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NUMERICAL SIMULATIONS OF A HOLLOW ELECTRON LENS AS A SCRAPING DEVICE FOR THE LHC

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Abstract

The use of hollow electron beam lens for scraping high energy proton beams has been extensively tested at Fermilab's Tevatron collider. In order to evaluate a possible application of a similar a device in the LHC, a dedicated new routine has been implemented in the standard 6D tracking code used at CERN for the design of the LHC collimation system. The effects of a finite length cylinder of electrons encompassing the main proton beam and traveling in the opposite direction is described in the routine. Realistic electron distributions, including measured radial imperfections, have been included in the model. Various operating modes have been simulated for the 7 TeV machine operation with sextupoles and octupoles included. The loss rate caused by the electron lens has been studied through an extended simulation campaign; the obtained halo removal rates for the different electron lens operating modes are presented.

INTRODUCTION

The electron lens (e-lens) [1] is a device which generates a beam of electrons traveling parallel to the proton beam. The desired transverse electron beam profile can be obtained by selecting an appropriate shape for the emitting cathode: at the Tevatron flat beams (for abort gap cleaning), gaussian beams (beam-beam compensation) and hollow beams (collimation) have been tested. It was shown that an hollow beam can be effectively used to quickly drive the halo particles on the primary collimator while being virtually transparent for the beam core [2]. The particle removal is then provided by the collimation system in place.

This work aims to evaluate the applicability of the same technique to the LHC and to give an evaluation of the possible e-lens performances. The current LHC collimation system provides a very efficient halo cleaning [3]. However, when trying to push the machine to - and over - its design limits, all the accelerator components are required to boost their performances. For example the loss spikes observed in 2012 during the beam squeeze [4], which are no issue for the current machine parameters, could be potentially dangerous when scaled to higher energy. It is believed that depopulating the halo over 4σ could help minimizing unwanted losses, and there are many reasons why the e-lens seems to be a particularly interesting option:

- it is not obvious to find a solid scraper which could sustain the heat load given by the high-energetic LHC halo without major damage, especially in case of machine failure;
- not having a solid material close to the beam core would not touch the already tight transverse impedance budget;
- with different operation mode and tunable electron beam current, the loss rate can be adapted to different machine needs;

In addition to the scraping application, the e-lens could be used for other purposes, such as to generate the betatron tune spread for improved Landau damping of coherent instabilities.

SIXTRACK SIMULATIONS

In this paper we present, for the first time, an estimate for the scraping efficiency of the e-lens at LHC. For our simulations we used the standard tool for collimation studies at CERN, SixTrack [5]. In order to calculate the impact of a hollow e-lens on the LHC collimation, a new dedicated subroutine describing the e-lens has been written and integrated in the collimation routine of Sixtrack. The routine does not take into account the interaction with the electron beam at the insertion and extraction region of the e-beam, or the fringe field in the same regions.

The hollow e-lens is implemented as a thin lens. The e-lens kick is calculated assuming a distribution of the electron beam between an inner and an outer radius (respectively R_1 and R_2). The radial profile can be either considered a uniform distribution (perfect e-lens model), or a measured beam profile can be implemented (radial model); but the distribution is always invariant by rotation. Thanks to this symmetry, the EM field in the space enclosed by the ideal electron beam is perfectly zero, thus not affecting the beam core. On the contrary, protons with transverse radius larger than R1 will experience both the electric and magnetic field from electron beam space charge. The two forces can either sum up or have opposite sign, depending on the relative orientation of the circulating and electron beam velocities and by the particle charges. Using the Gauss and the Biot-Savart law to calculate the e.m. force and integrating over the device length L, the integrated kick for a particle at transverse amplitude r results:

$$\theta(r) = -\frac{2L\, I_r\, (1 \pm \beta_e \beta_p)}{4\pi\varepsilon_0\, r\, (B\rho)_p \beta_e \beta_p\, c^2} \tag{1}$$

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Table 1: Hardware parameters for the e-lens installed in the Tevatron: maximum electron beam current I_{max} and current jitter $(\Delta I/I)_{max}$, maximum extraction voltage V_{max}, ratio between inner and outer cathode radius R_1/R_2, minimum achievable inner radius for the electron beam R_{1min} and cathode modulator rising time Δt_{min} .

$I_{max} \pm (\Delta I/I)_{max}$	1.2 A $\pm 2\%$
V_{max}	5 kV
R_1/R_2	4.5 mm/ 7.5 mm= 0.60
R_{1min}	0.58 mm
Δt_{min}	250 ns

where I_r is the current encompassed by the radius r, β_p and β_e are the relativistic β for the proton and the electron beam and $(B\rho)_p = m_p v_p/q = 3.3356(mv)_p[GeV/c]$ is the magnetic rigidity of the proton beam.

The hardware parameters for the e-lens previously installed in the Tevatron are shown in Table 1; our simulations assume the same parameters. Given the extremely fast rising time of the cathode modulator it is possible to modulate the intensity of the electron beam on a turn-by-turn basis. This allows to operate the e-lens both continuously or with a specific pattern. In the simulations, three different operational modes have been implemented: DC, AC and diffusive. The details of the different operation modes will be given in the discussion of the simulation results.

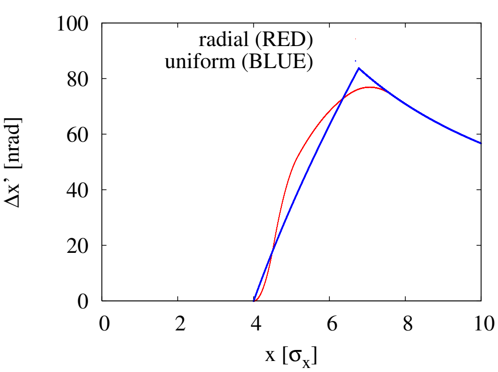

Figure 1: Radial kick given by the e-lens, for both perfect e-lens and radial profile model.

The kick for a 7 TeV beam is presented in Fig. 1, both for the uniform and the experimental radial profile. The inner radius of the e-beam has been fixed to $4\sigma_x$ (1.2mm) which is well within the e-lens capabilities for the assumed hardware. The nominal 7 TeV LHC optics in collision has been considered, sextupoles and octupoles included. The case of purely horizontal, on-momentum halo has been studied, with normalized beam emittance of 3.75 10^{-6} m rad.

For a future installation of the e-lens in the LHC two possible locations, immediately downstream and upstream of IP4 (RB44-RB46), are being considered. The location RB46 has been selected for the simulation campaign because of the favorable beam parameters, being the β-functions close to round beam condition (β_x=β_y=300m). Only the horizontal primary IP7 collimator has been included in the simulation, with aperture 6.2 σ_x.

Table 2: Main optics parameters in simulation.

name	settings $[\sigma_x]$	σ_x $[\mu$m]	σ'_x $[\mu$rad]	σ_y $[\mu$m]	σ'_y $[\mu$rad]
ELENSE	4	302.3	1.74	300.7	2.32
TCP.C6L7	6.2 H.	275.02	4.17	203.9	3.76

SIMULATION RESULTS

In DC mode the e-lens is continuously on and the scraping effect relies on creation of resonances given by the combination of the highly non linear electron lens force and the other non linearities of the machine [6]. Being the e-lens kick focusing, it produces a positive tune shift. By dedicate studies it was observed that the tune shift is roughly linear with respect to the particle amplitude in the region between $4\sigma_x$ and $6\sigma_x$, with the exception of the region at about 5.7σ_x where a high-order resonance sits (Fig. 2).

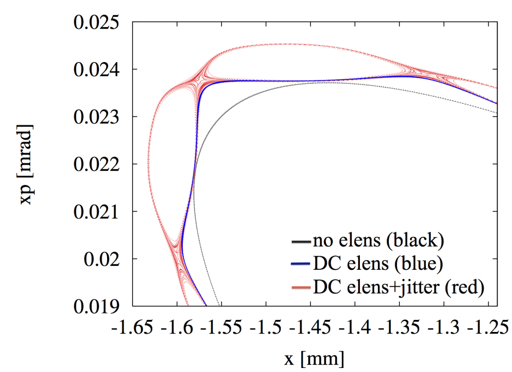

Figure 2: Close-up of the phase-space ellipse in the horizontal plane for a particle at 5.7σ_x, with no e-lens (black), DC e-lens (blue), DC+2% current jitter (red).

At this stage of simulation details, the first resonances generated by the combination of non linearities already appear. The scraping effect, however, is still very mild (less than 1% of the halo particles are lost), but the efficiency is expected to increase for a more realistic description of the machine, including multipole errors, alignment errors, diffusion and, for collision case, beam beam.

To enhance the electron lens loss rate, it was proposed to put the electron lens in resonance with the betatron oscillation of the particles (AC mode). The equation of motion of a circulating particle subjected to a time-variable force was therefore considered (linear approximation):

$$m\ddot{x} + kx = -f(x)g(t) \tag{2}$$

where the natural oscillation frequency $\omega_0 = \sqrt{k/m}$ is the particle betatron tune in the considered plane, $-f(x)$ is the force generated by the e-lens and $g(t)$ is a positive modulation function:

$$g(t) = (1 + \sin\omega_e t)/2 \tag{3}$$

being ω_e the e-lens modulation frequency. If $f(x) \propto x$, equation 2 describes a parametric oscillation also known, in physics mathematics, as Mathieu equation, with resonance condition $\omega_e = 2\omega_0$ [7]. However, when considering an highly non linear force such as the one generated by an hollow e-lens, the solution of the differential equation is not straightforward. That being the case, it was attempted to simulate modulation frequencies which are integer multiples of the natural frequency $n\omega_0$, with n in the range $[1, 2...10]$: the most effective resonance frequency resulted again twice the natural frequency. Because of the detuning introduced by octupoles, it is impossible to define uniquely the betatron frequency ω_0. For this reason the e-lens excitation frequency is continuously varied to cover the whole tune range of interest (from 0.3104 to 0.3136).

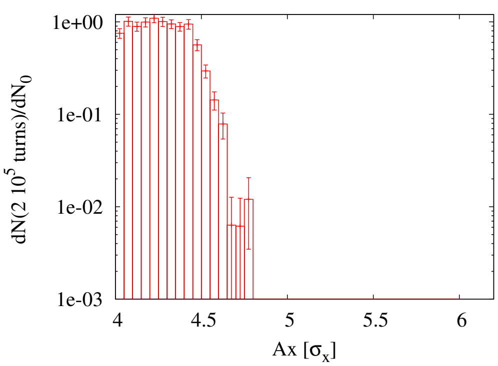

Figure 3: Particle distribution versus amplitude after 2 10^5 turns, normalized with respect to the initial distribution.

With the described AC mode, the electron lens drives onto the primary collimator about $75 \pm 1\%$ of a uniform distributed halo between 4 and 6 σ_x after 2 10^5 turns. In Fig. 3 the final number of particles over the initial population is shown for different particle amplitudes. It is clear that the e-lens is much more effective for high amplitude particles (after about 4.5 σ_x), where the scraping inefficiency is lower than 10^{-3}. The low amplitude particles, on the other hand, are hardly affected.

It is worth noting that the AC mode requires accurate knowledge of the machine tune and a separate procedure for the horizontal and for the vertical case. A possible alternative is the diffusive mode, which aims at increasing the random motion of the halo particles. At each turn, the particles can either receive a full e-lens kick or no kick, on a random basis: this maximizes the rms kick provided by the e-lens, therefore maximizing the diffusion speed. A clear advantage of this mode is the lack of correlation with the particle amplitude and tune. Moreover, being the electron

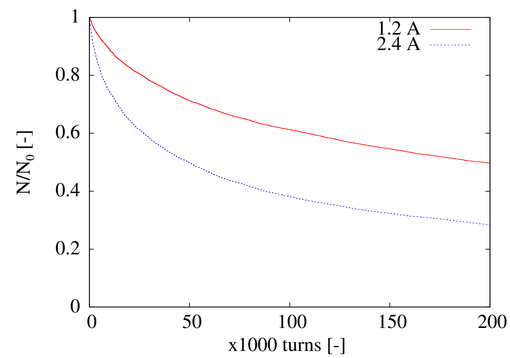

Figure 4: Normalized number of circulating particles versus the turn number.

lens kick proportional to the total electron beam current, the scraping efficiency can be easily tuned by changing the e-beam current. With the usual 1.2 A for the e-beam, after 2 10^5 about 50% of a uniform distributed halo between 4 and 6 σ_x is scraped; however, by increasing the current of a factor 2 (which is compatible with the Tevatron e-lens latest upgrades), performances close the AC mode ones are reached, as shown in Fig. 4.

CONCLUSIONS

A new routine describing the effect of the e-lens in the LHC collimation system has been implemented in Sixtrack. Simulations assuming to use a hardware similar to the one presently installed in the Tevatron have been performed. Three different operation modes, compatible with the hardware requirements, have been tested: while the DC mode does not provide noticeable scraping efficiency, both the AC and the diffusive modes appears to be a viable solution for the LHC scraping needs. While the AC modes is at present the fastest option (removing 75% of halo particles in about 20s), the diffusive mode has the undeniable advantage of not depending on particle tune, and therefore being more robust, of much easier implementation and usage. Moreover, by increasing or decreasing the e-beam current, the scraping efficiency can be adapted to the machine needs. Scraping performances comparable to the AC mode seems achievable by doubling the e-beam current.

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