CLEANING INEFFICIENCY OF THE LHC COLLIMATION SYSTEM DURING THE ENERGY RAMP: SIMULATIONS AND MEASUREMENTS*

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Abstract

The cleaning inefficiency of the LHC collimation system for the operational scenarios in 2010-12 has already been studied in detail at injection and top energy (450 GeV and 4 TeV respectively). In this paper, results are presented for the cleaning inefficiency at intermediate energies, simulated using the SixTrack code. The first comparisons with measured provoked losses are discussed. This study helps in benchmarking the energy dependence of the simulated inefficiency and is thus important for the extrapolation to future operation at higher energies.

INTRODUCTION

The LHC is a two-beam proton collider, built to handle a stored energy of 360 MJ for each beam [1]. Since the energy deposition from particle losses could quench superconducting magnets, a system of collimators [1, 2, 3] has been installed in different points along the ring. Two of these insertions are mainly dedicated to the cleaning of the beam: one cleans the beam from protons with high betatron amplitudes (IR7) and one (IR3) is dedicated to the particles with a large momentum offset.

For both regions, a multi-stage collimation system has been designed. Primary collimators (TCPs) remove particles that have left the core of the beam. At LHC energies, the TCP cannot absorb all protons from this primary halo and a secondary halo leaks out. Secondary collimators (TCSGs), downstream of the TCPs, intercept it. Most residual particles are captured by additional absorbers (TCLAs) or tertiary collimators (TCTs).

To quantify the performance of the collimation system, the local cleaning inefficiency is defined as:

$$\eta = \frac{N_{lost}^{\Delta s}}{\Delta s \cdot N_{abs}}, \tag{1}$$

where $N_{lost}^{\Delta s}$ is the number of particles lost locally over a length of $\Delta s = 10$ cm and N_{abs} refers to the total number of particles absorbed in the collimation system.

Collimation studies at the LHC are carried out with the well established SixTrack [4] code: it allows the tracking of a large number of halo particles, both through the magnetic fields of the accelerator lattice and collimators. When a particle hits a collimator jaw, a Monte-Carlo routine samples random scattering events [5].

So far, the betatron cleaning performance has been deeply investigated at injection and top energy [6, 7]. In this paper, SixTrack simulations are presented for several intermediate energies during the energy ramp (acceleration phase) and compared with data taken from Beam Loss Monitors (BLMs) in the LHC during experimental tests in November 2012.

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SIMULATION SETUP AND PROCEDURE

Energy and Collimator Setting Changing

A first set of simulations has been run considering eight different energies between 450 GeV and 4 TeV, in which the positions of the collimators follow the same function of energy as in the machine [8]. To speed up the preparation of the SixTrack input, a Mathematica script has been implemented to automatically generate the SixTrack input for a given energy.

The aperture of each collimator is expressed in units of standard deviation of the beam in the collimator plane (hor, ver or skew), which in plane i is derived by $\sigma_i = \sqrt{\beta_{x,i}\, \epsilon\, cos^2\theta_i + \beta_{y,i}\, \epsilon\, sin^2\theta_i}$, where $\beta_{x,i}$ and $\beta_{y,i}$ are the optical lattice functions (always constant during the ramp at collimator i), θ_i is the tilt angle of the i-th collimator and ϵ is the nominal geometrical emittance, given by $\epsilon = \epsilon_n/\gamma$, with $\epsilon_n = 3.5\,\mu$m rad normalized emittance and γ ratio between the relativistic energy and the proton rest mass.

In the simulations, 2012 tight settings [9], summarized in Table 1, have been used to set the collimator half gap at the end point. The collimator position (in σ) during the ramp, obtained by linear interpolation of the values from injection to flat top, are shown in Fig. 1.

Table 1: Collimator Settings used in SixTrack Simulation

Location	Collimator Type	Half-gap [σ] 450 GeV	2 TeV	4 TeV
IR3	TCP	8	9.75	12.0
	TCSG	9.3	12.1	15.6
	TCLA	10	13.3	17.6
IR7	TCP	5.7	5.09	4.3
	TCSG	6.7	6.53	6.3
	TCLA	10	9.26	8.3
IR6	TCSG	7	7.04	7.1
experiments	TCT	13	18.7	26

For each energy, 6.4×10^6 particles have been tracked for 200 turns. Simulations have been performed for both beams and with the initial loss in both the horizontal and vertical planes. In this paper, only the results for Beam 1

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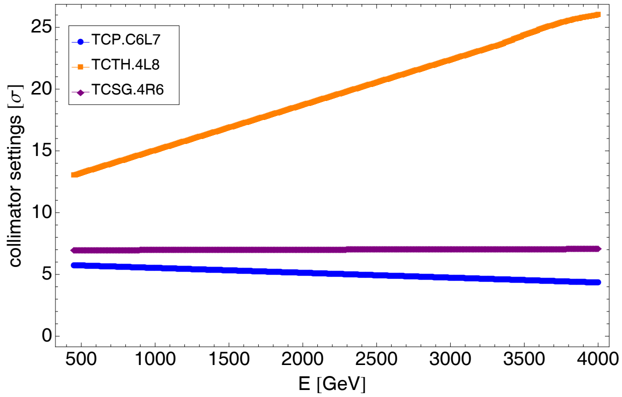

Figure 1: Collimator settings during the energy ramp.

and horizontal losses are shown.

Figure 2 shows the distribution of the losses along the ring at 2 TeV and it well reproduces the typical trend of losses in the machine: the highest losses occur in IR7; losses appears also in the Dispersion Suppression (DS) system downstream of IR7 and in the off-momentum insertion, where the local ratio of particles lost is above 10^{-4} of the level in IR7.

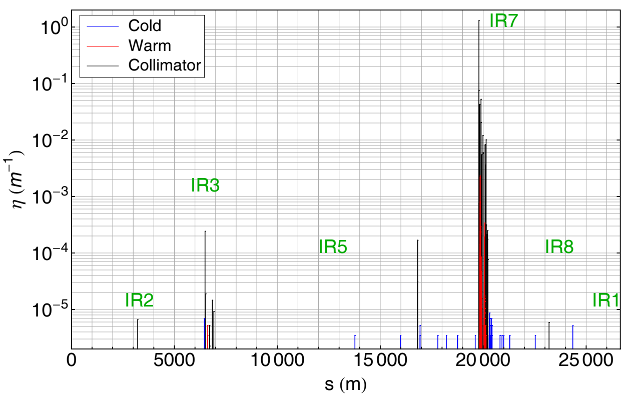

Figure 2: Loss map from SixTrack simulation at 2 TeV.

In Fig. 3, η in the IR7 DS (blue line) is shown as a function of energy. Only a small variation is observed which is within the statistical error of the simulation.

Various factors may affect the efficiency of the collimation system: the proton energy, the collimator positions and the impact parameters of the particles inside the jaw. In order to have a more complete understanding of the quantitative influence of these aspects on the collimation performance and the inefficiency trend in Fig. 3, several simulations have been run, varying different parameters. It was found that neither an increase of statistics, with one order of magnitude more particles tracked, nor the change in the impact parameter (from 60 to 10 μm) show any significant modification in the curves in Fig. 3.

Separate simulations have been performed by varying only the energy or the position of the collimator jaws to isolate the effects of the energy dependence of the scattering

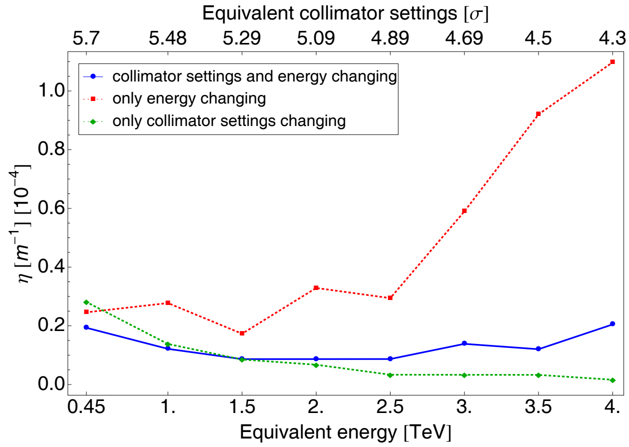

Figure 3: Cleaning inefficiency at the IR7-DS (Q8) that represents the worst location at all energies.

and the collimator movements with respect to the aperture.

Collimator Positions Changing Only

In this case, the energy is kept constant at 450 GeV, as well as the impact parameter, while the collimators are moved like in a normal energy ramp. It means that a collimator, even if the beam energy is 450 GeV, is set to the position (in mm) that it should have at the equivalent energy in the ramp. The collimator setting n_σ used in SixTrack, in units of σ, is

$$n_\sigma = n_{(\sigma,\,E)} \frac{\sigma_E}{\sigma_0} = n_{(\sigma,\,E)} \sqrt{\frac{\gamma_0}{\gamma_E}} \qquad (2)$$

where the subscript 0 refers to 450 GeV and E to the equivalent energy.

The result of the simulations shows, as expected, a decreasing trend with the increase of the equivalent energy (see green dotted line in Fig. 3). This can be understood from the fact that the scattering physics is unchanged due to the constant energy, while the collimators move closer to the beam center as in a normal ramp. They are therefore farther away from the aperture, and the scattering angles required to reach the aperture are larger.

Energy Changing Only

An other possibility is to simulate a normal energy ramp, but keeping the collimator half-gaps constant at their position in mm at 450 GeV. The n_σ is given by:

$$n_\sigma = n_{(\sigma,\,0)} \frac{\sigma_0}{\sigma_E} = n_{(\sigma,\,0)} \sqrt{\frac{\gamma_E}{\gamma_0}} \qquad (3)$$

From the analysis of the simulation results, the efficiency of the system worsens with the energy (see red dotted line in Fig. 3). The change of the particle-matter interactions inside the jaw could explain this behaviour: the scattering angle from Multiple Coulomb scattering decreases with energy (meaning a lower probability of scattering onto the

TCSs) while the cross-section from single diffractive scattering increases slightly [7]. The combined effect is that fewer protons are absorbed by the collimation system. The result is compatible with a similar study in Ref. [7].

From the comparison of the three cases in Fig. 3, a qualitatively good match between the complete simulation (blue line in Fig. 3) and the dotted curves can be seen, with the effects of the energy and collimator openings counter-acting each other. The starting points of the three lines agree within the statistical error.

MEASUREMENTS IN THE LHC

To understand how close the simulation results are to the real behaviour of the machine, data taken during a session in November 2012 has been used to benchmark the simulations.

For this purpose, four nominal LHC bunches of $1.1 \cdot 10^{11}$ protons and four pilot bunches with intensity $2 \cdot 10^{10}$) were injected. For the two beams, repeated excitations at different energies were performed with the transverse damper (ADT) [10], which provides a bunch-by-bunch excitation that makes the particle amplitudes larger and pushes them onto the collimation system in order to provoke fast beam losses. Excitations with a duration of four seconds were done in the horizontal plane during the ramp close the energies used in the simulations. The beam loss data were recorded at the ionization chambers along the ring. Figure 4 shows the measured loss map at 2 TeV. Loss levels are reached with approximately the same order of magnitude as in Fig. 3, but with a higher leakage to IR6 [11].

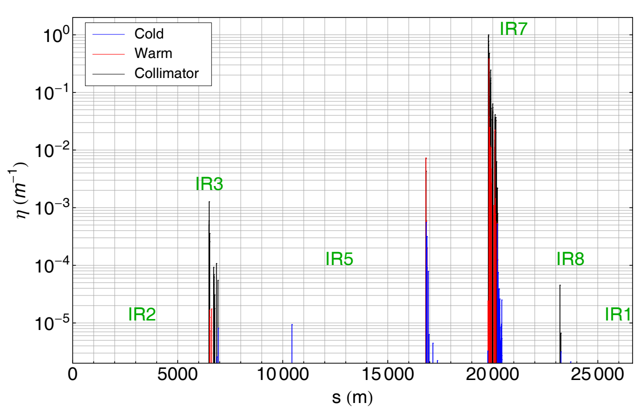

Figure 4: Measured horizontal loss map at 2 TeV.

The losses as a function of energy in simulation and measurement at selected locations are shown in Fig. 5. It should be noted that the measured signal coming out from the BLMs is related to the hadronic showers, produced by the protons interaction inside the collimator material. The response of the ionizing chamber cannot be directly compared with SixTrack output that, instead, refers only to the number of particles absorbed in the jaw. Therefore, a normalization in Fig. 5 has been done: assuming the BLM response to be constant with energy, the data from the simulations have been re-normalized to the first value of the related measurement.

The simulations reproduce well the overall behaviour in the machine. In the DS (green), the trend is almost constant as discussed above, while the decaying trend in IR6 is slightly overestimated by the simulations. The tertiary collimator in IR8, instead, shows a decreasing slope in agreement with its opening during the ramp. The discontinuity in the line for the TCTH around 3 TeV might be justified by a statistical issue, that could be solved by increasing the number of particles tracked in the simulation.

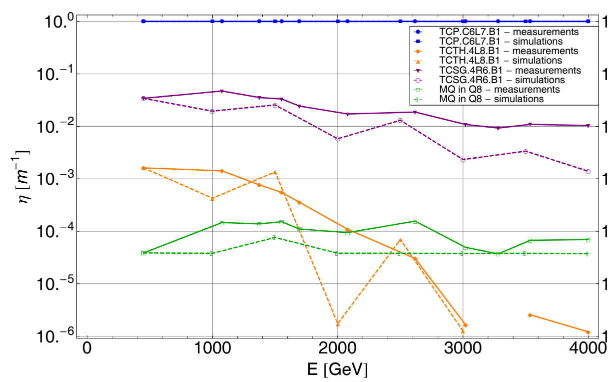

Figure 5: Cleaning inefficiency for selected collimators in the ramp: measurements and simulation compared.

SUMMARY

This article has given an overview of the performance of the LHC collimation system during the energy ramp, focusing on the determination of the parameters that are most relevant for the inefficiency calculations. Qualitatively, a very good agreement is found between measured loss locations and SixTrack simulations at different energies. Furthermore, within the uncertainties from comparing the simulated number of locally lost particles with the measured BLM signals, a good correspondence between the measurement of the energy dependence of the cleaning inefficiency and SixTrack results could be established. The results give an increased confidence in using SixTrack at higher energies for simulations of future configurations.

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