AN ALTERNATIVE NONLINEAR COLLIMATION SYSTEM FOR THE LHC

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Abstract

The optics design of an alternative nonlinear collimation system for the LHC is presented. We discuss an optics scheme based on a single spoiler located in between a pair of skew sextupoles for betatron collimation. The nonlinear system allows opening up the collimator gaps, thereby, reduces the collimator impedance, which presently limits the LHC intensity. After placing secondary collimators at locations behind the spoiler, we analyze the beam losses and calculate the cleaning efficiency from tracking studies. The results are compared with those of the conventional linear collimation system.

INTRODUCTION

In previous works [1] we proposed a nonlinear collimation system for the 7 TeV LHC as a possible solution to the difficult trade-off between cleaning efficiency, collimator robustness and collimator impedance. This system is based on a single spoiler between a pair of skew sextupoles separated by an optical transfer matrix $-I$. The first skew sextupole increases the transverse beam size at the spoiler, thus allowing larger aperture of the mechanical jaws, which is desired to reduce impedance. Higher transverse beam sizes further mean lower transverse energy density at the spoiler, increasing in this manner the probability of spoiler survival in case of miskicked beam impact.

In this paper a two-stage collimation is considered. Secondary collimators are located downstream of the spoiler or primary collimator. An improvement of the performance with respect to the design of Ref. [1] is presented.

It is worthwhile to mention that the principle of nonlinear collimation studied in this paper for the LHC is general, and adaptations can be performed for other storage rings and even for future linear colliders operating at center-of-mass energies of 1–3 TeV [2].

OPTICS LAYOUT

At the skew sextupole a charged particle suffers deflections $\Delta x' = -\partial H_s/\partial x$, $\Delta y' = -\partial H_s/\partial y$, where $H_s = K_s(y^3 - 3(x + D\delta)^2 y)/6$ is the Hamiltionian for the beam motion in a skew sextupole. Here x and y are the transverse betatron amplitudes at the sextupole, D the dispersion at the sextupole, δ the relative momentum offset and K_s the integrated strength of the sextupole. The kick at the sextupole causes the following position offset at the spoiler:

$$\Delta x_{\rm sp} \;=\; R_{12}\Delta x' \simeq K_s R_{12} xy \; , \qquad (1)$$

$$\Delta y_{\rm sp} \;=\; R_{34}\Delta y' \simeq -\frac{1}{2}K_s R_{34}(y^2 - x^2) \; , \qquad (2)$$

where R_{12} and R_{34} are the optical transport matrix elements between the first sextupole and the spoiler. In the second step, $D\delta \ll x$ is assumed.

Let $\pm n_x\sqrt{\beta_{x,\rm sext}\epsilon_x}$ and $\pm n_y\sqrt{\beta_{y,\rm sext}\epsilon_y}$ be the collimation amplitudes for the horizontal and vertical betatron motion respectively, and $\pm n_{x2}\sqrt{\beta_{x,\rm sp}\epsilon_x}$ and $\pm n_{y2}\sqrt{\beta_{y,\rm sp}\epsilon_y}$ the physical transverse apertures of the primary spoiler. Then for the collimation to function in either transverse plane, we must have [1]

$$n_{y2}\sqrt{\beta_{y,\rm sp}\epsilon_y} \;=\; \frac{1}{2}K_s R_{34} n_x^2 \beta_{x,\rm sext}\epsilon_x \; , \qquad (3)$$

$$n_{y2}\sqrt{\beta_{y,\rm sp}\epsilon_y} \;=\; \frac{1}{2}K_s R_{34} n_y^2 \beta_{y,\rm sext}\epsilon_y \; . \qquad (4)$$

On the other hand, to collimate particles at the orthogonal or radial plane a horizontal collimator with half gap aperture of $n_{x2}\sqrt{\beta_{x,\rm sp}\epsilon_x}$ is used,

$$n_{x2}\sqrt{\beta_{x,\rm sp}\epsilon_x} = K_s R_{12} n_x n_y \sqrt{\beta_{x,\rm sext}\epsilon_y}\sqrt{\beta_{y,\rm sext}\epsilon_y} \; . \qquad (5)$$

A minimum beam size $\sigma_{r,\rm min}$ of about 200 μm is required for spoiler survival in case of beam impact, so that $\sigma_{x,\rm sp}\sigma_{y,\rm sp} \geq \sigma_{r,\rm min}^2$. This condition constrains approximately the minimum values of K_s, R_{12} and R_{34} permitted. However, detailed energy deposition studies should be done.

The optics for the betatronic cleaning insertion IR7 in LHC optics version 6.5 has been matched to fulfill the above nonlinear collimation requirements. A skew sextupole with $K_s \simeq 7$ m^{-2} was used. From preliminary particle tracking studies for 10^5 turns we obtained a dynamic aperture of $\approx 22\sigma$, if only the following linear errors are considered: $\Delta\beta_y/\beta_y \simeq 17$ %, $\Delta D_x/D_x \simeq 12$ % and $\Delta p/p \simeq 0.02$ %. Nevertheless, more realistic studies including all kind of errors are still necessary in order to compare with the dynamic aperture of $\simeq 12\sigma$ for the nominal LHC optics version 6.5 at collision [3].

Figure 1 shows the betatron functions and dispersion of an optics solution for a normalized transverse nonlinear collimation depth of $n_x = n_y = 6$. Particles at transverse amplitudes $|x| \geq n_x\sigma_{x,\rm sext}$ and $|y| \geq n_y\sigma_{y,\rm sext}$ will be caught by a single vertical spoiler of half gap $n_{y2} = 8$, i.e., a physical aperture $2\sigma_y$ higher than that of the primary collimators of the linear collimation system [4].

Assuming $\beta_{x,\rm sext} = \beta_{y,\rm sext}$ and $R_{12} \simeq R_{34}$, the horizontal collimator aperture for cleaning in the diagonal plane is $n_{x2} = 2n_{y2} = 16$.

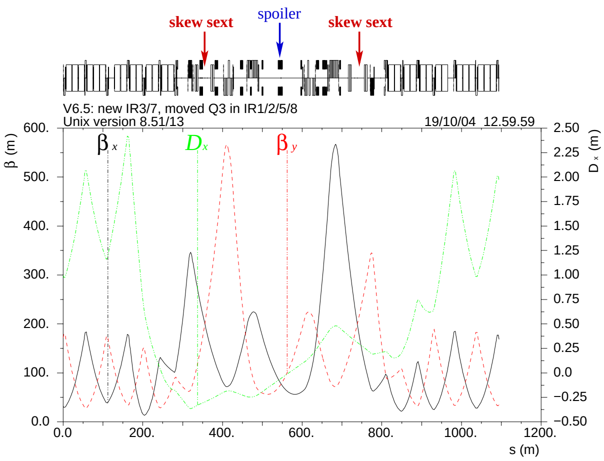

Figure 1: The optics solution proposed for LHC IR7 with a nonlinear collimation section based on two skew sextupoles.

TWO-STAGE COLLIMATION

Until now we have only considered primary collimators located at IP7. However, protons which are not absorbed can be scattered elastically off the jaw, thus generating a secondary halo which can induce quenches of the superconducting magnets. Therefore, secondary collimators are necessary to intercept the secondary halo. The gaps of the existing collimators in the IR7 insertion of the LHC [4] were set to the required apertures for nonlinear collimation. A total of 12 secondary collimators are retained downstream the primary collimators. Notably two vertical collimators are located at the optimum phase advances $\Delta\mu_0 \simeq 0.476$ rad and $\Delta\mu_0 = 0.476 + \pi/2 \simeq 2.0468$ rad from IP7 respectively, calculated from $\Delta\mu_0 = \pm\arccos(n_{y2}/n'_{y2})$ [5], assuming a primary vertical aperture $n_{y2} = 8$ and a secondary vertical aperture $n'_{y2} = 9$. Secondary collimators between IP7 and the second skew sextupole have been set with a radial aperture of 9σ, and those downstream of the second skew sextupole with 7σ. See the schematic of Figure 2.

Figure 3 compares the half gap of the collimators for the linear and the alternative nonlinear collimation systems. The total number of active collimators is 14 for the nonlinear system and 19 for the linear system (phase 1 system). The empty space in the histogram of Figure 3 indicates the space reserve for future system upgrades. For the nonlinear collimation system we have added the secondary collimators #14, #15 and #17 using that existing space reserve.

CLEANING EFFICIENCY

Tracking studies have been performed for the nonlinear and linear collimation systems by using a modified version of the tracking code `SixTrack` [6, 7]. This tool allows us to calculate the cleaning inefficiency of the collimation system and to save the particles trajectories for an offline analysis of beam losses.

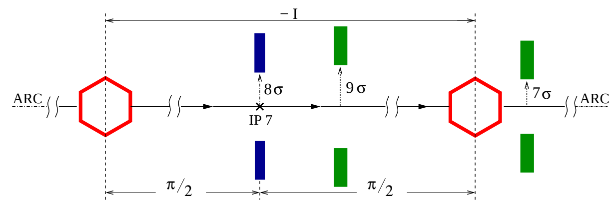

Figure 2: Schematic of a two-stage nonlinear collimation layout for the LHC.

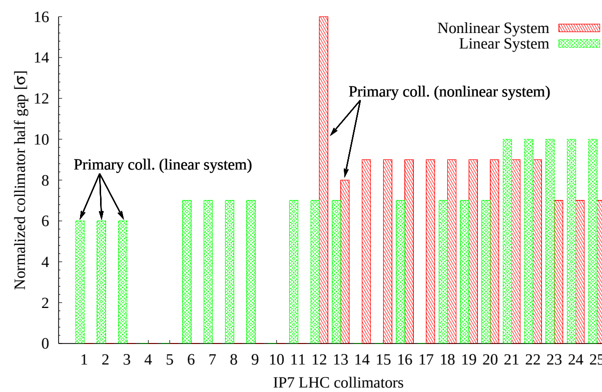

Figure 3: Comparison of the normalized collimator apertures for the nonlinear and the linear collimation systems. In the nonlinear case, the collimators [#1, #11] are not used, and collimators #12 with $n_{x2} = 16$ and #13 with $n_{y2} = 8$ play the role of primary spoilers at IP7.

The cleaning inefficiency $\eta_c(A_0)$ of the collimation system is defined by [6]

$$\eta_c(A_0) = \frac{N_p(A > A_0)}{N_{\rm abs}}\,, \tag{6}$$

with $N_p(A > A_0)$ the number of beam protons with amplitude above A_0 and $N_{\rm abs}$ the total number of absorbed protons in the cleaning insertion.

Beam halos have been generated from a tracking of initial distributions of $N_p \simeq 5 \times 10^6$ protons for 200 turns. At first, initial horizontal and vertical halos were separately considered. The initial horizontal distribution in normalized phase space is an annulus with radii $A_x = \sqrt{X^2 + X'^2} = 6.003$ and $A_y = \sqrt{Y + Y'^2} = 0$ and thickness $\delta\sigma = 0.0015\sigma$. Similarly, for the vertical halo we used $A_x = 0$ and $A_y = 6.003$. In a second step, a square particle distribution with diagonal amplitude $A_r = \sqrt{A_x^2 + A_y^2} = 8.503$ ($A_x = A_y \simeq 6$) has been considered to study the skew halo components.

The resulting $\eta_c(A_0)$ for the nonlinear collimation system compared with the linear one is shown in Figure 4. The nonlinear system presents better cleaning efficiency (lower cleaning inefficiency) for $A_0 \in [6\sigma, 7.4\sigma]$ and $A_0 \in [9.5\sigma, 15\sigma]$ for the vertical halo. In the range $(7.4\sigma, 9.5\sigma)$ the linear system is more efficient by not more than a factor 2 superior to the nonlinear one. However, for a horizontal halo, the inefficiency of the nonlinear system in the range

$[7.5\sigma, 15\sigma]$ is higher by approximately a factor 10. In the case of a radial halo, the present nonlinear system is less efficient by a factor 3.

The number of impacts and absorptions at every collimator of the nonlinear and linear systems is displayed in Figure 5 for the vertical halo. Unlike the linear system, that registers the peak of impacts and absorptions at the begining of the insertion, the nonlinear system registers the peak at the collimator $\#13$, located close to the IP7.

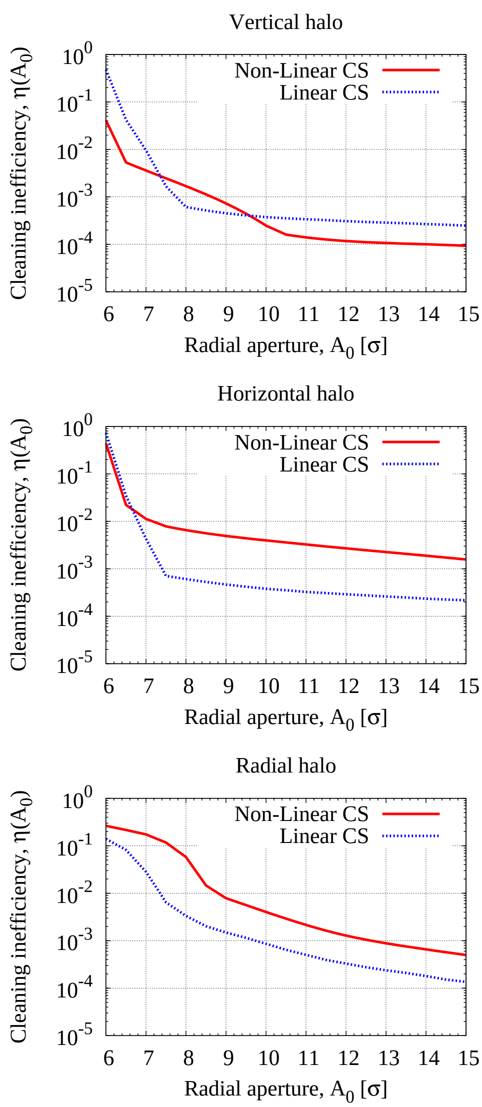

Figure 4: Cleaning inefficiency, $\eta_c(A_0)$, as a function of the radial amplitude A_0 for the nonlinear collimation system (red solid line), compared with $\eta_c(A_0)$ for the conventional linear system (dotted blue line) considering a vertical halo (top), a horizontal halo (middle) and a radial halo (bottom) at 7 TeV.

CONCLUSIONS AND OUTLOOK

A nonlinear collimation system allows larger aperture for the mechanical jaws, thereby, reduces the collimator impedance. Furthermore the transverse energy density is reduced at the spoilers, thus increasing the probability of spoiler survival in case of miskicked beam impact.

The performance of a two-stage nonlinear betatron collimation for the LHC has been studied. We obtained a considerable improvement of the cleaning efficiency up to the level of the linear system for vertical directions. However, a careful study is still necessary to tune the orientation and positions of secondary collimators to achieve the same level of efficiency as the linear system for cleaning of horizontal and radial halo components.

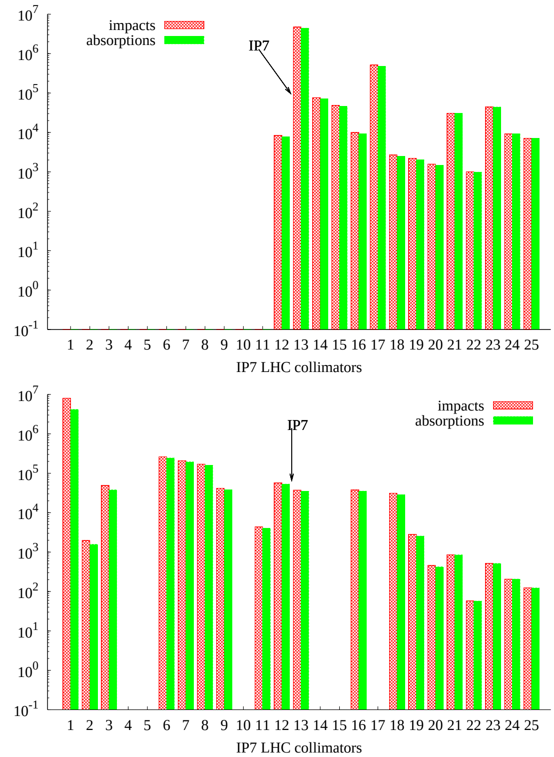

Figure 5: Number of particle impacts and absorptions in the collimators of the insertion IR7 of the LHC for nonlinear collimation (top) and for linear collimation (bottom), if a vertical halo is considered at 7 TeV.

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