STUDIES ON HEAVY ION LOSSES FROM COLLIMATION CLEANING AT THE LHC

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Abstract

The LHC collimation system protects superconducting magnets from beam losses. By design, it was optimized for the high-intensity proton challenges but so far provided adequate protection also during the LHC heavy-ion runs with ^{208}Pb^{82+} ions up to a beam energy of 4 Z TeV. Ion beam cleaning brings specific challenges due to different physical interactions with the collimator materials and might require further improvements for operation at 7 Z TeV. In this article, we study heavy-ion beam losses leaking out of the LHC collimation system, both in measurement and simulations. The simulations are carried out using both ICOSIM, with a simplified ion physics model implemented, and SixTrack, including more detailed starting conditions from FLUKA but without including online scattering in subsequent collimator hits. The results agree well with measurements overall, although some discrepancies are present. The reasons for the discrepancies are investigated and, on this basis, the requirements for an improved simulation tool are outlined.

INTRODUCTION

The CERN Large Hadron Collider (LHC) [1] is equipped with a multi-stage collimation system [2] designed to intercept halo-particles at large amplitudes which could hit otherwise the superconducting magnets and potentially cause them to quench. The efficiency of the collimation system depends on the collimator and optics settings. Simulation tools have been developed to enable a thorough analysis of the cleaning efficiency before operating with specific machine configurations. At the passage through the collimator material, proton and heavy-ion beams are subject to different physics processes. Unlike protons, heavy ions can break up into lighter isotopes having a different magnetic rigidity from the reference beam. Both the tracking and scattering/fragmentation routine of a simulation code for heavy-ion collimation must be able to handle the different isotopes. LHC collimation simulations for protons are usually realized with the SixTrack code, while heavy ion loss maps have previously been simulated with the ICOSIM software [3]. The aim of this study is the comparison of the measured losses during the first LHC run with simulated loss maps using either ICOSIM or SixTrack, where for the latter we track protons of equivalent magnetic rigidity.

SIMULATION SETUP

ICOSIM

ICOSIM (Ion COllimation SIMulation) is the present state of the art simulation code for heavy-ion loss maps [3]. Ions are tracked by means of a linear transfer matrix formalism, until all particles have hit a collimator. Chromatic effects are taken into account in linear approximation. Nuclear fragmentation and electromagnetic dissociation due to the ion-matter interaction in collimators are simulated using a built-in routine based on tabulated cross section tables generated by FLUKA [4–6]. From the particles generated by these processes, only the heaviest fragment in each interaction is kept track of and kicks in energy or angle are not taken into account. Besides, the software contains an integrated routine to calculate multiple scattering in Gaussian approximation and ionization using the Bethe-Bloch equation [7]. Information about the beam and optics properties as well as the collimator settings is given by the user via input files. Optics input is generated using MAD-X [8] which facilitates the simulation with new machine configurations. ICOSIM generates the beam halo based on different models which can be chosen by the user. For the presented simulation $2 \cdot 10^6$ initial ions are generated as an annular halo at IP1, sufficiently large to hit the primary collimators (TCP) without including diffusion, following the methods outlined in Ref. [9, 10]. Based on the the hierarchy of the LHC collimation system the TCPs in the betatron collimation region IR7 are the only collimators which should be exposed to the initial beam halo.

SixTrack with Protons of Ion-Equivalent Rigidity

SixTrack with protons of ion-equivalent rigidity is introduced as an alternative tool for the simulation of heavy-ion loss maps. In this framework, protons of effective energies are tracked to simulate the rigidities of the different isotopes. In the presented approach, the tracking of effective protons starts from a distribution of fragments exiting the TCP in IR7. No subsequent scattering at the collimators is applied.

Tracking tool SixTrack [11, 12] provides an integrated environment for the magnetic tracking of protons together with a Monte-Carlo module to simulate interactions of protons with the collimator material. The software provides predictions of the performance of the LHC collimation system which have proved to be very consistent with the measured proton losses in the LHC [9]. A thin lens model of the accelerator lattice is used to calculate the particle transport. Chromatic effects are taken into account up to 20th order.

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ISBN 978-3-95450-173-1

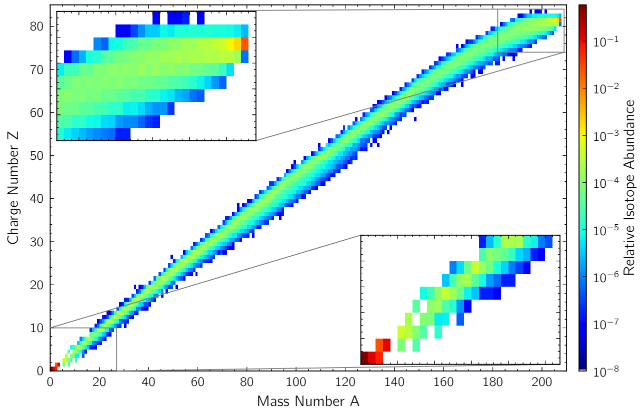

Figure 1: Abundances of the individual fragments from the lead ion beam impacting the carbon collimator material.

The software is designed for simulating proton beams, so no information about the ion charge or mass is stored or processed to provide the tracking. The implementation of the scattering routine is also specific to protons.

Simulation of fragmentation at the TCP We simulate the ion fragmentation at the TCP using the Monte-Carlo package FLUKA, with exactly the same simulation setup that was previously used for the SPS [7]. A beam of 10^6 ions was simulated to impact the TCP, modeled as a simple block of carbon with an impact parameter (the transverse distance of an impacting ion from the collimator edge) of $b = 1\,\mu$m. This choice is somewhat arbitrary since the actual impact parameters in the machine are not precisely known, but are believed to follow approximately an exponential distribution of b. The angle of incidence is calculated from phase-space information extracted from MAD-X and assuming that the collimator is hit at the phase of the maximum excursion. Fig. 1 shows the simulated abundances of the various ions coming out of the collimator as a function of the nuclear charge number Z and the nuclear mass number A.

In the fragmentation process, the isotopes are subject to kicks in the kinetic energy and in the angle of movement. Both can differ significantly from the central angle or the reference kinetic energy. In the next step, we use the FLUKA output for the generation of the SixTrack initial conditions.

Setup of the ion tracking with SixTrack SixTrack is designed for the exclusive handling of protons. Heavy ions of the reference ion species can however be tracked as protons if the synchrotron motion is neglected (which is acceptable for the simulation case as the particles are only tracked for 100 turns) and if the total ion energy is substituted by the energy per charge. Rigidities of isotopes different from the main beam can be accounted for by introducing a momentum offset of the tracked protons. One can show that the magnetic rigidity of an isotope (described by the nuclear mass number, charge number and the ion mass A, Z, m), different from the ion type (A_0, Z_0, m_0) of the reference beam, can be taken into account by an effective momentum offset δ_{eff}. It is related to the ion mass and charge as described by the formula [7]:

$$(1 + \delta_{\text{eff}}) = \frac{Z_0}{Z}\frac{m}{m_0}(1 + \delta_{\text{kin}}), \tag{1}$$

where δ_{kin} is the kinetic momentum offset of the ion. Every particle obtained from the fragmentation simulation is tracked twice, with (x, x') being mirrored, to simulate the particle generation at both collimator jaws. The equivalent energy E_{eq} of the protons we use to represent the heavy ions is calculated based on the total ion energy E_{ion} extracted from the fragmentation simulation. For ultra-relativistic particles the equivalent proton energy can be described as

$$E_{\text{eq}} = \frac{E_{\text{ion}}}{Z} = \frac{E_{\text{Pb},0}}{Z_0}(1 + \delta_{\text{eff}}), \tag{2}$$

where $E_{\text{Pb},0}$ is the energy of an on-momentum ^{208}Pb nucleus. For this simulation, all particles are assumed to have no initial offset or angle in the vertical direction, thus $y = 0$ and $y' = 0$. Note that all generated secondary particles other than ion fragments are ignored in the generation of the SixTrack input. For the particle tracking in SixTrack, all collimator materials are set to black absorbers to avoid calling the proton-specific scattering routine. The tracking is done for 100 turns, which is sufficient for the vast majority of fragments to be lost on collimators or machine aperture.

SIMULATION RESULTS

All simulations are carried out considering a beam of $^{208}\text{Pb}^{82+}$ ions at an energy of 1.38 A TeV, corresponding to an equivalent proton energy of 3.5 TeV. The considered optics and collimator settings are the same as in the 2011 heavy ion run, with $\beta^* = 1$ m in IP1, IP2, IP5 and 3 m in IP8. The collimator settings are summarized in [13]. All simulations are carried out for LHC Beam 1. The results are compared to loss maps measured using the LHC beam loss monitors (BLM) in the 2011 heavy ion run. The BLMs are ionization chambers which are installed on the outside of the LHC magnets and beam pipes recording particle showers generated by particles hitting the aperture or a collimator [14]. For a loss map measurement, the beam emittance is artificially blown up using either tune resonance methods or beam excitations with the transverse damper [9]. The losses are then large enough for a satisfactory signal to noise ratio. Note that, contrary to the simulations where the losses of the incident ions are recorded, the BLMs measure the secondary shower particles with a limited azimuthal coverage. Therefore, the simulated loss distribution of primary ion fragments cannot be directly compared to measurements with a high quantitative accuracy.

ICOSIM Simulation

Figure 2 a) and Fig. 3 a) show the loss map from the simulation using ICOSIM with the optics and collimator settings of the 2011 LHC run compared to the losses measured with the BLMs, shown in subplot d). The energetic weight of each impacting ion scales roughly with the nuclear mass number A

ISBN 978-3-95450-173-1

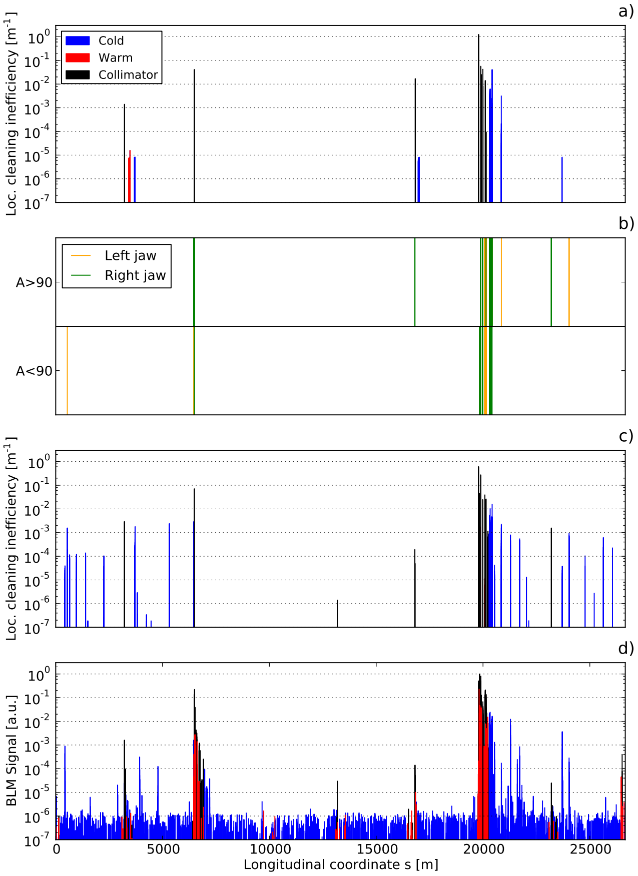

Figure 2: a) LHC loss map simulation of the 2011 heavy ion run using ICOSIM for the full LHC ring. b) SixTrack simulation with starting conditions at the TCP, without considering kicks in angle and energy. The upper half of the plot on top shows losses from particles with a nuclear mass number $A > 90$, the lower half for $A < 90$. c) SixTrack simulation for ion fragments including kicks in energy and angle. d) BLM signals measured in the 2011 heavy ion run. The simulations a) and c) include a weighting of the losses with the nuclear mass number A.

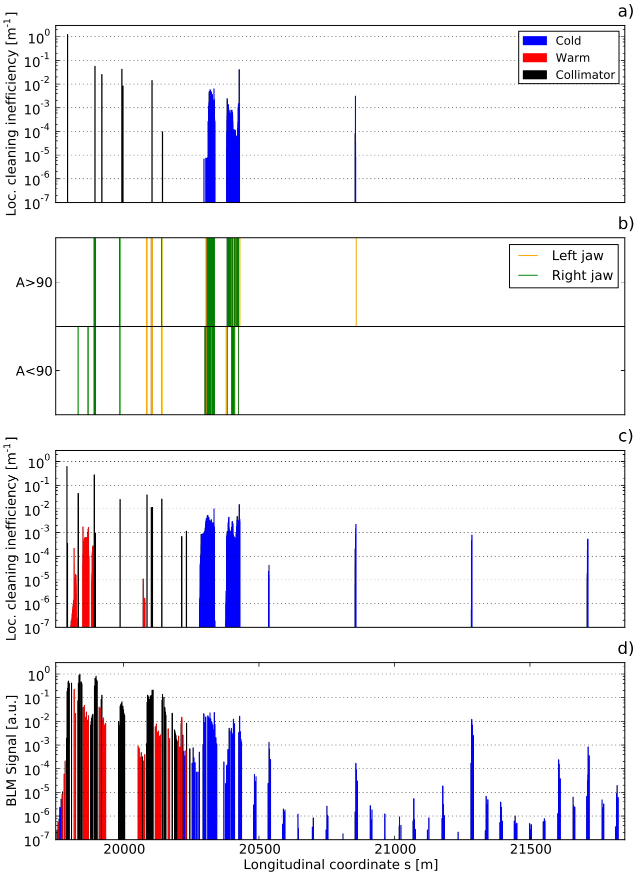

Figure 3: Comparison of the different simulation tools with the measured heavy-ion loss map for the betatron collimation region IR7. The subplots are labeled identically to Fig. 2.

which is accounted for in the normalization of the losses in each bin. The lightest ion generated from the fragmentation algorithm has a nuclear mass number of $A = 90$. The average impact parameter on all collimators is $b = 1.7\ \mu$m. The two clusters in the IR7 dispersion suppressor (DS) are clearly visible and at the same order of magnitude as the measurements (see Fig. 4 for a more detailed comparison). Some of the major loss peaks in the cold magnets of the arc region are not predicted by the ICOSIM simulation. Furthermore, none of the measured losses in warm regions are visible.

SixTrack with Protons of Ion-Equivalent Rigidity

Tracking of light fragments The impact of the lack of light fragments in ICOSIM (e.g. particles with $A < 90$ as mentioned above), is first simulated using SixTrack with the isotopes obtained by the fragmentation simulation. For this part of the study, kicks in angle and energy are neglected as done in ICOSIM. The angle of incidence is determined by the phase-space and the effective energy is calculated using Eq. (1) with $\delta_{\text{kin}} = 0$. Thus, every isotope starting at one collimator jaw is lost in a specific location. The unweighted result of the simulation is shown in Fig. 2 b) and Fig. 3 b). The loss distribution for the heavy isotopes essentially reproduces the ICOSIM result. The color coding shows that in distinct regions only particles starting from one collimator jaw are being lost. This effect can be traced back to the interplay between the betatron oscillations and the locally generated dispersion function. Betatron motion can either partly compensate or enhance dispersive offsets. With these approximations, the inclusion of the light fragments does not improve the simulation result in the arc region after IR7.

Tracking of all fragments including energetic and angular kicks The full simulation result, including the energetic/angular kicks as well as all light fragments from the fragmentation simulation is shown in Fig. 2 c) and Fig. 3 c). Also here, the ion impacts are weighted with A. In this simulation losses in the warm regions become visible. A traceback of the losses confirms that particles lost in the

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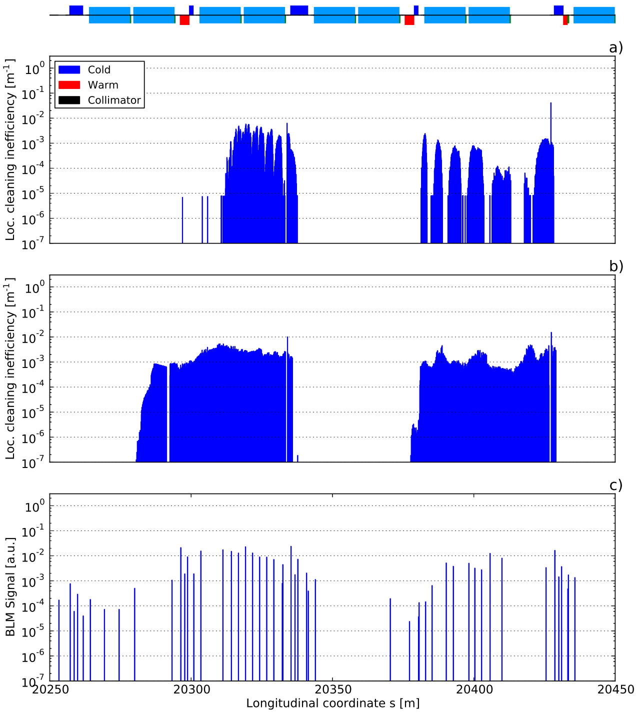

Figure 4: Comparison of the losses in the IR7 dispersion suppressor. a) Losses simulated with ICOSIM. b) Losses simulated with SixTrack with protons of ion-equivalent rigidity. c) BLM signals measured in the 2011 heavy-ion run.

warm regions are mainly very light fragments, from protons to helium nuclei. Ions scattered out from all other collimators are not visible, since they are set to black absorbers. The main contribution to the final losses at the TCP is from $^{208}\mathrm{Pb}^{82+}$ ions which survive at least one full turn of the machine. With the inclusion of the angles and energies, more of the measured losses in the arcs become visible in the simulation. The individual peaks in the arcs are composed of a number of different isotopes, also of very light fragments (e.g. $^{3}\mathrm{H}^{+}$). Complementary simulations showed that with increasing impact parameter, the fraction of light fragments composing these peaks is increasing. In this new setup, the losses of one isotope starting at a given collimator jaw are not confined to one specific location but distributed all over the LHC ring. This is a consequence of a smearing of the trajectories of the fragmented ions for a given type of isotope. As shown in Fig. 4, the smearing of the loss positions leads also to a longitudinal enlargement of the IR7 DS clusters. In the regions far downstream of IR7, new loss peaks appear that are not seen in the measurements. Additional simulations are planned in order to investigate the origin of these losses. The discrepancies could for example be caused by small magnet misalignments in the machine, which shift the local bottlenecks to other locations.

ICOSIM/SixTrack comparison for ions with large δ_{eff} In the case of isotopes with with large δ_{eff}, significant differences between the chromatic tracking of SixTrack and ICOSIM can be expected. To evaluate the importance of the chromatic modeling, a simulation of specific isotopes with initial conditions using both ICOSIM and SixTrack was realized. As an example we present the light isotope $^{8}\mathrm{Li}^{3+}$ with an effective momentum offset of $\delta_{\mathrm{eff}} = 0.054$. The comparison of the particle tracks is presented in Fig. 5.

After a longitudinal distance of 200 m, the horizontal difference between the two tracks is in the order of 1 mm. This is particularly remarkable, as the locally generated dispersion function in this region is still small compared to the values it reaches in the bending dipoles of the arc regions. Such deviations can have considerable impacts on the simulation of the cleaning efficiency. Thus, higher orders in the chromatic modeling should be considered to provide appropriate tracking precision for such particles with large δ_{eff}. This is particularly important if all light fragments are included in the simulation.

HEAVY-ION SIXTRACK

As shown in the previous chapters, the accuracy of the ICOSIM code is limited by the approximations it makes, in particular the simplifications of the fragmentation routine and the linear chromatic modeling. The SixTrack simulation with protons of ion-equivalent energy provides better accuracy compared to the measurements, but still suffers from the absence of multiply fragmented ions.

The remaining discrepancies between simulations and measurements show the need for an improved simulation tool. Such a tool should include the better chromatic tracking of SixTrack *and* keep track of all light fragments. It should also include heavy-ion scattering in all collimators, accounting for the offsets in energy and angle. This could possibly be achieved by using an online coupling of SixTrack with FLUKA, similar to what is under development for protons [15–17].

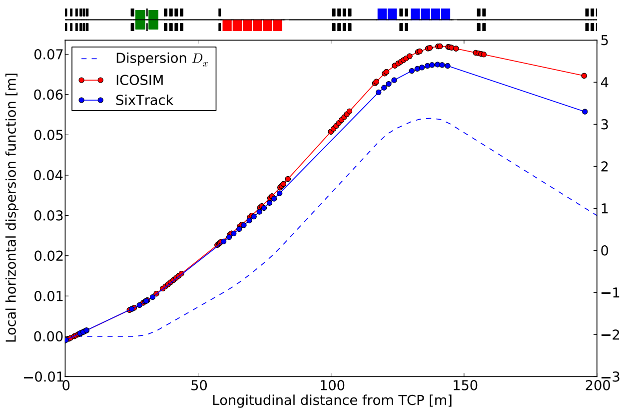

Figure 5: Tracks of $^{8}\mathrm{Li}^{3+}$ starting from the left collimator jaw calculated using ICOSIM (red) and SixTrack (blue). The local dispersion function D_x is calculated using MAD-X.

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SUMMARY AND OUTLOOK

In this paper simulations of the performance of the LHC collimation system for heavy ions using different tracking and particle-matter interaction models were compared. Using the ICOSIM code, which provides a simplified modeling of the particle-matter interaction but a multi-pass model of the generated fragments, the main loss locations in the IR7 DS, but not the losses in the arc after IR7, could be reproduced.

Another method was to use SixTrack and track protons of ion-equivalent rigidities. A sample of ion fragments coming out of the primary collimator, generated with FLUKA, was used as starting conditions. All subsequent collimators were acting as perfect absorbers without scattering. When the changes in angles and energies from the fragmentation process were ignored, the ICOSIM result was reproduced. Further, it was shown that the loss map prediction at locations far from IR7 could not be improved by adding light fragments if the kicks in angle and energy were neglected.

By adding the kicks in angle and energy to the initial distribution of fragments, the agreement with measurements could be significantly improved. The highest measured loss locations in the arc were reproduced. Warm losses became apparent by adding also the light fragments into the simulation. However, this simulation approach could still not reproduce all small loss peaks in the arc region. These losses might be induced by fragments starting from secondary collimators which are neglected in the present single-pass setup.

The chromatic modeling used in the two simulation codes was compared. For particles with magnetic rigidities very different from the main beam, the discrepancies are significant. Therefore, a higher order treatment of these effects must be considered.

Both codes provide good results within the limits of the approximations made. However, the results presented indicate that the general level of agreement with the measurements could be improved if the advantages of both simulation codes were combined. To close this gap, a new simulation code for heavy-ion collimation is envisaged.

ACKNOWLEDGEMENTS

We thank the rest of the LHC collimation team for support and discussions: R. Assmann, M. Cauchi, D. Deboy, A. Marsili, D. Mirarchi, E. Quaranta, A. Rossi. We thank the FLUKA team for useful discussions.

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