IONS IN THE LHC

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Abstract

The LHC should make a "hot switch" from colliding protons to colliding lead nuclei in order to maximize the physics yield in a limited running time. I shall describe how we plan to achieve this and review the pre-conditions including the readiness of the RF system and beam instrumentation. The initial run should have the beam structure foreseen in the "Early beam" parameter list but the collision optics and beam energy may be different, depending on what has been achieved in proton operation. I shall show how the performance, including luminosity and lifetime, depends on these variables and discuss possible operating energies..

INTRODUCTION

The LHC will collide beams of heavy ${}_{208}\mathrm{Pb}^{82+}$ nuclei ("ions") as well as protons [1,2]. Plans for the commissioning and first ion runs have been discussed before [3]. The purpose of this talk is to update them, taking account of the present conditions of the LHC, in particular the strong likelihood that these will be at somewhat reduced energy.

POTENTIAL PERFORMANCE IN THE FIRST LEAD-LEAD RUN

Let me start with a simplified survey of the parameter space, indicating the range of energy and luminosity that we can expect in the first heavy ion runs of the LHC.

To fix notations for energy in the following, recall that, for our fully-stripped ${}_{208}\mathrm{Pb}^{82+}$ nuclei in the same magnetic field as 7 TeV protons:

$$\begin{aligned} E_{\mathrm{Pb}} &= Z\,E_{\mathrm{p}} = 82\times 7\ \mathrm{TeV} = 7Z\ \mathrm{TeV} = 574\ \mathrm{TeV} \\ &= A\,E_n = 208\times 2.76\ \mathrm{TeV} = 2.76A\ \mathrm{TeV} = 574\ \mathrm{TeV} \\ &= 82\times(\text{kinetic energy of mosquito at 1m/s}) \qquad (1) \\ &= (\text{kinetic energy of 1 mm diameter} \\ &\qquad \text{grain of sand at 40 km/h}) \end{aligned}$$

Since discussions in this workshop have centred around the maximum energy at which we can run the LHC in 2009-10, I shall use the proton-equivalent energy E_{p} as abscissa in most plots.

Table 1 serves to recall the reference values of the most important parameters of the LHC in Pb-Pb collision mode. The main differences between the "Nominal" and "Early" beams is that the number of bunches is reduced by roughly a factor of 10 (the injectors are almost ready to do this [4]) and the value of β^* is increased to 1 m. The value obtainable in practice will depend on the overall state of commissioning of the LHC with protons by the time of the first Pb-Pb run. For the lowest values of β^*, the luminosity lifetime is mainly determined by burn-off from ultraperipheral electromagnetic interactions so depends strongly on the number of experiments taking data.

Table 1: Key parameters of the "Early" Pb ion beam from the LHC Design Report. The "Nominal" parameters are shown greyed-out as they are not relevant to the initial run in 2009 or early 2010 but considered as a goal for the 2-3 years beyond.

Parameter	Units	Early Beam	Nominal
Energy per nucleon	TeV	2.76	2.76
Initial ion-ion Luminosity L_0	$\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	$\sim 5\times10^{25}$	1×10^{27}
No. bunches, k_b		62	592
Minimum bunch spacing	ns	1350	99.8
β^*	m	1.0	0.5 /0.55
Number of Pb ions/bunch		7×10^{7}	7×10^{7}
Transv. norm. RMS emittance	μm	1.5	1.5
Longitudinal emittance	eV s/charge	2.5	2.5
Luminosity half-life (1,2,3 expts.)	h	14, 7.5, 5.5	8, 4.5, 3

To illustrate the range of possible luminosities in the first Pb-Pb run, let me consider three possible dependences of β^* on energy, colour coded in blue, red and green in the plots that follow:

$$\beta^*(E_p) = \begin{cases} \min(1.(7/E_p),10.) & \text{m} & \text{"Early"} \\ \min(3.(5/E_p),10.) & \text{m} & \text{Initial} \\ 10. & \text{m} & \text{Injection} \end{cases} \quad (2)$$

These functions are plotted in Figure 1

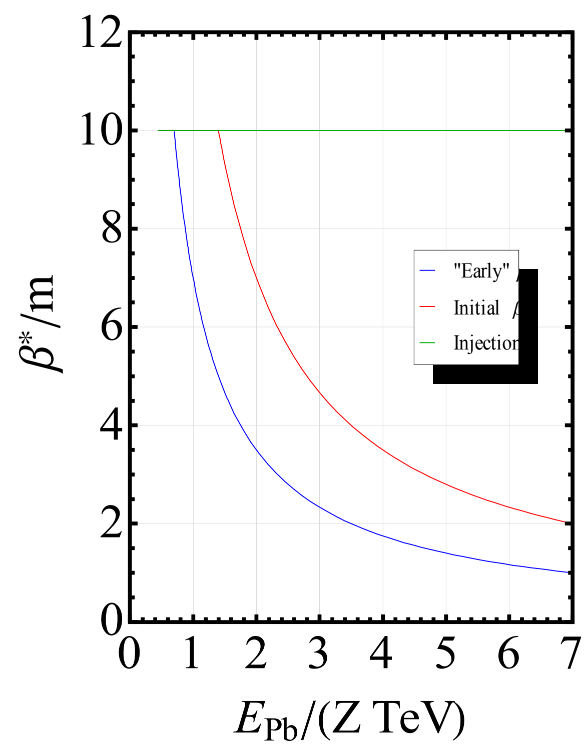

Figure 1 Energy dependence of the focusing function at the IP according to the three models of (2).

Here the energy dependence is taken to be of the form determined by the usual low-beta triplet aperture scaling

$$\beta^* \sim \frac{1}{E_p}, \quad (3)$$

with the value in the first "Early" case scaled from $E_p = 7$ TeV, corresponding to the "Early" beam of the LHC Design Report. In the second "Initial" case, the value is scaled from $\beta^* = 3$ m at $E_p = 5$ TeV in the parameter set prepared for initial proton operation at 5-TeV [5]; I regard this as a reasonable expectation (for protons or ions) in the first few months of running the LHC. Finally, the third "Injection" case is the most pessimistic and assumes no squeeze at all. This might be realistic in the case of a very short heavy ion run embarked upon in the last few days before a shutdown, with no time to commission a squeeze, for example. Compared with the previous speaker [6], who considered the ultimate limits on β^* from the triplet aperture in a well-commissioned machine, even the "Early" model here is conservative by about a factor of 2. Even if this is achievable optically in the first year or so of operation, it would be difficult to live with the low luminosity lifetimes that would occur if all three experiments took collisions, because the time between dumping beams and putting a new fill back into collision is likely to be long.

With a dependence of the form (3), the luminosity scales as

$$L = \frac{k_b N_b^2 f_0}{4\pi \sigma^{*2}} \propto \frac{E_p}{\beta^*} \propto E_p^2 \quad (4)$$

and is plotted in

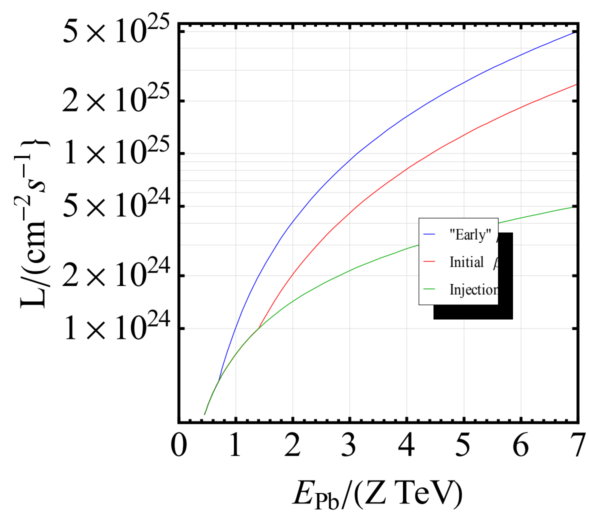

Figure 2: Potential peak Pb-Pb luminosity for the three β^* variations in (3) at design emittance and full bunch intensity $N_b = 7\times10^7$ in every one of the 62 bunches of the Early Beam structure.

With these parameters the initial luminosity decay time from "burn-off" by collisions [2,7] is

$$\tau_L = \left(\frac{\dot{L}}{L}\right)^{-1} = \frac{k_b N_b}{n_{\text{expt}} L \sigma_{\text{total}}} \quad (5)$$

where the total cross-section for ion removal from the beam by hadronic interactions, bound-free pair production (BFPP) and various electromagnetic dissociation (EMD) processes is

$$\begin{aligned} \sigma_{\text{total}} &= \sigma_{\text{hadronic}} + \sigma_{\text{BFPP}} + \sigma_{\text{EMD}} \\ &\approx (8+281+226)\ \text{barn} \end{aligned} \quad (6)$$

Neglecting other processes, there is an often-quoted approximate relation between the initial decay time and the half-life: $\tau_{L/2} \approx \left(\sqrt{2}-1\right)\tau_L$. The luminosity lifetime *due to this process alone* is plotted in Figure 3.

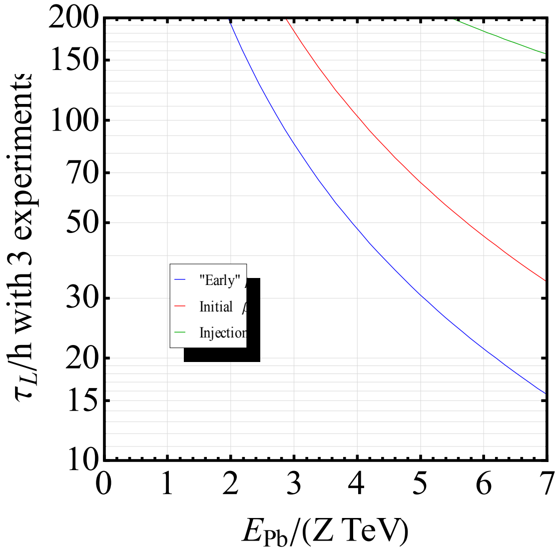

Figure 3: Initial luminosity decay times by burn-off alone for the three β^* variations in (3) at design emittance and full bunch intensity $N_b = 7\times10^7$ in every one of the 62 bunches of the Early Beam structure.

Note that a proton equivalent energy $E_{\mathrm{p}} = 2.6\ \mathrm{TeV} \Rightarrow \sqrt{s_{\mathrm{NN}}} = 2\ \mathrm{TeV}$ already exceeds the centre-of-mass energy of colliding nucleon pairs available at RHIC by a factor 10.

We should also consider the time-scales of the evolution of emittance. As mentioned elsewhere, the Pb beams in the LHC will be the first hadron beams for which synchrotron radiation damping leads to a significant reduction of emittances. This however is strongly dependent on energy

$$\tau_{\varepsilon x} \propto E^{-3}, \quad \tau_{\varepsilon z} = \tau_{\varepsilon x}/2 \qquad (7)$$

and rapidly becomes less important for $E_{\mathrm{p}} < 7\ \mathrm{TeV}$. In addition, we have to consider the possible growth of emittances due to intra-beam scattering (IBS). Somewhat paradoxically, this can be aggravated by radiation damping because the longitudinal emittance damps twice as fast at the transverse, enhancing the IBS growth of the transverse emittances. The emittance growth times are proportional to bunch intensity and have a somewhat more complex functional dependence on energy and the emittances

$$T_{\mathrm{IBS}xz} \propto N_b^{-1} \times F(E, \mathrm{emittances}) \qquad (8)$$

These time scales are indicated in Figure 4. Controlled blow-up of longitudinal emittance by RF noise will be useful but is not essential for the first runs.

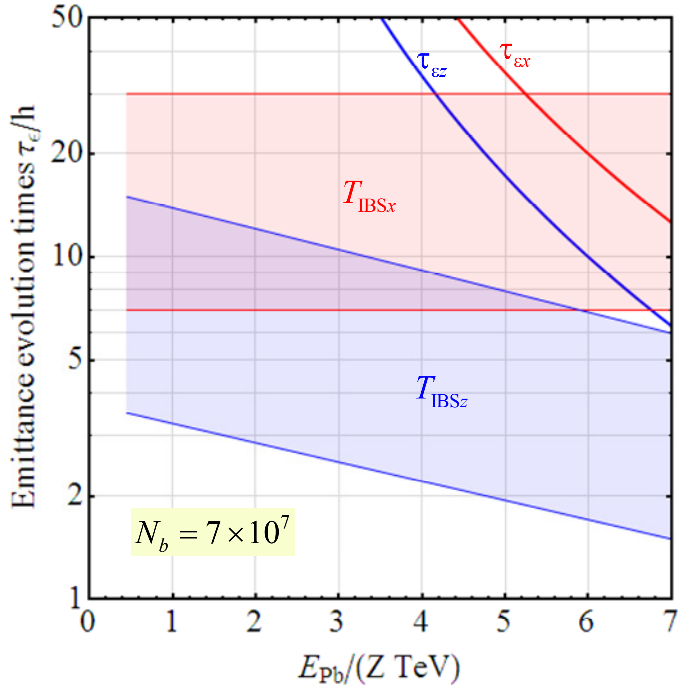

Figure 4: Time scales for emittance evolution by shrinkage due to radiation damping and IBS growth in transverse ($\tau_{\varepsilon x}$, $T_{\mathrm{IBS}x}$) and longitudinal ($\tau_{\varepsilon z}$, $T_{\mathrm{IBS}z}$) planes. A range of possible values for the IBS growth times is indicated depending on factors such as betatron coupling and the availability of controlled blow-up of longitudinal emittance using RF noise.

While we can put all effects together to predict luminosity evolution scenarios through a fill (except for the difficulty of estimating losses from longitudinal debunching), these plots already allow us to infer the important consequence that initial runs can be quite long (provided the emittance does not degrade and we do not lose the beams for some other reason) and relatively little time should be lost with frequent refilling. This will change dramatically at lower β^* later.

Recalling the conversion factor

$$10^{25}\ \mathrm{cm^{-2}s^{-1}} = 0.864\ \mu\mathrm{b^{-1}day^{-1}} \qquad (9)$$

and allowing for typical ratios between peak and average luminosity, we see that the initial goal of 1 $\mu\mathrm{b}^{-1}$ integrated luminosity could be achieved in a about one week of running at $E_{\mathrm{p}} = 5\ \mathrm{TeV}$ and $\beta^* \leq 3\ \mathrm{m}$.

READINESS OF SYSTEMS

As discussed in previous Chamonix workshops, certain key accelerator systems perform, or have to be operated, somewhat differently from proton operation. In this part of the talk, I will summarise the latest discussions with members of various groups concerning the readiness and performance of their systems for the switch-over to operating with Pb ion beams.

RF

The first thing one thinks of is that ions of mass $m_{\rm ion}$ and charge $Q_{\rm ion}$ will have a slightly different revolution frequency from protons and that this will required adjustment of the **RF frequency**:

$$f_{\rm RF} = \frac{c\, h_{\rm RF}}{C\sqrt{1+\left(\frac{m_{\rm ion} c}{Q_{\rm ion} p_{\rm p}}\right)^2}} \qquad (10)$$

where $h_{\rm RF} = 35640$ is the same harmonic number as for protons, $m_{\rm ion} = 207.932\ {\rm GeV}/c^2$ is the mass of a $_{208}{\rm Pb}^{82+}$ nucleus and C is the circumference (measured, essentially, by the radial loop). This leads to a larger frequency swing (some 5 kHz rather than 1 kHz) and a difference in RF frequency at injection of -4.7 kHz. Given the very rapid initial synchronization and capture of proton beams on 11 September 2008 [8], there is no reason to think that this will pose any difficulty or take any longer. The beams must then be ramped to the chosen collision energy with the suitably adapted RF frequency programme in LSA.

When the time comes to inject more than one ion bunch, there will already have been experience injecting into a variety of proton **filling patterns** and no problems are expected to fill in the corresponding 62-bunch pattern.

An upgrade to a more sensitive **phase-loop pickup** has been considered for ions. While this remains very desirable, it was shown in the September 2008 run that the present one works perfectly well down to

$$N_b = 2.44\times10^7 \ \text{ ions/bunch} = 2.\times10^9 \ \text{ charges/bunch} \quad (11)$$

which is an acceptable minimum intensity for commissioning.

Controlled **RF noise** to blow-up longitudinal emittance (and so reduce transverse IBS) will help to maximise integrated luminosity. However the longitudinal damper will be only available next year and this is not essential for the first run. On ther other hand, uncontrolled RF noise should have the same effects on longitudinal emittance as for protons. The good lifetime observed at injection in the September 2008 run indicates that this is not a concern. However **debunching rates**, an important factor in the luminosity decay of RHIC, should be watched closely.

Finally, even though present indications are that they will not be necessary, I would like to remind you of the possibility that we might need the **200 MHz capture cavities** [1] one day (this possibility has not been mentioned much in the last few years).

Beam instrumentation

As already discussed in this workshop [9], the September 2008 run showed that the **beam position monitors (BPMs)** are somewhat more sensitive than previously expected. This will be invaluable for ion commissioning, allowing us to operate with lower currents and reducing the frequency of refilling and opening up the possibility of longer physics fills before it becomes difficult to measure the orbit. This allows us to update Figure 21.9 on the second last page of [1].

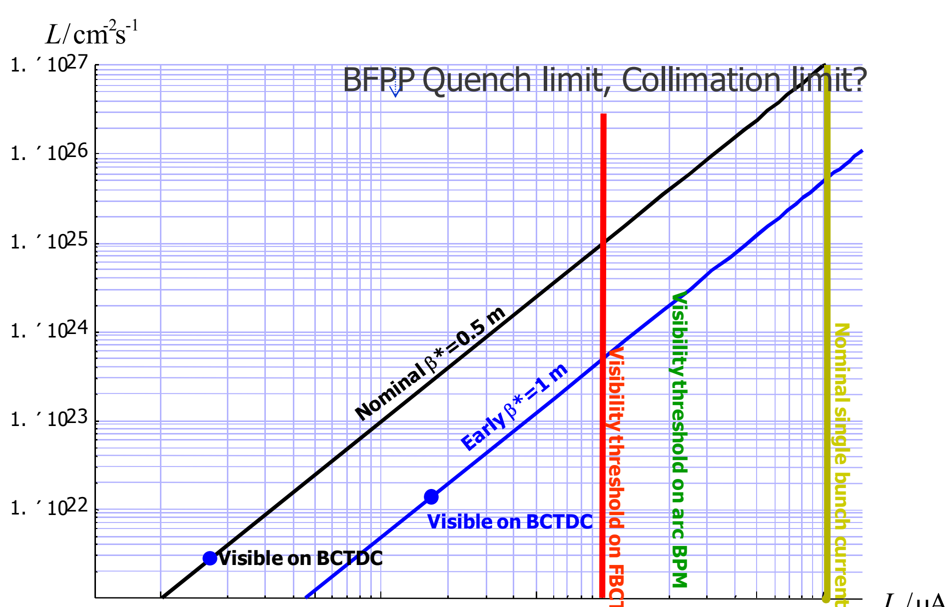

Figure 5: Variation of luminosity with single bunch current, I_b, for both the Earlly and Nominal ion schemes. Threshold of visibility on the FBCT and the arc BPMs are shown as vertical lines. Thresholds for the total current measured on the BCT DC are shown as points on the curves for the two schemes.

It is always good to have a number of different ways to measure emittance and this is true for proton operation but less so for ion operation.

- **Ionization profile monitors**: we will have to rely mainly on these to measure the emittance of Pb beams. This assumes that the situation concerning the gas injection and the available performance with Pb beams will be clarified.
- **Wire Scanners:** these impose a limit on intensity because of damage to the wires and/or the risk of quenches of nearby magnetic elements. It is not even clear that it will be possible to measure the emittance of the Early beam bunches at injection:
  - Injection: only 58-82 nominal ion bunches
  - Collision energy (7 *Z* TeV): only 16-23 nominal ion bunches.
- Synchrotron Light Monitors: these are not expected to work for the very soft spectrum of synchrotron radiation from ${}_{208}Pb^{82+}$ ions. For the future the possibility of installing an infra-red detector or building a new undulator are being considered. These upgrades would be very desirable.
- **Schottky monitor:** This is of special interest because, unlike most other instruments, it is not simply sensitive to the macroscopic bunch charge. Since the signal $S \propto N_b Z^2$, it turns out to perform about as well for Pb ions as for protons, despite the reduced bunch charge. In recent months, I had hoped that it would be possibly to implement the very accurate new method developed at RHIC to measure emittance [10]. This involves moving the pickup back and forth around the closed orbit and fitting to the way in which the relative intensity of the betatron sidebands of the main mode depend on position. This might be simulated electrically (with suitably varying attenuation) in the LHC. However it has been stated recently [11] that it is unlikely to work at 4.8 GHz in the LHC because of sideband overlap. It should still be possible to apply the classical method to measure emittance with an immobile pickup; this requires a good absolute calibration of the spectrum.
- **Abort-gap monitor:** insofar as this depends on a synchrotron light monitor, it will not work for ions. If the errors can be controlled well enough we might try to measure debunched intensity by accounting for the differences in measurements made with the fast (single-bunch) and DC beam current transformers. However the fall-back strategy will be just to clean the abort-gap continuously.
- **Beam Loss Monitors (BLMs):** the LHC has been equipped with a number of extra BLMs to monitor the regions in which we expect to see beam losses peculiar to Pb ion operation (I shall discuss this further below).

Optics

The principle here is to m*ake the absolute minimum of changes to the working p-p configuration.* Then, since the beams have the same magnetic rigidity, most of the optical configurations occurring in the operational magnetic cycle can be magnetically identical. Moreover, since the design emittance is chosen so that protons and ions have the same geometrical beam size everywhere in the ring, one can expect the aperture, collimator settings, etc. to need little more than some fine adjustment.

Therefore transfer, injection, ramp, orbits, optics, tunes, chromaticity and so on can all be the same. If they work for protons, they will work for ions.

The main difference optically is that IR2 will have to be squeezed for the ALICE experiment (recall that it will not be squeezed in p-p operation). This squeeze will be prepared, with zero crossing angle, at collision energy with the unsqueezed optics in the other IRs. The final value of β^* will be similar to whatever has been achieved by then in p-p runs at ATLAS and CMS. By the time of the first ion run, there will have been some experience of squeeze preparation in the LHC and it will be possible to update the time estimate for this procedure. After that, it may be desired to put back the squeezed optics in IR1 and IR5. If, for example, this creates poor operating conditions or there are time pressures, then it might be necessary to run with different β^* in different experiments. Guidance from the physics coordinator or CERN management will be needed to clarify the priorities.

Collimation

Collimation setup for initial runs should be straightforward and similar to that of protons. However, the collimation of ion beams is a very different matter from that of protons—the two-stage collimation principle does not work—and we expect the collimation inefficiency to emerge as a major performance limit at higher intensity. For this reason, we need to test our predictions of loss maps and collimation inefficiency at low intensity.

Extra BLMs have been installed [12] to monitor the losses in the dispersion suppressors downstream of the collimation insertions where we expect a number of loss peaks corresponding to various isotopes created by nuclear and electromagnetic interactions of incident ${}_{208}Pb^{82+}$ nuclei with the carbon nuclei of the primary collimators.

There is a problem connected with the tertiary (triplet protection) collimators TCTVs in IR2. They were installed in a location in which they interfere with the spectator neutron flux to the ALICE Zero Degree Calorimeters (ZDCs) so cannot be closed to their proper positions during Pb-Pb collisions. A solution is currently being worked out, probably involving a movement of vacuum chambers and the installation of additional tertiary collimators in positions analogous to those around

IR1 and IR5. This will be discussed in the forthcoming collimation review.

Machine Protection

It is clear from the simple fact that the stored energy in a Pb ion beam is typically two orders of magnitude less than that of a proton beam (at analogous stages in the intensity ramp-up of the LHC) that, if the machine protection system works for protons, it will also work for ions in most situations. The few instances where differences may emerge have been treated within the I-LHC Project in some detail and are rather well documented [13,12]. Furthermore we have taken opportunities to compare our predictions with experiments on ion beams in RHIC [14] and the SPS [15].

Thanks to a very fruitful collaboration with the FLUKA team, the FLUKA event generators have been upgraded in recent years to provide us with a good model of the interactions of very high energy nuclei with materials [16]. This has been benchmarked as far as possible with other implementations (EPAX, MARS, RELDIS, ABRABLA, …) and empirical data. The results are used in FLUKA itself and also in the ICOSIM program that we use for the simulation of ion collimation processes. Many FLUKA simulations have been carried out to look at losses in dipole magnets and their neighbourhoods.

As already discussed in the LHC Design Report, differences may arise because the initial ionization energy loss (according to the Bethe-Bloch formula) on impact with a material can be high. However the nuclei immediately start to undergo fragmentation in a hadronic shower which sees them quickly transformed into a swarm of individual nucleons. This behaviour is illustrated in Figure 6 which we use to recall a key point of the analysis in [13]. In this FLUKA simulation, which can be regarded as a generic case from the machine protection point of view, a pencil beam of ${}_{208}Pb^{82+}$ ions impinges on the beam screen inside an LHC dipole at an angle of a few mrad, typical of beam losses in the LHC. The corresponding energy losses for a beam of 82 7 TeV protons or 208 2.76 TeV protons, i.e., three beams normalised to have the same energy, are also shown for comparison. The worst-case longitudinal dependence of the energy deposition is plotted at three successive stages of development of the hadronic shower. First, in the beam screen itself, the high initial ionization due to the large charge of the ions results in a significantly higher initial energy deposition. A little later, however, in the magnet coils, fragmentation of the ion via hadronic and electromagnetic processes has mostly converted the incident ions into a shower of individual nucleons (plus pions, etc.) with the result that the three cases have very similar energy depositions (the ${}_{208}Pb^{82+}$ being particularly close to the case of 208 protons with the same energy per nucleon. The same hold true in the third plot, the energy deposition in the BLM outside the cryostat. It follows that a given energy deposition in the superconducting coil will give rise to a similar signal in the BLM in each of the three cases and, therefore, that *similar thresholds for dumping the beam to avoid quenches can be applied independently of the type of beam*.

Indeed the differences between the red and black/green curves are such that the strategy of using identical BLM thresholds will provide somewhat more cautious protection in the case of ions than in that of protons. Experience with the beams will show whether the levels can be relaxed slightly but this will be the initial strategy.

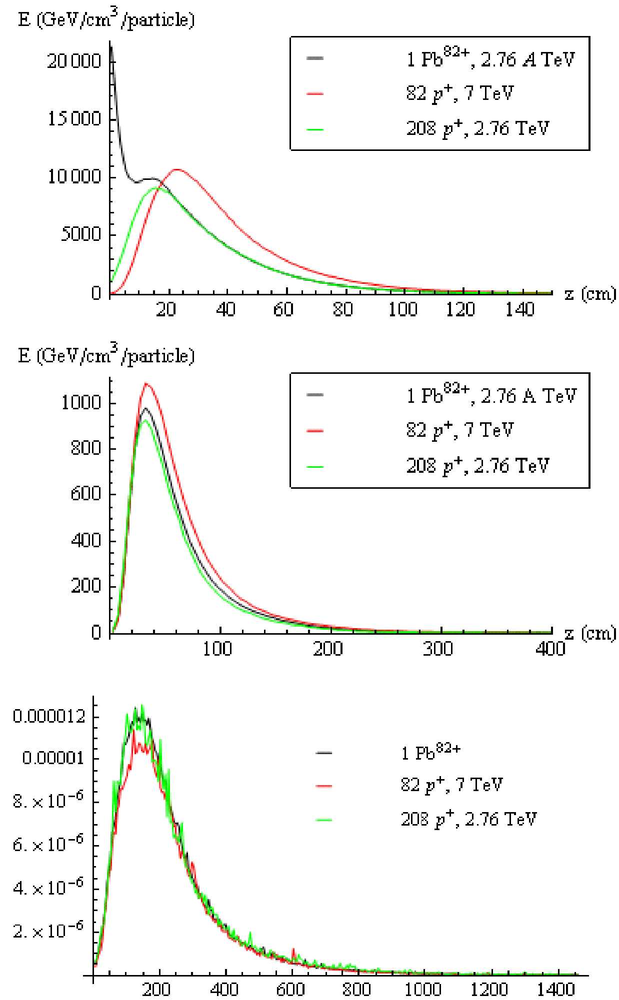

Figure 6: Levels of heat deposition resulting from a pencil beam of ${}_{208}Pb^{82+}$ nuclei impinging on the beam screen at typical loss angles inside a dipole magnet, as simulated using FLUKA . From top to bottom, the plots shows the hottest bin in the beam screen, the hottest bin in the superconducting coil and the energy deposition in a BLM outside the magnet cryostat (from R. Bruce).

Similarly, since most instruments are sensitive to bunch *charge* which is directly proportional to bunch stored *energy*, the definitions of concepts such as “Safe Beam” are straightforwardly extended from protons to ions.

Special cases, where the initial high ionization energy loss, seen in the first plot of Figure 6, or in Figure 21.7 of [1], may have an impact have been analyzed separately.

For example, the performance of the beam dump has been checked for ions, including a FLUKA simulation of the energy deposition in the thin beam dump window.

Vacuum

The subject of beam vacuum was treated in some detail following consultations with members of the vacuum group at Chamonix 2004. In the meantime little has changed apart from the recognition of local pressure bumps around collimators and any consequences of the Sector 3-4 incident. While the residual gas pressures required for heavy ion beams are lower than for protons, the reduction of beam lifetime is not expected to be significant.

Controls and other software

As an example of the syndrome by which the specificities of non-proton beams tend to be treated as an afterthought, I want to mention that some well known accelerator physics programs, which may purport to treat ion beams properly, have hard-coded assumptions about charge and mass of particles sprinkled here and there in their code. This results in some, perhaps not all, quantities being wrongly calculated. (This isn't meant to be a criticism of anyone in particular—I've been guilty of doing the same thing myself in the days before I started working on these beams.) It's conceivable that such things may also occur somewhere in the controls software and I can only ask the developers, once again, to review their code from this point of view. Of course we are ready to help clarify exactly how and where the appropriate factors should appear.

Similar remarks apply for other differences between beam types (filling scheme, labels, etc.).

COMMISSIONING PLAN

Plans for the commissioning of the LHC with protons were drawn up by the former LHC Commissioning Working Group and are updated at a Web site. The corresponding plans for ions, discussed at earlier Chamonix workshops [3] and elsewhere, have been added more recently. They are based on the pre-condition that the "hot-switch" from protons to ions will be done with a machine that is already operational with protons and that the SPS is ready to inject the Early Ion Beam or something close to it. Thus it will not be like a start-up from shutdown. I have already mentioned the simplifications and shortcuts that accrue from the facts that the machine will be magnetically identical for most of its operational cycle and that the beam sizes should be the same.

These arguments can be confronted with previous experience of species-switch at other hadron colliders. RHIC, for example, has changed species several times in recent years, usually from ions to protons. Even in this mature machine, this takes about one week to set up and another week for performance ramp-up. Is it reasonable to claim that we can do better on our very first try with the LHC?

I believe we can because the species-switch in RHIC requires more complicated optics changes than in the LHC. RHIC's injection energy is below transition for ions but not for protons. It is below transition for both beams in the LHC. Moreover RHIC's protons have to be polarized. Neither of these complications apply to the LHC.

Indeed, it is arguably more appropriate to look further back into the history of CERN, when the commissioning of light ion (deuteron, alpha) beams in the ISR was done in less than a day, precisely because the proton and light ion beams had the same magnetic rigidity. I believe that LHC is somewhat closer to the ISR from this point of view (of course the ISR did not have to ramp).

The present outline plan, Figure 7, for the initial commissioning foresees about 6 days to first collisions of a single bunch in an unsqueezed optics. A few more days should allow the IR optics to be squeezed and the full 62 bunches of the Early Scheme to be injected.

The plan does not foresee collisions at injection energy because these are of no interest to the experiments [17].

The plan will be fleshed out in greater detail in coming months and formal LHC Commissioning Procedures will be defined. Nevertheless it will be kept under constant review and adapted in the light of the experience with protons.

As already mentioned in the Optics section above, situations may arise in which it is not optimal to try to equalise luminosity among the three heavy-ion experiments.

Stage I	Initial commissioning Early Ion Beam (DRAFT)	Ring factor	Total Time [days]	Comments
I1	Injection and first turn	2	0.25	Magnetically identical to protons; 1 bunch/beam.
I2	Circulating beam	2	0.25	Magnetically identical to protons. Synchronisation of transfer lines and RF capture at -4.7 kHz frequency shift. Check lifetime in particular (IBS?).
I3	450 Z GeV initial commissioning	2	0.25	Beam instrumentation slightly different. Optics OK.
I4	450 Z GeV optics measurements	2	.5	Magnetically identical to protons but do minimal check.
I6	450 Z GeV - two beams	1	.5	>0.4 nominal bunch intensity, otherwise magnetically identical to protons.
I7	Collisions at 450 Z GeV	1	0	Not interesting.
I8	Snapback and ramp	2	0.5	Single and then two beams, Magnetically identical to protons. Check beam dump at various energies.
I9	7 Z TeV flat top checks	2	0.5	Single beam initially, performed following successful ramp
I12	Commission experimental magnets			Included already since done for protons.
I10	Setup for collisions - 7 Z TeV	1	0.5	
	Physics un-squeezed	1	?	Zero crossing angle in ALICE, leave as-is in CMS & ATLAS. LHCb separated.
	TOTAL to first collisions		6	
I11	Commission squeeze	2	2	Commission squeeze of ALICE to same as presently achieved with CMS and ATLAS (with ATLAS and CMS unsqueezed). May have been started with protons. Check separation. Include CMS & ATLAS squeeze depending on time.
I5	Increase intensity	2	1	Increase bunch number to 62 (Early Scheme).
	Set-up physics - partially squeezed.	1	2	
	Pilot physics run			Parasitic measurements during physics (BLMs, ...) of great interest.

Figure 7: The outline of the plan for first commissioning of the Early Ion Beam (http://lhc-commissioning.web.cern.ch/lhc-commissioning/ions/stage_1_EarlyIons.htm).

CONCLUSIONS

Given the pre-conditions (injectors ready, LHC operating fairly well with protons), commissioning first Pb-Pb collisions should be rapid. A commissioning plan is available and will be updated in the light of experience with proton beams. The initial Pb-Pb physics goal ($1\,\mu b^{-1}$) is attainable in a few days, after about one week commissioning. Hence, to reduce risk, a good 4 weeks would be an appropriate length for the first run.

Most LHC systems are ready for ion beams. The beam instrumentation generally provides sufficient flexibility and safety for commissioning of the low total charge of the Pb bunches. Nevertheless we have some concerns about the lack of redundancy in emittance measurements. Experience with the Early Beam will be important for future stages of the LHC ion programme. A lot of important data can be logged parasitically, particularly from the BLM system.

There is a clear need for policy guidance concerning luminosity priorities among experiments

If the HI commissioning is scheduled later (say to end 2010) then it may be possible to accelerate the approach to higher luminosity:

- Development on the ion injectors during 2009-10 (or another approach) could allow injection of more than 62 bunches, making a substantial step beyond the Early Beam parameters.
- By then the optics may be in good enough shape to lower β* further than indicated in (2)

Despite the conservative approach of reduced intensity in the Early Beam, we should not forget that LHC Pb-Pb will be a new accelerator regime with new loss mechanisms (see other reports concerning the luminosity limitations from Bound-Free Pair Production, collimation inefficiency, etc.). It will be of great interest to log and study the beam loss patterns and quench limits. While data from the SPS and RHIC has already been exploited as far as possible, the low-intensity run will be our first real opportunity to calibrate and test the validity of calculations and simulations of these mechanisms at the LHC itself. We may also be able to learn about performance limits in future phases beyond Pb-Pb.

Acknowledgements

My thanks are due to many colleagues who provided information for this talk, in particular: G. Arduini,

R. Assman, R. Bailey, G. Bellodi, R. Bruce, T. Böhl, A. Butterworth, C. Carli, F. Caspers, M. Chanel, E. Ciapala, P. Collier, B. Dehning, S. Gilardoni, M. Giovannozzi, B. Goddard, J-J. Gras, M. Ferro-Luzzi, W. Höfle, R. Jones, M. Lamont, T. Lefèvre, D. Manglunki, S. Maury, S. Redaelli, A. Rossi, J. Schukraft, J. Wenninger (CERN) and K. Brown, M. Minty (BNL).

REFERENCES

[1] LHC Design Report, CERN-2004-003, Vol. I, Chapter 21.

[2] J. M Jowett 2008 *J. Phys. G: Nucl. Part. Phys*. 35 104028

[3] J.M. Jowett in J. Poole (Ed.) Proc. Workshop on LHC Performance- Chamonix XIV-, 17-21 January 2005, CERN-AB-2005-014 (2005).

[4] E. Métral, this workshop.

[5] R. Bailey et al, LHC Project Document LHC-OP-ES-0011 rev 2 (2008)

[6] W. Herr, this workshop.

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

[8] S. Redaelli, this workshop.

[9] R. Jones, this workshop.

[10] K.A. Brown et al, *Phys. Rev. Special Topics - Accelerators and Beams* **12** 012801 (2009)

[11] F. Caspers, private communication.

[12] G. Bellodi et al, LHC-Project-note-402 (2007)

[13] R. Bruce et al, LHC-Project-Note-379 (2006)

[14] R. Bruce et al, *Phys. Rev. Lett*. **99**, 144801 (2007)

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

[16] H.H. Braun et al, *Hadronic and electromagnetic fragmentation of of ultrarelativistic heavy ions at LHC*, to be published.

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