FERMILAB-CONF-13-152-APC

HOLLOW ELECTRON LENS SIMULATIONS FOR THE SPS

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Abstract

The hardware of the Tevatron hollow electron lens, which has been used in the past for collimation purposes, is presently available. Possible applications of similar devices in the LHC are under evaluation, but a realistic date for installation of electron lenses in the LHC would be not earlier than the machine shutdown scheduled for 2018. We investigated the possibility of beam tests with the available hardware in the meantime in the SPS. This article aims to answer this question by presenting the results of dedicated numerical simulations.

INTRODUCTION

The hollow electron lens (e-lens) is a soft scraping device which generates a hollow beam of electrons encompassing the proton beam, as described in [1]. The removal efficiency of the device was proven in the past with extended tests at the Tevatron collider, where it was successfully used for driving the 980 GeV antiproton beam halo on the collimation system [2]. Using the e-lens for the 7 TeV LHC beam is an option currently under evaluation [3]. In case of positive answer to the LHC proposal, it is likely that two brand new e-lens devices will be built to accommodate the tight LHC tunnel constraints; however, in the meantime, the hollow e-lens used at the Tevatron is available and it was considered for possible beam tests at CERN. The possibility of using the available e-lens at the SPS as a test bench for the LHC has been investigated [4]. Tests at the SPS could provide an opportunity to gain operational experience with the device and to prepare the control software compatible with the LHC controls. Moreover, dedicated beam studies to assess the effect of the electron beam edges on the circulating beam emittance could be performed. Last but not least it would be beneficial to validate the numerical simulations where new and untested operation modes are proposed for the LHC [3]. In the studies presented here, we investigate the application of the same operational modes to the SPS. These studies represent a reference for future applications even if the present CERN strategy does not foresee an immediate implementation in the SPS [5].

E-LENS MODEL IN SIXTRACK

A new routine describing the hollow e-lens has been included in the tracking software used at CERN for collimation simulations, SixTrack [6]. The device is implemented as a thin element, and it is described as a hollow distribution of electrons centered with respect to the circulating beam and symmetrical with respect to the angular coordinate. The absolute values of the internal (external) radius R_1 (R_2) of the electron beam can be modified to fit the desired scraping aperture, but the ratio $g = R_1/R_2 = 0.6$ is fixed by the geometry of the cathode. Different radial profiles are available: for the simulations presented here a fit of the measured profile presented in Fig. 1 was used.

The kick provided by the electron lens is:

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

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. Since the electric component of the Lorentz force is always directed inward, and the electron beam versus is chosen such as the magnetic field component adds up to the electric one, the kick given by the electron lens is always directed inwards (focusing), both for the vertical and for the horizontal plane. For the SPS case, the maximum kick is of the order of 1μrad. To reproduce the measured current stability, and random jitter of $\pm 2\%$ is added to the electron beam current.

Three different operational modes are implemented in the simulation code:

- DC mode: the e-lens beam is constantly at it maximum value. This is the operation mode which has been used at the Tevatron, where the scraping relied on the resonances generated by the highly non linear e-lens field combined with the nonlinearities of the machine[7].
- AC mode: the electron beam current is modulated in order to resonate with the betatron tune, by using a positive modulation function $f(t) = (1 + \sin\omega_e t)/2$ with a frequency $\omega_e = 2\omega_0$, where ω_0 is the horizontal tune of the halo particles, see details in [3].
- diffusive mode: the electron beam current is randomly switched ON or OFF on a turn-by-turn basis, in order to enhance the diffusive motion of the halo particle and, therefore, their diffusion speed.

It is clear that, given the symmetry of the model, the e.m. field within the inner radius R_1 is perfectly zero, therefore no effect on the beam core can be simulated with the available model. However the aim of these simulations is to

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[†] Fermilab is operated by Fermi Research Alliance, LLC, Contract No.DE-AC02-07CH11359 with the United States Dep. of Energy. This work was partially supported by US LARP

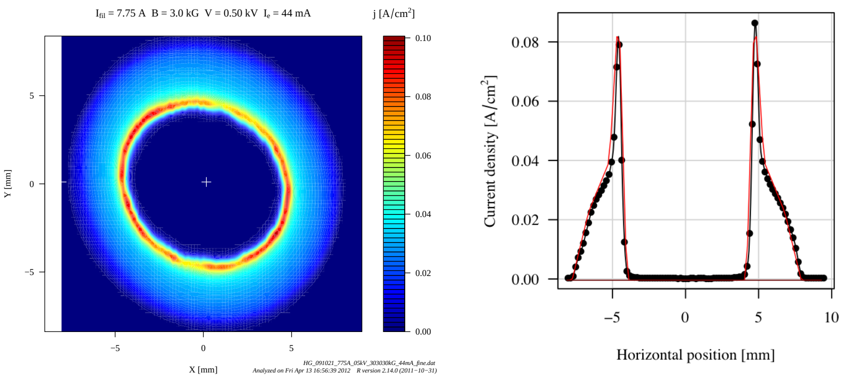

Figure 1: On the left had side, 2D hollow beam measured profiles for a total current of 44 mA, V=.5 KV. On the right hand side the profile in the y=0 plane is shown, both experimental data (dotted line) and fit (red curve).

evaluate the impact of the device on the beam halo and, as a consequence, on the collimation system. A separate routine is currently being developed to simulate the effect of the e-lens fringe fields and angular imperfection on the beam core [8].

SIMULATION INPUTS

A possible installation location of the device was identified in the SPS - BA4, where the COLDEX setup sits [9]. The optical functions in BA4 are shown in Fig From preliminary inspection, enough space seems to be available, both in transverse and longitudinal direction and, if available, the COLDEX facility could ensure cryogenics liquids. A 2m-long hollow e-lens with inner radius $R_1 = 4\sigma_x$ has been installed in the lattice file at this location. The total electron beam current is 1.2 A, the electron momentum is 4.8 keV and the ratio $R_1/R_2 = 1.67$, which are the typical parameters of the electron gun which was mounted on the e-lens at Tevatron. Since the only LHC-type collimator currently installed in the SPS has a horizontal orientation, a purely horizontal scraping has been simulated. The initial halo is a flat distribution between $4\sigma_x$ and $6\sigma_x$, and the collimator aperture is set to $6.2\sigma_x$. The SPS optics is the coast beam optics with an energy of 270 GeV, sextupoles included, no octupoles. The main horizontal optics parameters for the e-lens and the collimator location are detailed in Table 1. 2.

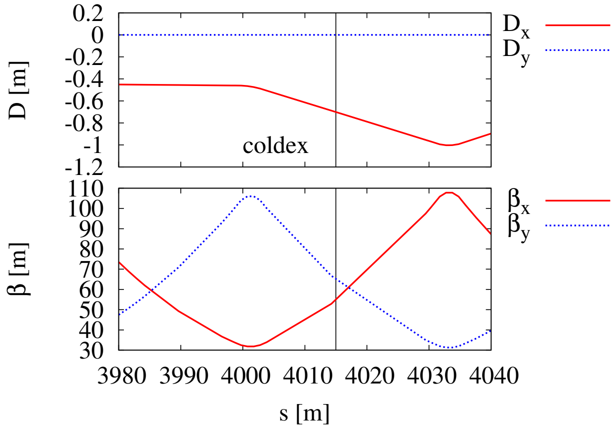

Figure 2: Local scraping inefficiecy after 2 10^5 turns.

Table 1: Horizontal optics parameters of the system.

name	settings [σ_x]	$1\sigma_x$ [μm]	$1\sigma'_x$ [μrad]	D_x [m]
ELENSE	4 H.	645	25.7	-0.575
COLLIMATOR	6.2 H.	513	24.8	-0.206

SIMULATION RESULTS

A full set of simulations has been performed to evaluate the possible scraping efficiency achievable in the SPS with the available hardware. Two parameters are used to qualify the removal effect of the e-lens, ie:

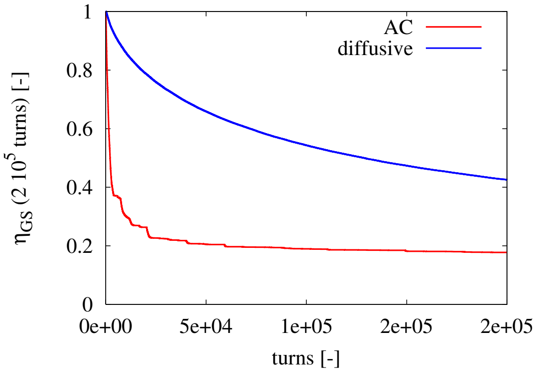

Figure 3: Number of halo particles circulating in the machine versus the number of turns for AC and diffusive e-lens.

- The (horizontal) global scraping inefficiency $\eta_{SG}(t)$, which is defined as the number of particles which escaped the collimation system over the initial number of particles, after a certain number of turns t.
- The (horizontal) local scraping inefficiency $\eta_S(A_0, dx, t)$, which is defined ad the number of particles with amplitude $(A_0) < A_x < (A_0 + dx)$ after a certain number of turns t versus the initial number of particles in the same amplitude interval.

The primary effect of the e-lens in DC mode is to induce a positive tune spread of few 10^{-4}, but it has been verified that, with the available degree of complexity of the machine modeling, no appreciable scraping effect is detected. In Fig 3 the global scraping inefficiency for the AC and the diffusive operation modes are compared. Knowledge of the operational details of the AC mode is needed to understand the shape of the associated curve. In order to have a resonance, in fact, the e-lens modulation must precisely match the particle tune; however the tune spread requires for the e-lens to cover a total range of tunes of $4\,10^{-4}$ in steps of $5\,10^{-5}$ every 1000 turns. This is reflected in the step-like shape of the global scraping inefficiency for this mode. Only 15% of the initial halo distribution survives after $2\,10^5$ turns, which are equivalent to about 5 seconds of machine time. On the other hand the diffusive mode presents a smooth curve as expected by a diffusive process, reaching a global inefficiency of 42% after about 5 s of time machine.

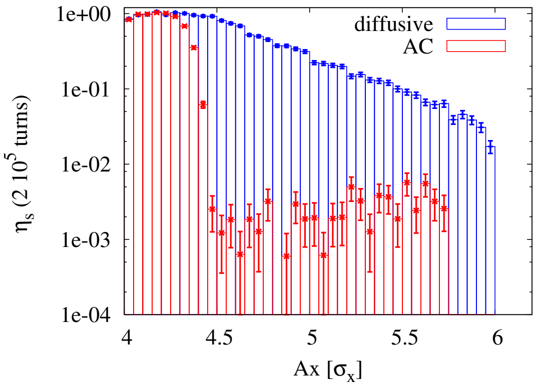

Figure 4: Local scraping inefficiecy after $2\,10^5$ turns.

While the global scraping inefficiency allows us to directly compare different operational modes, the local parameters give more insight on the e-lens effect for different particle amplitudes. The comparison of the local scraping inefficiency presented in Fig. 4 shows how the AC mode is very effective for particle amplitudes higher than $4.5\sigma_x$while lower amplitude particles are weakly affected by the e-lens presence; in particular the halo population over $5\sigma_x$ is almost totally suppressed, reaching local scraping inefficiency values systematically smaller than 0.1%. For the diffusive mode, on the contrary, the local scraping inefficiency decreases slowly and smoothly with amplitude, reaching a value of few percents near the collimator edge.

By simulation results it could be concluded that the AC mode is the most effective scraping mode, however it must be considered that it relies on a fine tuning of the e-lens modulation with the betatron tune, with consequent complications to the operation and set up. The diffusive mode, on the other hand, does not depend on the beam parameters and it appears more robust.

CONCLUSION

A full set of simulations have been performed to understand the possible tests which could be conducted in the SPS with the available e-lens hardware. According to the results given by our model, the DC operation mode of the e-lens would not be effective as a scraper; however, since the DC mode relies on generating resonance regions, this result could be an artifact of the simulations where sextupoles are the only non-linear element in the optics and no imperfections are included. Both the AC and the diffusive modes are effective scraping system, with global inefficiency values of 42% for the diffusive mode and 15% for the resonance mode in $2\,10^5$ turns. These results are very similar to the results obtained by LHC simulations [3], confirming the validity of using the available electron lens hardware at the SPS as a test bench for the LHC.

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