HEAVY IONS IN 2011 AND BEYOND

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Abstract

The LHC's first heavy ion run set - and tested - the operational pattern for 2011 and later years: a rapid commissioning strategy intended to ensure delivery of integrated luminosity despite the risks associated with the short time-frame. It also gave us hard data to test our understanding of the beam physics that will limit performance.

The 2010 experience is fed into the commissioning plan, parameter choices and projected performance for 2011.

The prospects for future stages of the LHC ion program, Pb-Pb collisions at higher energy and luminosity, hybrid collisions and other species, depend critically on the scheduling of certain hardware upgrades.

INTRODUCTION

This talk is part of a session on the LHC luminosity in 2011. To understand what we can expect in 2011, we shall first review some aspects of the 2010 run. Given the limited time, we can only touch on a few highlights of the many things we learned from this first experience of nucleus-nucleus collisions in the LHC. We shall then discuss expectations and strategy for 2011, the possibility of hybrid proton-nucleus collisions in 2012 and recall what upgrades are needed in the coming years to explore the three dimensions of the LHC's performance parameter space (energy, luminosity, beam species).

THE 2010 LEAD-LEAD RUN

The principles of the commissioning plan for the first Pb-Pb run have evolved over the years and were summarised at the 2009 workshop [1]. A key idea in the plan was to recognise that, with a Pb beam of the same magnetic rigidity as the protons, minimising the changes to the magnetic configuration would reduce the time taken for the initial commissioning steps (achieving circulating beam, ramp, squeeze) and allow us to move quickly on to dealing with the substantial differences in beam physics between heavy ions and protons. In order to take account of the operational state of the machine and the accumulated experience with protons, final details of the plan were worked out in the weeks immediately preceding the start of the run and updated in real time on the Web [2] as they were executed.

Following the first injection of Beam 1 at 20:00 on 4 November 2010, the RF frequency was adjusted to the new value to obtain circulating beams. First collisions were obtained 54.5 h (including 11 h down time on 6 November) later at 00:28 on 7 November. Stable Beams were declared for physics at 11:20 on 7 November. In the following days, the number of bunches per beam changed on every single fill, through $k_b = 2, 5, 17, 69, 121$, injecting single bunches or batches of 4 from the SPS in variants of the "Early" filling scheme [3]. In the last few days of the run, injection of batches of 8 bunches allowed $k_b = 137$.

The integrated luminosity went up very quickly and exceeded expectations. Figure **1** compares Pb-Pb and p-p luminosities, showing clearly that the strategy allowed us to move quickly past the usual initial commissioning steps and produce luminosity useful for physics.

In practice, some care was needed to reproduce the same orbit and injection optics because of the much lower charge per bunch of the Pb beam as compared to the recent p beams. The beam position monitors had to be used in their lower dynamic range and it was necessary to transfer the reference orbit data by injecting a low intensity p beam before the species switch. Since p-p physics had been done with $\beta^* = 3.5\ \mathrm{m}$ at IP2, it was not necessary to change the optics but the crossing angle had to be adjusted so that the the large angle induced by the ALICE spectrometer bump was cancelled and collisions were head-on. The vertical tertiary collimators in IR2 were then fully opened to allow the spectator neutrons to pass unimpeded from the colliding nuclei to the Zero-Degree Calorimeter (ZDC) of the ALICE experiment.

At the other two experiments, ATLAS and CMS, the crossing angles were reduced to zero.

In addition. the beam sizes, though equal in the nominal parameter lists, were not so in practice (see the section on *Emittance Growth* below). As usual, a significant fraction of the commissioning time was devoted to collimator set-up.

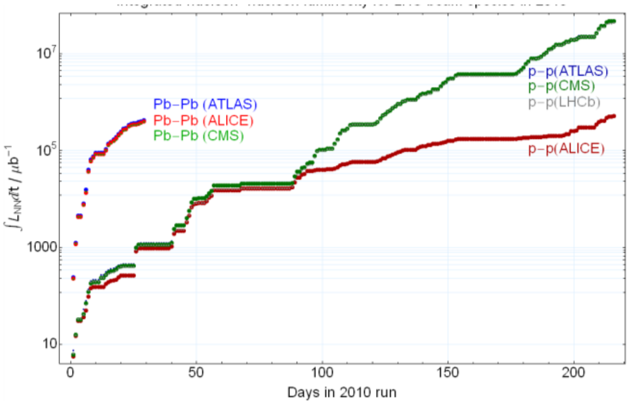

Figure 1 Integrated nucleon-nucleon luminosity ($A^2 L$, for comparison between species) in 2010 as a function of days since the start of the proton and lead runs.

There were no beam- or luminosity-induced quenches so far.

Overall, the strategy of scheduling the heavy-ion run just before the end-of-year stop, with a magnetic configuration kept as close as possible to the one used in the preceding p-p operation, seems to be a good one. It sets the pattern for future years.

Performance of Injectors

The injectors performed very well in the "Early Scheme" mode [3]. Indeed, despite the fact that the source was providing only 50% or less of design intensity, the Early mode of operation of the injector chain, without the bunch-splitting in the PS, was able to deliver bunch intensities about 70% beyond design. This was also thanks to very efficient transfer between the accelerators in the chain.

For the last fill of the year, 17 batches of 8 bunches were injected into each LHC ring from the SPS. Despite a shorted intermediate electrode in the source and thanks to the double injection into LEIR, the single bunch intensity was then 1.15×10^{8} ions/bunch, some 64% above design. The normalised emittances at injection were

$$\varepsilon_{xn} = 0.5\ \mu\text{m},\quad \varepsilon_{yn} = 1.1\ \mu\text{m} \tag{1}$$

substantially less than the design value of $\varepsilon_{xn} = \varepsilon_{yn} = 1.4\ \mu$m [3]; see also Figure **2**.

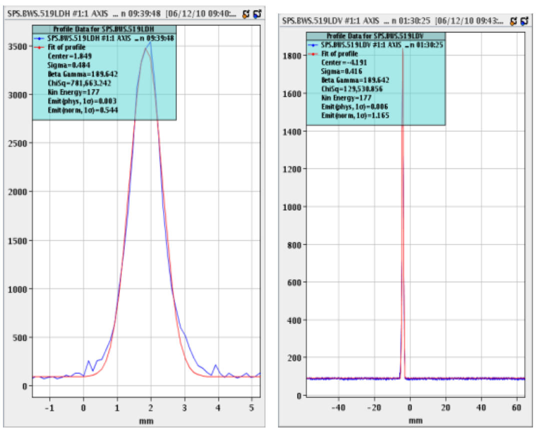

Figure 2 Wire scanner measurement of the injected Pb emittance on the last fill of 2010.

While peak performance was reached quickly, luminosity accumulation was interrupted twice for source refills. The first of these was expected (about 3 weeks uninterrupted operation expected between refills) scheduled, but grew into 5 days of "parasitic" electron cloud studies with proton beams. The second source refill had to be done unexpectedly near the end of the run. Unfortunately it turned out that it extended another interruption for cryogenics. To avoid such delays in future, it has been decided to refill the source whenever there is any kind of stop expected to last more than 24 h or so.

Beam instrumentation

In the past, concerns were often expressed that the commissioning of Pb ion beams would be slow and difficult because the initial bunch intensities would barely be visible on the beam position monitors (BPMs). This was not the case because the BPMs performed well and the injectors were able to deliver the design bunch intensities immediately. In the event, we never once had to dump beams because they fell below the threshold of visibility on the BPMs.

Emittance measurements were certainly more difficult than for protons. To avoid the risk of quenches, the wire scanners, considered to provide the best absolute calibration, could only be used at injection energy and low intensity (a few bunches).

The BSRT (synchrotron light monitors) provided the world's first image using synchrotron light from nuclei. On the first occasion, this appeared on the screens at around 1 Z TeV but was later just visible at injection. The bunch-by-bunch capability of this device was important in revealing the differences in IBS growth rates according to individual bunch intensity. However the calibration and point-image corrections to be applied to the measurements leads to some uncertainty in absolute calibration.

The beam-gas ionisation monitors (BGI) were originally expected to be the main source of emittance data for Pb beams. They appear to provide a good continuous relative measurement but again absolute calibration is difficult and certainly changed a number of times during the ion run.

We are presently analysing the data, comparing the recommended calibrations of the instruments and attempting to achieve a consistent picture of the transverse and longitudinal emittance growth in correspondence with our simulations.

Vacuum

During the run, pressures were recovering all around the ring (following the run with protons) and the only pressure rise observed with ions were in the injections at the TDI and linked to losses [13].

Emittance growth and de-bunching

Bunch-lengthening, emittance growth (longitudinal and transverse) and de-bunching (loss of ions from the RF buckets) from intra-beam scattering (IBS) at injection were significant, as expected [4]. However the higher-than-nominal single-bunch intensity increased their importance. This subject deserves a much more extensive analysis than I have time for here but let me briefly summarise the experience and our understanding of it.

Manipulations of the RF voltage were proposed to mitigate the de-bunching. The initial value of 3.5 MV, corresponding to matched injection might be expected to best preserve the initial longitudinal emittance. However a small longitudinal emittance increases the transverse IBS, leading to loss of particles from the tails. Applying the simulation described in [4] (which includes a detailed model of IBS, going beyond the usual calculation of the emittance growth rate for a Gaussian distribution), we find results like those shown in

Figure 3. The initial mismatch blows up the longitudinal emittance and reduces the intensity loss from the transverse beam tails.

A first attempt to reduce the effects of IBS is shown in **Figure 4**. The 7 MV voltage is linearly reduced to 3.5 MV in 1 s just before injection, kept at 3.5 MV for the 3 seconds following the injection, then raised back to 7 MV in 1 s. This greatly reduced the intensity of the uncaptured beam, revealed by the difference between the DCCT (DC current monitor) and FBCT (fast current monitor for individual bunches) being suddenly reduced at the start of the ramp. However, the RF modulation creates so-called ghost bunches: there is debunching at each voltage reduction followed by recapture in nearby buckets when the voltage returns to 7 MV.

Finally it was found best to maintain the voltage at a constant 7 MV, as simulated in Figure 3. The unmatched injection produced an initial increase in longitudinal emittance from filamentation which was of overall benefit in reducing losses and, to some extent, the transverse emittance growth.

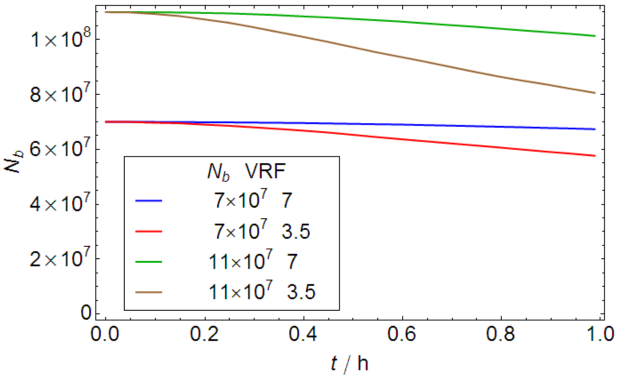

Figure 3 Simulation of the effect of doubling the RF voltage on the intensity decay of a single Pb bunch due to IBS, at nominal intensity and the higher intensity typically injected in 2010. In both cases, the higher voltage reduces the intensity decay.

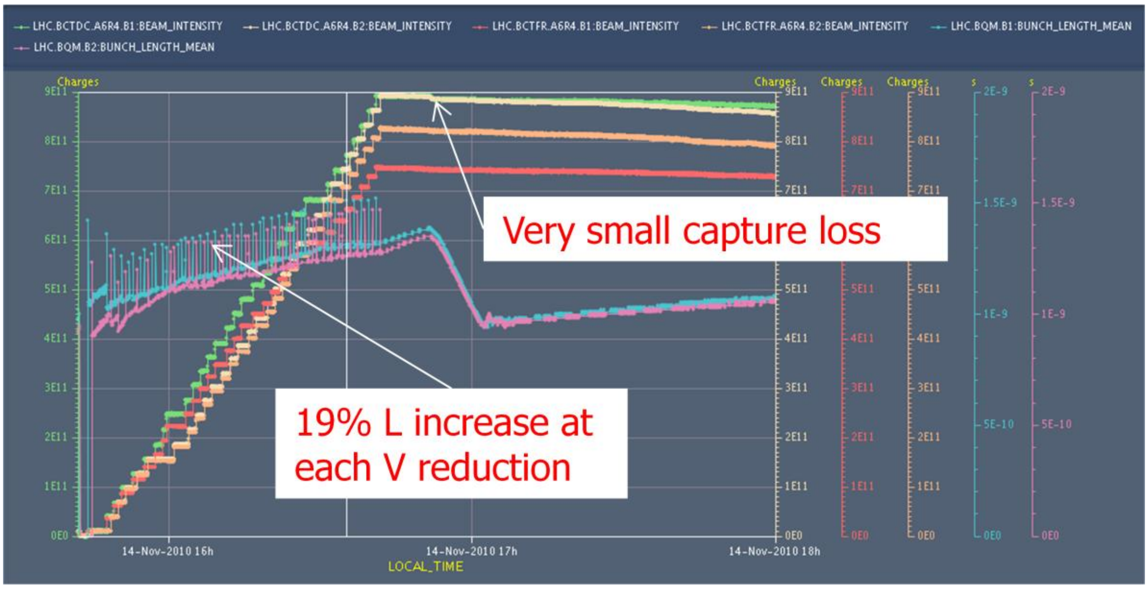

Figure 4 RF voltage manipulations and their effects. These data from the logging system in a fill (12-13 Nov 2011) show the total beam charge during accumulation and the bunch length (called L here) which jumps up at each voltage reduction for injection. The capture losses at the beginning of the subsequent ramp were reduced as compared to injection with the constant $V_{RF} = 3.5$ MV . The bunch length is reduced adiabatically in the ramp before starting to grow again by IBS at top energy.

Comparing simulations to the logged data is complicated by the fact that the injection process took about an hour. The bunches injected first have much more time to grow by IBS. We can see this in the individual bunch lengths. However at injection we can only measure averages of the transverse emittance so we can only try to use the simulation of a single bunch evolution as a "Green function" to fold together with the logged intensity history to predict it (the BSRTs do not work at injection for Pb beams). And there are the calibration questions and threshold intensities for operation of the BGI, maximum allowed intensities for the very few wire scans, etc.

Figure 5 shows an example of an attempt to simulate the emittance evolution during injection. The BGI provides the only continuous data on the emittances and is calibrated in this case using fits to the longitudinal IBS growth rate. This gives initial transverse emittances consistent with those estimated by other means. Note that the raw data is also smoothed using moving averages. The BGI data only appears when the intensity reaches a threshold. While the example mainly serves to illustrate the difficulty of the procedure, it also seems clear that there is an emittance growth effect beyond those (mainly IBS) included in the simulation. This is, presumably, the so-called "hump" [14] and is particularly strong in the vertical plane.

Work continues to improve these results and we hope also to apply the technique to protons.

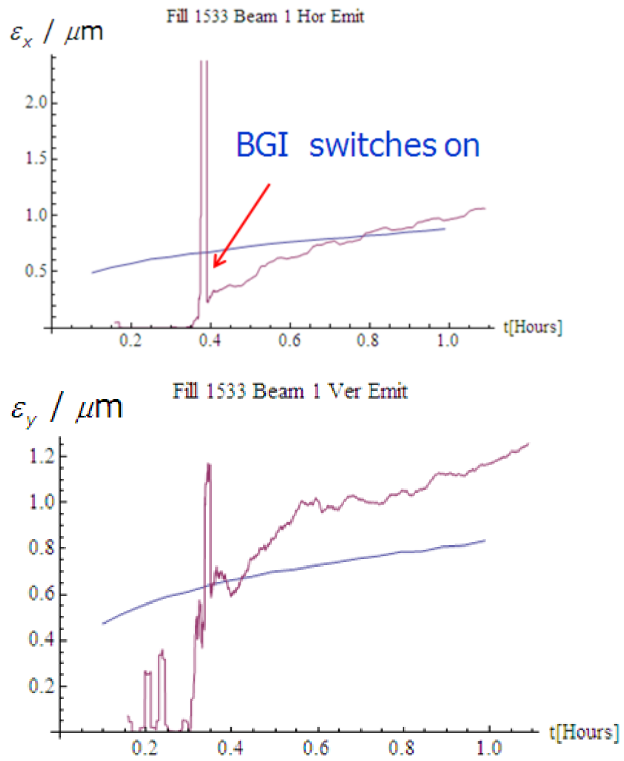

Figure 5 Simulation (blue) vs BGI data (purple) on transverse emittances at injection.

Beam losses

Beam losses have been a major focus of the studies of heavy ion beams for several years and will be discussed in more detail elsewhere.

Generally speaking the measured collimation loss maps corresponded quite well to what was expected [17,6] although some so-far-unidentified peaks have been seen in the loss maps measured during collimation set-up, particularly for the case of momentum cleaning.

Note that for ion beams, we expect the loss distribution in physics to contain peaks corresponding to the products ultraperipheral interactions such as bound-free pair production (BFPP) [16,7]. The analysis of these losses is not yet complete but will be important in estimating the ultimate luminosity reach until "cryo-collimators" are installed around experimental IPs.

Figure 6 is an example of a passive loss map measured in the highest luminosity conditions with an interpretation of the various measured peaks. Note, in particular, that the BFPP peaks occur exactly in the predicted locations and their intensity is very well correlated with luminosity.

Global cleaning with Pb beams

Following the same approach and notations as for protons at the Evian workshop [15], an analysis has been carried out for qualification measurements on 7-8/11/2010 at 3.5 Z TeV physics conditions. The highest global leakage into the cold aperture was found for Beam 2 in the vertical plane but the other planes are comparable.

$$\frac{\sum L_{\mathrm{coll}}}{\sum L_{\mathrm{all}}} = 0.948 \tag{2}$$

$$\frac{\sum L_{\mathrm{coll}} + \sum L_{\mathrm{warm}}}{\sum L_{\mathrm{all}}} = 0.981 \tag{3}$$

$$\frac{\sum L_{\mathrm{cold}}}{\sum L_{\mathrm{all}}} = 0.0186 \tag{4}$$

An overview of the leakage into specific regions is given in Table 1 [15].

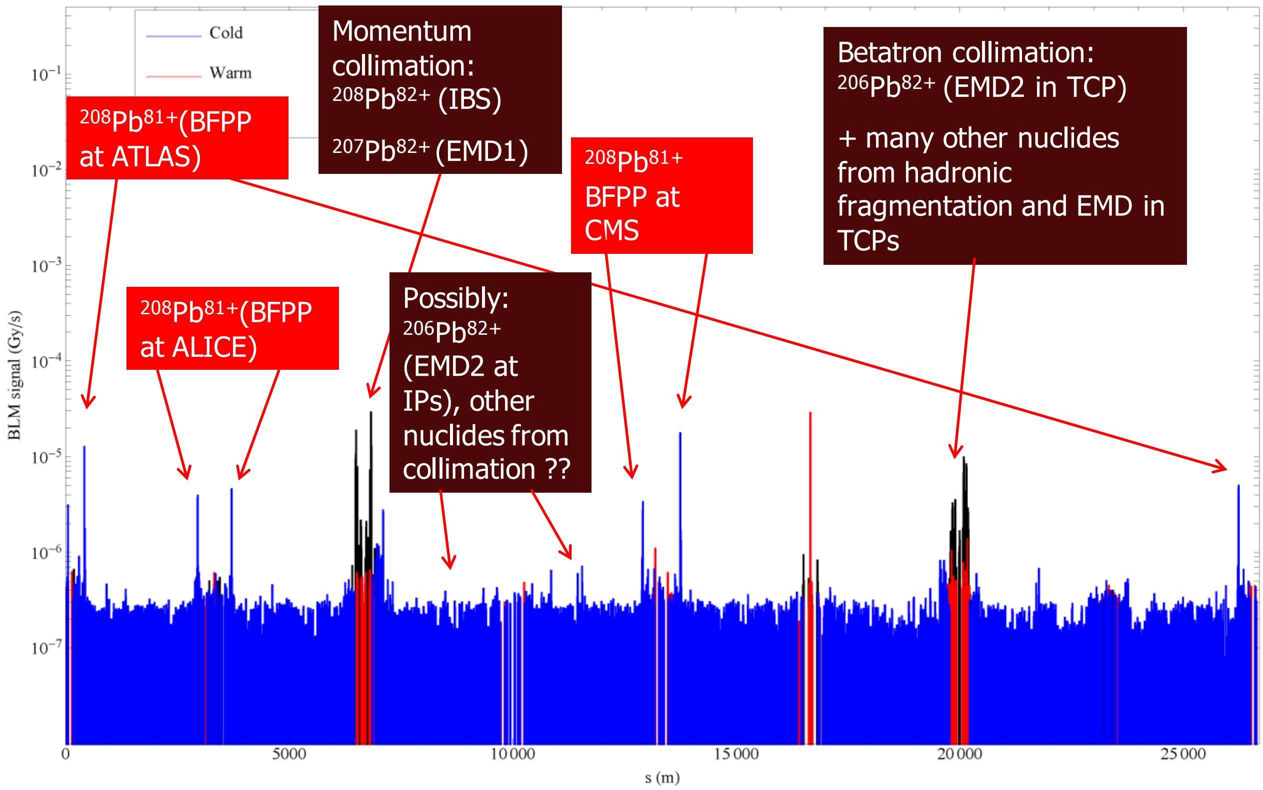

Figure 6 Global view of losses with Pb-Pb stable beams, in the last fill of the year which provided record luminosity. The identification of the loss peaks is done according to long-standing expectations. It is of course not possible to identify the lost isotopes from the BLM data.

Intensity limit from collimation

We can derive a first estimate of the ultimate intensity limit for Pb beams

$$N_{\rm tot}^{q} = \frac{\tau_{\rm min} R_q}{\eta_{\rm corr}} c_{\rm BLM}\, c_{\rm FLUKA} \qquad (5)$$

It was assumed that the measured cleaning inefficiency is diluted over the length of one metre, i.e. $\eta_{\rm corr} = \eta_{\rm meas} / (1\,{\rm m})$. As the BLM response for the same losses is different for a collimator and a superconducting magnet the measured cleaning inefficiency had to be corrected by a factor of 0.36. This factor was achieved during an aperture measurement experiment earlier. The assumed quench limits R_q were taken from C. Bracco's thesis (see quotation in [15]). The minimum life time for steady state losses was derived from the data. Two ion runs have been analysed (with BLM integration times of 80 µs, 640 µs, 10.24 ms and 1.3 s):

- 20/11/2010, 121 bunches, $N_{\rm tot} \approx 8.3\times10^{11} / Z$
- 22/11/2010, 121 bunches, $N_{\rm tot} \approx 8.5\times10^{11} / Z$

The lowest steady state life time (1.5 h) was found in the run of the 20/11/2010 for 10.24 ms BLM integration time. Table 2 shows the parameters of the calculations for the intensity limits.

loss cases	DS	COLD	TCT
B1h	0.02	0.006	1.0e-4
B1v	0.027	0.005	0.001
B2h	0.03	0.011	8.0e-5
B2v	0.025	0.006	1.4e-4
B1+B2 pos. off momentum	0.045	8.0e-4	0.06
B1+B2 neg. off momentum	0.007	2.0e-4	0.005

Table 1 Highest leakage in local cleaning inefficiency $\eta_{\rm meas}$, of ions into specific regions (DS = dispersion suppressor, COLD= cold aperture excluding DS, TCT = tertiary collimators).

The nominal intensity is 4.1×10^{10} ions (592 bunches, $N_b \approx 7\times10^{7}$ ions per bunch), i.e. $N_{\rm tot} \approx 3.4\times10^{12} / Z$ (in terms of measured charges). Assuming the same performance and stability suggests that we are ready for nominal intensity with ions, even at 7 Z TeV/c. At

3.5 Z TeV/c the intensity can be increased by a factor 17.5 compared to the maximum achieved in 2010.

These estimates are preliminary and do not take into account a possible reduction of the collimation inefficiency between the present and future energies (a factor 2 reduction was found for protons in simulations).

	with measured proton life time	with measured ion life time
η_c [1/m]	3e-2	3e-2
BLM response	0.36	0.36
η_{corr} [1/m]	1.08e-2	1.08e-2
τ_{min} [s]	4680	5667
R_q [p/m/s] @3.5 TeV	2.4e7	-
R_q [p/m/s] @4 TeV	1.9e7	-
R_q [p/m/s] @7 TeV	7.8e6	-
BLM factor	0.33	0.33
FLUKA factor	3.5	3.5
N^q_{tot} [charges] @3.5 TeV/c	1.20e13	**1.45e13**
N^q_{tot} [ions] @3.5 TeV/c	1.47e11	1.77e11
N^q_{tot} [charges] @4 TeV/c	9.52e12	**1.152e13**
N^q_{tot} [ions] @4 TeV/c	1.16e11	1.4e11
N^q_{tot} [charges] @7 TeV/c	3.9e12	**4.73e12**
N^q_{tot} [ions] @7 TeV/c	4.76e10	5.76e10

Table 2 Overview of measured parameters for Pb ions and the results of calculating the total intensity limit. For this analysis the lowest life time of the proton runs and the lowest life time of the 2 analyzed ion runs was used. For protons this fill took place on 26/10/2010 and had 368 bunches per beam with 150 ns bunch spacing. For ions the fill was on 20/11/2010 with 121 bunches per beam and 500 ns bunch spacing.

THE 2011 LEAD-LEAD RUN

Some of the physics conditions, such as the β* values, will be determined by what is already in place for p-p. All details will be finalised by the time of the run, taking account of the experience gained with protons.

Orbits and optics

As for protons, we assume $\beta^* = 1.5\,\mathrm{m}$ which will already be implemented for ATLAS and CMS. Since p-p running in 2011 will be done with $\beta^* = 10\,\mathrm{m}$ in ALICE, some additional commissioning time, about 2 days, will be needed to implement this additional squeeze. If lower values have been implemented, we will of course take them over.

As in 2010, it is highly desirable to operate with the smallest possible crossing angle in ALICE to avoid problems for the ZDC due to the present location of the TCTVs. This point is further illustrated in the slides of this talk

We will likely also reduce crossing angles for ATLAS and CMS as this was done quickly in 2010.

The TCTVBs should be kept fully open in IR2. This caused on problems in 2010. At present we are awaiting the green light from Machine Protection to do this at higher intensity.

Filling scheme

We are considering two types of filling scheme, based either on the Nominal (100 ns bunch spacing, about 540 bunches, reduced from the 592 of [3] by the present abort gap keeper restriction) or a variation of the Early beam (called Intermediate, 200 ns spacing, about 340 bunches) in the injectors. The choice will depend on the bunch intensity that can be achieved. We expect up to 70% higher values with the Intermediate scheme for several reasons.

With the Intermediate scheme, there will be two bunches spaced at 200 ns in the PS but no splitting, a configuration that can be set up rather quickly. One would then inject up to 15 times into the SPS. Work on the injection kicker should allow us to achieve a constant spacing of 200 ns [20] (this improvement is potentially of interest for the Nominal scheme as well). Batches of up to 30 bunches can then be sent to the LHC.

In either of the currently envisage schemes, it should be possible to obtain

$$
\begin{gathered}
L = 1 - 1.4\times 10^{26}\ \mathrm{cm^{-2}s^{-1}} \\
\text{Integrated luminosity 30-50}\ \mu\mathrm{b}^{-1}
\end{gathered}
\tag{6}
$$

in the 2011 run, with the number of days presently foreseen, and there are some prospects for doing better.

Nonetheless we should always remember that a short run is very sensitive to time lost for whatever reason (MDs, down time, …).

Luminosity evolution from simulation

The choice of filling scheme also depends on how the luminosity evolves during a fill.

Figure 7 shows some predictions based on the simulation program described in [4]. There are 4 different combinations of initial bunch intensity and emittance as indicated in the captions. The higher intensities correspond to a bunch number $k_b = 340$ and the lower to $k_b = 540$. The lower initial emittances are more likely obtained with lower bunch intensity of course.

The three plots show the bunch intensity, transverse emittance and the resulting luminosity. The emittance is growing due to IBS but no "hump" effect is included in the present simulation. The further two plots show in Figure 9 are two components of the losses, first that from de-bunching, ie, particles being lost from the tails or the RF bucket due to IBS effects, second that from luminosity burn-off due to the extremely large electromagnetic cross sections (we have calculated values appropriate to the beam energy of 4 Z TeV, a value still envisaged at the time this talk was given). Initially the luminosity losses dominate but as time goes on, the IBS losses take over.

Simulations like this can predict the integrated luminosity and will be used to decide between the filling schemes. The experiments have indicated that either scheme would be acceptable.

At present, the choice is essentially between the two cases shown as blue and brown curves and the choice is not clear. Further studies and the performance of the injectors should make the choice clearer in the coming months.

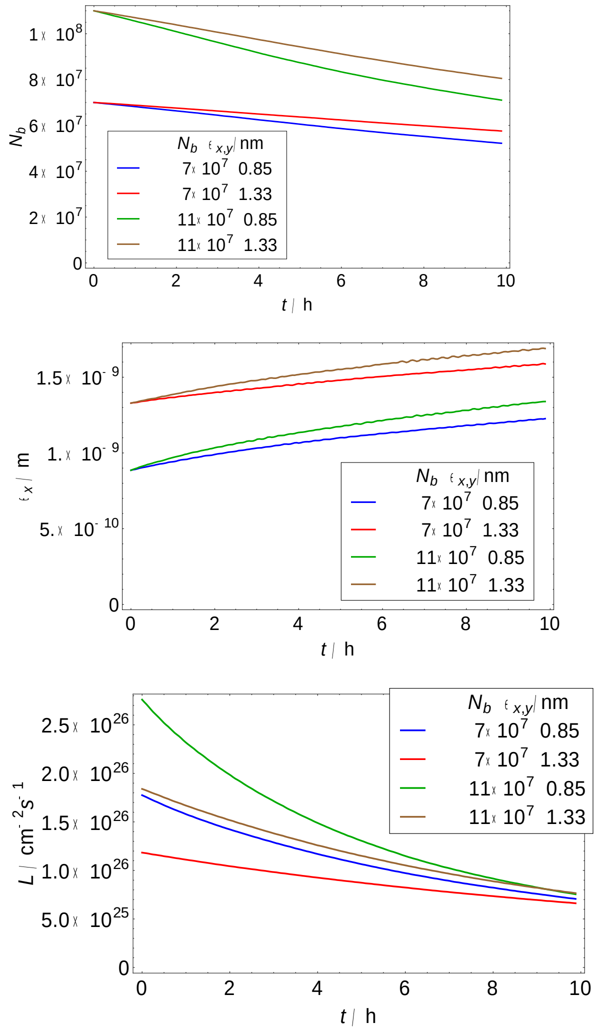

Figure 7 Simulation of luminosity evolution for various combinations of initial emittance and intensity in 2011.

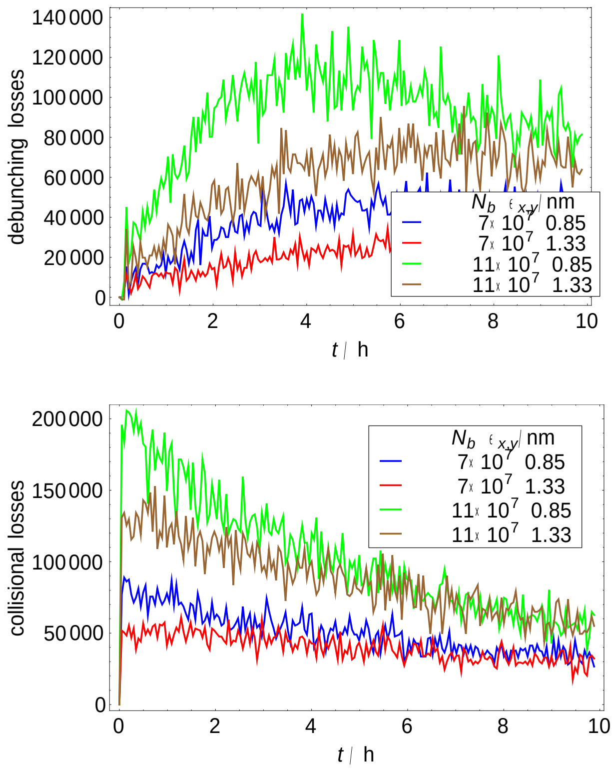

Figure 8 Losses of different physical origins (debunching and luminosity) from the same simulation as Figure 9.

THE 2012 X-LEAD RUN

The ALICE experiment has asked us to consider two possibilities for the 2012 run.

Pb-Pb collisions

The obvious possibility is to continue to accumulate luminosity since we will still be far short of the initial goal of 1 nb^{-1}. Since the beam energy is unlikely to increase (much) in 2012 there are, at present, no obvious ways to provide a significant increase in peak luminosity over 2011. However this should certainly be reviewed after the 2011 run and there is little point in discussing it further today.

p-Pb (and Pb-p) collisions

We might also consider a first attempt at providing hybrid collisions of protons with lead nuclei. Although this mode of operation of the LHC was not mentioned in [3], a first workshop was held a few years ago [9], an executive summary of the accelerator aspects was approved for inclusion in a report describing the physics case and experiments' performance [10] and a short paper was published [11].

Thanks to this preliminary work, many aspects of p-Pb operation are already clear:

- We have a clear prescription for operating the injectors: how to construct a proton beam with a 100 ns filling scheme to match that of the Pb beam (there are some concerns because of the lack of spare 80 MHz cavities in the PS).

- We have an outline of the operational cycle of LHC when operated with two beams of different mass.
- We know that no significant changes of the LHC hardware are required. In particular, the RF systems of the two rings can be operated at different frequencies during the injection and ramp. With a small upgrade to the low-level RF (to be made in 2012), it will become possible to equalise the frequencies at top energy and "cog" the beams so that collisions take place at the proper interaction points. At that point the central momentum shifts required will be [9,11]

$$\delta_{\rm p} = -\delta_{\rm Pb} = \frac{c^2 \gamma_T{}^2}{4 p_{\rm p}^2} \left(\frac{m_{\rm Pb}^2}{Z_{\rm Pb}^2} - m_{\rm p}^2 \right) \approx 3\times10^{-4} \quad (7)$$

at 3.5 Z TeV and the displacements of the central orbits in the arcs will be a fraction of a mm.

- The beam instrumentation is not expected to have any special difficulties.
- The BFPP problem will disappear.
- The collimation setup should be as for each beam individually.
- Although the preferred initial configuration for ALICE will be protons in Beam 1 (nucleon-nucleon centre-of-mass moving towards the spectrometer), there should be no difficult in switching beams between the rings (p-Pb to Pb-p). At [9] no preference was apparent for ATLAS and CMS.

The principal uncertainty related to this mode of operation is whether the modulation of the long-range beam-beam effects due to the moving parasitic encounter points at injection and during the ramp can lead to intensity loss or unacceptable emittance blow-up. These effects were certainly seen at RHIC in early attempts to accelerate deuteron and gold beams with equal magnetic field in the two rings [9]. However the magnitudes of the modulated beam-beam kicks and "tune-shifts" will be small at the LHC [9,11] thanks to the large separation and high beam rigidity. In addition, some local cancellation of the effects will occur because each Pb bunch will encounter a few p bunches at different betatron phase advances within each experimental straight section where the two beams can interact.

Note also that the present tentative parameter list [9,11] provides an acceptable luminosity at 7 Z TeV with only 10% of the nominal proton bunch intensity against the Nominal Pb beam.

Nevertheless, at present, a good quantitative understanding of these effects is lacking and we cannot consider the feasibility of the p-Pb mode as established.

For this reason, further studies are essential. An *experimental test* could be envisaged around the start-up of the 2011 ion run, when *both beam species are available* from the injectors. There is unlikely to be time prepare the 100 ns proton beam in the injectors but a test of injection of one or a few Pb bunches against one of the available proton beams (say, a 75 ns beam), followed by a ramp with the appropriate independent frequencies for the two beams, should be sufficient to demonstrate feasibility. If difficulties were encountered it would give us some opportunity to try mitigation strategies with present hardware.

Whatever the outcome, the information obtained would clear up the uncertainties and allow better planning for the future. This proposed experiment needs to be planned in detail but should not cost too much beam time.

A further reason for scheduling a p-Pb run in 2012 is that the centre-of-mass energy per colliding nucleon pair

$$\sqrt{s_{NN}} \approx 2E_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}} \quad (8)$$

at the present proton energy, $E_p = 3.5\,\text{TeV}$, would be close to that obtained in later Pb-Pb collisions, and may be useful as comparison data, as shown in Figure 9.

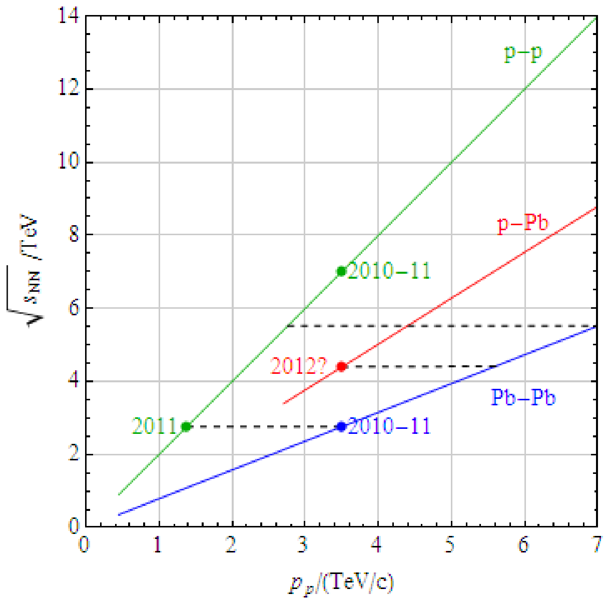

Figure 9 Nucleon-nucleon centre-of-mass energy, given by (8), for different combinations of beam species, shown as a function of the equivalent proton momentum, throughout the operating range of the LHC. The horizontal dashed lines indicate some possible correspondences of $\sqrt{s_{NN}}$ between runs of different species. These include p-Pb collisions in 2012 and Pb-Pb at a later, higher energy and the so-called "intermediate energy" p-p run requested for early this year. Note the lower limit for p-Pb collisions, as derived in [9,11].

CRITICAL UPGRADES

The following upgrades are important for the heavy-ion programme:

LLRF

For the p-Pb collision mode, as mentioned above, a small upgrade to the low-level RF will be necessary to equalise the revolution frequencies of the two beams and move the collision points to their proper positions. This will be available in 2012.

TCTVs in IR2

As discussed above, the present installation of vertical tertiary collimators (TCTVBs) in IR2 needs to be replaced to avoid interference with an essential physics signal, the spectator neutrons on the ZDCs. This involves moving the recombination chambers towards the IP and installing new TCTVs behind the ZDCs [12].

DS collimators in IR2

With our present knowledge of the performance limits, the most important upgrade would be to install dispersion suppressor collimators around IR2 to raise the peak luminosity limit (from BFPP) for ALICE. This modification is comparable to that discussed for IR3 [5] although only half as many "cryo-collimators" need to be installed.

DS collimators in IR3

This installation has been discussed in detail for protons [5] but is expected to also be very effective in raising the intensity limit due to collimation inefficiency for ion beams. Simulations of the effect of DS collimators in IR7 [6] strongly suggest that the IR3 DS collimators will be beneficial in raising the intensity of Pb beams. However simulations of the proposed combined betatron and momentum collimation in IR3 for ion beams have still to be carried out.

DS collimators in IR7

In the event that combined betatron-momentum collimation in IR3 is insufficient, it may also be necessary to install such collimators in IR7.

Note that a preliminary study of the collimation of Ar^{40+} beams [6] suggested that this might be the most demanding collimation scenario out of all beam species (including high-intensity protons) envisaged for the LHC. However almost no resources have yet been devoted to studies of light ion beams in the LHC and it is not yet possible to make meaningful estimates of beam parameters or performance.

CONCLUSIONS

The 2010 Pb-Pb run demonstrated that the LHC performs very well as a heavy-ion collider, producing physics results at energies exceeding those available elsewhere by a factor 13. The strategy for species-switch and subsequent operation were extremely efficient in terms of use of beam time.

Nevertheless the physics of heavy nuclear beams is complex and quite different from that of protons, previewing, in some ways, what we can expect with future proton-proton luminosity and energy upgrades. We now have a substantial amount of data which, when further analysed, should provide much better information on the ultimate performance limits for Pb-Pb.

The so-called "hump" [14] has a significant impact on Pb-Pb performance as well as p-p. Curing it is a high priority.

A substantial factor in peak and integrated luminosity appears possible for the 2011 run. Options for filling will be clarified in discussions over the coming months and in the injector commissioning. The experiments are flexible enough to accommodate variations of the bunch spacing.

Depending on the integrated luminosity accumulated by the end of 2011 and other physics considerations, the first p-Pb collision run may be requested in 2012. Otherwise, with present planning, first experience with hybrid collisions—and the resolution of the uncertainties related to their feasibility—would not be obtained until much later. A feasibility test can and, in my opinion, should be carried out in 2011 and need not cost much beam time.

Looking further ahead, the main focus of the LHC heavy-ion programme will always be to accumulate the maximum possible luminosity in Pb-Pb collisions. At higher beam energies we can expect gains due to smaller beams, the onset of significant synchrotron radiation damping and reduced importance of IBS in physics. However other performance limits, particularly BFPP [7]—already a prominent signal on the BLMs—will come into play. The luminosity lifetime will be shorter, particularly if there are three experiments taking collisions with low values of β^*.

As with protons, certain modifications and upgrades will be critical to maintain a steady ramp-up of luminosity in the coming years.

From the point of view of the ALICE heavy-ion programme, the priority would be to install dispersion suppressor collimators (one on each side of IR2) in the 2013 shutdown (although IR3 is of higher priority for protons and also very beneficial for ions). The idea of doing *no such installation in 2013*, followed by IR3 only in 2017, could severely limit the Pb-Pb luminosity for many years to come.

Similar modifications would ultimately be required in IR1 and IR5 to raise the Pb-Pb luminosity for ATLAS and CMS.

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Risselada, F. Roncarolo, M. Sapinski, M. Solfaroli, R. Steerenberg, and W. Venturini.

REFERENCES

[1] J.M. Jowett *Ions in the LHC* in C. Carli (Ed.) Proc. Workshop on LHC Performance- Chamonix XIV-, 2 - 6 Feb 2009, CERN-ATS-2009-001 (2009).

[2] http://lhc-commissioning.web.cern.ch/lhc-commissioning/ions/IonCommissioningPlan2010.htm

[3] LHC Design Report, CERN-2004-003, Vol. I, Chapter 21 and Vol. III Part 4.

[4] R. Bruce et al, *Phys. Rev. Special Topics - Accelerators and Beams* **13,** 091001 (2010).

[5] V. Parma, this workshop.

[6] G. Bellodi et al, in the *Conceptual Design Review LHC Phase II Collimation*, CERN April 2009, http://indico.cern.ch/conferenceDisplay.py?confId=55195

[7] R. Bruce et al, , *Phys. Rev. Special Topics - Accelerators and Beams* **12,** 071002 (2009).

[8] M. Ferro-Luzzi, this workshop.

[9] Workshop on Proton-Nucleus Collisions at the LHC, CERN, 25-27 May 2005, http://ph-dep-th.web.cern.ch/ph-dep-th/content2/workshops/pAatLHC/pAworkshop2.html

[10] C. A. Salgado et al., "Proton-nucleus collisions at the LHC: Scientific opportunities and requirements", CERN Report and LHC Project Report 1181, *to be published.*

[11] J. Jowett and C. Carli, Proc. Tenth European Particle Accelerator Conference, Edinburgh, 2006, p. 550, http://accelconf.web.cern.ch/AccelConf/e06/PAPERS/MOPLS009.PDF and LHC Project Report 928.

[12] R B Appleby, J.M. Jowett, J. Uythoven, *Moving the Recombination Chambers to Replace the Tertiary Collimators in IR2,* CERN-ATS-Note-2011-014

[13] M. Jimenez, private communication.

[14] G. Arduini, *Hump: how did it impact the luminosity performance?*, Proc. of the LHC Beam Operation Workshop, 7-9 Dec. 2010 (Evian), http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=107310

[15] D. Wollmann, *Multi-turn losses and cleaning,* Evian Workshop, see [14] for reference details.

[16] J.M. Jowett et al, Proc. EPAC 2004, Lucerne, Switzerland (2004).

[17] H.H. Braun, et al, Proc. EPAC 2004, Lucerne, Switzerland (2004).

[18] R. Bruce et al, , *Phys. Rev. Special Topics - Accelerators and Beams* **12** 011001 (2009).

[19] Slides from this workshop: http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=103957

[20] E. Carlier, private communication.