FIRST ION COLLIMATION COMMISSIONING RESULTS AT THE LHC

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Abstract

First commissioning of the LHC lead ion beams to 1.38 A TeV beam energy was successfully achieved in November 2010. Ion collimation has been predicted to be less efficient than for protons at the LHC, because of the complexity of the physical processes involved: nuclear fragmentation and electromagnetic dissociation in the primary collimators creating fragments with a wide range of Z/A ratios, that are not intercepted by the secondary collimators but lost in the dispersion suppressor sections of the ring. In this article we present first comparisons of measured loss maps with theoretical predictions from simulation runs with the ICOSIM code. An extrapolation to define the ultimate intensity limit for Pb beams is attempted. The scope of possible improvements in collimation efficiency coming from the installation of new collimators in the cold dispersion suppressors and combined betatron and momentum cleaning is also explored.

PHYSICS OF HEAVY-ION COLLIMATION

The first LHC heavy-ion run took place in November 2010 [1], affording the first opportunity to fully test the understanding of the physics of collimation of nuclear beams [2, 6]. Previous studies with a single collimator in the SPS [3] had tested our understanding of the interactions of a $^{208}Pb^{82+}$ beam with a single collimator at $5.9A\,\mathrm{GeV}$ in single-pass mode and with a circulating beam at $106.4A\,\mathrm{GeV}$. Circulating Pb beams in the LHC interact with the full collimation system of the LHC [2,8] at energies up to $1.38A\,\mathrm{TeV} = 3.5Z\,\mathrm{TeV}$.

Beam losses were a principal focus of study during the ion beam commissioning because of the expected differences in ion-material interactions and lower collimation efficiency compared to protons.

When a Pb nucleus hits a carbon atom in a primary collimator jaw, nuclear fragmentation (NF) and electromagnetic dissociation phenomena (EMD) such as

$$^{208}\mathrm{Pb}^{82+} + {}^{12}\mathrm{C} \rightarrow \begin{cases} {}^{203}\mathrm{Tl}^{81+} + X & \text{(NF)} \\ {}^{206}\mathrm{Pb}^{82+} + {}^{12}\mathrm{C} + 2\mathrm{n} & \text{(EMD)} \end{cases}$$

produce heavy isotopes with a different charge-to-mass ratio from the primary beam. Because of the large cross sections of these processes, these fragments are produced before the ions can acquire the necessary scattering angle from multiple Coulomb scattering to hit the secondary collimators. The LHC collimation setup, conceived as a three-stage system for proton operation, thus effectively works as a one-stage system for ions. The primary beam halo is then constituted of fragments of different magnetic rigidities that are lost at well localised spots around the ring, depending on the value of the local dispersion functions and momentum acceptance. Fig.1 shows a typical simulation loss map for betatron collimation of Beam 1 at $7Z$ TeV beam energy and nominal beam parameters: the main losses appear in the dispersion suppressor regions of the cleaning insertions (IR7 in this case), which act as a kind of spectrometer for the various isotope species. The individual contributions of the various fragments have been highlighted in different colours.

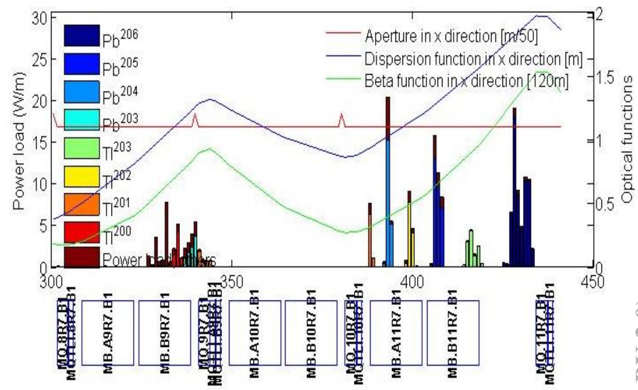

Figure 1: Simulated betatron losses in the IR7 dispersion suppressor (beam1 at $7Z$ TeV).

For an assumed beam lifetime of 12 minutes, nominal ion beam intensity [2] and no machine imperfections, the maximum predicted loss peaks measure ~20 W/m, with a local collimation inefficiency of $7.\times 10^{-3}$ (highest leakage in the dispersion suppressor cold aperture normalised to the maximum impact load on a primary collimator). The global cleaning inefficiency is instead defined as the ratio between the total leakage in the machine aperture and the integrated losses on collimators (~0.045 for the case simulated). Similar behaviours are expected for both beams and cleaning insertions. For the values assumed, predicted ion losses significantly exceed the expected theoretical quench limit of 8.5 W/m [4], thus anticipating an intensity limitation on ion beam performance in the LHC.

ION COLLIMATION COMMISSIONING

After an initial setup of beam-based collimator alignment procedure, loss maps were measured during ion commissioning at several stages, for qualification of beam behaviour. For betatron cleaning (IR7) in the horizontal and vertical planes, losses were induced by crossing a 1/3 integer tune resonance for both planes and beams; for momentum cleaning (IR3) the RF frequency was increased (decreased) to qualify the system for negative (positive) off-momentum particles (both beams in parallel).

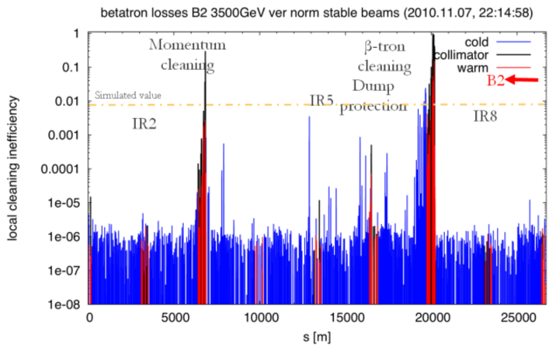

Figure 2: Horizontal betatron losses generated by crossing a 1/3 integer resonance in Beam 2 at 3.5 *Z* TeV ion beam energy.

Fig.2 shows a horizontal betatron loss map generated by crossing a 1/3 integer resonance for Beam2 at 3.5xZ TeV and β*=3.5m optics. The blue/black/red bins indicate respectively the BLM signal in the cold/warm aperture and on collimators (in terms of local cleaning inefficiency, i.e. normalised to the highest load on a primary collimator). The dashed orange line indicates the highest simulated local cleaning inefficiency in the cold aperture without any machine imperfections. The expected loss pattern in the two cleaning insertions of IR3 (s~7000 m) and IR7 (s~20000 m) for momentum and betatron collimation is clearly visible, though the leakage from IR7 downstream to IR3 is more important than predicted, possibly as a result of off-momentum fragments' feed-down that is not presently correctly simulated. The highest cold aperture leakage observed in active betatron loss maps is found as expected in the IR7 dispersion suppressor, with local inefficiencies of up to $3x10^{-2}$. Leakage to the IR7 DS is higher for Beam2 than for Beam1, due to an asymmetry in the local dispersion function between the two beams. Localised loss spots are also present in different parts of the machine. These are not currently matched by simulations and need to be better understood. Table 1 summarises the highest measured leakage into specific regions of the LHC ring for different types of loss maps [5].

Focusing now more specifically on the IR7 dispersion suppressor, Fig.3 shows a comparison of simulated (histogram) and measured (marks) losses for beam1 horizontal betatron cleaning (renormalized to the highest load on a primary collimator). Simulations were performed with the code ICOSIM [6] for an ideal case of no machine imperfections. Different colours are adopted in the histogram to highlight the contribution of individual fragments. As the plot shows, measured positions of loss peaks are well reproduced by simulations, even though there is some discrepancy at a quantitative level, with the measured leakage being higher or significantly higher than predicted.

Table 1: Highest leakage, in local cleaning inefficiency, of ions into specific LHC regions (DS = dispersion suppressor, COLD= cold aperture excluding DS, TCT = tertiary collimators).

Loss cases	DS	COLD	TCT
B1H	0.02	0.006	1e-4
B1V	0.027	0.005	0.001
B2H	0.03	0.011	8e-5
B2V	0.025	0.006	1.4e-4
B1+B2 positive off- momentum	0.045	8e-4	0.06
B1+B2 negative off-momentum	0.007	2e-4	0.005

In addition higher losses are observed in IR3 than was expected, possibly as a combination of BFPP-luminosity effects [1] and off-momentum feed-down from IR7. These differences need to be further understood either with the aid of higher statistics runs or, failing that, by improvement of the physics modules used in the simulation code to reach a better agreement with the experimental results.

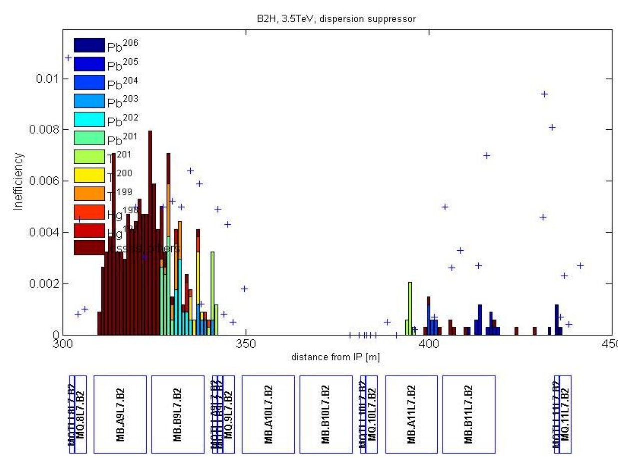

Figure 3: Comparison of simulated (bars) and measured (crosses) beam losses in the IR7 dispersion suppressor (expressed in local cleaning inefficiency, for beam1 horizontal betatron losses at 3.5 *Z* TeV).

Long-standing uncertainties in the calculated cross-sections for hadronic fragmentation and electromagnetic dissociation (EMD) processes of lead ions on collimator material (Carbon and Tungsten) have recently been narrowed by ALICE ZDC measurements in Pb-Pb collisions [7]. These show a very good agreement between experimental results and predictions from the RELDIS model, used in ICOSIM to model ion-matter interactions (via stored look-up tables of calculated cross-sections).

Intensity limit from collimation

Based on these first experimental results from the LHC ion commissioning, an attempt has been made to derive a first estimate of the ultimate intensity limit for Pb ion operation using the relation:

$$\eta N_{MAX} = \tau R_q \qquad (1)$$

where η is the highest local cleaning inefficiency, N_{MAX} the maximum beam intensity, τ the minimum lifetime, and R_q the lower quench limit.

The minimum lifetime for steady state losses was derived for Pb ions from the data. Two runs were analysed with different BLM integration times. The lowest steady state life time (1.5 h) was found in the run of 20/11/2010 with 10.24 ms BLM integration time.

A recent experiment to estimate quench thresholds in proton operation at 3.5 TeV with artificially provoked high losses has established a lower limit of 336 W in the power that can be safely deposited on a dispersion suppressor quadrupole magnet (Q8). Considering the different loss pattern of ions, with more extensive leakage on the main dipoles, an average ~100 W lower quench limit has been assumed in this case (from the power deposited on a main bending magnet in the proton loss map during the quench test). Substituting in Eq. (1) the worst measured inefficiency value of $\eta = 0.045$ (for a conservative approach, see Table 1) and a minimum lifetime $\tau = 3600\,\mathrm{s}$, one reaches an expected performance limit for ion beams at $3.5Z$ TeV of 1.7×10^{11} ions (~4 times the nominal ion intensity).

With the same reasoning, one can attempt an extrapolation to $7Z$ TeV ion beam energy. Assuming a minimum beam lifetime independent of the beam energy and intensity, identical cleaning inefficiency and scaling down the lower quench limit by a factor of 2.5 for dependence on the magnet current [3], one reaches a performance limit of 3.2×10^{10} ions (or 80% of the nominal ion intensity).

A potential weak point of this extrapolation is that the estimates are based on very few experimental results and important assumptions that may not be entirely justified. Some correction factors accounting for longitudinal loss distribution patterns inside the magnets (a sort of dilution length concept for beam losses) and different BLM responses in different parts of the machine (by collimators or superconducting magnets) have been neglected in Eq.(1). Some preliminary estimates are available for protons at certain energies, but it is felt there are not enough solid bases yet for an easy rescaling to ion beams behaviour. The reliability of this prediction should therefore be improved with dedicated quench test measurements and BLM response studies using ion beams in the 2011 run.

FUTURE COLLIMATION UPGRADES

The LHC collimation was initially conceived as a staged system, with an initial Phase 1 for beam commissioning and early years of operation and a Phase 2 to eventually reach nominal, ultimate and higher beam intensities.

A recently considered upgrade solution consisted in equipping the IR3 dispersion suppressors with so-called “cryo-collimators” at two different locations per beam. Simulations have shown that this scheme is very promising, especially for ions, with all leakage to the dispersion suppressors (and, mostly, the rest of the machine) being completely absorbed by the new collimators even at 20 sigma jaw opening.

Similar results were obtained for Pb ion beams at nominal beam intensities and also for lighter ion species ($^{40}Ar^{18+}$ was taken as example) to be included in the future LHC operational programme.

The installation of these cryo-collimators was initially foreseen to take place in the long LHC shutdown planned in 2013 (LS1). However the results of recent MDs indicate that nominal proton beam intensity at 7 TeV can justifiably be achieved in the LHC with a comfortable margin without the installation of additional collimators in the IR3 dispersion suppression region. On the basis of these results and considering the non-negligible risk associated with the upgrade (many machine elements needing re-positioning), it was recently decided, to postpone this collimation upgrade of the IR3 and IR7 dispersion suppressors to later in the future (with IR2 following in priority).

A possible system of combined betatron and momentum cleaning in IR3 with additional vertical primary collimators could be used instead as an alternative to reduce the impact of radiation-induced damage to electronics in IR7. This solution is however not expected to be particularly beneficial for ions, with a performance comparable to that obtained for betatron (momentum) only schemes, and hence insufficient to meet the needs of nominal operation at $7Z$ TeV.

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