HEAVY IONS IN 2012 AND THE PROGRAMME UP TO 2022

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Abstract

The 2011 lead-lead run of the LHC not only exceeded all expectations for luminosity but also yielded very valuable information on future performance limits. An additional highlight was the partial demonstration of the feasibility of proton-lead collisions, the first upgrade of the LHC. Although uncertainties still remain, this operating mode has been adopted for the 2012 heavy ion run. The implications of running at special energies choice of bunch spacing and filling scheme are discussed. An outline of the future heavy-ion programme up to 2022 (between LS1 and LS3) is given.

THE 2011 LEAD-LEAD RUN

There were many interesting developments during the 2011 Heavy Ion Run, some 4 days of setup and 24 of operation for physics, and it is impossible to give even a minimal account of them in the time available for this talk. However summaries of luminosity performance, operational efficiency and other statistics can be found in talks given yesterday [1,2].

The performance of the heavy-ion injector chain was crucially important in reaching high luminosity. The injection scheme, 15 injections of (mostly) 24-bunch batches, spaced at ≈ 200 ns, giving a total of $k_b = 358$ bunches per beam (to compared with the design value of 592 with ≈ 100 ns spacing), is discussed in more detail in [3]. This so-called "Intermediate" scheme gave higher bunch intensities, N_b, than the "Nominal" ≈ 100 ns scheme. Figure 1 shows the intensities along the bunch train in a typical fill (7 Dec 2011 07:44:32).

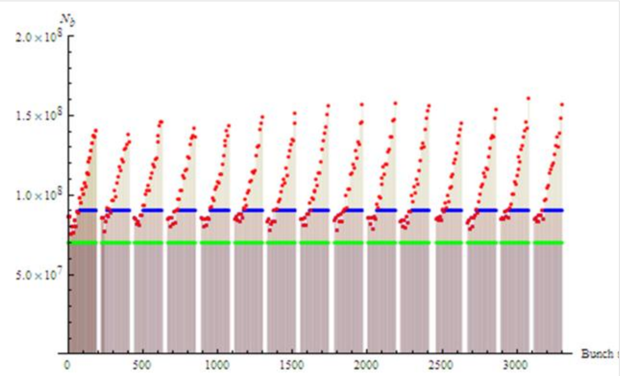

Figure 1 Bunch intensities in the LHC in fill 2351. The green points show the design single bunch intensity, the blue ones an intensity that could be regarded as constant along the bunch trains. The actual intensities are shown in red.

There is a significant spread of intensities along each train, reflecting the time spent at the injection plateau of the SPS where space-charge and intra-beam scattering (IBS) affect intensity. A similar gradation from train to train is due to the time spent at the LHC injection energy. Nevertheless, every single bunch is significantly above the design value of $N_{bo} = 7\times10^7$. Indeed, at this particular time we have

$$\begin{aligned} \min N_b &= 9.\times10^7 = 130\% \times N_{b0} \\ \sum N_b &= 4.13\times10^{10} \Rightarrow W = 1.90 \text{ MJ} \\ \langle N_b \rangle &= 1.07\times10^8 = 153\% \times N_{b0} \\ \langle N_b^2 \rangle &= 242\% \times N_{b0}^2 \end{aligned} \tag{1}$$

where W is the stored energy per beam. The mean-square value $\langle N_b^2 \rangle$ is significant as it represents the gain in luminosity with respect to nominal due to the single bunch intensities.

At the start of the run, we increased the number of bunches extremely rapidly with $k_b = 2, 8, 168, 358$ on successive fills. With hindsight, this was perhaps a little over-cautious but, as shown in Figure 2, that took us close to peak luminosity, a gain of more than an order of magnitude over 2010, within 3 days of declaring the first stable Pb-Pb beams.

Thus, for the greater part of this short, 4-week, run, the peak luminosity was $L \approx 5.\times10^{26}$ cm^{-2}s^{-1}, about half the design value for $7Z$ TeV. Allowing for the natural scaling, $L \propto E^2$, this is equivalent to *twice design luminosity*. Moreover, stepping back to compare the integrated luminosities quoted by the experiments [1], we see that we have already achieved 15-18% of the overall long-term goal of $1\,\text{nb}^{-1}$ in just 8 weeks of running in 2010-11.

IR2 optics, aperture and crossing angle

In 2010, the Pb-Pb run was made with the same values of $\beta^* = (3.5, 3.5, 3.5)$ m in the three heavy-ion experiments (ATLAS,ALICE,CMS). This facilitated commissioning of the optics as only the crossing angle configuration in ALICE had to be changed. In 2011, the preceding p-p physics had been done with $\beta^* = (1.0, 10., 1.0)$ m and a further squeeze to $\beta^* = 1.0$ m had to be added for ALICE. For technical reasons, this was set up with low-intensity proton bunches in advance of the Technical Stop. Aperture measurements found an unexpected restriction on the left of IP2 which constrained the choice of crossing angle, we had to collide at a vertical crossing angle $\theta_y = 60\ \mu\text{rad}$ instead of the $\theta_y = 0$ that had been hoped for. This was at the limit of the acceptable level of spectator neutron shadowing by the TCTV collimators that could be accepted by ALICE.

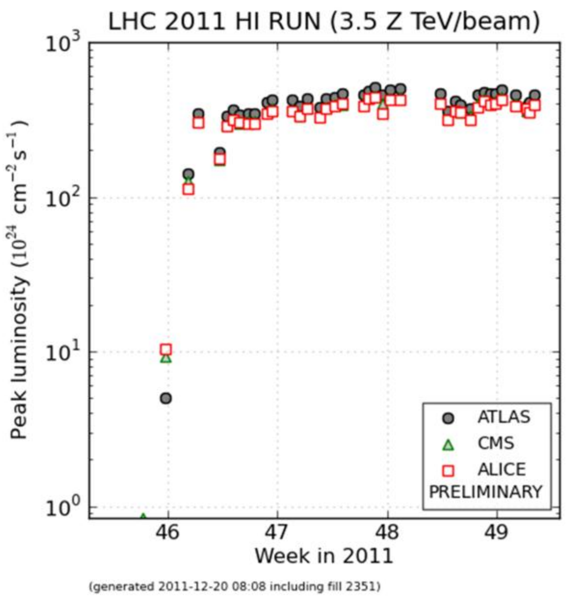

Figure 2 Evolution of peak luminosity by fill in the 2011 run as reported by the experiments [1].

Although the TCTVs will be replaced in the 2011-12 Christmas shutdown with substantial modifications to the vacuum chambers in IR2 [4], this unidentified restriction may constrain the choice of β^* for ALICE in 2012. It will be imperative to measure the available local aperture as early as possible in 2012.

Beam parameter evolution, emittances, IBS

As usual, the IBS effects for Pb beams are much stronger than for protons. Since the spread in injected intensities results in a spread of emittances, the situation is quite complex, with a spread of beam lifetimes along the bunch trains. The net result for overall performance is shown in Figure 3. The effective emittance is defined in terms of the luminosity and total beam intensities by inverting the simplest formula for luminosity as

$$\varepsilon_N = \frac{N_{tot1} N_{tot2} f_0 \gamma}{4\pi L \beta^* k_b} \qquad (2)$$

It starts at slightly above the design value of $\varepsilon_N = 1.5\ \mu\text{m}$, a reflection of the fact that the injectors are exceeding design performance in terms of emittance as well as intensity. The IBS growth during the fill, the consequent debunching losses and the luminosity "burn-off" from the collisions all contribute to the luminosity decay and determine the optimum length of a fill about 5-6 hours. The final plot showing the luminosity lifetime as derived from intensity losses (luminosity burn-off, debunching from the RF bucket, etc.) alone indicates that the emittance increase due to IBS is the dominant contributor to the luminosity decay.

Although incomplete, the wire-scanner data in Figure 4 show that the emittance blow-up from IBS is predominantly in the horizontal plane, with little coupling to the vertical. There is also a variable amount of blow-up in the ramp, particularly in the horizontal plane.

Losses during Pb-Pb collisions

The mechanisms for beam loss during heavy-ion collisions were extensively studied before the start of LHC operation because of their expected role in limiting either total beam intensity or luminosity. Data from the 2010 run was already in good accord with expectations. With the much higher luminosity in 2011, we expected the losses from collision processes such as bound-free pair production (BFPP) and electromagnetic dissociation (EMD) to be much more evident and indeed they were. Figure 6 shows a steady-state loss map during Pb-Pb collisions from the beam loss monitors with an identification of the loss peaks based on theoretical expectations.

"MD" results during the Pb-Pb run

No regular machine development (MD) time was scheduled during the heavy ion run. However some important results were obtained in brief end-of-fill MDs.

- **ALICE polarity reversal:** ALICE had requested a reversal of its spectrometer bump polarity in the middle of the run. In order to avoid setting up the ramp and squeeze again, we tested a procedure where the reversal of the external crossing angle was done after the squeeze. Although this required a passage through very small separations at parasitic beam-beam encounters, there were no ill effects on the beam. This procedure was adopted for the rest of the run and the result gives us some useful flexibility in planning future configurations .
- **BFPP mitigation:** immediately after the polarity reversal test it happened that the injectors were not available to refill for a new physics fill. We took the opportunity to test an idea for reduction of the peak energy deposition due to the BFPP losses [7] by means of orbit bumps that would spread out or reduce the incident flux of $^{208}Pb^{81+}$ ions from the BFPP process. Applied to the worst loss point, on the right of CMS, we achieved a reduction in the highest beam-loss monitor (BLM) reading by about a factor 5. Applied systematically on both sides of each experiment as part of the future setup of collision conditions, it has the potential to raise the luminosity limit from BFPP quenching when we come back with Pb-Pb colllisions in 2015.

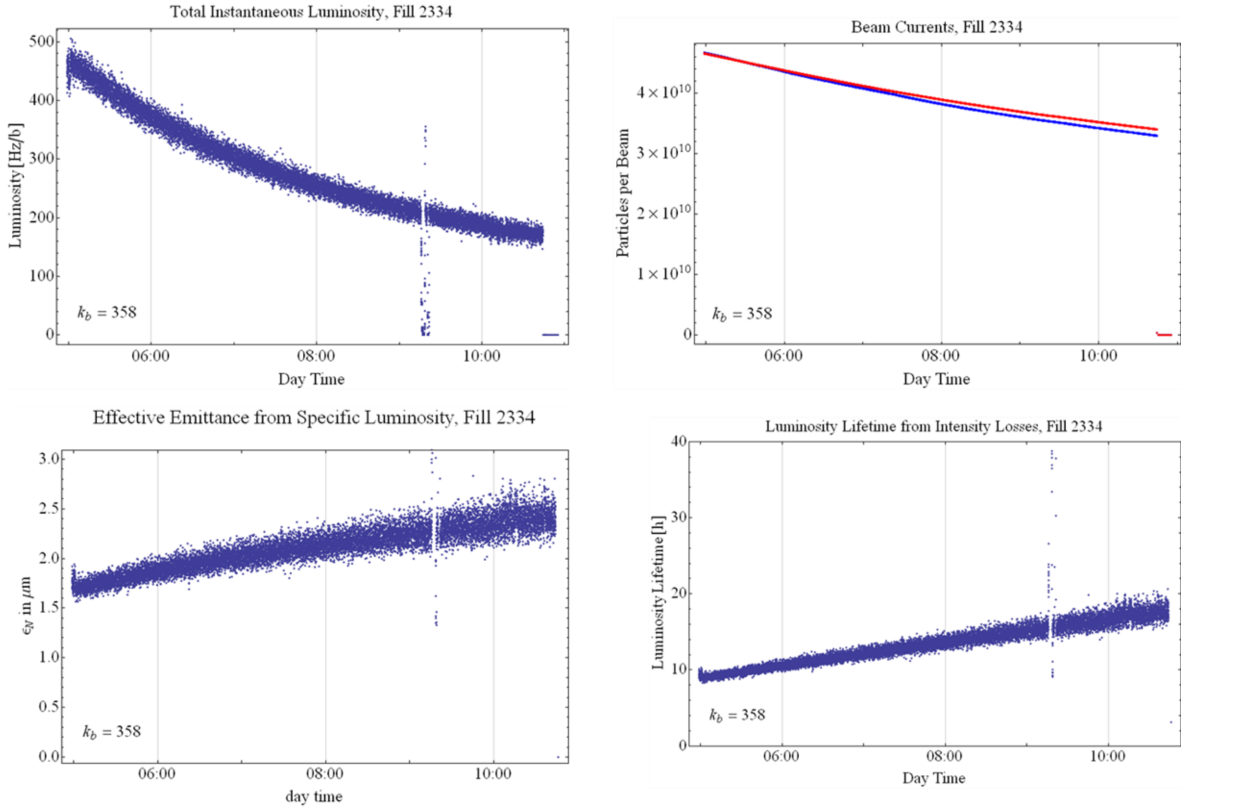

Figure 3 Evolution of the luminosity (from ATLAS), total intensities, effective emittance and luminosity lifetime in a good Pb-Pb fill in 2011. Effective emittance is defined in (2).

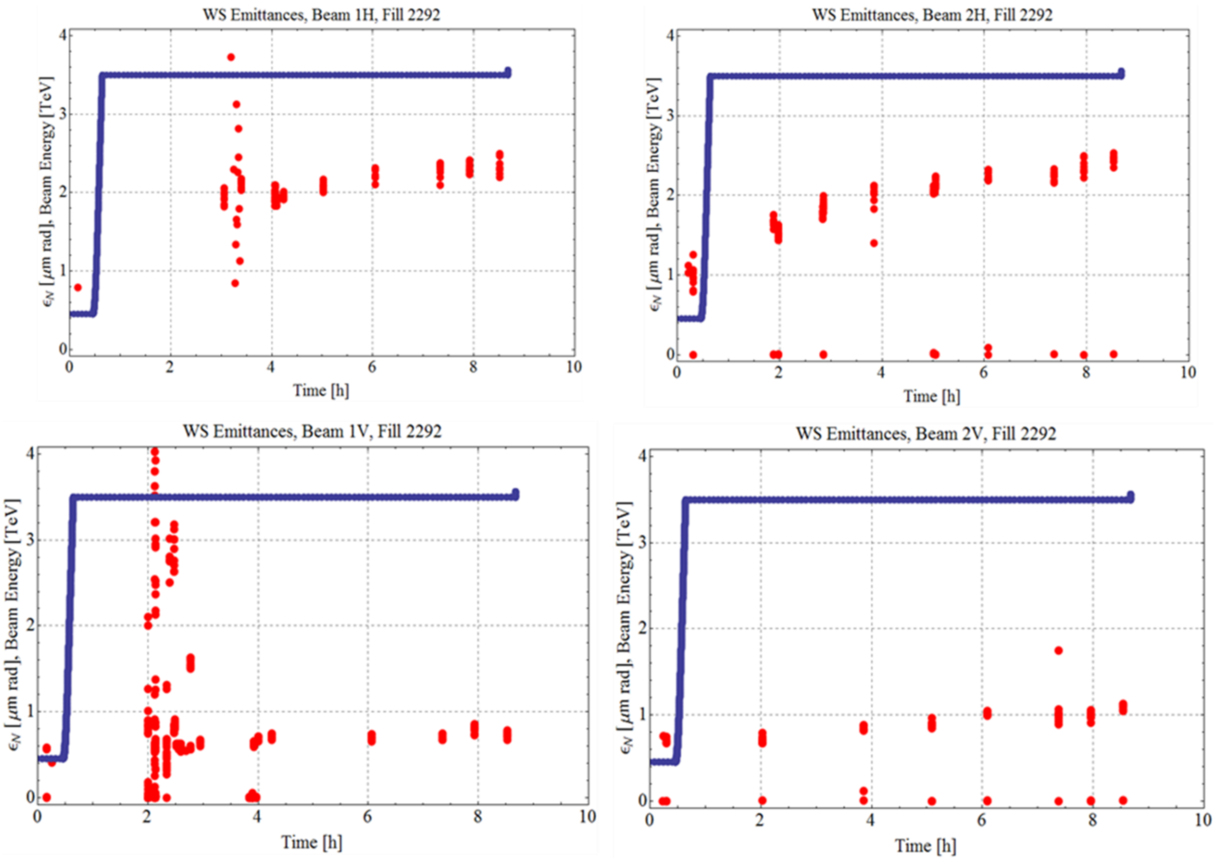

Figure 4 Emittances and energy during a fill from the wire scanner.

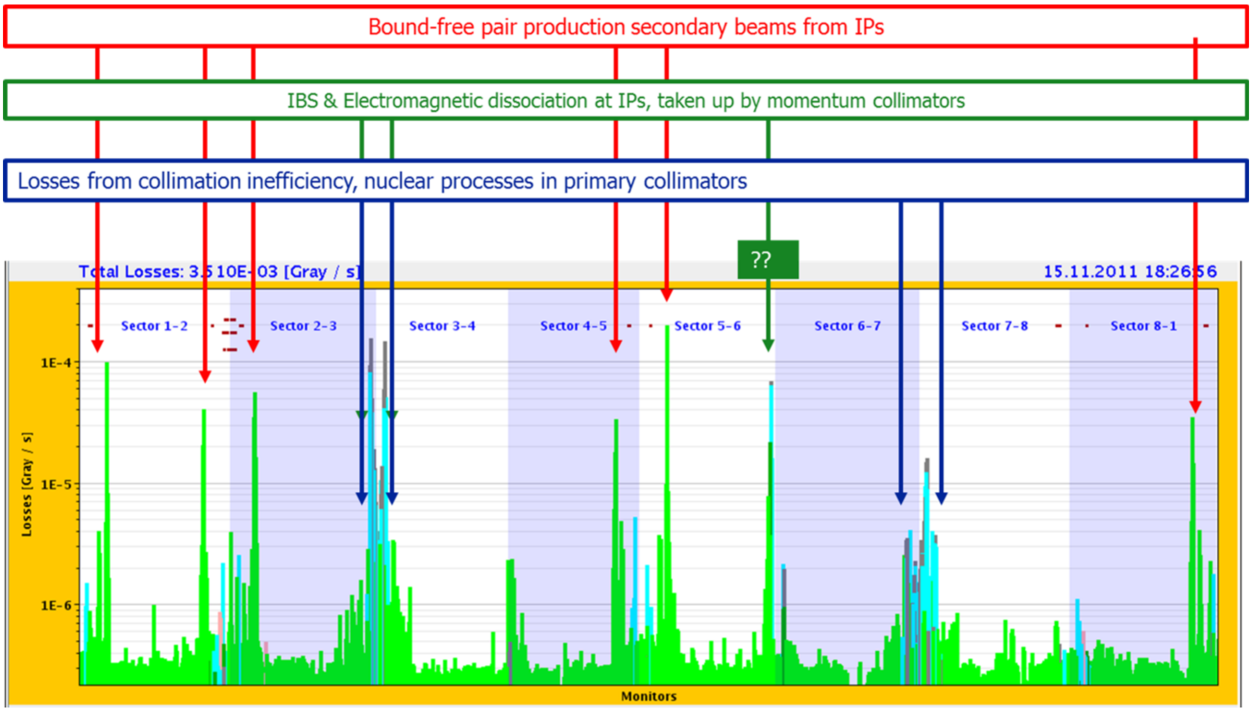

Figure 5 Interpretation of beam losses around the ring during Pb-Pb collisions with an identification of the principal loss mechanisms contributing to the major peaks.

- **Quench limit with heavy ions:** in the final days of the run we took a short time to test the limits for enhanced collimation losses in IR7. The results are discussed in some more detail in [9] and will be further documented. During this MD, Pb beam losses were provoked on the primary collimator in IR7 and were increased substantially beyond the expected quench threshold, translating into an expectation that the Pb beam intensity will not be limited by the relatively poor collimation efficiency due to the nuclear processes occurring in the collimators.

It now seems likely that we will be able to reach design luminosity. In the longer term, dispersion suppressor collimators will probably still be needed to reach luminosities beyond design and to reduce the long-term radiation damage to the magnet coils.

These encouraging results open up prospects for Pb-Pb luminosity substantially beyond design, especially if higher total intensity can be attained with shorter bunch spacings from the injectors. In 2015, the maximum luminosity in ALICE will likely be limited by capabilities of the detector.

POTENTIAL LEAD-LEAD RUN IN 2012

Although it now seems practically certain that the experiments will choose to run p-Pb in 2012, it is worthwhile considering what the alternative Pb-Pb run at $4Z$ TeV might yield. What improvements could be expected compared to the 2011 run at $3.5Z$ TeV?

First of all, it is hard to imagine a faster luminosity ramp-up or significantly better up-time for physics than we had in 2011 (Figure 3). There is no immediate prospect for higher bunch intensities with any filling scheme and the optimum would be expected to be the same 200 ns scheme that we used in 2011. Anticipating that we can achieve $\beta^* = 0.6$ m in ALICE (see discussion later) as well as ATLAS and CMS, then we can hope to gain from this as well as the reduction in geometrical emittances that comes with the increase in energy. With these assumptions, we can estimate the peak luminosity as

$$L = \frac{k_b N_b^2 f_0 \gamma}{4\pi \beta^* \varepsilon_n}$$
$$\Rightarrow L_{2012} \approx \left(\frac{4Z\ \text{TeV}}{3.5Z\ \text{TeV}}\right)\left(\frac{1.0\ \text{m}}{0.6\ \text{m}}\right) L_{2011} \qquad (3)$$
$$\approx 10^{27}\ \text{cm}^{-2}\text{s}^{-1}$$

which happens to be the design luminosity for $7Z$ TeV [11]! Allowing for faster burn-off, and similar operational efficiency in a slightly shorter run (which of course can easily fluctuate!), we estimate the potential integrated luminosity

$$\int L\,dt \approx 250\ \mu\text{b}^{-1}, \qquad (4)$$

a useful increase, but less than a factor 2, over 2011.

THE PROTON-LEAD FEASIBILITY TEST

Reminder of p-Pb status (as of August 2011)

Proton-nucleus collisions are a long-standing request of the heavy-ion physics community but were not included in the "baseline" LHC programme described in [11]. Nevertheless, the beam physics implications were first considered in a workshop in 2005 [12,13,14] and, in the meantime, we took care to ensure that no "showstoppers" were built into the design of any LHC systems. After the publication of a document describing the physics programme [14] and a request from ALICE, p-Pb collisions were recognised as part of the LHC programme at the 2011 Chamonix workshop [15].

The feasibility of this mode has been somewhat controversial since it requires beams of unequal revolution frequencies during injection and the ramp with the consequent moving long-range beam-beam encounters. RHIC abandoned equal-rigidity acceleration in early 2003, because of the resultant drastic beam losses and emittance blow-up, and switched to equal-frequency acceleration by adjusting the magnetic fields in the two rings separately. This escape route is not available to the LHC with its two-in-one magnets.

In the meantime, the beam dynamics calculations outlined in [12,13] have been extended. It is clear that with the LHC parameters, "overlap knock-out" resonances will not play a role but that the quasi-random *fluctuations,* by which the long-range beam-beam kicks deviate from their non-moving versions, may give rise to a diffusive emittance growth with a time scale on the order of an hour or so. Calculations of these effects are under way.

In view of these uncertainties, we proposed [15] a feasibility test during the 2011 heavy ion run in view of a possible physics run in 2012.

Implementation: LHC as proton-nucleus collider

In the months following last year's Chamonix workshop, work was carried out to verify compatibility of all systems and re-purpose the LHC control system for this new, more complicated, mode of operation. A number of new systems or procedures were developed. Among these, we mention:

- Machine Protection: new software interlock permit tree to avoid the injection of protons into a ring configured for ions and vice versa
- RF: New re-phasing and cogging procedure, plus FESA properties and sequencer tasks to configure each ring for the right particle type
- BI: New BPM calibration task to calibrate each beam independently according to the bunch spacing
- Sequences: the new LHC PROTON-NUCLEUS NOMINAL sequence
- Timing: the new accelerator mode, PROTON-NUCLEUS PHYSICS, and new telegram line with particle type assigned separately to each ring.
- Injection schemes: New injection schemes mixing protons and ions. The injectors prepared a new 100 ns proton beam with about 10% of the nominal proton bunch intensity to match the filling scheme of the Pb beam.
- Transverse feedback systems were already independent

As an example, Figure 6 show the new SIS permit tree for machine protection at injection. The proton/Pb conditions are applied for each ring with checks that the RF frequency is appropriate, to within 1kHz of the reference for the species. In the LHC, the particle type in the CPTY telegram must correspond; in the SPS, the user name should be correct. The injection line TT10 settings must be consistent with 26 GeV/17 GeV per nucleon. There is a current interlock on 2 dipole and 2 main quadrupole strings.

Thus, the SIS will allow injection into a given ring if the settings are consistent with ions or with protons. On top of being an efficient machine protection mechanism, it is flexible – no a priori knowledge on which ring is used for which species is necessary. It will also work to avoid injecting ions during p-p runs (and vice-versa).

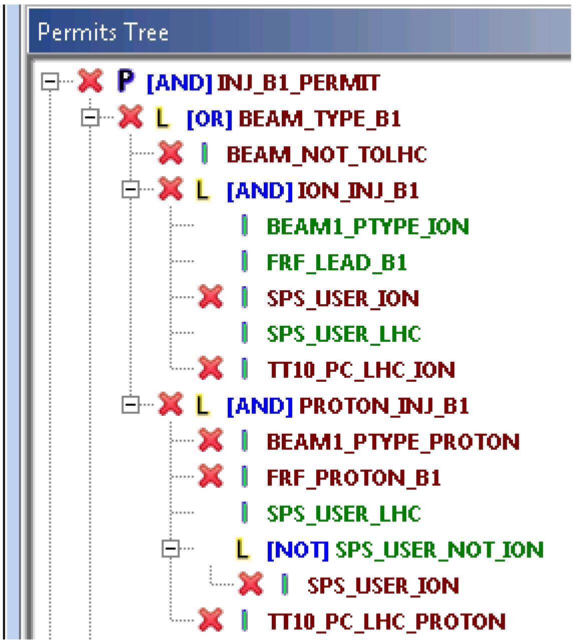

Figure 6 The new injection permit tree.

This kind of extension to more general cases often introduces useful clarifications in system design.

Injection and ramp with unequal revolution frequencies

The first 16-hour MD on proton-lead operation took place on 31 October 2011 a few days before the start of the Pb-Pb run. After some hours spent overcoming some timing problems and establishing what was the first Pb beam of the year, we were able to inject some Pb bunches as Beam 2. The lifetime of this first Pb beam was poor because the RF voltage was still at the proton setting of $V_{\mathrm{RF}} = 6\ \mathrm{MV}$ (it was later raised to $8\ \mathrm{MV}$). However we were able to inject some proton bunches as Beam 1 without degrading the lifetime further. Subsequently the situation was reveraed and we were able to inject a few Pb bunches against an existing beam of 304 p bunches, each with about 10% of nominal intensity. Because of a filling scheme error, these were not in the normal buckets and we decided not to try to correct this but rather to attempt a first ramp in the remaining time. On the first attempt, with transverse feedback adjusted for each beam, we were able to ramp 2 Pb and 2 p bunches together, for the first time, with negligible losses and a good lifetime at flat top.

RF: re-phasing and cogging procedure

At top energy $E = 3.5Z\ \mathrm{TeV}$, in the feasibility test, the beams arrived at the end of the ramp, as shown in Figure 8, with separate RF frequencies required to keep them on their respective central orbits:

$$f_{\mathrm{RF}} = \begin{cases} 400.789715\ \mathrm{MHz,\ p\ (Beam\ 1)} \\ 400.789639\ \mathrm{MHz,\ Pb\ (Beam\ 2)} \end{cases} \tag{5}$$

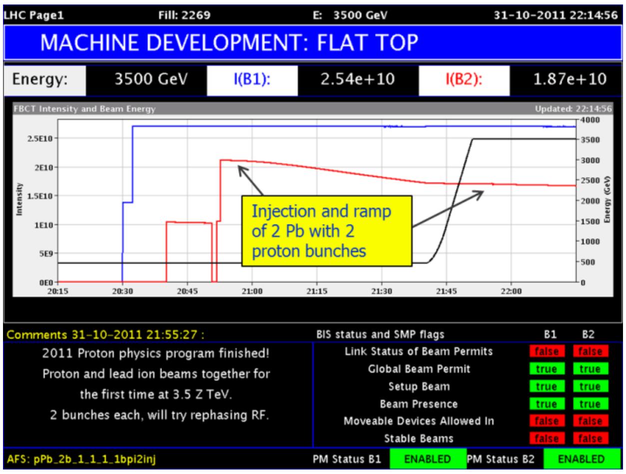

Figure 7 Historic Page 1 display showing the injection and ramp of the first hybrid beams to reach top energy in the LHC. The proton bunches have about 10% of nominal intensity while the Pb bunches have typical intensities.

Locking RF frequencies together imposes offsets of the central trajectories. We chose to get approximately the mean RF frequency, implying that the fractional rigidity offsets would be $\delta \approx \pm 3\times 10^{-4}$ for p and Pb respectively.

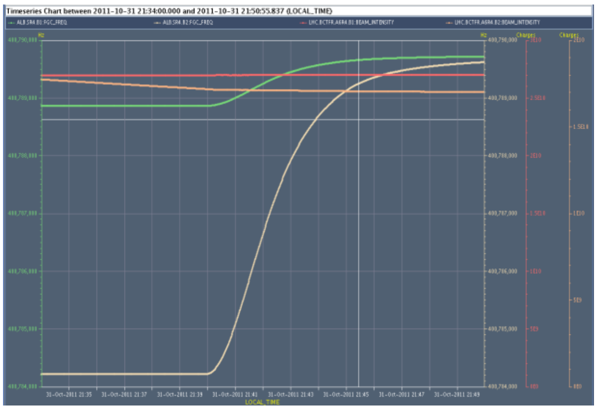

Figure 8 RF frequencies and intensities during the ramp of two different beams in the LHC.

The final common frequency was $f_{\mathrm{RF}} = 400.789685\ \mathrm{MHz}$, resulting in the Pb orbit shown in Figure 9. After locking the two RF systems together, we used the ATLAS BPTX for the cogging to restore the encounter point between Bunches 1 of each beam to its proper place at IP1. The initial shift between buckets 1 of each beam was 19 μs (~9 km). The 30 min taken for this very first cogging operation should be substantially reduced in future.

Emittance growth

The major concern arising from the RHIC experience was that the presence of another beam circulating with a different revolution frequency would blow up the transverse emittances via the effects of the moving long-rang beam-beam encounters. To test this, many wire scans of the Pb beam (Beam 2) were made during the experiment.

In this first fill with Pb beams, the RF voltage was set at a the value $V_{\mathrm{RF}} = 6\ \mathrm{MV}$, taken over from proton operation, which resulted in a rather fast emittance growth from IBS. This was later suppressed by an increase to $V_{\mathrm{RF}} = 8\ \mathrm{MV}$. However it meant that we had to look for a possible increase in growth rate due to the moving beam-beam encounters superposed on the underlying IBS rate. No such increase is evident in the data. Although there was an underlying growth of the emittance due to IBS (the low RF voltage) even in the absence of the proton beam, Figure 10 shows that it did not become any worse for the presence of the opposing proton beam. This continued to be so throughout the ramp and on flat-top where the IBS growth was much reduced.

While extremely encouraging, we stress that this is a partial result: we only had time to study the effect of many (304) proton bunches at injection energy and not in the ramp. We planned to do this in the second part of the MD scheduled during the first week of Pb-Pb operation.

The missing second half ...

On the basis of these results, the plan for the second MD, scheduled for 16-17 Nov 2011, was extended to include a first pilot physics run with moderate numbers of bunches in each beam. This would have clarified the potential of detectors in this new mode.

This would follow the critical test of ramping many p and some Pb bunches. Unfortunately, the proton injection septum in the PS developed a leak just before. Expert assessment was that continuing to run it to inject protons carried a risk of a major leak and down-time that would have jeopardised the Pb-Pb run (this could of course have happened earlier in p-p operation!).

Therefore the plan was abandoned and we have no data on ramping with the full complement of bunches in the beams.

Consequently, we are basing a physics programme with a complex new operating mode ion 2012 on the results of a single MD! The uncertainty in luminosity predictions is much greater than usual!

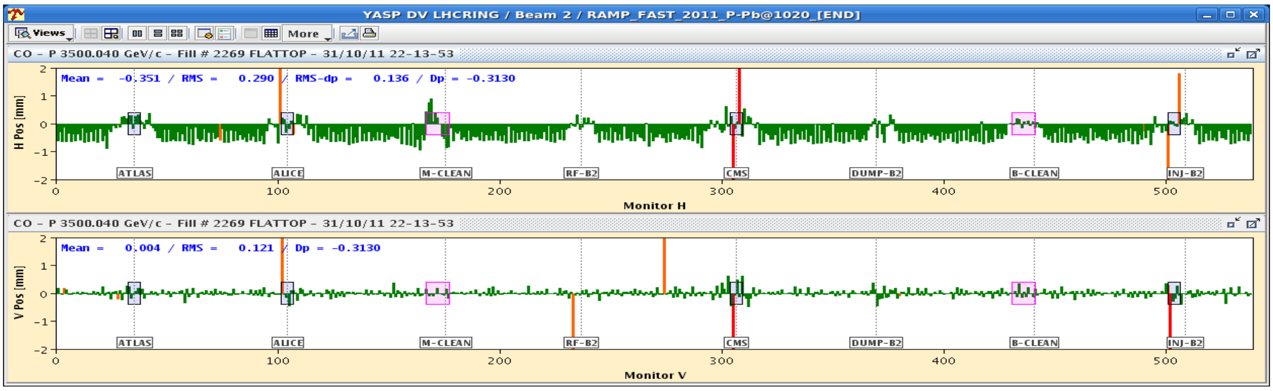

Figure 9 Closed orbit of the Pb beam after RF frequency locking.

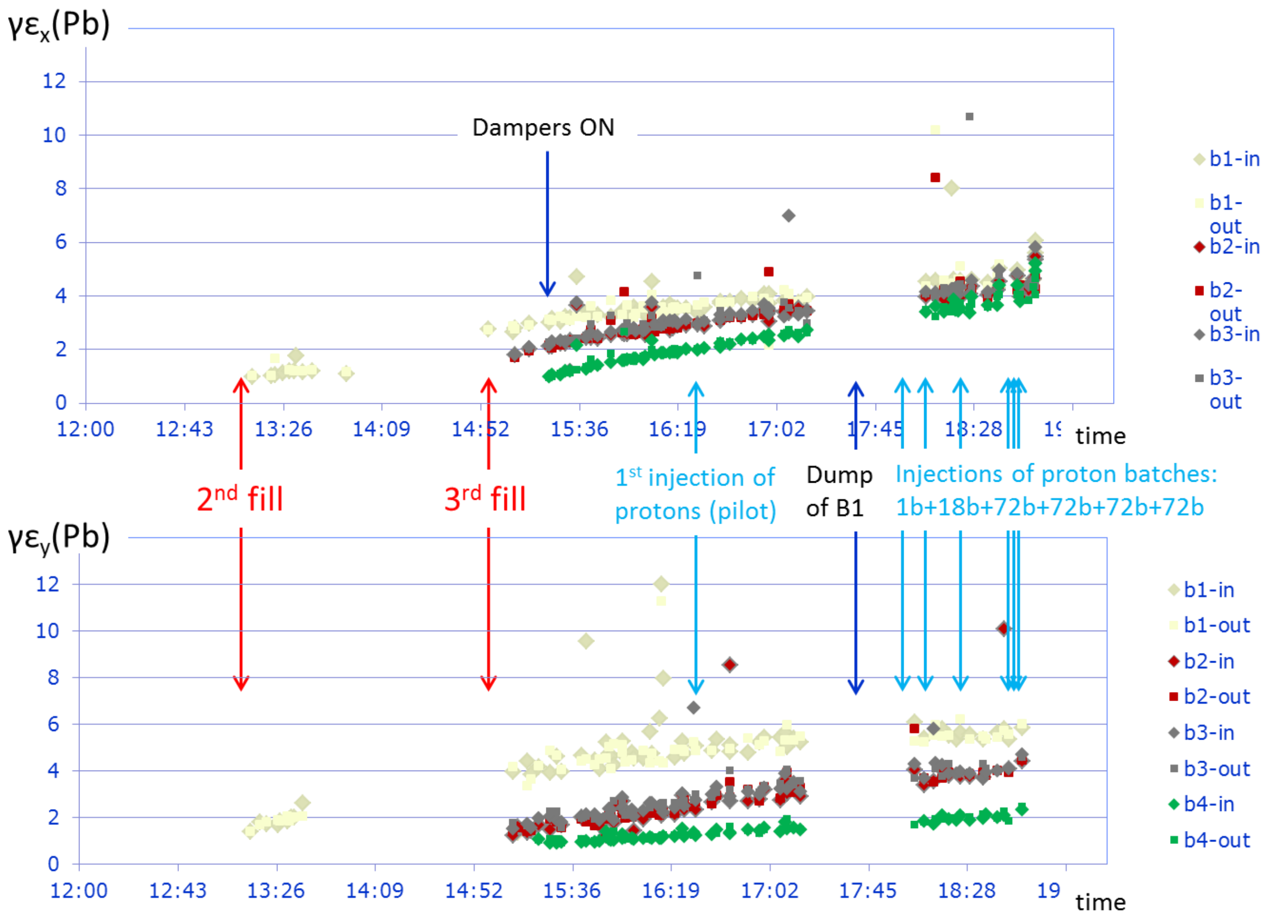

Figure 10 Wire scans showing the emittanceof the Pb beam on the 2nd and 3rd fills during the feasibility test. The notation b1,b2,b3,b4 refers to bunches of the Pb beam, Beam 2.

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Clearly there is a strong motivation to do the second part of the test as soon as Pb beams are available in 2012, perhaps in August-September. This would give both accelerator and detectors a chance to react to any surprise findings before the start of the p-Pb run

THE 2012 PROTON-LEAD RUN

The LHC schedule for 2012 foresees 4 days of setup starting after a Technical Stop on 27 October, followed by a little over 23 days of physics.

This is optimistic: even if everything goes very smoothly, it will certainly not be so fast to setup as the previous two Pb-Pb runs. For example, there will be additional optics correction and collimator setup phases to take account of the off-momentum optics as well as the squeeze of IR2. As usual, the commissioning plan will be defined carefully on the basis of experience in p-p operation.

Choice of operating energy for p-Pb in 2012

When particles of charge Z_1, Z_2 and nucleon numbers A_1, A_2 circulating in rings with magnetic field set for protons of momentum p_p collide, the centre-of-mass energy and rapidity of colliding nucleon pairs is

$$\sqrt{s_{NN}} \approx 2c\, p_p \sqrt{\frac{Z_1 Z_2}{A_1 A_2}}, \quad y_{NN} = \frac{1}{2}\log\frac{Z_1 A_2}{A_1 Z_2} \qquad (6)$$

Figure 11 shows the range values of $\sqrt{s_{NN}}$ accessible to the LHC in p-p,p-Pb and Pb-Pb collisions with the values achieved to date and those in prospect.

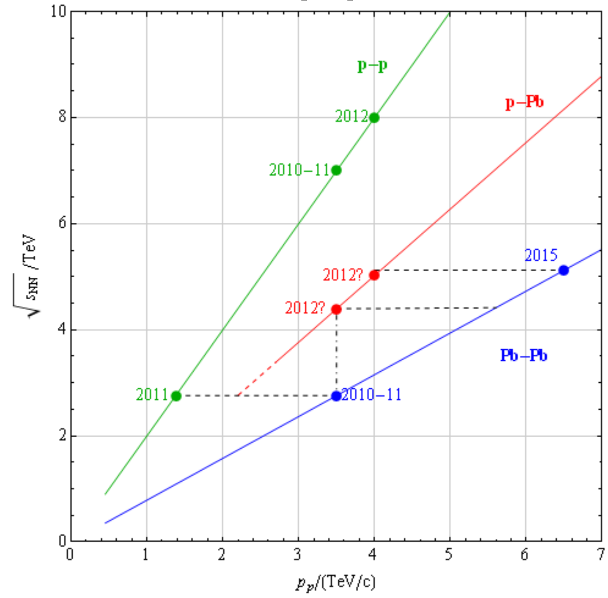

Figure 11 Centre-of-mass energy of colliding nucleon pairs as a function of proton beam momentum for the various beam species that the LHC has accelerated.

While 2.2*Z* TeV would provide the same $\sqrt{s_{NN}}$ as in the 2010 and 2011 Pb-Pb runs, it would cost a factor ~6-7 in integrated luminosity and exceed the 1 mm orbit limit in physics in the arcs. Clearly 4 Z TeV would be easiest from the accelerator point of view

The preferences of the experiments have been given in [16]: some have expressed a preference to return to 3.5 Z TeV. It does not seem that we can finalise the choice of energy this week, nor is it necessary.

Costs of experimental choices

The time available for heavy-ion operation is limited and a few days of additional set-up can have a significant impact on the integrated luminosity especially if we are unlucky with unscheduled interruptions. As usual, we must consider very carefully the time needed to set up the various required experimental conditions and arrange the transitions between them in the optimum way. Some of the important considerations are:

- If the p-p run is done at 4 TeV, we estimate an extra 2 days commissioning to set up p-Pb at 3.5Z TeV. After a maximum of offline advance preparation to adapt the settings, it will still be necessary to re-commission the squeeze in all IRs. In any case, a new squeeze of ALICE will have to be commissioned with proton beams as part of the setup if it cannot be done earlier.
- The β* will be higher for aperture reasons at the lower energy. There will be somewhat larger off-momentum orbits and associated chromatic effects.
- The switch of the beams, from p-Pb to Pb-p that is also requested will cost about 1 day of setup time, again including some collimator re-adjustments.
- ALICE polarity reversals, for each of p-Pb and Pb-p (if requested) would total <1 day.
- The crossing angle and separation in IR2 are related to choice of bunch spacing: in 2011 the choice for maximum Pb-Pb luminosity was clearly 200 ns because of the gain with the square of the single bunch intensities. In p-Pb, the gain is only with the first power of Pb bunch intensity so this choice must be reconsidered. We will return to this question in the late summer when the potential performance of the injectors is clearer.

Operating the LHC off-momentum

At top energy, the revolution frequencies must be equalised. If this is done so as to shift each beam by an equal amount, protons to the outside of the ring and lead ions to the inside, then the beams will be off-momentum by

$$\delta_{\rm p} = -\delta_{\rm Pb} = \frac{c^2 \gamma_T{}^2}{4 p_{\rm p}^2}\left(\frac{m_{\rm Pb}^2}{Z_{\rm Pb}^2} - m_{\rm p}^2\right) = \begin{cases} 0.00030 & \text{at} \quad 3.5Z \text{ TeV} \\ 0.00023 & \text{at} \quad 4Z \text{ TeV} \end{cases} \qquad (7)$$

although there are some arguments for, say, keeping the protons on the central orbit and applying twice the shift to the Pb beam. The shifts of the horizontal central orbits at the collimators are shown in Figure 12. The largest shifts, up to 1.5 RMS beam sizes, occur at the large negative dispersion locations in the momentum collimation insertion IR3. The more modest shifts at the tertiary collimators around the experiments may also necessitate some adjustment of jaw positions. Small shifts in the vertical plane are also calculated because of the vertical dispersion created by the crossing-angle bumps. Additional shifts due to the imperfections may have to be compensated empirically.

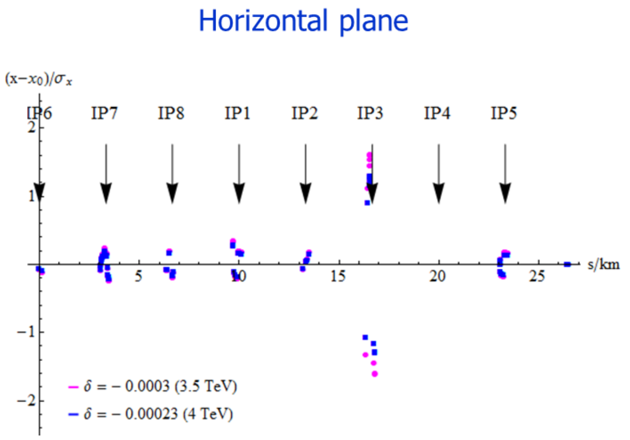

Figure 12 Shifts of the horizontal orbit of the Pb beam at the collimators for the potential physics energies; the values are given in units of nominal beam size.

The chromatic variation of the optical functions on the off-momentum orbits gives rise to a significant β-beating of the order of 10%, comparable to what is normally generated by the imperfections of the machine. Figure 13 Beta-beatingshows the computed effect in an optics where ALICE is squeezed to the same value envisaged for ATLAS and CMS in the p-p run. LHCb is kept at the same value that will be used in the p-p run.

If, as hoped, the p-p run is successful with $\beta^* = 0.6$ m in ATLAS and CMS, the addition of a similar value in ALICE will nevertheless increase the chromatic effects include a stronger tune-dependence on momentum. The consequences will be all the more marked on the off-momentum orbits required by p-Pb operation. We will investigate measures to compensate these but at the present stage it cannot be excluded that the β^* values may have to be increased at all experiments.

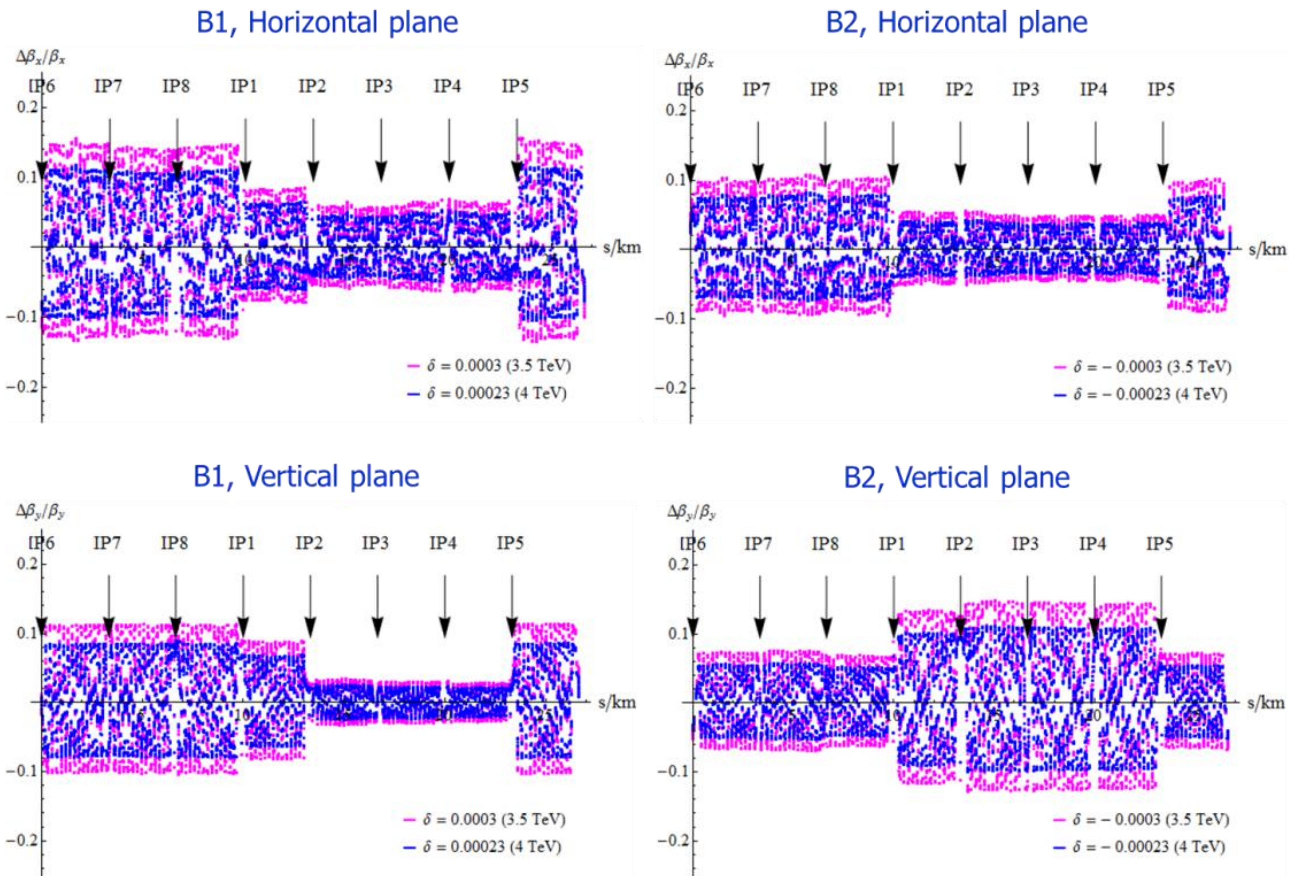

Figure 13 Beta-beating in the ideal optics with $\beta^* = (0.6, 0.6, 0.6, 3.0)$ m in IP1, IP2, IP5 and IP8 respectively at the energies of 3.5 and 4 Z TeV, showing the advantage of the reduced off-momentum orbits at the higher energy.

LHCb joins in …

Up till now the LHCb experiment has not participated in the heavy-ion runs and the filling schemes provided no collisions at IP8 which is located at the irregular azimuthal position:

$$s_{IP8} = \frac{1039}{1188} C = \frac{7}{8} C - 6\lambda_{\mathrm{RF}} \quad (8)$$

Now that LHCb has expressed interest in p-Pb collisions [16], we will have to adapt the filling schemes to provide collisions at their IP LHCb optics kept at $\beta^* = 3\ \mathrm{m}$. The number of colliding bunches will depend on the bunch spacing finally adopted and the possibilities and priorities for re-arranging collisions among the experiments.

Clearly the luminosity in LHCb will be substantially lower than in the other experiments.

Crossing angle in ALICE

As usual, the crossing angle in ALICE for heavy-ion physics is constrained by the need to provide sufficient acceptance for spectator neutrons at the Zero Degree Calorimeter (ZDC) detectors. This constrains the magnitude of the half-crossing angle to be $|p_{yc}| < 60\ \mu\mathrm{rad}$ so the contributions from the ALICE spectrometer bump and the external crossing angle bump must be arranged to mostly compensate each other. With $\beta^* = 0.6\ \mathrm{m}$ this will imply a somewhat reduced beam-beam separation than in 2011.

Performance estimates

Table 1 provides estimates of potential performance in for ALICE, ATLAS or CMS in the 2012 p-Pb run. The values depend on a number of assumptions. Of course, we have never collided hybrid beams in the LHC before and there is very little applicable experience at any other collider so these estimates are much more uncertain than usual. Until we get some experience, it is not excluded that the performance could be much worse than indicated. The untested moving encounter effects in a multi-bunch injection or ramp could be damaging.

On an optimistic view, if we are able to increase the proton bunch intensity without affecting the Pb bunches, there may be scope for somewhat higher performance than indicated.

The ratio of peak to integrated luminosity is obtained by scaling from 2011 and allowing for a slightly shorter run. However we should not forget that the availability was extremely good last year.

The average Pb bunch intensities are estimated from the best obtained in 2011. In the case of the 100 ns scheme, they are extrapolated from the best values obtained in the SPS. We follow previous estimates for p-Pb performance in taking proton bunch intensities of about 10% of nominal. Of course, we will increase them if possible.

Proton emittances are also conservative.

From these estimates it is hard to choose between the two bunch spacings. This decision will be made late in the summer when we have some experience with each in the injectors. Other things being equal, the separation around ALICE would be better with 200 ns.

Main choice:	**Units**	**200 ns**	**200ns**	**100 ns**	**100**
Beam energy/(Z TeV)	*Z* TeV	3.5	4	3.5	4
Colliding bunches		356	356	550	550
b^*	m	0.7	0.6	0.7	0.6
Emittance protons	µm	3.75	3.75	3.75	3.75
Emittance Pb	µm	1.5	1.5	1.5	1.5
Pb/bunch	10^8	1.2	1.2	0.8	0.8
p/bunch	10^{10}	1.15	1.15	1.15	1.15
Initial Luminosity L_0	$10^{28}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	**6.2**	**8.3**	**6.4**	**8.5**
Operating days		**22**	**24**	**22**	**24**
Difficulty (subjective assessment)		**0.9**	**1**	**0.9**	**1**
Integrated luminosity	$\mu\mathrm{b}^{-1}$	**15.4**	**22.4**	**15.9**	**23.1**

Table 1: Potential parameters and estimates of the resulting peak and integrated luminosity performance for the 2012 p-Pb run.

LHC HEAVY-ION PROGRAMME TO 2022

During 2011, an implementation of the long-approved physics programme for the ALICE experiment was agreed. It takes account of the technical and scheduling constraints arising from p-p operation, the planned shutdowns and the SPS heavy-ion programme. After a first discussion among the ATS Director, ALICE management, S. Maury and the speaker, it was presented to the 2011 IEFC workshop, to the LHC Machine Committee, including representatives of all experiments (20 April 2011) and presented publicly at the EPS-HEP 2011 Conference in July 2011. Some flexibility still remains in this plan if priorities change.

A further update, reflecting what we have learned from the 2011 run, is presented in Table 2. This includes only those beam species that have been officially requested. Some other possibilities are discussed from the point of view of the ALICE experiment in [10].

Given that the prospects for exceeding design luminosity $L \geq 10^{27}$ cm^{-2}s^{-1} after LS1 now appear very good and that ALICE is considering an upgrade in LS2 to handle peak luminosity $L \approx 6.\times 10^{27}$ cm^{-2}s^{-1}, it will be important to study upgrade measures that may achieve it in 2019. At present, it seems essential to install collimators in the dispersion suppressors downstream from the interaction points of ALICE, ATLAS and CMS to intercept the BFPP losses and avoid luminosity-induced quenches.

A missing factor 2-3 in peak luminosity might be achieved if we can increase the number of bunches in the ring (reducing the minimum spacing to 50 ns, for example [3]. Alternatively, all, or some fraction, of such an increase could come from measures taken in the LHC, eg, reduced β^* in collision.

Emittance growth from IBS at injection might be mitigated by implementing a stochastic cooling system [17] but such a project will require study and a lead time for development of hardware. A sufficiently powerful system might even improve integrated luminosity at collision energy as has been done so successfully at RHIC.

Year	Colliding species	Remarks
2013-14		Long shutdown LS1, increase *E*
2015-16	**Pb-Pb**	Design luminosity, ~ 250 μb^{-1}/year, Luminosity levelling?
2017	**p-Pb** ***or*** **Pb-Pb**	P-Pb to enhance 2015-16 data. Energy? Pb-Pb if μb^{-1} still needed
2018		LS2: ? install DS collimators to protect magnets ? ALICE upgrade for 6 × design luminosity
2019	**Pb-Pb**	Beyond design luminosity … as far as we can. Reduce bunch spacing?
2020	**p-Pb**	
2021	**Ar-Ar**	Intensity to be seen from injector commissioning for SPS fixed target. Demanding collimation requirements?
2022		LS3, upgrades ?? Stochastic cooling ??
>2022		See talks later in this workshop [10]

Table 2: Outline of the LHC heavy ion programme from 2013 to the start of Long Shutdown 3 in 2022

CONCLUSIONS

In a total of about 8 weeks of LHC operation in the two Pb-Pb runs of 2010-11, the following milestones have been achieved:

- The peak luminosity (scaled with E^2) has reached twice the design.
- We have already achieved 15-18% (depending on the experiment) of the overall long-term Pb-Pb luminosity goal of $1\ \mathrm{nb}^{-1}$.
- We learned a lot from 2011 Pb-Pb run and have a better understanding of the performance limits of the LHC as a heavy-ion collider.
- We have demonstrated the feasibility of p-Pb operation and are ready for the first LHC upgrade, a p-Pb physics run in 2012

Some further discussion with the experiments will be required to fully determine the conditions of the 2012 p-Pb run. The energy in particular must be decided. At present, performance estimates in this unprecedented mode of operation are uncertain so Table 1 only indicates the relative luminosities obtainable with the various options.

Important preparatory steps for the 2012 run include:

- Part 2 of the feasibility test (multi-bunch ramp + pilot physics) a few weeks before the run.
- Aperture measurements in IR2.
- RF re-phasing MD.

Finally, the LHC heavy-ion programme up to LS3 has been briefly reviewed. Performance prospects look ever better but will need focus on key upgrades.

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