SIMULATION OF HEAVY-ION BEAM LOSSES WITH THE SIXTRACK-FLUKA ACTIVE COUPLING *

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Abstract

The LHC heavy-ion program aims to further increase the stored ion beam energy, putting high demands on the LHC collimation system. Accurate simulations of the ion collimation efficiency are crucial to validate the feasibility of new proposed configurations and beam parameters. In this paper we present a generalized framework of the SixTrack-FLUKA coupling to simulate the fragmentation of heavy-ions in the collimators and their motion in the LHC lattice. We compare heavy-ion loss maps simulated on the basis of this framework with the loss distributions measured during heavy-ion operation in 2011 and 2015.

INTRODUCTION

The CERN Large Hadron Collider (LHC) [1] is a collider for proton and heavy-ion beams designed to accelerate and store particles of energies up to $7Z$ TeV[1]. In the operational period carried out with $^{208}Pb^{82+}$ ion beams in 2015 [2], the stored beam energy reached unprecedented values up to 9.5 MJ, compared to the design value of 3.8 MJ. With the envisaged High Luminosity (HL) LHC upgrade [3] an even further increase of the stored heavy-ion beam energy up to 24.1 MJ is considered.

Even small fractions of the energetic and bright LHC beams can quench the superconducting magnets and thus interrupt the operation of the machine. Higher amounts of lost particles can even cause severe damage of machine components. Therefore, the LHC is equipped with a multi-stage collimation system [1,4] to protect the machine from uncontrolled beam loss. The two cleaning insertions IR3 and IR7 provide momentum and betatron cleaning respectively. Both host primary collimators (TCP) to intercept and scatter beam particles at large betatron or momentum amplitudes. Secondary collimators (TCS) downstream of the TCPs are dedicated to intercept and absorb the resulting secondary beam halo. Tertiary collimators (TCT) are installed around the experimental insertions to protect the superconducting triplet magnets and reduce machine induced background at the detectors.

While the system provides an excellent cleaning performance with proton beams [5], heavy-ion cleaning is less efficient by two orders of magnitude. At their passage through the collimator material, the interaction with the nuclei of the collimator material can cause the fragmentation of the ions into isotopes with different magnetic rigidities. They continue moving along the machine until the dispersion increases in the dispersion suppressors (DS) at the transition from the cleaning insertion to the LHC arcs, where the fragmented ions are lost on the machine aperture. The superconducting DS magnets downstream of IR7 are the magnets in the LHC which are exposed to the highest amount of beam losses for both heavy-ion and proton beams.

The heavy-ion collimation quench test carried out in 2015 it was shown that, assuming a beam lifetime of 12 min, the upper boundary of the achievable stored beam energy is 10.8 MJ, very close to the intensity already achieved in operation [6].

Sophisticated simulations of heavy-ion collimation are required to optimize the LHC collimation system for the best cleaning efficiency. They also provide important input for the study of upgrade scenarios like the installation of new collimators.

In this article, a new simulation tool for heavy-ion collimation is presented and employed for the cases of the operational periods with heavy-ion beams in 2011 and 2015.

THE SIXTRACK-FLUKA COUPLING FOR HEAVY IONS

The SixTrack-FLUKA coupling for heavy ions is an integrated simulation tool for heavy-ion collimation based on the coupling between a modified version of the tracking software SixTrack [7,8], called heavy-ion SixTrack (hiSixTrack), and the Monte-Carlo package FLUKA [9, 10], similarly to the coupling developed for protons [11].

SixTrack was designed for the symplectic tracking of relativistic proton beams through the magnetic lattice of a storage ring over a large number of turns. It can use a thin lens model of the magnetic lattice. To keep track of ion fragments generated in the LHC collimators, the tracking routine in hiSixTrack is modified to allow for the tracking of different ion species. The corresponding symplectic tracking maps are derived from a generalized Hamiltonian for multi-isotopic particle beams [12]. The software provides an integrated aperture check [11] which compares the particle tracks with the dimensions of the beam pipe, tabulated in a detailed aperture model including all elements around the ring, and thus determines when a particle is lost.

FLUKA is a fully integrated Monte-Carlo package to simulate the interaction of particles with matter. In the hiSixTrack-FLUKA coupling it is used in the framework

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[1] Z is the charge multiplicity of the ion

of the SixTrack-FLUKA coupling [11] to simulate the scattering and fragmentation of the ions in the LHC collimators. Accurate models of the geometry of LHC collimators are available in the FLUKA element database (FEDB) [13] and used for this purpose.

The SixTrack-FLUKA active coupling relies on a network port providing the particle exchange between SixTrack and FLUKA. At every collimator the bunch of tracked particles is sent to FLUKA, where their interaction with the collimator material is simulated. The distribution of surviving particles is sent back to SixTrack, where the tracking is carried on.

The output from such a simulation is used to compute the local cleaning inefficiency $\eta(s)$. For heavy ions, we define $\eta(s)$ as the integrated ion energy $E(s)$ lost in the longitudinal range $[s, s + \Delta s]$, normalized by the amount of losses at the highest loss location E_{max}

$$\eta(s) = \frac{\int_s^{s+\Delta s} E(\tilde{s})d\tilde{s}}{E_{max} \Delta s} \, . \tag{1}$$

This normalization is required because heavy ions can carry an energy two orders of magnitude larger than light ion fragments, which requires a corresponding weighting of their energetic impact.

MEASURED AND SIMULATED LOSS MAPS

The hiSixTrack-FLUKA coupling was used to simulate the cleaning performance with $^{208}\text{Pb}^{82+}$ beams in the 2011 operation at 3.5Z TeV and in the 2015 operation at 6.37 Z TeV. We compare the simulated loss maps to betatron loss patterns measured with the LHC Beam Loss Monitors (BLM) during artificial transverse beam blow ups.

The BLMs [14, 15] are ionization chambers installed on many magnets and other important machine elements. They measure shower particles arising from the interaction of lost beam particles with the material of the surrounding elements. The LHC is equipped with more than 3000 BLMs, thus they can provide a detailed measurement of the loss distribution around the ring. The BLM response per locally lost beam particle varies for the different locations because the shower propagation depends on the traversed material, as well as the angle and location of incidence. If comparing the simulation, which counts the energy lost on the beam pipe, with the shower-dependent BLM signals, a significant uncertainty is introduced, which should be kept in mind. Detailed quantitative comparisons require dedicated simulations of the radiation-matter interaction.

The simulations are carried out with an initial annular beam halo in the horizontal plane, starting from IP1 at an amplitude large enough to hit the horizontal primary collimator without diffusion. The initial beam halo contains 5×10^6 particles of the species $^{208}\text{Pb}^{82+}$.

Heavy-Ion Operation in 2011

The cleaning efficiency of the collimation system with $^{208}\text{Pb}^{82+}$ beams in 2011 is simulated for the scenario of
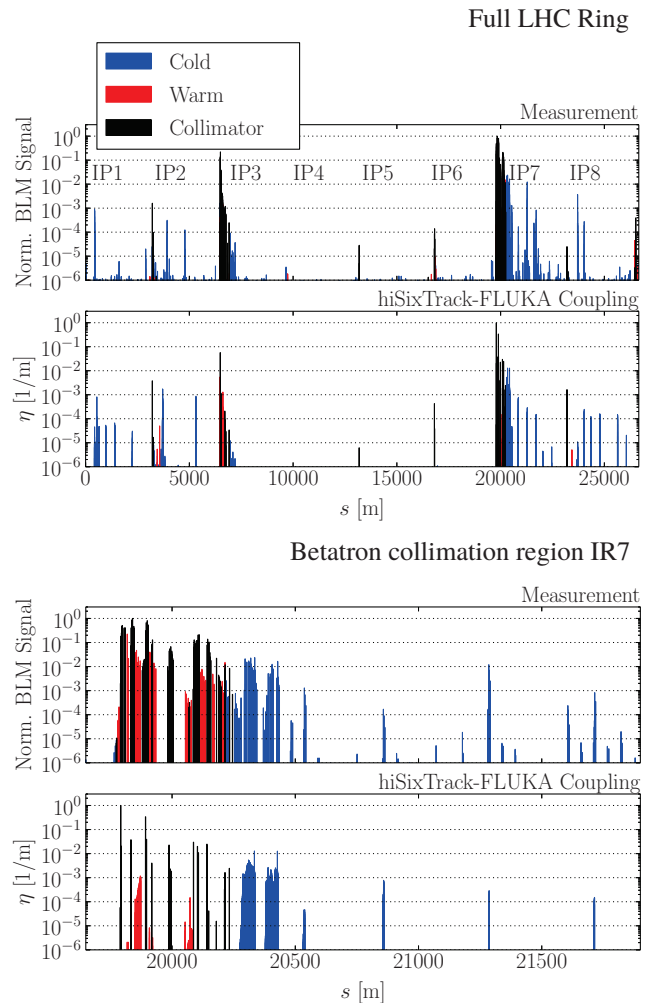

Figure 1: Measured and simulated loss pattern for the 2011 heavy-ion run. Top: Full LHC ring, bottom: IR7.

squeezed beams. The ion energy is 3.5 Z TeV and the beams are squeezed to $\beta^* = 3$ m in IP8 and $\beta^* = 1$ m in the remaining experimental IPs. The primary collimators in IR7 are set to half gaps of 5.7 σ and the secondary collimators to 8.5 σ. The full set of applied collimator settings is given in [16].

The measured and simulated loss patterns for the horizontal plane of LHC Beam 1 are shown in Fig. 1. Qualitatively the loss patterns are in a good agreement. The losses in the warm region of IR7 cannot be directly compared because they are mainly shower particles from the interaction of the main beam with the collimators, which are not included in the simulation [5]. The two loss clusters in the DS downstream of IR7 are visible in both simulation and measurement. The four measured loss peaks in the arc region between IR7 and IR8 are also visible in the simulation.

The two measured loss spikes in the cold region downstream of IR8 are also predicted by the coupling. The simulation predicts additional loss peaks in the arc region between IR8 and IR1, which are not seen in the measurement. On the contrary the measured losses at the IR1 TCT are significantly

larger than simulated. The pronounced measured peak in the cold aperture downstream of IP1 is also seen in the simulation. The simulation shows also additional losses in the arc between IP1 and IP2, which are not seen in the measurement. After the TCT in IR2 which intercepts many heavy ions in both measurement and simulation, two aperture loss peaks are visible. In the simulation they are displaced with respect to the measured loss map. The losses in IR3 and the DS downstream are in very good agreement. The losses at the IR5 TCT and the dump protection in IR6 are visible in both cases.

Overall the qualitative agreement between simulation and measurement is considered to be very good. Displacements of simulated loss peaks with respect to the measurement can possibly be explained by local aperture displacements and/or shifts of the orbit in the real machine, but further simulations with machine imperfections should be carried out to investigate and understand this.

Heavy-Ion Operation in 2015

The operation with heavy-ion beams at 6.37 Z TeV in 2015 was substantially more demanding for the collimation system. With a stored beam energy of 9.5 MJ (compared to 2.0 MJ in 2011), the operation was interrupted several times by protection dumps because the measured collimation losses in the IR7 DS were above the BLM thresholds. The collimator settings in mm were identical to the settings of the previous proton run at 6.5 TeV, with a TCP half gap of 5.5 σ and the TCS retracted by 2.5 σ.

The measured and simulated loss maps for the horizontal plane of LHC Beam 1 are compared in Fig. 2. The two loss clusters in the IR7 DS are clearly visible in both simulation and measurement. Two of the four predicted loss clusters in the arc downstream of IR7 are visible in the 2015 measurement. The losses in the cold aperture downstream of IP8 are partly reproduced in the simulation. The losses at the IR1 TCT are lower in the simulation than in the measurement. Between IP1 and IP2, three loss peaks in the aperture are visible in the measured loss map and the simulation, but they are shifted with respect to each other. The measured high loss peak at the IR2 TCT is clearly visible also in the simulation. The measured loss peak downstream of IR2 is slightly shifted in the simulation, which shows also a second peak. The losses in IR3 and IR6 are in good agreement.

This scenario confirms the requirement for additional studies to analyze the effect of orbit offsets and aperture displacements. Preliminary checks showed that the two loss peaks which were simulated but not measured in the arc between IR7 and IR8 shift towards other locations when the aperture is displaced by 0.5 mm. On the contrary, the losses at the IR2 TCT have been simulated to impact the jaws with an impact parameter of several mm.

SUMMARY AND CONCLUSIONS

The LHC collimation system is an essential component on the path of the LHC to higher luminosities. Sophisticated
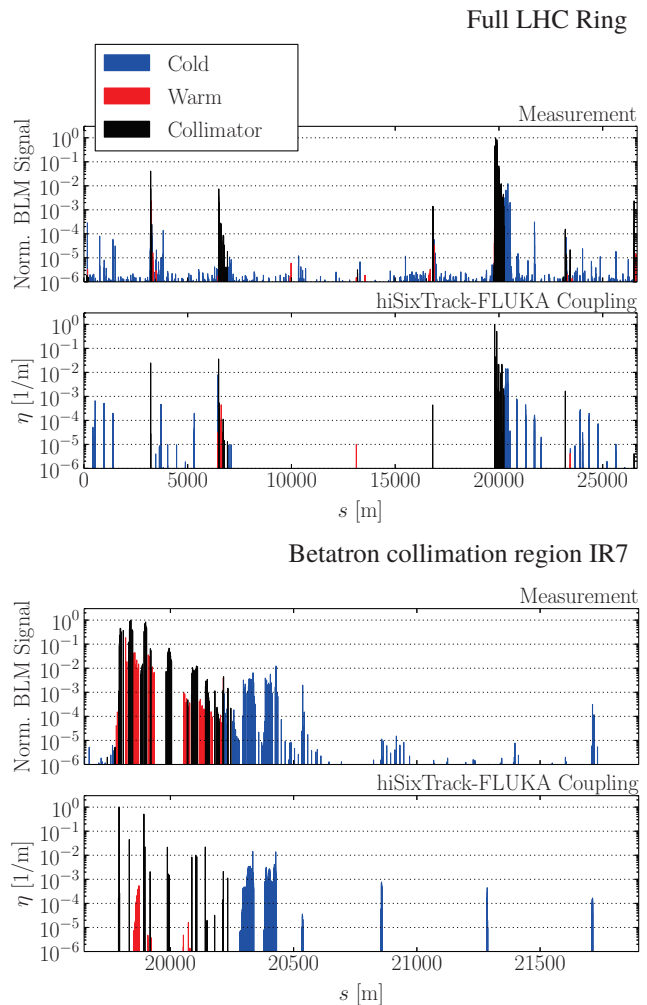

Figure 2: Measured and simulated loss pattern for the 2015 heavy-ion run. Top: Full LHC ring, bottom: zoom to IR7.

simulation tools for both heavy-ion and proton beams are needed to optimize the system for the best possible performance. The new hiSixTrack-FLUKA coupling was developed to serve as a simulation tool for heavy-ion collimation. It is based on an active coupling between hiSixTrack, a modified version of SixTrack, and FLUKA. The software includes chromatic and isotopic dispersion of particles of arbitrary species and computes their interaction with the collimator materials.

The simulation results for the 2011 and the 2015 heavy-ion runs were compared to the measured BLM data. The comparison shows a good overall agreement, although some discrepancies are present. Additional studies on the impact of aperture displacements or orbit offsets on the loss pattern are foreseen. Furthermore, simulations of the shower propagation will enable more detailed quantitative comparisons.

ACKNOWLEDGMENTS

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