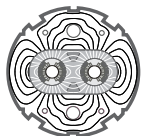EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

CERN-LHC-Project-Report-1084

The LHC as a Nucleus-Nucleus Collider

John M. Jowett

Abstract

This paper begins with a summary of the status of the Large Hadron Collider at CERN, including the lead-ion injector chain and the plans for the first phases of commissioning and operation with colliding proton beams. In a later phase, the LHC will collide lead nuclei at centre-of-mass energies of 5.5 TeV per colliding nucleon pair. This leap to 28 times beyond what is presently accessible will open up a new regime, not only in the experimental study of nuclear matter, but also in the beam physics of hadron colliders. Ultraperipheral and hadronic interactions of highly-charged beam nuclei will cause beam losses that dominate the luminosity decay and may quench superconducting magnets, setting upper limits on luminosity and stored beam current. Lower limits are set by beam instrumentation. On the other hand, coherent radiation by the nuclear charges should provide natural cooling to overcome intra-beam scattering. As with protons, a flexible, staged approach to full performance will test the limits and make optimal use of scheduled beam time.

Invited Paper at Quark Matter 2008, 20th International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions
Jaipur, India - 4-10 February 2008

CERN-LHC-PROJECT-REPORT-1084
30 Jun 2008

The LHC as a Nucleus-Nucleus Collider

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1. Introduction

CERN and its world-wide network of collaborating institutions are almost at the end of the long road from the first public "Feasibility Study of a Large Hadron Collider in the LEP Tunnel" in 1984 [1] to colliding protons and heavy (lead) nuclei in the LHC. A recent survey of the machine design, superconducting technology and the accelerator physics relevant to its performance as a proton collider can be found in [2]. After a brief update on the status (as of February 2008), this paper will describe the LHC's second role as an ultra-relativistic nucleus-nucleus collider, with emphasis on performance expectations and the physical phenomena that will limit luminosity. The heavy-ion physics programme itself is described in other papers at this conference.

The project has required a host of technological developments [2, 3] of which industrial scale production of the 15 m long dipole magnet is the most prominent. There will be 1232 of these, operating with their superconducting coils bathed in superfluid helium at a temperature of 1.9 K.

Inevitably, in such a large and immensely complex enterprise there have been a few setbacks. Well-known examples were difficulties with the main cryogenic helium transport line, the low-β triplet quadrupoles and the interconnect modules that have to keep the beam impedance low while compensating the thermal expansion of sections of the beam screen (inside the vacuum chamber) during warm-up and cool-down of the machine. As part of the enormous efforts made in recent years to minimise slippage of the schedule, technical solutions have been found and implemented. Installation of the collider's hardware is now complete and hardware, then beam, commissioning will soon be under way.

1.1. Luminosities

The nucleon-nucleon luminosity, L_{NN}, and ion luminosity, L, of the LHC are given by

$$L_{\mathrm{NN}} = A^2 L = \frac{A^2 N_b^2 k_b f_0}{4\pi \sigma_x \sigma_y} F(\theta_c, \sigma^*, \sigma_z) = \frac{A^2 N_b^2 k_b f_0 \gamma}{4\pi \, \epsilon_n \beta^*} F(\theta_c, \sigma^*, \sigma_z) \qquad (1)$$

where f_0 is the revolution frequency, N_b is number of particles (protons or ions) per bunch, k_b is the number of bunches per beam, $\gamma = E/(mc^2)$ is the usual relativistic factor; $\epsilon_n = \sqrt{\gamma^2 - 1}\,\sigma_{x,y}^2/\beta^*$ is the "normalised" (independent of beam momentum p) emittance related to the beam size σ^* and β^*, the optical function at the interaction point (IP) (the beams are round so these quantities are the same in both planes); finally, $F(\theta_c, \sigma^*, \sigma_z) = (1 + (\theta_c \sigma_z/2\sigma^*)^2)^{-1}$ is a reduction factor from the half-crossing angle, θ_c, and bunch length σ_z.

With its nominal bending field of 8.3 T, the LHC will provide collisions at the centre-of-mass energy

$$\sqrt{s} = \begin{cases} 14 \, \mathrm{TeV} & \text{(p-p)} \\ 1.15 \, \mathrm{PeV} = 5.52 \, A \, \mathrm{TeV} & (^{208}\mathrm{Pb}^{82+} \text{--}^{208}\mathrm{Pb}^{82+}) \end{cases} \qquad (2)$$

in the first years of operation, eventually aiming for the design nucleon-nucleon luminosities

$$L_{\mathrm{NN}} \approx \begin{cases} 10^{34}\,\mathrm{cm^{-2}\,s^{-1}} & \text{(p-p)} \\ 4.3 \times 10^{31}\,\mathrm{cm^{-2}\,s^{-1}} \;= 10^{27}A^2\mathrm{cm^{-2}\,s^{-1}} & \left(^{208}\mathrm{Pb}^{82+}\!-\!^{208}\mathrm{Pb}^{82+}\right) \end{cases} \tag{3}$$

Each of the four large experiments will study p-p collisions while heavy-ion (nuclear) collisions will be provided to ALICE, ATLAS and CMS.

2. Present status of the LHC

2.1. Schedule

At present, we expect the whole machine to be cold by early June 2008, some 2-3 weeks behind the schedule published in October 2007. The schedule, which is constantly updated at [4], is technically feasible but remains sensitive to any major new problem.

Proton commissioning and operation for physics will continue through 2008 and 2009. At present, the target date for the first Pb-Pb collisions is at the end of the 2009 run, before the winter shutdown. The ion injectors will not run in 2008 and must be made ready earlier in 2009.

2.2. Commissioning with proton beams

Since the injector chain and transfer lines from the SPS to the LHC are already fully capable of delivering the required proton beams, commissioning of the accelerator with protons will start with procedures to achieve injection, RF capture and good lifetime at injection energy for single, moderate intensity bunches. Thereafter commissioning will proceed in defined stages (labelled A–D), gradually increasing k_b, N_b and "squeezing" β^* to smaller values. Further details of the beam parameters and procedures are given under "Commissioning" at [4].

Experience of previous colliders shows that it is hard to predict the time necessary to achieve first collisions although the estimate for the LHC is about 2 months. This machine will require particular care to establish a precise knowledge of the orbit and beam optics. The aperture available to the beam is small and the stored energy in the beams will be quite unprecedented. Therefore the luminosity attainable will depend on the ability to protect the machine from losses ($\sim 1/\beta^*$), experience with the collimation system and other factors. Unlike any previous collider, the collimation system's primary purpose is to clean the beam and protect the machine rather than to reduce backgrounds in the experiments.

3. Ion Injector Chain

The heavy ion beams required for the LHC are much more demanding in intensity and emittance than those used in the SPS fixed target programme. This has required a new electron-cyclotron resonance (ECR) ion source, the electron cooling ring LEIR and

many other changes and upgrades to the CERN injector complex [5]. Together these constituted the bulk of the cost of the "Ions for LHC" project.

Two reference sets of LHC beam parameters (dubbed "Early" and "Nominal") correspond to different modes of operation of the injectors (see [3, 5] and Table 1).

The status of the injector chain was most recently reviewed in [6]; only more recent developments are summarised in the following.

Source and Linac3 achieved adequate intensity for Early beam (record of 31 e μA of Pb^{54+} out of the linac). The stability and reliability required for Nominal beam will be supplied by an upgrade of the source generator to 18 GHz. Numerous other improvements have been implemented or are on the way.

LEIR is working well for the Early beam and there has been progress towards Nominal.

PS and transfer lines will require further work for the Nominal beam.

SPS was commissioned for ions in late 2007 although there were substantial delays with some hardware. The Early beam parameters were essentially achieved but there are concerns about beam losses on the longer injection plateau needed for Nominal. If these are not reduced by further development on the RF system, it may be necessary to change the LHC filling scheme to shorten the plateau. Nevertheless a ^{208}Pb^{82+} beam was ejected along one of the transfer lines from the SPS towards the LHC.

4. Pb-Pb collisions

Historically, the Nominal parameters (Table 1) were defined, on the basis of experimental requirements, many years ago. The ion injector chain was accordingly designed to provide appropriate beam intensities. More recently, it was recognised that the Pb-Pb luminosity in the LHC might be limited by new beam physics effects, not seen in any previous collider. A peak luminosity $L_0 \simeq 10^{27}$cm^{-2}s^{-1} has been kept as a goal although quantitative uncertainties in the performance limits (discussed below) might limit it to values 2–3 times less.

The Early parameters (Table 1) were introduced more recently [3] as a first step in a staged commissioning plan, allowing more rapid commissioning of the injectors, exploration of the new performance limits in the LHC itself, and a luminosity sufficient for initial physics.

Ultraperipheral and hadronic interactions of beam nuclei with other nuclei, either in the opposing colliding beam or in the stationary beam environment are at the root of the main performance limits of the LHC when it collides heavy nuclei.

4.1. Ultraperipheral collision processes

The cross section for free e$^+$e$^-$ pair-production in collisions of nuclei with charges Z_1 and Z_2 is $\sigma_{PP} \propto Z_1^2 Z_2^2 \approx 2. \times 10^4$ b for Pb-Pb at the LHC. A small fraction of the

Parameter	Units	Nominal	Early
Energy/nucleon	TeV	2.76	
Peak luminosity L_0	$cm^{-2}s^{-1}$	$\sim 10^{27}$	$\sim 5. \times 10^{25}$
No. of bunches k_b		592	62
Bunch spacing	ns	99.8	1350
Optics (β^*) at IP2/IP1,5	m	0.5/0.55	1.0
No. of Pb ions/bunch N_b		$7. \times 10^7$	
Transverse normalised RMS emittance ϵ_n	μm	1.5	
Longitudinal emittance/charge ϵ_l	eV s	2.5	
Luminosity half-life (1,2,3 experiments)	h	8, 4.5, 3	14, 7.5, 5.5

Table 1. Selected performance parameters for the "Nominal" and "Early" Pb-Pb collision modes; for full details see chapter 21 of [3].

pairs are produced with the electron bound to one nucleus in *bound-free pair production* (BFPP):

$$Z_1 + Z_2 \rightarrow \left(Z_1 + e^-\right)_{1s_{1/2},\ldots} + e^+ + Z_2 \tag{4}$$

and with a cross section [7] depending much more strongly on Z:

$$\sigma_{\text{BFPP}} \simeq Z_1^5 Z_2^2 \left[A \log \gamma_{CM} + B\right] \approx 281 \text{ b}, \tag{5}$$

for Pb-Pb at the LHC; [7] gives values for the constants A and B. This process, together with the electromagnetic dissociation (EMD) via the Giant Dipole Resonance

$$^{208}\text{Pb}^{82+} +^{208}\text{Pb}^{82+} \longrightarrow^{208}\text{Pb}^{82+} +^{207}\text{Pb}^{82+} + \text{n} \tag{6}$$
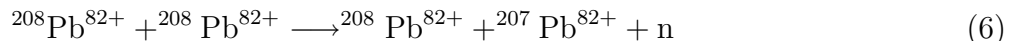
dominates the intensity loss ("burn-off") from collisions [8, 9]. The collision products have a different charge-to-mass ratio and are lost from the main beam [10]. The beam aperture and optics are such that the $^{207}\text{Pb}^{82+}$ nuclei produced by EMD are lost safely in the momentum collimation system. However the beams of $^{208}\text{Pb}^{81+}$ ions from BFPP, emerging from each side of each collision point, strike the beam screen inside one of the first superconducting bending magnets at the start of the main arc (the dispersion suppressor section) of the LHC. The 281 kHz loss rate at nominal luminosity generates 25 W of heating power in a ~ 1 m long spot.

Detailed analysis [11], including simulations of the hadronic showers, and revised estimates of the tolerable energy deposition (thermodynamics of liquid He and heat transfer), suggest that the magnets are not likely to quench because of BFPP beam losses; however, quenches remain possible within the uncertainties. Additional beam loss monitors have been installed around the IPs to monitor these losses in LHC operation and strategies are being prepared to redistribute them to some extent.

Despite much smaller rates during the RHIC Cu-Cu run, it was just possible to detect this process [12] and test the methodology used to predict the energy deposition in the magnet coils and signals on beam loss monitors in the LHC.
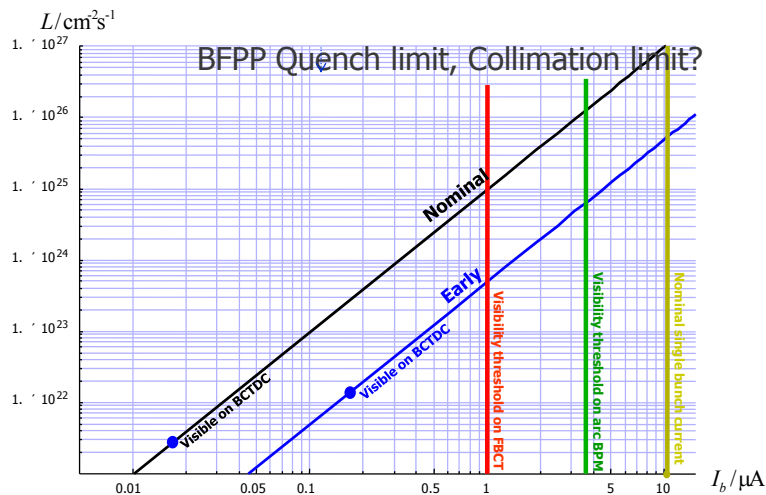
Figure 1. Luminosity, L, vs. single bunch current I_b, limited from below by the dynamic range of BPMs and current monitors (BCTDC, FBCT) for both Early and Nominal bunch filling schemes. L is limited by BFPP and total current $k_b I_b$ by collimation inefficiency. Operation is restricted to the diamond at upper right.

4.1.1. Collimation inefficiency The collimation system is essential to protect the LHC machine from particles that would be lost causing magnet quenches or damage.

The principle of collimation for protons is that particles at large amplitudes undergo multiple Coulomb scattering in a sufficiently long, (carbon) primary collimator, deviating their trajectories onto properly placed secondary collimators which absorb them in hadronic showers. However ions undergo nuclear fragmentation or EMD before scattering enough so the secondary collimators are ineffective [13]. The machine then acts as a spectrometer with isotopes lost in other locations, including superconducting magnets, with consequences as described above. Simulation of these processes requires detailed nuclear physics input with cross sections for many fragment channels. Again, the results suggested the locations of additional beam monitors.

This may turn out to be a more severe limit on Pb-Pb luminosity than BFPP. Nevertheless it should be kept in mind that the conventional (1996) quench limit (tolerable heat deposition in superconducting magnet coils) now appears pessimistic. This is also a soft limit: losses are evaluated with the hypothesis that the single-beam (not including collisional) losses have reached a level corresponding to a lifetime of 12 min. Meanwhile the simulations have been successfully benchmarked with Pb beams and an LHC collimator in SPS.

Since there will be a Phase 2 Collimation upgrade for p-p operation, we are looking at what might be included to improve collimation efficiency for ion beams (cryogenic collimators, crystals, magnetic collimation, optics changes, etc.)

4.1.2. Beam Instrumentation The total charge in a Pb bunch is only a factor 3-4 above the lower limit of visibility on the beam position monitors (BPMs); therefore it

will always be necessary to inject close to nominal bunch current and (very likely) dump beams when their intensity decays below this threshold. There are similar limits on the beam current monitors, all indicated in Figure 1. Any limits on *total* bunch will be respected by adjusting the number of bunches.

The methods for measuring beam sizes and emittances are also limited, with greater reliance on beam-gas ionization monitors and Schottky spectra than for protons.

4.1.3. Beam and luminosity lifetime Once beams are put into collision, the subsequent evolution of the intensity and lifetime depends on the interplay of a number of effects. Predictions of the net results are shown in Figure 2.

Beam-gas interactions, reducing intensity and increasing emittance, are not expected to be significant once good vacuum conditions are established.

Intra-beam scattering (IBS) or multiple Coulomb scattering within bunches tends to blow up the beams on a time scale of several hours. However, since the nuclear charges radiate coherently at relevant wavelengths, the LHC ions will be the first hadron beams to be significantly affected by synchrotron radiation damping. Somewhat surprisingly, radiation damping for Pb ions is about twice as fast as for protons (see Chapter 21 of [3]) and fast enough to overcome IBS at full intensity, hence the shrinking emittance in Figure 2. In addition (although it is not immediately apparent in these plots), longitudinal RF noise is also being used to counteract the damping of the longitudinal emittance, keeping it roughly constant. This helps to reduce the effect of IBS on transverse emittances.

The intensity decay is dominated by the strong "burn-off" in collisions from the large electromagnetic cross-sections. Instantaneous beam and luminosity lifetime are reduced in proportion to the number of active experiments. This is partly compensated by the faster emittance damping as the intensity drops. But beams must also be dumped sooner and the average and time-integrated luminosity will depend strongly on the time taken to dump, recycle, refill, ramp and re-tune the machine for collisions. Clearly, the *integrated luminosity per experiment will fall as more experiments take collisions.*

4.2. Commissioning Pb-Pb collisions

The "hot-switch" to Pb-Pb collisions will be done when the LHC is already operational with protons and the ion injector chain is ready. It will not be a start-up from shutdown. The rapid commissioning strategy is based on the principle of making the absolute minimum of changes to the working p-p configuration.

The quasi-static *magnetic fields* of the LHC magnets will have *exactly the same effect on the spatial trajectory* of a Pb ion as on a proton (for equal momentum per charge, p/Z, or magnetic rigidity). Thus, all the magnetic settings established in p-p operation for the transfer, injection, ramp, and squeeze of the ATLAS and CMS collision optics should also work for Pb ions. Moreover, the nominal emittances are chosen to give equal beam sizes so all related considerations (e.g., of aperture) should be similar.
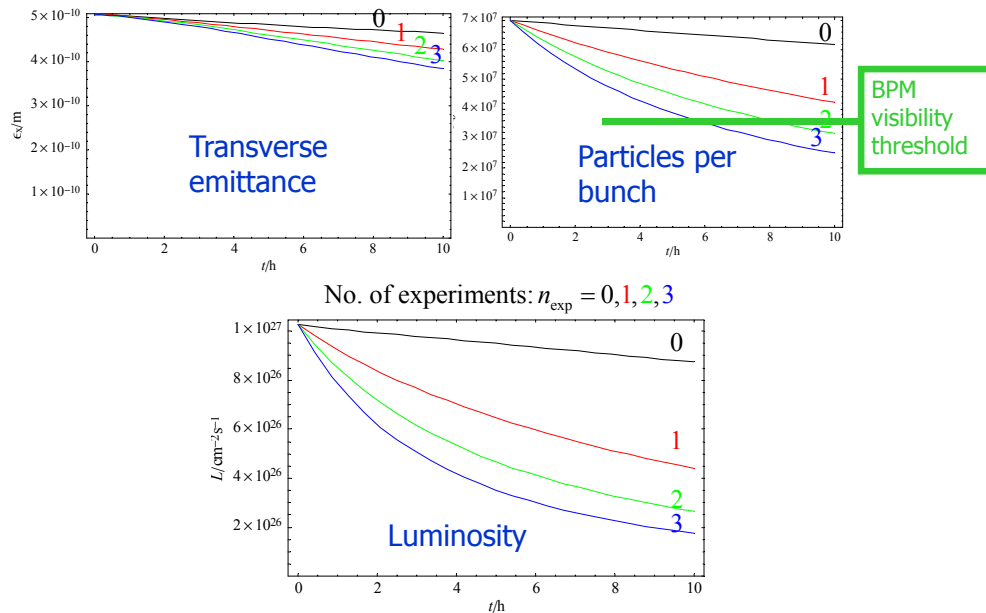
Figure 2. Evolution of emittance, bunch intensity and luminosity in an "ideal" fill, starting from design parameters giving Nominal luminosity. Cases of 0,1,2 or 3 active experiments are shown. Beams will most likely be dumped when the intensity decays to the BPM visibility threshold.

The main change to the magnetic cycle will be the completion of a β-squeeze for ALICE; we expect that the experience gained by then with the other experiments will allow this to be commissioned quite efficiently. Indeed, most or all of this setup may well have been done with proton beams.

The LHC beams see few externally applied electric fields apart from the time-dependent electric fields of the RF system, localised near Point 4. Adjustments of the RF frequency and phase will compensate for the change in speed and revolution frequency of the ions—"energy matching" and "capture" at injection, then a calculable shift at each energy in the ramp—will match the ions' orbit to that of the protons.

Other operational differences will arise from the different bunch filling patterns and adaptation of the beam instrumentation but these should generate little overhead.

This may seem inconsistent with the experience at RHIC, which has switched species several times, typically from A-A to p-p. However RHIC requires more complicated changes to the magnetic fields (transition crossing in the ion ramp, polarized proton beams) that are not necessary in the LHC. A better comparison might be with the CERN ISR which switched from p-p to light ion collisions a few times in the late 1970s. Those switches went very quickly [14], in less than a day, precisely because the

machine was kept magnetically identical.

After a first run with the Early beam, we will gradually push up the number of bunches towards Nominal, always maximising the single-bunch current within the overall limitations. As with protons, it may be worth changing the bunch filling pattern in the light of better quantitative knowledge of the performance limits.

5. Beyond Pb-Pb collisions

So far resources have been concentrated on the "baseline" of p-p and Pb-Pb collisions. However the heavy-ion physics programme at the LHC is expected to include further stages not yet scheduled within the CERN programme. These may include:

p-Pb collisions are a crucial element of the physics programme, just as d-Au collisions are at RHIC [15]. A preliminary study [16] has shown that the injector chains for protons and ions can work in tandem to efficiently fill the two LHC rings with matching bunch trains. However the two-in-one magnet design of the LHC (as opposed to the separate magnets of RHIC) means that provision of hybrid collisions in the LHC gives rise to quite different beam dynamics. Concerns have been raised about different revolution frequencies during injection and part of the energy ramp and the consequent moving beam-beam encounters. At present, [16] gives plausible indications that an acceptable luminosity can be obtained or even surpassed.

A-A collisions of lighter ions such as Ar, Ca, ..., the choice of ion being determined by the physics requirements and ease of production by the ion source.

Electron-ion collisions: If, one day, $e^{\pm}$-p collisions are implemented (the LHeC option) then it would be natural to provide $e^{\pm}$-A collisions also.

To widely varying degrees, each of these would require further study and adaptations of the CERN accelerator chain and the LHC rings themselves. Detailed scheduling will have to take into account other uses and upgrades to the LHC in the years to come.

6. Conclusions

- The LHC is on track for the first proton beams and collisions in summer 2008. The schedule nevertheless remains tight.
- The first nucleus-nucleus (Pb-Pb) collision run is expected at the end of 2009. The timing of this is very sensitive to the scheduling of beam time and resources for the ion injectors in 2009 and to the allocation of LHC beam time.
- The Pb-Pb luminosity is limited by new beam physics, particularly nuclear electromagnetic interactions that lead to energy deposition in superconducting magnet coils. Measures are being taken to monitor and alleviate these effects. Furthermore, our understanding has been steadily improving and subjected to experimental tests.

- Integrated luminosity per experiment decreases with the number of active experiments, particularly for smaller β^*.

- The programme for collision species beyond the baseline p-p and Pb-Pb remains to be established and studied.

Acknowledgements This paper outlined the work of many people, over many years. I particularly thank G. Bellodi, H. Braun, R. Bruce, C. Carli, L. Evans, A. Ferrari, W. Fischer, S. Gilardoni, D. Kuchler, D. Manglunki, S. Maury and G. Smirnov for specific input and discussions.

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