LHC IMPEDANCE REDUCTION BY NONLINEAR COLLIMATION *

J. Resta-López†, A. Faus-Golfe, IFIC, Valencia, Spain;
F. Zimmermann, CERN, Geneva, Switzerland

Abstract

A nonlinear collimation system can allow larger aperture for mechanical jaws, and it thereby can help to reduce the collimator impedance, which presently limits the LHC beam intensity. Assuming the nominal LHC beam at 7 TeV, we show how a nonlinear betatronic collimation insertion would reduce considerably the LHC coherent tune shift for the most critical coupled-bunch mode as compared with the conventional baseline linear collimation system of Phase-I. In either case, the tune shifts of the most unstable modes are compared with the stability diagrams for Landau damping.

INTRODUCTION

Most of the LHC collimators in Phase-I [1] will be made of graphite. This material is a poor conductor (its electrical conductivity is 1.7×10^{-3} that of copper). In addition, the collimator jaws of Phase-I will be located close to the beam ($a \sim 6\sigma$). These conditions will contribute to a dramatic increase of the machine impedance. Calculations [2] have shown that the achievable LHC beam intensity, and therefore the luminosity, will be limited by the impedances introduced by the collimators.

A nonlinear collimation system, allowing larger aperture for most of the collimators, could be a cure overcoming the performance limitations associated with the collimator impedances.

A study of a two-stage nonlinear collimation system for betatron cleaning in the LHC has extensively been presented in [3]. This system is based on a pair of skew sextupoles located in the betatron cleaning section of the LHC (IR7 insertion), which we call nonlinear IR7. Fig. 1 compares the normalized collimator apertures for the nonlinear and the linear insertion IR7. Optics details are given in [3].

DECREASING THE LHC IMPEDANCE

The resistive-wall tranverse impedance can generate coherent coupled-bunch tune shifts, which can be written in terms of an effective impedance as [5]

$$\Delta Q_\perp = -i\frac{N_\mathrm{b} N e\omega_0\beta_\perp}{8\pi^2 E}\frac{\Gamma\left(m+\frac{1}{2}\right)}{2^m m!}Z_\perp^{\mathrm{eff}}(\omega_k-\omega_\xi), \quad (1)$$

where N is the bunch population, N_b the number of equidistant bunches and E the beam energy. It is important to

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† Present address: John Adams Institute, Oxford University, UK.

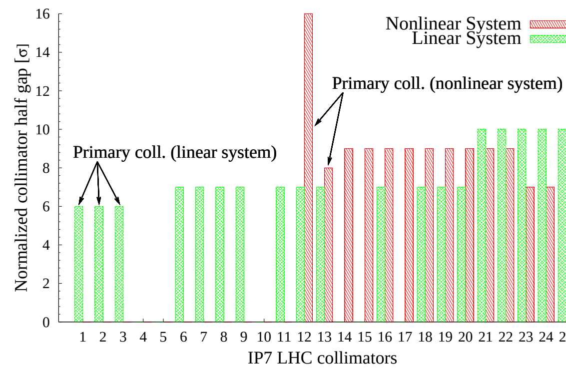

Figure 1: Comparison of the normalized collimator apertures for the nonlinear and the linear collimation systems. In the nonlinear case, the collimators $[\#1, \#11]$ are not used, and collimators #12 and #13 play the role of primary spoilers at IP7.

stress the dependence on the frequency $\omega_k = \omega_\beta + k\omega_0 + m\omega_s$, containing the following oscillation modes: the head-tail mode, characterized by the number m, and the coupled-bunch mode, characterized by the number $l = k - N_\mathrm{b}k'$ with $-\infty \leq k' \leq +\infty$ and $0 \leq l \leq N_\mathrm{b} - 1$. The frequency $\omega_\beta = Q_\beta\omega_0$ denotes the betatron frequency as a function of the unperturbed betatron tune Q_β and the revolution frequency of the particles ω_0; ω_s denotes the synchrotron angular frequency and $\omega_\xi = \xi\omega_\beta/\eta$ is the chromatic frequency depending on the chromaticity ξ and the slippage factor η.

We have computed, using *Mathematica*, the total coherent tune shift for both cases, namely the baseline linear system of Phase-I and the nonlinear system. The transverse impedance of each collimator has been calculated by using the Burov-Lebedev theory [4]. In a first step, we added exclusively the contribution of the collimators belonging to the IR7 insertion (for both cases linear and nonlinear system). In a second step, we also included the contribution from the total list of collimators, including the insertions IR7, IR3 (momentum collimation) and the tertiary collimators for local protection and cleaning at the triplets in IR1, IR2, IR5 and IR8 (experimental insertions), and IR6 (dump insertion). Other contributions such as the broad-band (BB) impedance and the resistive wall (RW) impedance for the rest of the ring without collimators have also been considered.

In order to select the most unstable case, we have computed the tune shift versus the coupled-bunch modes. The most critical mode is generally that which gives the maximum modulus of the tune shifts. Figure 2 shows the modulus of the horizontal and vertical tunes shifts as a function of the mode number l for the case of the nonlinear IR7. The maximum values of $|\Delta Q_\perp|$ are found at $l = 0$ or $l = 3564$.

For all calculations we have taken the head-tail mode $m = 0$, related to rigid dipole oscillations, zero chromaticity and the LHC parameters of Table 1. In order to consider a pessimistic case, and since the theory assumes equi-distant bunches, we have used $N_\mathrm{b} = 3564$ instead of the nominal number of bunches $N_\mathrm{b} = 2808$. Results of $Z^{\mathrm{eff}}_{\perp=x,y}$ and $\Delta Q_{\perp=x,y}$ are summarized in Table 2 and Table 3, respectively, for each of the different contributions.

The tables demonstrate that when the nonlinear IR7 insertion is used, $|Z^{\mathrm{eff}}_x|$ is reduced by about a factor 2 and $|Z^{\mathrm{eff}}_y|$ by about a factor 3 with respect to the linear IR7 insertion of Phase-I.

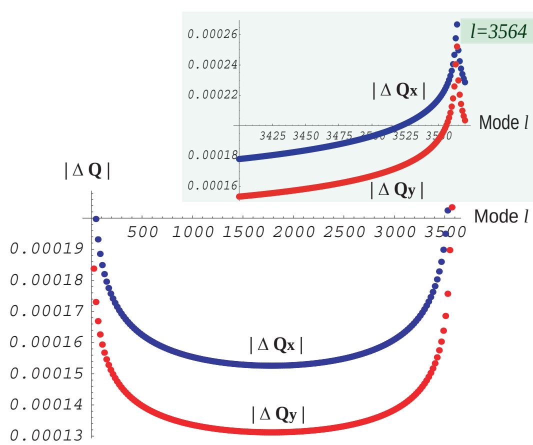

Figure 2: Module of the horizontal ($|\Delta Q_x|$) and the vertical ($|\Delta Q_y|$) coherent coupled-bunch tune shifts as a function of the coupled-bunch mode l for the case of the nonlinear IR7. The figure on the top shows a zoom of the region $l \in [3400, 3575]$. The results have been obtained assuming $m = 0$ and $\xi = 0$.

Table 1: LHC nominal parameters used in the tune shift calculation.

parameter	value
proton energy (at collision): E [TeV]	7.
bunch length: σ_z [mm]	75.5
bunch population: N	1.15×10^{11}
number of bunches: N_b	2808
bunch spacing: Δt_b [ns]	25
revolution frequency: $\omega_0 = 2\pi f_0$ [kHz]	70.6544
betatron tune: Q_β	65.32
machine slippage factor: η	3.22×10^{-4}

Transverse stability diagrams

In the LHC arcs there are two families of magnetic octupoles which control betatron detuning and provide Landau damping of coherent beam oscillation modes [1]. Potentially unstable oscillation modes with negative imaginary tune shifts can be stabilized by this method.

In order to compare the complex transverse coherent tune shift generated by the collimator impedances from the nonlinear and the linear collimation system, we use the so-called stability diagrams, introduced first by J. S. Berg and F. Ruggiero [6]. This kind of diagrams represents the limits of the stable beam area in the $[-\mathrm{Im}(\Delta Q_\perp)]$–$[\mathrm{Re}(\Delta Q_\perp)]$ plane (or equivalently in the $[\mathrm{Re}(Z_\perp)]$–$[\mathrm{Im}(Z_\perp)]$ plane), granted by the octupole system.

Figure 3 compares the complex tune shift due to the impedances of the nonlinear IR7 and the linear IR7 systems with the Landau damping stability curves, assuming maximum available octupolar strength. The stable area is below the two curves in the figure. The dashed (blue) curve is the stability for maximum Landau octupole current with negative anharmonicity; the slid (red) curve with positive anharmonicity. The nonlinear system reduces the coherent tune shift by a factor 2–3, compared with the linear system.

Similarly, Figure 4 compares the tune shifts introduced by the nonlinear and linear IR7 plus the contribution of the IR3 insertion (momentum collimation) and other tertiary collimators in IR1, IR2, IR5, IR6 and IR8 for local protection. The contributions from BB impedance and RW impedance without collimators have also been added. Including all these contributions the nominal LHC beam may be unstable for both the linear and the nonlinear collimation systems in IR7, though in the latter case it is closer to the stability border.

The largest contribution to the real part of the remaining tune shift comes from the tertiary collimators and from resistive wall (see Table 2). Extending the nonlinear scheme and adding further nonlinear elements close to those tertiary collimators might move the maximum coherent tune shift into the stable area for the nominal beam.

CONCLUSIONS

A nonlinear collimation system allows larger aperture for the mechanical jaws and thereby reduces the collimator impedance. We have shown how a nonlinear betatronic collimation insertion for the LHC would reduce considerably the coherent tune shift for the most critical coupled-bunch mode as compared with the conventional baseline linear collimation system of Phase-I.

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Table 2: Transverse effective collimator impedance for the IR7 Phase-I (linear), for our proposed nonlinear IR7, and for other additional contributions from: IR3, other tertiary collimators for local protection (in IR1, IR2, IR5, IR6 and IR8), broad-band (BB) impedance and resistive wall (RW) impedance without collimators. These results have been obtained considering the most unstable case $m = 0$, $l = 0$ and $\xi = 0$.

	$Z_x^{\rm eff}(m=0,l=0,\xi=0)$ [MΩ/m]	$Z_y^{\rm eff}(m=0,l=0,\xi=0)$ [MΩ/m]
IR7 Phase-I (linear)	$9.309 - 272.321i$	$8.795 - 303.901i$
IR7 (nonlinear)	$9.068 - 120.62i$	$7.084 - 113.64i$
IR3	$1.955 - 38.841i$	$1.089 - 19.917i$
Others (tertiary)	$10.059 - 58.508i$	$9.19 - 47.8i$
RW (w/o collimators)	$41.272 - 8.334i$	$56.994 - 11.508i$
BB (w/o collimators)	$9.237 \times 10^{-6} - 2945.66i$	

Table 3: Transverse coherent coupled-bunch tune shift due to collimator impedance of IR7 Phase-I (linear), our proposed nonlinear IR7, IR3, other tertiary collimators for local protection (in IR1, IR2, IR5, IR6 and IR8), broad-band impedance (BB) and resistive wall (RW) impedance without collimators. These results have been obtained considering the most unstable case $m = 0$, $l = 0$ and $\xi = 0$.

	$\Delta Q_x(m=0,l=0,\xi=0)$	$\Delta Q_y(m=0,l=0,\xi=0)$
IR7 Phase-I (linear)	$-(6.637 + 0.197i) \times 10^{-4}$	$-(5.127 + 0.146i) \times 10^{-4}$
IR7 (nonlinear)	$-(2.662 + 0.174i) \times 10^{-4}$	$-(2.512 + 0.223i) \times 10^{-4}$
IR3	$-(0.2729 + 0.0217i) \times 10^{-4}$	$-(0.973 + 0.0375i) \times 10^{-4}$
Others (tertiary)	$-(1.259 + 0.222i) \times 10^{-4}$	$-(1.208 + 0.185i) \times 10^{-4}$
RW (w/o collimators)	$-(0.0867 + 0.43i) \times 10^{-4}$	$-(0.12 + 0.593i) \times 10^{-4}$
BB (w/o collimators)	$-(0.438 + 0.i) \times 10^{-4}$	

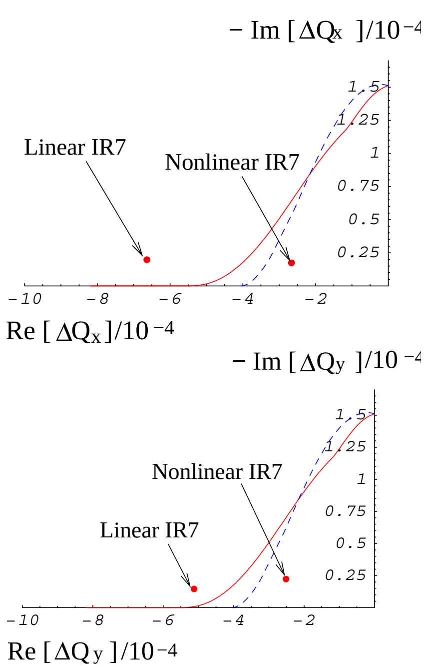

Figure 3: The transverse stability diagram in LHC at 7 TeV, with the nominal bunch population $N = 1.15 \times 10^{11}$ protons. The points compare the tune shift introduced by the nonlinear and the linear collimation sections IR7.

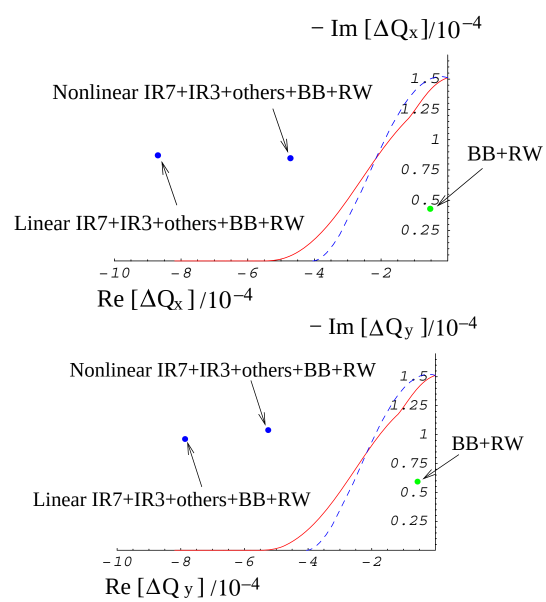

Figure 4: The transverse stability diagram in LHC at 7 TeV, with the nominal bunch population $N = 1.15 \times 10^{11}$ protons. The points compare the tune shift introduced by the nonlinear and the linear collimation systems, adding all contributions from Table 3.

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