HEAVY ION BEAMS IN THE LHC

J.M. Jowett, J.-B. Jeanneret, K. Schindl, CERN, Geneva, Switzerland

Abstract

In addition to protons, the LHC will collide beams of heavy ions. The beam intensity in the LHC ring is tightly constrained from below by beam instrumentation (visibility on the beam position monitors in particular) and from above by magnet quench limits, the capabilities of the injectors and beam lifetime. We summarise current plans for beams of lead ions with emphasis on nuclear electromagnetic interactions, commissioning strategies and the differences from operation with protons.

INTRODUCTION

The LHC experiments have requested collisions between pp, Pb-Pb, p-Pb and p-A beams, where 'A' denotes one of a few possible species of light ion. Soon after start-up of the collider, Pb-Pb collisions will be provided to the heavy-ion detector ALICE and one or both of the general-purpose detectors CMS and ATLAS. The design of the chain of injectors, including the new LEIR accumulator ring, is described elsewhere [1,2].

Given that the nominal emittance of the ions corresponds to beams of the same size as the nominal protons at the same magnetic field, many considerations for protons [3] can be applied quite directly to the ions. In this paper, we concentrate on collisions between fully stripped $^{208}Pb^{82+}$ ions, highlighting some of the main issues in the main LHC ring itself. Earlier studies on the beam parameters for ions are summarised in [4].

Recall that the momentum of a fully-stripped ion of charge Z and mass number A (in AMU) in a ring with magnetic field and radius appropriate for a proton of momentum p_p is Zp_p while its momentum per nucleon is Zp_p / A. Table 1 shows some main parameters for lead ions at the nominal collision energy corresponding to $p_p = 7$ TeV.

NUCLEAR INTERACTIONS OF IONS

Besides the hadronic nuclear interactions

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\text{nuclear}} X\,, \tag{1}$$

nonlinear QED effects come into play in the peripheral collisions of heavy ions at LHC energies [5]. Cross-sections for electromagnetic interactions, notably those involving e^+e^- pair production, are very large. These processes include the familiar Rutherford elastic scattering:

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \tag{2}$$

and free pair production:

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} + e^+ + e^- \tag{3}$$

Table 1: Parameters for Pb-Pb collisions in the LHC common to all performances scenarios given later.

Energy per nucleon	E_u	2.76	TeV
Crossing angle	ϕ	~80	μrad
Transverse (RMS) normalised emittance	ε_n	1.5×10^{-6}	m
Longitudinal emittance	ε_z	2.5	eV s/charge
Bunch length (RMS)	σ_z	0.075	m
No. of experiments	n_{exp}	2 / 3	

Although copious, these two processes are harmless because the momentum changes of the ions are small.

Electron Capture by Pair Production (ECPP)

This process is closely related to (3) but the final state electron is captured by one of the ions

$$^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{81+} + e^+ \tag{4}$$

The cross section for ECPP has been discussed in numerous works; among them the extrapolation from measurements in fixed-target experiments at the SPS [6] and recent QED calculations [7]. Table I of [7] provides the best currently available estimate of the Pb-Pb ECPP cross-section at LHC energies. Summing the partial cross-sections for a few of the lowest bound states gives $\sigma_{\mathrm{ECPP}} \approx 281\,\mathrm{barn}$, significantly higher than in earlier discussions.

The magnetic rigidity of the ion is increased by the capture of the electron and the equivalent fractional momentum deviation is

$$\delta_p = \frac{1}{Z-1} = 0.012 \quad \text{for Pb} \tag{5}$$

This shifts the momentum right outside the acceptance

$$\left|\delta_p\right| > \delta_p^{\max} \approx 6\times10^{-3} \tag{6}$$

and the lost ion will follow a dispersive trajectory from the interaction point towards the downstream arc until it strikes the beam screen at a point where the horizontal dispersion function satisfies the condition

$$x_\delta(s) \approx D(s)\delta_p \approx R_{\mathrm{eff}} = 18\,\mathrm{mm} \Rightarrow D(s) \approx 1.5\,\mathrm{m} \tag{7}$$

The angle of incidence at the point of impact $x'_\delta(s) \approx D'(s)\delta_p$. To see where this point is, we inspect the example of the ions of Beam 1, travelling away from an interaction point to the right (Figure 1). Impact on the

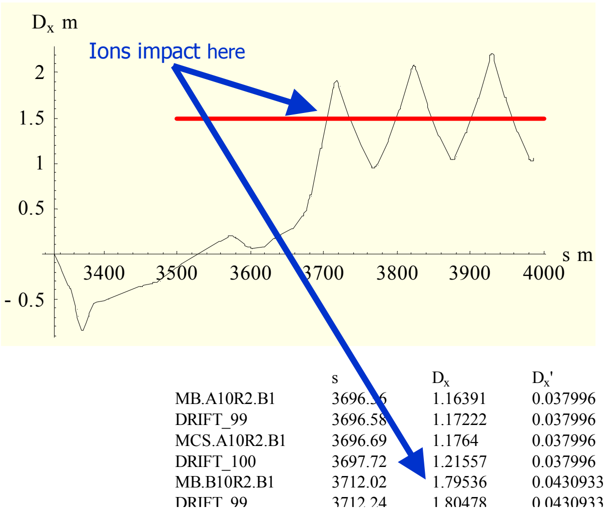

Figure 1: Identification of ion impact in the first magnet of the dispersion suppressor. The plot starts at the collision point in the ALICE detector.

beam pipe occurs inside the first superconducting dipole magnet of the dispersion suppressor (MB.B10R2.B1). A similar situation prevails for ions of Beam 2 travelling to the left and at every interaction point where ions collide.

Thus, ECPP creates secondary beams of $^{208}Pb^{81+}$ ions emerging in both directions from each collision point and hitting the beam pipe in well-defined locations [8]. The beam-pipe heating may be strong enough to quench superconducting magnets. The distance over which this secondary beam's energy is diluted, can be estimated as

$$l_d = \frac{2\sqrt{\varepsilon \beta_x + D_x{}^2 \sigma_\delta{}^2}}{D'(s)\delta_p} \approx 1.4\,\mathrm{m} \tag{8}$$

Note that this estimate assumes that the full energy is distributed over a distance corresponding to $\pm 1\sigma$ of the beam distribution in the horizontal plane. On one hand this is pessimistic because the real distribution is somewhat wider. On the other, the energy density at the peak of the distribution in the centre will be higher so the present estimate seems reasonable. The shower length, also of the order of 1 m, further dilutes the energy. Adding this "in quadrature" leaves us with $l_{\mathrm{deff}} \approx 1.7\,\mathrm{m}$.

Assuming rather complete fragmentation of the ions in the material, the quench limit for Pb ions at 7 TeV,can be inferred from that of protons by dividing by the charge

$$f_q(\mathrm{Pb}) = \frac{1.7\times 10^7\ \mathrm{p/m/s}}{Z} = 8\times 10^4\ \mathrm{Pb/m/s} \tag{9}$$

Equating this to the flux of $^{208}Pb^{81+}$ ions from the ECPP process,

$$f_q(\mathrm{Pb}) = \frac{L\,\sigma_{\mathrm{ECPP}}}{l_{\mathrm{deff}}} \tag{10}$$

Table 2: Cross sections (barn) for collisions of protons, Argon (for comparison) and Lead ions at LHC energy.

	σ_{H}	σ_{EMD}	σ_{ECPP}	σ_{tot}
p	0.1	0	4×10^{-11}	0.1
Ar	3.1	1.7	.04	4.8
Pb	8	225	281	514

shows that the luminosity is limited to $L \approx 0.5\times 10^{27}\,\mathrm{cm^{-2}s^{-1}}$, a factor 2 below the nominal [4].

The cross section increases only weakly with energy, $\sigma_{\mathrm{ECPP}} \approx A \log\gamma_{\mathrm{col}} + B$. Possible cures (e.g., collimation) and various safety factors and uncertainties in this calculation will be clarified by more detailed study.

Electromagnetic Dissociation (EMD)

One nucleus can make a transition to an excited state that subsequently decays by emitting a neutron:

$$\begin{array}{l} ^{208}\mathrm{Pb}^{82+} + {}^{208}\mathrm{Pb}^{82+} \xrightarrow{\gamma} {}^{208}\mathrm{Pb}^{82+} + ({}^{208}\mathrm{Pb}^{82+})^* \\ \qquad\qquad\qquad\qquad\qquad\qquad\qquad\downarrow \\ \qquad\qquad\qquad\qquad\qquad\qquad {}^{207}\mathrm{Pb}^{82+} + \mathrm{n} \end{array} \tag{11}$$

The change in mass number is a decrease in magnetic rigidity of the ion equivalent to a momentum deviation

$$\delta_p = -\frac{1}{A-1} = -4.8\times 10^{-3} \text{ for Pb} \tag{12}$$

from the nominal momentum. Comparing this with the momentum acceptance $\delta_p^{\max}$,

$$\begin{aligned} |\delta_p| + \sigma_\delta &= 4.8\times 10^{-3} + 0.8\times 10^{-3} \\ &< \delta_p^{\max} \approx 6\times 10^{-3} \end{aligned} \tag{13}$$

These off-momentum ions should be intercepted by the momentum collimation system. A small fraction of them, which have large enough betatron amplitude, will be lost in the nearby dispersion suppressor. Their longitudinal loss map will be large, thus making them harmless.

LUMINOSITY AND BEAM LIFETIME

The total cross-section for removal of an ion from the beam is $\sigma_{\mathrm{tot}} \approx \sigma_{\mathrm{H}} + \sigma_{\mathrm{EMD}} + \sigma_{\mathrm{ECPP}}$ (see values in Table 2). Nuclear electromagnetic processes dominate the beam loss rate. Rather than discussing the non-exponential decay during a fill, we limit ourselves here to quoting the *initial* beam (intensity) lifetime due to beam-beam interactions for a configuration in which beams collide at n_{exp} interaction points:

$$\tau_{\mathrm{I}} = \frac{k_b N_b}{n_{\mathrm{exp}} L\,\sigma_{\mathrm{tot}}} = \frac{22.4\ \mathrm{hour}}{n_{\mathrm{exp}}} \left(\frac{10^{27}\,\mathrm{cm^{-2}s^{-1}}}{L}\right) \tag{14}$$

and the initial luminosity half-life is $\tau_{L1/2} = \left(\sqrt{2}-1\right)\tau_{\mathrm{I}}$.

But the luminosity may be limited by the experiments or by the ECPP quench limit. Given that

$$L = \frac{k_b N_b^2 f_0}{4\pi\sigma^{*2}} = \frac{k_b N_b^2 f_0}{4\pi\beta^*\varepsilon_n}\gamma \qquad (15)$$

the decay could be offset by varying $\beta^* \propto N_b^2$ as the intensity decays. This "β^*-tuning" [9] would be very valuable during collision to maximise integrated luminosity—especially if we can find some scope for increasing the initial value of N_b, whose value is limited by injection from the SPS [2]. It is not expected to be a straightforward operational procedure in the LHC as the beams will have a tendency to move apart by distances comparable with the beam size at the IP.

A higher initial value of β^* would also increase the margin for the ECPP quench limit if necessary and further increases the interest in β^*-tuning.

A further operational complication is that the beam position monitors (BPMs) in the LHC require a minimum charge per bunch in order to function properly. Even with recent improvements, this corresponds to $N_b \approx 2\times10^7$ for Pb ions in the arc BPMs, little more than a factor of 3 less than the nominal intensity, implying a very narrow gap between "commissioning" and "design" values. With the full complement of 592 ion bunches, commissioning would also be dangerously near the ECPP quench limit.

These and other reasons related to the project schedule, led to the recent proposal [2] of an additional "Early" mode of operation of the injector chain, leading to about 10 times fewer bunches in the LHC. In this scheme, which we envisage using in an initial period of ion running, N_b and β^* (and hence the beam lifetime) could have their nominal values but the ECPP quench limit would be far away, the bunches would be visible on the BPMs, the injector scheme would be simplified and some interesting heavy ion physics would be accessible with the reduced luminosity. If necessary, the initial value of β^* could be raised to increase the beam lifetime.

Although the present estimate of ECPP gives serious cause for concern, we would like to emphasise that the uncertainties and safety margins still in hand do not allow the design luminosity of $L \approx 10^{27}\,\mathrm{cm^{-2}s^{-1}}$ to be definitively excluded.

The *initial* performance parameters in various operational scenarios are summarised in Table 3.

The relative importance of the various physical effects limiting performance can be quite different with ions other than lead.

Other issues remaining to be studied for ions include the optimum crossing-angles, collimation and a review of the beam instrumentation.

Finally we mention that a full design report for the "Ions for LHC" project is due in the coming months.

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Table 3: Initial performance in various running scenarios.

		Nominal	**Intensity quench-limited**	**Quench-limited, β*-tuning**	**Early scheme**	**Units**
Number of bunches	k_b	592			~60	
Bunch spacing (typical)	S_b / c	99.8			1350	ns
Twiss function at IP $(x = y)$	β^*	0.5		1.0	0.5	m
Number of Pb ions/bunch	N_b	7×10^7	5×10^7	7×10^7		
Beam size at IP	σ^*	16		22.5	16	μm
Luminosity half-life for $n_{\exp} = 2,3$	$\tau_{L1/2}$	4.6 / 3.1	9.2/6.2		4.6 / 3.1	hour
IBS growth time	τ_{IBS}	15	21	15		hour
Initial luminosity	L	1.0	0.5	0.5	0.1	10^{27} cm^{-2}s^{-1}