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First proton-nucleus collisions in the LHC: the p-Pb pilot physics fill

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Summary

During the night of 12–13 September 2012 the LHC collided protons with lead nuclei for the first time, demonstrating the feasibility of hybrid collisions despite the basic two-in-one magnet design. The centre-of-mass energy was $\sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{TeV}$ per colliding nucleon pair, "Stable Beams" were declared 9 hours after the first injection of Pb beams in 2012. The integrated luminosity delivered to the four large LHC experiments was sufficient to yield new physics results. Within the same fill, stable beams were declared twice more, with the collision points displaced longitudinally by $\pm 0.5\,\mathrm{m}$ from their usual locations.

We provide a general overview of this p-Pb pilot physics fill before focusing on beam data at injection energy and at flat-top, before stable beams for physics were declared. We monitored the beam parameters throughout the fill and present an analysis of their evolution based on a simulation of intra-beam scattering (IBS), synchrotron radiation and the consumption of the beam intensity by collisions ("luminosity burn-off"). We also present some considerations on beam-beam effects with unequal beam sizes and the pilot run is compared, in this respect, to expectations for the forthcoming physics run in January.

This pilot run was a major step in the preparation of the physics run. However it was not possible to perform an additional feasibility test designed to clarify the limits to the intensity of two beams injected and ramped with unequal revolution frequencies. We describe the plan for this test and discuss the reasons why it could not be carried out.

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1 Introduction

As a consequence of the two-in-one magnet design and their different mass to charge ratios, proton and Pb beams do not have the same revolution frequencies in the LHC [1, 2, 3]. Injection from the SPS at beam energy $E = 450\,Z\,\mathrm{GeV}$ and the ramp up to $E = 4\,Z\,\mathrm{TeV}$ have to be done with unlocked RF frequencies. Only at flat top, when the induced orbit is small enough, the RF frequencies are locked together. The maximum central orbit shift is then 0.5 mm.

As long as the frequencies are separated, the encounter points between bunches of the two beams are shifting around the ring, modulating the long range beam-beam interactions. This phenomenon severely limited the D-Au operation of RHIC when it was tried with the same rigidities in the two rings [4]. The main goals of the feasibility tests for p-Pb in the LHC were to inject and ramp the different beams with unlocked frequencies, in order to learn more about the effects of moving encounters, and to get more information about the p-intensity limit for Pb stability. The first part of the programme was carried out in 2011, namely the injection and ramp of a few p-bunches against a few Pb-bunches, and injection a few Pb-bunches against about 300 p-bunches [5]. The second part was cancelled in 2011 and was rescheduled to take place one day before the pilot run.

The p-Pb pilot physics run was needed for both the experiments and the operation of the injector chain and the LHC in order to prepare the coming p-Pb run in January 2013. The first Pb beam of the year was injected into the LHC, both the p-beam and the Pb-beam were ramped up to 4 Z TeV with unlocked RF frequencies. They were then brought into collisions and “Stable Beams” were declared in just over 9 hours. All four large experiments, ALICE, ATLAS, CMS and, for the first time in the heavy-ion programme, LHCb, participated in this run. The first p-Pb data were taken for about 8 hours. After the first 5 hours of data acquisition, the interaction points were shifted by -0.5 m and then by $+0.5$ m, as requested by ALICE.

This note presents an analysis of the pilot fill. First, in Section 2, a general overview and the context of the run is given. Proton losses observed while putting beams into collisions are analysed in Section 3, together with the loss maps done before going into physics.

Special care was taken to monitor the beams' profiles during the whole fill. Transverse emittances, bunch intensities and bunch length evolution are compared with simulation of intra-beam scattering (IBS) and radiation damping in Section 4, at injection and during physics. As the proton beam transverse emittance delivered by the injectors can be significantly reduced compared to the nominal value, one of the concerns for p-Pb operation is the stability of colliding beams of unequal transverse dimensions. This is studied in Section 5.

The pilot run was very successful but a factor of several hundreds in luminosity is still to be gained for the main physics run in January-February 2013. Many uncertainties remain as bad luck three times prevented us from carrying out the feasibility tests as planned, first in November 2011, then again, twice, in September 2012. The last section of the note is dedicated to the second part of the tests, the Machine Development (MD) on proton beam intensity limit. Motivations are given, and the experience and information acquired so far are discussed.

2 Overview of the run

15:45	Injection of the first Pb bunch.
17:37	Injection of protons in B1.
18:54	Injection of Lead in B2.
19:19	Beam dump during the ramp due to TCTs interlocks.
22:40	Start of ramp.
23:07	Locking the RF frequencies together.
23:30	First collisions.
00:43	Start of loss maps.
1:27	Stable Beams declared.
6:25	Stable beams, IP moved by -0.5 m in ALICE.
7:55	Stable beams, IP moved by $+0.5$ m in ALICE.
9:35	Beam dump by operators.

Table 1: Main events of the p-Pb pilot physics fill on 12–13 September 2012.

The p-Pb pilot physics fill was scheduled on Wednesday, 12 September 2012 from 16:00. It was supposed to occur one day after the second part of the p-Pb feasibility tests so that possible problems related to injection or ramping with unlocked frequencies would already have been dealt with. But a number of technical problems occurred during the MD on Monday, 10/9/2012, preventing us from taking advantage of it for the pilot run. As a result the injection and ramp had to be commissioned during the pilot run. As the high-beta physics run preceding us was finished, we started a little earlier than foreseen and the first Pb bunch was injected before 16:00. Its intensity was about 7×10^9 charges (or 8.5×10^7 $^{208}\mathrm{Pb}^{82+}$ nuclei). In physics runs, it is preferable to inject Pb after protons to minimise the time spent by the Pb beam at injection and limit the influence of IBS. The low intensity proton beam was injected at 17:37, with about 1.2×10^{10} charges per bunch. The injection of Pb was delayed due to a timing problem between the SPS and the LHC. Two bunches were injected at 18:13 and dumped to finally start a clean injection of Pb in Beam 2 (B2) at 18:54.

It was decided by the Collimation Group and Machine Protection that loss maps had to be performed before going into physics, and that collimators' settings had to be modified. In order not to lose the fill while doing the loss maps, two additional bunches were inserted in the filling scheme for both beams (one for each plane). Loss maps could then be done thanks to bunch-by-bunch excitation induced by the transverse damper (ADT) [6]. The initial filling scheme was composed of 13 bunches, giving 8 collisions in each of the four experiments plus one non-colliding bunch for beam parameters analysis. The details are shown in Figure 1.

The new collimator settings were implemented but energy thresholds were not modified accordingly and the TCTs' position interlocks dumped the beams during the ramp. We had

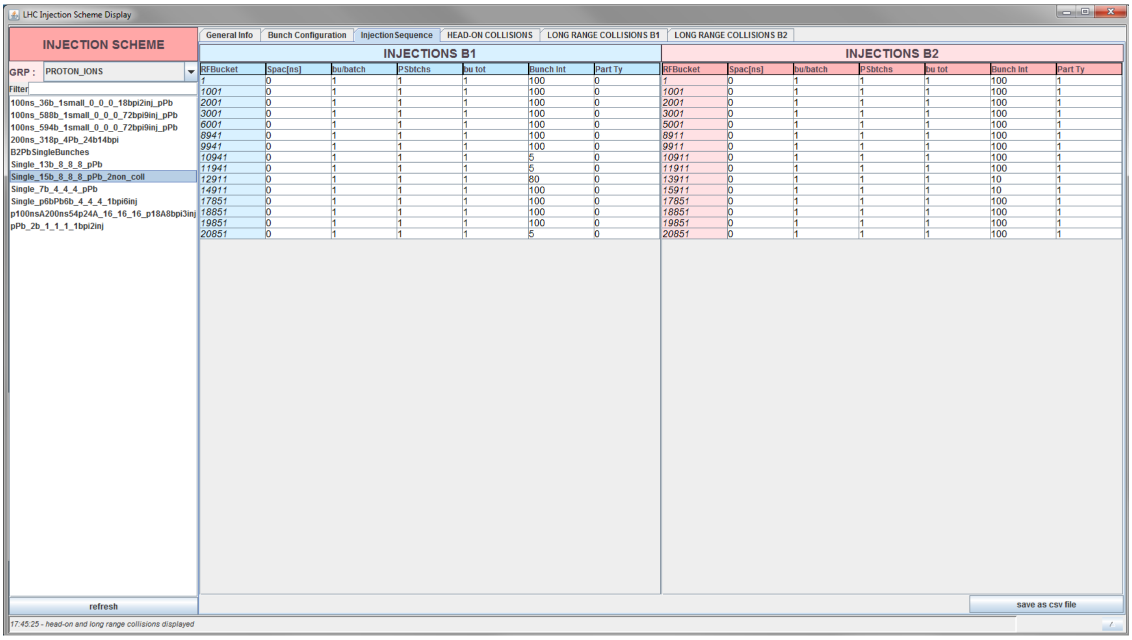


Figure 1: Screen copy of the LHC filling scheme application showing the filling scheme used for the p-Pb pilot physics fill.

to go back to usual collimator settings for p-p physics and the second attempt to ramp was successful, between 22:40 and 22:52. Figure 2 shows the increase of unlocked frequencies. At $E = 4\,Z$ TeV, the frequency difference was reduced to $\Delta f_{RF} \approx 60\,\text{Hz}$.

Once at flat top, the automatic re-phasing procedure was used to lock the RF frequencies together [7]. It made the orbit go off-momentum as illustrated by mean beam position in the rings in Figure 3. No squeeze was planned so the β^* at IP1, IP2, IP5, IP8 were 11 m, 10 m, 11 m, 10 m. Separations were collapsed and the adjustment phase started at 23:30. The loss maps were performed from 00:43, and stable beams were declared at 01:27. After 5 hours of data taking the IPs were shifted by -50 cm and then by $+50$ cm for additional data acquisition. The beams were finally dumped by operators to continue the planned schedule at 09:35 on Thursday, 13 September. Table 1 summarizes the main steps of the run.

Figure 4 shows the beam intensities through the run and the luminosity production in ATLAS and ALICE as examples. The absolute values of luminosities are unreliable as luminosities of this completely new kind of collision were not calibrated. We clearly see the effect of IBS on B2 (Pb) intensity, provoking a continuous decrease of the number of charges. It is negligible for Beam 1 (B1) thanks to intensities much smaller than in usual p-p operation. After the ramp, depicted by the energy curve in blue, one can notice a drop of proton intensity around 23:35. This will be discussed in the next section. Then losses in both beams around 01:00 correspond to the loss maps, where two bunches were successively blown up by the ADT in B1, then in B2.

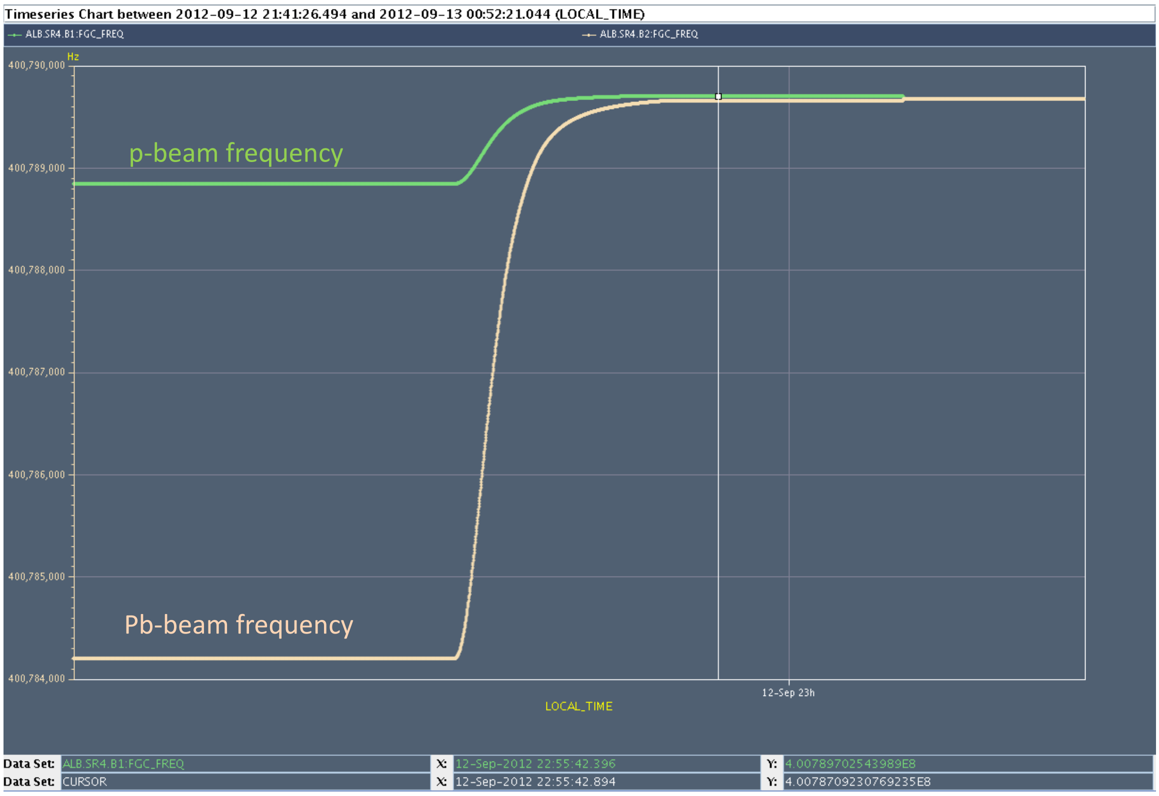


Figure 2: Evolution of RF frequencies during the ramp of p and Pb beams. The frequencies were locked together at 23:07.

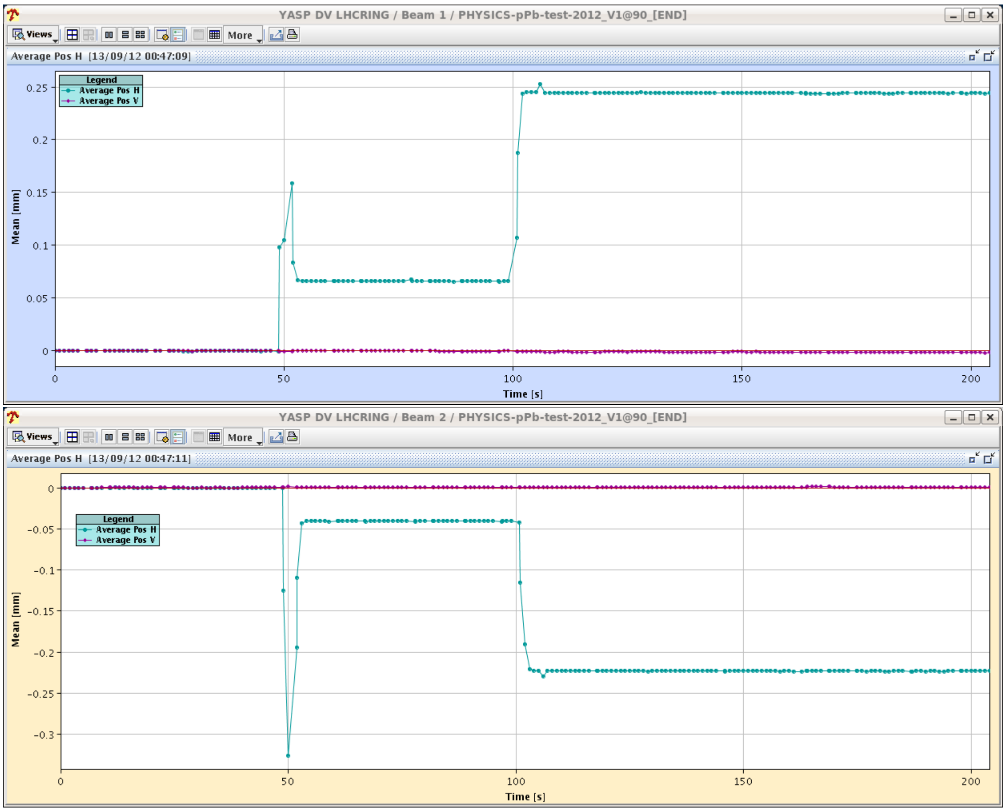


Figure 3: Horizontal mean position of the beams during the re-phasing procedure. Top: B1, p-beam; bottom: B2, Pb-beam.

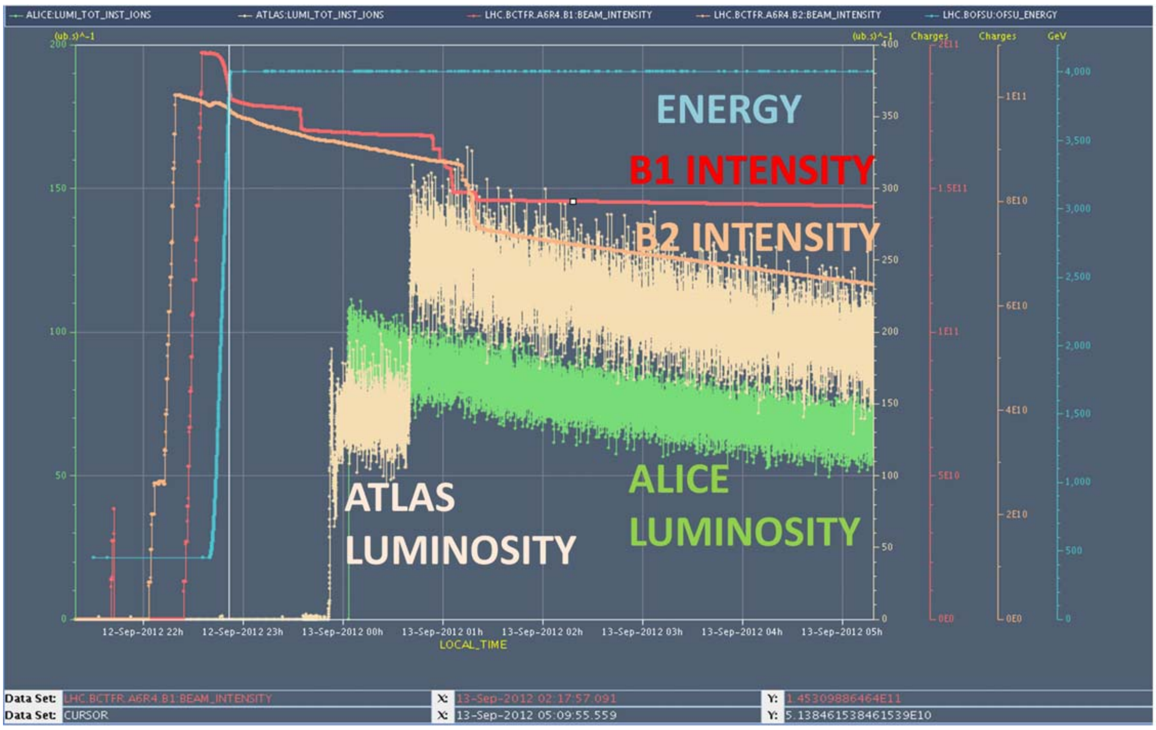


Figure 4: Getting to collisions and producing luminosity during pilot run.

3 From first collisions to stable beams

Losses on TCPs

Once the RF frequencies were locked together after the ramp, we entered the Adjust phase to optimise collisions without going through any squeeze procedure. As mentioned earlier, we observed a sudden drop of proton intensity at this stage . Looking more closely at the data, it was found to be correlated with the change of tunes from injection $(0.28, 0.31)$ to collision values $(0.31, 0.32)$, as shown in Figure 5. The tune change was effected locally using the dispersion suppressor quadrupoles in IR1 and IR5. This is not as smooth as a global change and therefore induces orbit perturbations. As the beams were already off-momentum, their central trajectory was off-centred, implying reduced margin. In addition we were operating with tight collimator settings [8], so these perturbations could have led to losses on primary collimators (TCPs). From Figure 5 we can see that the intensity loss was about 7×10^9 charges, which corresponds to about 4% of the beam intensity at the end of the energy ramp.

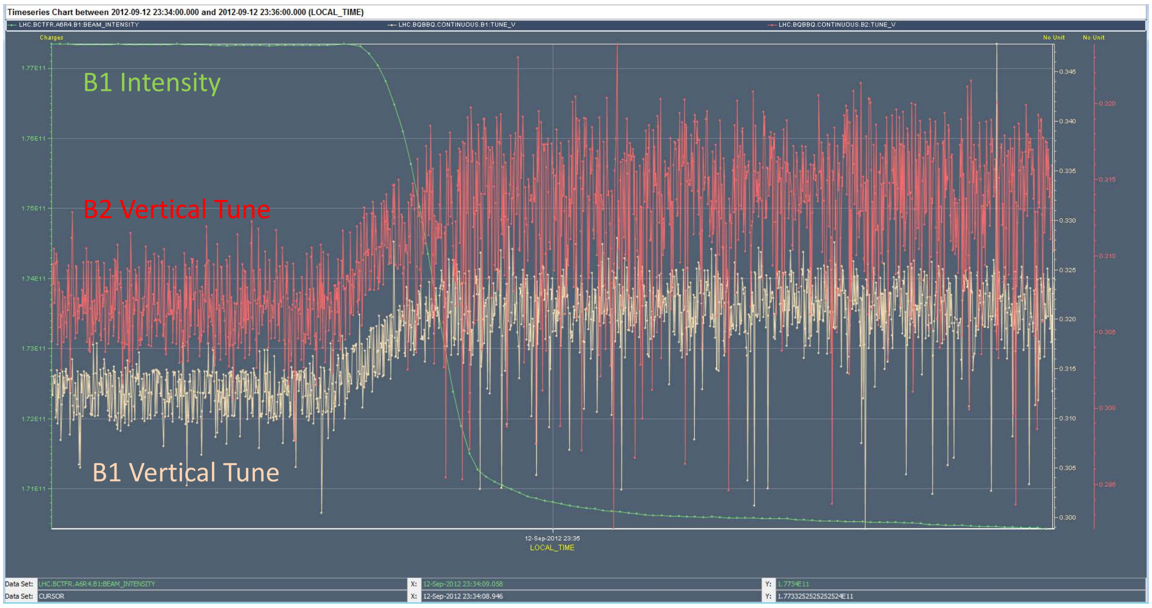


Figure 5: Vertical tunes and B1 intensity when moving from injection to collision tunes.

The orbits of Beam 1 at the collimators, in the collimator plane, are shown in Figure 6. The angle of the skew collimator is 127°, defined counter-clockwise from the vertical axis. The beam position is interpolated using the Aperture Meter application [9]. As the interpolation is based on BPMs measurements and transfer matrices between elements, the accuracy of the absolute orbit value is only of the order of 100 μm and could even reach 1mm. But the accuracy of relative changes in the orbit is about 10 μm. An orbit perturbation can clearly be seen at the horizontal collimator (TCP.C6L7.B1), the skew collimator (TCP.B6L7.B1) and the momentum collimator (TCP.6L3.B1). The shift in the vertical plane is very small.

These positions were compared to the collimators' jaws settings, taking the beam size into account. Corresponding schematics are shown in Figure 7, assuming gaussian beam profiles.

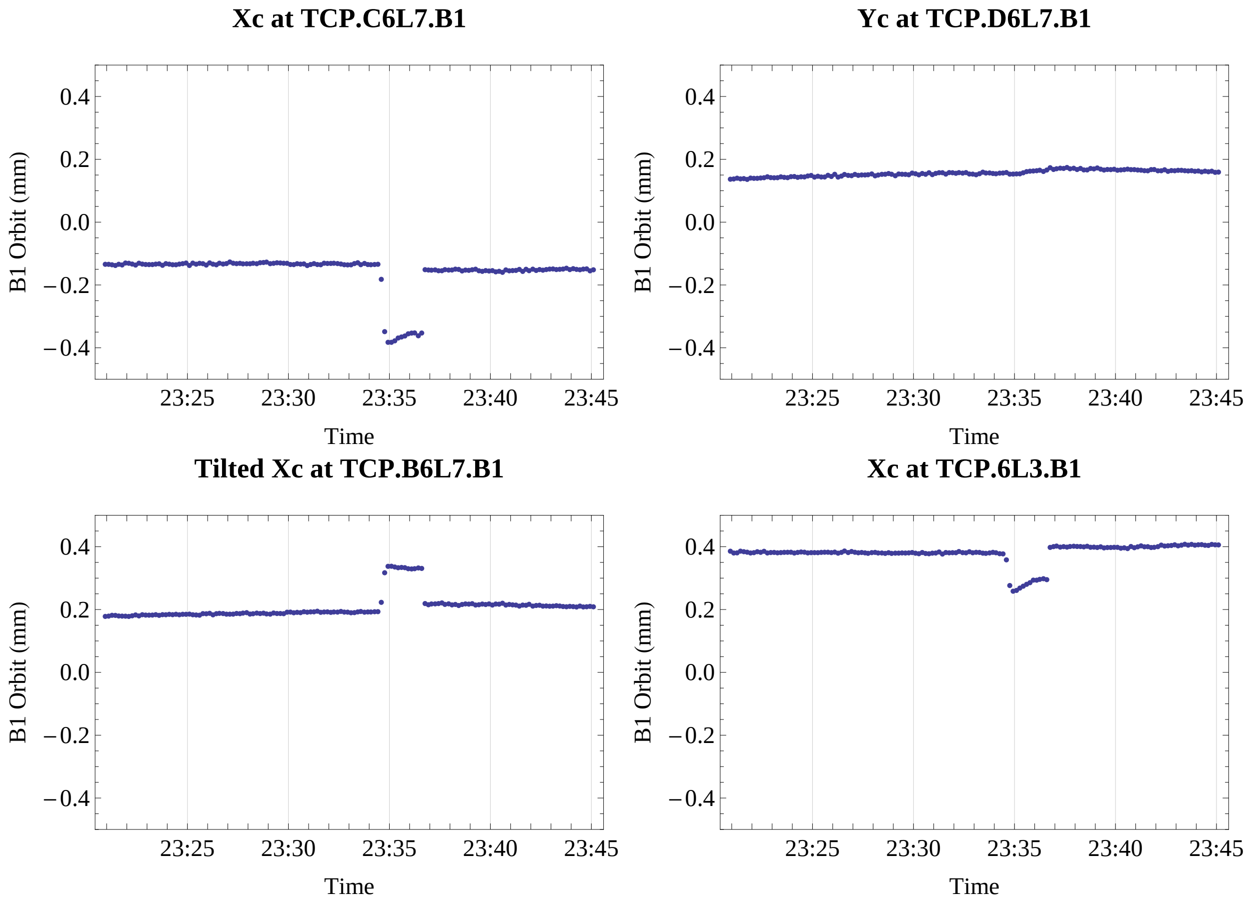


Figure 6: B1 central orbits at the primary colimators. Orbits are given in the collimator plane.

The collimators' settings are extracted from the logging database using the Timber application [10]. They correspond to the tight settings used in p-p physics in 2012. Beam sizes at the collimators are calculated using measured beta-functions [11], and the average value of the normalized emittances over the 15 bunches for (ie, $\epsilon_x = 2\,\mu$m and $\epsilon_y = 1.3\,\mu$m). Given the errors on the measured beta functions and interpolated orbits, this comparison cannot give precise results but it can help to localise the possible losses.

Figure 7 shows that the beam central orbit before the change of the tunes was well centred between the jaws at the horizontal, the vertical and the momentum collimator. This indicates that the orbit is close to the on-momentum orbit in these cases. The situation is different at the skew collimator, where the shift due to momentum offset is about 0.4 mm.

The orbit perturbation had no impact in the vertical plane and its effect at the momentum collimator is negligible as the jaws were very far from the beam. On the other hand the orbit change pushed the proton beam very close to one side of TCP.B6L7.B1 in the other two cases, which strongly indicates that losses may have occurred there.

From this simplified picture one can get a rough estimate of the percentage of the beam

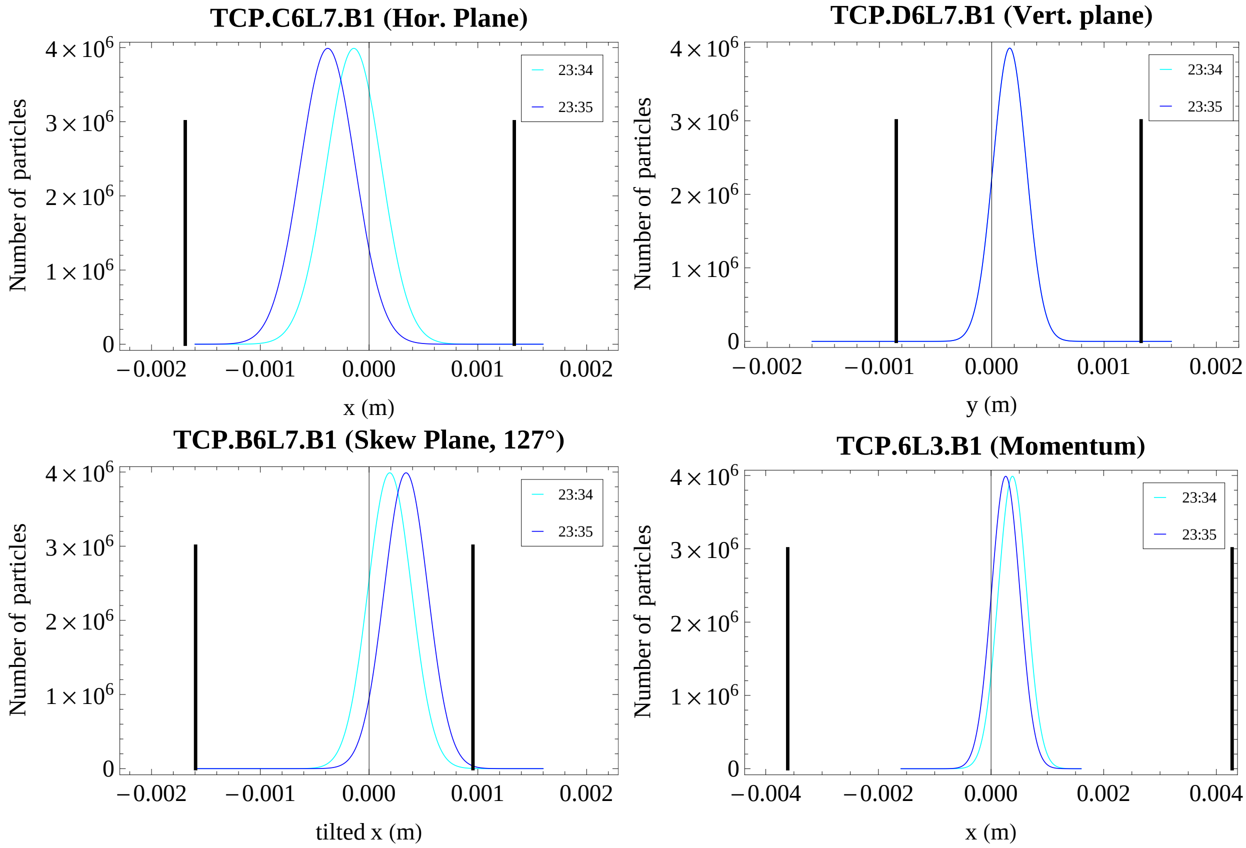


Figure 7: B1 profiles at the primary collimators, compared to the latter's jaws positions (in black), before (in cyan) and after (in blue) the orbit shift.

lost on the TCPs by integrating the gaussian distribution outside of the region defined by the jaws. The fraction is negligible in all cases except for the skew plane, giving about 1.3% of the beam being scraped by the collimator. This result corresponds in order of magnitude to the intensity loss mentioned earlier (4%). Uncertainties remain on the measured central orbit on- and off-momentum, but, again, this gives an estimate of the losses as well as their location. Furthermore they are consistent with losses monitored during the run as shown hereafter.

A way to check that losses occurred on TCP.B6L7.B1 and possibly on TCP.C6L7.B1 is to look at the beam loss monitor (BLM) signals at the TCPs. The BLM data are shown in Figure 8 in gray per second and confirm the predictions since the losses at the vertical collimator are negligible. The two highest signals were monitored at the horizontal and the skew primary collimators. Given the position of collimators with respect to each others (vertical then horizontal and finally skew), we expect bigger losses on the skew collimator as it actually monitors losses from all three planes. Consequently, integrating its signal over time should give the total amount of losses. Knowing the calibration factor of the BLM signal these losses can then be expressed in protons ($1\,\mathrm{Gy/s} = 1.94 \times 10^{12}\,\mathrm{p/s}$, [12, 13]). The BLM signal is integrated from the start of losses to its maximum. Intensity loss is estimated to be 1.7×10^{10} protons. This corresponds to about 9.5% of initial intensity, the loss is over-estimated but still of the correct order of magnitude. The uncertainty on the calibration factor is most probably the origin of the error.

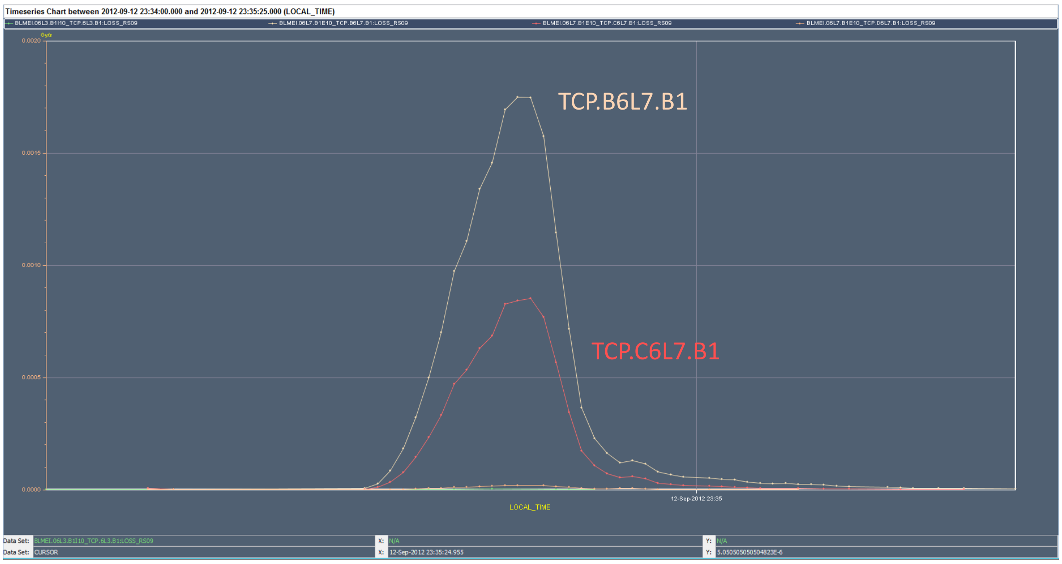


Figure 8: Beam losses observed at the BLMs of skew (TCP.B6L7.B1) and horizontal (TCP.C6L7.B1) primary collimators.

To summarise, two different methods were applied to explain the intensity loss. They are in good agreement as they predict losses on the same collimator and in the range of what was observed. Consequently the effect is very likely due to the observed orbit shift. In regular operation, the change to collision tunes is performed at the beginning of the squeeze procedure, and the orbit is corrected using feed-forward control. Once this is set up similar losses should not occur in the coming physics run.

Loss maps

Loss maps at flat top were done once the beams were put into collision in order to check the absence of unexpected loss peaks and qualify the configuration for operation as “Stable Beams”. One bunch was sacrificed for each beam and plane using ADT bunch-by-bunch excitation. The measured loss maps are given in Figure 9 where the cleaning inefficiency is normalised to the maximum peak in IR7. The loss thresholds used as references were based on data available at the time of the pilot run, which did not correspond exactly to our off-momentum beams. Data from March 2012, ie, on-momentum protons at $E = 4\,\text{TeV}$ and tight collimators settings, served as reference for B1. Data from the Pb-Pb run in 2011, ie, on-momentum beam at $E = 3.5Z\,\text{TeV}$ with relaxed collimators settings, served as reference for B2. Based on these, the main criterion used to validate the loss maps was to check that the cleaning inefficiency ratio between cold magnets and collimation section remains less than 10^{-4} for protons, and less than 10^{-2} for Pb. Of course, these thresholds will be updated after new dedicated measurements during the commissioning phase in January 2013 and loss maps will be repeated before the run.

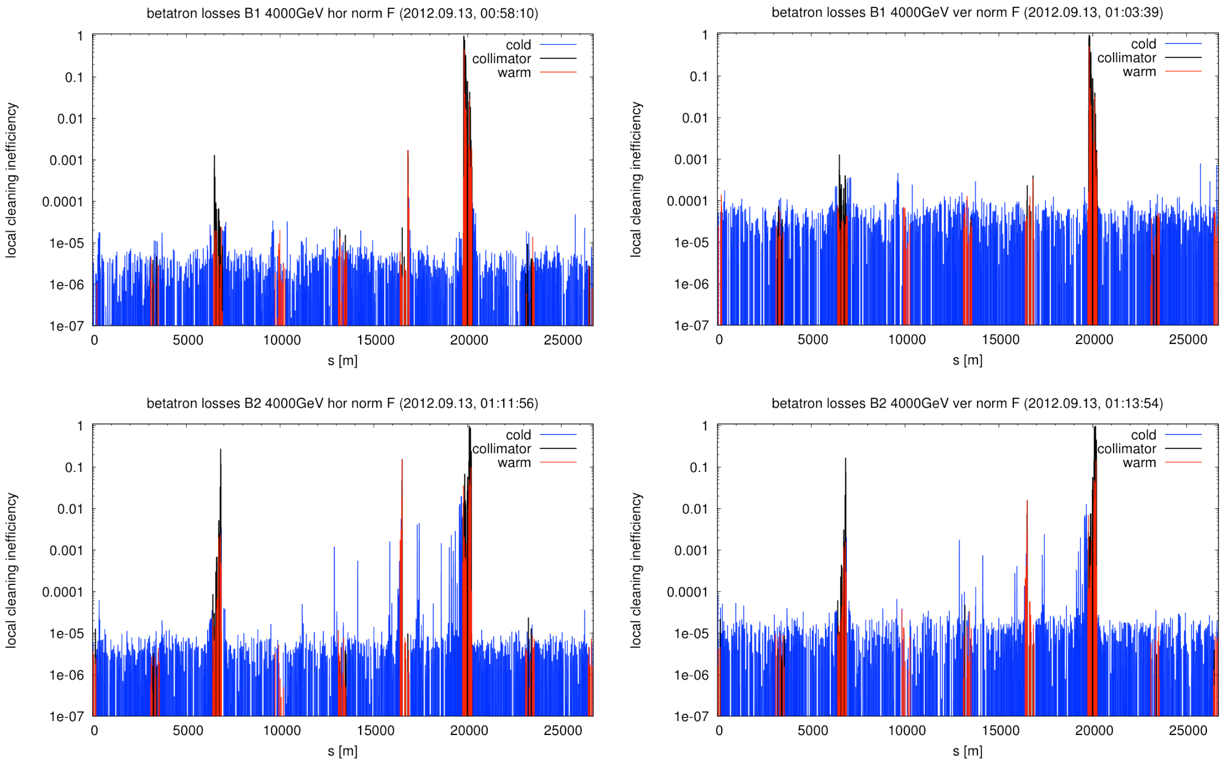


Figure 9: Loss maps of B1 (p) and B2 (Pb) during collision at flat top ($E = 4Z$ TeV). B1 propagates from left to right on the two upper plots, B2 from right to left on the two bottom plots.

We see on the plots in Figure 9 that we have three orders of magnitude in cleaning inefficiency between IR6 and IR7 in the horizontal plane. This is to be expected from tight collimator settings [8]. Losses on cold magnets behind the collimation section (Q8-Q10) are acceptable as local cleaning inefficiency is about 7×10^{-5}. The overall higher level of losses in the vertical plane is due to background noise resulting from a too low excitation by the ADT. Regarding the case of B2, losses on cold magnets are also in the acceptable range if we consider the 2011 threshold. Again a peak in cleaning inefficency, some ten times higher than in 2011, appears in IR6. Further analysis and new data with tight collimator settings are required to check if this corresponds to the expectations for ions.

4 Evolution of beam parameters

Having two different species in B1 and B2 could be the source of several unwanted effects affecting the beam quality. While our main concern for p-Pbn operation is the effect of moving encounters due to unequal revolution frequencies, we did not expect such effects to be significant with the small number of bunches in this fill. On the other hand, the low intensity allowed us to monitor proton and Pb beams transverse emittances during the whole cycle. Wire scanners (WS) could be used as beam intensities were low enough not to risk any damage of the wire or beam dump due to loss thresholds. Unfortunately, the synchrotron light monitors (BSRTs) were not available. The beam-gas ionization monitors (BGIs) could be used only for B2 (Pb beam).

Pb-Emittance at injection

Injection problems were encountered at the beginning of the run. While timing problems between SPS and LHC were being dealt with for Pb injection, we had the opportunity to observe two Pb bunches circulating in B2 against 15 p-bunches in B1 for about 50 minutes. Many wire scans of one of them could be done to study the emittance evolution at injection energy.

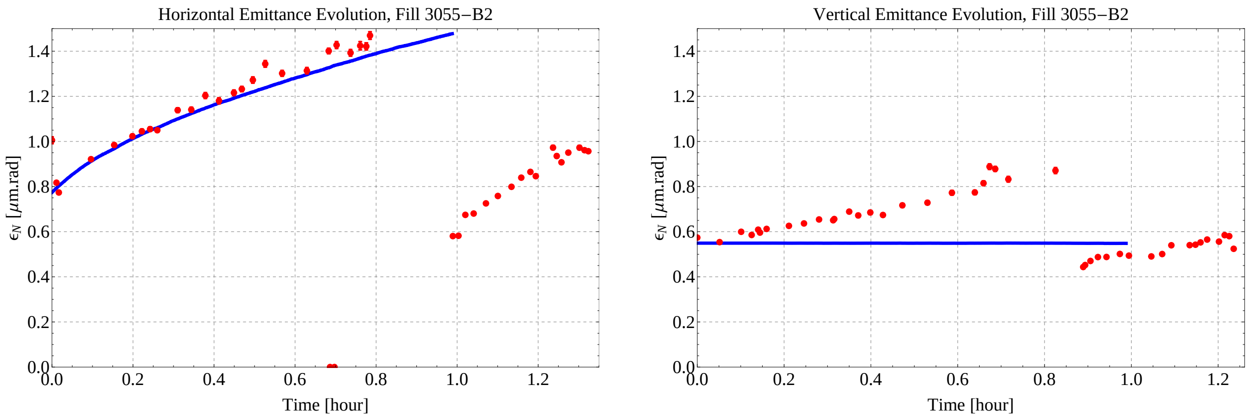


Figure 10: Horizontal (left) and vertical (right) Pb-emittance at injection energy. Red dots are wire scanners data, blue line is IBS simulation (without coupling). Time zero is 18:00 pm.

Data are plotted and compared to IBS simulation in Figure 10. Simulations of these conditions were performed using the Collider Time Evolution Program (CTE program [14]), assuming gaussian beam distributions in both transverse and longitudinal planes. The origin of the time scale is taken at 18:00. The beam was dumped just before 19:00 to prepare a new clean injection for physics so after one hour the data plotted correspond to a newly injected bunch. Initial parameters given by WS data (see Table 2) were used as initial conditions for an IBS simulation without coupling (blue line). We can see that the IBS model in CTE fits the data nicely in the horizontal plane, but measurements show an increase of emittance slightly faster than the simulation after some time. No emittance growth is expected in the vertical plane if we consider IBS, but we clearly see one. It could be the effect of moving encounters but we do not expect different behaviour between horizontal and vertical planes. Furthermore such an emittance increase was not seen in 2011 with about 300 p-bunches in B1, and these measurements were taken during some set-up and tests for injection so there could have been another parameter influencing the emittances.

Parameter	**Units**	**Pb bunch at injection**
Bunch intensity	charges	7.6×10^9
Bunch length	cm	6.5
Horizontal emittance	μm.rad	0.8
Vertical emittance	μm.rad	0.55

Table 2: Initial Pb bunch parameters for IBS simulation at injection energy.

At flat top, during stable beams

All bunches were regularly scanned to get transverse bunch profiles, and bunch-by-bunch intensity and length are automatically monitored and logged. That way we could analyze bunch-by-bunch parameters evolution from injection to dump. One non colliding bunch was introduced in the filling scheme to have reference data. Bunch intensities are given in Figure 11. Each color corresponds to one bunch, the non colliding one appears in thick red. In the case of protons, one can see the intensity loss described in the previous section approximately two hours before time zero which corresponds to stable beams being declared (at 01:27). From there the number of charges within the beam remains quite stable through physics. In case of Pb, intensity decreases all along the fill until the beam was dumped. Sudden losses just before time zero are the two bunches used for loss maps being excited by the ADT.

It has to be pointed out that the non colliding bunches behave the same way as the others for both beams, meaning that no significant losses arose from collisions. Same observation can be made for transverse normalized emittances (Figure 12) and bunch length (Figure 13).

The emittance data show an increase in both planes for the Pb beam. The vertical proton emittance is rather stable while an increase in the horizontal plane was observed during physics. The Pb bunch length increases more or less exponentially as expected from IBS. On the other hand proton bunches shrink longitudinally, meaning that radiation damping is preponderant. IBS simulations including radiation damping have been performed to compare previsions to experimental data in order to see if additional unexpected effects deteriorated the beam quality. The non-colliding bunch initial parameters were used as starting point for the simulations (see Table 3).

Results for the proton beam are given in Figure 14. Experimental data are compared to three simulation conditions: one includes IBS and radiation damping but no coupling of transverse betatron motions (in blue), the second includes only radiation damping (in dark red) and the third case includes all effects, ie, IBS, radiation and coupling. (In this context,

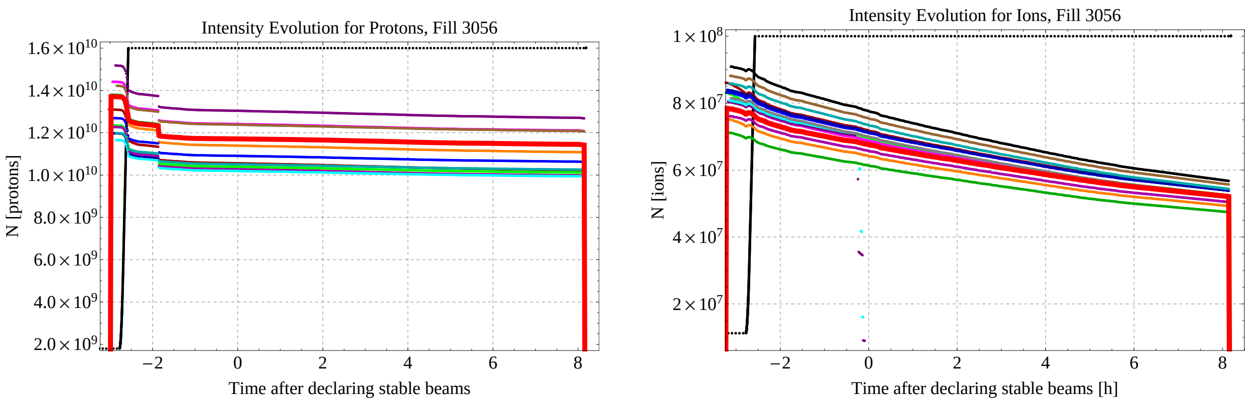


Figure 11: Proton (left) and Pb (right) bunch intensities during physics. Each color corresponds to one bunch. The thick red line represents the non colliding bunch data. The black line shows the energy in arbitrary units. Time zero corresponds to the declaration of Stable Beams (at 01:27).

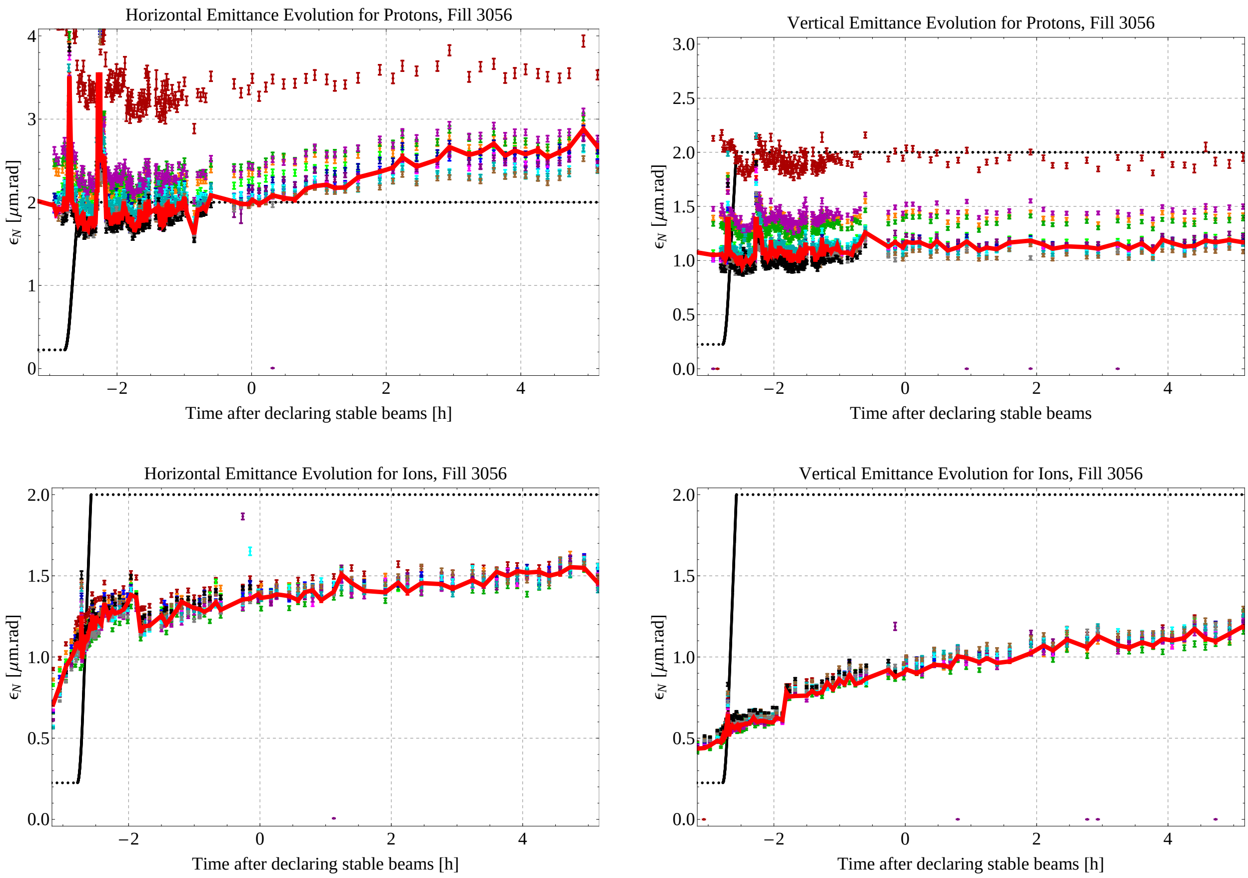


Figure 12: Proton (top) and Pb (botton) bunch normalized emittances during physics. The thick red line represents the non colliding bunch data. The black line shows the energy in arbitrary units. Time zero corresponds to the declaration of Stable Beams (at 01:27).

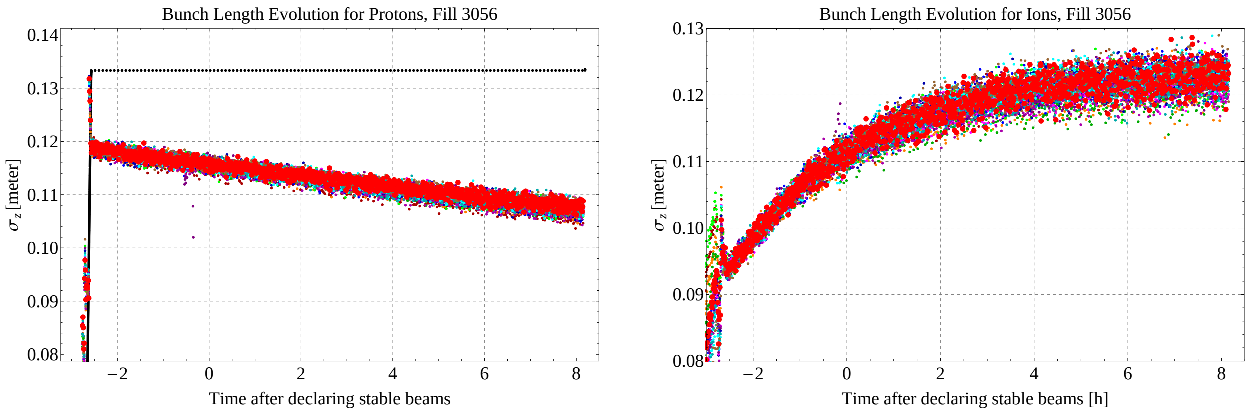


Figure 13: Proton (left) and Pb (right) bunch length during physics. The thick red line represents the non colliding bunch data. The black line shows the energy in arbitrary units. Time zero corresponds to the declaration of Stable Beams (at 01:27).

Parameter	**Unit**	**B1 (protons)**	**B2 (Pb)**
Bunch intensity	charges	1.2×10^{10}	5.5×10^{9}
Bunch length	cm	11.5	11.1
Horizontal emittance	μm.rad	2.0	1.4
Vertical emittance	μm.rad	1.2	0.93

Table 3: Initial proton and Pb bunch parameters for IBS simulation at flat top.

coupling is included in IBS simulations by sharing the sum of the uncoupled horizontal and vertical growth rates, equally between the two planes.)

Simulation results are very similar no matter what the conditions, showing that radiation damping was indeed dominant over IBS for protons. The latter is of course the only source of intensity loss as beam-beam interaction is not active here. Bunch length is in good agreement with simulation. As observed earlier, the vertical emittance was stable. On the other hand we observe an emittance blow up in the horizontal plane which is not at all predicted by the very low IBS rate.

The Pb beam data are presented in Figure 15. In this case we only plot results of simulation including coupling (dark red) or not (blue) with WS measurements (red dots). While the betatron coupling has almost no influence on the intensity or bunch length evolution, it obviously helps to explain the evolution of the horizontal and vertical emittances. A discrepancy is apparent between data and IBS prediction for the bunch length. This was already seen in former Pb-Pb fill analysis and is still under investigation. It could be due to the high initial value influencing the simulation behaviour or to a non-gaussian initial longitudinal distribution.

Coupling is usually very well corrected in the LHC and therefore not included in the IBS

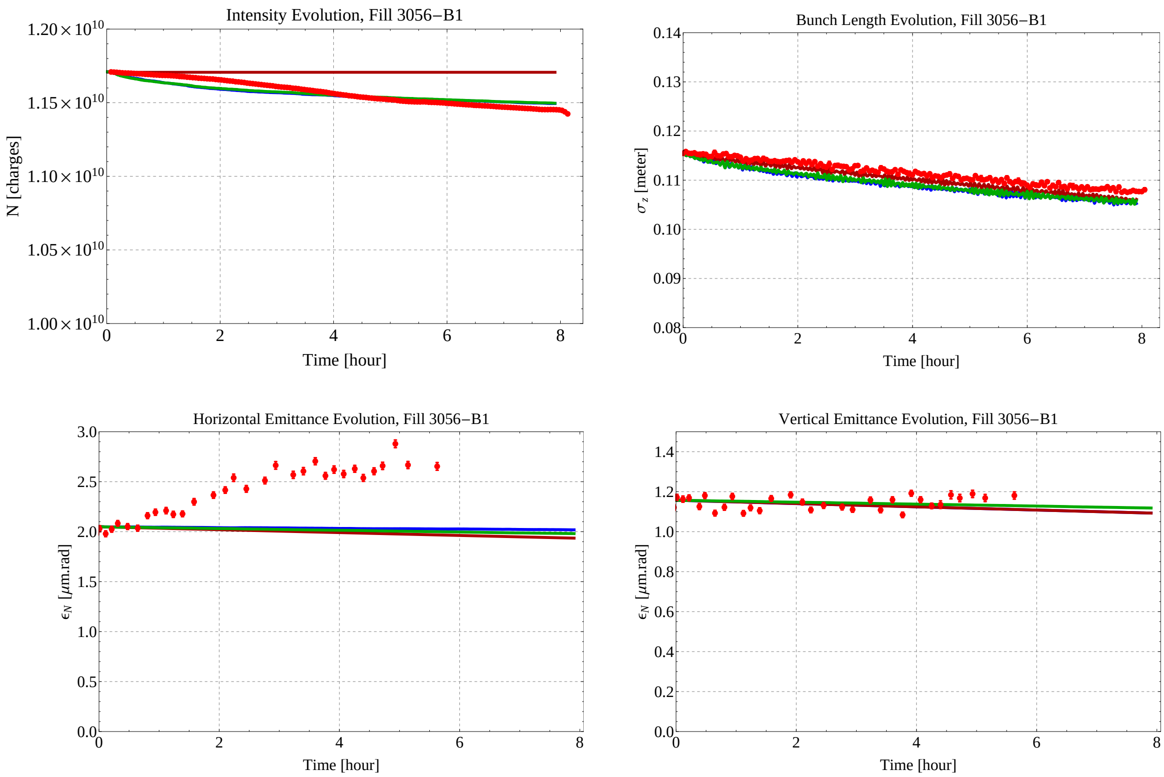


Figure 14: Proton parameters during physics: red dots are wire scans of the non colliding bunch, the blue line is the IBS simulation without coupling, the dark red line is a radiation damping simulation without IBS, and the green line is IBS simulation with coupling. Time zero corresponds to the time when stable beams were declared.

simulations. However we noticed a modification of the coupling coefficient c^{-} as the tunes were changed and the orbit shifted. Logged data are shown in Figure 16. Tunes and coupling are plotted against time during the process of putting beams into collision. Measurements are very noisy as the tune window of the BBQ application was probably not correctly set up to find the tune peak but a small increase of coupling cannot be excluded and would be consistent with IBS simulations.

In conclusion, we can say that the Pb beam intensity and transverse emittance evolutions are well reproduced by IBS simulation if coupling is included There is no unexpected effect arising from the unsqueezed off-momentum operation. As all bunches behave the same way as the non colliding one, there was also no bad effect resulting from beam-beam interaction with 12 colliding bunches in the machine. However an unexpected emittance growth was observed for the proton beam in the horizontal plane.

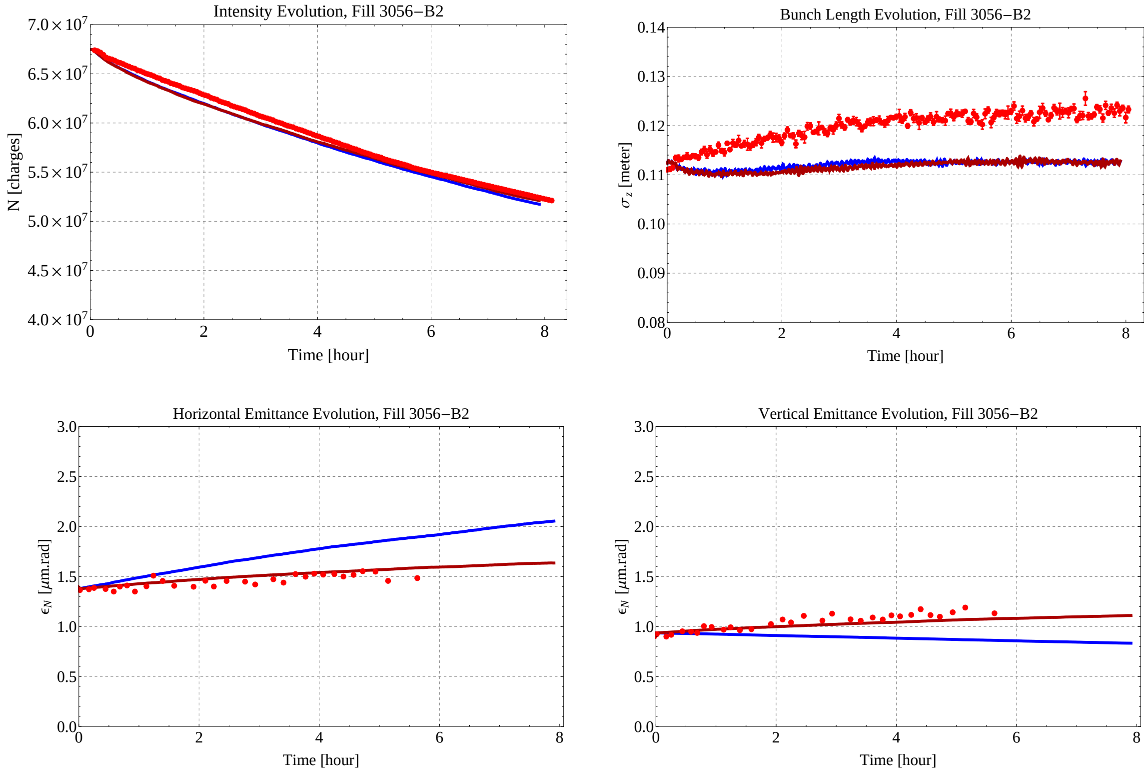


Figure 15: Pb parameters during physics: red dots are wire scans of the non colliding bunch, the blue line is the IBS simulation without coupling and the dark red line an IBS simulation with coupling. Time zero corresponds to the time when stable beams were declared.

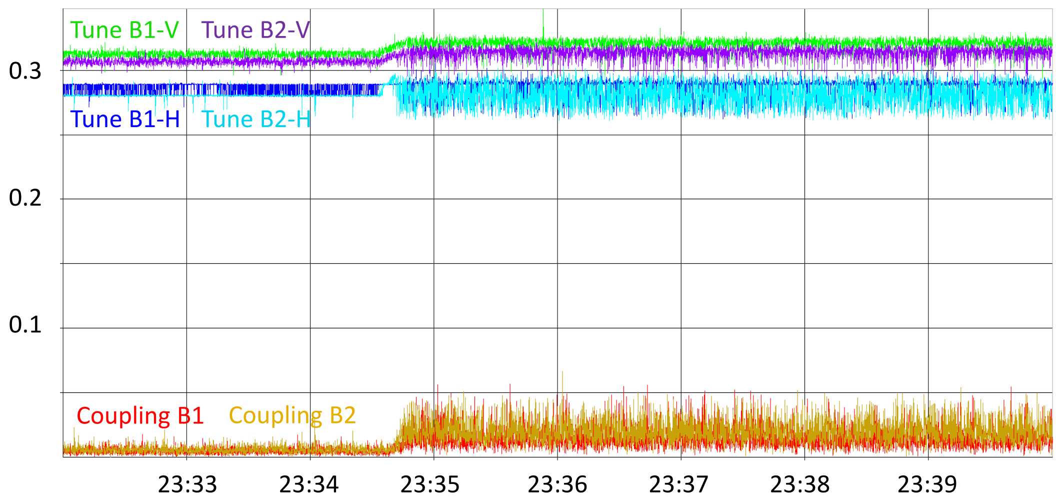


Figure 16: Evolution of coupling as tunes were changed from injection to collision tunes.

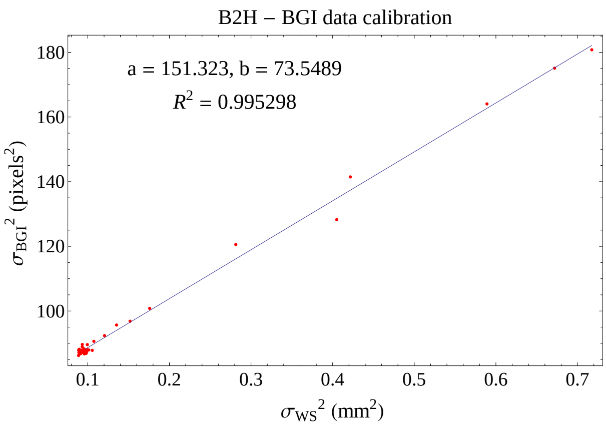
BGI measurements

The BGI was working only on the Pb beam (B2) during the fill. As wire scans could be done regularly during the ramp thanks to reduced intensity, it was a good opportunity to cross-calibrate the two emittance measurement devices. BGI data can either be calibrated using WS and β-function measurements, or using the image pixel size [15]. The pixel size was measured in the laboratory but it can also be estimated using orbit bumps in the machine. With the latter method scaling effects arising from various components of the device can be taken into account but it relies on orbit interpolation which has an accuracy of about $100\,\mu$m. The calibration factor was found to be 115 ± 3 μm.pixel^{-1} in the laboratory and 97 ± 4 μm.pixel^{-1} from beam position measurements [16].

The Pb beam data of p-Pb pilot run were first calibrated using WS measurements (bunch-by-bunch data were averaged to have data comparable to the BGI). We assumed a linear relation between squared beam size at the WS σ_{WS} and squared beam size measured at the BGI σ_m (in pixels):

$$\sigma_m^2 = a\sigma_{\mathrm{WS}}^2 + b \tag{1}$$

The ramp period is used for calibration as it gives a wider range of beam dimensions. Linear fits are shown in blue in Figure 17, measurements are in red. Fit parameters are given on the plots.



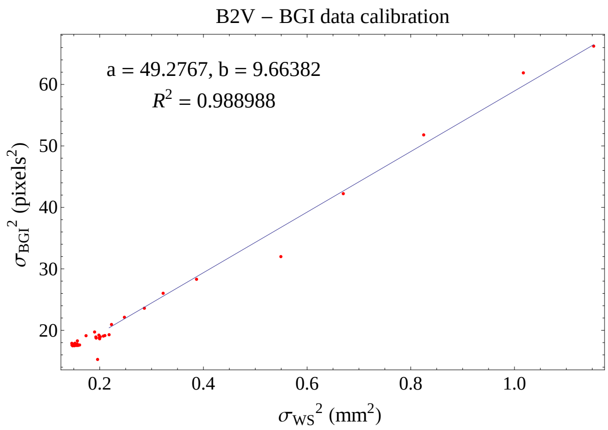


Figure 17: Horizontal (left) and vertical (right) calibration of BGI data using WS measurements. Fit parameters a and b as well as the adjusted coefficient of determination R^2 are given.

Now considering a calibration using the image pixel size, we can express σ_{BGI}^2 (in mm^2) the following way:

$$\sigma_{\mathrm{BGI}}^2 = N^2\sigma_m^2 - \sigma_{PSF}^2 \tag{2}$$

with σ_m the measured beam size in pixels, N the pixel's size and σ_{PSF} a point spread function.

This implies:

$$a = \frac{1}{N}\frac{\beta_{BGI}}{\beta_{WS}} \tag{3}$$

$$b = -\frac{\sigma_{PSF}^2}{N} \tag{4}$$

Numbers mentioned in reference [15] had to be adjusted to be consistent with WS data. The same calibration results were obtained with the parameters given in Table 4. but they are different in each plane. The vertical plane is described in reference [15]. Here we find a larger pixel size than was measured with orbit bumps in the machine, but the point spread function is similar. In the horizontal plane, the pixel size is close to the value measured in the laboratory. The point spread function is significantly larger than for the vertical monitor (by a factor of about 3).

The data are plotted in Figure 18; the calibration resulting from Figure 17 is shown in blue, the calibration given by Table 4 in green and WS data in red. Normalized emittances were calculated using measured β-functions from reference [11], assuming a linear dependence on the energy during the ramp.

	N (mm/pixel)	σ_{PSF} (mm)
Horizontal plane	0.1162	0.9870
Vertical plane	0.1023	0.3220

Table 4: Pixel size and point spread function of B2 BGIs.

The BGI measurements were noisy because of the low beam intensity. Sudden variations of emittances are artefacts most probably due to a change of gain. The data are in good agreement during the ramp but BGI and WS slowly diverge as time goes on during physics. The WS seems to overestimate emittances with respect to the BGIs when values get larger. This may be due to a lack of accuracy in the calibration which was done with small emittances.

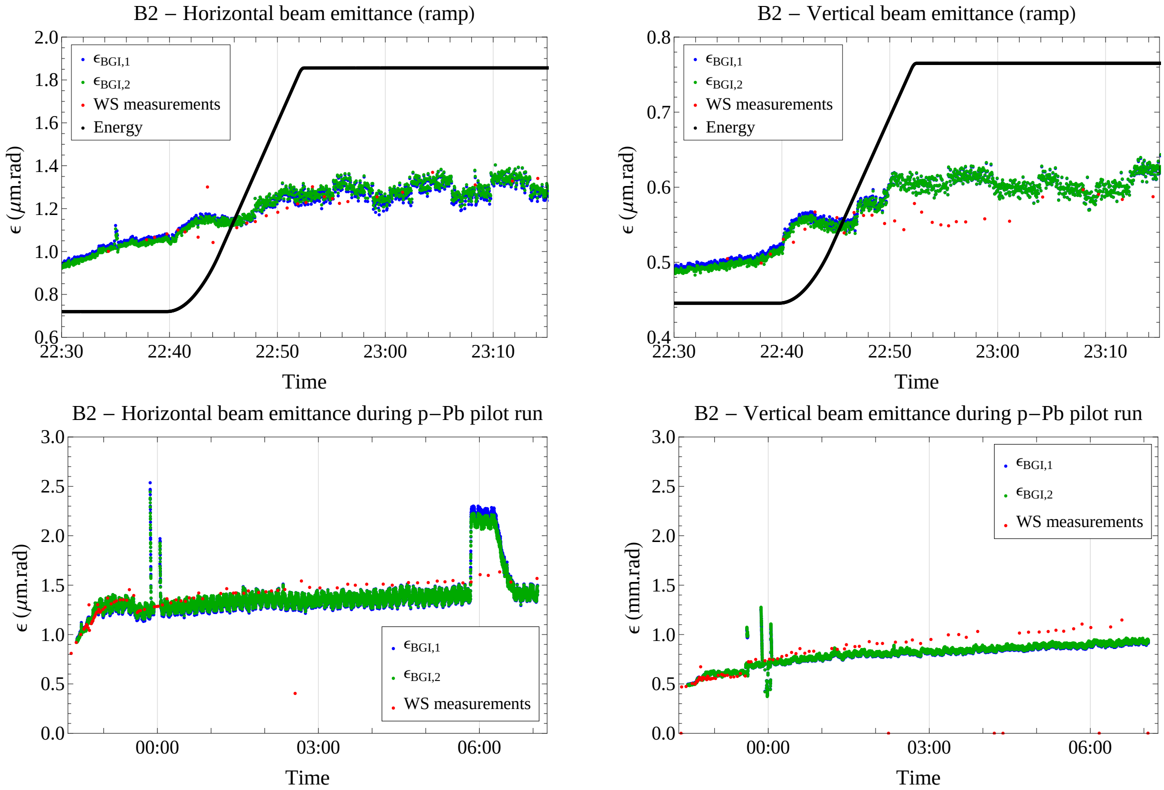


Figure 18: Horizontal (left) and vertical (right) normalized emittances evolution measured using WS and BGIs, and depending on calibration method of BGI data. $\epsilon_{BGI,1}$ uses WS measurements, $\epsilon_{BGI,2}$ uses the pixel size. The upper plots are a zoom in the ramp, while evolution during physics is shown on the bottom. The energy is given in arbitrary units (in black).

5 Colliding beams of different transverse sizes

The LHC was originally designed as a p-p collider and a heavy-ion collider. On that baseline beam parameters were optimized so that transverse dimensions of colliding beams in either one or the other case were similar. That is why nominal normalized emittances are different: $3.75\,\mu$m for protons and $1.5\,\mu\text{m} = (Z/A)3.75\,\mu$m for Pb ions. But recent p-p operation showed that thanks to the high performance of the source and the injector chain smaller p-emittances are achievable. Furthermore in the specific case of p-Pb, p-beam intensity will be one order of magnitude smaller than nominal and should allow even smaller transverse emittances. As shown in Figure 12 we had emittances as small as $1.6\,\mu$m in the horizontal plane and $0.9\,\mu$m in the vertical plane for B1.

From experience at various past colliders, it is well known that beam lifetime can be significantly reduced when colliding beams have unequal sizes [17, 18, 19]. The larger beam sees all the non-linearities of the beam-beam force while the smaller experiences only the linear central part. In the first case, the beam-beam effect induces a large tune spread, which potentially leads to resonances and particle losses. This phenomenon would get worse during a p-Pb fill since the larger beam would be Pb and Pb-emittances also grow due to IBS.

The tune shift with amplitude is given by [20]:

$$\Delta Q(\alpha) = \frac{2\xi}{\alpha}\left[1 - \exp\left(-\frac{\alpha}{2}\right) I_0\left(\frac{\alpha}{2}\right)\right] \tag{5}$$

with ξ the linear beam-beam tune shift induced by the proton bunch, I_0 the modified Bessel function of order 0, $\alpha = a^2/2$ and a the amplitude of a Pb particle in the transverse plane at the IP.

Assuming gaussian transverse distributions, the distribution of Pb particles in amplitude a is given by the Rayleigh distribution:

$$\frac{\mathrm{d}N_{\mathrm{Pb}}}{\mathrm{d}a} = \frac{aN_{\mathrm{Pb,tot}}}{\sqrt{2\pi}\sigma_{\mathrm{Pb}}^2}\exp\left(-\frac{a^2}{2\sigma_{\mathrm{Pb}}^2}\right) \tag{6}$$

where $N_{\mathrm{Pb,tot}}$ is the total number of particles per bunch and $\sigma_{\mathrm{Pb}}$is the RMS beam size. We get the tune distribution by mapping this number to the tune shift at a given amplitude a.

	Horizontal				**Vertical**			
	$(\gamma\epsilon)_{\mathbf{p}}$	$(\gamma\epsilon)_{\mathbf{Pb}}$	r	ΔQ_{RMS}	$(\gamma\epsilon)_{\mathbf{p}}$	$(\gamma\epsilon)_{\mathbf{Pb}}$	r	ΔQ_{RMS}
First collisions	1.6	1.4	1.48	8.3×10^{-5}	0.9	0.7	1.40	1.4×10^{-5}
After 6.5 hours	2.4	1.6	1.30	5.2×10^{-5}	1.0	1.2	1.74	1.4×10^{-5}

Table 5: Proton smallest and Pb largest bunch emittances, beam size ratios and resulting Pb beam-beam tune spreads due to the interaction with protons during the pilot physics run. Emittances are normalised and given in μm.

Tune distributions were examined considering p-Pb pilot run conditions and possible beam parameters for the coming physics run.

We define r as the ratio of beam sizes at the IPs (independent of β^*),

$$r = \frac{\sigma_{\rm Pb}}{\sigma_p} = \sqrt{\frac{\gamma\epsilon_{\rm Pb}}{\gamma\epsilon_{\rm p}} \frac{\gamma_{\rm p}}{\gamma_{\rm Pb}}} \tag{7}$$

Extreme values in terms of bunch emittances occurring during the pilot run are considered so that r is maximum (smallest for protons, largest for Pb). We look at first collisions and at the end of the fill (after 6.5 hours of collisions). Variation of proton bunch intensity over the fill is neglected ($N_{\rm p,tot} = 1.2 \times 10^{10}$ protons), and $N_{\rm Pb,tot}$ is taken to be 8×10^7 ions initially and decreases to 6×10^7 ions after 6.5 hours of collisions (see Figure 11). Corresponding transverse parameters in both horizontal and vertical planes are given in Table 5, and tune distributions are plotted in Figure 19.

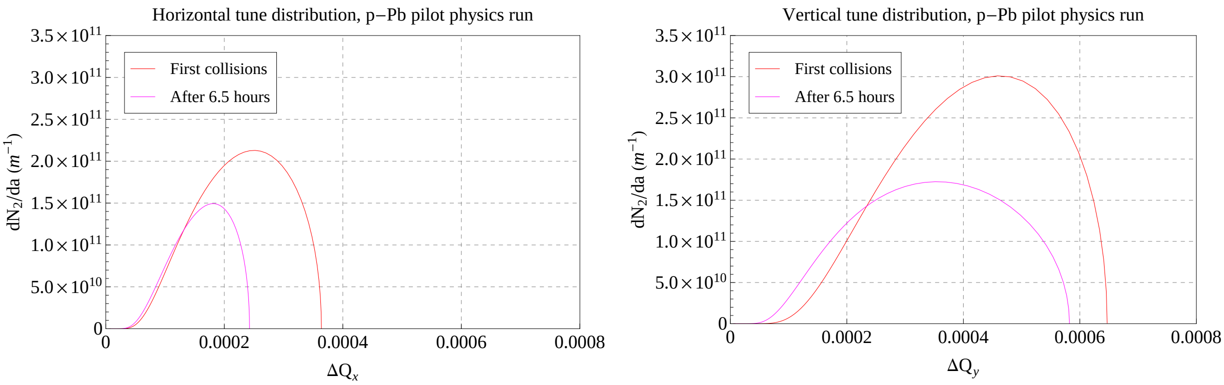


Figure 19: Horizontal (left) and vertical (right) Pb tune distributions resulting from beam-beam interaction with protons during p-Pb pilot physics run.

The maximum tune shift is equal to the linear beam-beam tune shift. It became smaller after 6.5 hours of collisions as proton emittances got larger. According to the RMS value of tune distributions (in Table 5), the vertical tune spread did not change between start and end of fill. The increase of beam size difference was compensated by the reduction of linear beam-beam tune shift. In the horizontal plane, the tune spread got smaller as the linear tune shift decreased as well as the r ratio. This is a consequence of the unexplained horizontal emittance growth.

We finally consider possible situations for the coming physics fill. Supposing round beams and taking the most pessimistic parameters, we can expect a normalized proton emittance as small as about 1 μm and a Pb emittance as big as about 1.5 μm (the nominal value). This leads to a beam size ratio close to $r = 2$. Furthermore we consider the case of same pilot intensity for protons as for the pilot run (1.2×10^{10} protons), but also twice as much, as this could be the first parameter upgrade to increase the luminosity if Pb stability allows it. A parameter table with resulting linear beam-beam tune shifts and tune spreads for Pb is shown in Table 6, and tune distributions are plotted in Figure 20.

Predicted cases are shown in green and pink. We can clearly see the factor of two in linear tune shift and tune spread resulting from the doubling of proton bunch intensity. In that case we could reach tune variations of the order of 10^{-3} which approaches the level of tolerance on tune shift in the LHC ($\Delta Q = \pm 2.5 \times 10^{-3}$). In orange is superimposed the

	Pilot run		Low intensity		High intensity	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
$\epsilon_{\rm p}/\mu$m	1.6	0.9	1		1	
$\epsilon_{\rm Pb}/\mu$m	1.4	0.7	1.5		1.5	
$N_{\rm p,tot}$	1.2×10^{10}		1.2×10^{10}		2.4×10^{10}	
r	1.48	1.40	1.94		1.94	
ξ	3.6×10^{-4}	6.5×10^{-4}	5.8×10^{-4}		1.2×10^{-3}	
ΔQ_{RMS}	8.3×10^{-5}	1.4×10^{-4}	1.4×10^{-4}		2.9×10^{-4}	

Table 6: Beam-beam parameters and Pb tune spreads for pilot run initial conditions, and predicted results for the physics run for two different proton beam intensities and 1 μm p-emittance. $N_{\rm Pb,tot} = 7 \times 10^7$ particles in all cases.

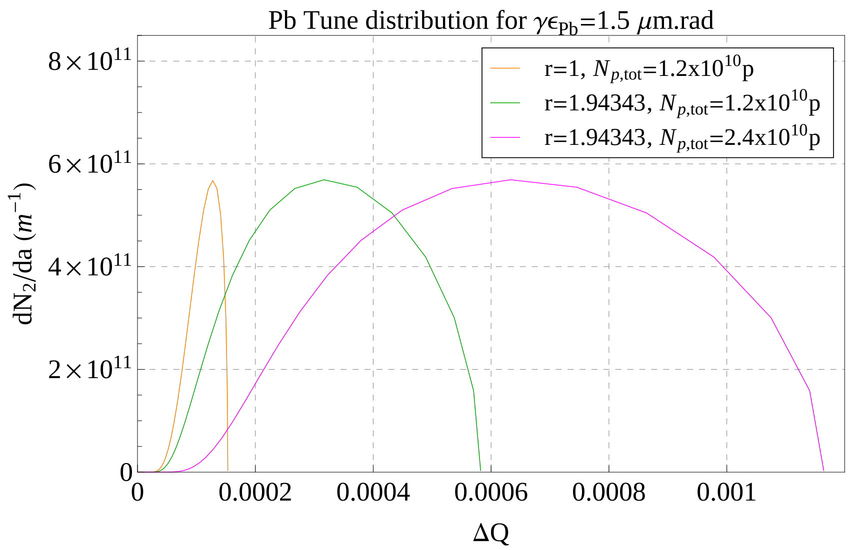


Figure 20: Predicted Pb tune distributions resulting from beam-beam interaction with protons and assuming 1.5 μm Pb-emittance for the physics run.

tune distribution for the lowest intensity and in case of equal beam sizes for comparison (this would correspond to 3.8 μm proton emittance, very close to nominal parameters). It shows how the distribution shrinks for similar transverse dimensions of the two beams. So even if we double the proton intensity, blowing the proton transverse emittance up would be a way to keep the beam-beam tune shift and tune spread at a very small level. But the instantaneous luminosity would be reduced.

6 MD on intensity limit

A machine study on the proton intensity limit was originally the second part of the p-Pb feasibility programme. It had to be cancelled in 2011 because of a leak at the PS injection septum, and was rescheduled in September 2012 before the pilot physics run. Unfortunately tests still could not be performed, first because of the apparition of a vacuum leak at one wire scanner, then because of BPM interlocks in IR6 preventing the injection proton batches of pilot intensities.

The first part of the feasibility test done in 2011 consisted in injecting and ramping a few p-bunches against a few Pb-bunches [5]. This was very successful, and it was repeated this year for the pilot run with fifteen bunches. We then had time to inject about 300 p-bunches with 100 ns spacing. We could not fill the machine entirely because of an error in the filling pattern. Tests had to stop at this stage.

Our goal for the second part as reprogrammed in 2012 was to fill B1 with many proton bunches with the new alternating 200/225 ns spacing filling scheme and one tenth of nominal bunch intensity, ie, 1.2×10^{10} charges, then ramp with a few Pb bunches in B2. It would have been the chance to study Pb bunches behaviour (transverse emittances, lifetime...) at injection and during the ramp in the presence of 318 p-bunches regularly distributed in the machine. If time had allowed, we would have repeated this test with twice as much intensity in B1.

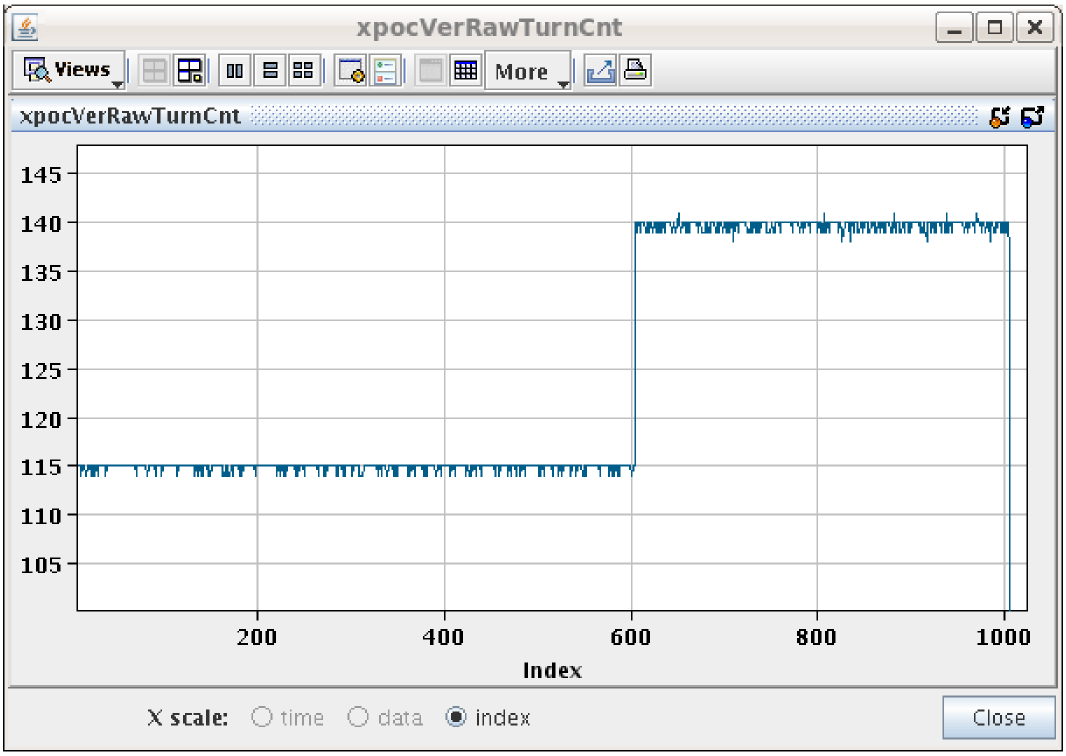


Figure 21: Miscounting of number of bunches by one of the BPMs in IR6 during MD on September 14, 2012.

We cannot fully rely on the results obtained in 2011 with 100 ns proton beam since it was not the bunch spacing now adopted for the run in 2013. Moreover, since the machine was not filled properly, proton beam intensity limit for Pb stability remains very uncertain even if we did not see any unexpected variations of Pb transverse emittances. This will have to be tested at the beginning or during the physics run in January. In addition ramping many bunches with unlocked RF frequencies was not tested so we may encounter unexpected difficulties during the commissioning period.

The second attempt done on 14 September 14 2012 was useful in that it showed that injecting pilot intensity p-batches would not be possible without an intervention on the BPMs in IR6. Because of bunch signal reflections, the BPMs in high sensitivity range miscount the number of bunches as illustrated in Figure 21. They then trigger interlocks and provoke a beam dump.

To conclude it is still of high importance to perform the test on the proton intensity limit, if possible in 2012, to have reliable data to confirm or not the results seen at injection energy and shown in Figure 10, and to estimate a reasonable limit for the proton beam intensity. Otherwise p-Pb operation will start with 1.2×10^{10} charges as planned. As many aspects of the operation are totally new, and specific procedures were created for p-Pb, we may still encounter technical problems as well as unexpected beam behaviour. Once proper operation is established we could try to increase proton beam intensity in order to produce higher peak luminosity.

7 Conclusions and perspectives for the coming physics run

The p-Pb pilot physics fill was a major success for the injector chain and the LHC. Beams were injected and ramped with unlocked RF frequencies. RF rephasing was done successfully with the new procedure. LHC delivered p-Pb collisions with off-momentum beams for more than 7 hours. The maximum expected peak luminosity of about $10^{26}\text{cm}^{-2}\text{s}^{-2}$ was achieved. Estimated luminosity from beam parameters is plotted in Figure 22—it decreased by approximately 30% over 6.5 hours. IBS predictions fit well with Pb beam parameters' evolution and is the main cause of luminosity decay as Pb intensity was reduced by about 25%. Nevertheless horizontal emittance blow up was observed in proton beam, and some discrepancies between bunch length evolution and IBS simulations are still to be understood.

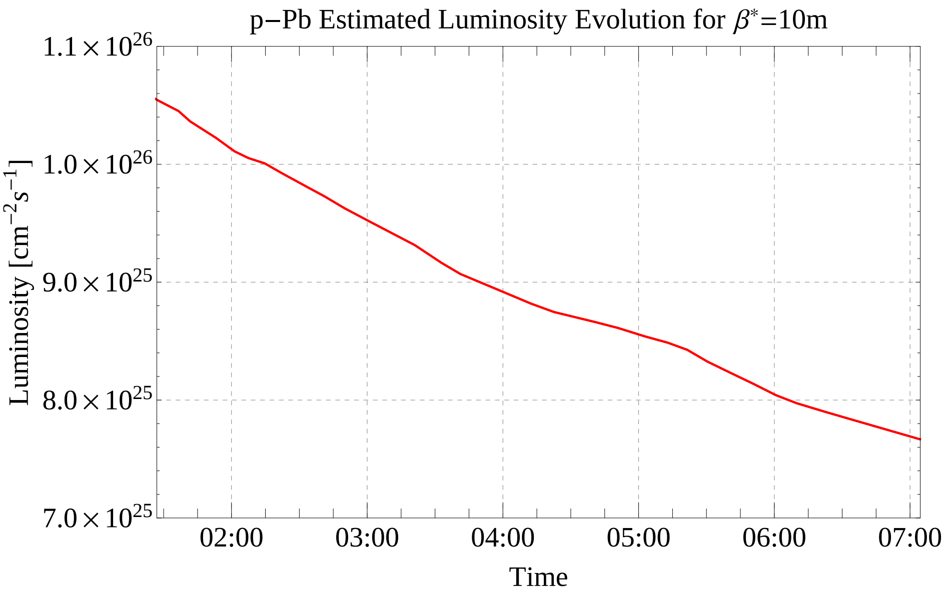


Figure 22: Delivered luminosity during pilot physics run as estimated from measured beam parameters.

In Table 7 we compare the parameters reached during the pilot run with the parameters announced at the Chamonix 2012 workshop [3]. A factor of several hundreds remains to be gained on initial luminosity. Filling scheme is not yet final and the number of colliding bunches could have been slightly over-estimated. Aperture measurements are required to squeeze down to 0.6 m, and the run may start with $\beta^* = 0.8$ m. The Pb bunch intensity corresponds to maximum value achieved in 2011. During pilot run mean value was close to nominal 7×10^7 ions, so it will probably be smaller than 1.2×10^8 ions at least at the beginning of the run. All this could contribute to reduce luminosity although emittances were conservative. Unless the p-emittance has to be blown up on purpose to match it to the Pb beam the nominal value is about twice what could be obtained from the injector chain. We will also most likely be able to get smaller Pb emittances than nominal 1.5 μm.

It is still very difficult to give strong predictions about the performances during the physics run in January 2013, but luminosity goal seems realistic unless unexpected problems

Parameter	**Unit**	**Pilot run**	**Chamonix'12**
Beam energy	Z TeV	4	4
Colliding bunches		8	356
β^*	m	10/11	0.6
p / bunch	10^{10}	1.2	1.15
Pb / bunch	10^{8}	0.7	1.2
$\gamma\epsilon_p$	μm	1.7	3.75
$\gamma\epsilon_{Pb}$	μm	H: 1.4; V: 1	1.5
Initial luminosity	10^{26}cm^{-2}.s^{-2}	1.2	830

Table 7: Main beam parameters reached during the p-Pb pilot physics fill (mean values over the thirteen bunches) and announced in Chamonix'12 [3] as prediction for the physics run in 2013.

arise. Reprogramming the machine studies on intensity limits in December 2012 is recommended to be as well prepared as possible as the time windows for commissioning and for the run itself are very short. Some emittance growths remain unexplained. It would be very good to have additional data to check if the discrepancies observed between emittance measurements and IBS simulation for Pb at injection in the vertical plane, and for protons at $E = 4$ TeV in the horizontal plane, are reproducible. This would allow us to check if what we saw was or not related to some specific conditions of operation during the last test.

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References

[1] C. Carli and J. Jowett, "The LHC as a Proton-Nucleus Collider," in *Proceedings of 2006 European Particle Accelerator Conference*, 2006.

[2] J. Jowett *et al.*, "Heavy Ions in 2011 and beyond," in *Proceedings of Chamonix 2011 workshop on LHC performance*, 2011.

[3] J. Jowett *et al.*, "Heavy Ions in 2012 and the Programme up to 2022," in *Proceedings of Chamonix 2012 workshop on LHC performance*, 2012.

[4] T. Satogata *et al.*, "Commissioning of RHIC Deuteron-Gold Collisions," in *Proceedings of 2003 Particle Accelerator Conference*, 2003.

[5] R. Alemany, P. Baudrenghien, D. Jacquet, J. Jowett, M. Lamont, D. Manglunki, S. Redalli, M. Sapinski, M. Schaumann, D. Valuch, R. Versteegen, and J. Wenninger, "p-Pb Feasibility Test and Modifications of LHC Sequence and Interlocking," *CERN-ATS-Note-2012-052-MD*, 2012.

[6] D. Boussard, W. Höfle, and T. Linnecar, "The LHC Transverse Damper (ADT) Performance Specification," *CERN-SL-Note-99-055 HRF*, 1999.

[7] R. Alemany, P. Baudrenghien, A. Butterworth, J. Jowett, T. Mastoridis, J. Noirjean, A. Pashnin, and R. Versteegen, "Commissioning the p-Pb rephasing using protons," *CERN-MD-Note to be published*, 2012.

[8] R. Bruce, R. Assmann, F. Burkart, M. Cauchi, D. Deboy, L. Lari, S. Redalli, A. Rossi, B. Salvachua, G. Valentino, and D. Wollmann, "Collimator settings and performance in 2011 and 2012," in *Proceedings of Chamonix 2012 Workshop on LHC Performance*, 2012.

[9] G. Müller, K. Fuchsberger, and S. Redaelli, "Aperture Meter for the Large Hadron Collider," *CERN-ATS-2012-059*, 2011.

[10] R. Billen and C. Roderick, "The LHC Logging Service, Capturing, Storing and Using Time-series Data for the World's Largest Scientific Instrument," *CERN-AB-Note-2006-046(CO)*, 2006.

[11] "Beta-beating measurements, 2012 LHC data." http://beta-beating.web.cern.ch/Beta-beating/jnlpRun/LHC/2012/.

[12] F. Burkart, R. Assmann, R. Bruce, M. Cauchi, D. Deboy, L. Lari, S. Redalli, A. Rossi, G. Valentino, and D.Wollmann, "Halo Scrapings with Collimators in the LHC," in *Proceedings of IPAC'2011*, 2011.

[13] G. Valentino, R. Assmann, R. Bruce, F. Burkart, V. Previtali, S. Redalli, B. Salvachua, G. Stancari, and A. Valishev, "Halo Scraping, Diffuson and Repopulation MD," *CERN-ATS-Note-2012-074-MD*, 2012.

[14] M. Blaskiewicz, R. Bruce, W. Fischer, and J. Jowett, "Time evolution of the luminosity of colliding heavy-ion beams in BNL Relativistic Heavy Ion Collider and CERN Large Hadron Collider," *Phys. Rev. ST Accel. Beams, 13, 091001*, 2010.

[15] M. Sapinski *et al.*, "The First Experience with LHC Beam Gas Ionization Monitor," in *Proceedings of IBIC2012*, 2012.

[16] M. Sapinski, "Private communication," 2012.

[17] R. Brinkmann and F. Willeke, "First Experience with Colliding Electron-Proton Beams in HERA," in *Proceedings of PAC'1993*, vol. 5, pp. 3742–3744, 1993.

[18] K. Cornelis, M. Meddahi, and R. Schmidt, "The beam-beam effect in the SPS proton anti-proton collider for beams with unequal emittances," *CERN SL/90-73 (AP)*, 1990.

[19] M. Syphers, "Beam-beam Tune Distribution with Differing Beam Sizes," *Fermilab-AD, Beams-doc-3031-v1*, 2008.

[20] E. Keil, "Beam-beam dynamics," *CERN Accelerator School, CERN 95-06*, 1993.