BETATRON CLEANING FOR HEAVY ION BEAMS WITH IR7 DISPERSION SUPPRESSOR COLLIMATORS *

P. D. Hermes†, CERN, Geneva, Switzerland and University of Münster, Germany
R. Bruce, J. M. Jowett and S. Redaelli, CERN, Geneva, Switzerland

Abstract

The betatron collimators in IR7 constitute the backbone of the collimation system of the LHC. A fraction of the secondary halo protons or heavy-ion fragments, scattered out of the primary collimator, is not captured by the secondary collimators but hits cold magnets in the IR7 dispersion suppressor (DS) where the dispersion starts to increase.

A possible approach to reduce these losses is based on the installation of additional collimators in the DS region. In this paper, simulations of the cleaning efficiency for Pb^{82+} ions are used to evaluate the effect of the additional collimators. The results indicate a significant improvement of the heavy-ion cleaning efficiency.

INTRODUCTION

The CERN Large Hadron Collider (LHC) [1] is a proton and heavy-ion collider designed for an unprecedented energy of 7 Z TeV (with Z indicating the charge multiplicity). The envisaged High Luminosity (HL) LHC upgrade is aiming to increase the total stored proton beam energy from the present design value of 362 MJ to 700 MJ [2]. Also the LHC heavy-ion programme aims to deliver more luminosity to the experiments by an increase of the number of stored $^{208}Pb^{82+}$ ions [3].

A multi-stage collimation system [1, 4] is installed to provide adequate protection of the superconducting magnets and avoid quenches. The primary (TCP) and secondary (TCS) collimators, as well as the shower absorbers (TCLA) are installed in the two collimation insertions IR3 (momentum cleaning) and IR7 (betatron cleaning), while tertiary collimators (TCT) protect the superconducting triplet magnets of the experimental insertions. For both, proton and heavy-ion operation, the most critical locations of beam cleaning losses are the dispersion suppressor (DS) magnets of IR7. Protons which were subject to single diffractive scattering in the TCPs and heavy-ions having undergone fragmentation processes to isotopes with different magnetic rigidities are likely to be absorbed in this region where the dispersion increases. The heavy-ion collimation inefficiency in this region was measured and simulated to be two orders of magnitudes worse than with protons. This could become a limiting factor for the reachable luminosity, in spite of the much smaller heavy-ion beam intensities [5, 6].

The cleaning performance of the collimation system is quantified by the number of lost nucleons $N_{\text{loc}}(s) = \sum_i n_i(s) A_i$ (with n_i being the number of lost nuclei of the isotope i and A_i the mass number) at the position s over the distance Δs normalized by the total number of losses at the collimators N_{tot}, the so called local cleaning inefficiency $\eta(s)$, given by [7]

$$\eta(s) = \frac{N_{\text{loc}}(s)}{N_{\text{tot}}\,\Delta s}\,. \tag{1}$$

With regard to the envisaged increase of the stored proton beam energy, the installation of additional collimators (called TCLD) is discussed at the DS regions of IR7. Simulations for protons predict a significant improvement of the cleaning efficiency with these collimators [8–10].

In this article, we study the simulated cleaning efficiency of the collimation system for a beam of $^{208}Pb^{82+}$ ions for the three cases: no TCLD, one TCLD in cell 8 (TCLD8) and two TCLDs installed in the cells 8 and 10.

SIMULATION METHOD

The proposed layout of the collimation system with the TCLD collimators as well as the collimator settings and beam properties are presented in detail in [9]. The concept is based on the replacement of two 8.33 T dipole magnets [1] in the cells 8 and 10 (at distances of 292.4 m and 371.9 m from IP7) of the IR7 DS by two shorter and stronger dipole magnets respectively [11]. The freed space is used for the installation of the TCLDs.

In proton operation, a large fraction of the particles interacting with the TCP are scattered into the secondary collimators and absorbers or hits the TCP again on a subsequent turn, making the collimation system very efficient. With heavy-ion beams, numerous ions are fragmented into isotopes with different magnetic rigidities while their angular deviations are mostly not sufficient to be intercepted by the TCS. In consequence, the local cleaning inefficiency in the DS is much more critical in the heavy-ion case than in the proton case. For many of the incoming ions, the collimation system acts effectively like a single-stage system with the primary collimators only.

SixTrack [12, 13] is a program designed for multi-turn proton tracking in storage rings. It provides an integrated environment for symplectic tracking based on a thin-lens model of the accelerator lattice together with a Monte-Carlo module to simulate proton-matter interactions in the collimators [14]. The particle loss positions in the aperture are computed by comparing the simulated particle tracks with a detailed model of the machine aperture. Losses in the collimators are identified if protons undergo inelastic interactions (except single-diffractive scattering) with the material.

* Work supported by the German Wolfgang Gentner Programme of the Bundesministerium für Bildung und Forschung. Research supported by FP7 HiLumi LHC – Grant agreement 284404.
† phermes@cern.ch

ISBN 978-3-95450-168-7

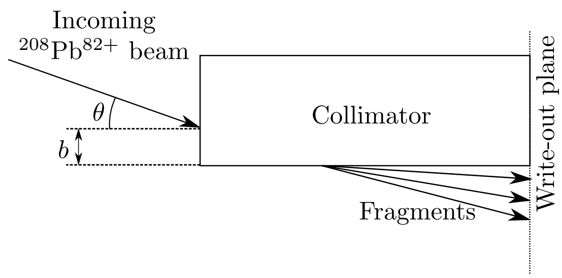

Figure 1: Schematical illustration of the fragmentation simulation. The collimator is modeled as a block of carbon. A beam of $^{208}Pb^{82+}$ ions hits the material at an angle θ with an impact parameter b. At the end of the collimator, the coordinates and species of all ions are written out.

SixTrack cannot by default be used for the simulation of heavy-ion collimation, due to the different interactions of the ions with matter. Furthermore, different ion types, whose effective magnetic rigidities are given by both the energy offset and a different charge-to-mass ratio, are presently not supported by SixTrack. However, the software calculates momentum dispersion for particles of the reference ion species, which can be used to simulate the heavy-ions as protons with ion-equivalent rigidities [5]. In this case, an effective momentum offset δ_{eff}, taking into account both, isotopic and kinematic dispersion, can be introduced, which is defined as follows

$$\delta_{\text{eff}} = \frac{\beta\gamma}{\beta_0\,\gamma_0}\,\frac{m}{m_0}\,\frac{q_0}{q} - 1\,, \quad (2)$$

where β, γ, m, q are the normalized particle speed, Lorentz factor, rest mass and atomic number of the ion. Quantities subscripted with zero are related to the reference particle.

Our simulation setup consists of tracking with SixTrack the distribution of ion fragments, which exit the TCP, as protons with equivalent magnetic rigidities. Under the assumption that most of these fragments do not interact with other collimators before they are lost on the aperture, and that the amount of out-scattering from other collimators is therefore small, we do not simulate the scattering in the downstream collimators and assume them to be perfect absorbers. We call this simulation setup STIER (SixTrack with ion-equivalent rigidities). STIER has been found to be in better agreement with LHC data than previous simulation tools [5]. Nevertheless, it is planned in the future to implement an even better simulation tool that includes online scattering in all collimators.

In the presented studies, the starting conditions for the tracking distribution of fragmented ions that exit the TCP is simulated using the Monte-Carlo tool FLUKA [15–17]. We study an energy of 7 Z TeV and initial losses in the horizontal plane. The angle of incidence was calculated using phase space coordinates together with the collimator opening in terms of σ. The impact parameter was chosen as $b = 10\,\mu$m, using previous estimates for protons [7]. The collimator is modelled as a simple block of carbon with 60 cm length and the properties of all atomic nuclei coming from the interaction are written out at the end of the collimator as illustrated in Fig. 1.

The nominal optics settings with $\beta^* = 0.55$ m were used and the collimator openings are summarized in [9]. For the tracking with SixTrack, the change in energy and angle that occur in the scattering, known from the fragmentation simulation, are accounted for. The ion rigidities are taken into account by the usage of δ_{eff}.

RESULTS

The simulation results with and without the TCLD collimators are shown for the full LHC ring and with magnified scale showing IR7 in Fig. 2. Between the TCP and the first TCLD location, the loss distribution is identical with two, one and zero TCLDs. Losses in the warm regions are mainly caused by light isotopes with large δ_{eff} and scattering angles. Many of these light fragments are also intercepted by the secondary collimators.

For the case without TCLD collimators, two clusters of losses in the cold cells 8-9 and 11-12, located in the IR7 DS, are clearly visible. Further losses appear throughout the entire LHC ring. With the sole inclusion of the TCLD8, the losses in the aperture of the cells 8-9 are completely removed. The losses in the cells and 11-12 are slightly reduced. Given that the highest losses were observed in the cells 8-9, the performance of the collimation system is improved already by the usage of one TCLD.

When the second TCLD is included, all particles which were lost at the aperture downstream of the TCLDs are removed from the beam. With the simulated statistics, losses in cold regions are completely suppressed with the two TCLDs. In reality however, losses in the aperture downstream of cell 10 could still occur from the fragments leaking out of sub-sequent ion-collimator interactions which are evidently invisible in the simulation approach chosen.

CONCLUSIONS

In both proton and heavy-ion operation, the high losses at the IR7 dispersion suppressor could limit the achievable beam intensity due to the risk of quenching the magnets. One possible solution to improve the cleaning efficiency in this region is the installation of one or two new collimators (TCLD) closely upstream of the affected areas. This can be achieved by replacing one or two existing dipole magnets by two shorter and stronger magnets and installing a collimator in the space obtained.

The loss distribution at the LHC with an initial beam of $^{208}Pb^{82+}$ ions was simulated using a new simulation approach STIER that tracks the ion fragments coming out of the TCP as protons with equivalent magnetic rigidity.

It was shown that the installation of the new collimators could significantly improve the cleaning efficiency especially in the case of two installed collimators. Besides the losses occuring directly in the DS region, losses further downstream could also be greatly reduced by this approach.

If the DS losses become a limiting factor for the intensity, hence also for the luminosity, the installation of these collimators would be beneficial not only for proton but also for heavy-ion operation.

Further simulations of the cleaning performance, giving more detailed information about the ion interaction at collimators different from the TCP, can be envisaged with a new heavy-ion simulation tool which is under development.

ACKNOWLEDGEMENTS

We thank the rest of the LHC collimation team as well as the FLUKA team for useful discussions.

REFERENCES

[1] O. S. Brüning et al. (Eds.), “LHC design report v.1 : The LHC main ring”, CERN-2004-003-V1 (2004).

[2] L. Rossi, Proc. of IPAC11, San Sebastian, Spain, TUYA02, 908-912 (2011).

[3] J. Jowett et al., 10.5170/CERN-2014-006.167.

[4] R. W. Assmann et al., Proc. of EPAC 2006, Edinburgh, United Kingdom , TUODFI01, 986 (2006).

[5] P. D. Hermes et al., Proc. of HB2014, East Lansing, Michigan, USA, MOPAB43 (2014).

[6] G. Bellodi et al., Proc. of IPAC 2011, San Sebastian, Spain, TUPZ007, 1813-1815 (2011).

[7] R. Bruce et al., Phys. Rev. ST Accel. Beams 17, 081004 (2014).

[8] T. Weiler et al., Proc. of Hadron Beam 2008, Nashville, Tennessee, USA, 359, (2008).

[9] R. Bruce et al., Proc. of IPAC 2014, Dresden, Germany, MOPRO042, 170-173 (2014).

[10] A. Lechner et al., Proc. of IPAC 2014, Dresden, Germany, MOPRO021, 112 (2014).

[11] A.V. Zlobin et al., Proc. of IPAC 2014, Dresden, Germany, WEPRI097, (2014).

[12] F. Schmidt, CERN/SL/94–56 (AP).

[13] SixTrack webpage, `http://sixtrack.web.cern.ch/SixTrack/`.

[14] C. Tambasco, Master’s thesis, Università di Roma, Italy, 2014.

[15] T.T. Böhlen et al., Nucl. Data Sheets 120, 211-214 (2014).

[16] A. Ferrari et al., CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.

[17] G. I. Smirnov et al., Phys. Rev. ST Accel. Beams 17, 021006 (2014).

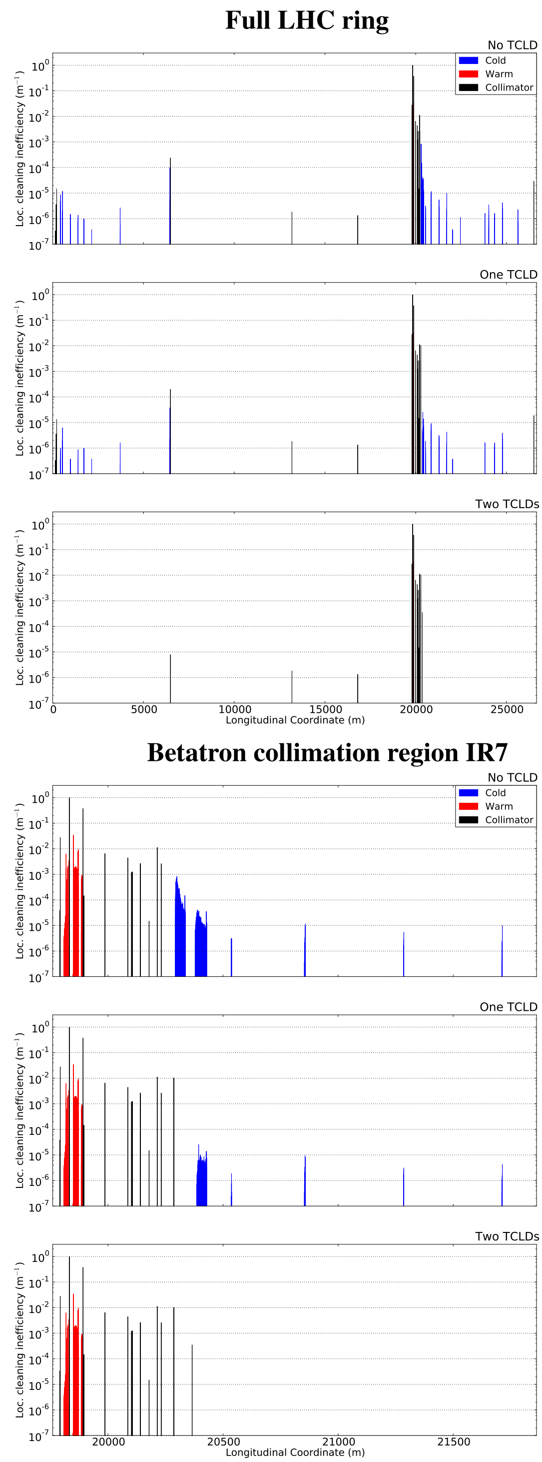

Figure 2: Simulated loss maps with and without the TCLD collimators for the full LHC ring and the betatron collimation region IR7.

ISBN 978-3-95450-168-7