UPDATE ON NONLINEAR COLLIMATION SCHEMES FOR THE LHC[*]

J. Resta-López[†], A. Faus-Golfe, IFIC (CSIC-UV), Valencia, Spain
L. Lari, IFIC (CSIC-UV), Valencia, Spain, and CERN, Geneva, Switzerland

Abstract

In this paper we review the status of the studies on nonlinear collimation schemes for the LHC. Concretely we describe the design of a nonlinear optics for betatron cleaning in IR7. The aim is to investigate alternative nonlinear collimation systems to reduce the collimator-induced impedance that may limit the beam intensity towards the LHC luminosity upgrade. The performance of the LHC nonlinear collimation system is studied by means of tracking simulations and compared with the present LHC system. Furthermore, the advantages and possible limitations of such nonlinear collimation scheme are discussed.

INTRODUCTION

Two arc sections of the LHC are dedicated to collimation: IR7 for betatron halo cleaning and IR3 for momentum collimation. Tertiary collimators and absorbers are also distributed around the different interaction regions (IRs) for protection and shielding of the detectors and other sensitive components. All these collimators can generate significant resistive impedances which may limit the upgrade of the LHC towards higher beam intensities.

In order to reduce the collimator-induced impedance we have proposed an alternative nonlinear collimation optics based on a skew sextupole pair for betatron halo cleaning [1, 2, 3, 4]. In this paper we describe the current status of the studies of this alternative nonlinear collimation system for the LHC betatron cleaning section IR7.

Figure 1 illustrates the concept of a two-stage collimation system based on a skew sextupole pair. The first nonlinear magnet gives a kick to the halo particles, thus increasing the angular divergence of the transverse phases. The effect is an increase of the amplitude of the halo particles and a blow-up of the transverse spot size at downstream primary collimators. This will allow to set the collimator jaws at larger apertures, which is advantageous in terms of impedance reduction. A second nonlinear magnet of the same family and placed at the right phase advance is intended to cancel the geometric optical aberrations generated by the former.

In the next sections we describe the optics and the multistage configuration of the nonlinear collimation system. The optical performance of the system has been studied by means of beam tracking simulations. The halo cleaning efficiency of the system is also studied.

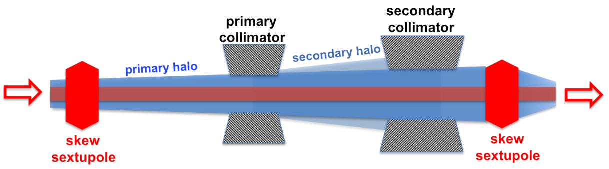

Figure 1: Basic schematic of a nonlinear collimation section based on a skew sextupole pair.

OPTICS DESIGN

The IR7 section of the LHC lattice V6.503 has been matched using the code MAD-X [5] in order to set the necessary conditions for nonlinear collimation. This matching has been performed without affecting the other LHC sectors. Two skew sextupole magnets of the same family have been placed symmetrically with respect to the IP7 and separated by a $-I$ transform to cancel the geometric optical aberrations between them. The phase advance between the sextupoles is π and $\pi/2$ between the first sextupole and IP7 (where the primary collimator is intended to be placed).

Figure 2 shows the matched LHC IR7 optics for nonlinear collimation.

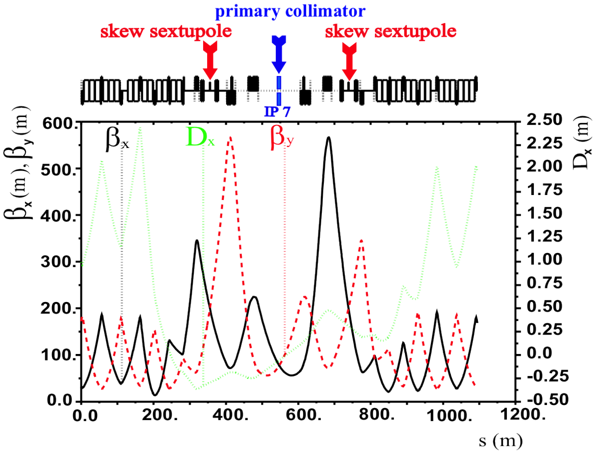

Figure 2: Optics solution for nonlinear collimation in the LHC IR7 sector.

COLLIMATOR SETTINGS

In the conventional collimation system the primary collimators for halo collimation, installed at IR7, have been set at $\sim 6\sigma$ (here and in what follows, we are considering the round beam mode of the LHC, $\epsilon_x = \epsilon_y$) from the beam axis, where σ is the nominal rms beam size. Secondary collimators, intended to intercept the secondary halo, are typically placed at 7-8σ. These apertures to cut the beam

---

[*] Work supported by EU FP7 HILUMI LHC Design Study (Grant Agreement 284404), and FPA2010-21456-C02-01.

[†] Now at the Cockcroft Institute and the University of Liverpool, UK.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-MOPRO035

have been computed and optimised to fulfil the collimation requirements: the reduction of the risk for damage and quenches of the superconducting equipment and to localise and minimise the impact of radiation and radioactive activation. Therefore, for the design of our alternative nonlinear betatron collimation system we establish the same primary collimation depth, 6σ. The necessary primary collimator aperture will be determined by this collimation depth and the strength of the skew sextupoles.

For the collimation of both horizontal and vertical halo, we use the fact that the first skew sextupole produces a vertical kick $\Delta y' \approx 1/2K_s\left(x_s^2 - y_s^2\right)$, where K_s is the integrated skew sextupole strength. It will allow us to set a vertical primary collimator at IP7 with the following half gap:

$$\begin{aligned} A_{y,\mathrm{p}} &= \frac{1}{2}K_sR_{34}x_s^2\ , \\ A_{y,\mathrm{p}} &= \frac{1}{2}K_sR_{34}y_s^2\ , \end{aligned} \tag{1}$$

for $|x_s| = 6\sigma$ and $|y_s| = 6\sigma$. For the collimation of the radial components of the halo, we use the fact that the first skew sextupole produces a horizontal kick $\Delta x' \approx K_sxy$, and therefore horizontal collimator jaws can be set at IP7 with the following half aperture:

$$A_{x,\mathrm{p}} = K_sR_{12}x_sy_s\ , \tag{2}$$

Assuming the optics of Fig. 2 and $K_s = 7\ \mathrm{m}^{-2}$, the half gaps of the primary collimators are $A_{x,\mathrm{p}} = 8\sigma$ and $A_{y,\mathrm{p}} = 8\sigma$. Starting from the base of the existing collimator system, the gaps of the existing secondary and tertiary collimators in IR7 have been rearranged to adapt them to the nonlinear system. Secondary and tertiary collimator jaws between IP7 and the second skew sextupole are placed at 9σ from the beam axis. On the other hand, for collimators downstream of the second skew sextupole a half gap of 7σ is used. This configuration is schematically shown in Fig. 3. Primary and secondary collimators are made of graphite, and tertiary collimators are made of tungsten.

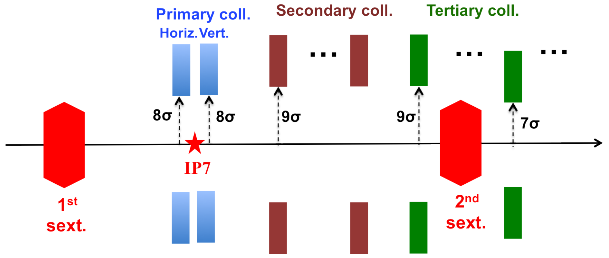

Figure 3: Collimator settings scheme.

OPTICS PERFORMANCE

The Dynamic Aperture (DA) of the machine has been computed by means of tracking simulations (for beam 1) using the code SixTrack [6] and the LHC optics version V6.503. The following simulation conditions have been considered: tracking scan over 10^5 turns, using a polar grid of particles distributed in such a way to have 30 particle pairs per amplitude step of 2σ; and scan over 17 (x-y) phase space angles from 0 (horizontal plane) to $\pi/2$ (vertical plane). 10 realisations of the machine (10 random seeds) have been used for the tracking, assigning magnetic errors to all magnets. These magnetic errors correspond to the measured errors for the field quality of the LHC as-built [7]. The beam energy has been set to 7 TeV and the machine tunes: $Q_x = 64.31$, $Q_y = 59.32$. Furthermore, for these simulations the value of the normalised rms beam emittance is $\epsilon_N = 3.75\ \mu$m and the initial beam momentum spread is $\Delta p/p_0 = 2.7 \times 10^{-4}$. Here the dynamic aperture has been computed without beam-beam effects.

Figure 4 shows the DA as a function of the angle in phase space for the following cases: the nominal LHC, the nonlinear collimation based LHC with skew sextupoles switched off and the nonlinear collimation based LHC with skew sextupoles switched on. According to these tracking simulation results, the nonlinear collimation system (with the skew sextupole pair switched on with normalised integrated strength $K_s = 7\ \mathrm{m}^{-2}$) induces a DA reduction of the order of $\sim$ 3-4 σ with respect to the present nominal system. In spite of this DA degradation, there is still some room to further optimise the system, reducing the necessary sextupole strength while still keeping a larger aperture than the nominal system for primary and secondary collimators.

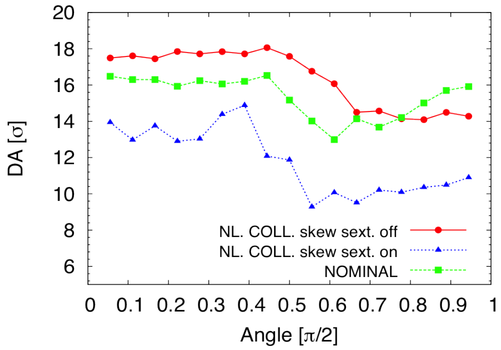

Figure 4: Dynamic aperture for beam 1 as a function of the (x-y) phase space angle for 10^5 turns.

HALO CLEANING

We have computed the local collimation inefficiency $\eta = N_{\mathrm{lost}}^{\Delta s}/(\Delta s N_{\mathrm{abs}})$ (where $N_{\mathrm{lost}}^{\Delta s}$ is the number of particles lost locally over a length of $\Delta s = 10$ cm and N_{abs} denotes the total number of particles absorbed in the collimation system) of the nonlinear collimation system in IR7 and its effect on the whole LHC ring, and compared it with the performance of the present LHC collimation system. For this study the same halo profile has been tracked in the horizontal and vertical plane, using the code SixTrack. The start point of the tracking is IP1. The initial halo consists of a particle distribution with normalised amplitude 6.003σ and a smear of 0.0019σ at collision beam energy 7 TeV. In addition, a fractional energy spread of 1.129×10^{-4} has been considered. Figure 5 (top) shows the collimation inefficiency results for the proposed nonlinear collimation system for the case of a horizontal halo. For the sake of comparison, the results for the present LHC collimation system are also shown (bottom). In these figures, the dotted green lines correspond to the beam dump threshold provided by the Beam Loss Monitor (BLM) in the LHC cold sections.

The nonlinear betatron collimation scheme presents higher losses in the dispersion suppressor region at the entrance of IP3 and a higher leakage (direct losses) on tertiary collimators in the experimental regions IP2 (ALICE). These residual losses need to be reduced with a further optimisation of the system. Similar results are obtained studying the case of a vertical halo separately. Note that the vertical and the horizontal halos are the two extreme cases of a real distribution of losses, the latter being a mix of these two extreme cases.

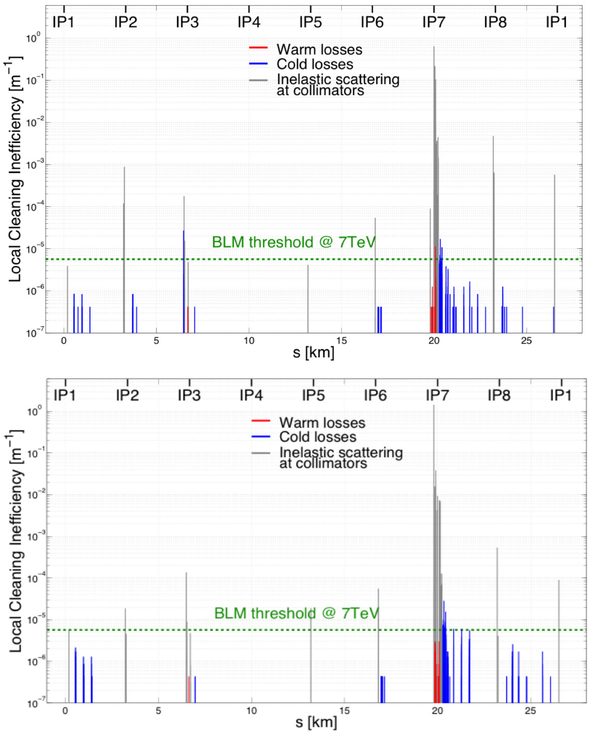

Figure 5: Local collimation inefficiency around the LHC ring considering the nonlinear collimation scheme in IR7 (top) and considering the present linear collimation system (bottom) at collision beam energy 7 TeV.

Tracking studies have also shown that the sextupole effect translates into a significant increase of the order of tens in the impact parameter value at the primary collimator location. The impact parameter is defined as the transfer offset between the jaw surface and the impact point. It is typically equal to 1 μm at the first impact for normal collimation on primary collimator location on the front face. This parameter is extremely important for the mechanical design of the collimator jaw itself and its cooling. The impact parameter increment is beneficial in terms of reducing the risks of local damage on the jaw surface and increasing the margin in allowed setting errors.

OUTLOOK

The nonlinear collimation is a promising technique to reduce collimator-induced impedances when increasing the beam intensity towards the LHC luminosity upgrade. In this paper we have presented the current status of the studies of a nonlinear collimation scheme adapted to the IP7 section of the LHC for betatron halo cleaning.

In spite of the present limitations of the nonlinear system in comparison with the linear one, there is still room for further optimisation: (i) in order to improve the DA; (ii) in order to improve the cleaning efficiency, optimising carefully the orientation and position of secondary collimators.

It is interesting to point out the potential combination of crystal [8] and nonlinear collimation. Since the nonlinear elements guide the particles in a preferred direction, the insertion of crystals could improve the efficiency of the system. The potential of this possibility has to be investigated in future simulations.

A more extensive description of the present status of the LHC nonlinear collimation studies can be found in [9].

REFERENCES

[1] J. Resta et al., “Exploring a nonlinear collimation system for the LHC”, Proceedings of PAC2005, Knoxville, USA, 2005; CERN-LHC-PROJECT-REPORT-842, 2005.

[2] J. Resta-Lopez et al., “An alternative nonlinear collimation system for the LHC”, Proceedings of EPAC2006, Edinburgh, UK, 2006; CERN-LHC-PROJECT-REPORT-939, 2006.

[3] J. Resta-Lopez, A. Faus-Golfe, F. Zimmermann, D. Schulte, F. Zimmermann, “Decreasing the LHC impedance with a nonlinear collimation system”, Proceedings of the third CARE-HHH-APD Workshop, LHC-LUMI-06, Valencia, Spain, 2006; CERN-2007-002.

[4] J. Resta-Lopez, “Design and performance evaluation of nonlinear collimation systems for CLIC and LHC”, CERN-THESIS-2008-018.

[5] http://mad.web.cern.ch/mad

[6] F. Smidth, “SIXTRACK Version 1.2: Single Particle Tracking Code Treating Transverse Motion with Synchrotron Oscillations in a Simplectic Manner: User’s Reference Manual”, CERN-SL-94-56, 1994.

[7] S. Fartoukh and M. Giovannozzi, “Dynamic aperture computation for the as-built CERN Large Hadron Collider and impact of main dipoles sorting”, Nucl. Instrum. and Methods A 671, 10 (2012).

[8] W. Scandale, “Use of crystals for beam deflection in particle accelerators”, Mod. Phys. Lett. A 27, 1230007 (2012).

[9] J. Resta-Lopez et al., “Update on Nonlinear Collimation Studies for the LHC”, in preparation.