HIGH LUMINOSITY LHC HOLLOW ELECTRON LENS COLLIMATION USING MERLIN*

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Abstract

The high luminosity large hadron collider (HL LHC) upgrade envisions an unprecedented stored beam energy of up to 700 MJ. To protect the machine during operation, an efficient collimation system is vital. The hollow electron lens (HEL) is being explored as a possible collimation enhancer for the LHC, based on Tevatron designs and operational experience [1], for active halo control. A HEL produces a hollow cylindrical beam of electrons through which the accelerator (proton) beam travels, particles that overlap undergo an electromagnetic interaction. As they can operate close to the beam core without being damaged, HELs may serve as soft scraper devices [2]. For the first time a HEL in high luminosity configuration is simulated in the HL LHC using the recently updated MERLIN 5 accelerator libraries [3–5]. The effects on the LHC beam halo are observed for various HEL operation modes.

INTRODUCTION

The LHC collimation system has operated efficiently over Run I, with stored beam energies of up to 150MJ, and continues to do so in the current Run II. The HL LHC upgrade aims to increase the luminosity of the LHC by reducing the emittance and doubling the beam current. Thus it is prudent to investigate methods of improving the LHC collimation system for the HL LHC upgrade.

HELs have been identified as a possible means of active halo control [6]. It has been shown at the Tevatron that HELs can increase the diffusion of halo particles onto an aperture restriction such as the primary collimator (TCP) of the LHC collimation system [1]. HELs can operate closer to the beam core than a solid scraper, as there is no impedence effect and no material damage is incurred [2]. This makes them ideal for use with beams of unprecedented stored energy.

A conceptual design report followed advanced studies of a HEL in the nominal LHC [7], more recently plans have been prepared to integrate a HEL into the LHC, with the indication to prepare a technical design for implementation beginning in 2018, based on Run II operational experience [6].

PROPOSED LHC HEL

It is proposed to integrate a superconducting HEL in IR4, where it has access to high pressure He for cooling, and there is the required space between beamlines. Inevitably two HELs will be required, one for each beam. Two candidate locations have been identified as RB-44 and RB-46, both in IR4, either side of the RF insertion [7].

Using MERLIN, a HEL was implemented into the LHC lattice at RB-46. The optics parameters for both the nominal and HL-LHC are shown in Table 1. Both the Tevatron HEL [1], and proposed LHC HEL [7] parameters are modelled. As HL integration studies are ongoing, the position used is a first case study to test the MERLIN implementation.

Table 1: Optics Parameters Calculated at the HEL in MERLIN for the Nominal LHC and HL LHC, HEL Parameters for the Tevatron and LHC HELs

Parameter [Unit]	**LHC**	**HL-LHC**
s [m]	10037	10037
β_x [m]	183.6	144.0
β_y [m]	175.5	259.6
σ_x [µm]	293.5	259.9
σ_y [µm]	286.9	349.0
μ_x [deg]	222.1	215.7
μ_y [deg]	202.4	202.8
E_p [TeV]	7	7
HEL Parameter [Unit]	**Tevatron**	**LHC**
E_e [keV]	5	10
I [A]	1.2	5
L [m]	2	3

MERLIN HEL PROCESS

Assuming an azimuthally symmetric e^- beam, no edge effects or fringe fields, and only considering the active part of the HEL (not the bending fields for injection and extraction of the e^- beam), the HEL is modelled in MERLIN 5 [4, 5] as follows.

For a HEL of length L, with electron beam current I, the kick for a particle at a transverse displacement r, is given by Eq. (1) [8].

$$\theta_{max}(r) = \frac{1}{4\pi\epsilon_0 c^2}\frac{2LI(1+\beta_e\beta_p)}{(B\rho)_p\beta_e\beta_p}\frac{1}{r} \quad (1)$$

where β_e and β_p are the Lorentz β of the HEL electron beam, and machine proton beam respectively, and $(B\rho)_p$ is the proton beam rigidity.

For a perfect radial HEL distribution (uniform between the HEL beam transverse radii R_{min} and R_{max} and axially symmetric), the kick exerted on a particle is a function of its transverse position, and is given by Eq. (2) [8].

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$$\theta_{kick} = \begin{cases} 0, & r < R_{min} \\ \frac{r^2 - R_{min}^2}{R_{max}^2 - R_{min}^2}\theta_{max}, & R_{min} < r < R_{max} \\ \theta_{max}, & r > R_{max} \end{cases} \quad (2)$$

A measured beam profile [9] is parameterised and included in MERLIN as well as the perfect profile detailed in Eq. (2).

As in the SixTrack [10] HEL routine [11], the MERLIN HollowElectronLensProcess offers 4 operation modes;

1. DC: HEL constantly at maximum.
2. AC: HEL beam current is modulated to resonate with the betatron tune.
3. Diffusive: HEL is randomly switched on/off on a turn by turn basis.
4. Turnskip: HEL is switched on every *n* turns, where *n* is an integer.

As discussed in previous work [8, 11, 12], the most interesting cases for collimation enhancement are the AC and diffusive modes.

SIXTRACK COMPARISON

To compare MERLIN's HEL process with SixTrack's elens routine, a simple bunch of 64 protons was generated in SixTrack, populating horizontal phase space between 1-10σ_x. This bunch is shown in green in Fig. 1, and was run for the nominal LHC (lattice v6.503, squeeze and separation on), in both MERLIN and SixTrack. The Poincaré sections at the HEL, which is operating in AC mode, are compared in Fig. 2. The HELs used in Fig. 2 are based on Tevatron hardware, and thus operate with the Tevatron paramaters shown in Table 1.

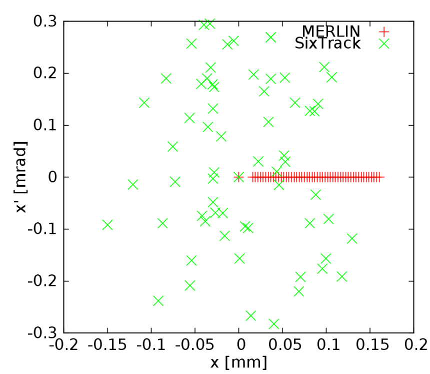

Figure 1: Distributions generated in SixTrack (green) and MERLIN (red) for similar bunches populated between 1-10 σ_x.

As the closed orbits in both programs are not the same, the slight difference shown in Fig. 2 is expected. It is clear however, that the MERLIN HEL process is operating similarly to the SixTrack elens routine. To clarify this comparison, it is repeated for the DC mode in Fig. 3, in this case MERLIN generates its own distribution, which is a purely horizontal bunch between 1-10 σ_x, but of 50 equally spaced protons,

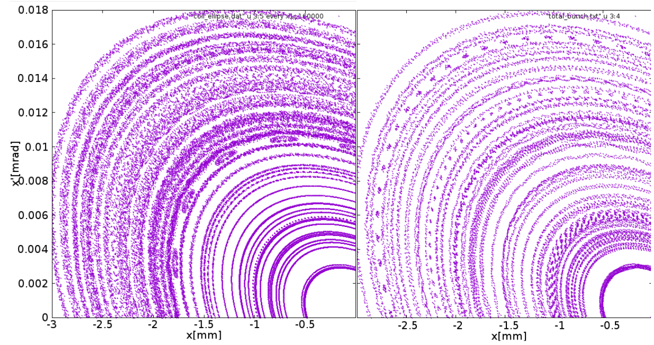

Figure 2: Poincaré sections at an AC Tevatron HEL in SixTrack (left) and MERLIN (right) for an identical bunch populated between 1-10 σ_x, shown in green in Fig. 1.

and a reference proton at (0,0), as shown in red in Fig. 1. The SixTrack bunch has a small non-zero momentum component, whereas this is zero in the MERLIN bunch. In spite of this difference it is clear that both codes are producing resonances in phase space, which perturb the protons by a similar amount.

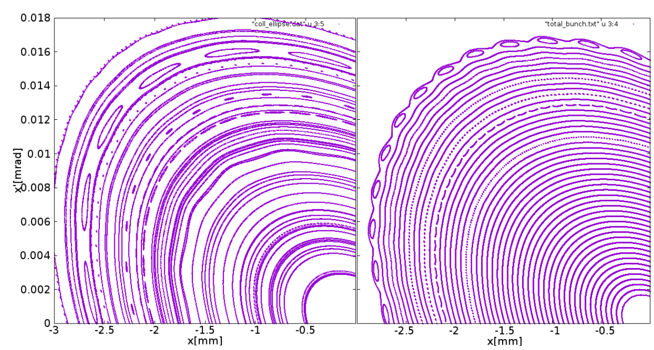

Figure 3: Poincaré sections at a DC Tevatron HEL in SixTrack (left) and MERLIN (right) for similar bunches populated between 1-10 σ_x, which are shown in Fig. 1.

HL LHC

As the LHC has a larger beam rigidity than the Tevatron, it is clear from Eq. (1) that using a Tevatron HEL in the LHC would result in a smaller effect on the protons that interact with the HEL. Thus an LHC HEL has been proposed, that should operate as a collimation enhancer in both the nominal and HL LHC [7]. Using the LHC HEL parameters, which are set out in Table 1, the previous plots are repeated; using the MERLIN generated bunch shown in Fig. 1, in both the nominal and HL LHC. Figure 4 illustrates that the optics differences in these two machines have a large impact upon the position and size of resonances that the HEL creates.

For collimation enhancement, the most promising modes of HEL operation are AC and diffusive. To illustrate why this is the case, both were run in the HL LHC lattice (v1.2) using the MERLIN bunch from Fig. 1, and the result is shown in Fig. 5. It is clear that the AC widens the Poincaré section of a given particle, thus making it more likely to impact upon

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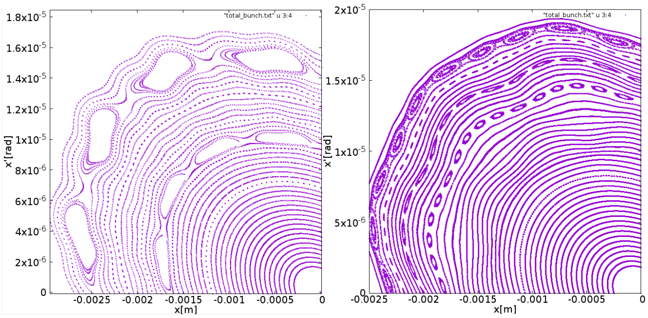

Figure 4: Poincaré sections at the position of a DC LHC HEL in the nominal (left) and HL (right) LHC using the MERLIN bunch from Fig. 1.

a collimator if it is already near one. The diffusive mode however shows a massive spread of particle coordinates in phase space, meaning that it should aid in collimation more than the AC mode.

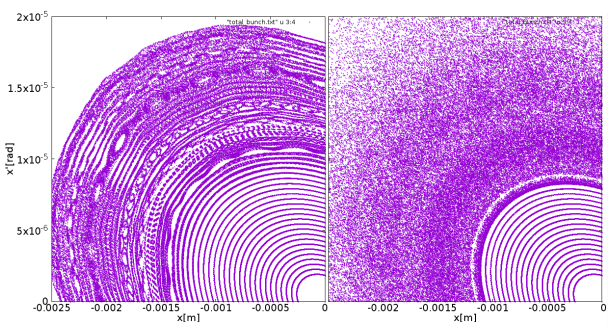

Figure 5: Poincaré sections at the position of an AC (left), and a diffusive (right) LHC HEL in the HL LHC using the MERLIN bunch from Fig. 1.

In all cases, the HEL does not interfere with particles with a transverse displacement smaller than the minimum radius. In order to estimate the HEL's impact on collimation, a simulation was set up such that a halo bunch populating 4-5.9 σ_x in x was tracked for 10^5 turns, with various or no HELs operating between 4-8 σ_x in the HL LHC lattice. Only a single primary collimator, TCP.C6L7 was present, with a jaw opening of 6.2 σ_x. The results are shown in Fig. 6.

As expected from this simulation, with no HEL present, the particles remain stable and never impact upon the TCP. It is clear also that with a DC HEL, cleaning enhancement is negligible. The AC mode appears to remove only particles that are closest to the TCP, in only a few hundred turns, this makes sense as from Fig. 5 we see that the Poincaré section is widened by a small amount - thus only particles close to the TCP location of 6.2 σ_x are likely to be excited onto it, leaving particles closer to the core intact. This is in agreement with past studies using SixTrack [8].

The diffusive case appears the most promising for cleaning enhancement, in fact nearly all halo particles have been excited onto the TCP after 10^5 turns (around 10 s of machine time), this is desirable as the collimation system exists to clean halo particles from the bunch. As the diffusive mode

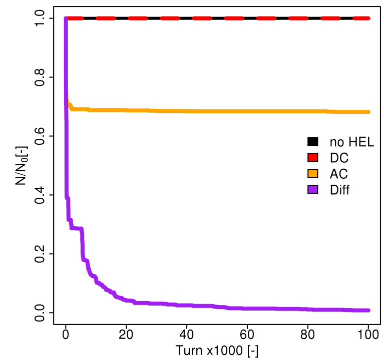

Figure 6: Normalised particle survival after 10^5 turns in the HL LHC with a single TCP at 6.2 σ_x, and a bunch populated between 4-5.9 σ_x.

gives each particle a random kick at each turn, particles do not remain stable, and may be focussed or defocussed by large amounts. It has been observed previously [8] that the diffusive HEL shows a steady decrease in the halo particle population - this is still the case, however now as we use the LHC HEL parameters, the particle kicks are larger and thus cleaning enhancement occurs over fewer turns.

Previous work found that the AC mode enhanced cleaning more than the diffusive [11], however we find that the diffusive case enhances cleaning more. There are differences between the simulations that could account for this. Firstly the distributions used are different - the lack of a transverse momentum component in MERLIN will equate to different particle tracks in the accelerator. Also the calculated machine tunes will be slightly different as one is done using thin lens (SixTrack), and the other thick lens (MERLIN) tracking, this is important as the AC mode requires accurate knowledge of the machine tune.

CONCLUSION

A HEL physics process has been included in the new version of MERLN, the effects of which have been demonstrated for the LHC, in its nominal and HL configurations. The effect of 3 HEL modes and 2 sets of HEL hardware parameters have been observed in many turn simulations. While the DC HEL mode in the HL LHC appears not to effect any cleaning enhancement, both the AC and diffusive modes show significant collimation enhancement. The diffusive case appears to be the more promising for cleaning a purely horizontal halo, exciting almost 100% of particles onto the primary collimator in around 10 s. Whereas the AC mode appears to leave particles closer to the beam core intact, the diffusive mode removes all particles that interact with the HEL. This is because the AC mode widens a particle's Poincaré section in x x' phase space, whereas the diffusive mode can create large focussing or defocussing effects.

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REFERENCES

[1] V. Shiltsev *et al.*, "Electron Lenses for Particle Collimation in LHC", FERMILAB-CONF-07-698-APC

[2] G. Stancari *et al.*, Phys. Rev. Lett. 107, 084802 (2011)

[3] `http://merlin-pt.sourceforge.net/`

[4] `https://sites.google.com/site/haroonrafiquemerlin/`

[5] H. Rafique *et al.*, "MERLIN for LHC Collimation", presented at ICAP'15, Shanghai, China, paper TUCBC1, these proceedings.

[6] S. Redaelli *et al.*, "Plans for deployment of hollow electron lenses at the LHC for enhanced beam collimation", Proc. IPAC15, Richmond, Virginia, 2015

[7] G. Stancari *et al.*, "Conceptual Design of Hollow Electron Lenses for Beam Halo Control in the Large Hadron Collider", FERMILAB-TM-2572-APC

[8] V. Previtali *et al.*, "Numerical Simulations of a Hollow Electron Lens as a Scraping Device for the LHC", Proc. IPAC13, China, 2013

[9] V. Moens, "Experimental and Numerical Studies on the Proposed Application of Hollow Electron Beam Collimation for the LHC at CERN", CERN-THESIS-2013-126

[10] `http://sixtrack.web.cern.ch/SixTrack/`

[11] V. Previtali *et al.*, "Hollow Electron Lens Simulations for the SPS", Proc. IPAC13, China, 2013

[12] H. Rafique *et al.*, "Simulation of hollow electron lenses as LHC beam halo reducers using MERLIN", Proc. IPAC15, Richmond, Virginia, 2015

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