LHC OPERATION FOR HEAVY IONS

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Abstract

Heavy Ion runs of the LHC will be scheduled most efficiently by reducing the changes to the established operational cycle (for protons) to the absolute minimum. The differences from p-p operation (RF, vacuum requirements, beam instrumentation, separation and optics in collision) are summarised. Pre-requisites for switching from p-p to Pb-Pb operation of the LHC are examined and a plan for rapidly commissioning the main rings with lead ions is outlined. The evolution of beam intensity, emittance and luminosity in ion fills are discussed. The first phase of running with the "Early Ion Scheme" will be used to elucidate performance limits (quenches from Pb^{81+}, collimation) and drive the subsequent evolution towards nominal luminosity.

There may be an opportunity for a very brief "Pilot Ion Run" at an early stage of the LHC commissioning. This could yield a first crop of interesting physics results at a very low scheduling cost.

INTRODUCTION

Received opinion has it that the royal road to getting high peak and integrated luminosity from a collider is to run continuously with the same basic operating configuration, gradually accumulating incremental improvements to the operational cycle and efficiency. Recent examples of the success of this strategy include factories like KEK-B and PEP-II although one might also point to CESR, LEP and RHIC (and perhaps even KEK-B), as exceptions that prove the rule. The latter colliders have demonstrated the flexibility required to accumulate luminosity successfully through many changes of operating modes.

In any case, it is clear that switching between different modes of operation of the LHC will have some cost in valuable operational time and this will certainly be most noticeable in the initial commissioning. In this talk, my main purpose is to show how the switch from proton to heavy-ion collisions can be managed as efficiently as possible by keeping changes to the operational cycle to a minimum.

Performance limits with ions are quite different from protons; I will also include a short update on recent work.

Early and Nominal Pb-Pb schemes

The LHC "baseline" described in the Design Report [3] includes the first phase of the LHC Heavy-Ion programme, operation with colliding beams of lead nuclei at a centre-of-mass energy of 1.1 PeV and design luminosity $L = 10^{27}$ cm^{-2}s^{-1}. I shall make frequent reference to it as background to this talk. However there is one important respect in which the Design Report is out of date. Parameters quoted there are given for the case of two experiments taking collisions, as seemed likely at the time of writing in 2003. Now that three experiments, ALICE, ATLAS and CMS have formally expressed their intentions to pursue heavy-ion physics, those parameters related to beam and luminosity lifetime therefore have to be updated. I will discuss what changes in this talk.

Following the 2003 Chamonix workshop [1], the initial phase of Pb-Pb colliding beams was split into the "Early Scheme" and "Nominal Scheme", defined in Tables 21.1-21.4 of [3]. As far as the LHC main rings are concerned, they differ in that the Early Scheme has about ten times fewer bunches (62 rather than 592) and a higher β^* value (1 m rather than 0.5 m) than the Nominal Scheme. The Early Scheme facilitates initial operation of both the ion injector chain and the LHC main rings. The lower luminosity will nevertheless provide access to a substantial physics programme in the first weeks of colliding ion beams.

DIFFERENCES FROM pp OPERATION

In this part of the talk, I will run through some of the principal ways in which operation with lead ion beams will be different from proton operation.

Instrumentation

Let me show you Figure 21.9 of [3]; this summarises how the operating range of bunch currents with Pb ions is tightly boxed in, from above by performance limits arising from nuclear and beam physics, from below by the sensitivity of key items of the LHC beam instrumetntation. Further detail is given for reference in and Table 2; see also [4]. Inpsecting these tables, we can see some practical implications for ion operation:

- The "Pilot" ion beam, to be used for setting up machine before injection of the full intensity just as for protons, should be a single bunch with 50-100% of nominal intensity.
- Because of the high initial ionisation loss of ions compared with protons, it may have a higher damage potential on surfaces than the proton pilot [3]. I mention this to bring it to everyone's attention. So far I am not aware that it leads to any real problem.
- The energy deposited by this pilot beam should not quench a magnet.
- We will have to work with most of the design intensity per bunch from the beginning
- There is a strong premium on minimising beam losses at every stage of the LHC's operational cycle with ions.
- Lifetime measurements will be slow (see also [7]).

- When LHC operation is stable enough, there is a possible interest of "flying blind", i.e., continuing to collect luminosity with beams that have fallen below the limit of visibility on the single bunch current monitors, in the latter parts of long fills. This may be of interest if turn-around times between fills are long or if injectors are temporarily unavailable. It seems unlikely that it would be worthwhile going below the limit of visibility on the DC current monitors.

	$\{N_b, 1\}$	$\{N_b\, Q_{ion}, 1\}$	$\{I_b, \mu A\}$	$\{I_{tot}, \mu A\}$	$\{W_{beam}, MJ\}$
InjectionEarlyVisibleFBCT	6.77×10^6	5.55×10^8	1.	62.	0.00248
InjectionVisibleFBCT	6.77×10^6	5.55×10^8	1.	592.	0.0237
InjectionEarlyVisibleDCCT	1.09×10^6	8.95×10^7	0.161	10.	0.0004
InjectionVisibleDCCT	114000.	9.38×10^6	0.0169	10.	0.0004
InjectionEarlyVisibleBPMs	2.44×10^7	$2.\times10^9$	3.6	223.	0.00894
InjectionVisibleBPMs	2.44×10^7	$2.\times10^9$	3.6	2130.	0.0854
InjectionEarly	$7.\times10^7$	5.74×10^9	10.3	641.	0.0257
Injection	$7.\times10^7$	5.74×10^9	10.3	6120.	0.245

Table 1 Beam Intensity parameters at injection energy at various thresholds of visibility on key instruments and at other reference intensity levels, as indicated by the key in the first column. The other columns show the number of particles per bunch, N_b, the charge per bunch, $N_b Q_{ion}$, the current per bunch, I_b, the total current per beam, I_{tot} and the stored energy per beam W_{beam}.

	$\{N_b, 1\}$	$\{N_b\, Q_{ion}, 1\}$	$\{I_b, \mu A\}$	$\{I_{tot}, \mu A\}$	$\{W_{beam}, MJ\}$	$\{\mathcal{L}, cm^{-2}s^{-1}\}$
CollisionEarlyVisibleBCTFR	6.77×10^6	5.55×10^8	1.	60.	0.0373	4.86×10^{23}
CollisionVisibleBCTFR	6.77×10^6	5.55×10^8	1.	592.	0.369	9.59×10^{24}
CollisionEarlyVisibleDCCT	1.13×10^6	9.25×10^7	0.167	10.	0.00622	1.35×10^{22}
CollisionVisibleDCCT	114000.	9.38×10^6	0.0169	10.	0.00622	2.74×10^{21}
CollisionEarlyVisibleBPMs	2.44×10^7	$2.\times10^9$	3.6	216.	0.135	6.31×10^{24}
CollisionVisibleBPMs	2.44×10^7	$2.\times10^9$	3.6	2130.	1.33	1.25×10^{26}
CollisionEarly	$7.\times10^7$	5.74×10^9	10.3	621.	0.386	5.2×10^{25}
Collision	$7.\times10^7$	5.74×10^9	10.3	6120.	3.81	1.03×10^{27}

Table 2 Beam Intensity at various Instrumentation Thresholds, as Table 1, but for collision energy. The corresponding luminosity is also given.

Vacuum Requirements for Pb Ions

In last year's workshop [6] it was pointed out that the cross sections for nuclear interactions between lead ions and the residual gases in the beam pipe are some 20-50 times proton values and that Pb ions therefore need much better vacuum conditions than protons. The values were updated using more recent calculations and to include electromagnetic dissociation processes in [8]. Meanwhile these requirements have been considered from the point of view of the vacuum system [9] with the conclusions that:

- The main source of gas in the cold parts of the LHC during Pb ion operation will be ion losses themselves.
- With a desorption coefficient of 10^5 molecules/ion, the ion loss rate required to reach the limit of 100 h beam-gas lifetime would be

$\Delta N \approx 2\times10^6$ ions/turn. But, taking the full Nominal beam values of $k_b = 592$, $N_b = 7\times10^7$, this would mean that the beam lifetime was already $\tau = \frac{N}{\dot{N}} \approx \frac{T_0 k_b N_b}{\Delta N} \approx 2$ s for some other reason.

- A localised fast loss of 10^8 Pb ions would be enough to quench one magnet. To get such a loss with full Nominal beam intensity, the lifetime would have to fall (for some reason) to 500 s for as long as 1 s. The pressure increase due to such a fast loss is estimated to have a negligible effect on beam lifetime.

Except for a few remaining uncertainties related to grazing angles, the vacuum pressure is therefore not expected to be a limiting factor for Pb ion beam lifetime.

Optics for the Early and Nominal Ion Schemes

Because the design values of the geometrical emittance are the same, proton and ion beams should have the same transverse beam sizes in a given magnetic configuration of the LHC rings. Since, moreover, they have equal magnetic rigidities, the optics, dynamic aperture or mechanical acceptance of ions should be the same as protons. It follows that injection and ramping can be done with exactly the same optics, orbits, corrections, collimator settings, etc. that have been established for protons. These simple facts alone will go a long way to shortening ion commissioning time!

Additional adjustments will be necessary only to the extent that the geometric emittances turn out not to be equal or if, contrary to expectation, the magnetic reproducibility is insufficient (in that case significant new adjustments would be necessary on *every* magnetic cycle, independently of which kind of beams are in the ring).

After the ramp, the optics in the interaction regions will be "squeezed" for physics, as described in [11]. Here, the main difference with respect to proton operation is that IR2 will be squeezed to a low value ($\beta^* = 1$ m in the Early and $\beta^* = 0.5$ m in the Nominal Schemes) for the ALICE experiment. It is shown in [3] that collisions in ALICE can be made with a small crossing angle ($\leq 20\ \mu$rad, or even zero, including the effects of the ALICE muon spectrometer magnet and its compensation). This helps to relax the aperture requirements. Crossing angles could be reduced, if necessary, also in IR1 and IR5 although, to minimise changes to the operational cycle, we are assuming for now that ATLAS, CMS would be use the same squeeze and crossing angles as in proton operation. Since LHC-B does not required ion collisions, IR8 would simply be left in the injection configuration.

As pointed out in [11] and in [12], squeezing to low β^* values in IR2, just as in IR1 or IR5, involves running some quadrupoles down to low excitation values, with the usual concerns about dynamic range. Another point to note is that the matching of IR2 for intermediate levels of β^* (the interpolation points of the squeeze) has not been carried through of the latest versions of the LHC optics; this requires an update of the work in [12].

IR2 also contains the injection region for Beam 1 which imposes a constraint on the phase advance between the injection kicker and the TDI protection dump. It turns out that it is not possible to match an "alignment optics" for IR2 respecting this constraint because the low-beta triplet quadrupoles have to be switched off. Nevertheless, if and when an alignment of the IR2 triplet turns to be necessary, it is always possible to carry through the alignment procedure using Beam 2, which is injected into IR8. A suitable alignment optics has recently been matched [13] and is shown in Figure 1. The alignment procedure could be done with protons and this optics would in fact allow IR1 and IR5 to be done at the same time with obvious advantages for scheduling.

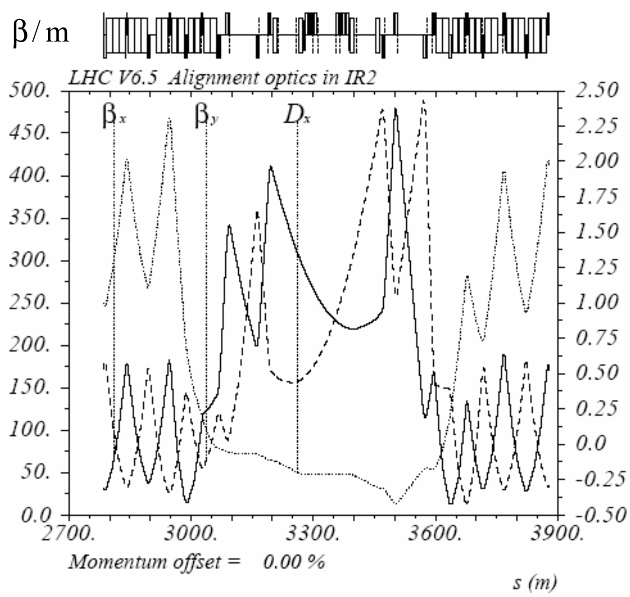

Figure 1 Alignment optics for IR2 [13]

Longitudinal dynamics and RF

The most significant differences in the basic machine settings between protons and ions are those of the RF system. The relevant parameters are listed in the Design Report [3]; they include the reduction of the longitudinal emittance at injection from the SPS since we no longer expect to have the 200 MHz RF system for capture.

The RF frequency required to keep an ion of charge Q_{ion} and mass m_{ion} on the central orbit of circumference C with harmonic number h_{RF} is

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

where p_p is the momentum of a proton in the same bending field. As shown in Figure 2, the frequency swing during the ramp is rather greater than for protons. However this is well within the tuning range of the RF system.

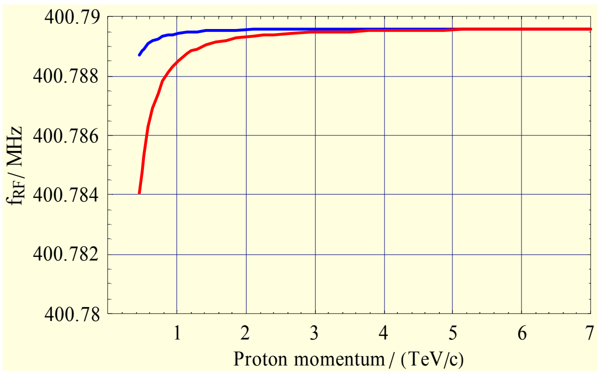

Figure 2 RF frequency variation during the LHC ramp for protons (blue) and $^{208}Pb^{82+}$ ions (red).

The different bunch filling schemes can also be accommodated straightforwardly.

As noted in [3] and in [8], it will be necessary to use artificial RF noise in a continuous fashion to increase the longitudinal emittance at top energy in order to reduce the blow-up of the transverse emittance by intra-beam scattering (IBS). It may be that this happens naturally because of intrinsic RF noise but it is not presently possible to estimate its strength. The operational feasibility of this technique will be clarified by machine development studies in the SPS.

PLAN FOR COMMISSIONING LHC RINGS WITH LEAD IONS

Having discussed the main practical differences between proton and ion operation, I can now outline a plan for commissioning the LHC main rings with lead ions. Many procedures will be similar to those for protons and I will not repeat details that can be found in some of the talks given earlier today.

First, I would like to mention some pre-requisites that should be thought about by all everyone in charge of LHC systems:

- All systems (software and hardware interlocks, instrumentation, etc.) should "know about", and do the right thing by, all species of ions that might one day be stored in the LHC. This may sound trivial and I know that in most cases the point is well taken but we must all beware of designing anything with the assumption that the beam is composed of protons! Whenever the particle charge, mass, energy or beam momentum appear, our systems and software must have sufficient generality.
- This will avoid any cases where the machine is inadequately protected from ion beams and, more likely, any unnecessary "safety" impediments to ion operation.
- Let us assume that protons can be collided, so the necessary injection, ramp, squeeze (where applicable) conditions are set up.

Then the steps required to commission the machine with ions are, briefly:

1. Re-commission injection and first turns with single ion "pilot" bunch. Adjust Beam Synchronous Timing and instrumentation.
2. Take care of any energy mismatch due to the different SPS cycle; in each ring.
3. Deal with any difference of geometric size of the injected beam from protons (collimator settings, etc.)
4. Set up RF and capture.
5. Re-commission ramp. Deal with any difference of geometric beam size from protons (collimator settings, etc.)
6. Commission squeeze of IP2 (if applicable), including appropriate crossing angle with ALICE spectrometer bump.
7. Alignment of IR2 triplet quadrupoles if necessary.
8. Collide Pb-Pb beams.
9. Re-optimise collimation, measurements, etc.

As explained above, steps 1 and 5 should be relatively easy if they have already been done for protons (magnetic reproducibility).

Step 6 appears to be the most substantial and could take a few days. We shall have a better idea when the squeezes of IR1 and IR5 have been carried out. It may—or may not—be operationally convenient to carry out the squeeze of IR2 first with low-intensity protons. This is an option to be kept in mind in the period preceding the switchover to ions. Step 7 is unlikely to be needed.

The Early Scheme is meant to provide at least 4 weeks of physics for ALICE, ATLAS, CMS in 2008. Like other speakers, I can only make an educated guess as to the time required to do this. Calibrating my degree of optimism or pessimism by following as closely as possible to the time estimates given in [14], I would estimate that the ion commissioning phase will take less than a week. I stress that this will have to be reviewed in the light of the experience with protons!

Evolution to nominal luminosity

The Early Scheme is just the beginning of course. As soon as it is running we will have to turn our minds to the evolution to the Nominal Scheme with $k_b = 592$. Indeed, an essential purpose of the Early Scheme, beyond yielding initial physics in safe conditions, is to allow us to explore the limits to performance that are expected to set in at higher intensity. If the total beam current is limited (by collimation, say) then the strategy will be to put the total current into fewer bunches. A straightforward way to do this is to simply drop pulses from ends of trains as required. Thus the pattern

$$8\ 13\ 13 \quad 12\ 13\ 13 \quad 12\ 13\ 13 \quad 12\ 13\ 13 \qquad (2)$$

corresponding to the Nominal $k_b = 592$ (where each unit represents a pulse of 4 bunches) might become, for example,

$$7\,7\,7 \quad 7\,7\,7 \quad 7\,7\,7 \quad 7\,7\,7 \qquad (3)$$

yielding a total bunch number $k_b = 336$.

AN OPPORTUNITY

As will be discussed in a later talk [16], ions should be ready for injection into the LHC in the spring of 2008. They may be ready even earlier if it turns out to be possible to commission the ion cycle in the SPS in 2006. Thus, depending on the advancement of the whole commissioning process, it may well happen that ions are available at an early stage in the commissioning of the machine with protons. In particular, they may be available at the time when the very first proton collisions have been achieved in the so-called Pilot Run with the parameters given in the first column of Table 3.

Beam energy (TeV)	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0	6.0, 6.5 or 7.0
Number of bunches (per beam)	43	43	156
β* in IP 1, 2, 5, 8 (m)	18,10,18,10	2,10,2,10	2,10,2,10
Crossing Angle (μR)	0	0	0
Transverse emittance (μm)	3.75	3.75	3.75
Bunch spacing (μs)	2.025	2.025	0.525
Bunch Intensity	$1\ 10^{10}$	$4\ 10^{10}$	$4\ 10^{10}$
Luminosity in IP 1 & 5 ($cm^{-2} s^{-1}$)	$\sim 3\ 10^{28}$	$\sim 5\ 10^{30}$	$\sim 2\ 10^{31}$
Luminosity in IP 2 ($cm^{-2} s^{-1}$)	$\sim 6\ 10^{28}$	$\sim 1\ 10^{30}$	$\sim 4\ 10^{30}$

Table 3 Parameters for protons in early commissioning, reproduced from [17].

These conditions actually constitute the *minimum* pre-requisites for switching from protons to ions. The squeeze of IR2—the biggest step in the commissioning plan for the Early Scheme—is not necessary. The proton luminosity would be so low that ALICE would be taking head-on collisions. If the injection, ramp and collisions work with protons then *no significant change to the magnetic machine is required in order to switch to colliding ions.* The main thing to be done is the RF capture.

These parameters would yield a luminosity $L = (\text{few}) \times 10^{24}$ cm^{-2}s^{-1} which does not sound like much but would nevertheless yield of the order of $\sim 10^5$ events in a few hours, maybe a day of running. Of course operational efficiency may not be high at this stage but the luminosity lifetime should be of the order of days.

Yet, as pointed out by the heavy-ion physics community, *this would already yield significant physics results.*

Of course it should be stressed that such a "Pilot Pb-Ion Run" would be a wonderful opportunity that could be seized if circumstances are right but does not in any sense replace the Early Scheme run.

PERFORMANCE AND ITS LIMITS

Evolution during a fill

The subject of the evolution of luminosity during a fill has been studied previously by several authors (see, for example [19] and references therein). During the past year, we have revisited this topic and included various physical effects that were not previously included. The present model solves a set of coupled ordinary differential equations [8] for the evolution of the emittances and bunch intensities and includes the following physical processes:

- Beam loss by nuclear scattering and electromagnetic dissociation on residual gas molecules
- Emittance blow-up from multiple scattering on residual gas
- Beam losses from collisions (nuclear and electromagnetic interactions) depending on the number of experiments illuminated and β^*
- Intra-beam scattering (Bjorken-Mtingwa theory with complete LHC optics)
- Synchrotron radiation damping
- RF noise
- Unequal beam sizes and intensities
- Any ion species (including protons)

Previous calculations did not include the effect of synchrotron radiation damping which we now expect to be of significant benefit to lead ion operation (lead ions damp twice as fast as protons [3,8]). It provides rather slow but free bunched-beam cooling at collision energy which is more than enough to cancel the blow-up of emittance due to IBS and can be expected to help clean the beam halo. The significance of this effect can be appreciated from Figure 4. The upper set of curves shows the expected evolution of the transverse emittance without radiation damping. Each curve in the family corresponds to a different number of experiments illuminated. The lower set of curves shows the same thing with radiation damping switched on and an RF noise intensity D_{RF} chosen to increase ε_l to 3 eV s over the first two hours.

Radiation damping is also very helpful as a remedy against any emittance blow-up during the ramp [8].

Figure 3 shows the expected evolution in the Nominal Scheme and how it is affected by increasing the number of experiments illuminated. Average luminosity depends strongly on time taken to dump, recycle, refill, ramp and re-tune machine for collisions. For this reason, fills may be quite long in the early days of operation. Figure 5 shows how the average luminosity depends on t_{run}, the time the beams are kept in collision with the assumption that the time taken to from dumping a fill to putting beams back in collision is 3 h and that fills start with the design parameters for peak luminosity. With just one experiment, the optimum t_{run} is about 8 h while, with 3 experiments active, it drops to about 5 h.

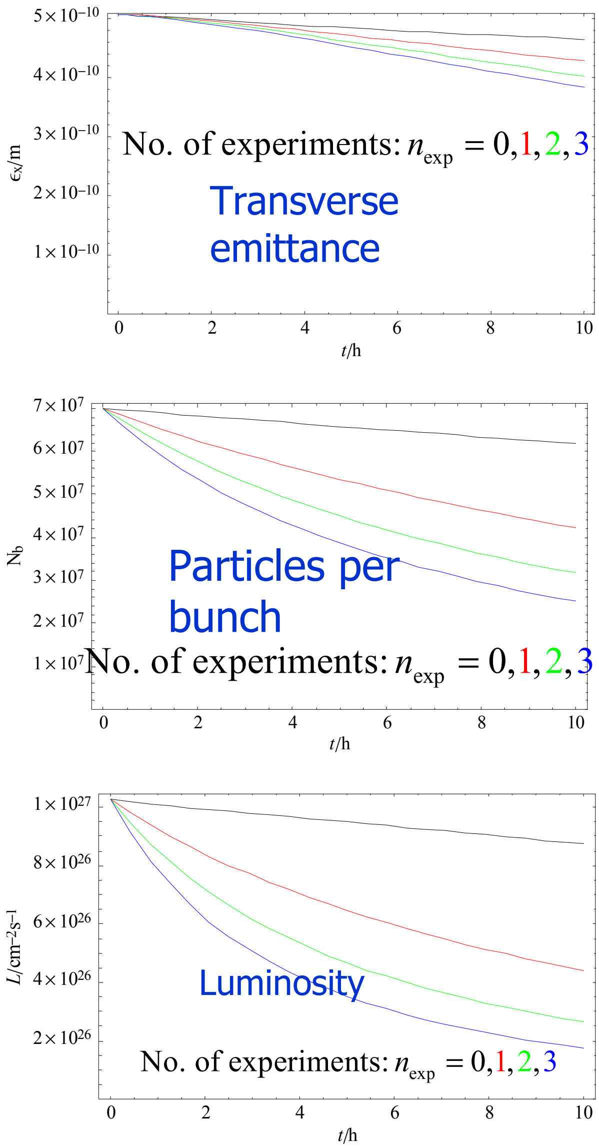

Figure 3 Evolution of emittance, bunch intensity and luminosity in the Nominal Scheme.

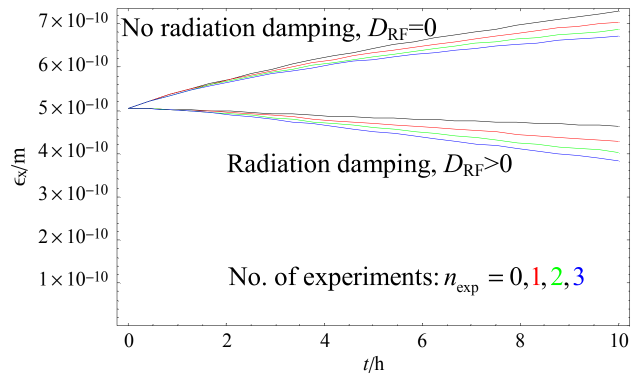

Figure 4 Effect of radiation damping on emittance starting from the nominal beam parameters.

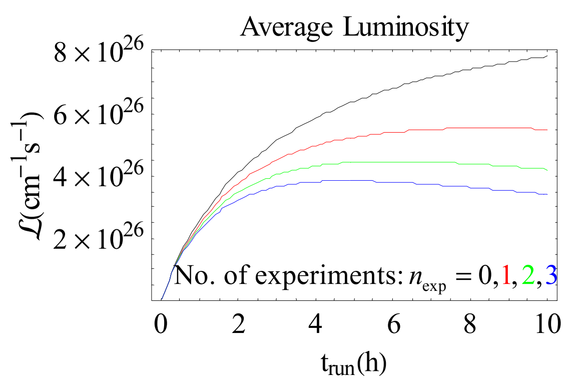

Figure 5 Average luminosity as a function of time beams are kept in collision.

Lifetimes are longer in the Early Scheme, thanks mainly to the higher $\beta^* = 1$ m than in the Nominal Scheme.; see Figure 6. This has the consequence that longer fills will be advantageous in the early operation.

PERFORMANCE LIMITS

There are two main performance limits for Pb-Pb operation of the LHC.

Collimation

Although the stored beam energy is much lower, collimation of ion beams is more complicated than proton beams [15] because ions fragment into many isotopes of different magnetic rigidity. A special simulation program, apparently the first of its kind, has been developed in the I-LHC project [15]. It is not possible, for example, to respect appropriate phase conditions between primary and secondary collimators and the presently envisaged collimation system will act like a single-stage collimation system for the ions. By the usual criterion, that the collimation system should protect the machine and prevent magnets from quenching once the lifetime due to *non-collisional processes* reaches 12

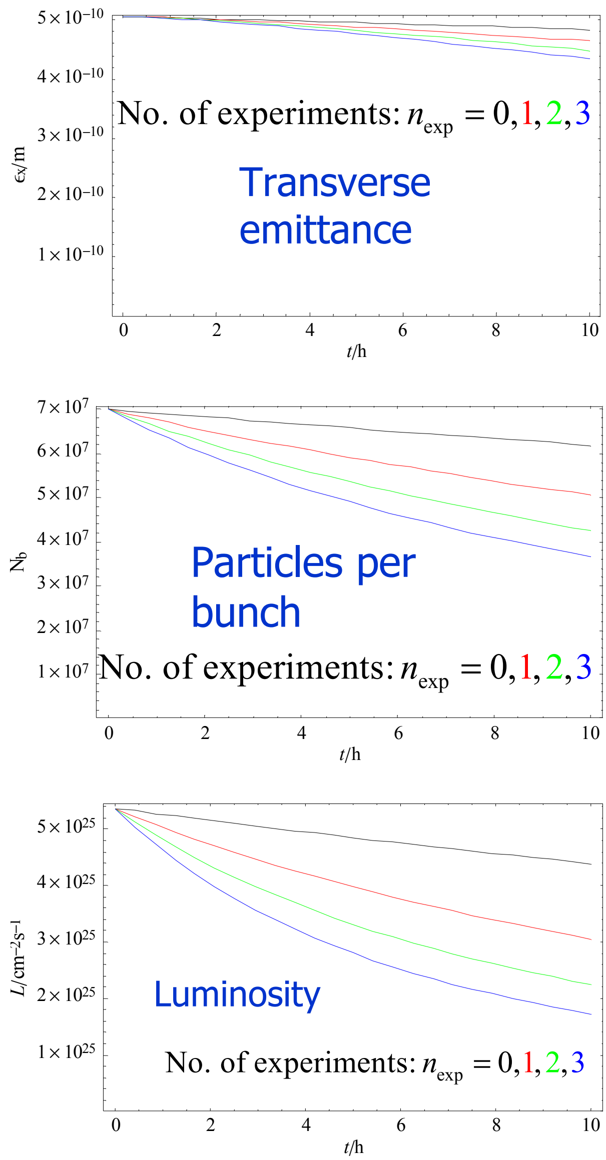

Figure 6 Evolution of emittance, bunch intensity and luminosity in the Early Scheme.

min, the present simulation results indicated that the total beam current will be limited to a value some 2–3 times below that of the Nominal Scheme.

In this respect, the situation is very similar to that of protons where an upgrade to the first phase collimation scheme will be necessary in order to reach the full design current and luminosity. At present, we do not have a solution that works on paper for the nominal luminosity of lead ions. On the other hand, it should be mentioned that:

- There are many uncertainties in the simulations; work is going on to resolve them although the manpower available in the I-LHC project is severely limited.
- The limit is expected to be well above the performance level of the Early Scheme so there are good prospects for increasing luminosity gradually by increasing the number of bunches.
- The limit depends on minimum lifetime accepted; as mentioned for the protons, we may be able to work with a value greater than 12 min.
- It will be important to study the loss distributions in the Early Scheme.
- Some effort is presently being made to compare the predictions of the special ion collimation simulation with measurements at RHIC.
- If a hardware solution can be found, either before or after start-up of the LHC, we need to identify an opportunity to schedule the appropriate installation.

Bound-Free Pair Production (BFPP)

This effect (which was formerly, somewhat inaccurately called "ECPP") is a direct limit on luminosity (see [8] and further references therein). Considerable progress is now being made in computing the energy deposition in the superconducting magnets of the dispersion suppressor that may be quenched by the secondary beam of $^{208}Pb^{81+}$ ions emerging from each IP.

Both this and the collimation studies require detailed understanding of the fundamental physics of extremely high energy heavy ions interacting with matter. Figure 7 shows, roughly speaking, the analogue of the traditional Bethe-Bloch theory for ion beams; "LS" denotes the Lindhard-Sorensen theory. Inclusion of the finite nuclear size suppresses the rise of the energy loss at high energy, giving the curve 1). However the additional contribution from pair production in the material dramatically increases it again the energy deposition at Pb ion energies typical of the LHC beam giving the curve 2). This physics is now being incorporated into the FLUKA program.

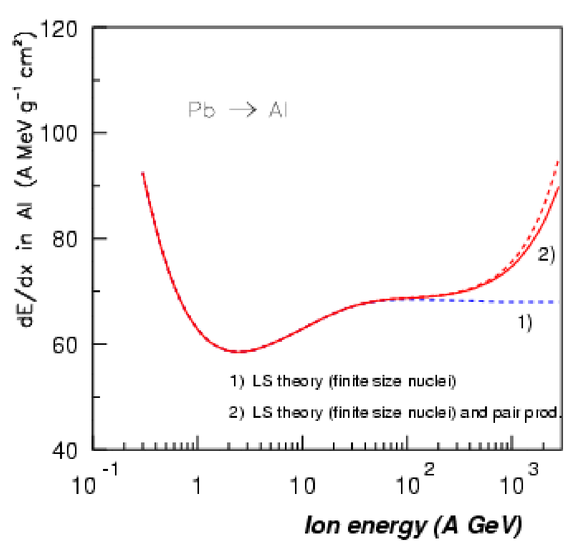

Figure 7 Energy loss of high energy Pb ions in in Al [20].

Results of a preliminary FLUKA simulation of the impact of the $^{208}Pb^{81+}$ ion beam in an LHC cryo-dipole are shown in Figure 9 and Figure 10. The main goals of these calculations are estimate the luminosity level at which quenches are likely to occur, to relate losses to signals on beam loss monitors outside the magnets and to study possibilities for alleviation of the problem. Computing requirements are heavier than for protons, again because ions fragment into many isotopes. However very good progress is being made now and the next step is to verify our understanding of the relationship between energy deposition in small volumes of the superconducting coils and the magnet quenches.

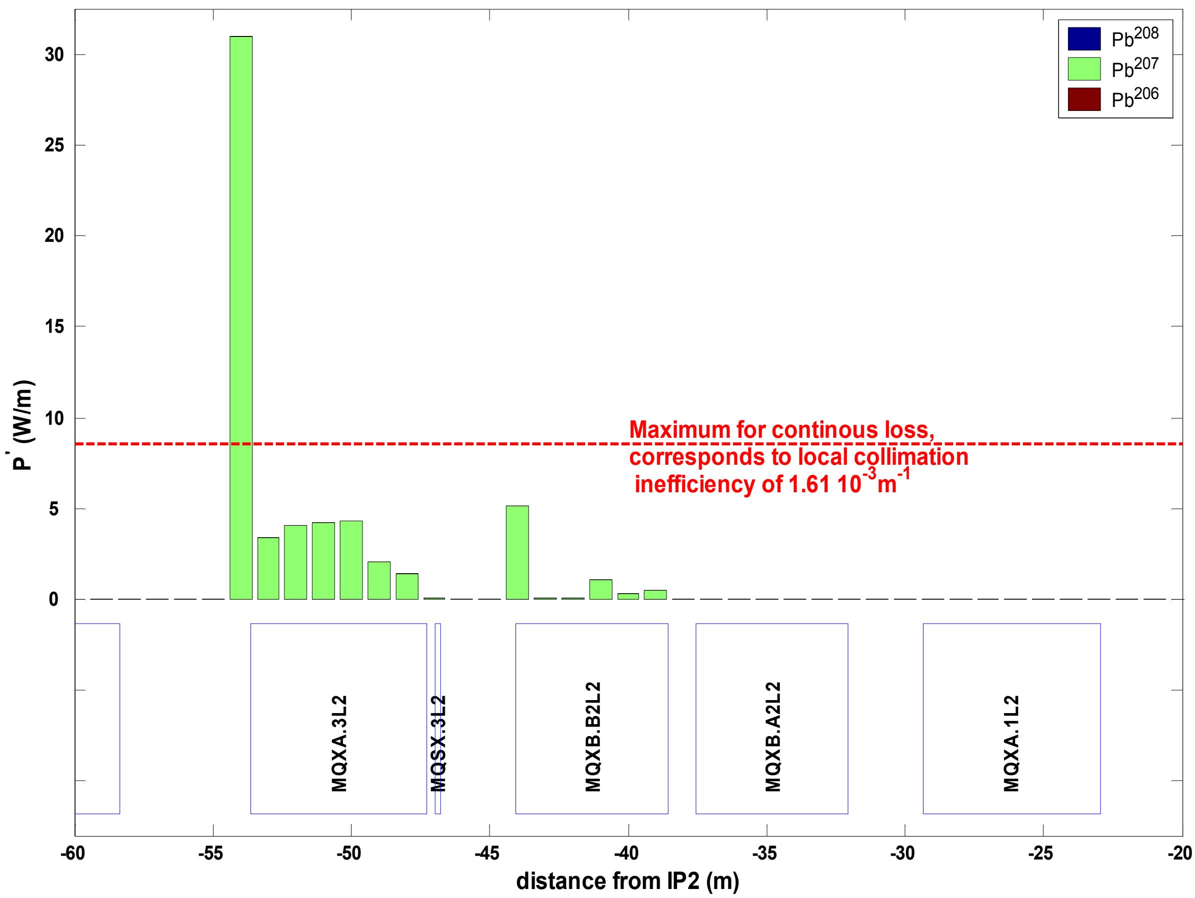

Figure 8 A critical region of the ion loss map near IP2 for non-collisional loss rates corresponding to a beam lifetime of 12 min; from the simulations described in [15].

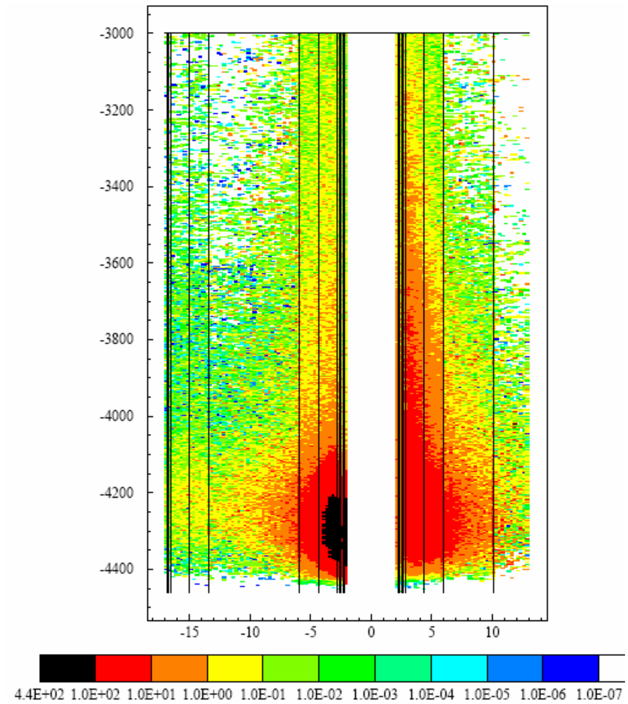

Figure 9 Heat deposition from BFPP in a horizontal plane passing through the middle of the beam pipe inside a cryo-dipole. The beam hits the inner surface of the beam screen right of IP2. The height of the plot corresponds to the length of the magnet and the other magnet aperture is to the left of the region shown.

SCHEDULING HEAVY-ION RUNS

Before winding up, I would like to summarise some general considerations relevant for scheduling LHC operation.

When scheduling periods of ion operation, great care will be taken to optimise the use of the precious resource of beam time. The choice of configuration (optics, separation bumps, etc.) should be as close as possible to whatever is established and working for proton operation at the time. This will minimise re-commissioning and setup time. This will be especially so in the first year of operation when the Early Scheme will have to be commissioned and brought into operation.

Many of the potential difficulties with commissioning proton operation need not delay ion operation.

Heavy-Ion runs will provide radiological relief to the accelerator complex by helping to avoid problems of over-activation of the PS-SPS complex and LHC by high proton intensity proton beams. They also provide useful cool-down periods afterwards.

We should not forget the need for machine development time in the early running periods in order to explore the performance limits.

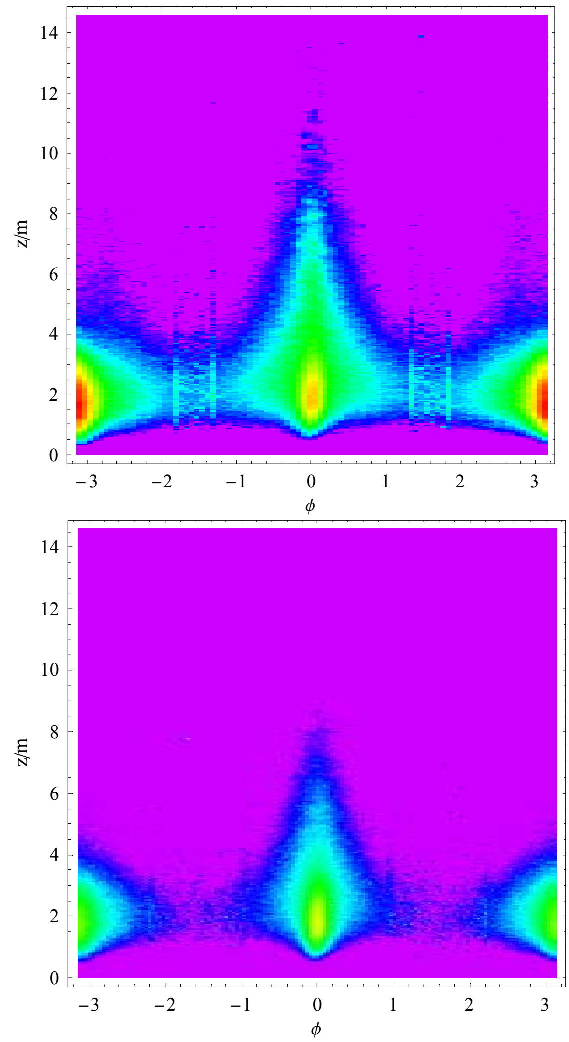

Figure 10 Heat deposition from BFPP in the inner (upper frame) and outer (lower frame) superconducting coils. This is an "unwrapped" view of the coil layer: the horizontal axis is the azimuthal angle around the beam direction and the height of the plot again corresponds to the length of a magnet. The beam impact point is on the left hand edge of the plots.

CONCLUSIONS

In general terms, there is little reason to deviate from the plan laid down after the Chamonix workshop in 2003:

- Operation with the Early Ion Scheme for ALICE, ATLAS and CMS can be scheduled in the first year of LHC operation.
- Present estimates are that this will require at least 1 week of setup time before about 4 weeks of physics.
- Careful handling should allow the changeover from proton to ion operation to be done without too many changes to the operational cycle; the most substantial will be the squeeze of IR2.
- There will very likely be an opportunity for an additional Pilot Ion Run with the potential for

significant physics results at very low scheduling cost (about a day) at a very early stage of LHC operation.

- Performance limits for Pb-Pb collisions will be explored with Early Scheme (MD time). Good progress is also being made in present studies.
- After the Early Scheme run, the number of bunches will be increased towards the nominal values to complete the first phase of LHC ion programme (Pb-Pb).
- Scheduling heavy-ion runs has advantages for overall operation of the CERN accelerator complex.

Acknowledgements

I would like to mention several colleagues who have contributed directly to this talk: Hans Braun, Roderik Bruce, Christian Carli, Alfredo Ferrari, Simone Gilardoni, Moira Gresham, Mateo Magistris, Stephan Maury, Amy Nicholson, Adriana Rossi, Karlheinz Schindl, George Smirnov and André Verdier. Thanks for valuable discussions and information are also due to others, too numerous to mention, in the I-LHC and wider LHC projects and at RHIC.

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