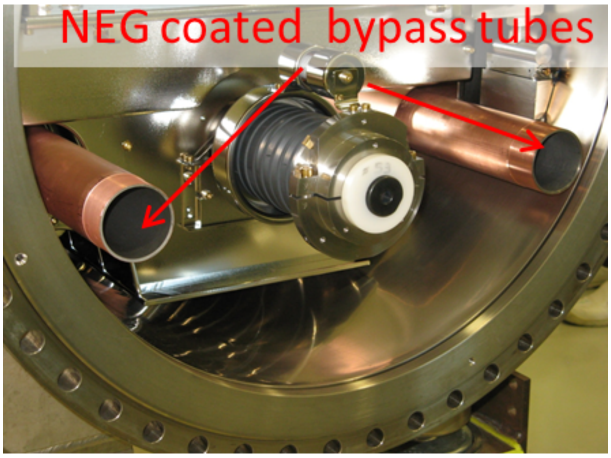

Figure 2: NEG coating of the MKI bypass tubes.

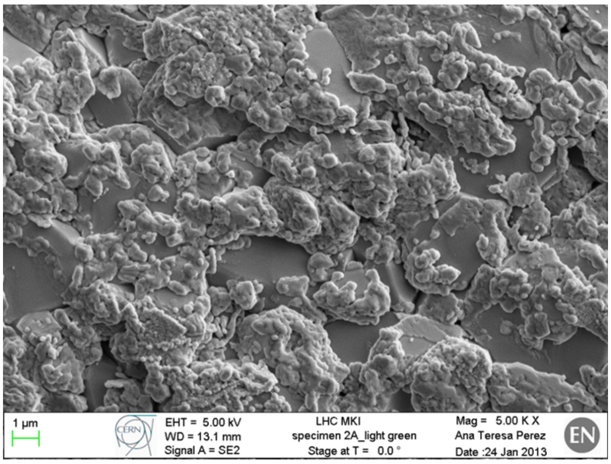

Figure 3: SEM analysis of the chromium oxide coating, courtesy of A. Perez.

ies on a Cr_2O_3 coating of the ceramic tube to further increase the flashover voltage and reduce the Secondary Electron Yield (SEY). Figure 3 shows the analysis of a test coating in the scanning electron microscope. One coated ceramic tube could possibly be installed during LS1 to obtain operational experience; the magnet could be exchanged in case of detrimental effects. Further studies include the effect of vacuum pressure on the surface flashover voltage and measurements of the beam coupling impedance with comparison to simulations.

TDI CONSOLIDATION

During LS1 both injection protection dumps (TDI), in point 2 and 8, will be removed and consolidated. The existing spare will be adapted as well and a second spare will be constructed with lower priority. The beam screen will be made out of reinforced stainless steel with copper coating and a new supporting frame, Figures 4 and 5. Its sliding systems will be improved. The central RF fingers will be replaced by a mechanical connection and the RF extremities will be bolted instead of electron beam welded. 16 more temperature sensors shall be added. The grease of the gearbox will be replaced by a coating to avoid the risk of torque increase due to radiation induced stiffening of the grease. Concerning the TDI coating, studies are ongoing on vacuum and impedance perfomance.

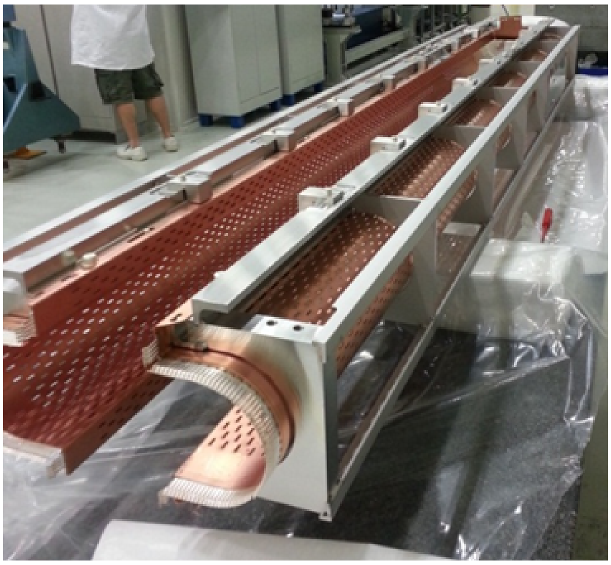

Figure 4: New reinforced TDI beam screen.

If the existing Ti coating can be removed, possibly a thin (1 μm) layer of Cu could be used with NEG coating to reduce the SEY. FLUKA simulations are ongoing to verify that copper does not sublimate in case of a grazing impact.

ABORT GAP KEEPER

Having the Abort Gap Keeper (AGK) not only connected to the MKI but also to the SPS extraction would avoid dumping the beam on the TDI in case of an inhibited MKI kick. However, this connection is impossible due to having different beam positions in the SPS with respect to the LHC. Improvements of the AGK will concern its monitoring; after each injection there shall be a measure of the delay between the end of the AGK and the trigger of the MKI and a measure of the delay between the trigger of the MKI and the beginning of the AGK. The sum of these two delays and the length of the abort gap should give the length of one turn.

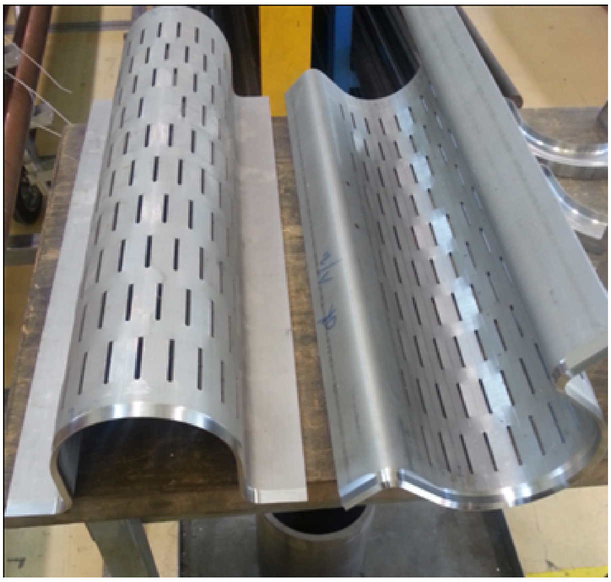

Figure 5: Prototype of new TDI beam screen.

INJECTION BETS CONNECTIONS

It is foreseen to interlock the current of the injection septum (MSI) with the Beam Energy Tracking system (BETS) applying a tolerance of a 1 σ beam oscillation. The BETS has to be connected to the injection Beam Interlock System (BIS). The injection BIS will stop the SPS extraction within a few microseconds which is acceptable compared to the expected timescale of MSI current changes. The interlock has to be maskable with the LHC Setup Beam Flag.

Also the TDI gap shall have a maskable BETS interlock with a ± 1 σ tolerance on the up- and downstream gaps. A reliable position monitoring is required in order not to compromise operational availability.

TCDI SETTINGS AND VALIDATION

After changing to the Q20 optics in the SPS and deploying a new optics also for the transfer lines TI-2 and TI-8 in September 2012 the gaps of the injection protection collimators (TCDI) were not adapted. To avoid such a failure in the future, a concept similar to the SIS β^* check as for the LHC ring is suggested. A TCDI Gap Control Parameter (TGCP) needs to be defined for the transfer line optics, just as β^* is defined for the squeeze functions. This will be used by the SIS-SMP-MTG chain to check the gaps in the TCDI, just as β^* is used for the gap control of the tertiary collimators (TCTs). For each transfer line optics the quadrupole currents have to be stored and associated with a unique TGCP value. The SIS reads reference settings, compares to published extraction currents for every cycle and in case the settings are within tolerance the value is published, otherwise zero is published.

On the TCDI side the TGCP value is read and checked if within limits.

The TCDI settings, TGCP values and optics are stored in a single beam process; if the beam process is wrong, the SIS check will fail.

Certain features need to be added to the existing infrastructure, like reference settings for the transfer line quadrupoles and TGCP values, TGCP limits for the TCDIs and additional SIS code.

TEMPORARY INHIBIT OF INJECTION BLMS

During RUN-1 of the LHC, beam loss induced showers from transfer line collimators were impacting the sensitive LHC ring Beam Loss Monitors (BLM) from the outside in the areas where the transfer line tunnel is adjacent to the ring. These losses trigger beam dumps already for low injected beam intensities. However, they are considered avoidable and therefore they unnecessarily limit the availability of the machine. Amongst other mitigations several options were studied to temporarily inhibit injection BLMs [1]. The option to be implemented in the BLM regrouping campaign during LS1 includes creating two crates (P2 and P8) dedicated to BLMs with the option to inhibit their interlock signal during injection (the option of blinding out dedicated BLMs is also known as the BLM 'sunglass' system).

In the 2012 run Little Ionization Chambers (LIC) were successfully tested with higher gas pressure [2]. LICs have a higher saturation level than standard ionization chambers and thus allow higher thresholds which could be used to avoid dumps at injection. However, these thresholds will be higher not only at injection but during the full time when the beam energy is at 450 GeV. A combination of standard ionization chambers with RC-filters and LICs will be selected to be connected to the dedicated crates. In selecting the monitors a trade-off has to be found between response time due to the RC-filters, noise limits in setting thresholds for different energies, and the reliability of the new monitors.

Monitor locations where injection losses could become critical for machine availability are described in detail in [3]. The aim is to have a factor 5 margin between maximum operational losses and the dump threshold. The data analysed is based on the 2011 run where the TCDIs had a 4.5 σ half-gap. Due to the increased number of avoidable dumps the TCDIs were opened during the run to 5 σ half-gap. For the restart after LS1 it is envisaged to come back to the original 4.5 σ opening.

It is foreseen to start the machine without blinding out these two crates, having the possibility to add the blind-out during the run in case avoidable dumps reduce the machine availability. Details on the implementation of the blind-out are described in [4].

OPERATIONAL CHANGES

A reproducible trajectory in the SPS to LHC transfer lines is mandatory to reduce injection losses which could lead to avoidable beam dumps as described in the section above. The main cause of shot-to-shot variations is the power converter ripple of the SPS extraction septum [5]. Work is ongoing to improve the stability of these power converters.

In order to facilitate a meaningful calculation of the trajectory corrections, the SPS extraction kicker timing has to be set up such that the trajectory of intermediate intensity beam (6 or 12 bunches) represents the behaviour of the full batch. The same kicker timing will be deployed for intermediate intensities and the full batch. In case corrections calculated on the full batch trajectory are sent to the hardware it is unavoidable to test the new trajectory with intermediate intensities. The same strategy must be applied for corrections to the ring orbit.

The Injection Quality Check (IQC) application is foreseen to become a more rigorous control for safety at injection. Possibly only one reset of injection oscillations per filling will be allowed and enforced by software. In terms of injection loss alarms, there shall be a warning level at 10% and an inhibit of further injections at 50% of the dump threshold.

SUMMARY

During LS1 modifications will be made to hardware and software of injection related systems. The upgrades of the MKI aim to reduce: high-voltage breakdowns of the screen, the beam induced impedance, the electron cloud build-up, and the UFO rate. The upgrades also aim to provide an improved cooling.

Both TDIs will be taken out and consolidated. Also the spare unit will be upgraded and another spare be constructed. The second spare might not be ready for the start-up.

Improved monitoring will be implemented for the AGK delays with respect to the MKI trigger.

The MSI current and the TDI gap will be connected to the injection BETS with a maskable BIS input to allow for the TDI setup.

TCDI settings will be validated by SIS using a β^* like check.

Two additional crates will be dedicated to the injection BLMs with the possibility of implementing their blind-out during the run to reduce the number of avoidable beam dumps at injection.

The transfer line trajectory stability is being improved by reducing the SPS MSE power converter ripple. Resetting injection oscillations and injection losses shall be limited by the IQC.

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CHANGES IN SPS INTERLOCKING

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Abstract

This document presents the current status of interlocking and machine protection at the SPS. The machine protection incidents that occurred in the period 2006-2013 are presented together with their mitigation. Future needs of the SPS in terms of machine protection will be discussed.

SPS MACHINE PROTECTION

All information relevant for the SPS Machine Protection System, which has been accumulated since the restart of the machine after the 2005 shutdown year, is concentrated on a dedicated WEB site [1]. This site stores information on configuration, MP tests, incidents as well as reports relevant for SPS MP and for SPS extraction MP.

The SPS MPS is not as tight as LHC MPS, but the risk is also much reduced since the maximum stored energy is ≈ 2 MJ per beam as compared to 360 MJ in the LHC. But even a high intensity SPS beam can cause damage, as will be shown in some examples below. The SPS ring has a very basic protection by Beam Loss Monitors (BLMs) and Beam Position Monitors (BPMs, only for horizontal plane). The SPS MP is relying heavily on the Software Interlock System (SIS), which is now widely used across CERN accelerators but that was originally designed for the SPS [2]. Multi-cycling poses a real challenge to the MPS, both to the Beam Interlock Systems (BIS) and to the SIS, due to cycle dependent settings, vastly different beam characteristics, gains (e.g. for the BLMs), etc.

The period 2006-2013 saw 5 MP incidents. Two incidents resulted in equipment damage (an electrostatic separator ZS and a dipole magnet MBB), the others were near misses.

In the short term (up to Long Shutdown Two / LS2) no major improvements are foreseen to the SPS ring MPS. The next major upgrade consists of new BLM electronics (with multiple integration windows as for the LHC system, but with fewer integration windows). The planned improvement of the BPM interlock system (new design, protection in both planes) did not work out due to reliability issues.

ZS incident

In the fall of 2007 the septum wires of one electrostatic septum (ZS1) were cut by slow extracted beam with an intensity of 9×10^{12} protons. Due to a high level controls problem, the slow extraction to the North Area through the LSS2 extraction channel was *de facto* transformed into a fast-slow extraction. As a consequence the entire beam was swept over the extraction septum in a few milliseconds. Due to the large losses that are associated with the slow extraction, the thresholds of the BLM in the extraction area that can react in a few µs were set too high to catch this failure. The BLMs downstream of the extraction area on the other hand were too slow. The following actions were put in place:

- Control system protections (limitations on some current) were put in place in the LSA controls database,
- One BLM channel at the entrance to TT20 that could have caught the failure was moved to the crate with the fast electronics. As a consequence its reaction time was lowered from 20 ms to some µs.

Details on this incident can be found in Reference [3].

CNGS - 2008

In June 2008 a problem in the Master Timing Generator (MTG) led to a ‘freeze’ of the timing in the SPS. As a consequence the CNGS beam that had just been injected was neither extracted nor correctly dumped at the end of the SPS cycle. The beam was still inside the ring when the magnetic fields started to ramp down. The beam became vertically unstable and impacted inside dipole MBB.12530. The vacuum chamber was ripped open by the beam of 3×10^{13} protons. Again the BLM reaction was not fast enough (20 ms reaction time of the ring BLMs), and the fast beam position interlock only protects the horizontal plane. As an action three protection layers were added against such timing failures. More details on the incident and the actions can be found in Reference [4].

SPS BIS

The SPS was the first CERN machine where the new ring BIS designed for the LHC was installed and used operationally [5]. The phasing out of the old SPS interlock system happened between 2006 and 2007. In 2007 the conversion had been completed. This also concerns the new JAVA-based SIS [2]. Both BIS and SIS have been operated without any problems since they were introduced.

Contrary to the LHC case where the BIS loop is manually rearmed together with the LHC Beam Dumping System (LBDS), the SPS BIS rearms automatically as soon as all inputs to the Beam Interlock Controllers (BIC) have returned to the ‘TRUE’ (OK) state. This strategy was necessary because the SPS is a relatively fast cycling machine where a manual reset cannot be done after each dump. To ensure that the next cycle/beam can be executed, the BIS re-arms automatically. The SPS SIS takes care of stopping beams where for example beam losses or large beam excursion are observed in consecutive cycle executions.

It was decided that the Safe Beam Flag (SBF) would not be used for the SPS ring BIS: the SBF state is forced to TRUE (safe beam state) for all the BICs. There is an accepted risk of masking certain interlocks with unsafe beams (in general beams are only unsafe at the flat top). Note that the SBF is used for the fast extractions.

SPS Emergency Dump

Currently the SPS emergency dump installed in BA1 is not synchronized to the beam (gap). All emergency dumps are always asynchronous which is acceptable in the LHC. It is foreseen to install a Trigger Synchronization Unit (TSU, similar to the LHC) during LS1. This will, however, introduce a dump trigger delay of up to 1 turn, which is acceptable for the SPS.

The SPS injection kicker MKP is directly inhibited by the SPS dump system (and not across the BIS loop like in the LHC), which creates a slight complication. In addition the MKP is directly connected to the power converter (PC) of the dipole corrector MDSH.119 (kick of 2 - 4.5 mrad), which is pulsed when the MKP is inhibited. This dipole corrector sends the injected beam cleanly into the injection dump.

SPS EXTRACTION INTERLOCK SYSTEM

The following extraction interlocks systems were installed in the SPS in 2012/2013 (see Fig. 1):

- in LSS4 : CNGS and LHC,
- in LSS6 : LHC and HiRadMat.

The following changes are expected sometimes after LS1 (new extractions to be confirmed, both would arrive around 2016):

- in LSS4 : CNGS is replaced by AWAKE (a proton plasma acceleration experiment) [6],
- in LSS2 : a new fast extraction using the MKP for a possible new neutrino facility SBLNF [7].

There is no extraction interlock system for the slow extraction in LSS2: this is due to the fact that it is difficult to interlock a slow extraction as there is no element like an extraction kicker that can be inhibited. The only possible MP action for the slow extracted beam is to dump the beam in the ring.

In the LSS where different beam types are extracted, the selection of the correct extractions BICs (and therefore interlocks) is based on energy flags (generated by the SPS Safe Machine Parameters (SMP) system, with windows of ± 2.5 GeV):

- CNGS : 400 GeV,
- LHC : 450 GeV,
- HiRadMat : 440 GeV.

This concept turned out to be simple and very reliable. New energy windows will have to be defined for:

- AWAKE: ≈ 400-430 GeV,
- SBLNF: ≈ 100 GeV.

The fast pulsing interlock signals (based on failsafe logic, with pulse widths of a few ms for PCs) required special applications to help OP crews to digest the rapidly varying BIS states. A top to bottom approach was used to present an “OP view” of the interlocks starting from the BIS output that is sent to the extraction kickers. This software presents the summary for a selection of cycles or dynamic destinations for the last 15 cycles, giving a simple and rapid overview over the situation. Special extensions where configured for each SPS beam/line combination. It is planned to merge this GUI back into main BIS application after LS1.

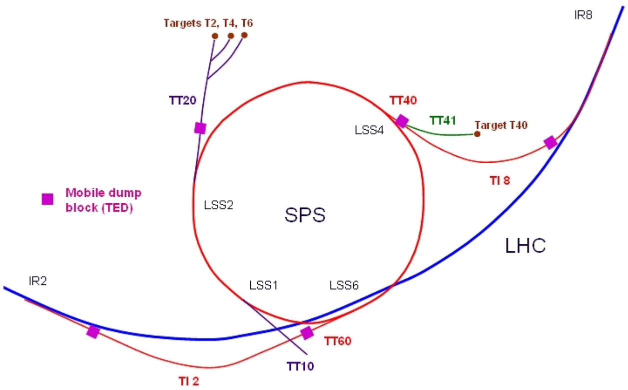

Figure 1: Overview of the SPS extractions and transfer lines.

Between 2006 and 2011 the overall reliability and safety of the extraction interlock system was excellent. In particular the interlocking of over 200 PCs in the LHC and CNGS transfer lines was crucial to ensure safe operation, and it worked extremely well! The Machine Critical Settings (MCS) system was used to protect the PC interlock settings (references, tolerances and configuration). Only the interlock reference of the smaller orbit corrector dipoles could be changed by the shift crews. All other settings required Expert or even Guru level authorization.

CNGS

The CNGS beam has been operated with high intensity from 2008 to 2012, with 1.5 MJ beams extracted routinely with high efficiency and without causing any damage, see Fig. 2. A total of 10 million extractions were triggered with beam and 1.8×10^{20} protons were delivered on the T40 target. This corresponds to a total energy of 7.5 PJ. The RMS beam stability on target was in the range of 40 – 100 μm (for an interlock limit at 500 μm). The position drifts at the T40 target were very small, see Fig. 3, and steering was only required every few days, or whenever the power on the target was changed. The beam losses in the TT41 transfer line were unmeasurable with BCTs, a very low residual activation at the level of some μSv/h can, however, be measured just above the natural background in the locations with high dispersion.

Things that did not work so well

The interlock on the beam position at extraction (interlocking of the maximum orbit excursion of the extraction bump, Fig. 4) is the only interlock that clearly “under performed”. The performance was just acceptable for CNGS beams (200 MHz RF structure beam), but it was not so good for LHC beams (limits had to be opened to 2 – 3 mm). This issue is due to the fact that the interlock was relying on position acquisitions by the MOPOS orbit system, which has known issues with LHC beams. A new system based on electronics using logarithmic amplifiers was tested, but the result is not conclusive.

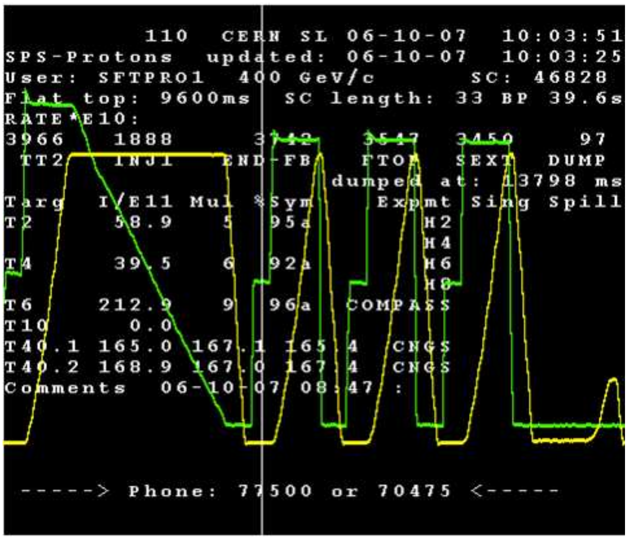

Figure 2: SPS super-cycle with the standard 3 CNGS cycles.

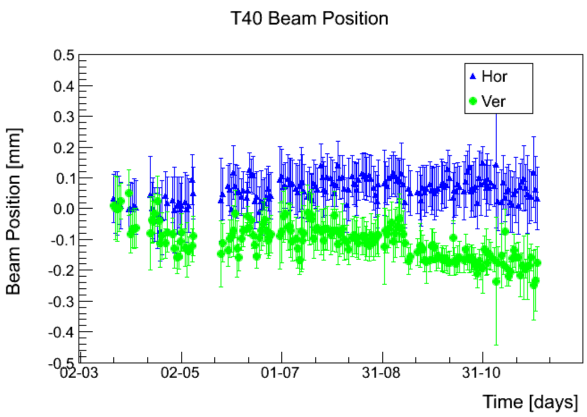

Figure 3: Beam position at the T40 target along a complete run.

SIS

The Software Interlock System was initially designed for the SPS to replace an existing system that could not cope with LSA, JAVA, FESA and other new features of the control system that were introduced in 2005/2006 [2]. The SIS plays a crucial role for SPS protection, and it is structured by geographical zone (transfer lines, extractions). In the SPS SIS acts always on 2 levels:

- It sets/clears an SIS interlock in a selected BIC module (ring or extraction).
- It set/clears an inhibit at the level of the MTG to stop beam production at the source according to the beam DESTINATION.

The SPS is a difficult environment for the SIS due to the multi-cycling. The relation between interlocks and beams (*Should this interlock be evaluated in the current cycle?*) is currently done through the USER names. This schema must be revised in the future since LSA cycles names should replace the standard user names in the future. This modification will require a clean and strict naming convention for LSA cycles. The management of reference settings is rather simple as long as the reference applies to a beam type (LHC, FT, CNGS), but it is currently very difficult to manage settings at the level of each individual cycle. One will have to evaluate the need for more flexibility and weight this against the increased complexity.

The SPS SIS acts normally at the end of the cycle when all data has been collected. There is one exception for the economy management, but in that case it is not an MP function of the SIS. The MTG is typically reacting in the following super-cycle. The interlock matrix between SIS and MTG destinations (dynamic or static) will have to be updated to account for AWAKE and SBNLF.

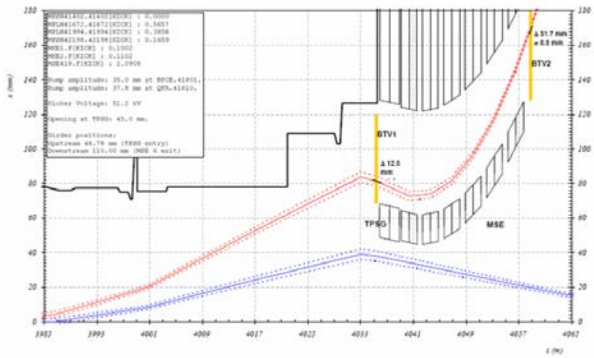

Figure 4: Layout of the fast extraction in LSS4. The amplitude of the extraction bump in the SPS is interlocked using the MOPOS system.

TIMING

A complex timing logic has been implemented to digest LHC beam requests and to ensure a coherent state of the machines. The diagnostics of timing problems for LHC beams remains rather tricky and more work on OP diagnostics is welcome. In 2012 a rather innocent looking change of injection timings in the SPS led to a problem where the LHC was expecting beam in one ring, and the SPS ended up sending the beam into the other ring. The wrong LHC injection kicker pulsed, and the beam was dumped on the injection protection collimator TDI. The problem has been understood and will be fixed, backed probably by some SIS interlocks.

OTHER CHANGES

The SPS Beam Quality Measurement system (BQM, longitudinal plane) will be based on new and better hardware. The core functionality will remain unchanged, but improvements will be introduced in the form of better diagnostics for satellites (number, location).

The existing tail scraper system will remain in place in BA1. A review has recommended to keep the current system [8]. Some actions have been defined for the existing scrapper. A system based on a fixed absorber and a magnetic bump (in LSS6) will be kept as "hot design spare".

The mixed p-Pb operation came with the issue of ensuring that the species are send to the correct ring since RF settings (frequency) are very different. The LHC SIS instance provides the protection by matching the TT10 PC settings (17 GeV for Pb, 20 GeV for proton) with the LHC ring frequency. One could consider more robust options in the future.

During LS1 the front-end control of the SPS power converters will be migrated from ROCS to FCG. The ramp cards that drive the actual converters remain in place. To first order this modification should be transparent, even if the state machine of the PCs will change. The PC interlocks (FEI) with MCS protection will have to be re-implemented. At the same time one should consider extensions of the PC surveillance to the SPS ring and to the fixed target operation of TT20.

A strong horizontal orbit corrector in LSS1 (MDHD.118) may be used to correct the orbit for the Q20 optics. This will require a hardware interlock, most likely an extension of the FEI concept.

Crab Cavities

It is planned to install prototype crab-cavities (CCs) in LSS4 (the only place with cryogenics in the SPS) during the 2015/2016 shutdown, see Fig. 5. CCs will be installed on a Y-chamber that can be moved in/out of the beam axis. Due to the limited aperture of only 84 mm and the fact that the CCs are inside the extraction bump for LSS4, it is unlikely that CCs are compatible with regular LHC beam operation.

New hardware interlocks (and probably a number of SIS interlocks) will have to be added:

- An extraction interlock in LSS4 if the CC is in beam (if not compatible LHC).
- A ring beam interlock if the Y-chamber is at an intermediate position.
- Interlocks on the CC state, etc.

Figure 5: Layout of the crab-cavities in LSS4.

SBNLF

A project for a new neutrino beam from the SPS (North Area, short baseline) is currently under study. The beam energy will be just above 100 GeV (to avoid the forbidden energy region of the SPS emergency dump: 37 – 100 GeV). The beam will be a fixed target type 200 MHz beam, with CNGS-like intensities of 4.8×10^{13} protons. The stored beam energy is ≈ 750 kJ, and the beam will be extracted in 2 batches. This stored energy value is close to the SBF limit when scaled to 100 GeV. The fast extraction will be non-local using the SPS injection kicker MKP as fast pulsing element, with orbit oscillations along the arc from LSS1 to LSS2 where the beam passes the MST and MSE septa magnets, see Fig. 6. SBNLF will not operate at the same time as standard fixed target beams (the electrostatic septa must be retracted to a safe position for SBLNF).

SBNLF requires a new extraction interlock system. The well understood concepts with slave-master BICs will be re-used, and the interlock system will cover 3 SPS BAs (BA1, BA2 and BA3) as shown in Fig. 7. The orbit correctors in sextants 1 and 2, as well as the main quadrupole (tune) and sextupole PCs (both located in BA3) must be interlocked at the level of the PC current. The use of an Extraction Permit Loop that would cover all the SPS rings and be connected to all extractions is being considered. Such a loop would also allow to close some gaps for LHC beam interlocking.

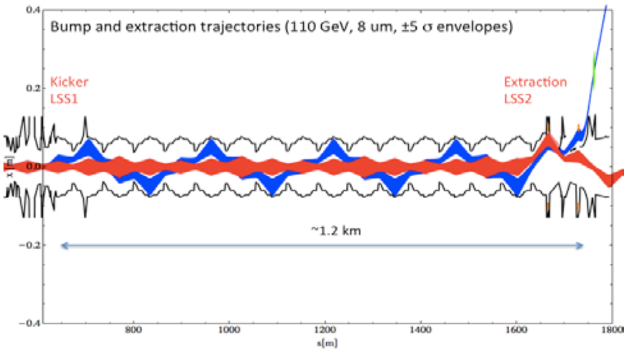

Figure 6: Extracted beam trajectory from LSS1 to LSS2 for SBNLF (in blue).

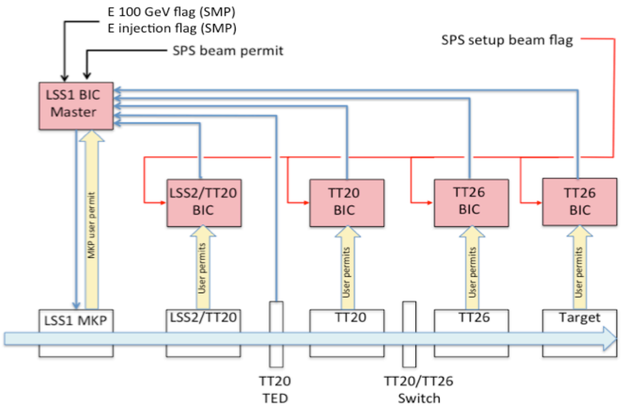

Figure 7: Schematic layout of the BICs for SBNLF.

SUMMARY

There are no major changes on the SPS side for MP during LS1, but a number of smaller items and a rather major change of the PC controls.

- The SPS emergency dump will be equipped with a TSU to avoid the asynchronous emergency dumps.

- The PC interlocks to be re-implemented and extended under the FCG umbrella.
- The SIS interlocks and diagnostics must be revised. The triggering will have to be adapted to cope with the change from FESA users to LSA cycle names.
- The SPS MPS will have to be prepared for new extractions that are expected to appear in 2016.
  - SBNLF in LSS2 will require many of changes and new hardware,
  - AWAKE in LSS4 will re-use the CNGS MPS/BIC infrastructure.

One question that remains open concerns the BPM interlocks for the ring and the extractions. This will have to be followed up with the BI group.

And a final point: a new Mister / Misses MP is needed for the SPS, since the author’s term ended ‘naturally’ at the end of 2011. This role is very important in such a flexible and complex machine. A large test campaign will have to be organized after LS1, and daily issues must be followed up.

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HARDWARE CHANGES IN THE LHC BLM SYSTEM DURING LS1

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Abstract

The strategy for machine protection and quench prevention of the LHC is heavily relying on the Beam Loss Monitoring (BLM) system. In this paper, a review of the operational experience with the system of the last running period, i.e. 2012, will be given together with the areas where required improvements were identified. Further, the foreseen changes during the first Long Shutdown (LS1) concerning the equipment, the code of the reprogrammable devices, the supporting applications, as well as the commissioning steps, will also be summarised.

INTRODUCTION

The strategy for machine protection and quench prevention of the LHC is heavily relying on the Beam Loss Monitoring (BLM) system. Each turn, several thousands of data values are recorded and processed in order to decide if the particle beams are permitted to continue circulating or whether their safe extraction should to be triggered. The decision involves a proper analysis of the loss pattern in time and a comparison with predefined threshold levels that need to be chosen dynamically depending on the energy of the circulating beam. The processing of the acquired data has to be performed in real-time and thus requires dedicated hardware to meet the demanding time and processing capacity requirements.

The BLM system is sub-divided geographically into the tunnel and the surface building installations. The tunnel installation consists of close to 4000 detectors, placed at various locations around the ring, and radiation tolerant electronics for acquiring, digitising, and transmitting the data. The electronics installed in the surface buildings receive the data via 2 km long redundant optical data links. This system conditions, analyses and stores the data, and when needed issues warnings and abort triggers. For this purpose, the system has connections to the Beam Interlock, the Logging, the Beam Energy Tracking, the Collimation, the External Post-Operation Checks (XPOC), the Injection Quality Check (IQC) and the Post-Mortem systems.

2012 PERFORMANCE SUMMARY

From the initial deployment of the system onwards, continuous maintenance, either preventive or to repair failures, has been performed. In addition, new features have been introduced regularly to match new requests or in responds to new observations. An overview of the major performance improvements made during the 2012 operational period and a summary of the fault statistics is presented in the following chapters.

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Automatic and Fast Collimator BBA

Maximum beam cleaning efficiency and machine protection are provided when the collimator jaws are properly adjusted at well-defined distances from the circulating beams. Therefore, each of the LHC collimator needs to be verified and aligned regularly. A jaw is aligned with respect to a pilot beam when,while moving in steps towards the beam, a sharp increase followed by a slow exponential decrease appears in the signal read out from a BLM detector located downstream of the collimator.

As of January 2012, a new BLM data buffer was implemented for an automatic collimator Beam Based Alignment (BBA) system. Beam loss values, integrated over 82 ms, are transmitted in User Datagram Protocol (UDP) packets to a new collimation client at a rate of 12.5 Hz (was 1 Hz). Fig. 1 shows examples of the standard and the new dedicated data delivered to the Collimation system.

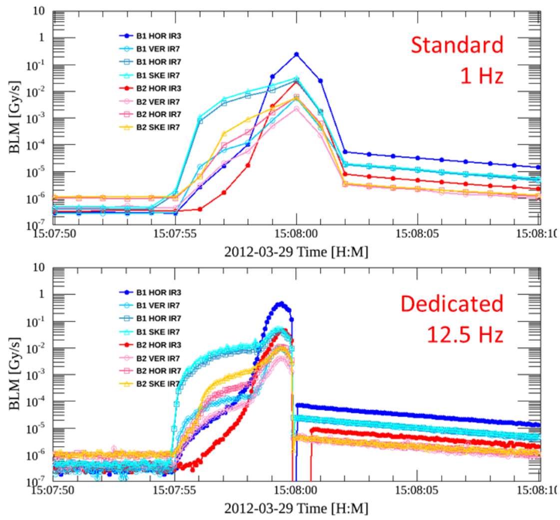

Figure 1: Comparison of the standard and dedicated data delivered to the Collimation system [courtesy of B. Salvachua and G. Valentino].

This development has resulted in a significant reduction of the beam time required to setup the collimation hierarchy [1]. In addition, it was found to be an excellent diagnostic tool that has been used successfully to study the time evolution of the losses in IR7 and IR3 during loss maps measurements as well as to study the halo diffusion and population.

UFO Buster

The *Unidentified Falling Objects* (UFOs) are potentially a major luminosity limitation for nominal LHC operation [2]. In order to provide better and more detailed observation capabilities and to assist in the understanding of their mechanism and damage capabilities, a new dedicated buffer has been introduced in the processing Field Programmable Gate Array (FPGA).

This new dedicated *Capture* buffer allows a selection of the recording length and the data type, of either 40 μs integral with 512 samples per channel or 80 μs integral with 4396 samples per channel. This implementation was complement by a new client process referred to as *UFO buster*. This process detects abnormal losses in real time, triggers a timing event to freeze the FPGA buffer and initiates the collection of the high frequency data from the capture buffer.

LIC Detector Development

During 2012 a vigorous program was followed to develop and characterise the Low-pressure Ionisation Chamber (LIC) detector. The aim was to provide a new type of detector to cover the sensitivity region between the standard Ionisation Chamber (IC) and the Secondary Emission Monitor (SEM) detectors. The first candidate installation of this new type will be part of the strategy for the mitigation of the injection losses.

As soon as the first batch of prototypes were produced, a set of these detectors were installed to observe losses from both LHC beams in parallel to the well-known IC detectors. In this way, it was possible to study their behaviour and reliability, to verify the calculated conversion factor to Gy/s and to validate the calculated thresholds.

Many issues were revealed with the first batch. This triggered several changes in the production and design parameters and additional detectors were installed during the following *Technical Stops*. For more information see also [3].

Fault Analysis for Preventive Maintenance

The LHC BLM system is quite large, distributed and holds significant complexity. The necessity to provide a "fail-safe" system, which at the same time is able to achieve the required availability, required an elaborate design with a large number of additional processes that evaluate, collect and monitor the state of the system in real-time.

A typical example is the data reception process. This process is hosted at the entry stage of the processing FPGA and has been implemented in a way that, besides ensuring a correct reception, also provides a highly capable detection of erroneous transmissions.

Fig. 2 shows a report example of the automated analysis of the communication links, which provides statistics on the Cyclic Redundancy Check (CRC) and the loss of packets for each of the optical links, as well as the loss of synchronisation between the redundant links.

It becomes obvious that the recording and relaying of such information can be used to identify weaknesses or failing components and will provide a history to understand

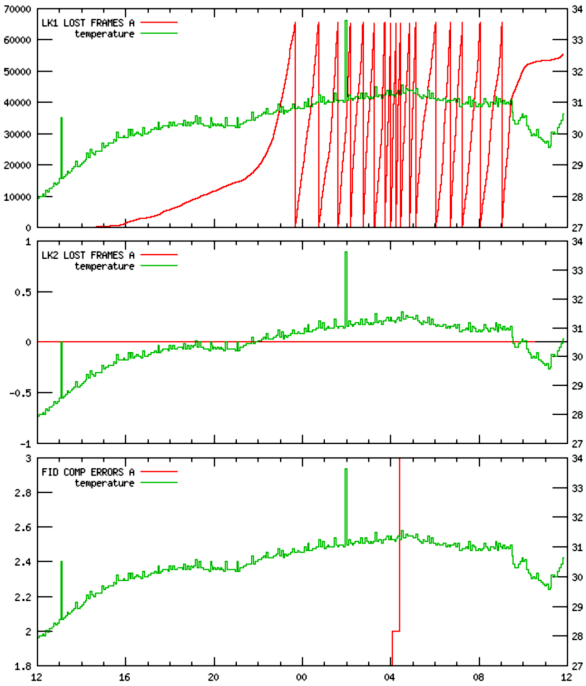

Figure 2: Example of the data transfer error reporting function for different types of checks presented over a period of 24 h (where red: check error count, green: temperature).

the events that forced an unintentional beam extraction request. Thus, a further effort has been made to use the gathered information in order to extract and provide the most relevant diagnostics. Several daily automatic analysis tasks are executed to asses the system's performance and state. In addition to the diagnostics of the communication links mentioned above there is an assessment of the detector response, the noise on the channels, the power supplies stability and many more.

Through the year these diagnostics provided input to the work planning of the technical stops and as a result several cards, detectors and cabling have been exchanged in the shadow of the interventions before their failure would affect the LHC availability. It should be further noted that the analysis tasks have shown that the errors in the optical link communications have increased significantly. This is also reflected in the unavailability of the system due to these errors. Their impact, as well as the additional mitigation measures under development, will be discussed in more detail below.

Issue and Task Tracking

For the recording of the observed incidents and the actions performed, as well as the planning and management of the tasks over the technical stops, the JIRA project tracker [4], hosted at BE/CO servers, has been extensively used during 2012.

In summary, for the LHC BLM system more than 100 operational incidents were recorded and an equal amount of

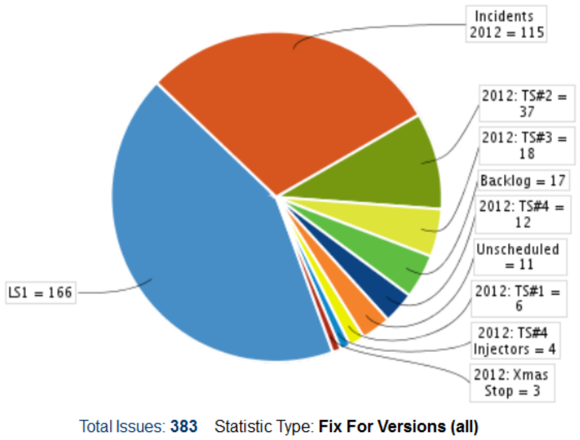

Figure 3: All issues and tasks recorded between March 2012 and March 2013 for the system classified by type.

tasks for the planning of the five *Technical Stops*. The tool is now also used for the planning of the first *Long Shutdown* (LS1). Fig. 3 shows a summary of all recorded issues and tasks classified by type.

Recorded System Faults

The system performed as expected and issued abort requests in all cases that the measurements exceeded the predefined thresholds.

Nevertheless, internal system faults have caused an additional 31 unplanned beam abort requests in the operational period between March 2012 and March 2013. The majority, i.e. 20 requests, can be accounted to the communication links between the tunnel and the surface installations. The system utilises around 1600 optical links and the processing electronics have been designed to demand a beam abort in case no data was received during a 40 μs cycle for any of the channels declared as part of the MPS.

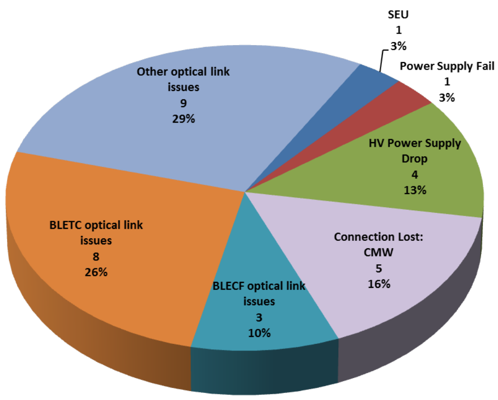

Figure 4: LHC BLM System fault events causing a beam interlock between March 2012 and March 2013.

Table 1: LHC BLM System fault events causing a beam interlock between March 2012 and March 2013.

Failure Type	**Occurrences**	**Percentage**
SEU (surface)	1	3%
VME Power Supply	1	3%
HV Power Supply Drop	4	13%
Connection Lost: CMW	5	16%
BLECF optical link	3	10%
BLETC optical link	8	26%
Other optical link	9	29%
Total	31	

Table 1 and Fig. 4 summarise the faults that caused a beam abort request.

Furthermore, looking at the complete list of faults that occurred over the same period, including those that happened during the preparation of the machine, there are several types of error (see Table 2 and Fig. 5) that had an impact on the machine availability and required an intervention.

From this view of system faults it is clear that, apart from the communication link errors, two other groups of errors show a significant contribution. Those were generated by the *Sanity Checks* and the *Controls MiddleWare (CMW)*.

The Sanity Checks [5] are systematically executed at the preparation of the machine before beam injection. Their purpose is to ensure the integrity of each beam loss detector and its cabling. To achieve this, predefined limits have been set and if any channel is found to be outside these limits, the test will fail and the beam permit will not be released. To resolve such a situation an expert intervention is necessary. During the 2012 operation, 23% of the fault events were generated by SEM and LIC detectors failing to pass the Sanity Check. These detectors, even though they are not part of the MPS, delayed unnecessarily the start of the physics program.

Table 2: All LHC BLM System fault events recorded between March 2012 and March 2013.

Failure Type	**Occurrences**	**Percentage**
SEU (surface)	3	4%
VME Power Supply	1	1%
HV Power Supply Drop	4	6%
Connection Lost: CMW	6	9%
Sanity Error: CMW	9	13%
Sanity Error: IC	3	4%
Sanity Error: LIC	6	9%
Sanity Error: SEM	10	14%
BLECF optical link	7	10%
BLETC optical link	11	16%
Other optical link	10	14%
Total	70	

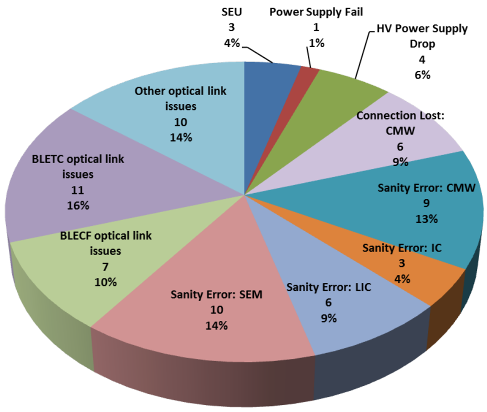

Figure 5: All LHC BLM System fault events recorded between March 2012 and March 2013.

The second group is related to CMW, whose purpose is to provide a common software communication infrastructure for the CERN accelerator controls. Partial or complete loss of CMW connection of the Front End Computers (FEC) with the control systems was responsible for 22% of the fault events recorded for the LHC BLM system.

Actions have been planned for LS1 to mitigate each of these types of system fault. These actions will be presented with the rest of the LS1 tasks in the following chapters.

HARDWARE CHANGES DURING LS1

Several modifications are planned for the system components, which are distributed in all tunnel sectors, as well as in several surface buildings. The actions in the LHC tunnel come with additional complexity due to the restricted access.

Dismantling and Relocation of Detectors

One of the main tasks during LS1 is the repair of the 1695 LHC magnet interconnects. The BLM system has detectors in the vicinity of the interconnects and in order to allow the intervention, all detectors and cable trays located in the arcs and dispersion suppressor regions have to be dismantled, i.e. approximately 2500 detectors in the arcs and of the order of 1000 detectors ($\approx$70%) in LSS regions.

Furthermore, detailed studies of the UFO characteristics showed that, in order to detect UFO events originating in the main dipoles, very low thresholds are required. Due to the positioning of all BLMs close to the quadrupoles, these thresholds would be very close to, or even below the system noise level. For this reason, it was decided to relocate 816 detectors in more appropriate positions that cover these blind spots, such to improve the overall protection (see also [6] for more information). To realise this task, a design and production of a new type of detector support, of signal and power cable extensions, as well as the cable trays to host them will be needed.

Modifications in the Tunnel Installation

In the context of improving all noisy cable installations to provide better measurements, 40 multi-wire cables will be exchanged with cables of NES18 type. It is expected that this modification will reduce the externally induced noise of 240 detector channels and hense should allow to set more accurately the beam abort threshold levels.

To improve the stability of the acquisition crates, and to improve features that at the moment only work partially, 360 backplanes will be exchanged with a newly developed printed circuit board. Furthermore, 309 signal distribution boxes will be modified to allow a remote reset of each sector independently. Finally, the connection to the WorldFIP bus will be adapted to provide remote access to each individual card. These features will be extremely useful to reduce the number of tunnel accesses required for some type of interventions. To establish the WorldFIP connections in the Straight Sections additional electronics will be needed.

The High Voltage distribution network, used for biasing the detectors, have shown some weakness in areas with very high losses and caused some unintentional beam interlock events. For this reason, approximately 20 High Voltage distribution boxes in the identified areas will be modified. A prototype of a modified box, containing additional suppressor diodes and resistors, have been installed and tested in LHC towards the end of the operational period. It was found that the change was sufficient to mitigate the effect. Fig. 6 shows a picture of the position of the box in the tunnel. See also [7].

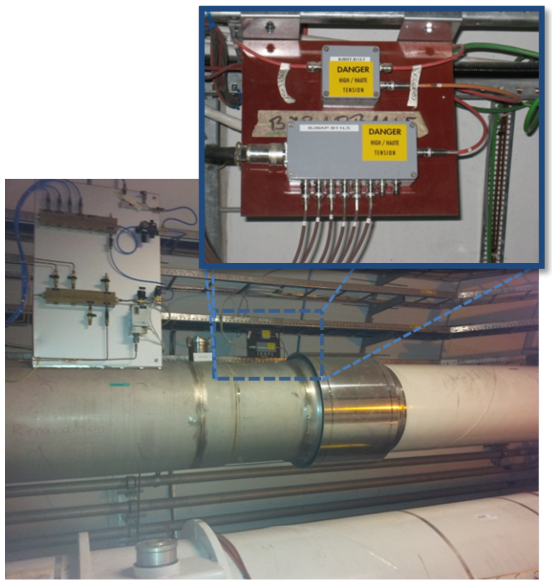

Figure 6: Picture of the High Voltage divider boxes.

Modifications in the Acquisition Electronics

To mitigate issues observed with the acquisition modules (BLECF) a modification has been planned of all of the approximately 750 printed circuit boards. The modification will change the limit for the HV level drop detection flag. The detection level will be changed from 1370 V to 950 V to allow longer high steady-state losses (see also [7]).

The original level was chosen to simply confirm that the HV power supply is connected and active. Later this HV status information was included into the Software Interlock System. However, for this application, the level was too restrictive and has given several false alarms, some of them also leading to beam interlocks.

Modifications in the Surface Installation

The surface installations are currently hosted in racks that are cooled by a forced vertical air flow traversing the different modules. This cooling provided poor temperature stability and the variation in the day cycle ranged from 5 to 10 °C. During the summer months, the modules often operated above 40 °C. This has been of particular concern, not only for the life expectancy of the electronics but also because of the impact of sudden temperature and humidity changes on the optical links.

For these reasons it was decided to replace all the racks with temperature regulated racks. Obviously the replacement will imply the removal and disconnection of the complete installation, i.e. crates, cables, and power supplies, but also the very tedious and delicate reconnection of all the fibre patchcords afterwards, i.e. approximately 1600 optical links connecting the distribution racks with the crates.

On the rear side of the rack, there are several daisy chain cables to control of the HV power supplies, to distribute the beam energy value received by the CISV module and to propagate the beam interlock signals to the CIBU modules. In the current configuration, these cables have to be disconnected each time before replacing a VME power supply. A new configuration is foreseen that will allow faster and more reliable interventions.

Finally, two new processing crates will be added to the 25 crates already employed, to optionally implement a *Dump-Inhibit during Injection* in the future. The additional racks, which are needed to host those crates, will be placed in the support buildings for Point 2 and 8. These two crates will be dedicated to host the detectors that are problematic during beam injection. This new configuration will allow, if needed, to deploy modified firmware on the installed modules that will filter beam interlock requests generated by this subset of detectors during beam injection (see also [8] and [9] for more information).

Modifications in the Processing Electronics

The BLM system employs approximately 400 processing modules hosted in VME crates. All of them will need to be maintained in order to provide the required availability during the next operational period.

The maintenance will include repair or replacement of approximately 20% of the mezzanines modules and cleaning all 1600 optical adaptor and connector pairs. There has been a significant accumulation of dust on the connectors after five year following their installation. Fig. 7 shows an example of the dust accumulation on the optical connectors.

Further analysis of the recorded optical link statistics over the last operational period showed that 80% of the optical link errors and failures occurred in the upper redundant connection pair, i.e. links 1 and 2. This is a clear indication of a weakness in the design. To avoid a possible a common mode failure, link 2 and 3 will be swapped on all modules, i.e. the physical connection in hardware and in the logical mapping in firmware. In this way, we aim to improve the availability by removing the commonality and by sharing the weak links between the two pairs arriving in the Processing and Threshold Comparator (BLETC) module.

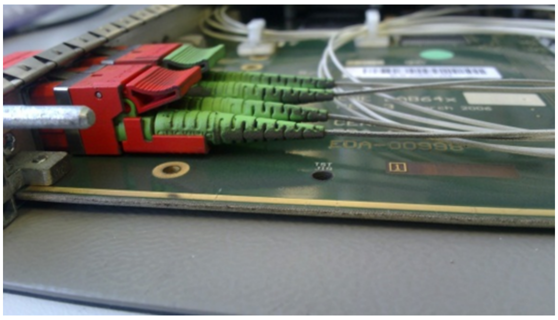

Figure 7: Example of dust accumulation on the optical link connectors.

FIRMWARE CHANGES DURING LS1

The system employs three FPGA devices. Two of them are reprogrammable and their code will be modified during LS1.

Modification of the BLETC firmware

The FPGA firmware modifications of the BLETC module aim to improve and extend the data delivered to external systems. The core protection mechanisms will remain unchanged since no weaknesses have been identified from the initial release.

One of the most important and mandatory modifications is to add compatibility with the new Linux based CPUs. This change implies the implementation of a new VMEbus core that provides the Multiplexed Block Transfer (MBLT) access mode. Moreover, to profit from the additional increase of speed, a new memory map optimized for block transfers is also necessary.

The buffers for the *Post-Mortem* system and *UFO Buster* will be increased in size to provide 43,690 samples per channel, profiting from the additional new CPU's performance.

An effort will be made to resolve an issue with the *XPOC* buffers by decoupling the buffers (i.e. the measurement trigger and recording) of the two circulating beams. Although it is not clear whether this separation is possible, mainly due to the limited resources in the FPGA, it would eliminate a major cause for the extraction analysis failures when the LHC operates with the two beam dump loops unlinked.

Finally, one last feature to be investigated is a further increase of the Collimation BBA measurement data rate, which is now at 12.5 Hz. A continuous stream of high frequency measurement data will be very useful, not only for the Collimation system but in many more cases of machine studies.

Modification of the BLECS firmware

The Combiner and Survey (BLECS) module receives all the beam interlock requests from the BLETC modules in the crate. The module is also responsible for distributing the beam energy within the crates. Finally, when there is no beam in the accelerator, the module initiates all the test procedures and checks the results. The firmware modifications will focus on improving the survey features that had a significant impact on the system availability, on making the beam energy value reception and internal distribution more resilient with respect to external errors, and on upgrading the communication link with the FEC.

To improve the regular automatic system checks, modifications are planned to limit the level of the internally injected input current offset. This additional current is a self protection mechanism against unintentional blockage of the current-to-frequency converter circuit by radiation, but has been seen to be activated erroneously after some checks. A timeout will be added to the test duration, to avoid deadlocks caused by e.g. CMW communication errors. Especially for the improvement of the Connectivity Check, these additional modifications will allow to increase the range of the input values and the allowed threshold limits. This will benefit mainly the SEM and LIC detectors by reducing the false positives of the Sanity Check.

The impact of proton losses on the magnets depends on the loss duration and on the beam energy. For this, the processing electronics applies abort thresholds that depend on the beam energy, which is distributed by the control system. During operation, the received energy value has shown a couple of times abnormalities such as very quick changes. Those erroneous values were propagated to the processing modules where the logic chose the wrong threshold values with respect to the real beam energy circulating in the machine. Due to the short duration of these glitches, and the way the used energy and threshold values are logged, it was not possible to reconstruct afterwards the sequence of events using the information in the database. Thus, the modification of the code will aim to improve the energy value reception and the logging of the fast changes such that all the energy values received and propagated to the BLETC modules are logged in the database.

Compatibility with the new Linux based CPUs will need to be added, which, as for the BLETC's tasks, implies a new VMEbus core with MBLT access mode and a memory map that is optimized for block transfers.

Finally, the firmware will be adapted in the light of a possible inclusion of the *Dump-Inhibit during Injection* feature.

APPLICATION CHANGES DURING LS1

The applications that support the configuration and that provide an operational view of the system are maintained and used by several sections and groups. Here we only present an improvement wish list.

The *Internal Parameters* application provides an interface to commit all the system parameters in the LSA database. In order to reduce erroneous entries from user actions, changes like automatically filling the serial numbers when a card is exchanged, or to step increase the connectivity check limits, could be added.

The *System Status* application could give a global overview and, when faults occur, display the system error cause. This will be beneficial to both the machine operators and system experts.

The *Monitor Factor* application could be improved by additional features like a viewer to show the history of changes, allowing to compare two points in time, and to roll back selected changes. All these modifications will contribute to a good overview of the system state after modification of the settings, especially those done temporary for MD studies or MPS checks.

Finally, a *System Management* application should be developed that a) will allow the generation of new monitors and their parameters in the database, b) will have the ability to load the settings to the electronics, and c) can initiate or abort system checks. Each of these actions already exists individually though generic applications, e.g. generation, trim and drive applications. However, these applications provide too many options not needed for the specific system, increasing the complexity and the probability for user errors.

COMMISSIONING AFTER LS1

Due to the large number of modifications and the reinstallation of the complete system, a commissioning effort equal to the effort made during the LHC start-up will be required. All optical connections will need to be checked, the serial numbers must be updated in the database, the behaviour of each individual module will be measured, and finally new Connectivity check limits have to be calculated.

Since the majority of the detectors will have been disconnected and reconnected, with some of them even relocated, verification of the complete chain will be necessary by inducing a signal in each of the detectors with a radiation source.

Finally, similar to every start-up, the complete MPS check-list will need to be revalidated.

SUMMARY

The majority of the system components will be completely removed, transported to the laboratories for refurbishment and later re-installed. All system modules will be modified and undergo maintenance with the aim to reduce failures and errors. All optical link patchcords will be redone after the replacement of the racks. The power network for the supply of the detectors will get additional components to improve the stability. The Sanity checks will be modified to provide less false positives.

A second set of changes will aim to improve the remote control of the cards and crates, the data collection and distribution for external systems and will improve ability to maintain the installation in an as good as new state.

Finally, a complete recommission will be necessary including a verification with a radiation source and complemented with all actions of the complete MPS checklist.

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BEAM LOSSES AND THRESHOLDS

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Abstract

The motivation for the original BLM locations and the arguments for their rearrangement during LS1 in order to protect against UFO losses are explained here. The results of several quench tests, their extrapolation to 7 TeV and the implications on the BLM thresholds are discussed. Special emphasis is put in the UFO timescale test, where a quench of an MQ magnet was achieved in 10 ms, reaching BLM signals over five times larger than the estimated quench level. During the quench test with the collimation system, a power loss of 1MW was achieved at the primary collimator in IR7 without the generation of a magnet quench in the dispersion suppressor. Signals five times higher than the estimated quench level were reached in the BLMs. Finally, the procedures for BLM threshold management as well as a more reliable and maintainable approach for the threshold calculation and deployment are described here.

BLM DETECTOR LOCATION AND UFO INDUCED RE-LOCATION

The BLM system in the LHC arcs is equipped with three Ionization Chambers (IC) located 1 m, 3.5m and 5m downstream of the interconnection between the Main Bending magnet (MB) and Main Quadrupole (MQ). In the following, we will refer to this detectors as BLM1, BLM2 and BLM3 respectively. The MQs were selected as the most likely loss location due to the larger beam size at this point and in agreement with the result of tracking simulations with dedicated aperture models [1]. The installation of three BLMs per beam was established in order to maximize the detection of beam losses originated at different positions within the MQ. Moreover, the presence of multiple BLM minimizes the uncertainties on the estimation of energy deposition in the magnetic coils based on BLM signals. Finally, the location of ICs on both left and right sides outside of the vacuum chambers allows for a determination of the beam causing the observed losses.

Before the start of the 2011 run, several extra ICs were installed within the LHC arc cell 19R3. This cell was chosen as it observed larger occurrence of UFO-like beam losses. Comparing the BLM data with dedicated simulations [2] it was possible to show that UFO-like losses are generated in MB magnets as well as MQs. Therefore, the BLM system in its current configuration does not protect against potential quenches generated by UFO losses in MB magnets. Various re-distributions of the monitors have been discussed, all of them based on the relocation of BLM2 to another position within the arc cell. Two proposals consisted of moving BLM2 to either a few centimeters downstream of the MB.A-MB.B (configuration BLM N2) or the MB.B-MB.C (configuration BLM N3) interconnection.

A summary of the simulated BLM signals [3] in configurations BLM N2 and BLM N3 for various UFO location can be found in Table 1. In particular, the numbers show the expected BLM signal normalized to the estimated signal at BLM1. In the final BLM relocation proposal, it is foreseen to move BLM2 to the MB.A-MB.B interconnection (configuration BLM N1). A schematic view of the current BLM configuration in the ARCs as well as the three poposed BLM relocations is presented in Figure 1. The detector will be centered with respect to the two beams. By doing the same with BLM2 of the opposite beam, this option ensures the protection against beam losses originated anywhere along the arc cell. Dedicated simulations to estimate the expected BLM signals and energy deposition in the coil are necessary to determine of the dump thresholds. Note that with this approach, the displaced BLMs will get dedicated thresholds while all other thresholds will remain identical.

Table 1: Signal gain factor for two BLM relocations and three UFO scenarios..

UFO location	BLM N2	BLM N3
MB.A end	80	13
MB.B beginning	–	50
MB B end	–	7

QUENCH TEST RESULTS AND CONSEQUENCES ON BLM THRESHOLDS

At the end of the 2013 run, dedicated beam time was allocated for experiments that probe the quench level of different magnets at various time scales. This section focuses on the preliminary results of these tests as well as on the consequences for the beam dump thresholds.

Millisecond scale quench test

A three corrector orbit bump combined with a MKQ kick and a sign flip (i.e anti damping mode) transverse damper (ADT) excitation was used to generate losses in the horizontal plane at the main quadrupole Q12L6. In this experiment, using a proton energy of 4 TeV, the beam losses reached a total duration of the order of 10 milliseconds before the magnet quenched.

A summary of the experiment is given in Figure 2. The signal observed at the BLM protecting Q12L6 (green line) rises up to values of 10 Gy/s and it has fully decayed within

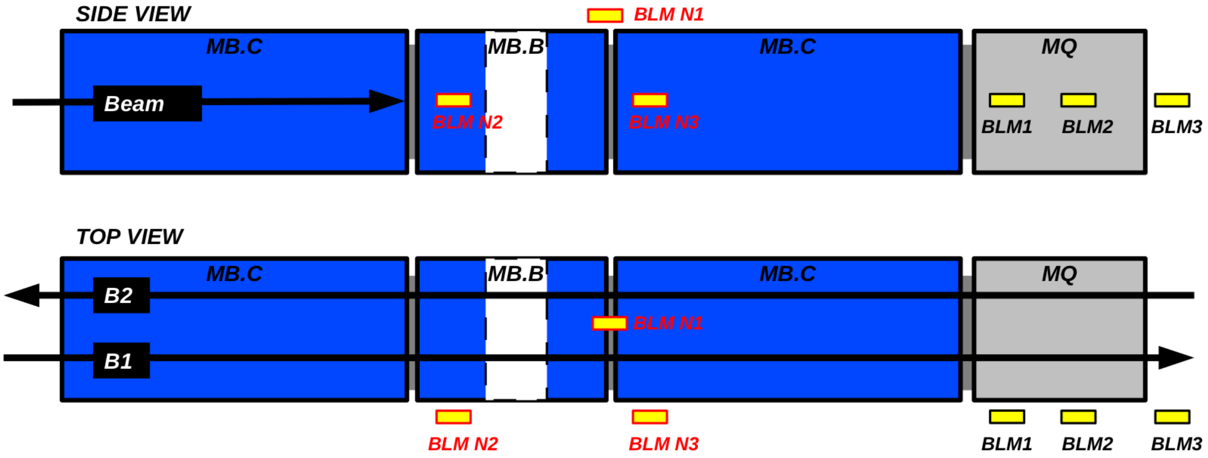

Figure 1: Side and top view of the current and various proposed BLM layouts in the ARC.

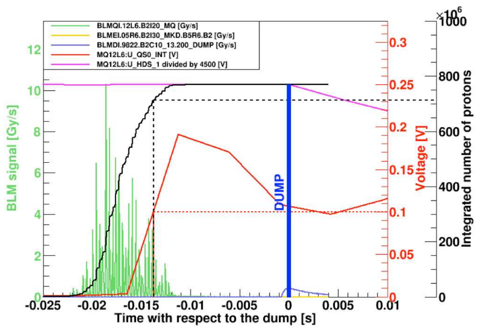

Figure 2: Measurements of BLM signals, voltage drops and number of lost protons during the quench test.

Table 2: BLM signals and ratio to estimated signal at quench in six integration windows.

Δt	S_{BLM} **(Gy/s)**	S/Q
40μs	10.28	2.8
80μs	7.61	2.3
320μs	2.31	1.2
640μs	1.99	2.1
2.56ms	1.46	6.1
10.2ms	0.73	12.0

15 ms. The quench, as defined by a 100 mV change in the coil voltage, occurred after 10 milliseconds equivalent to $7.1 \cdot 10^8$ lost protons. The total integrated number of lost protons reached $7.7 \cdot 10^8$. The signals observed in the IC compared to the signals expected at the quench (from simulation at different loss scenarios) are shown in Table 2. The largest difference was observed in the 10 ms integration window, where the signal exceeded the estimated quench level by a factor 12. However, the quench onset threshold for which no return from starting quench is expected, was reached before. For shorter time scales, the quench estimation were exceeded from a factor ranging from 1.2 to 6.1. With this results, it is clear that the BLM thresholds in the millisecond scale are largely overestimated and they can be safely increased. This modification will affect all the BLMs protecting cryogenic magnets around the machine.

Collimation Quench test. Performance reach

This test was performed by using relaxed collimation settings and an ADT excitation to produce beam losses at a primary collimator with a duration of 10 s [4]. The goal was to determine if losses leaking to the cold elements Q8/Q9 could produce a magnet quench. For beam losses of the order of 1 MW, the signals in the most limiting BLMs (Q8) exceeded the estimated quench level by a factor 5.2 (in the 5.2 s integration window) without the observation of a magnet quench. This is attributed to the different loss scenario considered for the estimation of the current quench level. In the scenario probed during this collimation quench test, the ICs are expected to receive a larger contribution from showers produced in upstream elements. Moreover, the energy deposition in the coils, as well as the relation between BLM signals and energy in the coil, are expected to be considerably different. Hence, dedicated simulations are required in order to study the possibility of increasing the dump thresholds at these specific locations in the dispersion suppressor.

Other tests

One experiment to probe the quench level with transient losses was performed. The test consisted on directing a single bunch with intensities on the order of $6 \cdot 10^{10}$ p onto a closed injection protection collimator (TCLIB) and observing the BLM signals in the ICs downstream. The electric current in magnet Q6 was increased in steps to study the dependency of the quench level as a function of the magnet current. A quench was achieved for a current of 2000 A, corresponding to a proton energy of 4.5 TeV. The signals at the BLMs protecting Q6 were in saturation; the readings from monitors in elements further downstream are still under investigations. Once again, the probed loss scenario is very different from the one used to set the BLM thresholds. Therefore, dedicated simulations are being conducted [5] to estimate the expected energy depositions in the coil and BLM signal for this type of beam losses. The outcome of this test may lead to an increase of the BLM thresholds in the shortest integration windows for monitors protecting specific cold elements in the injection region.

Finally, a second experiment explored the quench levels under continuous irradiation at 4 TeV. A rather constant loss rate over 20 s was achieved via an ADT excitation, which allowed to study the quench margin in a quasi-steady state. The observed signal at the quench was in agreement with observations performed in 2010. Hence, no threshold changes are indicated by this measurement.

Energy extrapolations

The results of the various test need to be extrapolated in order to determine the dump thresholds over the full energy range. Different approaches will be followed for different integration times, namely:

- The steady state quench level determined with direct impact of protons follows the prediction of the model of Note 44 [6]. A good agreement was found between measurements performed at 4 TeV and previous measurements at 450 GeV and 3.5 TeV. Hence, it is assumed that the current extrapolations will also apply to 7 TeV.

- A quench at the millisecond scale was exclusively performed for 4 TeV proton beam, hence energy extrapolation will be based on simulations. From the experience collected today, it is clear that the model of Note 44 fails to describe the quench levels at this time scale. Therefore, the QP3 code [7], which shows a better agreement, is expected to be used for estimation of quench levels at different energies.

- For the transient losses, two inputs will be taken into account in the extrapolation of the measured quench levels: The results obtained in the test at Q6 will be further studied, considering the differences in the probed loss scenario with respect to failure induced loss scenario. The experiment to study UFO-like losses, which showed large spikes signals in the 40 μs integration window of up to 10 Gy/s without the observation of a quench.

In all cases, comparisons of the quench levels as estimated by the QP3 code and the Note 44 model will be performed.

PAST, PRESENT AND FUTURE OF THRESHOLD HANDLING

The dump thresholds of the BLM system can be independently set, for each one of the 4000 detectors, in the form of a 12x32 master table that accounts for the 12 BLM integration windows and the 32 LHC energy levels. To allow correction of possible uncertainties, some extra flexibility in tuning the dump thresholds is provided through a table multiplier. This so-called Monitor Factor (MF) is an extra independent parameter for each BLM and is enforced to be lower than 1. Therefore, over 1.5 million critical parameters need to be calculated, stored and sent to the appropriate processing modules for the system to function. To minimize the risk of introducing errors during manipulations, the BLM team has defined specific procedures to be followed when a threshold modification is required [8]. Several test are executed both during the processing of BLM thresholds and after the thresholds have been sent to the electronics. But some of the potential errors are intrinsic to the calculation process.

The original threshold calculation code was based on a set of C++ classes using ROOT functions [9] to evaluate the dump thresholds based on several inputs. One script, producing a threshold table, was created for each BLM family, defined as a group of BLMs with the same master table. In the script, the C++ classes were configured with information from the required inputs: energy deposition in the coil, quench levels, BLM signal estimation, etc, and their functionality allowed to compute the threshold table with simple operations. Additional consistency checks were applied to ensure the expected behaviour of the quench levels as a function of energy and loss duration. Furthermore, multiple corrections were applied in order to account for several observations: no quench on UFO losses, margin for injection losses, margin for luminosity losses, effect of RC filters in the readout electronics, etc. The script/family approach provided flexibility but required the editing of source code for every threshold modification with the corresponding risk of human error. Moreover, the book-keeping of the scripts and tables (as well as the inputs necessary in the calculation) for each of the near 200 families had become difficult to manually handle. The tests and verifications requested by the threshold procedure during the modification process were performed by running standalone software that compares two tables of 12x32 numbers.

The current threshold calculation program tries to minimize the amount of source code editing and restricts the number of operations that can be executed on the threshold table. It includes two new classes: One implements all the corrections that had been used in the calculation of the BLM thresholds. The second handles the configuration of the original threshold calculation and the additional corrections that may be requested via CARD files (configuration files with a very simple syntax). In this case the full code is compiled and the executable program takes as input a CARD file. With this approach, no source code editing was required for the computation of new thresholds during the 2012-13 run. However, this still requires the book-keeping of one CARD/table per BLM family to be manually handled. The various test and verifications are still executed in stand alone programs.

The latest proposal for threshold calculation [10] aims to keep the flexibility and reliability of the current calculation and includes the functionality to perform the required test during the calculation process. Moreover, functionality will be provided for a safe and automatic book-keeping in order to maintain the different thresholds, as well as the inputs for their calculation. With this approach an appreciable performance improvement of the threshold deployment procedure can be expected, as some of the verification steps will be integrated into the designed tool. The proposed system is based on the migration from C++ standalone threshold generation to an implementation of the algorithms in Procedural Language/Structured Query Language (PL/SQL) to be executed in the LSA database. In order to execute specific algorithms, visualize parameters, generate thresholds and execute tests and comparisons, a Graphical User Interface (GUI) is foreseen.

CONCLUSIONS

The ionization chambers in the LHC arcs will be redistributed during LS1. The optimal new configuration will move one of the chambers on the side of the MQ to the MB-MB interconnection. Monte Carlo simulation are required to evaluate the new BLM thresholds at this detector locations. Several quenches produced under controlled conditions, will have important implications for the BLM dump threshold. An increase of thresholds for the millisecond integration widows is expected for all monitors protecting cold elements. The data obtained for the estimation of the quench level for transient losses may also be applied to all the BLMs around the ring. For the steady state case, the dump thresholds may be adjusted at several specific locations (dispersion suppressor). In all cases, dedicated Monte Carlo simulations and comparison of the different models for the quench level are required. Finally, a new approach for the calculation of BLM thresholds is proposed. It will include the flexibility of the current tools but it will also add features that improve the reliability, safety and long term maintainability.

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EXPERIENCES WITH FEEDBACK SYSTEMS AND FORESEEN IMPROVEMENTS FOR LS1

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Abstract

This contribution summarises the impact of the LHC real-time feedback systems on machine protection and availability. The effects leading to combined failure modes causing beam losses, and those stressing the machine protection system, as well as their planned and proposed mitigations during and after LS1 will be discussed.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN deploys a comprehensive suite of beam-based feedbacks (FB), which not only improves the performance of machine operation but also ensures the proper functioning of its machine protection and beam cleaning systems [1, 2, 3, 4, 5, 6, 7]. Subsequent improvements based on the gained experience with LHC beam are described in [8, 9].

Feedbacks on their own do not directly impact on LHC machine protection. However, incorrect or the absence of FB corrections may contribute to dangerous failure scenarios that, combined with another fast failure incident, may compromise machine protection. Two of the more frequently discussed possible failure scenarios are: a) local orbit bumps combined with, for example, a fast kicker failure, which may violate the global collimator hierarchy, and subsequently cause severe single-turn losses; b) insufficiently controlled tune or chromaticity deviations that, together with another beam instability incident, could unfavourably change the time-scale and distribution of particle losses inside the machine.

LHC FEEDBACK ARCHITECTURE

In order to cope with the large numerical complexity, 'firm real-time' (RT) requirements, the reliability and the availability aspects of high-performance computing hardware, the central feedback controller has been split into two functional parts as illustrated in Figure 1: the Orbit

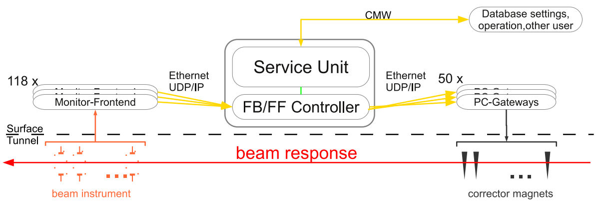

Figure 1: LHC Feedback Schematic.

Feedback Controller (OFC), responsible for the nominal FB controller functionality; and the Orbit Feedback Service Unit (OFSU), responsible for the higher-level feedback functionalities. These higher-level functionalities are setting management, beam parameter reference handling, triggering of feedback actions in response to external timing events, and general integration into the operational environment, e.g. relaying data to clients, interfacing to LHC experiments, logging infrastructure, triggering the software machine interlock system, control room interfaces, etc.

While the OFC and OFSU are the most visible single feedback sub-systems, the whole loop consists of more than 3500 devices (controlled via about 130 front-end computers), and depends on many technical infrastructure service i.e. the FESA front-end framework, CMW communication middleware, the timing system, and the technical network. Thus, the strength of the overall loop depends on the reliability of its weakest link – not necessarily always being the OFC or OFSU servers.

In order to achieve a maximum robustness and closed-loop performance, the OFC has been designed as a simple input-processing-output streaming server, utilising only a very limited number of concurrent threads. The reason for this restrained use of threads was to reduce the variance in dynamic load in favour of a constant periodic load, which is by-far the easiest RT paradigm to quantify and guarantee the compliance with the given real-time constraints. Consequently, conditional statements and semi-random/user-driven code execution are delegated to the OFSU in favour of keeping a predictable constant load on the OFC. More generally, most of the available software technologies (notably Java), algorithms or libraries that could not be thoroughly qualified in terms of worst-case RT latencies were omitted from the OFC.

EXISTING FB ERROR MITIGATION

FBs may amplify the effects of other failures, however, they mostly impact machine availability for physics. Most of the deteriorating effects linked to FB operation that may lead to combined failures are typically slow. They are detected or mitigated by either:

A) the feedback controller itself, with verification time-scales in the order of typically 40 to 80 ms. The large majority ($\approx 80\%$) of the OFC functionality thus deals with error handling rather than the main feedback logic ($\approx 20\%$): receiving the beam instrumentation data, computing the corrections that minimise the deviation of the given beam parameter, and sending the updated reference settings to the power converters and RF function generators (FGCs). In order to achieve an equivalent analogue bandwidth of up to about 1 Hz, the feedback controller handles the input and output data from about 118 front-end computers via a Gigabit-Ethernet backbone using UDP/IP at a sampling rate of typically 25 Hz. Most of the OFC error handling is related to sanity checks of the data integrity and the assessment of the beam parameter stability. This information is subsequently used to automatically de-select (or momentarily mute) an erroneous beam instrumentation input or – if necessary – to stop the FB loop. Many of the involved thresholds are subject to tuning, in particular the trade-off between availability and spurious quench protection system (QPS) trips that may occur if the FB acts on noisy input data.

B) the Software Interlock System (SIS), with surveillance and reaction time-scales in the order of seconds. The SIS monitors and provides slow interlocks on the global orbit, RF frequency, and closed-orbit-dipole currents. It also monitors the OFC/OFSU status to catch erroneously latched references. It also preventively dumps the beams in case of a loss of CMW communication with the front-ends (watch-dog time-scale: 10 seconds). Through the SIS, since many of these software interlocks depend on the OFC and OFSU functioning, the overall FB loop reliability and availability effectively becomes an interlock.

For the time being, the tune and chromaticity measurement values are not interlocked. However, most of the related failure scenarios are indirectly interlocked through the monitoring of the losses seen by the Beam Loss Monitors (BLM). The information related to issues regarding UDP latencies (missing packets, bursts, etc.), CMW communication, technical network latencies and timing infrastructure is already being monitored by the OFC but not yet further exploited (e.g. as forewarning). While some of these symptoms are not necessarily failures, they are often indicative of non-ideal situations that – if aggravated – could lead to a front-end or system failure and subsequent dump of the beam.

FB FAILURE STATISTIC

Overall, the FB performance was good. This proved to be essential for nominal LHC beams, in particular the Tune-FB during the ramp start (snap-back) and Orbit-FB during the beta* squeeze. The large majority of fills were made with minimal losses into physics [10, 11, 12]. Nevertheless, a few fills were lost due to non-nominal FB behaviour, which deserves careful scrutiny to identify and possibly improve systematic or recurring errors. As discussed in [13], based on the analysis of 131 beam dump post-mortem events in 2011 occurring during the operational 'ramp' and 'squeeze' phases where the feedbacks are nominally 'on', 33 dumps were attributed to feedback systems (Orbit- and Tune-FB combined). Most of the dumps (23 out of 33) were related to QPS triggers in response to noisy Tune-FB real-time trims (notably for the RQTH and RQTF tune trim magnet circuits). As a mitigation, the very tight QPS thresholds were raised for 2012 from 0.1 to 2 V and the noise performance of the beam instrumentation (BBQ) feeding into the Tune-FB has been improved. Based on these mitigations, in 2011 it was estimated that two to three FB-induced beam dumps were encountered during the LHC operation in 2012/13.

A similar post-mortem analysis has been repeated for the 2012/13 operational period. Table 1 shows the summary of the analysis. The numbers take into account only post-mortem events with energies above 450 GeV and beam intensities larger than 10^{10} protons per beam to exclude special MD-type experiments with pilot beams (PM comment key-words selection criteria: 'FB', 'Feedback', 'OFC', 'OFSU', 'BBQ', 'BPM', 'RT', 'Orbit', 'Tune', 'Instability'). The statistic includes only dumps, i.e. near-misses, events causing losses without a dump, or events that have been recovered by the operations crew or the sequencer are excluded. As can be seen in Table 1, the overall number of post-mortem events increased.

Table 1: Summary of FB-induced beam-dumps during 2010-2013 LHC operation.

	Total PM	FB-induced	Percentage
2010	453	8	1.7%
2011	684	30	4.4%
2012/13	851	28	3.3%

To first order, the number of FB-induced dumps did not decrease as predicted in [13] but was steady, indicating another new set of failures. Table 2 gives an approximate break-down of the FB-induced post-mortem events according to the FB sub-systems. Please note, some post-mortems are counted twice as the underlying effect could not always be unambiguously disentangled between the various subsystems. The numbers are thus indicating trends rather than being absolute. As predicted in [13], it can be seen that the vast majority of dumps related to the interplay between the QPS and BBQ signal integrity reduced significantly during 2012/13. However, a new source of equipment failure emerged related to problems with infrastructure, over which the equipment owners have only limited control (i.e. FESA, CMW, timing, technical network).

The main causes leading to FB induced beam losses or to stress of the machine protection system, can be grouped into three sub-categories:

- measurement quality (BPMs, BBQ), causing transients on orbit or tune that subsequently provokes losses through pushing the beam on the collimator or inducing triggers of the QPS.

- front-end or software infrastructure problems (OFC, OFSU, FESA, CMW, Timing & network). Many of these actually related to threading issues exhibiting non-RT behaviour, front-end crashes due to memory leakages or out-of-bound accesses, and external

Table 2: Break-down of FB-induced beam-dumps during 2010-2013 LHC operation according to FB sub-systems. The last two columns indicate PM events more related to orbit and tune related instabilities. The latter are not necessarily related to feedback operation but illustrate the increasing criticality of orbit and tune control.

	FB induced total	OFC	OFSU	BBQ	BPM	QPS	Orbit-Instability	Tune-Instability
2010	8	2	0	2	0	3	9	0
2011	30	2	5	18	3	14	13	6
2012/13	28	4	10	1	7	1	17	30

load factors such as slow clients blocking the BBQ or OFSU communication on front-end machines, and technical network switch overloads that suppressed operationally critical data streams. For example the non-RT behaviour of the input data stream, in particular for the BPM front-ends, has a fundamental impact on the feedback function as the absence of data causes the FB to accumulate latencies. These may either cause the beam parameter to drift and potentially push the orbit towards the collimators, or in some cases cause 'classical self-amplifying FB instabilities' when the correction is applied out-of-phase.

- insufficient loop stability margin, with the FB running at or beyond the design stability limit due to e.g. a mismatch between actual optics and the one used by the OFC.

Compared to 2011, some of the failures became more notable due to the newly added SIS interlocks in 2012/13 and the significantly tighter beam stability requirements and stability margin, as can be seen also in the last two columns of Table 2, which indicates the number of orbit- and tune-instability driven beam dumps.

FORESEEN FB IMPROVEMENTS

Many of the recurring or systematic errors (i.e. OFSU memory leaks and out-of-bound reads) have already been addressed during the 2012/13 operation and most of the dumps occurred before September 2012. However, there remains a number of additional improvements for after LS1, that couldn't be deployed during 2012/13 beam operation.

Measurement and Data Integrity

- Temperature stabilised BPM racks, which should minimise most of the temperature related beam position measurement drifts. If necessary, for a few dedicated pick-ups the remaining drifts could be further allayed by additional RF commutation switches at the pick-ups that can help to identify and compensate measurement errors w.r.t. real orbit drifts, as e.g. already installed for the BPMSW pick-ups closest to IP5.

- During LS1 and LS2, it is planned to deploy redundant read-out electronics for all IR-BPMs based on the positive experience with the newly developed high-accuracy Diode-Orbit acquisition system [14, 15]. The initial deployment will be done only for a selected number of BPMs close to the experimental IPs (BPMSW.1[L/R][1,5,8,2].B[1/2]) rather than the full deployment for all BPMs between cells Q1 to Q7. The naming convention of the additional channels needs to be addressed, as well as their integration with respect to the existing standard LHC BPM acquisition electronics.

- The yet to be deployed new TCTP collimators with integrated BPM buttons will also use the Diode-Orbit acquisition system [14, 15]. However, their integration w.r.t. the regular BPM data, reference management and possible future use within the FB loops needs to be evaluated.

- The Tune-FB presently uses an algorithm that only tracks a single, highest peak with a given minimum line width and within a preset tune frequency range. However, the BBQ spectra often shows multiple peaks in the tune range for nominal LHC beams, which sometimes hampers the correct tune detection as the desired tune line is not always the most dominant peak. In order to improve and avoid locking on spurious, non-tune-related peaks in the BBQ spectra, the possibility of tracking multiple peak candidates is being investigated. The relationship between multiple peak candidates could be used to distinguish between interferences, synchrotron side-bands, and the correct tune eigenmodes.

- In order to complement the existing BBQ based tune diagnostics, it was proposed to integrated the ADT transverse bunch-by-bunch feedback system as an alternate source for tune and chromaticity feedbacks [16].

Improvement of Loop Stability

- The operation and performance of the LHC FBs depends not only on the validity of the amplitude of the magnet current changes but equally on the time and latencies at which they are applied. The system can tolerate occasional latencies but reacts adversely if the 'firm real-time' constraints on the loop delay are not met for multiple subsequent samples or for a few seconds. Investigations indicated that under certain (unknown) conditions, the arrival time of the BPM information does not always comply with these requirements, causing a loss of loop stability and an increase in beam losses. The BPM/BBQ UDP transmission robustness and their implementation needs to be reviewed during LS1, in particular the interplay between CMW, FESA, CMW proxies and technical network infrastructure.

- In order to mitigate possible data congestion on the technical network it is planned to decouple the RT traffic used for the FB from those needed for operation and other services using the existing quality-of-service functionality of the installed network routers and switches. The robustness and reliability of this possible solution needs to be verified.

- For most of 2010-2013, the OFC operated with a single and only later with two beam optics configurations (the second being used for the squeeze). This mode of operation was acceptable for the initially very low FB bandwidths but became increasingly inefficient and reduced the stability margin for the higher bandwidths required during the later 2012/13 operation. Thus, for post-LS1 operation it is favourable that the OFC tracks and uses the actual optics of the machine more closely, particular during the squeeze.

- While the basic infrastructure for gain scheduling is already available, it is not yet used during regular operation. Higher bandwidths are typically only required during a very specific and brief operational period (e.g. start of the ramp, or during the beta-star squeeze) and could be reduced in favour of a more robust loop behaviour. This feature remains to be integrated into the operational environment.

- Most of the tracking and validation of the BPM functionality was done manually and thus was fairly infrequent in 2012/13. An automated procedure similarly to the BLM procedure that is executed before each fill, would help to improve the system performance. The proposed idea is to perturb the orbit with a given pattern at the beginning of each fill and to record the measured BPM response, noise, etc. The measurement itself requires less than a minute if automated, and – if done regularly – small deviation or drifts from the reference could indicate at an earlier stage that are on the verge of failing.

- Even though some of the orbit perturbations (e.g. during the squeeze) are fairly large and fast, and approaching the design limit of what the FBs can handle, most of the feedback actions are fairly reproducible from one fill to the next. A feed-forward of the recurring corrections averaged over several fills could reduce the effective fill-to-fill orbit deviations and their speed. This may allow to reduce the necessity and criticality of running the FBs at high bandwidths with reduced stability margin. An initial implementation is being prepared [17].

- Many of the specific feedback actions and stability depend on a wide range of external conditions, some as simple as the beam presence, availability and quality of beam input data, and response to orbit dipole corrector current settings. In order to allow new FB schemes and controls integration to be thoroughly tested under safe conditions and also during non-beam operation, the option of having a dedicated full FB test-bed should be revisited. This functionality is of particular importance for training and development during the approaching long shutdowns.

Diagnostics and Tracking

Most major problems have been quickly identified and addressed during the first years of operation. Further improvements would benefit from better and more specific monitoring, reporting and tracking of the underlying technical infrastructure, and monitoring of the FB and its subsystem errors. This would help isolating the original cause of the problem, rather than analysing the collateral symptoms that caused the beam dump. For example:

- a finer granularity of post-mortem reports attributing the errors according to the feedback sub-categories would be useful for the system experts to follow-up a given problem (e.g. FB function, FESA, CMW/communication, timing, network, BPM/BBQ input, etc.).

- a systematic monitoring of the infrastructure (FESA, CMW, timing, network availability/latencies, front-end statuses, etc.).

- both the OFC and OFSU collect and provide a lot of information, but only a fraction is being exposed to the control room.

Most of the required functionalities and tools are already available on an expert-level, but are still largely inaccessible or unintelligible for untrained people and day-to-day use in the control room. A better GUI-level integration would be desirable to communicate conditions that are not yet critical for beam operation but could lead to some down-time or beam dump if ignored or further aggravated.

FB REVIEW CONCLUSION AND RECOMMENDATION

In addition to this MPP workshop, another subsequent dedicated review has been organised at CERN to analyse the architecture of the existing FB systems in view of their consolidation and adaptation for post-LS1 LHC operation [18]. The conclusion and recommendations of the review board[1] as given in [18] are:

- the OFC appears to be essentially robust and good for its designed purpose. However, additional functionality is expected to be required, and a number of specific

[1] M. Lamont (BE-OP, chair), Javier Serrano (BE-CO), Jakub Wozniak (BE-CO), Stephane Degahaye (BE-CO), Quentin King (TE-EPC)

issues identified above and also detailed in [18] should be addressed, notably the establishing of a full test environment before proceeding with any significant new functionality.

- the OFSU is unmaintainable in its present state and a factorisation is required, notably the split between data re-distribution, settings controls and configuration flow.
- the staffing of the system has been identified as a serious issue and must be addressed urgently.

A complete list of specific items, new functionalities and actions are given in [18].

CONCLUSION

Feedbacks have a priori no 'direct' link to the LHC machine protection system but can create dangerous combined failure scenarios. The OFC/OFSU are the prominent components to the overall feedback loop, which itself depends on many more devices and technical infrastructure services. The main issues identified in 2012 leading the beam dumps were related to: Beam measurement quality; Front-end or software infrastructure problems; insufficient loop stability margin caused by the tighter loop constraints and requirements compared to 2010/11 operation. Many of these issues have been already addressed during 2012/13 and an important set of improvements are planned for LS1, notably the temperature controlled BPM racks and new Diode-Orbit acquisition system for the BPMs in the IR, ongoing improvements of the service infrastructure (FESA, CMW, TechNet, etc.), and upgrades of the OFC/OFSU infrastructure as outlined and confirmed by the FB review.

Better diagnostics, warning and status indication of the overall infrastructure, and better tracking and finer granularity of the given error assessment would be useful and help to track, understand and mitigate systematic, and rare but recurring errors of the feedbacks.

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Experiences with MPS related systems and foreseen improvements for LS1

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Abstract

This paper will focus on three instruments with implications for machine protection, namely: the abort gap monitor, the DIDT (current transformer) and the interlocked BPMs in IR6. For each of these instruments the current status will be presented, including existing performance and reliability issues as well as statistics and nature of failures observed during LHC RUN 1 (2010-2012). The plans for modifications and improvements during LS1 will also be presented highlighting the impact on performance and reliability alongside with the resources requirements to carry them out.

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 (DIDT) and the Abort Gap Monitor (AGM). 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 DIDT 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 DIDT is thus primarly used to protect from fast beam debunching (RF issues). The DIDT monitor is not yet connected to the beam dump interlock as it is still in development.

Finally the AGM 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 AGM is based on the detection of synchrotron light and is not yet connected to the beam dump system due to its limited reliability.

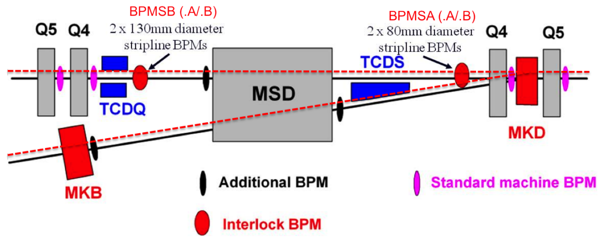

Figure 1: Layout of the beam dump channel.

INTERLOCKED BPMS IN IR6

The BPMs consist of shorted-strip-line pick-ups installed just after the Q4 quadrupole (BPMSA) and just before the TCDQ absorber (BPMSB). 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 design [1][2], 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 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 as explained in another presentation at this workshop [3]. It should be noted that the interlock is based on simple integration windows and not sliding integration windows and the interlock status is re-evaluated at the end of each integration cycle.

As for the other warm parts of the LHC, long coaxial cables are used to bring the electrode signals to the acquisition electronics (normalizer). As will be shown the long cables are at the origin of the main issue with this system. In fact, reflections at the normalizer side are totally re-reflected at the electrode side (short circuit) and can trigger false acquisitions if the amplitude of the reflection is above the detection threshold. The reflections are about 27 dB below the real signal meaning that the reflections from a nominal bunch (1.1 10^{11} protons) are stronger than the signal from a pilot beam (5 10^{9} protons). For this reason the detection threshold can be remotely switched, by the operators (and the LHC sequencer), between two hard wired values, one for low intensity beams like the pilots (*high sensitivity* mode) and one for high intensity beams (*low sensitivity* mode). The lower threshold allows pilot bunches to trigger the BPM acquisition while the higher threshold avoids that reflections from the nominal bunches trigger spurious acquisitions.

BPM interlock for the proton run

During the 2011 run the physics fills were often terminated by the BPM interlock when the weakest bunch approached 4 10^{10} protons; at this intensity level the position measurement became unreliable and produced unneeded beam dumps. In order to remove this limitation the attenuators installed on the strip-line signals have been reduced (shifting the curves in Fig. 2-top to the left). Due to errors in the documentation a few iterations were required to achieve the correct attenuation values. After this change the physics fills were no longer perturbed by the BPM interlock.

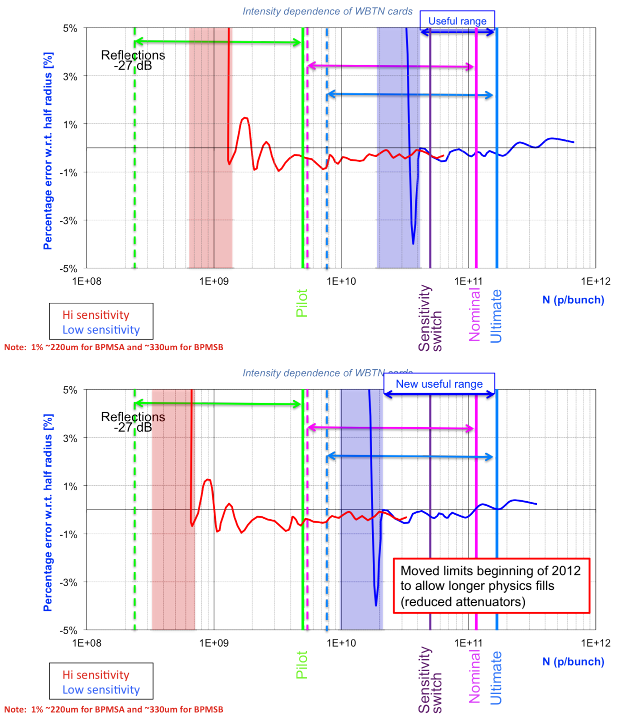

Figure 2: BPM error vs. bunch intensity for the two sensitivity modes. The left edge of the shaded areas corresponds to the detection threshold while the width represents the non-linear response region. The solid lines represent the intensity of specific bunch intensities, while the dashed lines represents the intensities of the reflected signals. The top plot shows the situation in 2011 while the bottom plot shows the situation at the beginning of 2012.

BPM interlock for the proton-lead run

With the change of attenuators a new problem was introduced; the overlap region between high sensitivity mode and low sensitivity mode fell now right around the intensity needed for the p-Pb run. In this configuration the nominal bunch signal sits just in the non-linear region in low sensitivity mode while in high sensitivity mode it is the reflection of the signal that sits in the non-linear region. This was discovered during p-Pb setup MDs at the end of 2012.

In order to correct this new problem the attenuators were changed again during the Christmas break as can be seen in Fig. 3 (only the high sensitivity mode is used in p-Pb runs).

Again the change solved one problem, but introduced a new one. The lower intensity limit of the BPMs after the change corresponded to about 4 10^9 charges with the consequence that almost all p-Pb physics fill have been dumped by the BPM system. Seen that the BPM interlock fired after the luminosity had already decayed to modest values it was decided not to intervene again.

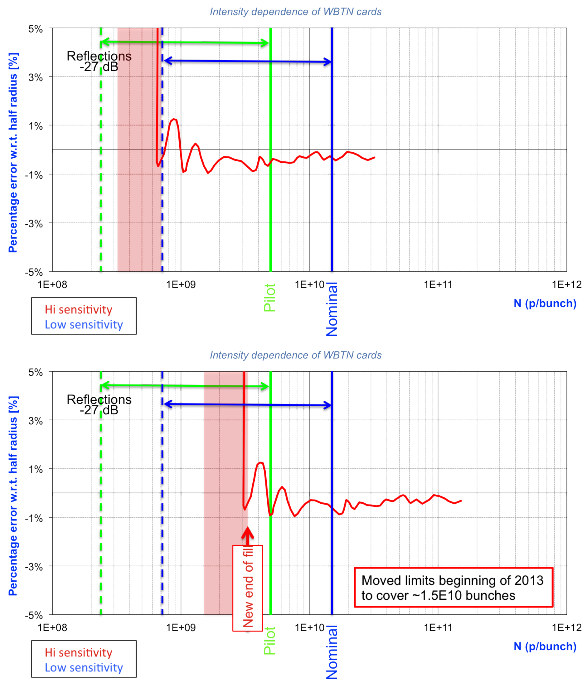

Figure 3: BPM error vs. bunch intensity during the p-Pb run. The top plot shows the situation at the end of the p-p run while the bottom plot shows the situation at the beginning of 2013.

Situation and outlook

The reflection/detection threshold problems have been aggravated by the fact that the software tools available for the analysis of a BPM induced dump event were not adequate. In fact only experts were able to find out what happened and verify if a dump was a spurious trigger due to reflection, weak bunch or real orbit excursion. Moreover every attenuators modification requires a lengthy validation process using beam scraping. During the 2012–2013 run there have been 158 dumps triggered by the BPM interlock. Of these dumps 1 was in SETUP mode, 120 in INJECTION, 3 in FLAT-TOP, 2 in RAMP, 3 in ADJUST and 29 in STABLE-BEAMS of which 22 during the p-Pb run. It has to be noted that the BPM interlock always acted as needed in presence of a real excessive orbit excursion.

In order to mitigate the spurious dumps, to simplify the threshold level changes and to make the system more user friendly, several actions are under study for LS1.

First of all, filters providing 50 Ω impedance both on the input and output ports will be installed right at the electrodes connector. This will avoid the total reflection at the electrode side and thus reduce the overall amplitude of the reflections, extending the usable range of the high sensitivity mode. Theoretically, if reflections could be completely removed, a single sensitivity mode could cover the whole operational range ($1\ 10^9$–$3\ 10^{11}$ protons or about 50 dB). In reality it will be impossible to achieve this result, the exact extent of the improvement can only be quantified by measurements on the real system.

Another measure being investigated is the replacement of the two fixed threshold levels by a programmable DAC. This will have the same effect of changing the attenuators, but can be done remotely via a dedicated control parameter. This modification requires an adequate handling of the threshold values (like the BLM thresholds.)

The normalizer card will also be improved trying to reduce the position error in the non-linear region near the threshold value.

On the software side an effort will be made to improve the diagnostics and event analysis. This will require some changes at the firmware level and possibly also a change in the hardware if the memory present on the acquisition cards proves not to be sufficient. OP should also be involved in this process since a new GUI may be needed. Certainly the diagnostics and analysis tools will be less important after LS1 if the improvements of the system reduce the number of spurious triggers.

DIDT

The fast current change (i.e. dI/dt) monitor (DIDT) 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 4 shows the schematics of the DIDT signal processing.

The signal from the FBCT is first digitized, 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 of the 40 MHz component are then 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 values is above the threshold, the interlock output is fired pulling the corresponding BIC channel (currently not connected). The thresholds are looked up in a table using the energy values distributed on the LHC timing telegram (MTG).

The system is contained in a box (Fig. 5) 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) as can be seen in Fig. 6.

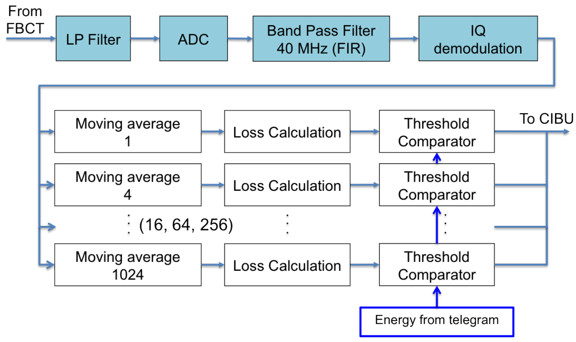

Figure 4: Schematic diagram of the signal processing inside the DIDT monitor.

Two different implementations have been tested in 2011. The two systems shared the same hardware design, but differed in the FPGA firmware. One system was based on a CERN developed firmware while the other came from a private company based on the Fast Magnet current Change Monitor (FMCM).

The CERN version was able to monitor the signals for both beams (GUI for online monitoring available and data logged in the database) while the other system was only available for one beam (no online monitoring available and data logged only locally on a PC). This allowed to test and compare the two implementations showing equivalent results.

The noise floor (i.e. the threshold below which the spurious triggers become relevant) is of about $2\ 10^{10}$ protons, but because of losses at injection the lowest *usable* limit is 0.3% of the full machine ($7\ 10^{11}$ protons). The injection losses will be masked by the data processing in the next version of the firmware and then the limit will be dominated by the performance of the FBCT, in particular by the position sensitivity of the FBCT. For the CERN system a small cross talk between beams of the order of 30–40 dB was also observed.

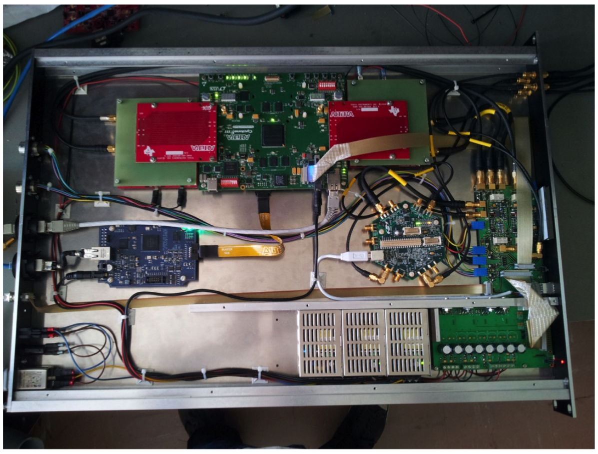

Figure 5: Picture of the prototype DIDT monitor.

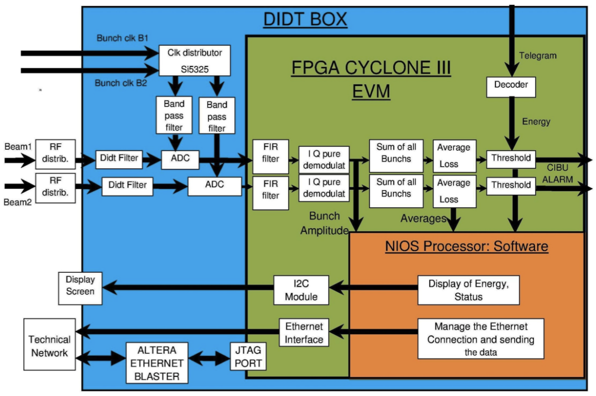

Figure 6: Layout of the DIDT monitor.

Plans for LS1

At the moment the DIDT electronics consists of a box containing several off-the-shelf boards. It is foreseen to design a new single PCB board that integrates all the different functions. This will allow the proper separation of analog and digital signals and reduce the electronic noise of the analog processing part, which is mainly caused by crosstalk from the digital part.

In order to eliminate the cross talk between beams each box will only be used to process the signals of one beam. In total six new boxes will be produced during LS1, two for B1, two for B2 and two spares, therefore each beam should be equipped with two redundant DIDT monitors for the start-up. For each beam, one DIDT will be connected to the existing FBCT and one to a new BCT.

The FBCTs themselves will be improved during LS1 with the aim of reducing the dependency on the beam position. At the moment this is considered the main limitation of the new DIDT monitors. Two different solutions are being investigated: BERGOZ ICT [4] and CERN inductive pick-up. The two monitors will be tested in the lab once ready and the one giving the best results will be deployed on system B (system A remains unchanged).

New software for the control and acquisition will also be developed during LS1. It is foreseen to have the complete and operational systems ready for the startup.

ABORT GAP MONITOR

The Abort Gap Monitor (AGM aka BSRA) is based on an MCP-gated-photomultiplier-tube measuring the intensity of synchrotron light (SL) emitted by the beam during the abort gap [5]. The abort gap itself is a 3 μs 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 a high reliability since the device was foreseen as a monitor, and not to be connected to the beam dump interlock. Only an alarm had to be generated for the control room operators if the level of particles in the gap surpasses a certain threshold. The AGM is part of the synchrotron light telescope and there are a few compatibility issues that reduce its reliability.

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 ($I_{\mathrm{SL}} \propto E^4$). 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 [6]. The relative error of this monitor is below 50% which is adequate to its use.

Reliability of the AGM

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 and the stability of the HV generator, the aging of the photocathode of the PMT and finally electromagnetic noise in the signal.

The Beam Synchrotron Radiation Telescope (BSRT) consists of a rather complex optics system in order to measure the transverse beam size precisely. This complexity has an impact on reliability by itself, even more considering that the BSRT is still under development with frequent and constant modifications in order to improve the resolution (which is still insufficient). In 2012 the BSRT has been simplified considerably by replacing a complex focusing mirror setup with achromatic lenses. The positive effects of these changes have been visible also on the reliability. The layout of the two versions of the BSRT is shown in Fig. 7.

Another appreciable step forward was the identification of an important problem of the BSRT. It was discovered in 2012 that the synchrotron light extraction mirrors (in vacuum near the beam) were overheating up to the point of damage. The heating induced deformations in the extraction mirrors with consequent loss of optical resolution and instabilities in the pointing of the mirror.

Furthermore, a non optimized software package was also contributing to the loss of reliability. The present software has few automatic adjustments and requires frequent interventions by experts, and is not always intuitive. In many occasions human errors during the calibration procedure or in the programming of the acquisition parameters caused down times of the AGM.

Finally, some still unexplained jumps of the distributed turn clock occurring after a technical stop caused the AGM to publish wrong values.

Changes in the BSRT telescope layout

As already mentioned, during 2012 the BSRT telescopes were heavily modified. This was done in an attempt to simplify the system, increase the stability and hopefully improve the optical resolution as a consequence (sensitivity to vibrations). The change consisted in moving from a reflective imaging system (reflector) to a refracting imaging system (refractor).

The disadvantage is that chromatic aberration are introduced, this effect was however studied and turned out not to be important because the BSRT operates using narrow band filters. With this modification the optical delay line at the entrance of the telescope, which has always been difficult to align and operate, could be removed. The optical delay line was needed to adjust the focus of the imaging system from the undulator to the dipole, task now accomplished by moving a lens. The two mentioned synchrotron radiation sources are about three meters apart.

With the present design there is no moving component before the AGM apart from the steering mirror (which is needed by the AGM as well).

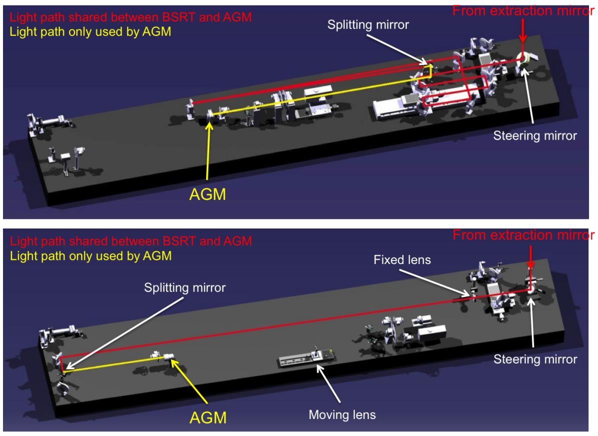

Figure 7: Old BSRT layout (top) and new (bottom). The red lines indicate the light path in common between BSRT and AGM while the yellow lines indicate the optical lines private to the AGM.

Plans for LS1

The main task for LS1 is to solve the problem of the heating mirrors. Several options are under investigation and a new solution should be ready for implementation soon. This task involves several people from different groups in different departments (BI, ABP, RF, VSC, MME and MEF) as the RF heating, optical properties, vacuum properties and mechanical constraints have to be considered at the same time. We will also take the opportunity to consolidate the installation as many changes were made in the short technical stops with no time for the polishing details.

The other big change will come from software improvements. We will try to reduce to a minimum the need for external interventions by adding automated calibration features, watch dogs, self tests, proper recovery from unexpected situations, and management of the alarms.

AGM after LS1

There will be no noticeable change in sensitivity as this is dominated by the light source and no change is foreseen here. The AGM hardware, excluding the part in common with the BSRT, will receive very little modifications, apart from a minor consolidation of the installation, as the AGM hardware has never been the cause for the problems.

Nevertheless we expect a substantial system stability improvement by: reducing the possibility of loosing the beam spot on the BSRT, obtaining more stable calibration factors/curves, and by introducing much more intelligence in the software controlling the acquisition, rising alarms when needed, but only when needed. To this extent a specification document is being written and will be circulated for comments among all the stakeholders before starting the ”coding” work.

CONCLUSIONS

The present status and limitations of the interlocked BPMs in IR6, the DIDT monitor, and the abort gap monitor have been presented together with the measures being taken by the BI group to improve the systems.

The BPMs should not be a performance limit after LS1. For this it is important that BI, OP and MPP work together and validate the proposed changes.

A full set of DIDT monitors will be available after LS1. The prototypes gave encouraging results, probably some debugging and fine tuning will be required going for the final systems.

The reliability of the AGM will be improved and although there will be no changes in performances, the system should become much more reliable and in particular self-diagnosing.

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LHC COLLIMATORS AND MOVABLE DEVICES

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Abstract

About 500 movable devices have the ability to touch the LHC beams. The list includes operational devices that are moved according to pre-defined sequences in the operational cycle, like collimators, protection elements and physics detectors, as well as non-operational devices that are not used in standard operation with high intensity beams, like vacuum valves, beam stoppers, beam screens. The proper interlock strategy of these devices has represented an important concern due to the high damage potential of the LHC beams. This topic has been addressed several times in the past. In this paper, the changes that are foreseen during the first LHC long shutdown, in preparation for the LHC energy upgrade, are reviewed. The operational experience of the LHC run 1 and the problems encountered are also discussed.

INTRODUCTION

The Large Hadron Collider (LHC) run 1 showed that the machine can be operated safely with stored beam energies up to a factor 70 larger than the previous state-of-the-art in particle accelerators set by the Tevatron. The LHC was routinely running with stored energies around 140 MJ at 4 TeV. On the other hand, the safe operation of the LHC remains a concern for the future due to the unprecedented damage potential of the LHC beams. After LS1, an increase by a factor 2 of beam intensities achieved through reduced bunch spacing (25 ns instead than 50 ns) and an increase by a factor 1.6 in particle energy (6.5 TeV instead than 4 TeV) are expected. In particular, movable devices that can intercept the beams require appropriate interlocking strategies. In the LHC and its transfer lines, there are about 500 of such devices, including vacuum valves, beam stoppers, collimators, screens and physics detectors.

An exhaustive list of the LHC movable devices can be found in [1]. More recently, the adopted interlocking strategy was reviewed for the different cases [2], covering both the “operational” devices (collimators and movable physics detectors) that are moved during the operational cycle and the IN/OUT “non-operational” devices (vacuum valves, screens, etc.) that must be out during high-intensity beam operation. The latter devices rely on hardware beam inhibit signals that trigger beam abort requests in case of incorrect positions. For example, a beam dump request is issued if a vacuum valve leaves its OUT position. Instead, devices like collimators must be dynamically adjusted during the cycle in order to ensure optimum settings while optics and orbit change. The interlocking strategy in this case is clearly more complex.

More than 130 operational movable devices are installed in the LHC and its transfer lines, including 100 collimators for cleaning and machine protection, 32 Roman pots and the LHCb VELO detector. Their operational settings are carefully established by using dedicated beam-based procedures that were worked out to ensure a safe operation in all conditions. Complex and redundant interlocks were designed to minimize the risk of errors in the positions of these devices. In this paper, the overall interlock strategy is reviewed for the different movable devices. The changes planned during the LHC Long Shutdown 1 (LS1) are listed. Particular emphasis is put on the operational devices and on the problems encountered in the 2012-13 run are discussed. Procedural aspects and the influence of human errors are also addressed.

MOVABLE DEVICE INTERLOCKS AND CHANGES DURING LS1

Non-operational movable devices

The non-operational devices that are typically OUT of beam during high-intensity operation are listed below [1]:

- Equipment under responsibility of the vacuum team:
  - vacuum valves (about 250 in the rings and transfer lines);
  - electron beam stoppers in the RF zones (4);
  - safety beam stopper in IR3 (2).
- Beam instrumentation:
  - beam screens (11);
  - mirrors of synchrotron light monitors (2);
  - wire scanners (4).
- 1 movable mask of type TCDD in IR2.
- Triplet magnets that are mounted on motorized jacks (32 per interaction point). This system is used for remote alignment of the magnets that is done without beam [3] to ensure optimum magnet positions.

Details of the interlock strategies for these devices are given in [2]. Note that the position of the movable TCDD mask [4] and of the mirrors for the synchrotron light monitors in IP4 are designed such that their IN position remains outside the local aperture restrictions. Beam screens and wire scanners can only be operated at appropriate beam intensities and energies. Vacuum elements individually inhibit the beams by removing the beam permit when moving away from their OUT position.

No major changes are foreseen during the LS1 for these devices. One outstanding issue is a recent proposal to add fast vacuum valves in IP4 in order to limit collateral effects to the RF cavities from a catastrophic magnet failures as the one of 2008 [5]. The proposed valves can close in 20 ms to 50 ms, which makes their interlock particularly tricky. This aspect was discussed in [6] and the final decision of the LHC Machine Committee was to avoid the installation fast valves because the potential closure with beam was considered potentially more severe than the pollution that these valves were designed to avoid.

Operational movable devices

List of devices and recap of interlocks The operational devices that are moved in vacuum during the operational cycle, following pre-defined settings for each cycle phase, are listed below:

- Collimators and protection devices in rings and transfer lines:
  - 98 four-motor, two-sided collimators[1];
  - 2 one-sided TCDQ's (IP6 dump protection);
  - note that 44 collimators feature a "5$^{\mathrm{th}}$ motor axis" for transverse jaw movements perpendicular to the collimator angle (designed to provide fresh jaw surface in case of collimator damage).
- Movable in-vacuum experiment detectors (only moved in stable beam conditions):
  - VELO of the LHCb detector [7];
  - 32 Roman pots in IR1 and IR5.

The control of the movable collimators is clearly a critical challenge for the LHC operation, since beam collimation and machine protection are needed continuously in all phases of the LHC operation. The complexity of the system is illustrated by the figures in Table 1, where the degrees of freedom for collimation movements as deployed in 2012 are listed [8]. The controls design was driven by the collimation system requirements [9].

Collimators are redundantly interlocked in order to ensure that optimum positions during the operational cycle [9]. Table 2 summarizes the different movement and interlocks types available for the four main hardware categories: LHC collimators (labelled LHC Coll), dump protection blocks (TCDQ), injection protection blocks (TDI) and Roman pots (XRP). The LHCb VELO is entirely handled by the LHCb and does not feature direct input channels on the LHC interlock system.

The collimators can be moved in discrete steps at a fixed speed of 2 mm/s or following arbitrary functions of time, e.g. like it is required in the energy ramp to follow beam size and orbit evolution [10]. This requires two different types of interlocks: limit functions and discrete limits. The latter apply when the collimators remains idle at the end of a function execution. The time-dependent position limits apply to individual jaw axes and to the collimator gap (6 sets of limits per collimator). In addition, energy-dependent limits are used to ensure that collimator gaps are reduced as expected during the energy ramp (see illustration in Fig. 1) and β^*-dependent limits are used during the betatron squeeze for the tertiary collimators[2]. All the reference settings are defined and stored by the system experts in appropriate tables and are loaded and executed repeatedly at every fill by the OP crew throught dedicated collimation sequences.

Table 1: 2012 collimation parameters table for the 98 four-motor collimators in the LHC rings and transfer lines.

Parameters	Number
Movable collimators in the ring	85
Transfer line collimators	13
Stepping motors	392
Resolvers	392
Position/gap measurements	584
Interlocked position sensors	584
Interlocked temperature sensors	584
Motor settings: functions / discrete	448/1180
Threshold settings versus time	9768
Threshold settings versus energy	196
Threshold settings versus β^*	384

This powerful but complex system is adopted for collimator-like devices with different hardware through an appropriate middle-ware interface that allows the operation crew to manage the settings in the same way [11]. Note that the Roman pots only move through discrete settings so redundancy cannot be achieved with the standard energy- and β^*-limits. Additional discrete redundant limits are added for this purpose by defining limits for the closest pot position to the beam that are always active in the system.

Changes foreseen during LS1 The main change that will take place in LS1 is that 18 ring collimators will be replaces with a new design with four beam position monitors (BPMs) embedded in the jaws, one at each corner [12]. These collimators will replace the tertiary collimators in all interaction points and the secondary collimators in the IR6 dump region [13, 14] for an improved operational flexibility in the interaction regions and an improved β^* reach [15]. This new design was extensively tested and validated at the SPS with a mock-up collimator with BPMs [16, 17]. In addition to the important performance gains, the new BPM feature is designed to provide a better monitoring of the collimator centre. Presently, this important parameter can only be measured by beam loss based techniques in

[1] Even if classified as non-operational device, the movable TCDD is accounted for here because its settings are managed through the same controls as the four-motor collimators.

[2] The implementation of the limits as a function of β^* is done for all the collimators and for the TCDQ even if so far this was only used for tertiary collimators.

Table 2: Summary of different setting and interlock types used for the four main hardware types defined in the text: LHC collimators (LHC Coll), dump protection block (TCDQ), injection protection block (TDI) and Roman pots (XRP). The TCDQ is the only device that does not used stepping motors but servo loop.

	N	Stepping motors	Discrete settings	Function settings	Timing receiver	Limit functions of: Time	Energy	Beta*	'Redundant' limits	Temperature interlock
LHC coll.	98	√	√	√	√	√	√	√		√
TCDQ	2		√	√	√	√	√	√		
TDI	2	√	√		√	√	√			
XRP	32	√	√			√			√	

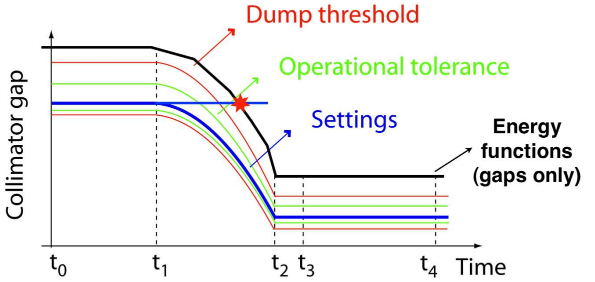

Figure 1: Illustration of collimation gap interlocks. In addition to standard limits (red) around the set point (blue), interlocks versus energy (black) are defined to ensure that the collimator gaps is reduced as expected when the energy increases. These limits are defined as arrays of maximum allowed gap versus energy [11]. The limit value at each time is calculated using as input the beam energy value distributed by the timing system. This allows catching a scenario when a collimator does not move at the start of the ramp (straight blue line), e.g. in case of problems with the start-of-ramp trigger that leaves the collimator still within the injection limits.

dedicated low-intensity fills. The BPM feature will allow an early detection of wrong collimator positions. We plan to add a software interlock that will dump the beams in case any collimator centre exceeds its pre-defined tolerance windows. See also [18].

Another change under discussion concerns the addition of redundant limits as a function of the beam separation and crossing at the IP [19], to provide redundancy when the collision functions are triggered (similarly to what is provided by energy- and β^*-limits during ramp and squeeze, respectively). This implementation, conceived to avoid some isolated problem occurred in 2012 (see below), requires the beam separation and crossing angle information to be computed and reliably distributed by the timing system, like energy and β^*. The feasibility of this implementation, which required a reliable caclulation of beam separation and crossing angles, is being addressed.

It is also planned to add new physics debris collimators cleaning the outgoing beams in IR1 and IR5 and to modify the hardware of the TCDQ [20] and TDI collimators [21]. These changes do not affect the interlocking of the system provided that the new hardware will ensure the same position accuracy. Other MP aspects specific for injection and dump protection are discussed in [20, 21]. The layouts of the Roman pots in IR1 and IR5 will also be modified by adding up to 8 new pots and by shifting the positions of the present ones[22]. The interlock philosophy will remain the same.

A crystal collimation experiment has been proposed for installation in IR7 during LS1 [23]. In its initial phase, the crystal installation is intended for MD purposes and will affect beam 1 only. Details of the interlock strategy have yet to be outlined. It is expected that "status" interlock based on monitoring the OUT position of the crystal will suffice (a maskable interlock will be activated when the crystal leaves its OUT position, it is to be masked during MD's with safe intensities).

PROBLEMS ENCOUNTERED AND OPERATIONAL FEEDBACK

Collimator settings and thresholds are stored in LSA "beam processes" and executed by the LHC sequencer. Settings are validated by loss maps [24] about every 4 weeks and/or when the machine configuration change. The following problems were encountered during the LHC operation:

1) Wrong parameters entered in the generation programs for collimator settings, causing wrong settings for two tertiary collimators and for an active absorber in IR3 [18].

2) Wrong settings of the injection protection devices after a change of optics in the transfer lines (gaps values were not updated following an optics change and kept at wrong values during some weeks [21]).

3) Operation with wrong injection protection settings in 2011 due to the use of an incorrect set of settings (wrong beam process used by the sequencer).

4) Tertiary collimators not moving in one interaction point when beams were brought in collision, due to a failure of the local timing (“start” timing event not received).

5) Similar problem as (4) during ion operation, due to a wrong sequencer usage by the operation crew (one sub-sequence skipped).

6) A few issues were encountered with setting handling (setting copy between beam processes, revert of operational settings after MD’s or special runs, problems with digital signatures of critical settings requiring expert interventions). Typically this affected operational efficiency rather than posing MP concerns.

7) A limited number of hardware problems, see [8], that were caught by the internal system monitoring. This is not discussed in this paper.

The HW timing problem (4) was detected by the operation crew through the machine state. The action taken was to call the collimation contact who requested an immediate dump of the beams. Such problems will be avoided by the new BPM features and/or by new limits versus beam separation [19]. The other issues in the list (except item 7) can be considered as human errors. It is interesting to note that they were typically identified by the system experts through internal checks. The complexity of the setting handling makes it very difficult to have people acquainted with the system within the standard operation crew. The question whether this should be changed by giving more responsibilities to the shift crew members was discussed at the workshop and needs more followup.

With the present controls environment it is very difficult to identify errors in the setting generation after settings are imported into the control system by the experts. The interlock limits described in the previous section make sure that the devices move as programmed, but cannot ensure that the settings are correct to provide the required functionality. Such verification is difficult to achieve because it must take into account a variety of sources of information (beam energy, optics, set point of IP bumps, position of other collimators, etc.) that are used to generate the settings.

There have been attempts to develop high level software to check the correct orbit and optics independently of the inputs imported at the generation phase (i.e. compare measured collimator gaps/positions to what they *should* be at a given machine condition). These were not really successful so far (see for example discussion on online model in [18]). Efforts are ongoing to improve the monitoring software but clearly the need for improved setting checks will remain crucial for the future. Note that the standard way to validate collimator settings is through loss maps. This is however not fully conclusive to detect setting problems with the accuracy ranging from a fraction of a beam sigma to a few beam sigmas, which can already be critical for MP [24].

The monitoring of collimator gaps is done efficiently in the present system by the independent collimator gap measurements (2 measurements per collimators). The addition of the BPM feature will improve significantly the monitoring of possible errors of the collimator centre. The tertiary collimators whose settings are affected by the frequent changes of IR configuration will be replaced first. The majority of the collimators will not have BPM after LS1 so improving the settings handling remain a priority. The addition of limits versus IP separation might be used to cover the issues (5) and (6) above.

An intrinsic weakness of the present setting management environment is that there is no tight protection against changes of the beam process used by the sequencer (this is done by assigning beam processes to “users” like injection, ramp, etc.). This is a manipulation that the whole OP crew is allowed to perform, as required in different operational conditions. A better protection for this manipulation against bad changes, which caused some problems when changing machine configurations for MD’s or special runs, should be put in place. For example, only authorised users should be able to change the injection beam process.

Finally, it is also important to remind that is some cases, critical validation of machine settings were not done in ideal conditions. In case of frequent changes of machine configurations, supporting teams are often required to intervene at any time during the day, under time pressure. A number of proposals were brought forwards in the discussion to improve the situation, like enforcing that no deployment of new settings and no validation of critical systems is allowed during the nights, enforcing one low-intensity fill after important setting changes and agreeing on minimal staged intensity ramp-up procedures after major machine configuration changes. Due to the increased damage potential of the LHC beams after LS1, the procedures to deploy MP-relevant settings after machine changes should be reviewed.

CONCLUSION

The operation of high-intensity and high-energy beams with damage potential well above the limits of accelerator components is a concern. The machine safety relies on several movable devices being the the right positions. The operation during the LHC run 1 was very successful from the MP viewpoint, but several improvements are under discussion to reduce even further the risk of inducing dangerous situations. A few problems occurred which could have been critical in case of combined machine failures. Online monitoring of beam losses cannot exclude in all cases dangerous conditions, so it is crucial to ensure the self-consistency of movable device settings during all operational phases.

The different types of devices and their interlock strategies were reviewed and the changes foreseen for the post-LS1 operation were discussed. No major modifications that change the overall MP protection aspects are foreseen. An important improvement is expected from the addition of collimators with embedded BPM that, amongst other benefits, will improve significantly the MP role of the collimation system: BPMs will provide – in theory – an easy way to exclude errors in the collimator centres that were experienced in a few cases. This type of errors are potentially critical and difficult to identify with the required precision by independent checks. The present controls are suited to ensure that the collimators go where they are told, but not optimum to verify that the settings are correct.

The operational experience with other encountered problem shows that the verification of settings remains a very hot topic for movable devices. Details on proposed improvements were reported in several companion papers presented at this workshop. We recall here the proposal under discussion to add new sets of collimator limits as a function of the beam separation at the collision points. This proposal becomes crucial if the production of new collimators with BPM cannot be guaranteed.

An important point of the interlock approach developed for operational movable devices is that different hardware types adopt the same interlock philosophy. This approach should be maintained for future upgrades. Hardware failures hardly caused dangerous situations because the systems reacted well in case of failures. The main concerns for movable devices arose from human mistakes in the setting handling/generation. This aspect should be improved in the future. The present setting management system is error prone when it comes to handle settings changes for multiple machine configurations. Human actions are still critical to ensure a safe operation in these cases. Some weaknesses of the present system were discussed and some suggestions for possible improvements, including the revision of procedures to ensure that critical validations are performed in optimum conditions, were outlined.

The main followup items, also presented in the summary of Section 4 of the MP workshop, are listed below. See also details in the companion papers [18, 20, 21]

– Decide on the implementation of new collimator limits versus of beam separation and crossing angles;
– Work out the detailed interlock implementation for the new BPM collimators;
– Improve protection of beam processes where settings are stored, whose handling caused several issues (in particular for injection settings);
– Review operational procedures for setting deployment and validation;
– Improve tools for the settings verification at generation level and during operation (on-line monitoring);
– Review validation procedures for MP systems in order to ensure that critical changes are done in optimum conditions.
– Deploy systematically the machine state tool.

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COLLIMATOR SETTINGS GENERATION, MANAGEMENT AND VERIFICATION

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Abstract

Different collimator settings are required throughout the LHC operational cycle following the evolution of key beam parameters like energy, orbit and β-functions. Beam-based alignment is used to determine the beam centers and beam sizes at the collimators at discrete times in the cycle, such as injection, flat-top and collisions. These parameters are then used to generate setting functions for the collimator positions and interlock limits. An overview of the settings generation, management and verification cycle is presented, and potential error scenarios in the settings generation are identified. Improvements foreseen for the post-LS1 operation are discussed. The present collimator status monitoring system is reviewed with suggestions for improvement. The role of MAD-X online is discussed. Finally, the results and current status towards maximizing the potential of the embedded-BPM collimators that will be installed in 18 collimator slots during LS1 is presented, including the tested automatic alignment procedure, software interlocks and orbit monitoring.

INTRODUCTION

The Large Hadron Collider (LHC) is at the particle accelerator technology frontier, with a stored beam energy higher than any previous collider. It is protected from potential damage by several machine protection systems. The collimation system removes the halo particles before they can quench the super-conducting magnets [1]. Collimators also protect the aperture from single-turn abnormal beam losses, which may occur if the beams are miskicked during injection or dump.

Collimation is required at all phases (injection, ramp, squeeze and physics) due to the high stored beam energies present in the machine. The jaw position settings depend on key beam parameters, such as the energy, orbit and β-functions, which change as a function of time, energy and/or β^*. The result is unprecedented complexity, with approximately 400 axes of motion [2] requiring function-based settings and a redundant interlocking strategy. The settings must be continuously monitored and compared to the desired values.

A schematic of the collimator settings parameter space is shown in Fig. 1. The jaw corner positions in mm (M1, M2, M3 and M4) for any point in the operational cycle are determined from the local beam-based parameters (shown in blue) and the half-gap opening in units of beam σ (shown in red) at each collimator. The beam-based parameters are typically measured via beam-based alignment [4] at four points: injection, flat top, after the squeeze and in collisions. Functions are generated to ensure that collimators are always at the optimal positions during dynamic changes of configuration. The settings are stored in a beam process, which also contains settings of other LHC devices for a given machine stage in the cycle. Beam processes are then played in the appropriate order by the LHC sequencer [5]. The jaw positions are interlocked at all times by three categories of interlocks:

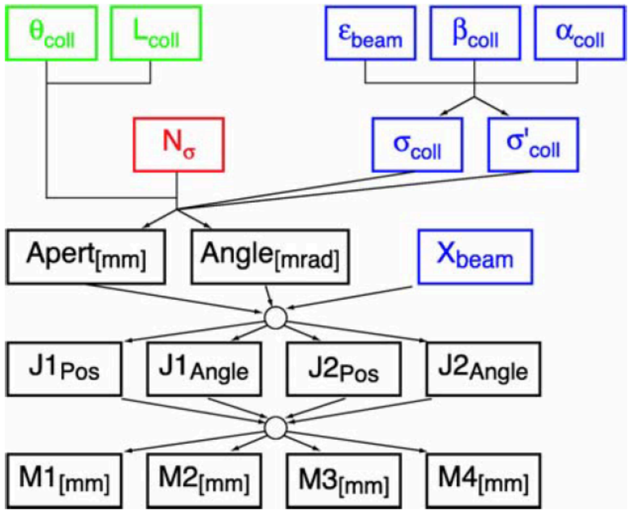

Figure 1: Collimator settings parameter space [3].

1. inner/outer limits for each jaw corner and gaps, stored in an actual or function beam process.
2. inner/outer β^* limits on the jaw gap, stored in a discrete beam process.
3. energy limits on the jaw gap, stored in a discrete beam process.

Typical values for the limits are ± 400 μm, or ~ 1 σ. If the limits are exceeded at any time, the beam is automatically dumped. As the β^* and energy limits are stored in a discrete (i.e. a non-function driven) beam process, they are independent of the jaw positions and will still cause a software interlock if the jaws fail to move e.g. during a ramp or squeeze.

This paper reviews the collimator settings generation cycle, the issues encountered during LHC operation and the

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measures taken. An overview of the present collimator status monitoring system is provided, together with suggestions for further improvement. Finally, the current status towards achieving operability of the new BPM collimators and the status of the MAD-X online tools is discussed as a further step towards improving the protection of the machine from the collimation point of view.

SETTINGS GENERATION CYCLE

There are four main stages in the collimator settings generation cycle, depicted in Fig. 2. In the first step, the beam center and beam size are measured via beam-based collimator alignment [4]. The measured beam center is calculated as the average of the aligned left and right jaw positions:

$$\Delta x_i = \frac{x_i^{L,m} + x_i^{R,m}}{2}$$

The beam size is inferred from the ratio of the aligned collimator gap to the cut expressed in units of beam sigma that was made by the IR7 TCP collimator:

$$\sigma_i^{inf} = \frac{x_i^{L,m} - x_i^{R,m}}{N_{TCP}}$$

The collimator settings to be used during operation are then calculated based on N_i, the desired half-gap opening in units of beam sigma:

$$x_i^{L,set} = \Delta x_i + N_i \sigma_i^{inf}$$

$$x_i^{R,set} = \Delta x_i - N_i \sigma_i^{inf}$$

The measured beam size is used at injection energy, but as the jaw gaps expressed in mm are smaller at flat top (and hence more sensitive to setup errors), the nominal beam size is used for the settings at top energy. The second step is to validate the measured settings using beam loss maps [6]. Normally, the validation is performed in the same fill after completion of the alignments. The number and type of beam loss maps that can be obtained is limited by the number of bunches injected at the start of the fill. Once this is completed and validated, the standard settings can be used for high-intensity operation with the standard sequence-driven generation. A list of beam processes and the required operations in each case is provided in Table 1.

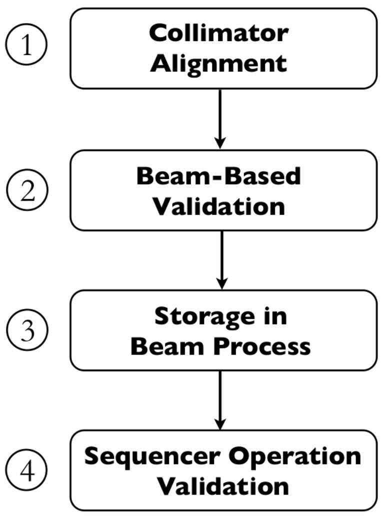


Figure 2: Collimator settings generation cycle.

At injection energy, all collimators are aligned. At flat top, all collimators except the injection protection collimators (TDI, TCLIA, TCLIB) are aligned. A ramp function is generated to move in the collimators as a function of time, using the time-dependent energy and optics functions of the beam, from the injection settings to the flat top settings. Details of the function generation are available in [7]. This procedure is repeated for only the TCT collimators in the squeeze and collisions. During the squeeze, the TCTs are moved as a function of the β^* in each experimental IP, while in collisions the transition depends on the collapse of the crossing bumps.

The beam centers and beam sizes measured during alignment were input manually during the 2010-2011 LHC runs, but following the automation of the alignment procedure, the values were automatically stored in local files on the CERN Control Center (CCC) machines. Using these alignment values, the functions are generated automatically by a Mathematica program and imported into the LHC Software Architecture (LSA) settings database in the third step of the settings generation cycle. Table 2 lists the collimator settings in units of beam sigma (N_i) as used throughout the 2010-2013 LHC run.

The fourth and final step is to validate the sequencer operation in a low-intensity fill. This is normally done in the shade of other fills required for beam-based validation or tune and orbit feedback checks.

COLLIMATOR STATUS MONITORING REVIEW

Current System

As is evident from Fig. 1, there are two levels of abstraction in the collimator system settings. The lower level consists of the jaw positions in mm and the related software interlocks, whereas the higher level consists of parameters which the hardware is not aware about, and which are used to calculate the settings in mm.

The collimator statuses and jaw positions online status display (vistar) shown in Fig. 3 is designed to monitor the system at the lower level. The vistar, displayed online and on the CCC overhead monitors, shows all the LHC ring and transfer line collimators ordered by beam and IP. The averages of the LU/LD and RU/RD LVDT jaw positions are displayed, and the size and position of a white space gives an indication of the gap opening and collimator center. The collimator status, Motor Drive Control (MDC) and Position Read-out Survey (PRS) statuses are shown.

A more detailed view of the MDC and PRS error and

Table 1: The beam processes for various beam modes, and the operations required to determine the settings for each case. This set of beam processes, which contain the necessary settings for all machine components from the start to the end of fill, form a unique hypercycle.

Beam Mode	Beam Process	Settings Generation
Injection	Ramp@start	Alignment of all collimators
Ramp	Ramp function	$f(\gamma, t)$
Flat Top	Ramp@end / Squeeze@start	Alignment of all collimators except inj. prot.
Squeeze	Squeeze function	$f(\beta^*, t)$
Adjust	Squeeze@end / Collisions@start	Alignment of TCTs
Adjust	Collisions function	$f(\theta, t)$
Stable Beams	Collisions@end	Alignment of TCTs

Table 2: Collimator settings in units of beam sigma used throughout the 2010 - 2013 LHC run.

Collimator Family	Injection	Top Energy (2010) Relaxed Settings	Top Energy (2011) Relaxed Settings	Top Energy (2012 - 2013) Tight Settings
TCP IR3	8	12	12	12
TCSG IR3	9.3	15.6	15.6	15.6
TCLA IR3	10	17.6	17.6	17.6
TCP IR7	5.7	5.7	5.7	4.3
TCSG IR7	6.7	8.5	8.5	6.3
TCLA IR7	10	17.7	17.7	8.3
TCSG IR6	7	9.3	9.3	7.1
TCDQ IR6	8	10.6	9.8	7.6
TCT IR1/5	13	15	11.8	9
TCT IR2/8	13	15	26 / 11.8	12
TCL	30	30	30	10
Inj. Prot.	8	30	30	30

warning messages is provided by the collimator controller application GUI (see screenshot in Fig. 4). Hence, the overhead vistar can act as a quick diagnostic tool for the collimator expert, while the exact warning or error message is viewed by hovering the cursor over the collimator name in the GUI. All the relevant errors and warnings are reported in the LHC Alarms SERvice (LASER) [8].

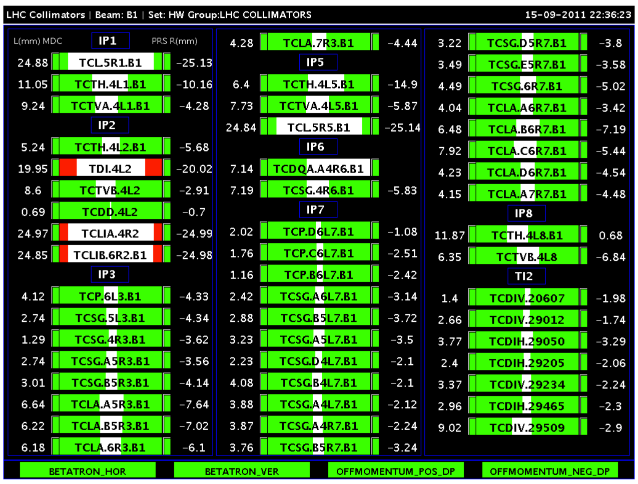


Figure 3: Collimator statuses and jaw positions B1 vistar [9].

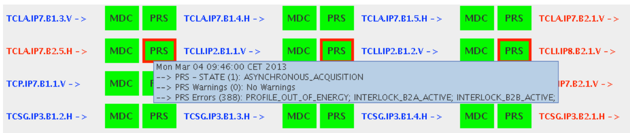


Figure 4: Collimator status display with detailed error and warning messages.

Parameters related to the higher level of abstraction can be viewed in the display shown in Fig. 5. These include the half gap opening in units of σ, as well as the nominal β-functions at each collimator. This display is also used between step 1 and step 2 of the settings generation cycle to confirm that the collimator settings in units of σ are correct before performing the beam loss maps. It is the only tool which provides an online view of the jaw gaps independently of the beam process settings.

Possible Improvements

Several possible improvements can be made to the existing monitoring system. Currently, the status of the injection protection collimators systematically turn red due to an energy interlock when the beams are ramped to top energy. To a non-expert, this may seem as though there is an issue which requires action. When the beams are dumped, all collimator statuses turn red until they are sent back to the

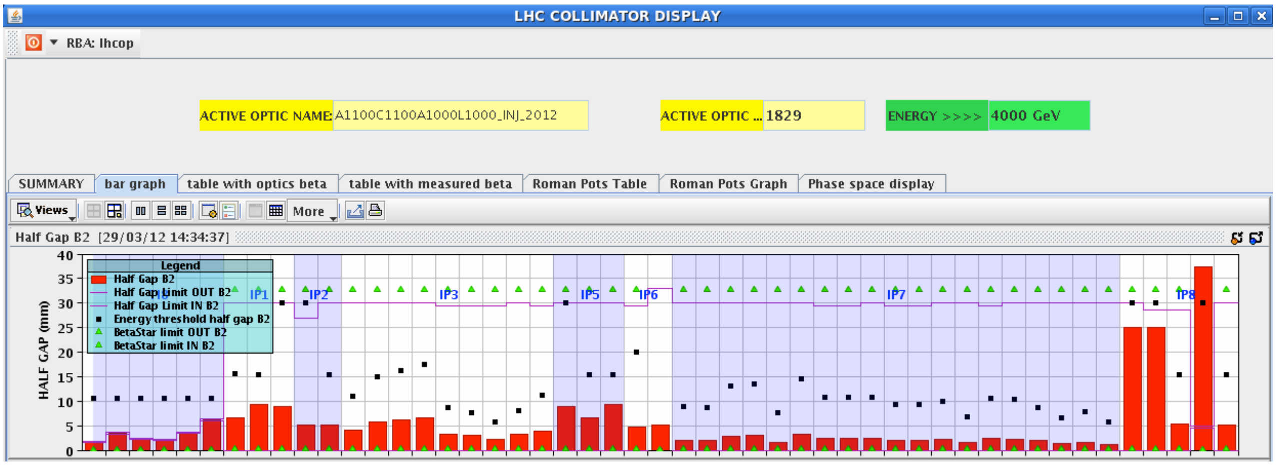


Figure 5: Higher-level collimator settings display (courtesy of D. Jacquet).

injection energy settings. Although improvements have already been made to the sequencer such that errors related to these collimators are caught during the ramp-down, the current colour-coding could potentially mask underlying problems which would otherwise be visible earlier in the fill. A clearer interlock colour-coding scheme can be introduced to cater for these scenarios.

There is a plan to develop the post-mortem collimation buffer, so that the collimation expert does not need to dig through the data when called by the operators in case of errors. Another possible improvement is the acquisition of the measured rather than the nominal β-functions by the collimator settings display in Fig. 5. Finally, the OP shift crews are encouraged to use LASER more frequently for diagnostic purposes, for example to identify warnings that appear in the collimator display. Actions can be assigned that should be taken by the shift crews for different categories of collimator warnings and errors. Input from the operations team regarding the colour-coding schemes and actions list will be required.

ERRORS ENCOUNTERED AND MEASURES TAKEN

Errors Encountered

Two types of human errors were found in the collimator settings in the March 2012 alignment campaign [10]. The first type of error occurred when aligning the TCTVA.4R1.B2 at flat top and the TCTVA.4R2.B2 in collisions. A mistake in sign was introduced for the right jaw when inputting the aligned jaw positions manually in the setup sheet used to temporarily store the values before they are imported into the beam process. This resulted in an effective shift of the TCTVA.4R1.B2 center by 1.8 σ at a correct gap of 26 σ, and of the TCTVA.4R2.B2 center by 3.8 σ at a correct gap of 12 σ.

In both cases, the increase in the losses during the loss map acquisition was too small to indicate problems with the set up. Indeed, the errors were discovered in an unrelated analysis three weeks after the alignment was made, and as the wrong settings were deemed to be not critical for the machine protection, the values were only changed two weeks later during a technical stop. These errors would not have occurred if the utility for automatic saving of the measured jaw positions would have been ready for deployment before the 2012 collimator alignment campaign.

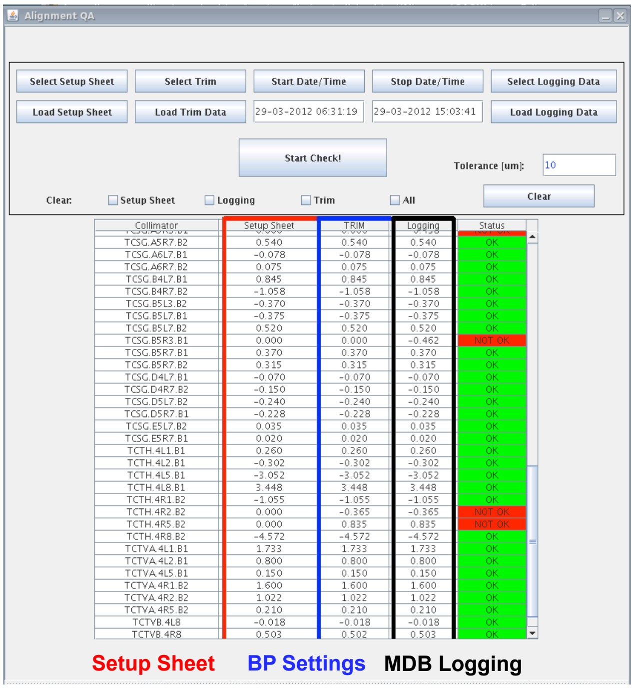
Table 3: Beam center errors encountered in the 2010-2013 LHC run, where Δx represents the shift in the beam center.

Collimator	**Beam Mode**	Δx **[σ]**	**Gap [σ]**
TCTVA.4R1.B2	Flat Top	1.8	26
TCTVA.4R2.B2	Collisions	3.8	12
TCLA.6R3.B1	Flat Top	0.2	17.6
TCLA.B5R3.B1	Flat Top	1.2	17.6
TCSG.A5R3.B1	Flat Top	2.3	15.6
TCSG.B5R3.B1	Flat Top	2.2	15.6

The second type of error was introduced when calculating the ramp functions for 4 IR3 collimators, whose beam centers were mistakenly set to zero by the Mathematica program at the end of the ramp. In this case, the errors were deemed to be small and were not corrected. As the beam process settings are generated from the measured beam center and beam size, and not from the calculated jaw positions in mm during alignment, the errors are never in the jaw gap but only in the jaw center. A list of all errors is provided in Table 3. For 1097 collimators aligned in 41 alignment campaigns in 4 years of LHC operation, this represents an error of 0.55 %.

Measures Taken

Several measures were taken to prevent similar issues in the future. The temporary setup sheet is now generated automatically by the alignment application, thus eliminating any potential human errors at this stage. In addition, a tool was created to check that the measured alignment values are consistent with the values in the setup sheet and the values in the beam process (see screenshot in Fig. 6). Since March 2012, no further issues were encountered. Future



Collimator	Setup Sheet	TRIM	Logging	Status
TCSG.A5R7.B2	0.540	0.540	0.540	OK
TCSG.A6L7.B1	−0.078	−0.078	−0.078	OK
TCSG.A6R7.B2	0.075	0.075	0.075	OK
TCSG.B4L7.B1	0.845	0.845	0.845	OK
TCSG.B4R7.B2	−1.058	−1.058	−1.058	OK
TCSG.B5L3.B2	−0.370	−0.370	−0.370	OK
TCSG.B5L7.B1	−0.375	−0.375	−0.375	OK
TCSG.B5L7.B2	0.520	0.520	0.520	OK
TCSG.B5R3.B1	0.000	0.000	−0.462	NOT OK
TCSG.B5R7.B1	0.370	0.370	0.370	OK
TCSG.B5R7.B2	0.315	0.315	0.315	OK
TCSG.D4L7.B1	−0.070	−0.070	−0.070	OK
TCSG.D4R7.B2	−0.150	−0.150	−0.150	OK
TCSG.D5L7.B2	−0.240	−0.240	−0.240	OK
TCSG.D5R7.B1	−0.228	−0.228	−0.228	OK
TCSG.E5L7.B2	0.035	0.035	0.035	OK
TCSG.E5R7.B1	0.020	0.020	0.020	OK
TCTH.4L1.B1	0.260	0.260	0.260	OK
TCTH.4L2.B1	−0.302	−0.302	−0.302	OK
TCTH.4L5.B1	−3.052	−3.052	−3.052	OK
TCTH.4L8.B1	3.448	3.448	3.448	OK
TCTH.4R1.B2	−1.055	−1.055	−1.055	OK
TCTH.4R2.B2	0.000	−0.365	−0.365	NOT OK
TCTH.4R5.B2	0.000	0.835	0.835	NOT OK
TCTH.4R8.B2	−4.572	−4.572	−4.572	OK
TCTVA.4L1.B1	1.733	1.733	1.733	OK
TCTVA.4L2.B1	0.800	0.800	0.800	OK
TCTVA.4L5.B1	0.150	0.150	0.150	OK
TCTVA.4R1.B2	1.600	1.600	1.600	OK
TCTVA.4R2.B2	1.022	1.022	1.022	OK
TCTVA.4R5.B2	0.210	0.210	0.210	OK
TCTVB.4L8	−0.018	−0.018	−0.018	OK
TCTVB.4R8	0.503	0.502	0.503	OK

Figure 6: Tool used to check the settings consistency across the values in the setup sheet, the beam process and the logged measurements.

developments envisage the storage of the beam-based measurements in LSA database tables, rather than in local files on the CCC machines.

MAD-X ONLINE AND THE LHC APERTURE METER

The online model [11] provides an environment a) for the use of MAD-X simulations and calculations as control system inputs, b) to support the operators while coping with the machine complexity, and c) to simulate various machine manipulations. The LHC Aperture Meter [12] is designed to inform operators about the current bottlenecks in the LHC. It has a number of uses, including orbit checks (e.g. ATS optics, β^* = 90 m) and aperture measurements, providing the BPM-interpolated centers at the collimator locations to speed up alignment [13]. Work is ongoing to provide a playback of the settings during ramp and squeeze, which will allow to catch errors in the settings (see example in Fig. 7).

RESULTS AND STATUS OF BPM COLLIMATORS

Collimators with embedded BPM pick-up buttons will replace the current TCTs and IR6 TCSGs in LS1. Proof-of-principle tests were held in the SPS in 2010-2011 [14], and an automatic successive approximation BPM-based alignment algorithm was developed and tested in 2012 [15]. A typical BPM-based alignment is shown in Fig. 8, with the BPM electrode signals, measured beam center and jaw positions as a function of time. The collimators are aligned by equalizing the electrode signals of the opposing buttons. The alignment is made at large jaw gaps and is completed in ∼30 s (a factor 120 less than the current BLM-based alignment time).

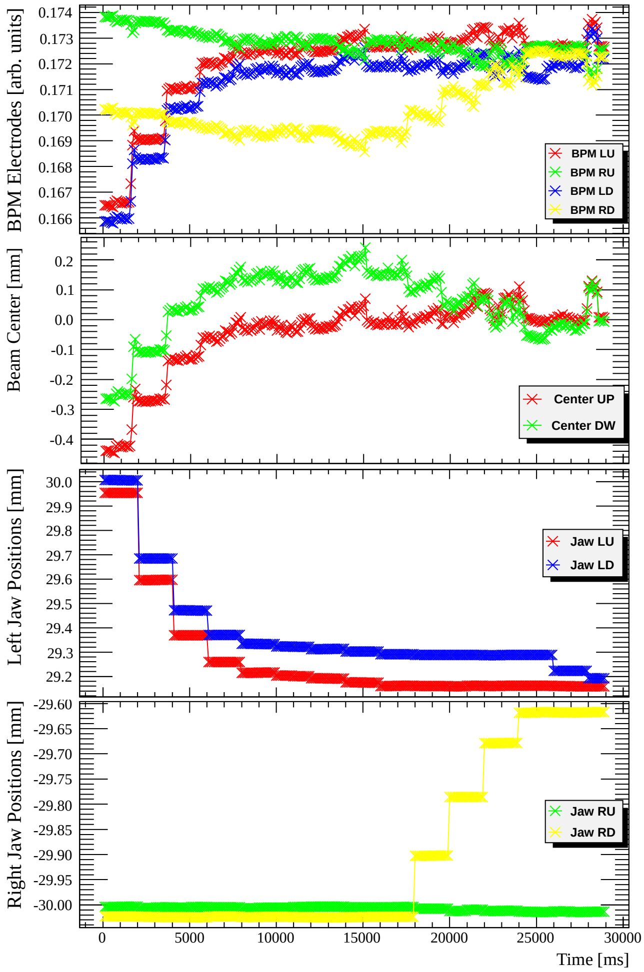


Figure 8: BPM-based collimator alignment [15].

In standard operation, the BPMs will allow to eliminate all orbit-related settings errors at the collimator locations. They will provide online monitoring of the beam position, including the possibility of placing interlocks on the orbit measurements, and fast TCT alignments, which can be performed every fill or as often as required. However, any collimator movements will have to be studied in detail to ensure that no additional risks are introduced for machine protection. A better monitoring in IR6 means that possible issues can be identified early on, rather then when the infrequent loss maps are acquired. In addition, the orbit measurement can be used for the SIS interlock of the TCDQ centering/retraction. The use of embedded-BPM collimators in operation can help to improve the β^* reach by about 15 % [16].

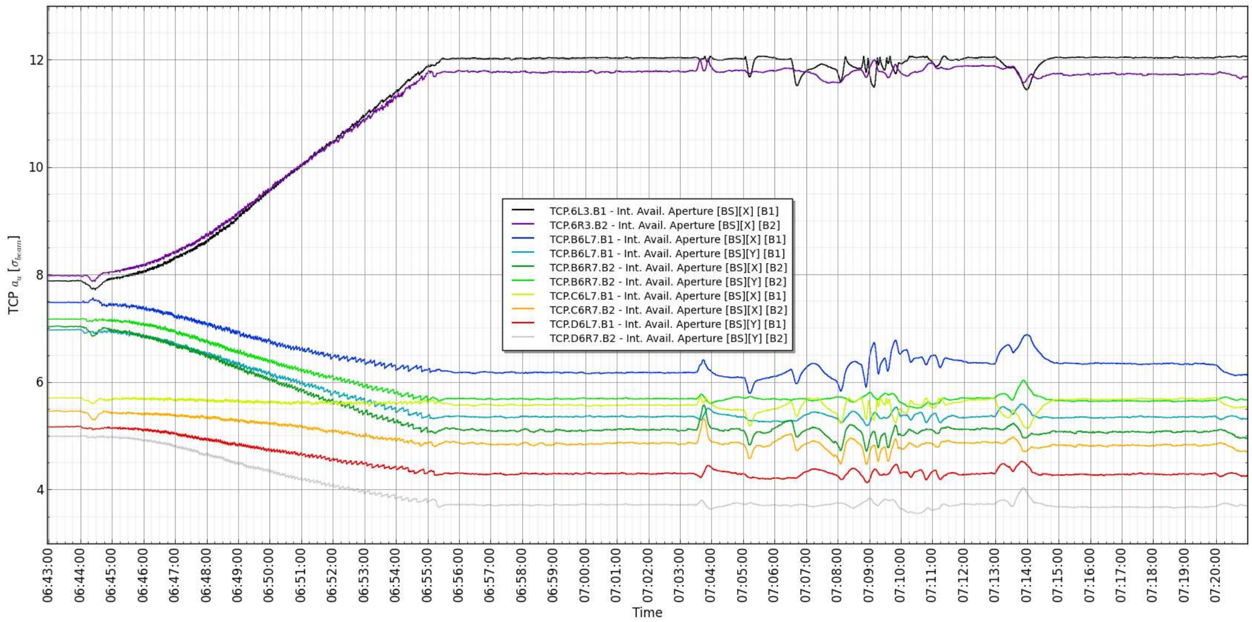


Figure 7: Evolution of the TCP collimator apertures during the ramp as calculated by the LHC Aperture Meter. Courtesy of G. J. Müller.

SUMMARY

The high energy LHC beams require cleaning at all times. The collimator settings generation and verification cycle was presented. Potential error locations in the cycle were identified, and tools to verify the settings were developed. The different components of the present top-level collimator monitoring system were discussed, highlighting the various layers of abstraction. The results and current status towards achieving operability of the new embedded-BPM collimators was discussed.

ACKNOWLEDGMENT

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BEAM BASED VALIDATION OF LHC COLLIMATOR SETTINGS

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Abstract

The collimator system provides efficient beam halo cleaning and plays an important role in passive machine protection. About 100 movable collimators are precisely aligned to the beam orbit with gaps as small as ~ 2 mm. In order to ensure the required collimation functionality, the collimator positions need to be validated. This is done by acquiring regularly controlled loss maps in each machine configuration.

During 2012, the use of the transverse damper (ADT) to excite transversally the beams in a controlled way has reduced the time to produce betatron loss maps. However, the validation of the off-momentum losses and asynchronous dumps still determines the minimum number of required fills. The experience with the loss maps in the 2010-2013 running period is reviewed and possible improvements are discussed. Aspects related to the minimum time between re-validation by loss maps, possible further improvements such as loss maps at the end of every physics fill and better online monitoring are also discussed.

INTRODUCTION

The LHC collimation system provides a multi-stage cleaning in two main cleaning insertions, IR3 for momentum cleaning and IR7 for betatron cleaning. The primary collimators (TCPs) are the closest elements to the beam in normalized transverse space, cutting into the primary halo. The secondary collimators (TCSGs) cut the particles scattered by the primaries (secondary halo) and the absorbers (TCLAs) stop the showers from upstream collimators [1, 2, 3]. The tertiary collimators (TCT) protect directly the triplets at the experimental IRs. Including the passive absorbers, the physics debris absorbers, transfer line collimators, injection and dump protection makes a total of 108 collimators. Hundred of them are movable and need to be aligned within $10-50$ μm precision to achieve the required cleaning.

During 2010-2011 betatron loss maps were made by exciting the beam by crossing the 3rd order resonance. This methods was proven to be adequate to generate loss maps of the full LHC ring, however losses were difficult to control and the full injected beam was excited with this method. In most of the cases, the fill was dumped after the first betatron loss map. In 2012, a new procedure was set in place. Loss maps were regularly acquired by exciting selected bunches with white noise using the transverse damper (ADT) [4]. This reduced the time spent in the betatron loss map validation enormously, however, due to beam-beam cross-talk, loss maps during physics had still to be generated with the tune resonance. This is now avoided by establishing the physics loss maps using non-colliding bunches with the ADT. Nowadays, all the LHC machine phases can be validated with betatron loss maps in a single fill.

We review in this paper the requirements to validate the collimation system. We discuss several improvements for better online monitoring and for loss maps procedures with a special focus on the off-momentum loss maps. The extrapolation of the loss map procedure to 7 TeV is also discussed.

MINIMUM REQUIRED VALIDATION

All collimators are set up symmetrically around the beam orbit for each phase of the LHC operational cycle (*i.e.* injection, flat top, squeeze and collisions). The alignment procedure consists of moving the collimator jaws towards the beam until a beam loss monitor (BLM) spike is observed when the individual jaws touch the beam halo. The beam centre is calculated as the average of the two aligned jaw positions. This is done only in dedicated low intensity fills with up to 3 nominal bunches, which is the safe limit to mask a subset of beam interlocks like collimator positions and BLMs.

The operational strategy during 2011 and 2012 run periods was to perform one full alignment per year of the main cleaning insertions (IR3 and IR7) and monitor regularly the losses along the ring to validate if a new alignment was needed by looking at the cleaning in the cold region and at the collimator hierarchy. For most of the new physics configurations, only the 16 TCTs collimators at the colliding IRs require to be re-aligned. This strategy proved to be successful thanks to the excellent reproducibility of the machine (orbit, optics, etc.) and collimator settings stability.

Beam loss maps are an effective way of validating the collimation system performance and of calculating the collimator BLM dump thresholds. During LHC commissioning, at the beginning of the year, all collimators are re-aligned at each individual phase of the operational cycle (*i.e.* injection, flat top, squeeze and collisions). A set of cross-checks are made during the generation of the settings, both manual and automatic [5], but the final check consists of analyzing the loss maps made in dedicated low intensity fills to quantify the leakage to the cold magnets and confirm the collimation hierarchy for both betatron-like losses and off-momentum-like losses.

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Table 1: Minimum required loss maps for commissioning.

Period	Fills	Description
Alignment	1	Parasitic betatron loss maps done during alignment
Inj. energy	3	Betatron (parasitic), positive off-momentum (1), negative off-momentum (1) and asynchronous dump (1)
Top energy	3	Betatron at flat top, squeeze and colliding (parasitic), positive off-momentum (1), negative off-momentum (1) and asynchronous dump (1) at colliding.

The two verification methods are completely complementary since loss maps will only spot losses of collimators that are close to the beam, for instance they might not spot a case when one jaw is at the correct position and the other is further out.

Table 1 shows a summary of the minimum required regular loss map validation that should be done either every 8 weeks, or after a technical stop, or after a change of the collimator settings or the machine configuration. For the first commissioning of the year, off-momentum loss maps are also required at every phase of the LHC cycle. For changes on the TCT configuration (in the colliding IRs) the minimum validation is required only for squeeze and colliding beams.

Betatron loss maps are done parasitically in all the cases. Nowadays the limiting factor are the off-momentum loss maps and the asynchronous dump, which require dedicated fills. We will review here the maximum RF frequency change required for the off-momentum loss maps.

BETATRON LOSS MAPS

Betatron loss maps are essential to check the leakage to the cold sector. This is the basic test that ensures that the machine is protected from standard collimator beam losses during the fill. Some of the quantities checked with betatron loss maps are:

- **Maximum leakage to cold sector:** for betatron losses this occurs in the dispersion suppressor (DS) of IR7. The local cleaning inefficiency is approximated to the maximum leakage to the cold magnets normalized by the losses at the primary collimator measured by the BLM:

$$\eta_c = \frac{\mathrm{BLM}^{Q8-9}}{\mathrm{BLM}^{\max}}$$

  where BLM^{Q8-9} is the measurement of the losses in Q8 or Q9 cell in IR7, which correspond to the magnets that will quench first in case of high losses. $\mathrm{BLM}^{\max}$ is the loss at the primary collimator. This quantity, the cleaning inefficiency η_c, was shown to be stable during the year but depends on the collimator settings. Any displacement from the expected value would indicate a problem on the alignment or a degradation of the cleaning system. Cold losses at the rest of the ring are also checked to be well below the maximum leakage, otherwise a detailed investigation of the loss peak is done.
- **Leakage to other collimators:** we compare the normalized losses in all IPs (at the collimators) with previous loss maps. The ratio with respect to the primary needs to be preserved, see Fig. 1.
- **Collimation cleaning hierarchy:** the cleaning hierarchy is consistently checked by looking at the distribution of the losses at the collimators in the cleaning insertion (in this case IR7). The losses at the collimators should decrease with the beam direction. This is seen in Fig. 2 for Beam 1 betatron cleaning.

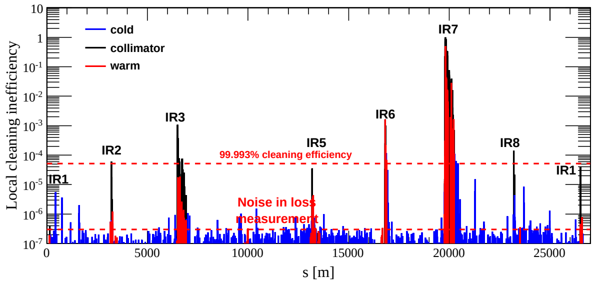

Figure 1: Distribution of the losses in the LHC ring while exciting Beam 1 in the horizontal plane.

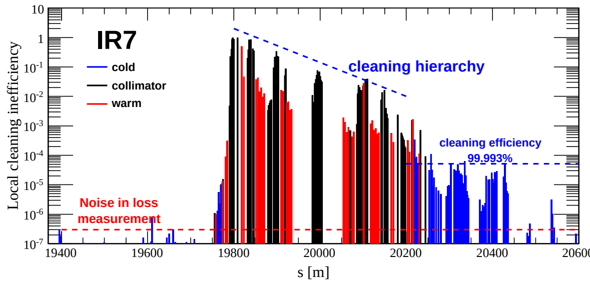

Figure 2: Distribution of the losses in the betatron cleaning insertion (IR7) while exciting Beam 1 in the horizontal plane.

OFF-MOMENTUM LOSS MAPS

Off-momentum cleaning in IR3 is also validated in dedicated low intensity fills by looking at losses artificially generated by changing the LHC radio frequency (RF) by ± 500 Hz in order to generate an off-momentum shift big enough to dump the beam on the TCP of IR3. Fig. 3 and 4 show the cleaning inefficiency for this type of losses. The quantities checked in these loss maps are:

- **Maximum leakage to cold sector:** typically the off-momentum cleaning inefficiency is about 10^{-4}.
- **Leakage to other collimators:** in off-momentum loss maps, for the IR3 settings used in 2010-2012, the highest loss occur at IR3 as opposed to the betatron

losses were the peak appears in IR7. The leakage to all IPs is checked with particular emphasis of TCTs. These are metal collimators with high-Z (Tungsten) to protect the triplet quadrupoles, they have enhanced efficiency but are more sensitive to damage. These TCTs catch the off-momentum leakage from IR3 and therefore the leakage to these collimators should be controlled, see Fig. 3.

- **Collimation cleaning hierarchy:** the losses peak at both TCPs (Beam 1 and 2) because the RF is coupled to the two beams, see Fig. 4. The losses should still decrease with the beam direction (as for the betatron loss maps).

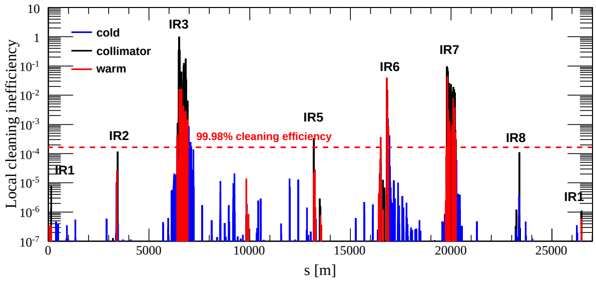

Figure 3: Distribution of the losses in the LHC ring for a negative off-momentum loss map.

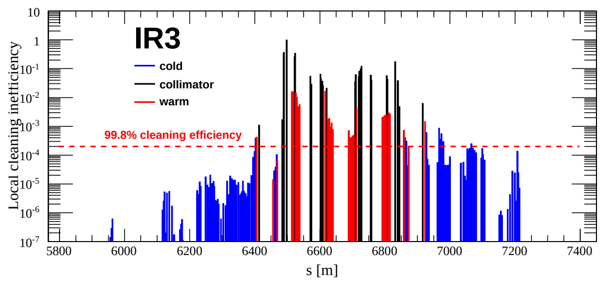

Figure 4: Distribution of the losses in the momentum cleaning insertion (IR3) for a negative off-momentum loss map.

THE NEED OF LOSS MAPS REFERENCES

During the previous running periods, the loss maps were extremely useful to spot problems during the collimator alignment. An example of this is shown in Fig. 5. This shows a broken cleaning hierarchy for Beam 2 during the proton-lead commissioning since the losses are not decreasing with the beam direction. The error was at the TCLA.A6L7.B2 collimator that was displaced by 700 μm. The problem was caught before the end of the alignment and corrected within few minutes (see Fig. 6). The correct settings were released for operation.

However, misalignment problems cannot always be spotted. Loss maps cannot catch cases where the misalignment is very small, neither can they distinguish between impacts at the left or the right collimator jaw. It is very important to have reference loss maps to compare the expected losses with the measured ones. For example, in

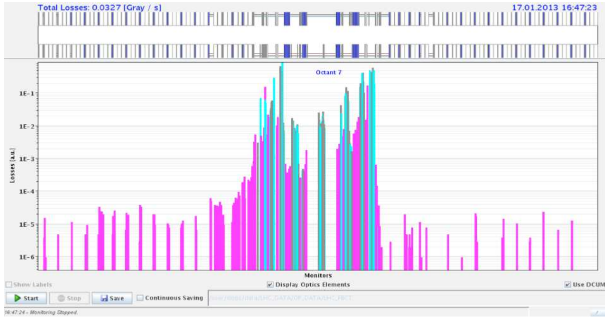

Figure 5: Distribution of the losses in IR7 during an alignment problem.

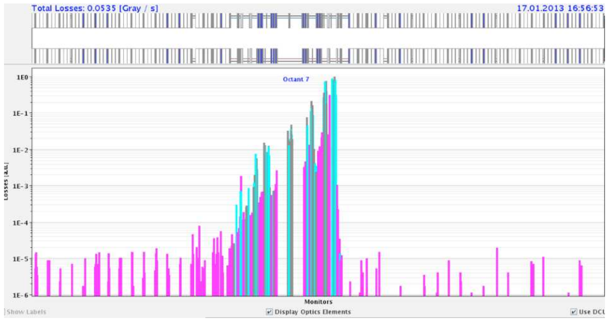

Figure 6: Distribution of the losses in IR7 after the correction of the alignment problem at the TCLA.A6L7.B2.

2012 we had a misalignment of the TCT in IR2 that could not be spotted in the first loss maps because it was the first time that they were measured with tight collimator settings at 4 TeV. In this case it was observed that the cleaning at the triplet was satisfactory but we could not spot that the losses at the TCT were higher than required due to the lack of references. Instead, the misalignment was spotted by the manual check of the generated settings. Since dedicated simulations did not reach the needed accuracy level to predict the exact leakage to other IRs, it is very difficult to predict the exact leakage to the other IRs for major changes to the collimator settings and optics. The simulations are being improved to increase the accuracy of the predictions, see [6].

PROSPECTS FOR IMPROVEMENTS

Betatron loss maps

At higher beam energies it will be more delicate to measure loss maps. At 7 TeV the beam is more dangerous and it is more difficult to mask interlocks, therefore we will be acquiring loss maps very close to the dump limit. The latest estimation of the damage limits for a tertiary (tungsten) collimator shows that about $5 \cdot 10^9$ protons impacting a tertiary collimator could permanently damage it [7, 8, 9]. Therefore, we evaluate here the minimum intensity loss to measure the betatron loss maps and how to control the loss rate:

- **Minimum excited beam intensity:** the minimum intensity loss, $\mathrm{R_{min}}$, needed to measure a cleaning inefficiency at Q8 of $\eta_c \approx 5 \cdot 10^{-5}$, is defined by the following formula

$$\mathrm{R_{min}} = \frac{\mathrm{BLM_{bkg}}}{\eta_c} \times f_{\mathrm{Gy \to p}}$$

where $\mathrm{BLM_{bkg}} \approx 3 \cdot 10^{-7}$ Gy/s is the BLM background or noise level and $f_{\mathrm{Gy \to p}} \approx 1.2 \cdot 10^{12}$ p/Gy the calibration factor to convert the BLM measured signal into number of protons lost per unit time. Thus the minimum intensity loss is of the order of $\sim 8 \cdot 10^9$ p/s [10]. This was tested during the proton-lead run, where loss maps were routinely made by exciting single pilot bunches of $\sim 10^{10}$ p/bunch with enough resolution to measure the cleaning.

- **Control of intensity loss rate:** the transverse damper has demonstrated its ability to control the intensity loss rate very effectively. As an example of small losses controlled by the ADT, several aperture measurements were done in 2012. In those cases the ADT was used to slowly blow up 1 pilot bunch ($\sim 10^{10}$ protons).
- **Excitation of individual bunches:** during the 25 ns run in December 2012, it was also proved that excitation of single bunches separated by 25 ns in a 12 bunch train was possible with the ADT, while leaving the adjacent bunches unaffected. This opens the possibility to make loss maps during standard fills *i.e.* fills with beam intensity above the setup beam flag (SBF) limit.

Off-momentum loss maps

Nowadays, off-momentum loss maps and asynchronous dump tests are the limiting tests after changes in the machine, since they require a dedicated fill at top energy each. This will remain the case for asynchronous dump. However, in the case of off-momentum loss maps, the fill is usually dumped by the unmaskable BLMs when the losses become too high. We investigate here the possibility of reducing the RF frequency change required to have dominating off-momentum losses.

Minimum frequency change For this analysis we use a 12 Hz logging of the BLM data, the 81.92 ms running sum (RS07), to identify precisely when the off-momentum losses dominate over the betatron losses. Fig. 7 and 8 show the evolution of the losses in the primary collimator of IR3 and primary horizontal collimator in IR7 for a negative off-momentum loss map at flat top using the 1 Hz logged data (~ 1.3 s running sum, RS09) and 12 Hz logged data (RS07) respectively. Beam losses start to appear after the RF frequency change (Δf) started, this is shown in Fig. 9. The losses in IR3 (off-momentum cleaning) start dominating over the losses in IR7 (betatron cleaning) when the RF frequency change is ~ 150 Hz and the maximum peak loss in IR3 happens at $\Delta f \approx 200$ Hz which is also when the beam is dumped. However, this strongly depends on the collimator settings, in particular on the sharing between IR3 and IR7. Nevertheless, this shows that in principle it is possible to stop the frequency change earlier (before triggering a beam dump) to observe the off-momentum cleaning hierarchy in IR3.

A detailed MD study is needed to get the optimal frequency change for the off-momentum loss maps, but tentatively a value around 150 Hz seems indicative from the present data.

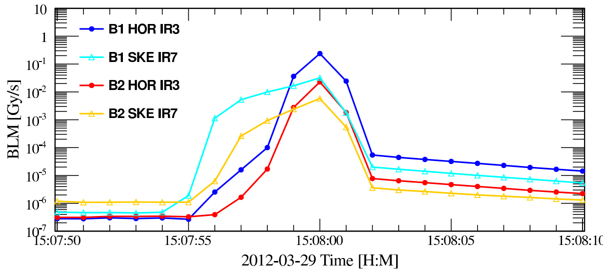

Figure 7: Loss distribution as a function of time for primary collimator in IR3 and primary skew collimator in IR7 using the slow logging of the BLM data (1 Hz).

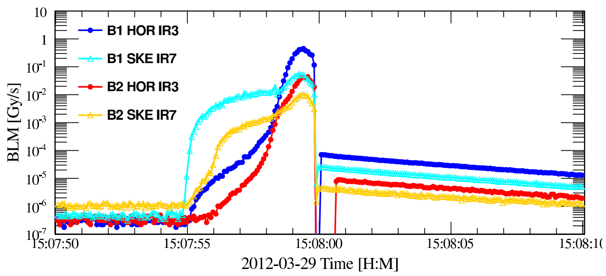

Figure 8: Loss distribution as a function of time for primary collimator in IR3 and primary skew collimator in IR7 using the fast logging of the BLM data (12 Hz).

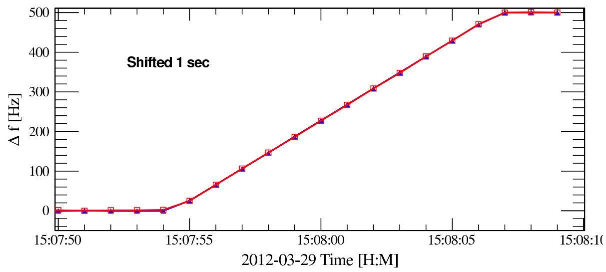

Figure 9: RF frequency change as a function of time.

OTHER IDEAS

Continuous loss maps during the cycle

During 2010-2013, loss maps were only taken at the start and end of each LHC cycle. However, if a combined ramp-squeeze at 6.5 TeV is envisaged it would be important to validate the cleaning during the ramp. Similarly, a continuos loss maps validation during the squeeze should be required if more complex squeeze configuration will be used *i.e.* moving secondary collimators closer to the beam after reaching a certain value of $\beta^\star$. On this subject, two

MDs were made in 2012 in order to check the possibility of making continuous betatron loss maps in Beam 1 and 2 (horizontal and vertical) during the energy ramp [11]. The cleaning at Q8 was measured as a function of beam energy while the collimators were moving from injection settings to tight settings. It is observed that the cleaning was stable during the cycle, see Fig. 10.

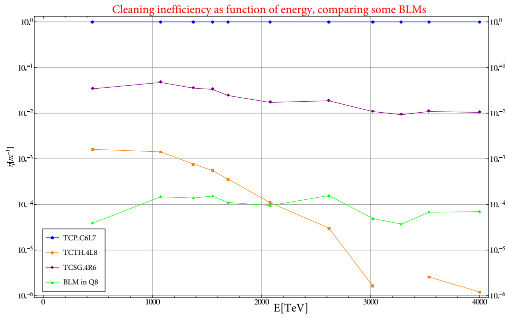

Figure 10: Leakage to Q8 and tertiary collimators during the energy ramp [11].

Online monitoring and post mortem analysis

During regular fills there are losses at the collimators due to beam instabilities, orbit shifts, etc. If the level of the losses is high enough ($> 10^{10}$ p/s) it is possible to observe the cleaning hierarchy in IR7 and to measure the cleaning inefficiency. An example of this is shown in Fig. 11, however:

- it is difficult to distinguish losses from the 2 beams
- it is difficult to disentangle the plane of the losses.

On the other side, a more realistic approach for semi-online monitoring would imply to perform end of fill loss map acquisitions and post mortem analysis, provided that we can control the loss rate, interlock the ADT, etc. However, the option to measure loss maps before dumping regular physics fills needs further studies (*i.e.* can we excite the beam with full intensity in the machine?).

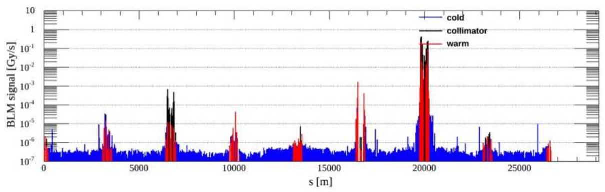

Figure 11: Losses during a regular fill on 2012-12-04 18:09:29 along the LHC ring.

CONCLUSIONS

The minimum requirements to validate the collimation system performance were shown. The adopted strategy (every 8 weeks or after a technical stop or after major machine configuration changes) was found to be adequate. The 8 weeks re-validation was hardly needed, almost all validation loss maps were driven by major machine configuration changes or technical stops.

Regarding improvements of the the betatron loss maps, the ADT was shown to be extremely useful. The beam losses can be controlled to keep the losses below the dump thresholds and moreover, individual bunches with 25 ns spacing can be excited independently. The ADT is also capable of generating continuous losses in dynamic situations *i.e.* during the energy ramp and squeeze. The minimum intensity loss needed for the loss maps was found to be about a pilot bunch of 10^{10} protons for an excitation of 1 second. This should be the similar at 7 TeV.

At this point, the off-momentum loss maps still need dedicated fills but there is the possibility of controlling more precisely the RF frequency change needed, to the point of not dumping the beam. In this case, we could envisage to measure both off-momentum sides in the same fill, reducing the operational time requirements for the loss maps validation, including the asynchronous dump test, to one fill instead of 3 fills. A more detailed evaluation on the minimum intensity and the masks required for the loss maps is under discussion, but it is important to remind that we need at least 3 bunches to find collisions everywhere. Moreover, the bunches should be in the dynamic range of the BPMs, so that the orbit before the test is reliable.

Online monitoring cannot easily substitute the standard validation with clean loss maps, since this would require having beam instabilities that generate high beam losses in the 2 planes in all the different phases of the operational cycle. However, online monitoring can give extra information between validation loss maps. Regular loss maps at the end of the fill, provided that there are non-colliding bunches and that they can be done safely with high intensity in the machine, might be a better option for a more regular validation of the cleaning. Overall, not much time was needed for the betatron loss maps validation, due to the dramatic improvement provided by the ADT. Moreover, this time was in the shadow of the machine commissioning. The majority of the beam-time needed for collimation setup and validation is nowadays coming from the fills for off-momentum loss maps and asynchronous dump test.

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COLLIMATOR HIERARCHY LIMITS: ASSUMPTIONS AND IMPACT ON MACHINE PROTECTION AND PERFORMANCE

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Abstract

Collimator settings are key parameters for the LHC performance. This paper summarizes first the evolution of the collimator settings, tightly connected to β^*, during the runs 2010–2012, followed by an overview of how the margins between collimator families are calculated. Ongoing work on improving the models of margins between collimator families for optics imperfections is presented. Finally we give an outlook towards the LHC performance after the long shutdown of the LHC and the possible gains from new collimators with integrated beam position monitors (BPMs).

INTRODUCTION

The LHC collimation system [1, 2, 3, 4] should provide both cleaning—the removal of unavoidable continuous beam losses during routine operation—and machine protection in case of failures and abnormal operation. The collimation system is based on a multi-stage cleaning hierarchy, where the different collimator families have to be ordered strictly with different distances to the beam for optimal cleaning performance and machine protection [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. We call the horizontal TCTs TCTH and the vertical ones TCTV. The TCTs are not robust themselves and should be positioned outside the aperture of the dump protection in IR6 in order to avoid the risk of being damaged during a dump failure [1]. The hierarchy is schematically illustrated in Fig. 1.

LHC collimation is directly related to the performance of the LHC as it limits the achievable β^*. When $\beta^*$is decreased to gain in luminosity, the beam size increases in the inner triplets, so that the margin to the aperture there decreases. In a squeezed optics, the triplets are the limiting aperture bottlenecks of the ring, which must always be protected by the LHC collimation system. Therefore, β^*should be as low as possible without compromising machine protection.

The cleaning and protection are qualified with provoked losses with safe beams after aligning all collimators [5] and, in subsequent high-intensity fills, the collimators are driven back to the previously qualified settings relying on the machine reproducibility. However, the reproducibility is not perfect and drifts may occur, e.g. in the optics or orbit. Therefore, sufficient margins are needed between the collimator families in order for the collimation hierarchy to be respected for all realistic drifts. These margins are calculated using the models outlined in Refs. [6, 7, 8] as a function of the observed machine stability—we give a review of how this is done later.

Thus, starting from the setting of the TCP7, and adding the necessary margin to each family, the required setting of the TCTs can be calculated and, by calculating the necessary margin between TCT and aperture according to the same principles, the minimum aperture that can be protected is defined [6, 7, 8, 9]. By comparing with the required aperture in different configurations of $\beta^*$and crossing angle, the minimum β^*can be calculated.

EVOLUTION OF COLLIMATOR SETTINGS AND β^*2010–2012

The collimator settings used during the previous years for physics operation at top energy, together with the resulting β^*, are shown in Fig. 1. All settings are shown in units of σ_n, 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. Instead we call the real standard deviation of the beam, accounting for the actual emittance, σ_r, which may vary between fills.

In 2010, a safe and conservative approach was taken. A TCT setting of 15 σ_n 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 [6] 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 [10] 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^* [11] and allowed $\beta^*$to be reduced to 1 m keeping the relaxed collimator settings. The results of all the aperture measurements in 2011 are summarized in Ref. [12]. This

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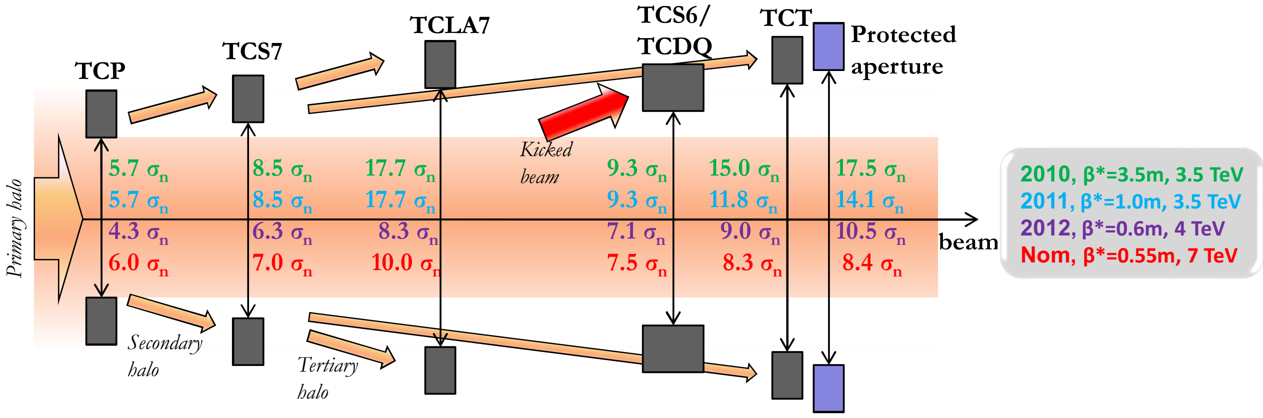

Figure 1: (color) Schematic illustration (not to scale) of the collimator settings and the minimum aperture that can be protected during the physics runs in 2010 (3.5 TeV), 2011 (3.5 TeV), and 2012 (4 TeV), together with the nominal settings (7 TeV).

reduction in $\beta^*$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 $\beta^* = 1$ 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 [13, 14, 15, 16]. The same studies showed also that a closer TCP7 setting was 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 realistic total error [8]. The combination of tight settings and smaller margins made it possible to squeeze $\beta^*$to 60 cm, resulting in a significant gain in luminosity.

CALCULATIONS OF MARGINS IN HIERARCHY

In this section, we summarize the models used presently (2012 and later) to calculate the margins in the collimation hierarchy, both for cleaning and machine protection. More details can be found in Refs. [6, 7, 8, 9].

TCP7 setting

The first ingredient in the calculation of $\beta^*$is the TCP7 setting—moving the TCP7 closer to the beam allows the rest of the hierarchy to follow, thus allowing a smaller aperture margin and β^*. The TCP7s cannot, however, be positioned so far in that they scrape significant fractions of the beam core, which constrains the settings to above 3–4 σ_r.

Furthermore, the impedance of the collimators and the risk of instabilities increase with tighter gaps [17]. Recent calculations indicate that the contribution of the TCPs to the total machine impedance is less than 30% [18].

Another reason for not having too small gaps is that this is more demanding for the orbit correction - if the orbit makes a sudden jump, more beam is scraped off at the TCP7s with a tight setting, possibly resulting in large losses or beam dumps.

Exact theoretical predictions of these limitations are very challenging. Therefore, the tight TCP7 setting used during the 2012 physics run was based on beam tests carried out at different occasions during the 3.5 TeV operation in 2011 [13, 14, 15, 16]. All collimators were moved to tighter gaps and a TCP7 setting of 4 σ_n was qualified at 3.5 TeV (to be compared to the 5.7 σ_n used in physics in 2011).

Margins for cleaning

The margins for cleaning, between TCP7 and TCS and TCS and TCLA in IR7, and between IR7 and IR6, are although important, less critical than the margins for machine protection. If the hierarchy would break and a TCS7 would intercept primary halo, the cleaning efficiency risks to drop, possibly causing beam dumps and the loss of valuable integrated luminosity for the experiments. Although this scenario should evidently be avoided, it does not imply an immediate danger for the LHC and it can be corrected if observed (for example by realigning the collimators or increasing the margins).

During 2010 and 2011 these *non-critical* retractions were kept constant in mm after the injection plateau (so-called relaxed settings [19, 20]). In order to decrease the non-critical margins as much as possible for the 2012 run, the limit for breaking the hierarchy after a long time of operation without re-aligning collimators was explored empirically in 2011 [13, 14, 15, 16]. Based on these studies, the retraction TCS7-TCP7 was reduced from 2.8 σ_n in 2011 to 2.0 σ_n in 2012. Note though that σ_n is not the same in the two cases, as the geometric emittance changes with energy.

The margin between TCS7 and TCS6 in the relaxed scheme was 0.8 σ [20], which was found to be already rather tight and close to the nominal retraction. Therefore, the 0.8 σ_n retraction TCS6-TCS7 has been kept unchanged in 2012.

The cleaning margins in the momentum cleaning in IR3 do not presently impose direct limitations on the machine performance and have been kept at the same relaxed setting in 2012 as in 2010-2011.

Margins for machine protection

The margins between the dump protection and the TCTs, or between the TCTs and the aperture, are needed for machine protection. If an asynchronous beam dump occurs with an incorrect hierarchy, fractions of one or several bunches could possibly impact and damage either the TCTs themselves or the aperture bottlenecks that they should protect [1, 21].

To calculate these *critical* margins between IR6 and the TCTs, and between TCTs and aperture, an in-depth analysis is performed. All factors that change the hierarchy have to be considered and combined. They are: orbit drifts, optics errors, setup error (inaccuracy of the collimator alignment), and positioning error (fill reproducibility of the collimator position). We work in the very conservative simplifying assumption of a 90° phase advance from the dump kickers to all subsequent collimators and aperture bottlenecks. This is approximately true for the dump protection (94° from the central kicker) while TCTs and triplet have phases farther away from 90°. This is clearly a pessimistic assumption, which gives room for the worst possible phase advance errors. A more detailed model, which accounts for the actual phase advance and the areas of the initial phase space that reach downstream apertures, is discussed later.

To assess the orbit margin, we calculate the reduction in margin caused by orbit movements with respect to the orbit that was used during the qualification. This calculation is performed using logged data from the run in the previous year. The change in *minimum* margin ΔM_{min} between a protection device (subscript 1) and a device to be protected (subscript 2) is [7]

$$\Delta M_{min} = |x_{r2}| - |x_{r2} + \Delta x_2 \pm \Delta x_1|. \qquad (1)$$

Here x_{ri} is the offset of the reference orbit at the time of the qualification at device i with respect to the center of the aperture, and Δx_i the change in orbit since then. All quantities are given in units of σ_n. If the device 2 is a collimator, which was centered around the beam at the time of the qualification, we set $x_{r2} = 0$.

As an example, Fig. 2 (top) shows the distribution of the obtained reduction in margin due to orbit movements between the vertical TCT in IR1 beam 1 (B1) and the triplet aperture during 2012. The orbit was sampled and analyzed every 10 s during stable beams in all physics fills. The

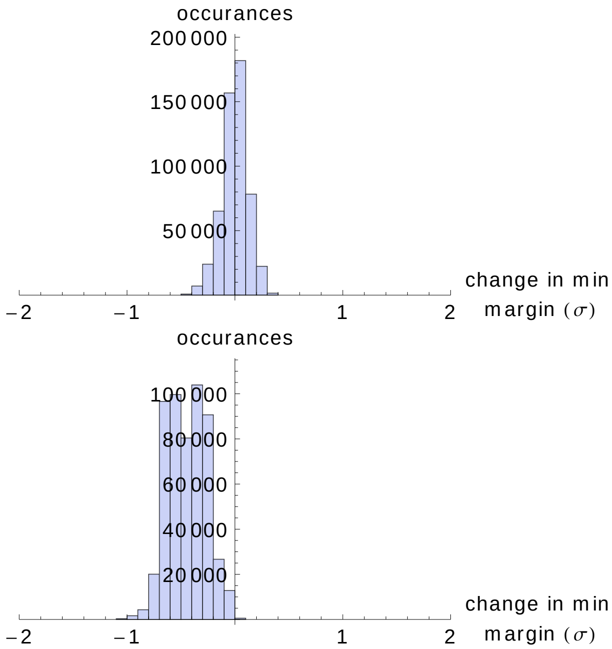

Figure 2: Change in margin due to orbit movements between the IR1 TCTV in B1 and the aperture bottleneck in triplet (top) and the corresponding distribution for the TCTH in IR5 B2 (bottom). All running periods in 2012 with stable beams and $\beta^* = 0.6$ m were accounted for, except where luminosity scans were performed. A negative change corresponds to a reduced margin.

observed orbit shifts are dominated by the fill-to-fill variations. Fig. 2 (bottom) shows the corresponding distribution for IR5 B2 in the horizontal plane. Here the distribution is not centered around zero—instead, there is a non-zero average shift in the orbits in stable beams from the reference orbit at the qualification. A shift of the center was observed also for the cases not shown in Fig. 2, although smaller than for IR5 B2.

Using the distribution of the reduction in margin, we calculate the final needed margin by demanding that it should be respected during at least 99% of the time spent in stable beams, which results in acceptable risk levels [6, 8].

The needed margin M_β for β-beat is [6]

$$M_\beta = n \left(\sqrt{\frac{\beta_n}{\beta_r}} - 1 \right), \qquad (2)$$

where we assume that the β-function has the value β_r instead of the nominal β_n. It should be noted that M_β depends only on the amount of β-beat and the nominal opening of the collimator—the smaller the opening, the smaller the absolute error in σ_n. We use an upper bound of 10% on the ratio of the β-functions [22, 23, 24].

The remaining margins for setup and positioning are assigned constant values of 10 μm and 50 μm respectively [6]. This typically corresponds to less than 0.1–0.2 σ_n. Furthermore, we assume a margin of 0.2 σ_n for lu-

Table 1: The estimated errors in units of σ_n from various error sources at the dump protection in IR6 and the TCTs.

(σ_n)	IR6	TCT
orbit	1.1	1.1
β-beat	0.35	0.4
Positioning	0.08	0.05
Setup	0.02	0.01
Lumi scans	—	0.2

minosity scans as calculated for the drifts between TCT and triplet at $\beta^* = 3.5$ m in Ref. [6]. This margin has proven to be sufficient also for larger scans to $\pm 3\sigma_n$ at smaller β^*.

To calculate the final margins, all errors at devices 1 and 2 have to be combined. In 2010 and 2011 the maximum possible error, given by the linear sum, was used. This method, although extremely safe, requires rather large margins, which in turn implies a larger β^*. Since it is highly unlikely that all errors would simultaneously assume their maximum values and add up in the same direction, we deploy a more moderate approach and treat the errors as statistically independent by summing them in square. Exception to this rule are the luminosity scans, since they are caused by a deliberate perturbation. In conclusion, we therefore obtain the total margin M_{tot} as

$$M_{\text{tot}} = M_{\text{scan}} + \sqrt{M_\beta^2 + M_{\text{orbit}}^2 + M_{\text{pos}}^2 + M_{\text{setup}}^2}.$$

As an example, obtained numeric values for the different components of the margins used at IR6 and at the TCTs in 2012 are shown in Table 1. As can be seen, the dominating error source is the orbit, followed by the β-beat.

ONGOING IMPROVEMENTS ON MARGINS FOR MACHINE PROTECTION

Although the margin models described in the previous section have allowed a significant reduction in β^*since 2010, they are still based on assumptions that under some circumstances are pessimistic, e.g. the assumed 90° phase advance from the dump kickers. To understand the influence of the phase advance on the needed margins, we consider the normalized betatron phase space (X_0, P_0) of one bunch at an extraction kicker, where it receives a kick θ. Using linear optics, the normalized phase space coordinates are propagated to any later position (X_i, P_i). The condition that a particle is outside the aperture A_i at location i can then be written as:

$$|X_i| \geq A_i \Leftrightarrow |C_{0i}X_0 + S_{0i}P_0 + S_{0i}\theta + D_i\delta| \geq A_i \quad (3)$$

Here (C_{0i}, S_{0i}) are the transfer matrix elements from 0 to i, D_i the periodic dispersion at i and δ the fractional momentum deviation.

The inequality (3) defines a region R_i in the initial phase space at the kick. Analogue to the method used in Ref. [25], the fraction of particles outside the aperture limit A_i is given by integrating the beam distribution ρ over R_i. If there are other aperture restrictions A_j with $j < i$ upstream of A_i, the integration region defining the particles hitting A_i is the phase space area inside all aperture limits A_j (denoted by the complement set R_j^c) but outside the aperture limits A_i.

The fraction f_i of particles outside A_i thus becomes

$$f_i = \iiint\limits_{R_i \cap R_{i-1}^c \cap \ldots \cap R_1^c} \rho(X_0, P_0, \delta)\, \mathrm{d}X_0\, \mathrm{d}P_0\, \mathrm{d}\delta. \quad (4)$$

In order to calculate the leakage fraction, we assume furthermore that ρ is Gaussian:

$$\rho(X_0, P_0, \delta) = \frac{1}{2\pi\sigma_n^2} \exp\left(-\frac{X_0^2 + P_0^2}{2\sigma_n^2}\right) \times \frac{1}{\sqrt{2\pi}\sigma_\delta} \exp\left(-\frac{\delta^2}{2\sigma_\delta^2}\right) \quad (5)$$

As an example, the leakage integral in Eq. (4) and its integration regions, taking into account only the dump protection situated at 7.1 σ_n as in 2012 and all TCTs are illustrated in Fig. 3 for $\beta^* = 60$ cm assuming a perfect machine. Each collimator is represented by a cut in the initial phase space, where earlier cuts shadow later ones. For easier readability, the IR7 collimators are not shown.

The TCT receiving the highest leakage in this case—evaluated numerically with *Mathematica* to 3‰ of the initial bunch at this particular θ, where half of the bunch passes the dump protection—is in IR1 B1 and we therefore focus on this collimator. The total impacts that it will see during a dump failure is Eq. (4) summed over all bunches, each having a different kick angle θ.

In Fig. 4 we show this summed leakage over all bunches, assuming a 50 ns bunch spacing, to the IR1 TCTH as a function of the retraction between the TCS6 and the TCTs. The results were obtained by keeping the TCS6 opening constant and checking the leakage for different TCT openings, using the kick angles for a single module pre-fire (1 of the dump kickers fires and the other follow after short delays). The exact form of $\theta(t)$ provided by Ref. [26] was used. This is considered as the worst dump accident in terms of beam risking to hit sensitive equipment. The results are obtained by considering 1000 random non-perfect optics configurations, with an average resulting β-beat of 10–15%. The point shown for every TCT retraction is the leakage which is larger than 99% of the studied scenarios.

In Fig. 4, we have included also the TCT 7 TeV damage limits as given in Ref. [27], and the same limits scaled by the energy ratio to 4 TeV. These limits were calculated assuming a fixed impact parameter of 0.5 mm for a single bunch and can be improved using our studies where instead fractions of several bunches impact.

We show two limits: both when plastic deformation starts to occur, and when particle detachment occurs. Above the latter limit, a considerable downtime of the LHC has to be envisaged. Between these two thresholds, the TCTs can be moved orthogonally to the collimation plane

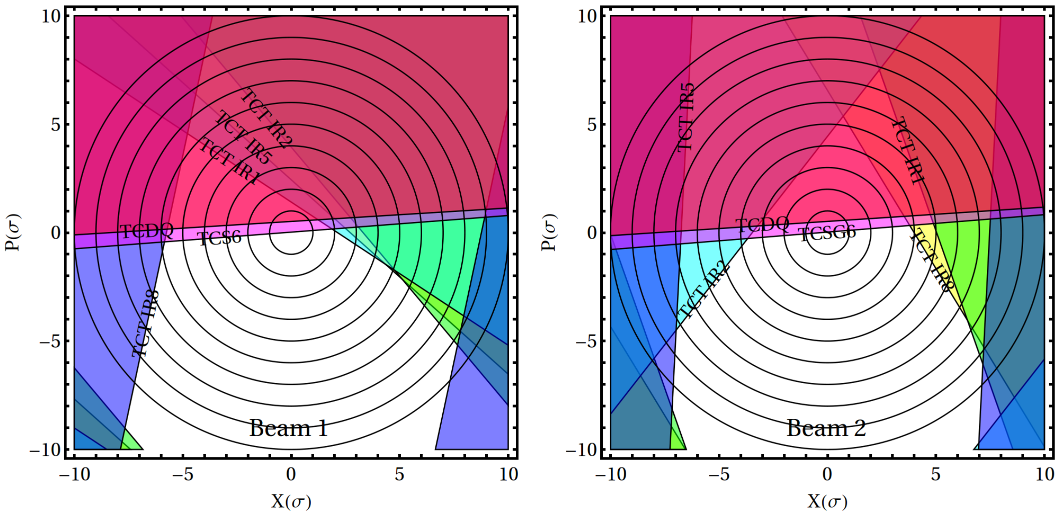

Figure 3: Example of the on-momentum integration regions defined by Eq. (3) for the dump protection collimators (TCS6 and TCDQ) and all TCTs in B1 (left) and B2 (right) for a setting of 7.1 σ_n for the TCS6 and the TCTs, while the TCDQ is positioned at 7.6 σ_n. The kick θ is also at 7.1 σ_n and a perfect machine is assumed. The circles represent lines of constant phase space density at every σ_n. The TCDQ is the first collimator seen by the beam, followed by the TCS6 and the TCTs. A perfect optics and $\beta^* = 60$cm was assumed.

to expose a fresh undamaged surface to the beam. Comparing to the assigned margin used in the 2012 run of 0.55 σ_n, we see that this was sufficient to be below even the 7 TeV limit for plastic deformations. This confirms that the method based on shadowing described in previous sections gives safe results but slightly on the pessimistic side. The protection was thus largely sufficient during the 2012 run.

Furthermore, out of the 1000 studied optics configurations we study the one with the highest leakage in more detail. This case has been simulated with a modified version of SixTrack [28, 29]. This simulation setup is more accurate than the numeric integral in Eq. (4), since nonlinearities and out-scattering from the collimators are accounted for, but at the same time significantly slower in terms of CPU time, which makes it impractical to study many configurations.

As an example of the SixTrack result, Fig. 5 shows the simulated losses around the LHC for the most critical bunch. As can be seen, the TCT in IR1 receives a very significant leakage, and, summed over all bunches, the integrated intensity hitting it is about 30% of a bunch. The coordinates of the inelastic interactions on the TCTs are available as starting point for further studies of energy deposition and structural analysis, as was done in Ref. [27]. This could in turn allow updated damage limits.

Our model for integrating the fractions of a bunch hitting a certain aperture bottleneck can also be updated to include random errors for the other sources, which will allow an alternative coherent model to calculate the margins.

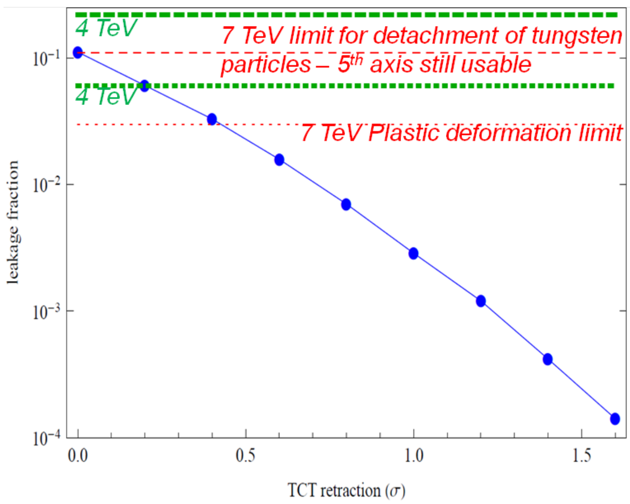

Figure 4: The integrated leakage to the TCTH in IR1, B1, during a single-module pre-fire dump accident, summed over all bunches with 50 ns spacing for an optics with β^*=60 cm, as a function of the retraction between the TCS6 and the TCTs. The leakage fraction is expressed in units of 1 nominal bunch. The point shown for every TCT retraction is the leakage which is larger than 99% of the studied scenarios.

COLLIMATION AND β^*REACH AFTER LS1

Upgrades and maintenance of the collimation system are planned to take place during LS1. One upgrade is of importance for the calculation of the hierarchy margins and β^*: the replacement of all TCTs and TCS6 by new collimators

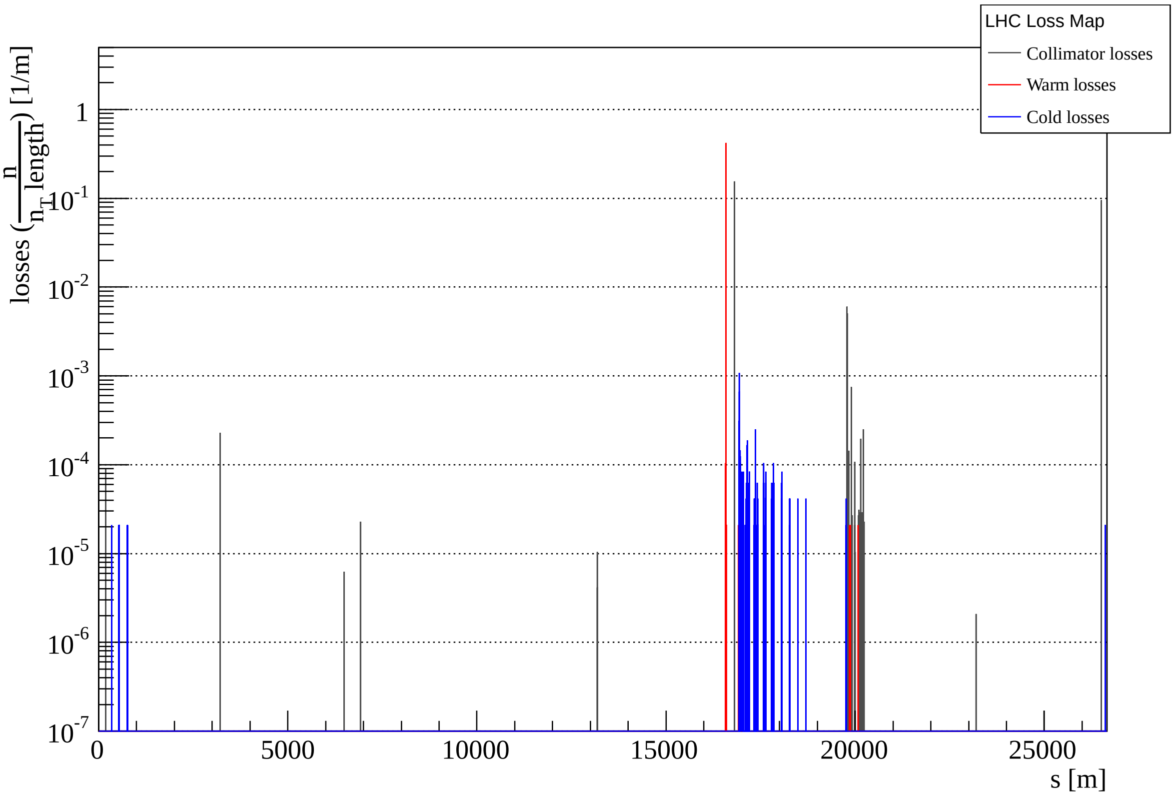

Figure 5: Loss map around the LHC, as simulated with SixTrack, for the bunch in a train causing the highest losses on the TCTs during a single-module pre-fire dump accident.

with integrated beam position monitors (BPMs). Several successful test have been performed previously with a prototype in the SPS [30]. These new BPM collimators can be aligned without touching the beam [31]. Thus, the alignment does not require special low-intensity fills. This drastically reduces the setup time and therefore increases the flexibility of the configurations of the experimental IRs in terms of $\beta^*$and crossing angle.

Furthermore, if the TCTs and TCS6 would always be centered around the real orbit with high precision, the margins for orbit in the collimation hierarchy could be significantly reduced, which would make room to squeeze $\beta^*$to smaller values. As potential gain we assume that the collimator can always be centered around the orbit within 50 μm, which is an upper limit given by the SPS measurements [30]. Such a reduction is, however, non-trivial, since allowing the collimators to move automatically during a high-intensity fill using a feedback algorithm implies in itself a machine-protection risk. Possible solutions could involve interlocking either the collimator movement or the orbit as read out by the collimator. Another option could be to insert the orbit measured by the collimators into the orbit feedback, although the gain is unclear as the default mode of the feedback does not necessarily correct local errors. Furthermore, the strategy required in case of a faulty BPM reading is still to be specified. As the detailed scheme for moving and interlocking the BPM collimators is yet to be decided, the gain in terms of $\beta^*$is likely not to be usable directly after the startup after LS1, but rather after some time of operation and beam experience.

Using the same models as used for the 2012 run, the margins in the collimation hierarchy can be calculated for the next LHC run scheduled to start in 2015 at 6.5 TeV. For the non-critical margins in IR7 we consider several different scenarios. If constraints from beam losses induced by tighter settings [32, 33] turn out not be limiting, the option where the 2012 settings in mm are retained is a safe and stable choice from the operational point of view—the cleaning hierarchy showed an excellent stability during 2012. Possibly this could be used directly after the restart. A slightly more pushed scenario, which could be introduced later, is to keep the 4 TeV retractions in σ_n, which implies smaller gaps in mm. This scenario might require more frequent collimation setups, but allows a gain in β^*.

At the time of writing, it is not clear how severe possible performance limits related to the collimator gaps will be after LS1 [32, 33]—e.g. there is a risk that octupoles will be needed to stabilize the beam and that the available current will not suffice or that beam losses caused by orbit jitter become critical. If the impedance turns out to be limiting, it is not clear by how much the settings have to be relaxed but, in order to approximately quantify the loss in performance, we study one scenario with relaxed settings, where the openings in mm in IR7 and IR6 are increased

Table 2: 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_n or more open (relaxed). We show also the resulting reach in $\beta^*$and the corresponding crossing angles ϕ for two different configurations of filling scheme (25 ns bunch spacing assuming 12 σ beam-beam separation needed, and 50 ns bunch spacing assuming 9.3 σ beam-beam separation) and normalized emittance ϵ_n.

Settings	Relaxed settings without BPM	mm settings kept, without BPM	σ settings kept, without BPM	mm settings kept, with BPM	σ settings kept, with BPM
TCP7 (σ_n)	6.7	5.5	5.5	5.5	5.5
TCS7 (σ_n)	9.9	8.0	7.5	8.0	7.5
TCLA7 (σ_n)	12.5	10.6	9.5	10.6	9.5
TCS6 (σ_n)	10.7	9.1	8.3	9.1	8.3
TCSDQ6 (σ_n)	11.2	9.6	8.8	9.6	8.8
TCT (σ_n)	12.7	11.1	10.3	10.0	9.1
protected aperture (σ_n)	14.3	12.6	11.7	11.2	10.3
25 ns, $\epsilon_n = 3.75$ μm, 12 σ beam-beam separation					
β^*(cm)	72	60	55	52	46
$\phi/2$ (μrad)	165	180	189	194	205
50 ns, $\epsilon_n = 1.6$ μm, 9.3 σ beam-beam separation					
β^*(cm)	52	43	38	35	31
$\phi/2$ (μrad)	98	108	115	119	127

by 23% compared to 2012. This value, which corresponds to a TCP7 setting of 7.1 σ_n at 6.5 TeV, has been obtained as a very rough estimation by assuming that the beam was stable in 2012 with 510 A octupole current at 4 TeV. The needed octupole current has then been scaled with energy and the square root of the gap, which is more pessimistic than the cubic root and is approximately valid at lower frequencies, to obtain a stable beam at 6.5 TeV and with a 550 A octupole current (the maximum allowed with the present hardware). These collimator settings are, evidently, less performing in terms of $\beta^*$and should only be used if the other tighter settings provoke too high beam losses.

Calculated collimator settings, for all these options, as well the aperture that can be protected, are presented in Table 2. Results are shown both with and without the additional gain in margin that the BPM button collimators could bring.

Given the aperture that can be protected, the reach in β^*at the high-luminosity experiments can be calculated, by considering the needed aperture as a function of β^*. This function varies depending on the assumptions that are made on the needed crossing angle, which in turn depends on the real beam emittance and the needed beam-beam separation. Several possibilities are available for the post-LS1 operation: one option uses 25 ns beams, with the envisaged emittance of 3.75 μm or with a new scheme from the injectors possibly delivering 1.9 μm. The other option would be to stay with 50 ns beams either with emittance of 2.5 μm as achieved in 2012, or using the new injector scheme, possibly providing 1.6 μm. The needed aperture as function of $\beta^*$is shown for the crossing plane for all these options in Fig. 6, as well as for the separation plane, where it has been assumed that the parallel separation remains at a value scaled from the previous 4 TeV operation. The shown values have been calculated by scaling the measured 2012 aperture [34] using the models described in Refs. [6, 8, 7].

The possible values in $\beta^*$are shown for the two extreme beam configurations in Table 2. As can be seen, a wide range of β^*values are possible between about 30 cm and 70 cm. The final β^*will be known once the collimator settings and the beam conditions are decided. The choice has to account for the intricate interplay between beam stability, i.e. the increased risk of high beam losses and dumps with tight collimator settings, and the peak luminosity. The choice should be made in order to maximize the delivered integrated luminosity. Before the final decision is taken, it is also necessary to perform new aperture measurements to validate that the aperture has not changed during the shutdown or that other effects decreasing the margins in the experimental IRs, such as spurious dispersion, do not become too important.

SUMMARY AND OUTLOOK

The LHC collimators are ordered in a strict hierarchy and the critical margins between families are calculated using a detailed error model including e.g. orbit movement and optics errors. The resulting aperture that can be protected by the collimation system imposes a limit on the achievable β^*. During the previous LHC run in 2010-2012, the collimator settings were optimized to squeeze β^*as much as possible. Based on theoretical and experimental studies on minimizing the margins in the hierarchy without compromising machine protection, β^* was decreased in steps from 3.5 m in 2010 to 60 cm in 2012. This resulted in a very significant increase of the delivered luminosity.

Work is ongoing to improve the models for the margins,

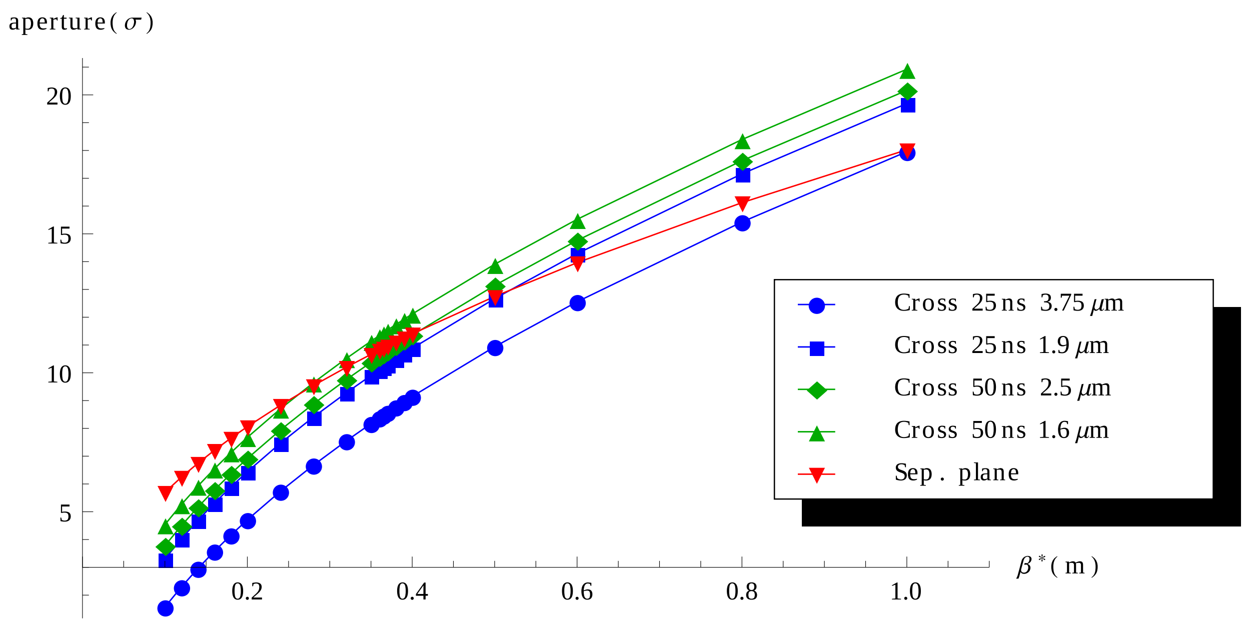

Figure 6: The calculated aperture margin in IR1 and IR5 as function of $\beta^*$for different configurations of bunch spacing (25 ns with an assumed needed beam-beam separation of 12 σ_r or 50 ns with 9.3 σ_r beam-beam separation). The aperture is shown both for both the crossing and separation planes.

where a small number of impacting protons—well below the TCT damage limit—is allowed during asynchronous dumps. We include realistic errors on the phase advance and the β-functions. With this model, the margin for optics errors used in the 2012 run could possibly have been reduced by a few fractions of σ_n without risk. A similar study can be done also for the margins between TCTs and triplets, and, in the future, the model can be expanded to include also the other error sources such as orbit deviations.

During LS1, all TCTs and TCS6 will be replaced by new collimators with integrated BPM buttons. They allow a faster collimation setup and much greater flexibility in the experimental IR configuration and, eventually, the BPMs could be used to ensure that these collimators are always centered around the orbit. This can in turn be used to further reduce the margins in the cleaning hierarchy and squeeze to smaller β^*.

Several options for collimator settings after LS1 have been studied under different assumptions on emittance and bunch spacing. Preliminary performance estimates shows that after LS1, the reach in $\beta^*$is between 30 cm and 60 cm if settings similar to 2012 or tighter can be assumed, unless it will be necessary to open the collimators more than in 2012 in order to avoid drops of the beam lifetime. The final decision on β^*has to be taken after a new aperture measurements and verifications on the beam stability.

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UPDATED ROBUSTNESS LIMITS FOR COLLIMATOR MATERIALS

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Abstract

State-of-the art complex numerical methods based on advanced wave propagation codes have been developed to study the extreme phenomena induced in Beam Intercepting Devices (BID) by accidental beam impacts. A first study, based on these methods, led to the identification of damage thresholds for LHC Tertiary Collimators which were presented at Chamonix workshop in 2011. However, numerical simulations were unavoidably affected by uncertainties due to the limited knowledge of the material constitutive models; two experiments in the HiRadMat facility were proposed to address this issue: the destructive test of a complete tertiary collimator for a thorough, integral assessment of beam accident consequences (HRMT09) and a controlled test on a multi-material test bench hosting a variety of specimens conveniently instrumented for online and offline measurements (HRMT14). Both experiments were very successful and confirmed the effectiveness of numerical methods and material models to reliably predict beam-induced damages. Preliminary data acquired during HRMT14 provided interesting results on the ability of various materials to withstand extreme accidents. These tests also highlighted additional potential machine protection issues, on top of mechanical damage, induced by the projection of fragments out of the tungsten jaw: these include UHV degradation, chamber pollution, contamination, etc. In line with updated accident scenarios, new damage limits are proposed for LHC Tertiary Collimators.

INTRODUCTION

At Chamonix 2011 workshop, a thorough numerical analysis of a Tertiary Collimator (TCT) was presented. It relied on advanced simulations performed with the wave propagation code Autodyn® [1], applied to a complex 3D model [2]. Several asynchronous beam abort cases were studied with different values of beam emittance, energy and intensity. The main results were:

- Single-bunch accidents at 3.5 and 5 TeV induce jaw damage which does not require collimator replacement, provided that the full collimator movement parallel to the jaw surface is available (so called “5th axis”).
- Multi-bunch accidents always require collimator replacement.
- Risk of very severe damage leading to long LHC downtime above four bunches (risk of water leakage detected at 8 bunches).

The most important issue of these simulations concerned the reliability of adopted constitutive material models, especially at the extreme conditions as to temperature, pressure and energy induced by the beam impact. In order to probe and evaluate such models, two experiments have been performed in the HiRadMat facility in 2012 [3]. The first experiment, known as HRMT09, entailed the destructive test of a complete tertiary collimator, in order to assess not only the mechanical damage provoked to the structure but also other consequences of the beam accident, such as degradation of vacuum pressure in the beam line, contamination of the inner tank, impacts on collimator dismounting procedure, etc. In the second experiment (HRMT14), six different materials, already used in collimators or under intensive R&D for future applications, have been tested at different beam intensities. For a comprehensive characterization, online measurements were carried out both with embedded instrumentation and remote devices.

Data gathered by these two experiments were used to refine the numerical material models; new simulations were then performed in order to determine the damage limits for LHC Tertiary Collimators, considering updated and more realistic accident scenarios [4].

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HRMT09 EXPERIMENT

The goal of the experiment was to verify the robustness and performance integrity of a fully assembled TCT direct beam impact [5]. Three different tests were performed, with different beam intensity and different goals (Fig. 1):

- **Test 1**: to investigate the effects of asynchronous beam dump with impact equivalent to 1 LHC bunch at 7 TeV.
- **Test 2**: to identify the onset of plastic damage.
- **Test 3**: to reproduce a destructive scenario, inducing severe damage on the collimator jaw (damage on the collimator equivalent to 4 bunches at 5 TeV [2]).

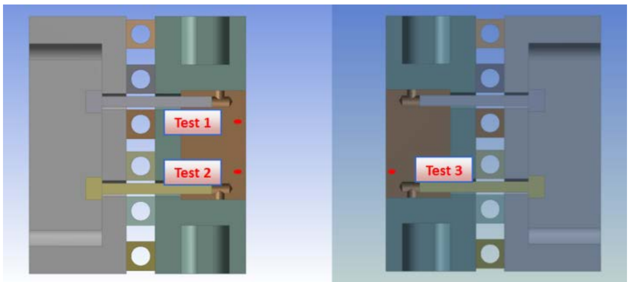

Figure 1: Schematic diagram of the three tests performed on the TCT during HRMT09 experiment. Impact locations are shown in red.

Table 1 resumes the parameters of each test. For each of the three tests, the equivalence between SPS and LHC energies is done in terms of mechanical damage induced to the jaw. For example, a SPS pulse with 3.36×10^{12} protons produces a mechanical damage on the jaw equivalent to one LHC nominal bunch at 7 TeV [6].

Table 1: Beam parameters and impact positions of tests performed during HRMT09.

	Test 1	Test 2	Test 3
Beam energy	440 GeV	440 GeV	440 GeV
Pulse intensity	3.36×10^{12} p	1.04×10^{12} p	9.34×10^{12} p
N. bunches	24	6	72
Bunch spacing	50 ns	50 ns	50 ns
Beam size [$\sigma_x \times \sigma_y$]	0.53 x 0.36 mm^2	0.53 x 0.36 mm^2	0.53 x 0.36 mm^2
Impact location	Left jaw +10 mm	Left jaw -8.3 mm	Right jaw -8.3 mm
Impact depth	2 mm	2 mm	2 mm
Jaws half-gap	14 mm	14 mm	14 mm

A post-irradiation visual inspection was performed at the beginning of 2013 (Fig. 2). The damage provoked by Test 1 and Test 3 is clearly visible; the observation also highlighted other possible issues:

- Contamination of bellows, tank, and vacuum chambers, due to activated tungsten particles; scenarios for future intervention and regular maintenance must take this into account.
- Ejected particle could affect the correct functionality of movable parts (RF fingers sliding on upper and lower rails).
- Degradation of ultra-high vacuum (UHV) along the beam line.

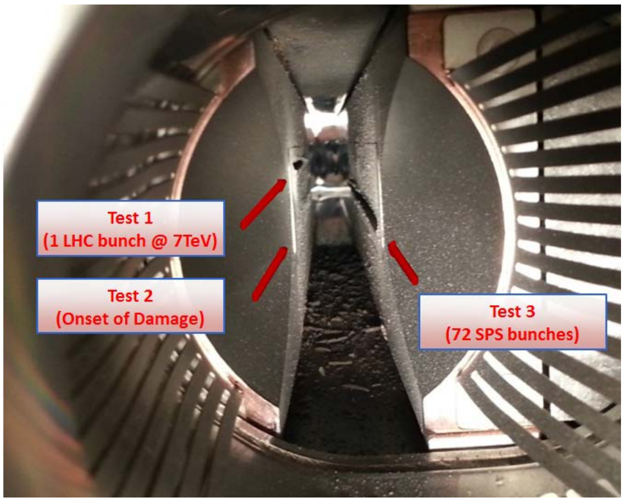

Figure 2: Post-irradiation visual inspection. Note the impressive quantity of tungsten ejected (partly bonded to the opposite jaw, partly fallen on tank bottom or towards entrance and exit flanges).

Qualitative comparison with Autodyn® simulation is given in Figs. 3, 4, 5. Simulations of Test 1 and Test 3 show good accordance with visual inspections, while it is impossible to visualize the plastic deformation produced by Test 2. The zone is, in fact, covered with particles ejected from the opposite jaw during Test 3, which reached a velocity of about 1 km/s according simulations; the damage produced during Test 2 will be evaluated during future metallographic inspections once the radiation dose rate will be low enough.

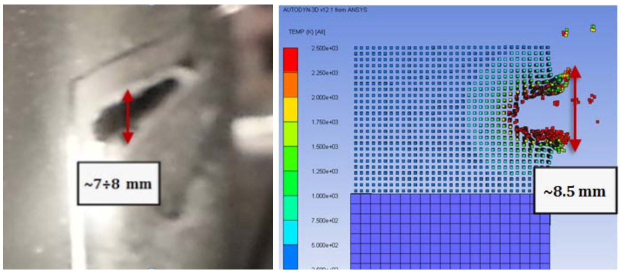

Figure 3: Qualitative numerical benchmarking of the damage generated by Test 1 beam impact.

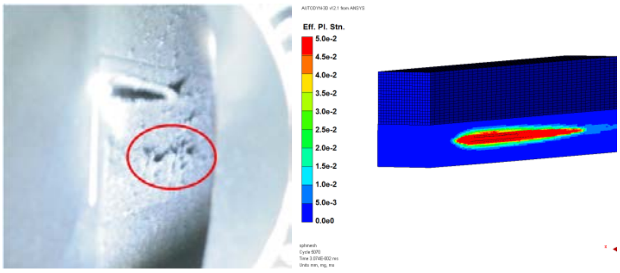

Figure 4: Qualitative numerical benchmarking of the damage generated by Test 2 beam impact. Note that the impacted zone is covered by particles ejected from the opposite jaw during Test 3.

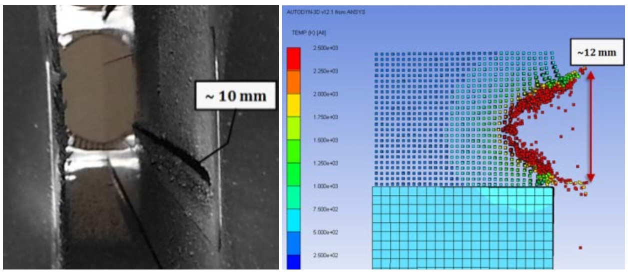

Figure 5: Qualitative numerical benchmarking of the damage generated by Test 3 beam impact.

HRMT14 EXPERIMENT

The goal of the HRMT14 experiment was to derive new material constitutive models collecting, mostly in real time, experimental data from different acquisition devices: strain gauges, laser Doppler vibrometer (LDV), high-speed video camera, temperature and vacuum probes [7].

The material sample holder was constituted by a vacuum vessel and a specimen housing featuring 12 material sample tiers arranged in two arrays of six (Fig. 6).

Specimens were made of materials currently used for collimators such as Inermet® 180 (tungsten heavy alloy), Glidcop® AL-15 LOX (dispersion-strengthened copper) and Molybdenum, as well as novel materials under development (Molybdenum-Copper-Diamond, Copper-Diamond and Molybdenum-Graphite composites) [8].

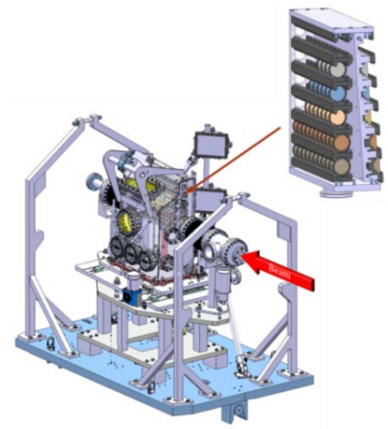

Figure 6: General assembly of the HRMT-14 test-bench.

Two different specimen shapes were chosen for each tested material: cylindrical disks (type 1) for medium-intensity tests, to measure axially-symmetric shockwaves; cylinders with a half-moon cross section (type 2) for high-intensity tests, allowing extreme surface phenomena (melting, material explosion, debris projections, etc.) to be visualized and optically acquired (Fig. 7).

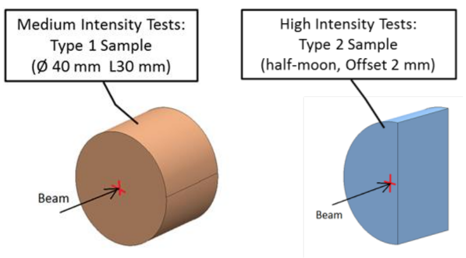

Figure 7: Material specimen shapes for medium intensity (type 1 - left) and high intensity (type 2 - right).

Part of the instrumentation was installed directly on the specimens; resistive strain gauges measured the strain produced on samples by shockwave propagation, to benchmark time-dependent simulations (Fig. 8). Temperature sensors, vacuum pressure gauges and microphones were also installed inside or in the vicinity of the tank. Optical devices (LDV and high-speed camera) were installed remotely in a concrete bunker, in order to protect them from the effects of radiation. The LDV acquired the radial velocity on the outer surface of one cylindrical sample per tier. The high-speed camera filmed the particle projection produced by high-energy impacts on type 2 specimens; the lighting necessary for the acquisition was provided by a battery of radiation-hard xenon flashes mounted atop the tank.

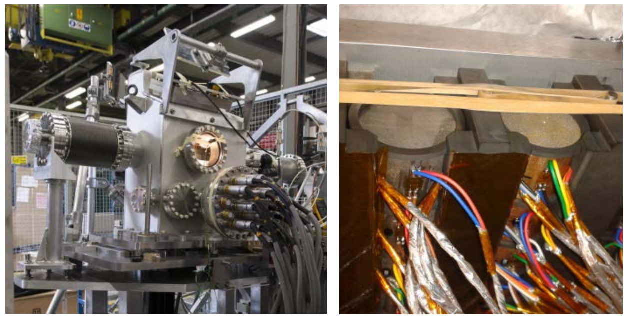

Figure 8: Assembled test-bench with DAQ cables and connectors (left); strain gauges mounted on Molybdenum-Copper-Diamond and Copper-Diamond (right).

Table 2 reports the characteristic values of the impacting beam during tests on Inermet® 180. Numerical simulations adopted the same parameters, except for the beam transverse dimension which was set to 2.5 x 2.5 mm^2.

Table 2: Beam parameters for tests performed on Inermet® 180 during HRMT-14 experiment.

	Medium intensity test	**High intensity test**
Energy	440 GeV	440 GeV
N. bunches	24	72
Bunch spacing	25 ns	25 ns
Pulse intensity	2.7×10^{12} protons	9.05×10^{12} protons
Energy on most loaded specimen	8.35 kJ	25.1 kJ
Impact point	Centre of *type 1* specimen	2 mm from *type 2* flat surface
Beam size $[\sigma_x \times \sigma_y]$	1.4 x 2 mm^2	1.9 x 1.9 mm^2

Medium intensity tests

Strain gauges measured axial and hoop strains on the external surface of type 1 samples, while the LDV acquired the radial velocity. Acquired raw data were then compared to the results of numerical simulations (Fig. 9).

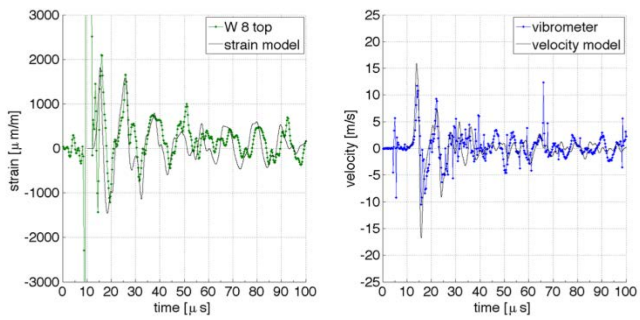

Figure 9: Comparison at r = 20 mm, L = 15 mm, measurements (dotted lines) vs. simulations (continuous lines); axial strain (left) and radial velocity (right).

A strong electromagnetic noise induced by the particle beam perturbed the strain gauge measurements during the first few microseconds after the impact, concealing the first deformation peak. However, this effect was limited to the beam impact duration, allowing to capture the remainder of the phenomenon. Measured and simulated signals are in good accordance, especially during the first three reflections of the shockwave. Random spikes in the signal of gauges and LDV will be treated during more accurate signal processing.

High intensity tests

The high-speed camera system allowed for the first time, to the best of authors' knowledge, to record images of the impact of a proton beam on solid targets and of the effects induced. As shown in Fig. 10, a large quantity of hot material was ejected at high velocity from the two most loaded Inermet® 180 samples; high temperatures reached are confirmed by the intense light emitted by the fragments during a few hundred microseconds.

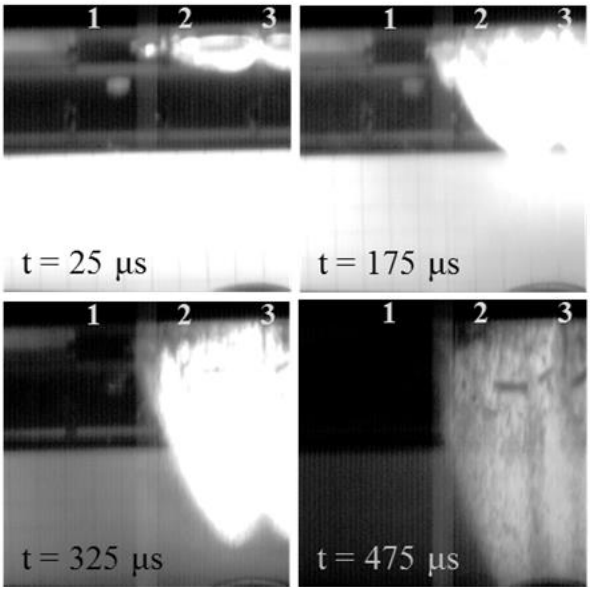

Figure 10: Image sequence of the impact on Inermet® 180 at high energy; three samples are partially visible.

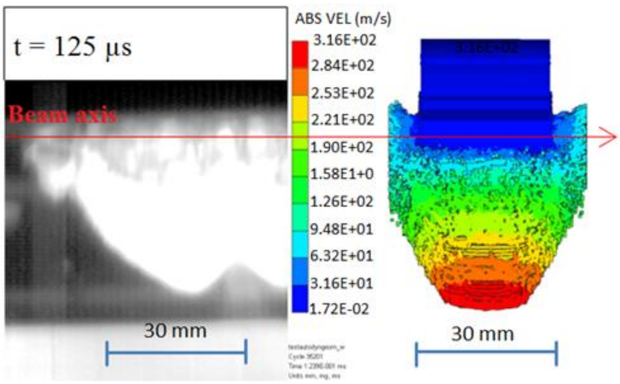

Figure 11: Comparison between simulation (SPH method) and acquired image ~125 μs after the impact.

Smoothed-particle hydrodynamics (SPH) simulation results are consistent with the camera acquisition (Figs. 11-12), even considering the differences in beam size between real and simulated scenarios. The acquired velocity of the fragment front has been estimated by measuring the displacement between two successive frames and is about 275 m/s, well matching the simulated velocity of 316 m/s (difference is about 15%).

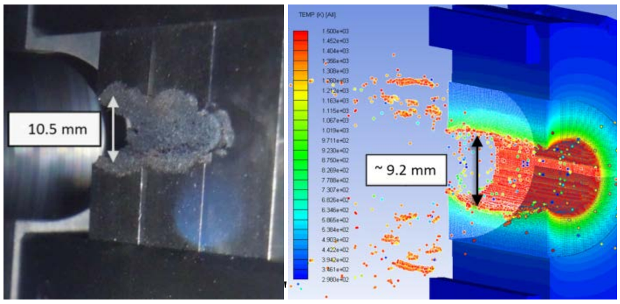

Figure 12: Post-mortem observation of Inermet® 180 samples (left) and simulated failure (right).

UPDATED ACCIDENT SCENARIOS

Preliminary results of the experimental tests performed show that the numerical methods and material models adopted to simulate beam impact accident scenario on a TCT are reliable (the error band is about 25%).

Actually, up-to-date beam parameters for asynchronous dump scenarios foresee fractions of several bunches impacting the jaw [4] but, at the moment, FLUKA [9] simulations are not yet available for this accident case. Nevertheless, new Autodyn® simulations have been performed considering one bunch with variable intensity impacting the jaw with a fixed impact parameter.

Three damage thresholds have been identified:

- **Threshold 1: onset of plastic damage**. Below this threshold, no permanent deformation is induced on the collimator jaw.
- **Threshold 2: limit for W fragment ejection.** The beam impact induces plastic deformation of the jaw without ejection of tungsten particles (no contamination or vacuum degradation).
- **Threshold 3: limit for 5th axis compensation.** The impact generates severe plastic deformation with projection of tungsten particles, but the mechanical damage can still be compensated by moving the collimator through the 5th axis (i.e. parallel to the jaw surface), therefore guaranteeing the required flatness (it should be noted that the vacuum quality will be affected by such an accident and the collimator will be contaminated by radioactive tungsten fragments).

Simulation parameters and results are summarized in Table 3. The calculation confirms the results presented at Chamonix 2011 workshop: the impact of a nominal LHC bunch is critical enough to require the collimator replacement (Figs. 13-14).

Table 3: Thresholds identified in case of accident on TCT (asynchronous beam dump).

	Threshold 1	**Threshold 2**	**Threshold 3**
Beam energy	7 TeV	7 TeV	7 TeV
N. bunches	1	1	1
Impact depth	0.5 mm	0.5 mm	0.5 mm
Beam size [σ_x x σ_y]	0.5x0.5 mm^2	0.5x0.5 mm^2	0.5x0.5 mm^2
Jaws gap	20 mm	20 mm	20 mm
Pulse intensity	***$5x10^9$ p***	***$2x10^{10}$ p***	***$1x10^{11}$ p***

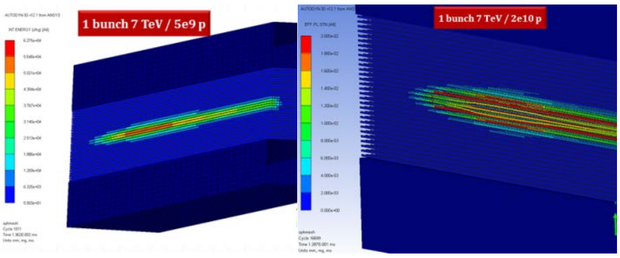

Figure 13: Threshold 1, $5x10^9$ p: no plastic deformation induced (left); Threshold 2, $2x10^{10}$ p: a crack is generated, but without ejection of tungsten particles.

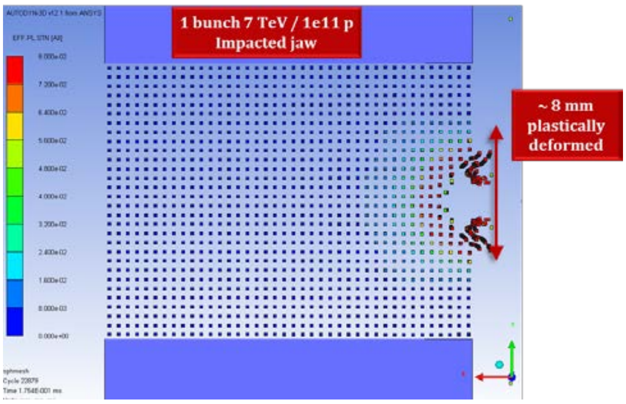

Figure 14: Threshold 3, $1x10^{11}$ p: groove generated in the jaw; Below this threshold the damage can still be compensated through 5th axis movement.

CONCLUSIONS AND FUTURE ACTIONS

A state-of-the art numerical method based on advanced wave propagation codes was developed in the last years at CERN in order to study beam-induced extreme phenomena including phase transitions, spallation, and explosions. The method was applied in 2011 to identify the beam-induced damage limits on LHC Tertiary Collimators. However, this complex numerical approach required a dedicated experimental validation: two different tests were therefore performed at the CERN HiRadMat facility. The first experience entailed the destructive tests of a complete TCT; in the second experiment, six different materials were characterized under intense beam impacts.

The two experiments confirmed the effectiveness of the numerical methods and material models to reliably predict beam-induced damages, also highlighting additional potential machine protection issues on top of mechanical damage, due to the projection of fragments from the impacted components.

New damage limits were then proposed in line with updated accident scenarios on TCTs, considering one bunch with variable intensity impacting the jaw with a fixed impact parameter.

- Onset of plastic damage : $5x10^9$ p
- Limit for fragment ejection: $2x10^{10}$ p
- Limit for 5th axis compensation (with fragment ejection): $1x10^{11}$ p

These simulations will be refined, to consider asynchronous dump scenarios where fractions of several bunches impact the jaw in different points, once FLUKA energy deposition maps will be available.

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LHC POWERING ISSUES – REVIEW OF BEAM DUMPS*

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Abstract

Following the near catastrophic quench event in September 2008, the LHC magnets have seen their magnetic field strength reduced to a maximum safe value, limiting the LHC's beam energy. Since then, the challenge of establishing the causes of such an event and ensuring that it is not likely to reoccur has been of paramount priority. The main topic of this paper is to discuss the significant powering issues and causes of beam dumps over the last three years of operation, correlating individual system statistics, year-to-year, with intermittent system changes/upgrades.

To complement this, predictions of the systems most likely to cause issues whilst operating at higher energies will be discussed, as well as a brief look at past 'near-miss' events, their causes, and plans for prevention of future reoccurrence.

INTRODUCTION

What is a Powering 'Issue'?

For the purpose of this paper a powering issue is defined as follows:

- An unintended powering system event which hinders global operation, resulting in either physical system damage or a loss to availability.

Powering Systems

With regards to machine protection of the LHC, a 'powering system' can be defined as a system responsible for the electrical powering and/or monitoring of magnet circuits. Each of these powering systems has an independent ability to trigger a power abort (i.e. magnet current discharge) and/or 'beam dump' if certain thresholds, implemented for machine protection purposes, are exceeded [1].

BEAM DUMP REVIEW

All data used in the study was extracted from the LHC's Logging System; the Post Mortem Database [2].

It was concluded that an in depth analysis of the most prevalent powering systems, and a direct comparison of the most stable years of operation (2011-2012), would be the most conducive. Systems analysed in study: Power Converters (PCs); Powering/Warm Interlock Controllers (PIC/WIC); Fast Magnet Current Monitor (FMCM); and the Quench Protection System (QPS). The results and analysis of the study are as follows.

Power Converters

Statistics of beam dumps due to either powering failures or discharge requests of the PCs shows a global improvement from 2011 to 2012, during all stages of beam operation (Fig. 1). This confirms that all improvements to software, firmware and voltage/current regulation that occurred during this period were making a difference, given the increase in operation energy from 3.5 to 4 TeV [3].

Note: Majority of dumps are in stable beam mode. This is explained by the fact that an average powering cycle spends > 70% of its time in this mode.

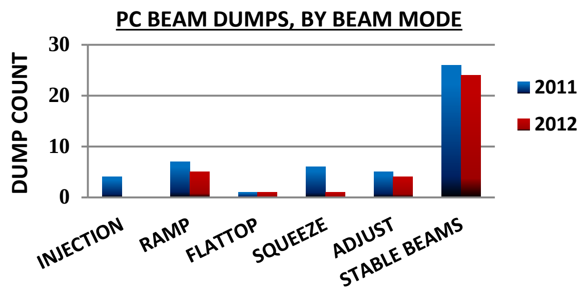

Figure 1: Comparison of Power Converter triggered beam dumps by beam mode, 2011 to 2012

A study looking at beam dumps by circuit type throughout 2012 found a large portion of triggers were caused by 600 A circuits. More interestingly, however, was the significant number of beam dumps caused by the Inner Triplets Systems; far greater than expected. Results can be found in Fig. 2.

Note: The peak of 60 A circuit triggers is explained by the large number of circuits relative to others circuit types.

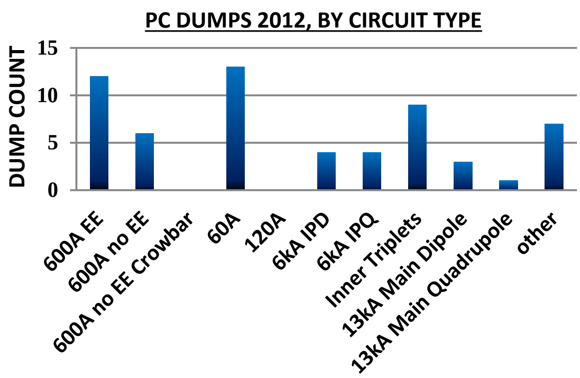

Figure 2: Power Converter triggered beam dumps by circuit type throughout 2012.

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Powering Interlock Controllers

The PIC results show a significant improvement during 2011 to 2012, having caused no spurious beam dumps since October 2011 (Fig. 3). In previous years, several trips occurred with nearly all being caused by Single Event Upsets (SEUs). The improvements were due to a successful Radiation to Electronics (R2E) mitigation relocation of systems in UJ14, UJ16 and UJ56 during Christmas shutdown in 2011 [4].

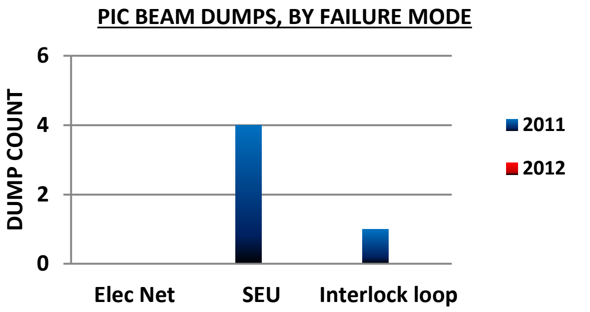

Figure 3: Comparison of beam dumps triggers by PIC by failure mode, 2011 to 2012. Elec Net – Electrical network fault, SEU – Single Event Upset.

The WIC results again show significant improvement from 2011 to 2012, particularly in beam dumps triggered due to electrical perturbations in the main electrical network (Fig. 4). However, unlike the PIC, no specific campaign or project was carried out to mitigate these effects and this may still be an issue in the future.

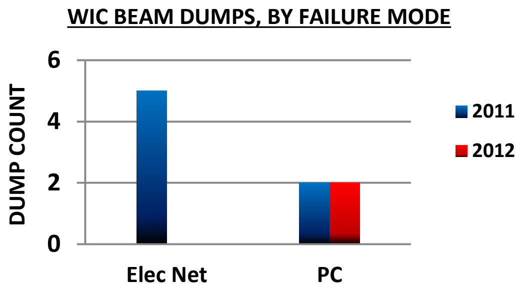

Figure 4: Comparison of beam dumps triggered by WIC by failure mode, 2011 to 2012. Elec Net – Electrical network fault, PC – Powering Converter failure.

Fast Magnet Current Monitor

In reviewing the FMCM the most significant results presented themselves when looking at all trips of specific individual circuits. Fig. 5 shows all FMCM trips since stable LHC operation began in 2009. Notably, the RD1 and RD34 circuits stand out as clear outliers.

Note: The graph shown includes all FMCM trips; when a beam dump is triggered due to electrical network issues, several monitors may trip simultaneously, resulting in large trip count. To quantify, the total beam dumps triggered by FMCM recorded was 78.

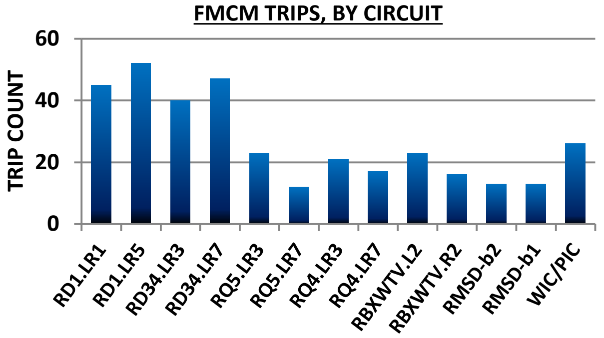

Figure 5: All FMCM Trips by specific circuit since 2009

Further investigation found that this is likely due to the fact that the RD1 and RD34 circuits are powered directly from the 18 kV grid instead of the more stable 400 V line like the RQ4 and RQ5 [5]. This drastically increases the circuit sensitivity to electrical network perturbations (Fig. 6). There are plans to design and implement an improved regulation characteristic for the thyristors of PCs that are connected directly to the 18 kV grid in attempt to reduce sensitivity [6].

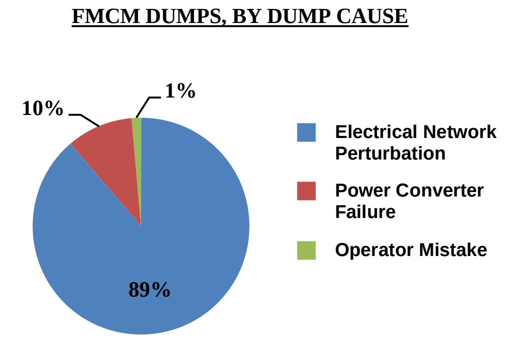

Figure 6: Pie Chart showing 89% of FMCM trips were due to electrical network issues.

Quench Protection System

The QPS of the LHC, protecting more than 8,000 magnets, is one of the most complex protections systems ever made [7]. Naturally this lends itself to having a high probability of being the cause of an unintended beam dump, especially if the individual system thresholds are too conservative.

Looking at beam dumps triggered by the QPS, by circuit type, showed quite drastic changes in beam dump triggers when comparing 2011 to 2012 (Fig. 7). The most significant being a reduction in dumps due to particularly problematic 600 A Energy Extraction (EE) circuits. This reduction was due to the continuous improvement of thresholds for the RQTD-F circuits both during and since the Christmas shutdown in January 2012; RQTD-F circuits are particularly sensitive to action of the tune feedback system [8]. There are also plans for R2E mitigation via radiation hardening of protection electronics of 600 A circuits in several sectors (all UJ underground regions) during LS1 which is likely to further reduce the number of spurious triggers [9]. In contrast, however, an important increase in beam dumps caused by the 6 kA IPQs is also seen. This may be due to a scaling effect of SEUs with the increase of beam energy from 3.5 to 4 TeV, though this is not likely to be the sole cause of the increase. Further study into the matter is called for.

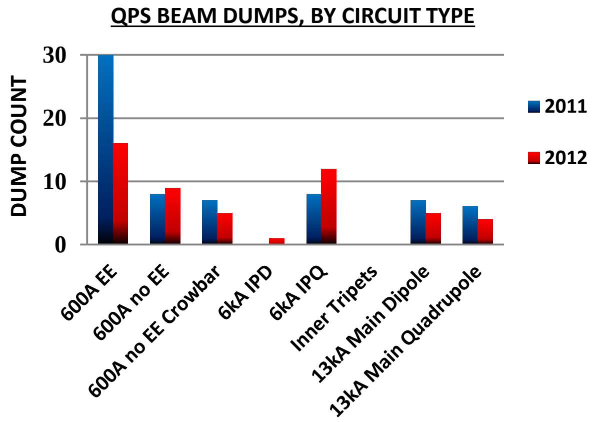

Figure 7: Comparison of beam dumps triggered by QPS by circuit type, 2011 to 2012

It is also of note that the 13 kA main dipole and quadrupole circuits have a notable reduction of beam dump triggers since 2011 but still have a high number of dump triggering when comparing with the number of circuits (e.g. LHC has only 8 13 kA dipole circuits [10]). However, the protection system of these circuits is of much higher complexity, containing significantly more QPS detection boards, naturally increasing the probability of false triggers. Fig. 8 shows this significance quite clearly; almost one trip for every two circuits.

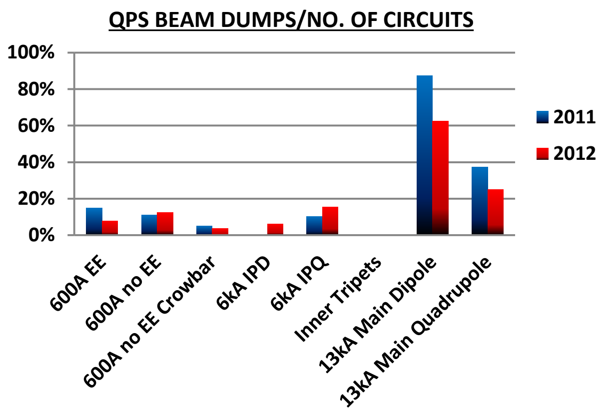

Figure 8: QPS triggered beam dumps in relation to the number of circuits of each type.

Looking at false dump triggers of the QPS by beam mode showed a significant reduction during the squeeze from 2011 to 2012 which correlates to the aforementioned reduction in beam dumps caused by fine tuning RQTD-F thresholds. Fig. 9 also shows a small increase in dumps during stable beam mode. As prior-mentioned, dumps are more likely to occur during this mode of operation throughout the beam cycle as it is the longest in time by a significant margin. The increase from 2011 to 2012 can likely be explained by the overall time spend in stable beam mode increasing by approximately 15%. It is, however, thought that beam instabilities (e.g. landau effects) which have been commonplace throughout 4 TeV operation, will have had a minor influence [11].

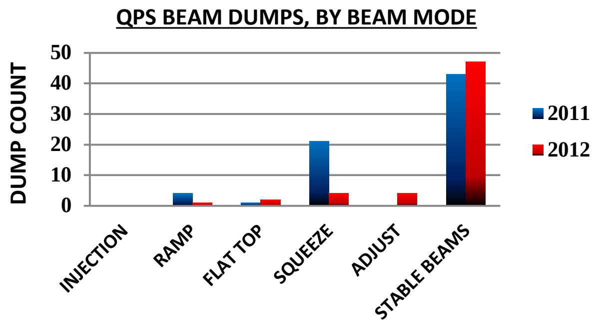

Figure 9: Comparison of beam dumps triggered by QPS by beam mode, 2011 to 2012

Single Event Upsets (SEUs) are becoming more prevalent as the LHC's performance and inherent radiation emissions increases, particularly for systems consisting of thousands of electronic circuits. SEUs are commonly understood as radiation effects that interfere with electronics at a component level which may results in system degradation, eventually resulting in a beam dump. Fig. 10 shows the proportion of QPS beam dumps caused by SEUs. It is clear that in high radiation areas, such as those surrounding the experiments (especially ATLAS and CMS) or beam cleaning regions (collimators), SEUs pose significant issues. The probability of such events occurring is likely to scale with LHC operation energy. Studies to further mitigate SEUs effects remain necessary.

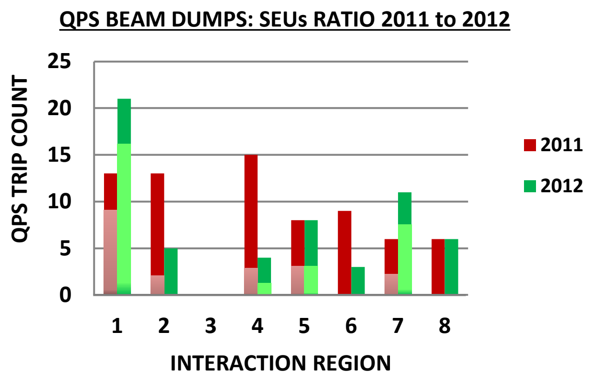

Figure 10: Comparison of QPS SEU dumps to total dumps in all regions 2011-2012. Note: Pale section represent number of dumps caused by SEUs.

As expected, the percentage of SEU/other dump is high in IR1 (ATLAS) and IR5 (CMS); IR1, being much greater than IR5 as only one side of the LHC electronics near CMS lies within a high radiation zone, roughly halving the probability. Furthermore, there is also a notable margin of reduction in other dumps at IR4, which can be again explained by the tuning of RQTD-F circuit thresholds. More interestingly, however, is the significant proportion of SEU dumps at IR7. This is likely due the radiation scattering from the beam cleaning collimators in this region, but it was deemed higher than expected and a closer look at individual circuits statistics surrounding IR7 was called for, see Fig.11 below.

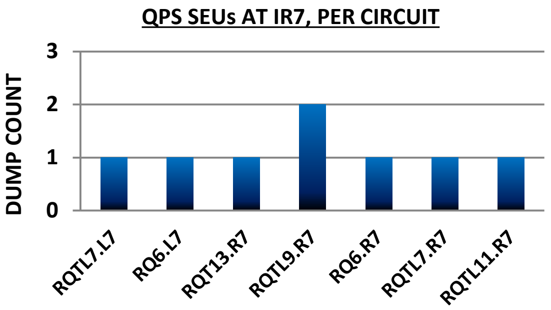

Figure 11: QPS beam dumps due to SEUs at IR7

First thing to note is that there is no specific circuit causing a majority of faults and the SEUs are essentially random. As prior-mentioned, the probability is likely to increase as radiation increases at nominal energy. To make matters worse there are no R2E mitigation relocation plans for LS1 and this issue may continue. However, all the circuits that have tripped so far are 600 A circuits, and all 600 A circuits are being improved and redesigned with radiation hardening in mind. Hopefully this will mitigate some of the effects as scattering due to collimation is likely to scale quite considerably with energy.

Discussion

Downtime in operation of the LHC curtails invaluable time allocated to physics experiments, thus maximizing availability is worthy of study, time and resources.

Following the study, a clearer understanding of what are the main causes of unintended beam dumps is attained, making decisions for mitigation/machine upgrades easier with respect to maximizing availability. One of the major causes of downtime is clearly shown to be false triggering of the QPS, however, several other unexpected statistics came to the forefront (e.g. Triplet PCs trips, extent of FMCM RD1/34 issues, SEUs prevalence at IR7).

Beyond LS1

A major aspect of the study was to determine which systems are most likely to be the problematic when operating near nominal energies and whether or not there are plans to help minimize potential issues. The following is a brief summary of these systems:

- Circuits powered directly by 18 kV lines, even after implementing the planned filter improvements.
- There are several improvements planned for the QPS system, however, as SEUs are likely to scale with luminosity they likely to remain a problem. In particular with regard to the 6 kA IPQs, until the installation of more radiation tolerant electronics has occurred.
- PCs show steady improvement year-to-year, however the issues with the Triplets may worsen. Furthermore, for the operation of Achromatic Telescope Squeezing (ATS) Optics and improved damping of beam instabilities, several 600 A circuits will be stressed at their operation limits (beyond nominal design) [12]; potential issues may arise.

‘NEAR-MISS’ EVENTS

A ‘near-miss’ event can be defined as a system non-conformity which if, however unlikely, were to occur in a more critical context, would result in a ‘catastrophic’ event.

Prime example of a ‘catastrophic’ event

The LHC was originally designed to run at a nominal energy of 7 TeV, however, just after first operation began, on 19th September 2008 an entirely unforeseen quench event occurred in the main 13 kA dipole circuit, resulting in severe mechanical damage and a yearlong magnet replacement/repair campaign [13]. Details of event were as follows:

- ‘Catastrophic’ quench originating at an interconnect during ramp at 8.6 kA
- Large helium leak
- Extreme pressures developed causing severe structural damage
- 53 magnets needed to be replaced/repaired

To prevent such an event occurring again, a global campaign for the consolidation of all interconnects within a resistance threshold has been planned for LS1. Furthermore, since it is hypothetically possible for this event to occur in the bypass diode leads, a measurement protocol, Copper Stabilizer Continuity Measurement (CSCM) [14], was designed to test if the diode leads were able to carry nominal currents; a type test was carried out successfully in April 2013. Analysis of results is on-going.

Examples of past ‘near miss’ events

All detailed events have been extensively covered in other studies/publications; information can be found on EDMS.

- Event in RB.A34 2011
  - QPS failed to respond and to trigger the EE system on discharge request.
  - Prevention of future reoccurrence involved the introduction of a new commissioning phase to check specifically for this issue.
- Event in RQX.A23 2011
  - Continuous firing of the Inner Triplet System’s quench heaters without request.

  - Prevention of future reoccurrence involved a firmware update of all relevant systems.
- Event in RCD.A12 Jan 2013
  - EE failed to open on direct request. This has occurred multiple times due to error initially going unnoticed.
  - Prevention of future reoccurrence involved a firmware update of all relevant systems.
- QPS failed to detect quench and to send discharge request
  - Prevention of future reoccurrence involved a system update and reset; update could have been scheduled prior to incident.

Reflection

'Near-miss' events, however worrying, give unique opportunities to witness, analyse and study the prevention of such errors. It is also important to point a common cause amongst both past, and recent, 'near-misses' as they were all a result of either human error or systems not being up-to-date. This in itself is a significant correlation and calls for more stringent system update protocols.

CONCLUSION

In summary, the study shows that a substantial amount of work is still necessary to improve the overall system protection, stability and availability. This is especially the case for failures caused by SEUs and network perturbations. Alongside the prevailing radiation and electrical network issues, almost all 'near-miss' and single non-conforming events studied were all due to either a lack of system software/firmware updates or human errors. This is not something to taken lightly, and certainly exhibits a need for a more meticulous standard of training/operation/ testing/commissioning and documentation.

ACKNOWLEDGMENTS

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Changes in QPS

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Abstract

During the upcoming first long shutdown (LS1) of the Large Hadron Collider LHC, the protection system for the superconducting elements of the LHC (QPS) [1] will be substantially upgraded with the principal objectives to extend its diagnostic capabilities and to enhance the system immunity to ionizing radiation. All proposed measures will serve as well to optimize the overall system dependability. The supervision of the quench heater circuits of the LHC main dipoles will be enhanced by adding additional measurement channels for the discharge current and by increasing the sampling frequency and resolution of the related data acquisition systems. By this measure it will be possible to identify potential fault states of the quench heater circuits, which may affect the integrity of the concerned magnet. At this occasion all main dipole protection systems will be submitted to general overhaul after four years of successful exploitation. The consolidation measures for the protection systems within the radiation to electronics project will be concluded by installing the latest versions of radiation tolerant quench detection systems. In addition some equipment will be relocated to shielded areas. All LHC main circuits will be equipped with earth voltage feelers allowing the monitoring of the electrical insulation strength of the LHC main circuits especially during fast discharges.

INTRODUCTION

The QPS of the LHC covers 544 superconducting circuits with nominal current ratings from 550 A to 11870 A. The systems incorporate a large number of individual protection and data acquisition devices requiring very high levels of reliability and availability. Due to the complexity of the QPS, major upgrades can only be implemented smoothly during long shutdowns. The refurbished and upgraded systems should then be able to run without major overhaul for at least for 3 to 4 years. The LHC operation after LS1 does not require principal changes of the protection functionality but a few quench detection settings have to be adapted to the higher energy of the accelerator. Within the preparation of LS1 several requests to enhance the supervision and diagnostic capabilities of the QPS systems have been submitted by equipment owners, experts and users. These changes are regarded necessary for the LHC exploitation as well as for the preceding hardware commissioning phase. Apart from the advanced supervision capabilities, other features will be implemented with the objective to ease maintenance and exploitation of the protection systems. These improvements comprise enhanced remote control options, automatic analysis and maintenance tools, and the implementation of a system configuration database.

RADIATION TO ELECTRONICS CONSOLIDATION

Within the radiation to electronics (R2E) project [2] several upgrades for the QPS electronics aiming to improve the immunity to ionizing radiation will be performed during LS1.

Relocation of equipment

An important part of the consolidation work consists in the relocation of QPS equipment presently installed in underground areas UJ14, UJ16 and UJ56. This equipment is used for the protection of the inner triplet low beta quadrupoles and the corresponding corrector magnets, and accounts for 12 out of 35 beam dumps caused by the QPS due to radiation induced faults in 2012.

Deployment of radiation tolerant hardware

The consolidation will be completed with the deployment of radiation tolerant hardware for the protection of the insertion region magnets and the 600 A corrector magnet circuits. These protection systems are currently installed in underground areas RR13, RR17, RR53, RR57, RR73 and RR77 and cannot be relocated during LS1. While the newly developed radiation tolerant quench detection sys-tems for the insertion region magnets (see figure 1) have been already fully validated and produced, the development of the more sophisticated systems for the 600 A corrector magnet circuit protection still needs to be concluded. The upgrade of these systems is absolutely mandatory as other-wise the rate of spurious system triggers after LS1 is likely to reach a level being no longer acceptable for LHC oper-ation. As complementary measures enhanced power-cycle options for DAQ systems including automatic re-start of stalled field-bus couplers will be implemented. This serves as an intermediate solution until new DAQ systems based on the radiation tolerant NanoFip [3] field-bus coupler chip are available.

ENHANCED QUENCH HEATER SUPERVISION

The upgrade of the quench heater circuit supervision of the LHC main dipole (MB) protection systems is driven by the intention to reduce the risk of damage to the quench heater circuits. The present system, monitoring only the

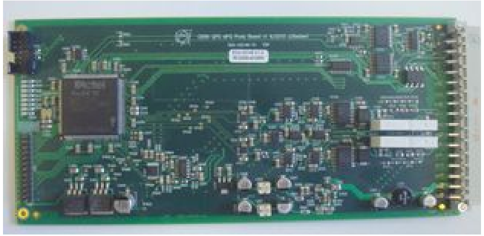

Figure 1: Radiation tolerant, FPGA based quench detection board type DQQDI used for the protection of insertion region magnets.

discharge voltage, is not sensitive enough to detect all fault states of the quench heater circuits, especially failures of the heater strips. All of the few quench heater faults observed so far during LHC operation could be mitigated by disabling the respective heater circuit and switching to one of the spare heaters located in the low field region of the magnet. There is, however, a non-negligible risk of a quench heater fault provoking a short to the magnet coil or compromise the electrical integrity of the magnet. The enhanced quench heater supervision is therefore supposed to reveal precursor states of such potential failures. The newly developed system (see figure 2) records simultaneously the discharge voltage and current using sampling rates up to 192 kHz and 16 Bit resolution analog to digital converters (ADC). In addition there is a special operational mode to verify the state of internal fuse of the quench heater power supply. This fuse is part of the grounding path of the internal capacitor bank and protects the power supply in case of a quench heater isolation fault. Up to now its state can only verified by manual inspection of the quench heater power supply. The full exploitation of the capabilities of the new systems requires as well the development of sophisticated high level software tools for the detailed analysis of the collected data. The present protection crates cannot be extended to house the additional measurement systems. It is therefore necessary to install newly developed protection crates; the existing quench detection electronics and DAQ systems however, can be re-used. The protection racks type DYPB housing the protection crates and the quench heater power supplies need as well to be refurbished completely.

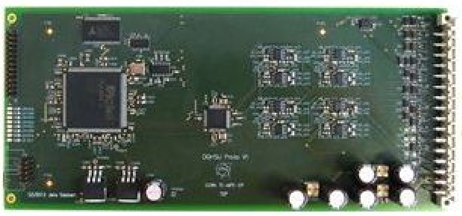

Figure 2: Dedicated DAQ board type DQHSU for the supervision of quench heater circuits.

Adaptation to redundant 230 V UPS powering

The new protection crate is adapted to the redundant 230 V UPS powering scheme introduced for QPS systems in 2009 [4]. Each crate will be fed by two external radiation tolerant AC/DC LDO converters. For the LHC main circuits RB and RQD/RQF the protection systems must remain active also during fast discharges of the superconducting circuits, e.g. in case of a electrical power cut. The redundant powering of the quench detection systems is therefore of particular importance for the main dipole circuits of the LHC, which have a nominal discharge time constant of $\tau = 103$ s.

Organization of protection rack upgrade work

Due to the significant number of modifications necessary to implement the enhanced quench heater supervision, it has been decided to perform this work outside the LHC in a dedicated assembly and test area. This simplifies also the testing of the upgraded systems after completion of the upgrade work. It requires, however, the transport of 1232 protection racks (160 tons of material, figure 3) from the LHC to the assembly area and back.

Figure 3: Protection rack type DYPB installed underneath the main dipoles.

EARTH VOLTAGE FEELERS FOR THE LHC MAIN CIRCUITS

The earth voltage feelers will monitor the electrical insulation strength of the LHC main circuits especially during fast discharges. The system (see figure 4) will as well measure the electrical insulation strength between adjacent bus-bars. As all data will be stored in the LHC logging database also the evolution in time can be studied. In case of an eventual earth fault the system will allow to identify the location of the fault position on the half-cell level. Per sector 54 devices for the main dipole circuit and 55 for each of the main quad circuits will be installed (1312 units in total).

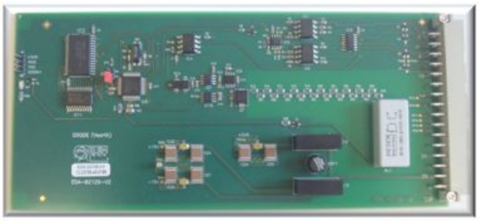

Figure 4: Earth voltage feeler type DQQDE.

GENERAL SYSTEM REVISION

The QPS systems have been exploited since 2007 and the respective hardware designs and firmware developments are dating back to the year 2002.

Hardware

Besides the extension for the supervision and protection of the bus-bar splices and the aperture symmetric quench detection implemented in 2009 (nQPS layer) [4], no major hardware change of the QPS systems has taken place so far. During LS1 some meanwhile obsolete systems will be replaced by new developments offering improved or enhanced functionality. In particular this concerns the quench detection electronics for the insertion region magnets and inner triplets as well as the systems for the 600 A corrector magnet circuits being exposed to ionizing radiation. The routing of the warm instrumentation cables for the protection of magnets Q9 and Q10 will be revised to achieve better immunity against electrical perturbations, especially during power outages and storms. At this occasion also a non-conformity in QPS / DFB instrumentation interface will be fixed. Apart from the mandatory upgrades, there are a number of optional but wishful improvements, such as the implementation of a hardware multi-trigger option for the DAQ systems and a revision of the quench loop (inter-lock) controllers focusing on the redundancy of loop cur-rent sources and enhanced diagnostics.

Energy extraction systems

The installation of arc chambers for the 13 kA energy extraction switches of the RQD and RQF circuits has to be completed in order to increase the maximum operational voltage of these circuits. This will allow to keep the discharge time constant of these circuits at $\tau < 20$ s. At the same time the installation of the snubber capacitor banks for the energy extraction systems of the RQF and RQD circuits will be executed [5]. All the 600 A energy extraction systems will subjected to a general upgrade, including an improved fixation of the holding coils and supervision of the internal current distribution [6].

Firmware

All detection system firmware will be reviewed with the objective to fix some vulnerabilities revealed during the last years and to identify possible other. This includes also an improved protection against non-conform user manipulations. The revised firmware is compatible with remote access to specified device parameters, thus allowing automatic crosschecks with configuration databases. The firmware of the QPS data acquisition systems will be adapted to to the increased resolution and higher sampling rates of analog signals. The QPS device firmware updates are relatively tedious as it concerns many circuit boards with only the last generation being fully adapted to automatic download.

QPS supervision

The transmission capacity of the physical layer of the QPS field-bus will be significantly improved by doubling the number of segments thus reducing the number of field-bus clients per segment. The reduced number of clients allows to shorten the macro-cycle length of the bus arbiter from 200 ms to 100 ms resulting in a maximum data update rate of 10 samples per second. The transmission of the QPS data to the LHC logging database will be improved and the filtering of analog data discarded. This will ease the data analysis and automatic checks of the system integrity. The full exploitation of all QPS upgrades presented so far requires a series of new high level supervision tools, *e.g.* for the enhanced quench heater supervision data analysis and for fully automatic signal integrity checks. Finally the QPS configuration database needs to be commissioned as well during LS1. With the help of this database all essential device parameters can be verified by software and the download of some parameters, e.g. the nQPS compensation coefficients, can be performed automatically. Critical parameters of course can only be manually set by experts.

Quench detection parameters

The quench detection parameters, especially for the 600 A corrector magnet circuits, have been carefully revised by quench calculation experts [7]. Their results show that some of the very conservative settings can be relaxed without compromising the integrity and performance of the protected elements. This will increases the QPS system dependability significantly, ease its exploitation and reduce the LHC machine downtime. It is noteworthy that longer evaluation times and higher threshold voltages may reduce the complexity of the detection electronics, which is especially beneficial for the development of radiation tolerant systems [8].

RECOMMISSIONING AND OPERATION AFTER LS1

All the work performed during LS1 by will require a full re-commissioning of the quench protection systems prior to the powering tests. The commissioning phase will be preceded by the complete electrical quality assurance for all superconducting circuits including the test of all QPS instrumentation cables. The individual system tests of the QPS comprise the validation of all (13722) hardware interlock channels, quench heater discharge tests, qualification of energy extraction systems, verification of data transmission to QPS supervision and the check of software interlocks. The re-commissioning activities will profit from the experience gained so far [9] but will remain as usual challenging. Additional tests will be required during the powering tests in order to qualify some newly installed items. The QPS system exploitation will change significantly after LS1 and some teething problems are expected during the initial exploitation phase. Due to the higher LHC energy the turn around time after trips will be significantly longer (about a factor 1.5); at the same time more real triggers, *i.e.* beam induced quenches are likely to occur. It is also noteworthy that after LS1 almost all superconducting circuits will operate outside their self-protecting range.

Operational support by service teams

Efficient training of service teams (MPE stand-by service, MP3, MPE-coms) will be essential to get all members familiar with the upgraded systems. In addition it is very likely that the scope and membership of the various service teams will change after LS1. In general and after an initial LHC operation phase less but more complex interventions of the stand-by service are expected; this will require a substantial training effort.

SUMMARY

The upgrade of the QPS systems during LS1 aims to increase the system dependability and to enhance its diagnostic capabilities. A successful upgrade will reduce the LHC machine downtime significantly, especially due to the reduced number of radiation induced trips. The newly installed systems allow by far more preemptive fault diagnostics and improve the maintainability, *e.g.* by adding more remote control options. The planned modification and enhancements of the QPS represent a major upgrade only feasible during a long shutdown period and requires a substantial effort. To make this work a success sufficient time for testing and re-commissioning including some contingency has to be allocated.

ACKNOWLEDGEMENT

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CHANGES IN POWERING INTERLOCKS

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Abstract

Powering interlocks guarantee the safe operation of both normal and superconducting magnets of the LHC and its injector complex. Experience gained during the last years has served to identify weaknesses of the system and allowed to review some aspects of the existing implementation.

This paper presents an overview of the operational experience with powering interlocks during the first LHC running period (2010-2012). It focuses on the issues encountered, the mitigations put in place and the improvements proposed to be implemented during LS1 that will have an impact on the overall dependability of the machine protection system.

INTRODUCTION

During the first 3 years of operation, magnet powering interlocks have successfully initiated more than 300 beam dump requests coming from different powering systems [1]. Despite the absence of major incidents related to such powering systems, the redundancy of powering interlocks with respect to the beam loss monitors (BLMs) have been compromised in several occasions. Such issues encountered in the past have been carefully analyzed and validated by equipment experts.

The improvements and consolidation measures to prevent such events from reoccurring are discussed in detail in the following.

OPERATIONAL ISSUES AND CONSOLIDATION WORKS DURING LS1

Radiation induced failures

The effect of ionizing radiation on the Programmable Logic Controllers (PLC) has been the main cause of false beam dump requests of the Powering Interlock System (PIC) during the first LHC operational period (2010-2012). A total of five preventive dumps have been triggered by the PIC in 2011 while operating with stable beams at 3.5TeV, following a suspected memory corruption of the PLC due to single event effects (SEEs) that provoked the passivation of the controller outputs.

At the end of 2011 all radiation sensitive components of the PICs installed in UJ14/16 and UJ56 were temporarily relocated to US152 and USC55 respectively. Such mitigation measures were demonstrated to be very effective and prevented the occurrence of SEEs during 2012. In addition, important consolidation works are foreseen during LS1 within the radiation to electronics (R2E) project. A total of 9 powering interlock controllers will be relocated to the bypass areas UL14/16 [2] and UL557 [3]. Moreover, the RD1-FMCM in UJ56 will also be relocated together with the Beam Interlock System (BIS) to USC55.

Following the relocation, all operational databases (i.e.: Layout DB, Logging DB, Alarms…) will be updated according to the new location and naming of the affected systems.

Trips due to electrical network perturbations

One of the root causes of beam dumps from the magnet powering systems in the LHC is due to electrical disturbances affecting the CERN electrical network distribution. Last year a total of 24 of these events were exceeding the defined thresholds of Fast Magnet Current Change Monitors (FMCMs), which led to preventive beam dumps in order to avoid dangerous beam excursions. In most cases (14 out of 24), these glitches were small enough to only trigger the FMCMs while no other equipment trips were recorded (Fig. 1).

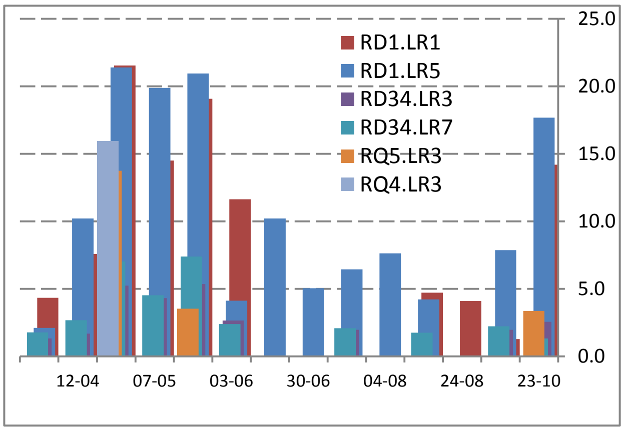

Figure 1: Beam dumps triggered by FMCMs in 2012 with no other equipment affected

An internal review [4] was organized in April 2012 within the TE department with the aim of finding solutions to mitigate the effect of minor electrical network perturbations and consequent FMCM triggers. The review focused on the effect of current changes on the most sensitive circuits: main separation dipoles (RD1), twin aperture main separation circuits (RD34) and the ALICE compensator circuits (RBXWTV). Simulations were presented to evaluate the effect of a typical +300mA magnet current change for the worst possible failure scenario at 450GeV that demonstrated the feasibility to safely relax the existing thresholds in both RD34 and RBXWTV circuit families by a factor 3 [5], as shown in table 1.

Additional mitigation measures are currently under investigation by the TE-EPC group. During LS1, a behavioural model of the thyristor power converters will be made available and the TE-EPC group is confident that a full rejection of minor perturbations can be achieved by changing the regulation characteristics of the most sensitive converters. However, the final mitigation will be the replacement of these thyristor type converters powering RD1/D34 by switch-mode power supplies, which are much less sensitive to network perturbations on the primary side.

Table 1: FMCM threshold upgrade

Electrical circuit	Initial Warning/ Dump Threshold	Modified Warning/ Dump Threshold
RBXWTV.L2	0.5/0.6	1.5/1.8
RBXWTV.R2	0.6/0.8	1.5/1.8
RD34.LR3	0.2/0.4	0.8/1.2
RD34.LR7	0.5/0.6	0.8/1.2

Access and 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, an ad-hoc interlocking of the LHC access conditions was put in place using the Software Interlock System (SIS) and the LHC timing system. Such solution depends on the Technical Infrastructure Monitoring (TIM) to propagate the access status to the SIS. Despite that the existing implementation has been properly working since 2010, a partial renovation of the system will be implemented during LS1 with the aim of improving the dependability of the communication link based on TIM [6].

The LHC Access Safety System (LASS) will provide the access conditions to a new Access-Powering PLC installed in a neighbouring rack in the CCR (Fig. 2). Then a FESA server will be in charge of propagating the access states to CMW and making them available for the SIS.

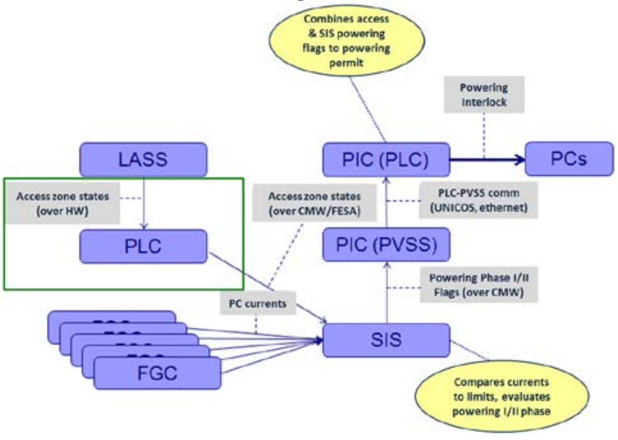

Figure 2: New layout of Access-Powering Interlocks

SPS magnet interlocks

The protection of the normal conducting magnets on the SPS accelerator complex relies on three different interlock systems, which are grouped by circuit families: mains, auxiliaries and ring-line. While the main and auxiliary interlock systems are split per BAs, where the interlock signals from two half-sextants are handled, the ring-line interlock system is made of interlock loops going around the SPS and terminated in a single rack installed in BB3. On the 2th of June 2012 a problem with the ring-line interlock chassis caused several hours of SPS downtime, and was finally traced back to an increase of the impedance of the line over time.

Due to the lack of diagnostics and the difficulties to maintain such an old system dating from the 70's, a new interlock system based on the standard WIC solution will be put in place during LS1[7]. The new interlock system will reuse the existing cabling infrastructure except for the ring-line interlocks that will be split in half sextants (Fig. 3)

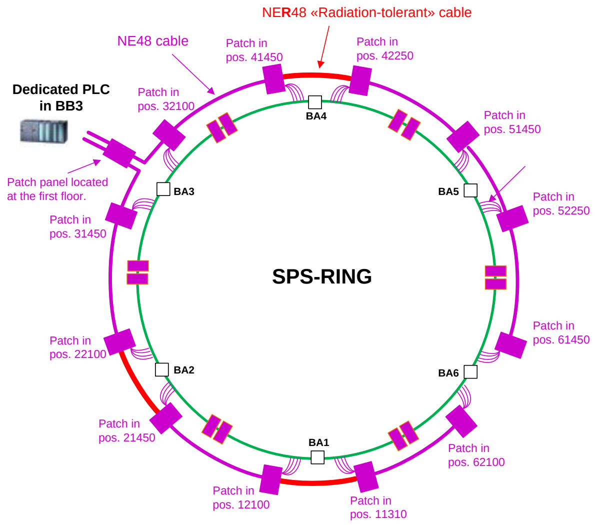

Figure 3: Ring-line interlocks in SPS ring after LS1

Late dump detection by Power Converters

Two issues have been discovered in 2012 when power converter trips provoked beam losses and beams were dumped by BLMs. On the 15th of June 2012 a broken diode inside a triplet power converter caused large circulating currents across the nested converters, which ultimately provoked beam losses [8]. This event was only detected by the FGC controls 300ms after the first current excursions due to the very relaxed interlock thresholds.

On the 7th of September 2012 a radiation induced latch-up affecting the FGC, provoked a 2 seconds delay in sending the powering failure to the PIC. This is caused by a watchdog which keeps the converter running for up to 2 seconds in the event of an FGC crash, to allow the FGC to reset and then to recover the control of the converter.

During LS1, FGC2 will be upgraded to achieve better sensitivity by reducing current threshold settings. In addition, the 2 seconds timeout will be removed to avoid late dump detection.

Late dump detection by Experiments

Protection of the magnets used in the four LHC experiments relies on the Magnet Safety System (MSS). Despite the smooth operation of the MSS, two important events have been recorded last year [9]. On the 10th of August a trip of the CMS solenoid (Fig. 4), caused by a cooling problem, provoked high beam losses along the machine. This fact demonstrated that the solenoid has a slow but non-negligible effect on the beams. MPP has requested that the MSS has to provide an interlock in case of fast discharges. These changes will be implemented during LS1.

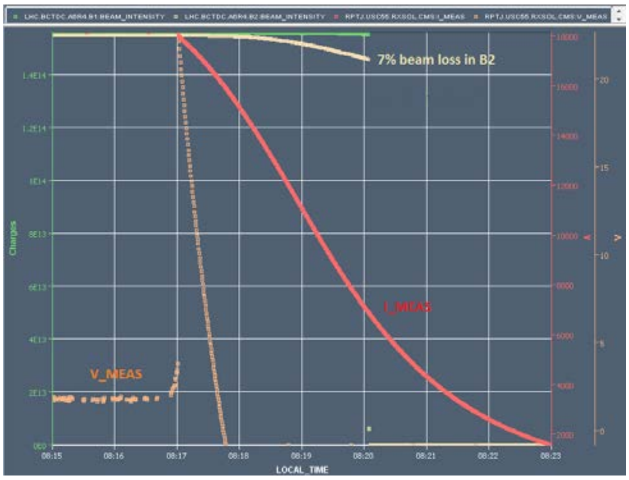

Figure 4: Beam losses after discharge of CMS solenoid

On August 19th beam losses were observed after a trip of the LHCb magnet. This is explained by the fact that the MSS takes some 25ms to generate the interlock event. In order to mitigate this problem, the MSS will be upgraded, including the replacement of the slow output safety relays by optocouplers.

Loss of 60A powering permit

Protection of the LHC 60A dipole orbit corrector magnets is ensured by Power Converters and no hardware interlocks are present. However, non-critical software interlocks prevent unnecessary magnet and current lead quenches and help operations. The PIC-PVSS provides a 60A Powering Permit for each LHC sector, which is derived from cryogenics and powering conditions and then transmitted to the FGC gateways using the LHC timing system.

On the 25th of October 2012 the 60A orbit correctors in sector 56 experienced a slow power abort due to a network communication problem and the following removal of the powering permit by the PIC-PVSS. This event lead to beam losses and the beams were dumped by the Beam Loss Monitors (BLMs). The cause of the problem was traced back to a wrong implementation of the logic in PVSS in charge of calculating the 60A Powering Permit. In addition, a second issue was found: the timing system should have inhibited sending the telegram to abort powering if beams are present in the machine [10].

During LS1, the PVSS interlock logic for the small dipole orbit correctors will be changed and the mechanism to mask such interlock in the timing system if beams are present will be reviewed.

Operational improvements

The protection of the LHC superconducting magnets is ensured on a circuit-by-circuit basis. On top of this and in order to prevent propagation of quenches across neighbouring magnets within the same powering subsector, a global protection mechanism has been implemented in the PIC. Experience over the past years has demonstrated that this implementation represents a bottleneck for testing during hardware commissioning periods since it excludes testing circuits of the same subsector in parallel.

A proposal to allow masking the global protection interlocks via PVSS has been presented to the MPP [5] and will be implemented during LS1. MPP recommended that masks have to be automatically removed if beam permit loops are armed and beam can potentially be present in the machine.

SUMMARY

Powering Interlocks have been working with no major issues during the first years of LHC operation. A huge effort has been put to detect and understand unexpected events and, as a consequence, some changes have been proposed to continue improving the dependability of such interlock systems. All changes or upgrades described in this document have been previously validated and approved by the TE-MPE group and/or MPP.

Considering the non-negligible number of modifications that will be carried out during LS1, special care will be taken to fully validate the interlock systems during the next hardware commissioning campaign.

ACKNOWLEDGEMENTS

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ELECTRICAL DISTRIBUTION FOR MACHINE PROTECTION SYSTEMS: HOW TO ENSURE SAFE POWERING AND HIGH AVAILABILITY?

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Abstract

The LHC machine protection system is powered by 64 Uninterruptible Power Supply (UPS) units distributed over the whole LHC tunnel. In this paper, the UPS distribution network is reviewed, highlighting the major improvement that was made in 2009 in order to provide redundancy in the powering. Although this important change has been considered as successful for the machine protection system, all other users have been strongly affected by the reduced availability that resulted from this modification. Indeed, the same UPS power distribution network is also employed for supplying other users (e.g. cryogenics) where the main constraint is availability in order to reduce LHC downtime. During the first long shutdown (LS1), the existing UPS units will be replaced in order to increase reliability in the electrical distribution. New UPS configurations have also been studied to improve both safe powering and availability for all users. Finally, a word about LHC machine availability with respect to electrical perturbations is given.

INTRODUCTION

The LHC machine protection system protects all equipment of the LHC accelerator against uncontrolled release of energy stored in the magnet system and the particle beams. The machine protection system requires safe electrical power supply, i.e. without any interruptions even in case of problems with the mains grid. Indeed a perturbation on the mains results often in a beam dump and, in some cases, requires an energy extraction from the superconducting circuits. When this occurs, the machine protection system, and in particular the quench protection system, must remain active to orderly carry out the shutdown procedure of the accelerator. The machine protection system, as well as all critical equipment around the LHC which does not withstand any power cut, is thus connected to UPS systems. In case of mains failure, the UPS systems continue to power, for a limited time, this critical equipment.

A problem arises when the UPS distribution network fails itself. Safe powering of the machine protection system must be guaranteed in all events, also in case of an internal failure within the UPS network distribution. Different measures were taken in 2009 to make the UPS power distribution network completely fail-safe. However, after three years of LHC operation and several UPS failures encountered, the UPS units will be replaced during the LS1 and new UPS configurations will be implemented in order to substantially increase the reliability and availability of safe power distribution for all users connected.

USERS REQUIRING SAFE POWERING

The UPS power distribution network supplies all critical equipment which does not tolerate any mains perturbations and which must remain powered and active in case the mains failure would last several minutes. The most critical system, the machine protection system, requires safe powering in all events and especially for initiating and carrying out the safe shutdown procedure. The machine protection system is mainly composed of the Quench Protection System (QPS), the beam dump system and the beam loss monitor system. The 10 min autonomy provided by the backup battery of the UPS units is defined by the QPS. It corresponds to more than twice (safety margin) the time required for extracting the energy stored in the magnet system and during which the QPS must remain active for quench detection and, if necessary, for protecting the superconducting circuits.

Other critical systems around the LHC tunnel require also safe powering, in particular cryogenics and vacuum control systems. Although the loss of these systems will not directly jeopardize the protection of the LHC machine equipment, the machine run will most probably be terminated whenever these systems are no longer available. So these systems demand a very high availability from the UPS systems in order to minimize LHC downtime.

UPS SYSTEMS AND DEFINITIONS

In this paper, a UPS unit refers to a single UPS apparatus while a configuration of two or more UPS units is called a UPS system.

UPS Topologies

A UPS unit protects sensitive loads when the input power supply deteriorates; whenever the input power fails it continues to provide power to these critical loads up to a maximum time defined by the capacity of the backup battery. Conventional UPS units use the double conversion topology. In normal conditions, the rectifier converts AC to DC power and feeds the inverter while maintaining the battery in charge. The inverter converts DC back to AC power and feeds the load (see Fig. 1). In case of input power failure, the load remains powered by the inverter using the battery stored energy. The load is automatically transferred to the mains (via the bypass) in case of inverter failure. This transfer is instantaneous and without any perturbations for the load as long as the inverter is synchronised to the bypass AC source.

The UPS units which date back to the initial LHC installation are of delta conversion type. This hybrid topology uses an additional AC to AC power path, so-called “pure power path” in parallel to the similar converter/inverter connection with a common battery (see Fig. 1). This power path allows the mains in series with a transformer to contribute to the direct powering of the load. The delta conversion topology also uses a bypass line, but contrary to the double conversion one, it does not provide dual inputs for connecting two independent input sources.

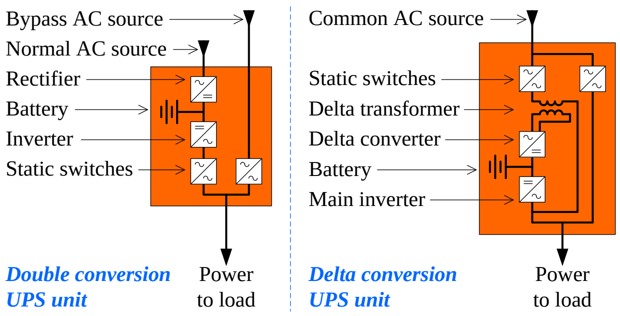

Figure 1: Comparison between UPS topologies.

Redundant UPS Systems

To increase the availability of a UPS-based installation for providing safe powering to critical loads at any given time and hence to minimise downtime, UPS units can be connected in parallel to the same downstream distribution switchboard. In this so-called parallel-redundant configuration, the load is equally shared between both units. In case one of both UPS units fails, the load is automatically transferred to the remaining unit without any perturbations. This parallel-redundant configuration requires a CAN bus (Controller Area Network) for communication between both UPS units. However, it may happen that the failure of the first UPS unit leads to the stop of the second and consequently, to the loss of power to the load.

An alternative to the parallel-redundant configuration is the “stand-by redundancy” where a backup UPS unit feeds the bypass line of the UPS unit being in the front line and supplying the critical loads. In case of failure of the latter, the load will be automatically transferred to the bypass and will end up supplied by the backup UPS unit. This configuration strictly requires no communication bus. Though very rare, the case when the front UPS unit fails to transfer to its bypass line has also to be considered. Nevertheless UPS literature reports that higher availability is obtained with this “natural” redundant configuration. This configuration is optimum for double conversion UPSs since the normal AC source of the front UPS unit can remain wholly independent from the normal and bypass AC sources supplying the backup UPS unit.

LHC UPS DISTRIBUTION NETWORK

Overview

The UPS distribution network dedicated to the LHC is shared out over 32 zones located in the underground infrastructures in order to cover all loads requiring safe powering. In particular, UPS systems are located in the 16 RE alcoves located around the LHC tunnel, each one covering up to 1.2 km for electrical distribution in the tunnel. In addition, UPS systems are installed in the service caverns of the 8 LHC points for supplying all critical loads around the interaction points. Finally, UPS systems are located in UA bypass tunnels on either side of US service caverns in LHC even points (8 UA tunnels in total) for supplying all critical electronic racks.

Original UPS Distribution Network

Each of the 32 zones was equipped with 2 parallel-redundant delta conversion UPS units connected to a single distribution switchboard (see Fig. 2). In each zone, the entire equipment requiring backup from a UPS system was supplied via the so-called F3 power distribution lines running in the LHC tunnel, F1 and F2 distribution networks being reserved to other equipment demanding normal power supply.

Magnet Powering Interlock with UPS Systems

Since the beginning, the status of the UPS systems has been fed into the Powering Interlock Control (PIC) system [1]. When a UPS system cannot back up its load, powering of all the magnets that are protected by the QPS equipment supplied from this non-available UPS system must be stopped. In each zone, the UPS systems are connected to the remote PIC controller by means of hardwired current loops. At the level of the UPS units, alarm relays providing dry contacts are used for the cabling of the interlock link. The PIC interlock logic is based on the information given by each UPS unit and consolidated for redundant UPS systems (with two UPS units).

At that time, it had been accepted that a machine run could continue if one of the two UPS units composing a redundant system would fail. Nevertheless, at the end of the machine run, an intervention was mandatory for repairing and restoring the redundancy within the faulty UPS system, i.e. a new machine run could only start when all 32 redundant UPS systems were fully operational. With such UPS configurations, all end users could thus benefit from the UPS redundancy.

FIRST UPS NETWORK CONSOLIDATION

After the accidental rupture at 9 kA of a bus-bar interconnection in September 2008, the QPS system was reviewed, and substantially changed and upgraded in 2009 [2]. The initial QPS system was complemented with a new QPS system which also performs as redundant system in some cases. In addition, maximum reliability of the QPS system was assured by duplication of every safety channel. However, the review of the QPS system also pointed out that the whole UPS distribution network was not completely fail-safe [3] and that it presented single points of failure. For instance, a short circuit inside the power distribution switchboard downstream a UPS

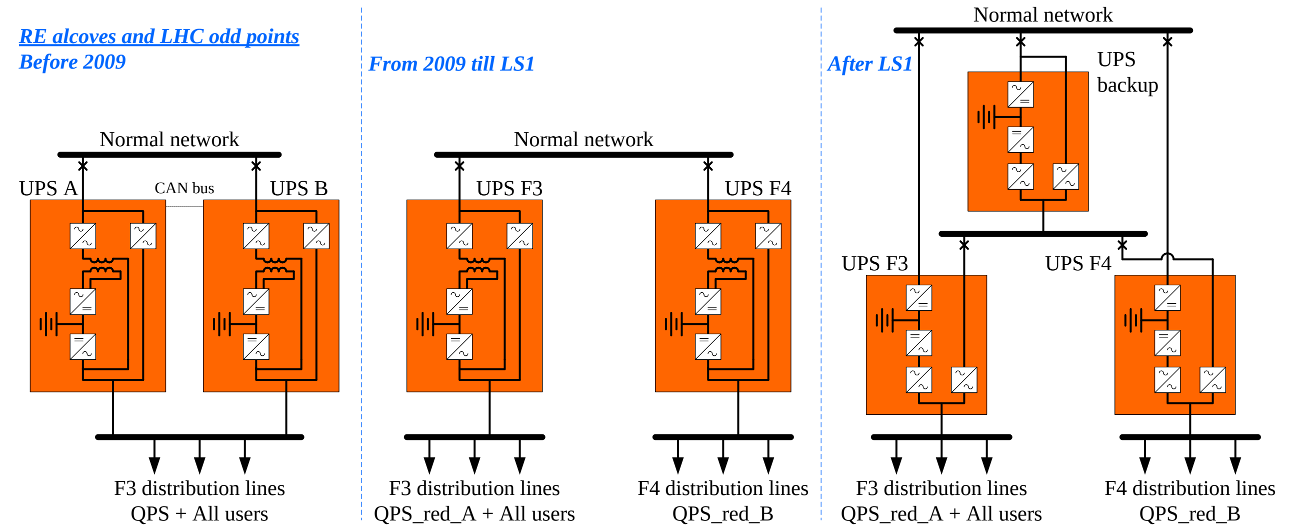

Figure 2: UPS power distribution network and its upgrades in the RE alcoves and the LHC odd points.

system, although extremely unlikely, could lead to the power cut of all QPS equipment protecting 92 main magnets (half an arc of the LHC machine). Consequently, major consolidation of the UPS distribution network took place in 2009 in order to make the UPS systems and the downstream distribution truly redundant.

Two Independent and Safe Power Paths

In order to supply redundant components of the QPS equipment, two independent power paths were requested that had to be supplied by independent UPS systems. The following measures were then taken in each of the 16 RE alcoves and 4 LHC odd points: a completely new distribution network, so-called F4 as a backup to the F3 distribution network, was created by pulling new cables and installing new distribution boxes in the whole LHC tunnel. Then the parallel-redundant UPS system in these zones was reconfigured as two independent UPS units (see Fig. 2), one dedicated to the original F3 distribution network (referred to as UPS F3) and the second for powering the new F4 distribution network (referred to as UPS F4). The new F4 distribution network was strictly reserved to redundant QPS equipment whilst all other users remained connected to the original F3 distribution network. However, other critical machine protection systems with redundant equipment quickly followed the QPS system and took advantage of a safe and redundant powering.

Overall Availability Reduced

The PIC interlock logic had to be adapted to this new distribution layout: the failure of one of both UPS units had to trigger the magnet powering stop. Indeed, in this configuration, all QPS systems would have lost their redundancy in case of a power outage, being only fed by a single operational UPS unit. Half of the redundant QPS equipment on UPS was the strict minimum for ensuring protection of the magnet system during the power ramp down procedure. Evidently, the repair of the faulty UPS unit was mandatory in order to be able to start again machine powering.

This new UPS configuration had a huge impact on the other users connected to the F3 distribution network only. They were no longer supplied by a parallel-redundant UPS system, but by one single UPS unit, losing drastically in availability. Moreover, the modification of the operating rules when losing a UPS unit strongly affected the machine availability. This also put an additional burden on the EN-EL Group, who operates these UPS units and had to repair and restart the faulty UPS system as soon as possible in order to reduce LHC downtime.

Full Redundancy in LHC Even Points

In UA tunnels, the redundancy of the powering for the QPS equipment was obtained by using the parallel-redundant UPS system located in the adjacent US cavern. Likewise, the redundancy of the F3 power distribution lines in the tunnel that were supplied by the UPS system in the US cavern, was established by pulling new F4 power distribution lines, which were connected in turn to the parallel-redundant UPS system located in the UA tunnel (see Fig. 3). This solution had the great advantage of not breaking the existing parallel-redundant configuration of the UPS systems while preserving the PIC interlock logic in these zones.

LHC UPS REPLACEMENT PROJECT

Over a few years of LHC operation, the failure rate of UPS units based on hybrid delta conversion topology was globally very high compared to the conventional double conversion UPS units also in operation at CERN [4, 5]. In particular, the failures of non-redundant UPS units in the LHC tunnel demonstrated, to our expense, the lack of reliability of this type of UPS equipment. Together with the loss of support from the manufacturer, who had stopped the production at the time the delta conversion

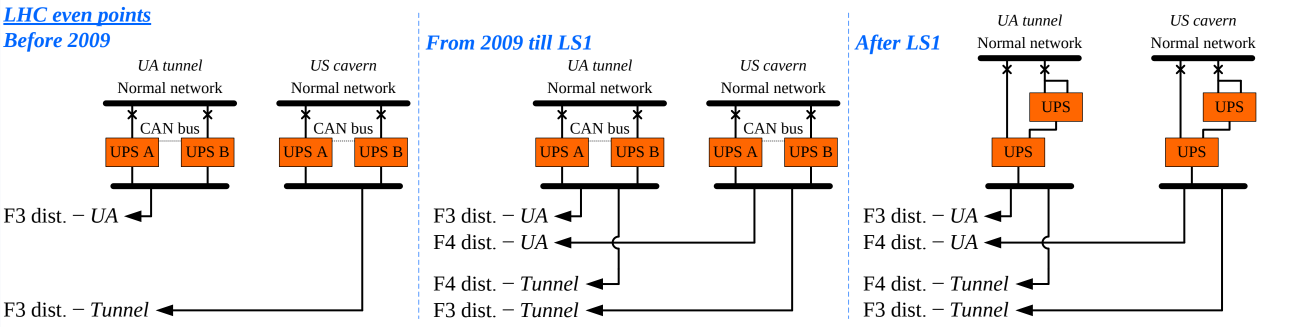

Figure 3: UPS power distribution network and its upgrades in the LHC even points.

UPSs were installed all over CERN. Based on these observations, the anticipated replacement of all delta conversion UPS units was proposed [4] and finally approved for an implementation during the LS1. So a total of 102 delta conversion UPS units, including the 64 dedicated to the LHC machine, will be replaced by new double conversion UPS units during the LS1.

NEW UPS CONFIGURATIONS

Restoring Redundancy within the UPS Systems

The introduction in 2009 of independent F4 power distribution lines dedicated to redundant machine protection equipment has been considered as a success and, for this reason, will be kept unchanged after the LS1. In the 16 RE alcoves and 4 LHC odd points, the UPS F3 and F4 will be replaced one to one with conventional double conversion UPS units during the LS1. But also, an additional UPS unit will be added in each zone for feeding the bypass line of the first two UPS units (see Fig. 2). In this “stand-by redundant” configuration, the third UPS will act as a backup for the two UPS units on the front line and will consequently restore the redundancy within the UPS system.

In the LHC even points (US caverns and UA tunnels), the UPS power distribution networks as well as the UPS systems were already fully redundant and thus will not be changed during the LS1. As shown in Fig. 3, the two parallel-redundant UPS units in each of these zones will be replaced by two double conversion UPS units connected in “stand-by redundant” configuration since this latter is considered as more reliable.

New Powering Interlock Rules

Based on the modifications brought to the UPS configurations, the UPS-related PIC interlock rules governing the magnet powering interruption will also be changed. In a three-unit UPS system, the failure of any of the three units will not stop the magnet powering provided that the latter transfers the load without any perturbation to its bypass. Indeed, it can be demonstrated that with one faulty UPS out of three, both F3 and F4 power distribution networks remain supplied by two independent UPS units. Hence, the non-availability of one of the three units within a UPS system will not inhibit the operation of the machine, leaving time for the EN-EL Group for preparing the repair intervention. Moreover, the repair may be scheduled together with access for other maintenance, further reducing the impact on the machine availability. Of course, the PIC system will definitely stop the magnet powering if a second UPS unit would come to fail within a system having already one unit down.

In UA tunnels, the failure of one of both UPS units will not trigger the PIC system. Even the failure of one unit of the corresponding redundant system in the adjacent US cavern will still be transparent for machine runs. However, the failure of the second and remaining unit in one UPS system will definitely stop the magnet powering.

Whatever the UPS system configuration, if one of the front line UPS units (powering directly the critical loads) would fail to transfer to its bypass, the UPS user permit to the PIC will remain valid. However, in this event, the magnet powering stop procedure will be triggered by the users’ equipment itself. The PIC will not act in this case but this situation is exactly the same if full or part of the power distribution network downstream the UPS system goes down (e.g. due to a short circuit). This worst case failure scenario has been accepted since 2009 when independent and backed-up power paths were introduced.

Testing the Redundant Powering

If one considers the amount of power cables to be connected over the whole LHC machine, the connection to the wrong power distribution network is more than likely (and it already happened!) and could lead to the loss of redundancy within a critical protection system. Therefore the safe and redundant powering of the machine protection systems will be tested during hardware commissioning at the end of the LS1.

The main objectives of such a test are to check that the machine protection system is still fully operational when losing a complete redundant power distribution network. Technically, this means to verify that the equipment with dual power supply modules is powered by two independent power distribution lines and that true redundant equipment is supplied by redundant power paths. The test will also be the best opportunity to check the worst case scenarios, i.e. when losing a full redundant power distribution network without triggering at all the PIC system.

The test will typically consist in switching off the switchboard powering one power path (F3), and then repeat the same test by switching off the second switchboard powering the redundant power path (F4).

LHC OPERATION FACED TO ELECTRICAL PERTURBATIONS

Impact of UPS Failures on LHC Operation

Ensuring the protection of the LHC machine equipment is of course the most important; however, failures of the UPS power distribution network will also contribute to an increased LHC downtime. Table 1 lists the major UPS failures that occurred during three years of LHC operation, each one causing a machine stop. Table 1 also indicates LHC downtime for each event as well as the time duration from beam dump to beam injection again (when applicable). The cumulated LHC downtime due to UPS failures reaches thus 126 h over three years. With the new UPS configuration layouts being implemented during the LS1, all these events would have been completely transparent for LHC operation.

Table 1: UPS failures during LHC operation

Date	Most probable cause of the UPS failure	LHC downtime / beam to beam [h]
12.01.2013	Surge on 18 kV network	26.5 / 26.5
29.09.2012	Single event upset	9 / 10
01.10.2011	Single event upset	8.5 / 14.5
29.09.2011	Single event upset	8.5 / 9.5
03.05.2011	Single event upset	26 / 28.5
02.09.2010	UPS design issue	4.5 / n.a.
27.08.2010	UPS design issue	8 / n.a.
23.04.2010	UPS design issue	5 / 12
18.02.2010	UPS design issue	30 / n.a.

The last event in January 2013 remains the most worrying: 2 delta conversion UPS units, located 4 km apart, broke down exactly at the same time when a short circuit on an 18 kV cable termination occurred in one of the major substations in Prévessin, the failures on both UPS units being strictly identical. The most probably cause was a surge on the 18 kV network although strictly no other equipment was damaged. Following this event, a re-qualification test campaign has been internally launched at CERN in order to confirm that the new double conversion UPS units can withstand surge levels much higher than those required in the IEC standards.

Outside Electrical Perturbations

The operation of the LHC machine is often affected by outside electrical perturbations (see Fig. 4), causing inevitably LHC downtime.

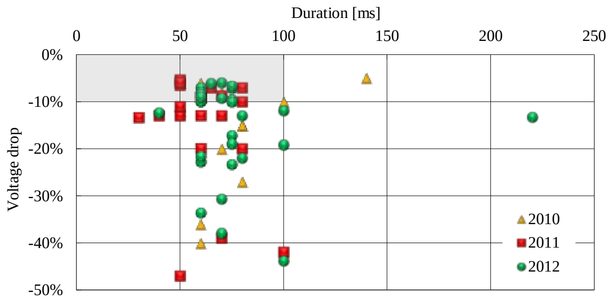

Figure 4: Voltage dips recorded on the CERN electrical network that led to LHC downtime (2010-2012).

The CERN electrical network is supplied by the French grid through a 400 kV line interconnected with the Swiss grid, providing good availability. However, the drawback is that CERN installations get exposed to many more outside electrical perturbations. A frequently asked question is “how to increase the quality of the electrical network”; actually the problem is not the quality of the power distribution network but rather the sensitivity of users’ equipment to electrical perturbations. Indeed, it is recommended that standard equipment installed at CERN tolerates voltage drops of up to 10 % and lasting up to 100 ms [6]. Fig. 4 depicts this recommendation with a grey zone and shows that the LHC machine has very sensitive equipment. One means to reduce the sensitivity of the LHC to electrical perturbations would then be to act directly on the users’ equipment and to increase tolerances on the input power supply modules.

CONCLUSION

The UPS power distribution network for the LHC has been substantially improved to ensure safe powering and high availability for all users. Though unwished, the first failure of a UPS unit occurring in the LHC after the LS1 will demonstrate the usefulness of the investment made to reshape the UPS network.

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POST LS1 OPERATION

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Abstract

The expected mode of operation and performance after Long Shut-Down 1 (LS1) are outlined based on the outcome of the LHC Beam Operation workshop - Evian 2012 [1]. The paper will focus on proton operation with particular emphasis on performance for the high luminosity interaction points.

ASSUMPTIONS

The characteristics of the beams delivered by the injectors and the beam parameters expected in collision, including the blow-up in the LHC, are based on the 2012 experience and are listed in Table 1. For the 25 ns beams no additional blow-up due to electron cloud is considered. This condition will be achieved after a scrubbing run at 450 GeV and a significant period of operation with 25 ns beams at 6.5 TeV. Both the nominal and BCMS (Batch Compression Merging and Splitting) schemes for producing the LHC beams in the PS are considered. For the BCMS scheme the considered number of bunches circulating in the LHC is smaller to account for the shorter trains delivered by the PS (in case of the 25 ns beam: 48 bunches per train for the BCMS scheme instead of 72 bunches per train for the nominal scheme, in case of the 50 ns beam: 24 instead of 36).

Table 1: Assumed beam parameters at SPS extraction and in collision at the LHC

	# bunches	$N_{bunch\text{-}coll}$ $[10^{11}]$	$\varepsilon^*_{SPS\text{-}ext}$ [μm]	$\varepsilon^*_{LHC\text{-}coll}$ [μm]
25 ns	2760	1.15	2.8	3.75
25 ns BCMS (48 bunches/ PS batch)	2520	1.15	1.4	1.9
50 ns	1380	1.6	1.7	2.3
50 ns BCMS (24 bunches/ PS batch)	1260	1.6	1.2	1.6

A beam energy of 6.5 TeV and a beam-beam separation at the first parasitic encounter of 10 σ (where σ is the r.m.s. beam size) for the 50 ns beam and of 12 σ for the 25 ns beam are considered. While the value assumed for 50 ns operation is approximately the same as in 2012 the value for 25 ns operation might be rather conservative if no-blow-up due to electron cloud occurs. However, for the initial phase where the scrubbing is not complete this is a reasonable assumption.

The same excellent aperture, orbit control along all the phases of the operational cycle, and beta-beating as in 2012 are assumed.

COLLIMATION

During LS1 new collimators with integrated Beam Position Monitors (BPM) (16 tertiary Tungsten collimators – TCT and 2 secondary collimators – TCSG - in point 6) will replace the corresponding collimators [2][3]. This will help in reducing the tolerances considered for the collimator set-up. This will allow a further reduction of the β* at the interaction point and an increase of the crossing angle to maintain the above mentioned beam-beam separation at the parasitic encounters. It must be noted that this will be possible only after some experience has been gained with the BPM collimators, likely in the second year of operation after LS1.

The collimator apertures expressed in beam σ (for a normalized emittance of 3.5 μm) corresponding to different tolerances are listed in Table 2 together with the expected impedance relative to the estimated impedance for the 2012 collimator aperture settings [3][4].

Table 2: Collimator apertures (in beam σ) for different operational scenarios and corresponding impedance.

	Case 1:	Case 2:	Case 3:	Case 4:	Case 5:
buttons	no BPM buttons			BPM buttons	
tolerance	*relaxed*	*tight** (same as 2012 in mm)	*nominal* (keep retraction in σ)	*tight** (same as 2012 in mm)	*nominal* (keep retraction in σ)
TCP 7	6.7	5.5	5.5	5.5	5.5
TCSG 7	9.9	8.0	7.5	8.0	7.5
TCLA 7	12.5	10.6	9.5	10.6	9.5
TCSG 6	10.7	9.1	8.3	9.1	8.3
TCDQ 6	11.2	9.6	8.8	9.6	8.8
TCT	12.7	11.1	10.3	10.0	9.1
Aperture	14.3	12.6	11.7	11.2	10.3
Relative Impedance w.r.t. 2012	0.75	1.1	1.5	1.1	1.5

In the following, case 4 of Table 2 (tight collimator settings) will be considered as it allows maximizing the performance reach in terms of peak luminosity (smaller β*) for a negligible increase in machine impedance. The single beam stability limits in bunch population for the 25 and 50 ns beams considered in Table 1, corresponding to the relaxed, tight and nominal collimator settings and resulting from impedance are shown in Fig. 1 [4]. Operation with maximum Landau Octupole current (550 A, positive polarity – as in the second part of the 2012 proton run), high chromaticity (Q'~15-20) and maximum damper gain (corresponding to a damping time of 50 turns) have been assumed for these estimates. The chosen polarity of

* These settings are referred to as the 'tight settings' for historical reasons. In reality they are more relaxed than the nominal settings.

the octupoles represents a conservative case form the point of view of single beam stability.

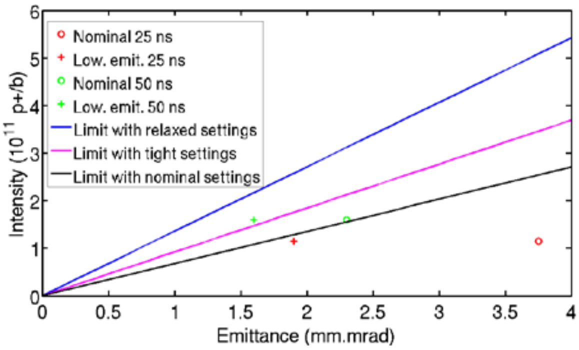

Figure 1: Single beam stability limits for the bunch population for different collimator settings. The dots correspond to the beam parameters listed in Table 1 for the LHC in collision [4]. Courtesy N. Mounet.

While operation with 25 ns beams does not pose any problem from the point of view of stability due to impedance, operation with 50 ns beams with small emittance (BCMS scheme) is marginal with the tight collimator settings and might imply operation with relaxed settings.

EXPECTED PEAK PERFORMANCE

The expected peak performance for 50 and 25 ns operation at 6.5 TeV with the above assumptions is presented in Table 3. Operation with 50 ns beams would entail an unacceptable pile-up for the experiments. Furthermore the peak luminosity for the 50 ns BCMS might be limited by the heat load induced by the luminosity debris at the triplets in IP1 and IP5 to ~1.75×10^{34} cm^{-2}s^{-1} [5]. Operation with 50 ns beams would therefore require the implementation of a levelling mechanism robust with respect to instabilities.

Levelling might be required also for 25 ns beam operation for the BCMS scheme.

Table 3: Expected peak performance at 6.5 TeV.

	50 ns beams		25 ns beams	
	nominal	BCMS	nominal	BCMS
β* [m] (separation/crossing planes)	0.4/0.4	0.4/0.35	0.4/0.55	0.4/0.45
ε*[mm] at start of fill	2.3	1.6	3.75	1.9
Max. Bunch Population [10^{11} p]	1.6	1.6	1.15	1.15
Max. Number of bunches/colliding pairs IP1/5	1380	1260	2760	2520
Bunch length (4 σ)[ns]/ (r.m.s.) [cm]	1.35/10.1	1.35/10.1	1.35/10.1	1.35/10.1
Max. Beam Current [A]/population[10^{14} p]	0.4 / 2.2	0.36 / 2.0	0.57 / 3.2	0.52 / 2.9
Max. Stored energy [MJ]	230	210	330	300
Peak luminosity [10^{34} cm^{-2}s^{-1}] in IP1/5	1.5	2.0	0.85	1.5
Half External Crossing angle IP1/5 [µrad]	140	120	195	155
Beam-beam tune shift (start fill)/IP [0.001]	5.3	7.3	2.5	4.3
Min. beam-beam separation (σ) d_{sep}	9.3	9.3	12	12
Maximum Average pile-up ($\sigma_{inel.}$=85 mb)	82	120	23	44

OPERATIONAL CYCLE

Ramp

Beam stability implies the use of the transverse damper at high gain (a few tens of turns damping time), nominal Landau Octupole current (550 – 600 A) and high chromaticity (Q' ~15-20 units) as soon as the collimator aperture is reduced to achieve tight settings at 6.5 TeV. Tighter collimator settings are required only when the β* is reduced below a few meters. Therefore the collimator aperture should be reduced to tight settings only when required and the ramp should be performed with relaxed collimator settings to avoid instabilities driven by the impedance, which at high energy is dominated by the impedance of the collimators.

It is possible to increase (double) the octupole equivalent strength if needed using the MCO and MCOX circuits but this implies a significant reduction of the dynamic aperture as shown in Fig. 2 [6].

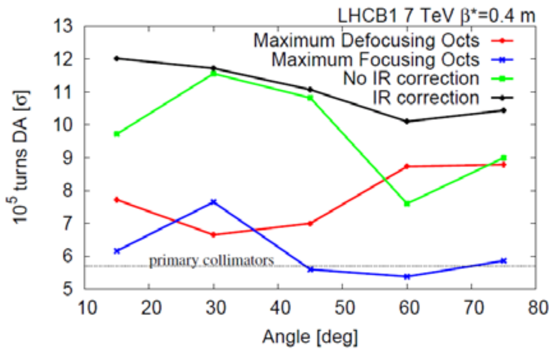

Figure 2: Dynamic aperture as a function of the phase space angle using all the available octupole circuits (Landau Octupoles, Octupole Spool pieces, Inner Triplet Octupole correctors). Courtesy R. Tomàs.

Squeeze

The collimators should be moved to tight settings only for small β* (< 3 to 5 m) when the triplets' aperture is no more in the shadow of the arcs' aperture.

The operation in 2012 has shown that the head-on beam-beam tune spread (which does not depend on β*) can be used to stabilize the beam, therefore it is suggested to go in collision at β*> 3 to 5 m and run the rest of the squeeze in collision [7][8]. The collimators would then be moved to tight settings only once the beams are in collision and before continuing the squeeze. The increased Landau damping provided by head-on beam-beam will damp the instabilities that might arise as a result of the increase in impedance when the collimators are moved to tight settings.

This restrains the presence of non-colliding bunches, which might suffer from instabilities due to the lack of the extra Landau damping. These instabilities might lead to significant population loss and might generate spurious position readings at the beam interlocked BPMs, resulting in beam aborts. An upgrade of the interlock logic based on the LSS6 BPM readings would solve this problem and could allow the operation with few non-colliding bunches. However, this would not avoid the above-mentioned losses.

Collision Process (Adjust)

Going in collision in IP1 and IP5 should be performed in sequence to avoid a minimum in tune spread in both planes at the same time [8].

Once in collision, chromaticity and Landau octupole currents should be lowered to few units and to less than 100 A, respectively, to guarantee a good lifetime taking into account that the squeeze below 3 m has to occur in collision. In this scenario the beams will be colliding for at least 10-15 minutes during the last part of the squeeze in adjust mode with the experiments in standby and therefore not using the luminosity delivered by the LHC.

It might be advantageous to combine the ramp and the first part of the squeeze down to 3-5 m and to move the collimators to their tight settings during the last part of this combined process. This in order to avoid beam loss peaks during the collimator movement at high energy that might lead to beam dumps. In that case the beams should be brought in collision during the same process.

Stable Beams and levelling

β* levelling is the preferred option to limit pile-up to acceptable values for the high luminosity experiments in case of operation with 50 ns beams and possibly for the 25 ns high brightness beams (BCMS beams).

Levelling by separation should be considered for “simplicity” of operation (at least initially) in IP2 and 8.

A schematic representation of the phases of the present and possible operational cycle after LS1 is shown in Fig. 3.

POTENTIAL ISSUES

Electron Cloud Effects [9]

During the scrubbing run in December 2012 the possibility of completely filling the machine with nominal trains of 288 bunches spaced by 25 ns and to control beam stability with an adequate setting-up of the transverse feedback and machine parameters has been demonstrated at 450 GeV. Unmistakable signs of conditioning (reduction of the normalized heat load in the arc beam screens and improvement of the beam lifetime) have been observed in the first part of the scrubbing run but this process slowed down and became almost undetectable during the last scrubbing fills at injection and during a series of fills at 4 TeV.

During LS1 most of the machine will be vented to air and it is expected that the Secondary Electron Yield (SEY), responsible for the onset of the electron cloud build-up, will recover the initial values observed at the beginning of the operation of the LHC. The same will happen for the beam induced desorption yield responsible for the pressure rises observed in the presence of LHC beams in the warm areas. Conditioning with 50 ns and 25 ns beams will be required at 450 GeV before operation with high intensity beams with 50 ns and 25 ns spacing. Based on the 2012 experience it is expected that a scrubbing run at 450 GeV will not be sufficient to provide an electron-cloud free environment. Physics at 6.5 TeV with 25 ns beams with degraded conditions in terms of emittance blow-up and significant heat loads in the arc beam screens are to be expected initially and will result in a slower intensity and performance ramp up.

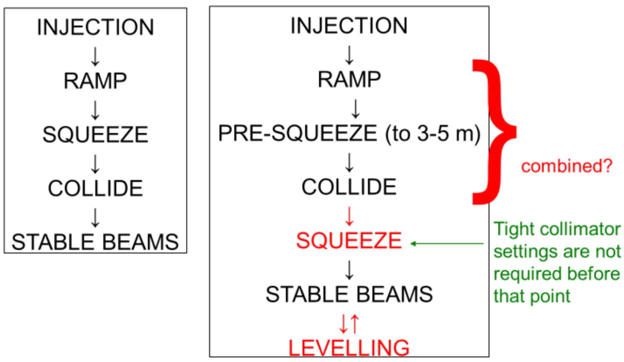

Figure 3: Comparison of the present (left) and possible future operational cycle.

UFOs [10]

Unidentified Falling Objects (dust particles falling into the beam and leading to beam losses) might hamper physics operation at higher energy due to the higher losses generated because of the higher energy as compared to 2012 and because of the lower beam loss thresholds. 91 arc UFOs in 2012 would have led to a dump at 7 TeV. It must be noted that conditioning has been observed in 2011-2012 with 50 ns beams.

A tenfold increase of the UFO rate has been observed with 25 ns beams at the beginning of the scrubbing run in December 2012 but signs of conditioning have been seen (see Fig. 4 [10]).

"Deconditioning" has to be expected after LS1 because (almost) all the vacuum sectors will be opened to air. The results of the quench tests might allow relaxing the BLM thresholds for the short timescales which are involved in the UFO events [11].

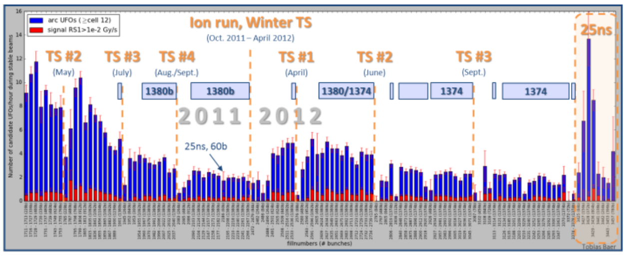

Figure 4. Evolution of the UFO rate during the 2011-2012 proton runs with 50 ns beams and during the 25 ns runs. Courtesy T. Bär.

Beam Induced RF Heating [12]

Beam induced heating related to impedance has been an issue for the operation at high intensity in 2012 leading to damage of components (e.g. BSRT), outgassing (TDI), deformation (TDI). This will remain an issue and it will be important to anticipate potential problems by adequate monitoring during the ramp-up phase. The main concern for the operation in 2015 is the TDI, which has been one of the limiting components during the 25 ns run in December 2012 [12]. Follow-up of the possible limitations resulting from beam induced heating is in place but should possibly be formalized in the form of a working group.

POSSIBLE STRATEGY IN 2015

During 2011-2012 it has been demonstrated that a short scrubbing run at 450 GeV is sufficient to operate for physics with 50 ns beams with no electron cloud effects [9]. However, operation with 50 ns is not attractive for luminosity production at nominal pile-up as it would require levelling at luminosities approximately twice smaller than with 25 ns beams as the pile-up depends uniquely on the bunch-by-bunch luminosity. Levelling might be required also for 25 ns operation in case high brightness beams produced with the BCMS scheme in the PS are required. The exact gain in integrated luminosity achievable with the 25 ns as compared to the 50 ns beam depends on the pile-up that can be handled by the experiments and on the expected average fill length.

Impedance related effects are expected to be milder for 25 ns but UFOs and electron cloud effects will imply slower ramp-up for this mode of operation.

The above considerations privilege the operation with 25 ns beams in terms of potential performance, provided that the electron cloud effects can be mitigated by a progressive reduction of the SEY in the cold regions. This remains to be demonstrated for SEY<1.45.

A running period at 50 ns after a short scrubbing run is desirable at the beginning of the run (it could be at a pile-up of up to 40 with a β* of 50 cm and close to nominal bunch intensity but low emittance) to re-discover the machine at 6.5 TeV. After this initial period in which the number of bunches will be progressively increased, operation with 25 ns beams after an additional period of scrubbing (~10 days) could be envisaged and followed by a ramp-up in the number of bunches. The length of this process will depend on the speed at which the SEY reduces with the electron dose generated by the multipacting.

Operation with 50 ns beams with levelling should be considered as a back-up in case of serious issues related to electron cloud and UFOs.

ISSUES FOR MACHINE PROTECTION

As mentioned above the high brightness beams produced with the BCMS schemes are very attractive in terms of peak luminosity performance, in particular for the 25 ns spacing but their average energy density is higher than that of the ultimate 25 ns beam (with a bunch population of 1.7×10^{11} p and a normalized transverse emittance of 3.5 μm at injection and 3.75 μm in collision at 7 TeV) as it is summarized in Table 5.

Table 5: Relative energy density of the BCMS beams with respect to the ultimate LHC 25 ns beam at injection and in collision (see Table 1 for the beam parameters of the 25 and 50 ns BCMS beams).

	Injection	Collision (6.5 TeV)
25 ns BCMS	1.7	1.25
50 ns BCMS	1.35	1.02

The 2012 experience has shown that operation at high intensity and tight collimator settings is heavily dependent on:

- Strong Landau Damping provided by the Landau octupoles running at maximum strength until the beams are in collision;
- Maximum damper gain until the beams are in collision;
- Tight orbit control with the orbit feedback during the squeeze to avoid sudden increase in beam loss rates. This is even more crucial if the squeeze is performed in collision to avoid loss of Landau damping when the beam are separated due to relative orbit variations.

Unavailability or degraded operation of any of these systems could result in instabilities and beam losses leading to beam dumps. The expected rise-times of the instabilities are in the range of more than 1000 turns and are presently being re-evaluated in light of 2012 experience.

As previously mentioned operation at high intensity and in particular with 25 ns implies:

- the co-existence with electron cloud and its effects (vacuum, cryogenic load, beam blow-up, lower lifetime) during the whole operational cycle;
- the occurrence of fast beam losses in the millisecond scale or sub-millisecond scale due to UFOs.

Both the above phenomena are expected to require a careful intensity ramp-up and conditioning taking into account that most of the machine will be vented to air during the long shutdown.

Several measures have been taken to address the non-conformities and to review the design of components that have led to beam induced heating in 2012. In spite of this, a thorough follow-up of the evolution of temperatures and vacuum levels in critical areas, and the implementation of alarms on warning levels and interlocks is suggested to timely intercept conditions that could lead to potential damage.

The capability of squeezing in collision routinely has been identified as the more realistic mean of fighting transverse instabilities at high energy with tight collimator settings and of providing luminosity leveling at the high luminosity interaction points if it is required to limit the pile-up at the experiments. The setting-up of this process and in particular the possibility of leveling the luminosity by varying the β* in stable beams will have implications for the collimation set-up and validation that need to be addressed.

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UPDATE ON BEAM FAILURE SCENARIOS

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Abstract

At the time the LHC machine protection system was designed a number of standard failures scenarios have been taken into account, like the D1 warm dipole failure and the asynchronous beam dump. This paper will analyse if these failures did take place and if the protection system worked as expected. An iteration is made to see if the failure catalogue needs to be extended, based on the past operational experience and on the 2015 beam parameters and whether we need to adapt the machine protection system to possible new failure scenarios.

INTRODUCTION

The LHC machine protection system needs to protect the machine from damage by the beam. Ideally it has to protect against any possible failure scenario. Different critical failure scenarios, which are either difficult to protect against or would cause a large damage, have been taking into account for the design of the machine protection system. This paper lists the standard failure scenarios, checks if they did occur, if the protection system worked as expected and whether a change of the machine protection system is required for specific failure scenarios. This paper also discusses failures that did occur but were not foreseen and failures for which the machine protection system reacted differently than expected.

It is worth mentioning that the splice failure, which occurred in 2008, was not part of the failure catalogue. The first reason being that it is a non-beam related failure mode. Only beam related failure modes are treated in this paper. The second reason being that, although people were aware of the splice quench possibility, they were not fully aware of the risk of a quench in a bad splice, i.e. not only did they underestimate the frequency of the failure, they also underestimated the large impact caused by collateral damage. This shows the importance of having correct estimates of failure rates and failure impacts.

THE BIG THREE

The Big Three failure scenarios were defined before the first operation of the LHC [1]. They are described and analysed below.

Injection kicker flashover

This is a single turn, fast failure. An electrical break-down or flash-over in an injection kicker magnet can affect the injected beam (with too little but also too much deflection), or the stored beam. In all cases the beam is to be absorbed by the injection absorber TDI. In case a large number of bunches is affected, a quench of the magnets downstream of the TDI is expected.

This fault occurred several times. In the case of grazing beam incidence on the TDI, downstream magnets quenched as expected. In one occasion, part of the ALICE detector was affected by the sprayed beam and a short circuit of a magnet corrector circuit occurred at the moment of beam impact. However, the short circuit could not be explained considering the power deposition.

On all the occasions a kicker magnet break down occurred, the protection system functioned as expected and the beam was absorbed by the TDI. For this reason no real changes of the protection system against this failure mode is foreseen. However, the importance of the correct positioning of the TDI has been demonstrated. Additional difficulties with the TDI occurred due to deformation of the jaws caused by beam induced heating. The following actions were or will be taken:

- During operation the TDI was moved to 'parking' position as quickly as possible to limit the beam induced heating.
- During LS1 the TDI will receive a reinforced beam screen and a general maintenance of the moving parts is foreseen.
- During LS1 a Beam Energy Tracking System (BETS) will be installed as additional interlock on the TDI position.
- During LS2 a complete overhaul of the TDI will take place.

Asynchronous beam dump

This failure is also a single turn failure which occurs when the firing of the extraction kicker magnets MKD is not synchronised with the abort gap. The expected scenario for this to happen was a pre-firing of one of the 15 extraction kicker magnet, followed by the re-triggering of the other 14 magnets.

This failure mode did happen, although not the way it was expected, possibly helped by the fact of running at lower than nominal beam energies. One asynchronous beam was caused by a Trigger Fan Out problem [2].

The protection worked as expected, as the TCDQ absorber was in the correct position. Changes to the beam dumping system are foreseen during LS1: the Trigger Synchronisation Unit (TSU) will be modified, including the powering. A strong dependency on the TSU was revealed and a redundant triggering of the beam dumping system from the BIS, not requiring the TSU, will be implemented during LS1 [2].

Normal conducting D1 failures

This failure is a multi-turn failure. The D1 dipole magnets in points 1 and 5 are normal magnets, having short time constants in case of failures, and are located at a position with a large beta-value. Following a D1 trip 10^9

lost protons (detection limit) can be expected after about 15 turns while the level of 10^{12} lost protons (damage limit) is reached after about 25 turns. Hence, the beam will need to be dumped between 15 to 25 turns [3]. Because of the criticality of this failure the D1 power converters have been equipped with Fast Magnet Current change Monitoring (FMCMs) to dump the beam when any perturbation of the D1 current is detected.

This failure mode occurred as part of general power perturbations, resulting in power converter trips. The beams were always cleanly dumped, triggered by the FMCM, before any significant change of the D1 current or the orbit could be measured. No losses on the BLMs were measured before the beam dump. Sometimes the FMCM protection is too sensitive as it occurred that the FMCM dumped the beam due to a real power perturbation, but no power converter trip took place.

The changes foreseen during LS1 are to relax the thresholds of the FMCM dumping the beam [4].

OTHER FORESEEN FAILURE MODES

Fast kicker systems

The fast tune and aperture measurement kickers MKQ/MKA, the AC-dipole and the transverse feedback system were considered potentially dangerous. The operation of the MKA and AC-dipole was limited to safe beam only and controlled by additional keys in the CCC. No dangerous beam loss related to any of these systems occurred.

Beam hitting the cold aperture

The beam never hit the cold aperture during normal operation. No beam induced quenches of magnets occurred besides those caused by the breakdown of the injection kicker magnets as mentioned above. The limits imposed on collimation, defined as the required cleaning efficiency, turned out not to be an issue.

The beam dumping system does not dump

Luckily enough this never occurred. However, a procedure [5] was put in place on what to do if ever this would happen. The procedure consists of:

- Force the opening of the BIS loop by using various client inputs.
- Generate an internal fault of the LBDS, which should result in an internal beam dump request.
- Scrape away the beam with the collimators in point 7, using the ADT as excitation.

The procedure was tested without beam, but never needed during normal operation.

Power Cuts

Many power cuts happened and the beams were always cleanly dumped by the FMCM. As we seem to rely heavily on the FMCM it might be good to calculate the safety (SIL level) of the FMCM for the hardware and the acquisition chains.

Magnet Quenches

No quenches at top energy ever occurred, only quenches due to injection failures, as is already mentioned above. The circulating beam was always cleanly dumped.

Beam instabilities

Beam instabilities, mainly during the squeeze process or when bringing the beams into collision, have been the origin of beam dumps. In all cases the beam was cleanly dumped. In these cases the beam dumps were triggered by either the BLMs in the collimation regions or the Beam Position Monitoring System (BPMS) in point 6.

FAILURE MODES THAT WERE NOT FORESEEN

Injection errors

Injection errors took place. On one occasion the wrong beam from the SPS was extracted for injection into the LHC. The problem was traced back to injection timing settings in the SPS. Other injections errors took place related to the timing system.

Local orbit bumps

The orbit feedback has been producing local bumps in the orbit. Protection exists by the SIS and additional software being put in operation towards the end of the run. Knowledge of these systems should be wider spread.

Beam Induced Heating

Various LHC equipment has been affected by beam induced heating, leading to potentially dangerous situations:

The injection absorber TDI suffered from deformation and was blocked in its movement on several occasions. As the TDI is one of the most critical machine protection devices, alignment of the TDI was verified with beam at several occasions after experiencing positioning problems. The heating of the TDI also resulted in background problems of the ALICE detector.

One mirror of the synchrotron light monitors BSRT has been heating significantly and there was a risk that it would fall from its support into the beam aperture. Beam operation was stopped to remove the mirror.

The injection kickers MKI were heating significantly. If the kicker ferrites would reach a temperature above their Curie point during injection the beam would be badly injected. Great care was taken to monitor the MKI temperatures and on several occasions a significant cool-down time was required before injection could take place.

UFOs

Unidentified Falling Objects, or UFOs, have been leading to significant beam losses and clean beam dumps. UFOs took place especially at the injection kickers and the Roman Pots after movement of the pots. Large beam losses can potentially lead to quenches of magnets and the associated risks.

Abort Gap Population

At several occasions the beam abort gap was filled with particles due to RF problems. In some cases the RF failure was only detected by the increase of the abort gap population. The cleaning of the abort gap by the transverse damper was not fully automatic and could potentially have led to dangerous situations. After the removal of the synchrotron light monitor mirror of one beam (see above) the situation was even more dangerous as no direct measurement of the abort gap population by the BSRA was available during several weeks.

Long Range Beam-Beam Kick

During an MD in December 2012 one large intensity beam was intentionally dumped while the other was kept circulating. A 0.6 σ effect was measured on the orbit. This is a one turn kick and the effect is very fast. It can also affect the protection by collimation. Simulations for post LS1 are foreseen.

Radiation leading to many False Dumps

Many dumps were initiated by radiation effects on the electronics, e.g. the electronics of the QPS. Possible dangers are that these radiation effects could have (temporarily?) reduced the redundancy of machine protection or surveillance elements.

Unprotected QPS Circuits

During the powering tests at the end of Run I, it was discovered that some powering circuits were not protected by the QPS system. This was traced back to the reset procedures of the QPS and some known system faults.

WHAT WENT DIFFERENTLY

Beam Loss Monitors

Taking into account the complexity of the BLM system, it was initially expected that masking of some BLMs, to cope with hardware failures, would be occasionally required. The availability of the BLM system turned out to be excellent and masking of BLMs was extremely rare. The BLM system performed extremely well and provided a general and reliable safety net against failures which are not ‘too fast’.

At the start-up of the LHC it was foreseen to connect some ‘direct BLMs’ at point 6 directly to the beam dumping system, without passing via the Beam Interlock System. This was only done in 2012, later than originally foreseen. However, it never triggered a beam dump, as it should.

Systems not implemented

A Beam Position Change Monitor was initially foreseen. It should trigger a beam dump in the case of beam position changers faster than 1 mm/ms, not using any absolute reference. This system was never implemented. However, the BPMS system at point 6 has dumped the beam at several occasions, using an absolute beam position reference and considering individual bunches. This system provided the required interlock in case of beam instabilities.

The Beam Current Change Monitor, seen as an alternative to the measurement of losses by the BLMs, was never implemented. It is now foreseen to be commissioned at start-up in 2015.

BIS channels that never triggered

Many of the Beam Interlock Channels never triggered during beam operation. Their functionality has been checked at the beginning of Run I, but a periodic check of these channels could increase the machine safety.

CONCLUSIONS

The LHC Machine Protection System functioned properly during Run I of the LHC. No major damage to the machine occurred after 2008. The Big Three failures scenarios originally foreseen all occurred and changes are foreseen on all three systems affected for start-up in 2015:

- Changes to the injection absorber TDI.
- Changes to the LBDS / TSU powering and direct link between BIS and LBDS.
- Changes to the FMCM threshold (dumping too often).

As expected, some unexpected failure scenarios also occurred. They have been related with the timing system, beam induced heating, orbit bumps, UFOs, abort gap filling and the QPS system. Our protection against these failures needs to be improved, either by improvement of the equipment involved or by improving the surveillance of these systems.

As a global conclusion one can once again state that one has to stay vigilant against foreseen and unforeseen system faults. Each beam dump needs to be properly understood by looking at the Post Mortem data in detail before operation can be continued.

ACKNOWLEDGMENT

The input from T. Baer, R. Schmidt, J. Wenninger, D. Wollmann, M. Zerlauth and other MPP members made this paper possible. Their contribution is highly appreciated.

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POST LS1 OPERATIONAL ENVELOPE & MPS IMPLICATIONS

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Abstract

Post LS1 operation will face multiple problems due to the high energy and intensity of the beams. Some machine parameters can be reviewed in light of the last three years of operational experience and the operational scenarios adopted. The different levels of the Setup Beam Flag can be re-discussed, as well as the "stable beam" flag, which, in the present configuration, would be incompatible with beta* leveling. The management of the critical settings is also to be discussed to improve quality and flexibility for non-standard operational configurations and machine developments.

THE SETUP BEAM FLAG

During the LHC beam commissioning in 2011 and 2012 the so-called Setup Beam Flag (SBF) was used many times to carry out measurements and test like collimators alignment, loss maps and optics measurements.

This functionality, without compromising machine protection, makes it possible to commission the machine in a faster way as it limits the risk of lost fills due to non-critical problems; consequently it allows to use a fill for multiple purposes. The SBF condition allows masking several channels in the Beam Interlock System (BIS), such as Beam Loss Monitor (BLM) (maskable), RF, collimator movements, AC dipole, Power Interlock Controler (PIC) (maskable) and IR6 Beam Position Monitor (BPM).

The origin - the safe beam flag

Some experiments [1] were carried out in 2007 to establish the effect of a high intensity beam impacting on equipment. This effect depends strongly on many parameters (e.g. impact angles, beam size) and it is therefore not easy to evaluate. A controlled beam experiment was performed in the SPS transfer line, by impacting a 450 GeV beam orthogonally on a target made of multiple layers of tin, steel and copper, varying the intensity of the impacting beam. The results clearly show that an intensity of $1.2 \cdot 10^{12}$ p^+ has no effect on the material, while tests done with higher intensities produce damages from visible effect up to creation of holes in the target. The intensity of $1.2 \cdot 10^{12}$ p^+ at 450 GeV was consequently considered safe; a factor 2 was then applied to account for the lower emittance used during LHC operation, resulting in a value of $5 \cdot 10^{11}$ p^+ at 450 GeV. The corresponding beam intensity was then calculated for all energies, establishing the maximum safe beam intensity for a given LHC energy. The Safe Beam Flag curve was then defined (blue curve in Fig. 1).

From Safe Beam Flag to Setup Beam Flag

For operational purposes there was a need of having at least one nominal bunch in the machine at high energy. As the possibility of an orthogonal impact in the machine is negligible, three different layers of safe beam flag were defined, invalidating the name of safe beam flag. The name was consequently changed to SETUP Beam Flag:

- **NORMAL:** it is a factor 2 above the damage limit at 7 TeV (it is assumed that the probability of an orthogonal impact is negligible)
- **RELAXED:** it was established to allow 1 nominal bunch at 4 TeV (resulting in a factor 5 higher than the normal, thus becoming a factor 10 above the damage limit at 7 TeV)
- **VERY RELAXED**: it was established to allow 3 nominal bunches at 4 TeV (resulting in a factor 13 higher than the normal, thus becoming a factor 26 above the damage limit at 7 TeV)

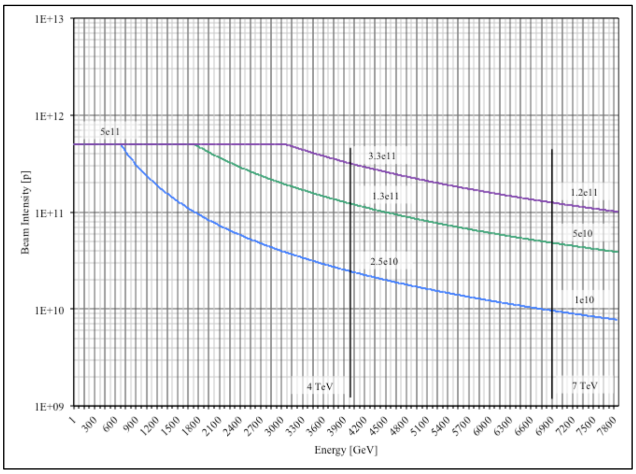

Figure 1: The setup beam FLAGS: normal-blue, relaxed-green, very relaxed-purple

Applying the same principle (to allow 1 and 3 bunches at maximum energy) to 7 TeV, the relaxed beam flag would result being 13 times higher than the safe limit and the very relaxed flag a factor 34 (there is an additional factor 2 due to the lower operational emittance). These numbers clearly show that the concept of SETUP beam flag has to be re–discussed for after LS1 operation.

On the other hand, assuming to accept the same level of damage in case of failure, up to 1 nominal bunch can be used at nominal energy of 7 TeV.

Commissioning at 7 TeV

After LS1 the LHC will be commissioned and operated at energy, close to 7 TeV. During the commissioning period many activities, presently done under setup beam conditions, have to be carried out. The impact of reducing the maximum allowed intensity would then have an impact on the commissioning efficiency and the time needed. In Table 1 these activities are listed, together with a comment about the impact of reducing the maximum allowed value.

Table 1: Activities affected by the allowed intensity change

Activity	Comment	Result
Betatron loss maps	It can be done with unsafe beam, adjusting the ADT parameters	Not affected by the change in intensity value
OFF momentum loss maps	It can be done with 1 pilot, but only 1 LM per fill	
Collimator alignment	It must be done with nominal bunches to have the right orbit reading	With unsafe beam would add complexity and time consumption
Optics measurements	Presently done with safe beam. It can be done with 1 pilot	More fills required as some intensity can be lost
Chromaticity measurements	Done with pilot	Not affected by the change in intensity value
Asynchronous beam dump	Done with pilot	Not affected by the change in intensity value

Some studies [2] show that it is theoretically possible to acquire off momentum loss maps without losing the full intensity on the collimators. Reducing the number of fills needed for commissioning would clearly increase the efficiency of the operation, however, it has to be noticed that nominal beam intensity is needed. A careful study on the timing of dump inputs received during measurements of off momentum loss maps performed in 2012 clearly shows that this operation can be done only if certain interlocks are masked. In fact, the following three (masked) interlocks trigger systematically before the beam losses needed to check the collimator hierarchy have been attained:

- RF frequency
- IR6 BPMs
- BLM-maskable

This technique could then be used only in presence of a setup beam flag system.

The Safe/Setup Beam Flag at 7 TeV

As said, the acceptance of the same level of beam energy as for the very relaxed beam flag in 2011 and 2012 would allow one nominal bunch at 7 TeV. This possibility would make the commissioning easier and faster, reducing the number of dumped fills due to non-critical problems.

The definition of a “relaxed” setup beam flag is not strictly mandatory as the beam commissioning operations can be done with nominal bunches. Nevertheless, its implementation is recommended, as it would increase the commissioning efficiency and it could be necessary for carrying out machine development studies; consequently some investigations will be carried out to review the safety scenario.

7 TeV operation

Many scenarios are being discussed for operation after LS1, such as a combined Ramp & Squeeze, injection at lower beta and beta* leveling. All these options have to be carefully studied as they have a large impact on the machine operation. Besides, as they require substantial changes in operational tools and software they might compromise the safety of the machine.

The generation of settings for Ramp & Squeeze is being investigated, as the optics optimization cannot be carried out within the present system. However, studies have indicated that the beams can be squeezed up to 3m during the ramp to 7 TeV. Many operational challenges have to be faced, like collimator function generation and tune corrections. Nevertheless, from a machine protection point of view the Ramp & Squeeze option does not create any particular problem.

In order to limit the pile-up in the experiments, the possibility to collide the beams at a higher beta* than the one used in 2012 is considered. The beams would be further squeezed in steps at a later stage, keeping the luminosity almost constant. With this option the beams could be put in collision after a short squeeze or even at the end of the ramp. The policy of the beta* levelling is very important. A fixed scheme where the beta* of all interaction points changes together and always in the same way is easy to implement and from an operation point of view pretty easy to manage. Allowing changes in beta* separately for each IP would drastically increase the number of machine protection checks to be done, as each possible configuration should be tested. Besides, the beta beating corrections in the arc would not be effective each time a local beta* is squeezed further, as they use correctors in the IRs. The beta* value is currently used in the safe machine parameters for the generation of the stable beam flag; this parameter should be changed or removed.

The possibility to inject the beams at a lower beta is also considered. The time spent in the squeeze would drastically decrease compared to 2011 and 2012 operation, but some machine protection implications have to be taken into account. In particular a solution should be adopted where the available aperture in the Inner Triplets is used for smaller beta*, without reducing the global aperture limit (thus avoiding changes in collimators settings at injection).

Possible improvements

After 3 years of operation, all teams involved have acquired a large experience. Many improvements are being discussed and they will be studied during LS1. If used, these improvements would increase the efficiency and the safety of the operation.

The reproducibility of machine settings and the limitation of the risks connected to erroneous trims is an important example. The implementation of an orbit-correctors-like system by creation of frozen beam processes (non-trimmable copies of the original ones) against which checking the settings in critical phases of operation (i.e. using the State Machine) are being considered.

The implementation of a dynamic settings check (as presently done for the collimators), improving the usage of beam process categories and the limitation on “non-CCC based” trims, are also under study.

A big effort also has to be spent by all teams involved in the LHC project to standardize the way hardware and software interventions are done and validated before releasing the machine for operation. To avoid using a non qualified machine, indeed, a rigid system has to be put in place that forces a requalification of the affected changes.

CONCLUSIONS

In the light of what was discussed in this paper, some conclusions can be taken.

The concept of setup beam flag has to be revisited in view of the gained experience. Simulations and studies have to be carried out to identify a safe scenario for post LS1 operation that allows the minimum flexibility needed to commission the machine without compromising its machine protection. The definition of a “relaxed” setup beam flag can be considered, this would help the commissioning process and it would be important for machine development studies.

From a machine protection point of view, there is no a priori showstopper to use Ramp & Squeeze and/or beta* leveling options. Nevertheless, it is important to continue the investigation in order to identify all possible operational problems.

Some improvements can be done on settings management and hardware re-validation to increase the protection as well as the reliability and reproducibility of the machine.

ACKNOWLEDGMENT

The author wants to express sincere thanks to all people involved in LHC operation for their inputs and help.

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SOFTWARE TOOLS FOR MPS

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Abstract

While dedicated Hardware systems protect the LHC against different types of failures, the role of software systems in the environment of Machine Protection is more in the area of configuration, supervision and diagnostics. This paper will present ideas for improvements on some of those systems as well as visions for further developments. A dedicated focus will be given to tools that shall improve the reliability of Machine Protection Systems (MPS) commissioning steps and other software improvements which could prevent human errors during operation, and thus increase availability.

MOTIVATION

For the commissioning of the LHC magnet circuits (in view of the large amount of work, i.e. about 7,000 individual tests), a lot of effort was put in the automation of tests, starting right from the beginning of hardware commissioning in 2005 [1]. Although slightly different (less tests, more manual tests), the commissioning of machine protection systems involves similar steps: Planning an appropriate sequence of tests, executing functionalities of the hardware and verifyinge the results (mostly manually). This similarity is the main motivation for the following proposals, as it seems appropriate to re-use the developed tools for commissioning of machine protection systems. This will be covered in the first part of this paper.

The second part of the paper describes ideas that should help to detect problems earlier during normal operational periods. The last part gives a short reminder on the Aperturemeter, which turned out to be a very useful tool during MPS commissioning and whose future is somehow uncertain and thus is worth some dedicated attention.

TESTS AND PROCEDURES

Current status

In the previous years, the progress of the MPS commissioning was tracked by the usage of a simple sharepoint site. Despite the simplicity of the usage, this solution had several disadvantages. Amongst them:

- The order of the tests could not be enforced at all. The scheduling was more or less done 'on the fly' by people on shift, based on their personal best knowledge.
- Nothing enforced that the tests were done at all.
- It was not possible to get a real overview of what was done already and what still had to be done.

Figure 1 shows an example view of the mentioned sharepoint site.

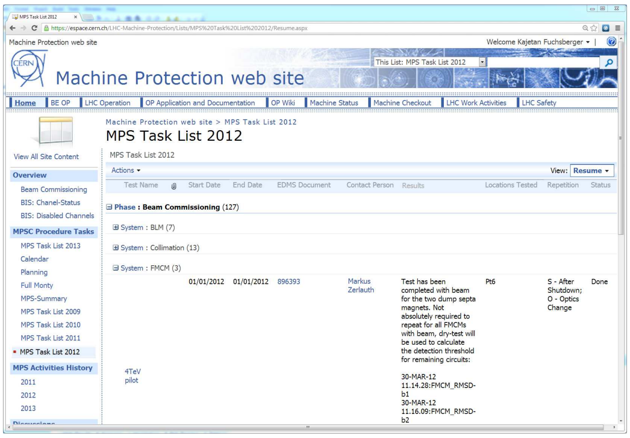

Figure 1: A screenshot of the Sharepoint site used in 2012 to track the MPS commissioning status.

The AccTesting Framework

The AccTesting framework ('AccTesting' in the following) was originally designed with the execution and tracking of tests for LHC hardware commissioning in mind. Nevertheless, since it soon turned out that a more general approach was appropriate, the goal was soon changed to create a general framework for the execution and tracking of tests for any kind of accelerator systems. In the following we will focus only on the explanation of those aspects that are necessary to understand the application of this framework for the use in commissioning of LHC machine protection systems. A more detailed explanation can be found at [2].

The framework is able to deal with a high workload and enables its users to work in parallel. Furthermore, it prevents execution conflicts and provides the current test status information to all of its users. A general overview over the architecture of the framework is shown in Fig. 2. The central point is the AccTesting server. The test execution and analysis results are stored in a database that only the server may access. The server itself is not aware of any specifics of the tests it handles. The test execution servers and the result analysis components are connected to the server with a plug-in like system. Each of them can handle a specific type of tests. If the main server wants to start the execution or analysis of a test, it provides each of the plugged-in test handlers with the test information, which in turn decide if they are able to handle the test. Once a test handler has accepted a test and started the execution or analysis, the main server will regularly poll it to retrieve the test status and result.

The AccTesting server can be accessed simultaneously by several users through the use of a specific Graphical User Interface (GUI). The AccTesting GUI displays all the information about the currently executing tests and scheduled tests. In this sense it replaces the former test tracking web pages. Furthermore, it allows to enqueue a scheduling request to the AccTesting server directly from within the test plan view. A sample screenshot of the GUI is shown in Fig. 3.

The AccTesting server is designed in a very robust manner. It can deal with unexpected behavior from its plugged-in test handlers, errors in the control GUI, incomplete test results and many other issues like a sudden crash of the virtual machine. Furthermore, it provides a robust scheduler which is responsible for executing the enqueued tests in the most efficient way, while respecting the correct order together with all the constraints and preconditions. Another interesting feature of the framework, which makes it an interesting candidate for the tracking of MPS commissioning, is the integrated statistics functionality. This makes it very easy to get an overview of the actual progress of a commissioning campaign. A screenshot of the statistics view is shown in Fig. 4

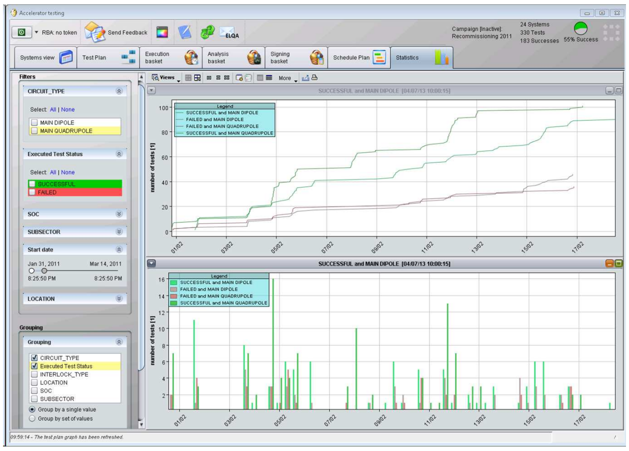

Figure 4: Screenshot of the AccTesting GUI, showing the statistics panel.

The whole system was successfuly used during recommissioning of the LHC circuits after the Christmas stops of 2012 and 2013 and has proved its stability and maturity.

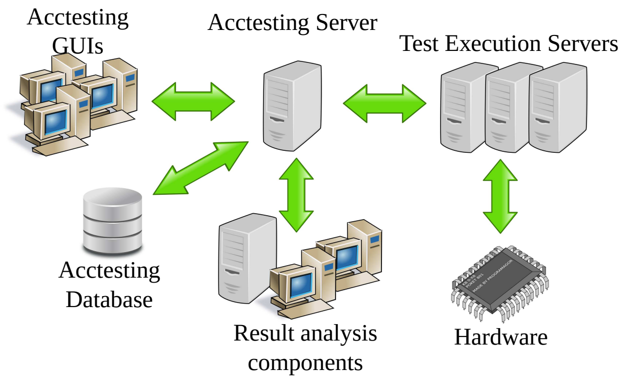

Figure 2: Components of the AccTesting framework.

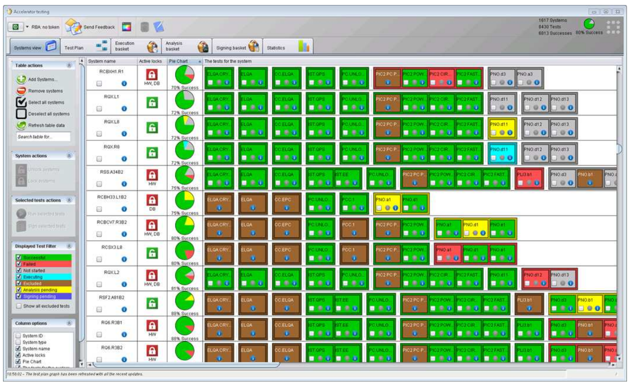

Figure 3: A screenshot of the graphical user interface (GUI) for the AccTesting framework.

From Sharepoint to AccTesting

In the following, the most importantent concepts of AccTesting, which are required to use AccTesting within the scope of of MPS commissioning, will be briefly sketched.

Currently, AccTesting uses three different 'granularities' in test exectution and tracking:

- The basic building block for a test plan is a *test*. A test is allowed to be executed on one or more system types and can be activated and deactivated per test plan.
- Each test has three *test steps*: Execution, Analysis and Signing. During the execution step actions are performed on the system under test. This means that this is the only time where the system is really blocked. During the analysis step, signals of the system (which were recorded during the execution step) are analysed either automatically or by some external system. The final step is the signing step, which requires human interaction of different experts (depending on the test), who have to verify the outcome of the execution/analysis and sign with their name.
- Each test belongs to exactly one *test phase*. A phase groups tests together and forms the basic building block in the execution sequence. The phases depend on each other. While tests within a phase can be executed in arbitrary order and even if the other tests within the phase are not (yet) successfully analyzed or signed, tests of a dependant test phase can only be executed, if all tests of the phases on which the phase depends were fully successful.

The relation between tests and phases is sketched in Fig. 5.

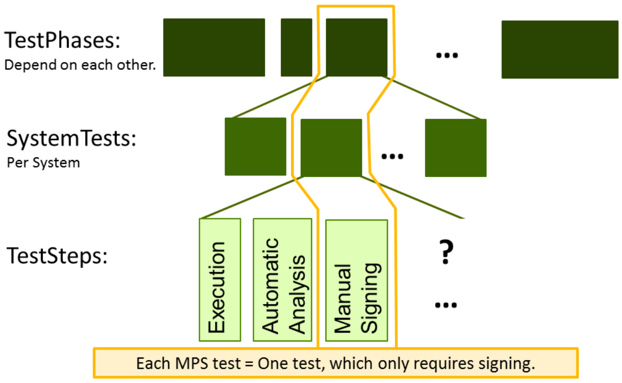

Figure 5: The relation between test phases, tests and test steps in the context of MPS commissioning.

To migrate the information from the old sharepoint site into AccTesting, the following roadmap should be followed:

1. Transform every MPS commissioning step into a test with 'always successful' execution and analysis steps (so called 'sign-only tests'). The tests might be grouped into test phases corresponding to the commissioning plan.
2. Later on, some of these tests can be replaced by automated versions, if possible.

Nevertheless, there are still some additional features which need to be implemented in AccTesting, in order to fully cover the needs of MPS commissioning. These will be desribed in the following section.

Newly required Features in AccTesting

Test Plan Editing Up to now, it was only possible to 'edit the test plan' by direct interacting with the database. Since this is problematic (due to e.g. security, consistency, required expert knowledge), GUI support for performing this task is in preparation. This will be especially needed, as soon as AccTesting is used in a broader field. The test plan for MPS commissioning might have to be adapted quite frequently – at least during the first campaign – with the experience gained. The plan is to provide at least basic functionality in the beginning of 2014 to be able to start with creating test plans (Creating campaigns, enable/disable tests). Extended functionality (Editing of Phases, Barriers and Composite Tests – see following sections) might have to be postponed until later in 2014.

Barriers Currently, AccTesting only takes care about test order and phase dependencies per system. Nevertheless, for MPS commissioning (and possibly for other applications in the future) a more flexible approach is required which allows to relate tests between different systems. The first naive approach would be to extend the concept of phases to a kind of 'global phases'. In the end, this approach turns out to be too strict for the purpose of MPS commissioning, as it would enforce that several tests of different systems have to be done exactly in one global phase. Nevertheless, the appropriate specification would be more like e.g. 'BLM individual system tests have to be done *at some stage before* injecting beam' but not necessarily 'in an individual system test phase' (e.g. there might be a phase 'Powering Tests' between 'Individual System Tests' and 'Injecting Beam'). Therefore, a new concept called *barriers* is proposed for this purpose:

A barrier can be put between two test phases of a several systems. It will allow each system which is affected by the barrier to perform its tests until the barrier point but not beyond. As soon as all the concerned systems reach the barrier point, each of them is allowed to continue with the following tests. This allows to complete the test plan in a very flexible way, while enforcing the required constraints. An example with two barriers is shown in Fig. 6.

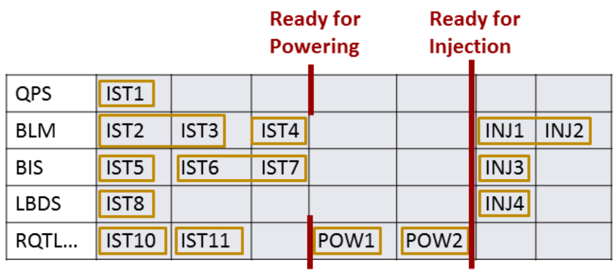

Figure 6: Test barriers in an example MPS commissioning plan. Boxes with brown boarders represent test phases, names within the boxes represent tests and red lines represent barriers.

Composite Tests & System Dependencies Currently one test in AccTesting is assigned exactly to one system. While this approach fits well to the needs of LHC hardware commissioning, the situation for other systems might not be that simple: One system might consist of several subsystems and tests might be formulated in a way that a set of tests on each subsystem have to be completed in order to contribute to the outcome of the test of the composite system. An example could be a test for a BLM crate consisting of one test for each BLM connected to that crate. To model this behaviour an additional feature has to be implemented in AccTesting to allow the definition and the tracking of such so-called *composite tests*.

Another service, which is required by this feature, was put in place recently: The so-called *System Relations Service*. This framework, which allows to plug in different sources of information (so-called 'System Relation Providers'), provides a central service for any kind of software application to query relations between systems. This service is currently embedded in the AccTesting server but can be extracted to a dedicated server if required. Already now, the service manages information of roughly 17000 systems and 28000 relations between systems.

Automated Analysis In previous hardware commissioning campaigns, most of the signals resulting from test execution were either analyzed manually or by semi-automated tools written in LabView. To unify the approach, a new subproject was started earlier this year which will provide the following components:

- A dedicated assertion language (Java embedded Domain Specific Language - eDSL), which will make it easy for experts to formulate test conditions and necessary related calculations (See Fig. 7).
- A viewer component for the GUI which shows the signals used in the assertions for a test and the outcome of the checks (See Fig. 8).

Also this feature will be useful for MPS commissioning in the future, when automation is applied in the tests. Further extensions are planned, e.g. the usage of different signal sources (Logging Db, Post Mortem, Files) as well as the implementation of more numerical operations on the data. A main concept for this analysis framework is its flexibility to replace implementations of operations at a later stage by more efficient ones (e.g. executed directly in the database), without changing the higher layers (eDSL). Furthermore, distribution of the analysis processing steps on clusters is under investigation, which would allow this framework to become a very fast, horizontally scaling, multi-purpose analysis framework.

```
public class PnoD1 extends AnalysisModule {
    {
        assertThat(I_MEAS)
                .isEqualTo(55.0, AMPERE)
                .withinRel(1.0, PERCENT)
                .at(1, SECOND)
                .before(Occurrence.FIRST, PM_EVENT_TRIGGER);

        assertThat(V_MEAS)
                .isEqualTo(-1.0, VOLT)
                .withinAbs(0.2, VOLT)
                .starting(50, SECOND)
                .after(Occurrence.FIRST, PM_EVENT_TRIGGER)
                .ending(70, SECOND)
                .after(Occurrence.FIRST, PM_EVENT_TRIGGER);
    }
}
```

Figure 7: Example of a script for automated test analysis, written in the dedicated Java embedded domain specific language.

EARLY DETECTION OF FAILURES

While the previous sections were focussing on the improvements of the environment for commissioning the machine protection systems, another aspect of potential improvement manifestated during the previous run: It turned out that many failures were detected rather late during operation, while the problems that led to them could have been detected much earlier. Consider the following example: If a trim is sent from the orbit steering application (YASP) to the LHC software architecture (LSA), then it will be sent directly to the machine. As soon as the power converters ramp the electric current, it might be that one or the other goes out of some interlock limits, for example. This would be detected by a interlock system, which would trigger a beam dump. This dump could have definitely been avoided (if, e.g. the interlock limits would have been taken into account before a real trim in the machine).

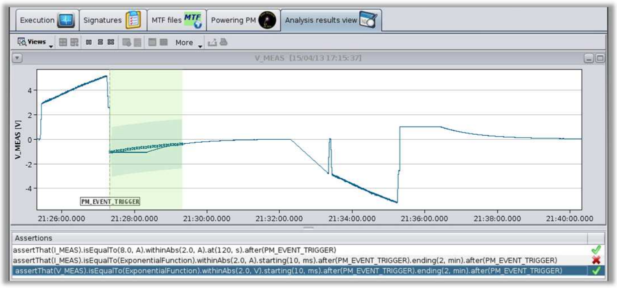

Figure 8: Example display of a result of the analysis of a powering test. The lower part of the window shows the assertions and the upper part shows the signals used in this assertions as well as markers for successful or failed regions.

The natural place to perform such additional checks turns out to be LSA itself, since all trims pass through it, no matter from which application they are sent. After some discussion with the LSA team, the following solution is proposed:

- A first implementation could be put in place using already available mechanisms which are called 'Trim-PostProcessor's. A trim postprocessor is invoked any time after a trim is saved into the LSA database, but before the trim is sent to the hardware. By implementing dedicated postprocessors, which would do the check against the interlock limits and throw exceptions if the trim should be aborted, LSA would enforced to perform a rollback on the database, the values would never be sent to the hardware and the application who sent the trim would receive an exception.
- On the longer term, an API which will allow to query the validity of a trim before really executing it, should be provided for the applications.
- Since the incorporation procedure is nothing else than a trim, the described mechanism would also prevent incorporating trims which would trigger a dump somewhere later in the beam process.
- An additional override mechanism might be required for machine development periods.

The following additional changes to LSA could further improve the security of the LHC operation:

- Currently, only selected methods in LSA are protected from usage without sufficent privileges (RBAC). All LSA methods should be reviewed, if they can do any harm or not, and should then be protected accordingly.
- The cycles which contain the settings for the PcInterlock and the software interlock system should also be protected by RBAC. A first solution could also be implemented by TrimPostProcessors, which evaluate the current RBAC roles.

APERTURE METER

Another tool which was already very useful during previous comissioning phases and will become even more important during the coming ones, is the so-called Aperture Meter. This tool is able to display online the actual aperture limits per beam and per plane over time. A sample screenshot of its main screen is shown in Fig. 9. Furthermore, it can display detailed information about the beam trajectory and plot it together with the aperture model as shown in Fig. 10.

Figure 9: Main Screen of the LHC Aperture Meter. For each beam and plane it shows the distances of the five elements closest to the beam over time.

The current implementation of the aperture meter offers already the most important required functionality: It can follow the operational cycle (optics, beam process, time within beam process) and listens to a selected set of LSA trims to reproduce the best known beam orbit of the beams. Nevertheless, some additional improvements have to be done, to help this application to become fully accepted as an operational tool:

- The user interface has to be improved, so that the operation is more intuitive.
- Performance improvements are required, in particular to improve the startup time (model initialization).

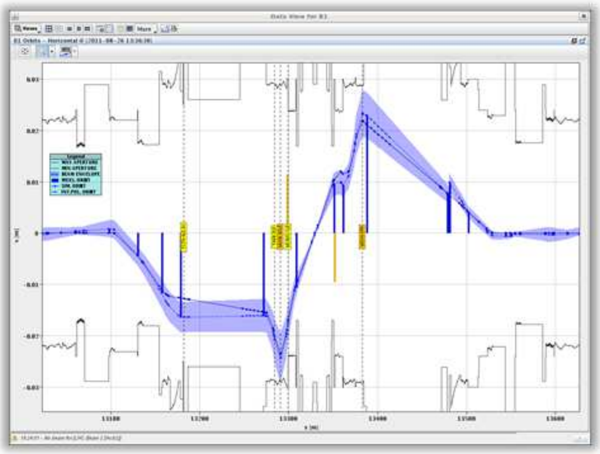

Figure 10: Example live plot of the LHC Aperture Meter. It shows the beam in an IP, together with an envelope of 1σ and the aperture limits.

- Some operational changes have to be better integrated. For example, collimator offsets after allignment or BPM usage information could be read automatically.

In the context of the previous section, the aperture meter itself could be used as an additional source for LSA trim verification (e.g. for collimator movements, collimator hierarchy). For this to work, the aperture meter would have to be implemented in a server, i.e. the functionality would have to be available indpendent if a GUI is running or not. This is not the case at the moment.

REMARKS

Although in the previous section we were discussing many different tools and possible improvements to them, it should be mentioned here that tools do, by no means, solve everything. On the contrary, more important is the development culture and communication during the development of the tools. Currently, software development in the accelerator sector is facing the following challenges:

- Large part of the software manpower goes into maintenance.
- A lot of ’grown’ projects exists, partly written by unexperienced programmers (e.g. Students).

To improve the situation, first of all awareness for this problematics has to be raised. Reliability of software is closely coupled to maintainability, which is again equivalent to quality. Quality basically boils down to self explaining code and automated testing. To avoid in the future adhoc software projects, which are often created by unexperienced programmers, it is recommendat that any upcoming student software project is supervised by two distinct persons with different views: One system expert and one software expert (Software ’Mentoring’). Another problem is that most of the time there is no single person who has the full picture and who can judge what tools are already available, which tools could be extended, or which framework would fit best for a newly required feature. Once again this boils down to communication. Similarly, there is also no single instance (persion, section or similar) with the authority to re-arrange priorities between different software projects. As a result, the limited manpower might not be optimally distributed amongst the projects.

SUMMARY AND OUTLOOK

The main focus of this paper was to elaborated the principal steps which should be taken to improve the commissioning phase of the LHC machine protection systems. We showed how the AccTesting framework could be the workhorse in future commissioning campaigns and we introduced the new features and concepts that will have to be implemented to achieve these goals.

Beyond this, of course further improvements could be envisaged: As soon as a testplan for the commissioning of the machine protection system system is in place, further automation should be discussed. The manual tests can then be easily replaced one by one by automated versions. Further steps could also be e.g. interlocks based on test plans, which would ensure that the tests really have to be performed before operation of the LHC can start again.

Finally, we emphasized that the reliability of a system starts with quality, which is not trivial to achieve and expensive (in time). Nevertheless it must not be reduced by any means. This is especially valid for software related to machine protection and operation, which has to guarantee the safe operation of the LHC and all its subsystems.

ACKNOWLEDGEMENTS

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INTERLOCKING STRATEGY VERSUS MACHINE AVAILABILITY

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Abstract

In addition of the hardware interlock system (BIS), the Software Interlock System (SIS) is providing a framework to program high level interlocks based on the surveillance of a large number of accelerator device parameters. Since its deployment in 2008, the LHC SIS has demonstrated that it is a reliable solution for complex interlocks involving multiple or distributed systems and when quick solutions for unexpected situations are needed. This paper presents the operational experience with software interlocking in the LHC machine and reports on the overall performance and flexibility of the SIS in the context of the overall interlocking strategy and availability of the machine

INTRODUCTION

The core of the LHC interlock system is the Beam Interlocks System (BIS) that is entirely implemented in hardware and designed to inhibit injection (Injection BIS) or dump the beams (LHC BIS) with extremely high reliability and availability requirements. As a complement of the BIS, the Software Interlock System (SIS) provides further protection by surveying and analyzing the state of various key equipment. Its open architecture allows for fast and easy configuration of more complex logic, which allows to anticipate failure rather than reacting to them. It is in particular possible to define complex interlocks that correlate the state of many different systems and that are difficult to implement as hardware interlocks. The system has been designed to be as highly reliable as possible for software, providing the flexibility for an easy reconfiguration of the logic to respond to the changing needs of the LHC operation. At the end of the LHC run period, it is worth to weight the interlocking strategy against the availability of the machine and to evaluate the need to move some interlocks from software into hardware or vice versa.

SIS FUNCTIONALITY AND PERFORMANCE

SIS structure

The central concept of SIS consists of boolean expressions represented as trees. The fundamental level is an Individual Software Interlock Channel (ISIC) associated to a reading of a state, value or property of a system based on the JAPC-Monitoring framework [1]. The acquired parameter is analyzed (tested) resulting in a logical state TRUE or FALSE. The logical states are then grouped into a tree-like structure and combined using logical operators (AND, OR, NOR,...) into intermediate nodes called Logical Software Interlock Channel (LSIC). The top of a tree corresponds to a so-called Software Permit, which itself can be TRUE or FALSE and is exported to Beam Interlock Controller devices:

- INJECTION (BEAM1, BEAM2 or BOTH BEAMS) PERMITS exported to inhibit the extraction(s) from SPS
- RING (RING1, RING2 or BOTH RING) PERMITS exported to the BIS to dump the beam(s)
- POWERING PERMITS (1 per octant) exported to the Powering Interlock Controller (PIC) to abort powering

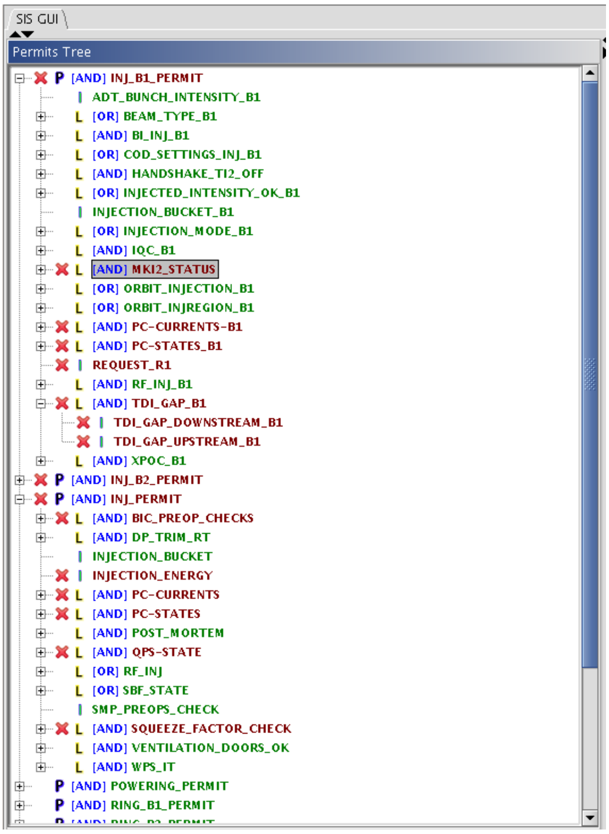

Figure 1: SIS GUI: the top permit like INJ_B1_PERMIT, INJ_B2_PERMIT are marked with a P; the tree can be expanded to see the channels.

The initial configuration of LHC SIS, using mainly AND and OR hard-coded logic, has been extended to allow more and more complicated Interlocks written in JAVA extension pulling together multiple signals and database references. All vital components are defined as Spring Beans [2] in an

XML file and managed in a bean container by this framework. Solutions from Spring have also been applied to provide remote access to the SIS core service via a Java Message Service (JMS) channel.

The SIS has a layered architecture which reflects the two major tasks of the system: Data Acquisition and Data Processing. The first layer deals with data subscriptions, providing values used later for the tree calculation. The second layer holds the definition of the trees and it is activated upon the tree calculation event, taking already prepared values from the internal buffer. One main architectural goal was to make the analysis as reliable as possible and thus as independent as possible of the data acquisition.

As the SIS is a server application, a (Swing) graphical user interface (GUI) was developed to show the system state to the operators in the control room. All permit trees are visible and dynamically updated; channel states are expressed with colors and markers (Fig. 1). Basic functionality for channel status analysis have been implemented in the GUI and will be extended for next run in order to improve the interaction with operators. The GUI also provides an interface for some user actions and a sophisticated analysis mechanism capable of identifying several typical fault scenarios, such as missing data or data with incorrect values.

To perform its job during last run, the LHC SIS was handling 2665 device/parameter subscriptions representing some 5500 checks grouped into 7 permits. All interlocks trees are evaluated every 2 second for the LHC (the typical update rate of the parameters being in the range of 1 to 10s) but can be faster if needed (in the order of 10-100 ms for the injectors SIS).

SIS AVAILABILITY

The LHC SIS core runs on dedicate HP server equipped with a timing receiver card (CTRI). Since the beginning of the operation in 2008 for the SPS and LHC SIS instances, only few crashes of the SPS server were observed during the 2009-2010 shutdown period. The problem was traced back to a concurrency problem in the timing library and was quickly fixed.

Table 1: Interlocks channels leading to dump.

SIS DUMP cause	Ratio
Communication problem	20%
Orbit feedback issues	20%
Power converter faults	15%
Beam position measurements	10%
Beam Loss monitors HV	10%
Others (wrong settings, masks)	25%

For the LHC machine, any time the beam is aborted a Post-Mortem file is produced tracing the root cause (first trigger) of the beam dump. Extracting the data of the Post-Mortem database for the 2012 operation period, 77 dumps are flagged with the LHC SIS as first input to the BIS. All events are real interlocking conditions (see Table 1), i.e. one of the ring permit changed from TRUE to FALSE status: none of the dumps are due to SIS failures, the programmed logic was always followed. In the "communication problem" case, data were not received by SIS and the logic of some of the interlocks (power converters, orbit, ...) is programmed to dump the beam in case there is no update for a time defined by programmer.

Ring permit

The Ring permit value is exported to the LHC BIS to trigger a beam dump (either for a given beam or for both beams) in case the evaluation result is FALSE. Taking into account the lengthy injection process and beam cycle in the LHC, dumping a circulating beam is really costly in terms of efficiency. Thus the reliability of ring permit should be as high as for the BIS system.

The initial configuration from 2010 (Table 2) has been

Table 2: Initial configuration of the ring interlocks.

TEST	Coverage
SMP energy	All RBs, SMP energy
SMP energy distribution	ALL BLM crates
BETS	Q4 and MSDs in IR6
TCDQ-Beam	Beam center in TCSG TCSG gap TCDQ-TCSG retraction
COD integral	All arc Hor CODs
Orbit	All ring BPMs
COD settings	All CODs in STABLE BEAMS
COD trips	60A CODS (not in PIC)

Table 3: Configuration of the ring interlocks at the end of 2012 run.

TEST	Coverage
RF voltage	Energy > 3.4 TeV
BLM High Voltage	All BLM crates
Feedback Mask	during RAMP & SQUEEZE if > 20 % BPM disabled
Ref Orbit	RAMP & SQUEEZE if zeroed/wrong orbit reference
COD integral	All arc Hor CODs
PC interlock	All 60A CODs

extended with several interlocks to fill the potential holes in machine protection that were discovered all along the operation period (Table 3).

Injection Permits

The LHC injection Permits are connected to the SPS Beam Interlock System in order to prevent injection into the LHC. In case one system is not ready or not in a nominal configuration for injection, an inhibit is sent to the the injector complex to prevent extraction or even production of the beams in the the injectors allowing a more efficient operation of the complex. As loosing one injection in the machine is not so critical for the operational efficiency, the interlock policy can be very strict and with a large number of checks.

Started mainly with checks of statuses and values in range for different equipment (Power Converters, Quench Protection, RF...) in 2010, as shown in Table 4, the injection interlocks have been extended to include more operational settings checks using the possibility to combine parameters published by different systems (see Table 5).

Table 4: Initial 2010 configuration of the injection interlocks.

TEST	**Coverage**
PC state	All PCs
PC current	ALL BLM crates RB, RQ, RD, MCBX
QPS_OK	All circuits with QPS
RF	Synchronization Cryo maintain
BTV position	Ring and dump lines BTVs
Orbit	All ring BPMs
Injection bucket	Abort gap and over-injection protection
Injection mode	
Energy	
(Pre)-ops Checks	XPOC, PM, IQC, BIC, SMP
triplet alignment	WPS in all IPs

Most of these additional interlocks were implemented to improve the machine protection level following some initially un-foreseen operational conditions. One example is related to the very large range of bunch intensities that has been used in the LHC during the 2012 operation: the configuration of some components, like the transverse feedback system, depends on the peak bunch intensity and the equipment may be damaged if the injected beam intensity is higher than the pre-configured one. No hardware interlock is available on the extracted bunch intensity but this information is available in time before extraction from the injector, so a software interlock comparing the actual feedback settings and the intensity just before extraction in the SPS has been added as part of the injection permit.

Table 5: Configuration of the injection interlocks at the end of the run. The lines marked with a $*$ covers holes in the machine protection of the initial configuration.

TEST	**Coverage**
ADT bunch intensity *	SPS intensity vs ADT settings
Beam type *	Check ions/proton beams
TL handshakes	IP 8 and 2 allow extraction on the TED
Injected Intensity *	SPS intensity versus circulating beam
Injection orbit *	All BPMs
Orbit in inj. region *	BPM around inj. IPs
TDI gaps *	
RF RT trims *	Radial modulation OFF
MKI vacuum	Magnets and interconnect
MKI temperature	MKI magnets
Ventilation doors	Non LASS interlocked doors

Interlock masking

Masking is a mechanism that allows operators to ignore an individual ISIC or LSIC. Masking a channel means overriding its real state and evaluating it always to TRUE. The ability to mask a given ISIC/LSIC is defined for each channel individually and the Permit signals are not allowed to be masked. The masking itself is done from the SIS GUI by operators. The role based access control framework is used to define the right to mask, however, the masking rights apply only to channels defined as maskable. Two roles are used: LHC-EIC (used by LHC Engineer in Charge) and MCS-SIS (SIS developers involved in the machine protection). After LS1, we should consider the possibility to make the masking more role-dependent and create different roles for different group of interlocks.

When applied, a mask is always active, independent of beam conditions or Set-up Beam flag. Therefore another way of “masking” interlocks automatically for a given period within the beam cycle or a given energy/intensity range is largely used in the SIS via the OR logic. A beam intensity, beam mode (describing the time in the beam cycle) or beam energy test is added as a ISIC with a OR logic to the channel that should be masked, see for example Fig. 2. As soon as the intensity, energy or mode condition is TRUE, the interlock is *de facto* masked.

After the initial commissioning period, a long list of interlocks have been made UNMASKABLE: Orbits in physics, XPOC, machine protection Post-Mortem permit,

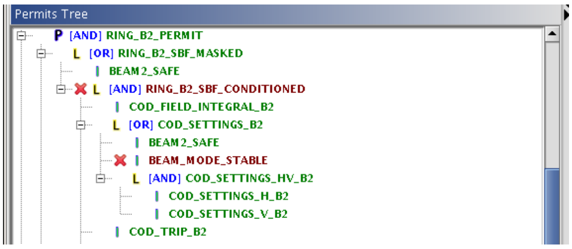

Figure 2: Example of masking using the beam intensity: the 60A power converter settings LSIC is combined in an OR logic with the BEAM_SAFE ISIC (intensity) and the BEAM_MODE_STABLE ISIC (collision period in the beam cycle).

IQC injection oscillation permit, etc. Even more will come for the 7 TeV operation.

SIS IMPROVEMENTS

CMW communication

During 2012 operation, several dumps were caused by a stop of the data streams. The most affected data source was the Power Converters Function Generator Controller publication, which was not received by the SIS data acquisition task for several minutes on some occasions. In such a case, the tree is evaluated to false if the data are not updated before a pre-defined time-out to avoid being blind with beams in the machine. SIS time-out was increased from 20 s (in 2010) to 120 s (end of 2012). The programmed logic was correctly followed. The problem was traced back to a problem within CMW, which was not protected against “slow clients”.

There was a clear degradation during 2012 operation but the problem should be fixed with the upgrade of CMW planned during the Long Shut-down.

GUI and Post-Mortem

In order to ease the diagnostic after the SIS has triggered a beam dump, some improvements are also planned/needed for the GUI and the link with the Post-Mortem server. Indeed, the tree structure display could be more user friendly to ease the understanding of the more and more complex structure, especially with the use of the OR logic to mask some interlocks. It must also be made possible to monitor any kind of parameter, including parameters that are complex combinations of various other parameters that are hidden in the construction of the logic (JAVA class). Furthermore, some extra protection is needed on the subscription management panel to avoid accidental stopping of critical data subscription.

Even though a local Post-Mortem file is produced on the SIS server for every SIS trigger of the beam dump, the data mining is quite painful and *de facto* reserved to trained people. Only the channel which triggered is present and there is no details in case of complex JAVA coded interlocks, like orbit interlocking. A straightforward improvement is to export the Post-Mortem file to the PM server, where a dedicated SIS analysis module could extract details on the triggered test.

*Beta**

The SIS also provides a Beta* publication to the Safe Beam Parameters system,which is used by collimators for their interlocking logic. The SIS uses the quadrupoles current in the IPs to derive the actual Beta* at each IP, publishing and reading back the value from the timing to cross-check with a reference table. For the time being, the calibration curves are hard-coded in SIS configuration files, one file per IP. It worked very well with the 2012 optics (nominal physics optics, HighBeta) because for this optics all quadrupoles have monotonic current functions during the squeeze, but it does not work for the Achromatic Telescopic Squeezing (ATS) optics, which is using quadrupoles of adjacent IP.

The proposal to improve the handling of the data is to migrate the calibration curves and the list of used IP quadrupoles in LSA to allow flexibility for different squeeze by using the hypercycle and beam processes concepts.

Orbit interlocking and PC interlock

Another important ring interlock is the Orbit and Correctors Orbit Dipole (CODs) interlocking. The principle is to limit the global orbit excursions of the beams to prevent beam losses and catch undetected orbit bumps. It uses distributed systems to compare the settings of each COD and the reading of each Beam Position Monitor (BPM) included enable flag, with a reference and a tolerance stored in LSA. A beam dump is triggered when 10 BPM or 2 kicks per beam or plane are out of tolerance. The tolerances are defined as a trade-off between machine protection and availability and have been set so far quite strict in STABLE BEAM ($\pm$ 2.5 mm in IR 1, 2, 5 and 8, $\pm$ 2 mm elsewhere), but are more relaxed during the ramp and squeeze process ($\pm$ 6 mm in IR 1, 2, 5 and 8, $\pm$ 3-3.5 mm elsewhere). The SIS configuration allows to condition the reference with a beam mode or an energy through the AND/OR logic and also to read the reference from the database settings with a predefined periodicity.

The interlocking strategy worked very well for standard operation but several problems occurred during special fills like Van Der Meer scans or injection optics collision. Indeed, it was needed to open the tolerances via a trim in LSA (RBAC protected to MCS-SIS role), which is very flexible but possibly also too flexible for critical parameters.

The proposed improvement for post-LS1 operation is to remove the CODs settings check which is now redundant with the PC interlock, presented at this workshop [3]. The PC interlock is designed to check that the CODs current is within tolerance for each beam process and triggers a beam dump when 2 kicks per beam or plane are out of tolerance. The settings are stored in a reference beam process in LSA which is cloned from the Power Converter beam process.

To allow following the complex change of current occurring during the ramp and squeeze, the change of tolerances function is triggered by timing events.

CONCLUSION

LHC SIS is successfully used in operation since 2008. It is a reliable solution for different class of interlocks: injection interlocks (when high reliability is less critical), complex interlocks involving multiple systems or distributed systems (like orbit) or as a fast answer to un-expected situation like feedback problems. It is all software, soft real-time, but the reliability, even if it will never be SIL3, is remarkably high. During the long shut-down period the following software interlocks will be moved to hardware interlock: TCDQ interlocking, TDI gap interlock and CODs setting. However, many more new software tests will be introduced in the SIS.

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