PROSPECTS FOR INTEGRATING A HOLLOW ELECTRON LENS INTO THE LHC COLLIMATION SYSTEM*

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Abstract

It has been proposed to use a hollow electron lens with the LHC beam collimation system [1]. The hollow electron beam would be used as a beam scraper and positioned at a closer sigma than the primary collimators to increase the halo particle diffusion rate striking the primaries. In this paper we use multi-turn beam tracking simulations to analyze the effectiveness of such a lens when integrated into the LHC collimation system.

THE HOLLOW ELECTRON LENS CONCEPT

There are no current plans for a beam scraper in the LHC. It has been found [2] that any material closer than 5 sigma would very quickly get destroyed due to overheating and mis-steered beams. The result is there is nothing to clean the beam halo below the primary location at 6 sigma. A beam scraper in the LHC, if one can be designed, would be used to clean out the beam halo down to 3 sigma.

An ideal hollow electron lens [1] consists of a beam of electrons similar to that already used in the Tevatron [3] except an azimuthally symmetric electron gun would be used to produce a hollow beam of electrons. The electron beam would be controlled by a roughly 3 Tesla superconducting solenoid field and steering dipoles. The proton beam core particles would pass through the hollow beam of electrons and provided the current density is evenly distributed about the electron beam, the core particles would experience zero electric field. The halo particles, passing through the electron beam, would experience an inward kick. This kick would heat the halo particles thereby increasing their diffusion rate.

An electron lens scraper would have several benefits to the LHC collimation system:

1. Halo particles as far in as 3 sigma could be effectively removed
2. The diffusion rate of halo particles would increase, which in turn would increase the impact parameter in the primaries.
3. The increase in the impact parameter would allow for the primaries (and secondaries) to be placed at greater sigma, decreasing the impedance contribution to the LHC.

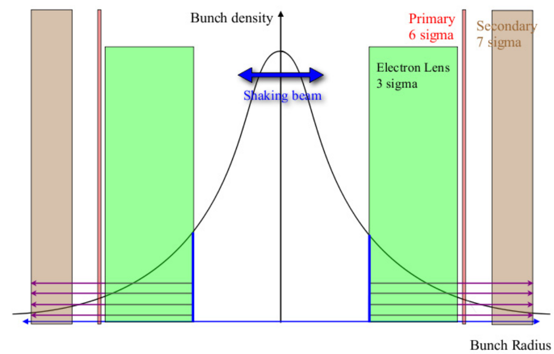

Figure 1: Conceptual drawing of LHC hollow electron lens beam scraping.

4. Loss spikes in the collimation system can be removed.
5. Since there is no matter-particle interaction, the e-lens scraper can be just as effective with ions.

The issue of loss spikes is of particular concern. If no scraper is present then any sort of beam jitter would result in spikes in the particle loss rate on the collimators and may result in magnet quenches. A beam scraper would allow for the beam halo to be cleared out well below the primary collimator giving the beam room to shake without generating loss spikes.

The idea would be to operate the electron lens just long enough to remove the beam halo, perhaps as short as a fraction of a second. The effect on the LHC beam is illustrated in Fig. 1. The particles within the electron lens would be heated and be caused to impact the primaries at a greater diffusion rate than due to natural heating. A further effect can be initiated if the e-lens is operated at AC. If the modulation frequency is in tune with the betatron frequency ($Q_x = 0.31$) then a resonance condition would develop helping to drive the halo particles to larger sigma even more quickly. Previous studies [4] have shown a two order magnitude increase in cleaning rate if the e-lens is operated in AC mode and in tune with the betatron frequency.

FIRST_IMPACT SIMULATIONS

A small program called `first_impact` has been created to perform simple 1-D normalized phase space analysis that

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utilizes the horizontal twiss functions to map the passage of each particle at a primary collimator. The electron lens is modeled using the formalization found in [1]. It consists of a radially symmetric hollow beam and the kick experienced by the protons as they pass through the electron beam is given by:

$$\Theta(r) = \Theta_{max} \begin{cases} 0, & \text{if } r < r_{min}; \\ \frac{r-r_{min}}{r_{max}-r_{min}}, & \text{if } r_{min} < r < r_{max}; \\ \frac{r_{max}}{r}, & \text{if } r > r_{max}; \end{cases} \quad (1)$$

and the maximum kick angle is given by

$$\Theta_{max}[\mu rad] = \frac{0.2L_e[m]J[A]}{(B\rho)r_{max}} \cdot \left(\frac{1+\beta_e}{\beta_e}\right). \quad (2)$$

where the minimum and maximum radii of the e-lens are r_{min} and r_{max} respectively, L_e is the effective length of the e-lens, J is the current, $B\rho = 2.3 \times 10^4$ Tm is the magnetic rigidity of the 7 TeV protons, and $\beta_e = 0.195$ is the relativistic beta factor for the 10 keV electrons. The maximum kick for a 2 meter long electron lens with inner and outer radii at 4 and 6 sigma with $\beta = 100$ and current of J amps is $\theta_{max} = 0.078053$ J μrad .

The e-lens results in a tune shift of the halo protons equal to [3]

$$dQ_{x,y} = \frac{\beta_{x,y}L_e r_p}{2\gamma_p ec} \cdot j_e \cdot \left(\frac{1-\beta_e}{\beta_e}\right), \quad (3)$$

where $\beta_{x,y}$ are the x and y beta functions at the e-lens, $r_p = e^2/mc^2 = 1.53 \times 10^{-18}$ m is the classical proton radius, $\gamma_p = 7463$ is the relativistic gamma function for the 7 TeV protons and j_e is the electron current density in the e-lens. The other parameters take the same meanings as in the previous equation. The resulting tune shift for a 2 meter long electron lens with inner and outer radii at 4 and 6 sigma, $\beta = 100$m and a current of J amps is $dQ = 0.000559J$. This is a non-negligible tune shift. The `first_impact` program computes this tune shift and sets the AC current frequency of the e-lens appropriately in order to maintain the resonance condition. It was found that not taking this tune shift into consideration results in poor performance of the AC e-lens.

Simulations were performed using a Gaussian distribution of halo particles with an inner action cut-off at 4 sigma, or the inner radius of the electron lens. The outer radius of the e-lens was set at 6 sigma and the primary was also set at 6 sigma. The time to clean the halo as a function of current for both the AC and DC e-lenses are shown in Fig. 2. The time to clean the halo is defined as the number of turns when 95% of all particles within 4 and 6 sigma have hit the primary collimator. As can be seen in the plot, the AC e-lens performs better at low current but the DC lens abruptly begins to work well at 16 amps. It has been found that the DC cut-off current is highly dependent on the betatron tune. For example, a tune of 0.32 requires only a 9 amp DC current to quickly clean the halo. This behavior will be further investigated.

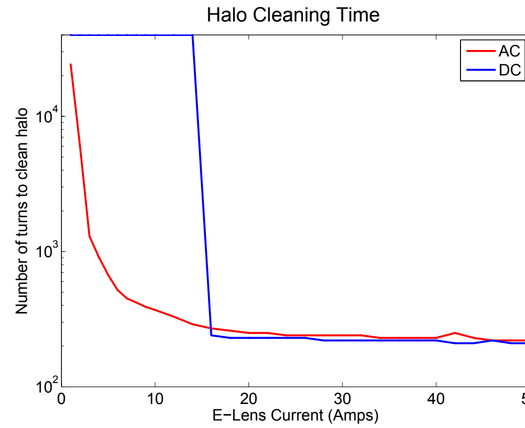

Figure 2: Cleaning time for the beam halo as a function of e-lens current.

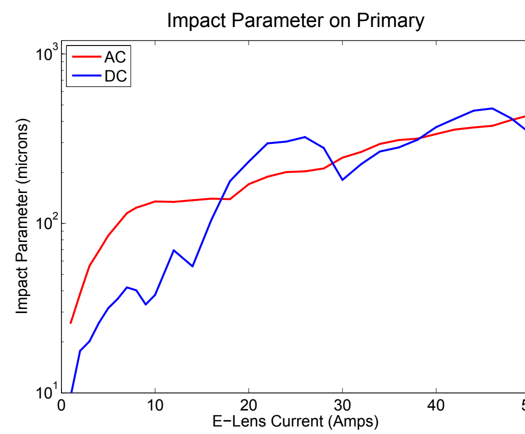

Figure 3: Impact Parameter on the primary as a function of electron lens current.

In addition to increasing the dispersion/cleaning rate of the beam halo below the primary, the electron lens would also increase the impact parameter on the primary. `first_impact` was used to measure the impact parameter of all particles hitting the primary and the results are shown in Fig. 3. As described in [5], the cleaning efficiency begins to increase dramatically when the impact parameters rises above 50 microns. Above 100 microns the cleaning efficiency is 5 times better than with the nominal value of 1 micron, which is the theorized impact parameter due solely to beam heating. The AC and DC e-lenses behave similarly with impact parameter and 12 amps is required to reach an impact parameter of 100 microns in either case.

SIXTRACK SIMULATIONS

Simulations have also been performed in the collimation version of SixTrack [6] using an electron lens element similar to that used in `first_impact`. Several electron lens locations were investigated including the TCHS scraper elements directly downstream of the primaries and the BBC elements near IR1 and IR5. It has been found that the electron lens placement is not critical for the effectiveness of beam cleaning. With a nominal current of 20 amps and 2 meters long, the electron lens was found to clear out the beam halo between 4 and 6 sigma within 1000 turns. Completely removing the primary and secondary collimators and relying on the diffusion rate of the electron lens results in beam halo cleaning out to 12 sigma to within 1400 turns. The tune spread in the LHC beam halo with realistic energy spread was measured to be 0.001, whereas the acceptance for the AC e-lens resonance condition has been found to be about 0.002, so, the resonance condition is obtainable for all halo particles. Further studies in SixTrack will directly measure the impact parameters and local collimation efficiency. There is also the option to use the e-lens as a primary collimator. With a 43 Amp current the maximum kick of the e-lens would be 4.5 μrad – the same as for the 0.6 m primary graphite collimators. A non-material primary would be indestructible however, in the event of a mis-steered beam, the first device to be hit would be the secondary collimators. It will have to be investigated if such a scenario is acceptable.

PRACTICALITIES OF ELECTRON LENS INSTALLATION IN THE LHC

The electron lens can only be cylindrical in shape and so it is ideal that the horizontal and vertical beta functions be equal at the location of the lens. Two locations have been investigated for installation of a e-lens scraper: the TCHS locations in the betatron cleaning section in IR7 which are located directly downstream of the primaries and the 4 BBC element locations which have large beta functions and were originally designed for Beam-Beam Compensation.

The TCHS locations are only 0.2 meters long each however, they are located right after another with only drift space between them and the total length for all three including the intervening drift space is 2.5 meters. This is long enough for one 2 meter long e-lens or potentially two 1 meter long e-lenses, one for horizontal scraping and one for vertical. However, the difference in horizontal and vertical beta functions is small (120 m vs. 100 m) and a single e-lens can effectively scrape both axis. With only 22.4 cm between the beams, the counter-rotating beam pipe would be required to be within the cryomodule of the e-lens. It may be possible to construct a cryomodule to accept the other beam pipe but more investigations are necessary. Another potential issue is that the TCHS elements are located directly downstream of the three primary collimators. This location is expected to get large amounts of particle spray due to the primaries. Radiation studies should be performed to ensure the e-lens cryomodule can withstand this spray.

The BBC locations have a much larger beta function which would make constructing the electron lens much easier, however, with a 1 sigma radius of 0.938 mm the counter-rotating beam is only about 6 sigma away – and at about the edge of the electron lens beam. For a DC e-lens operating with $\Theta_{max} = 1\,\mu$rad the counter-rotating beam would get a roughly dipole kick of about 0.87 μrad. With proper optics corrections this kick may be compensated. However, such an electron lens could not operate in AC mode without completely disrupting the other beam.

A further question is whether to operate the lens in AC or DC mode. Studies have shown that an AC lens can clean out the beam halo faster and with less current. However, a DC lens is just as effective if a sufficient current of above 16 amps is used. Studies at the Tevatron have shown that electron lens beam stability is well within 1 sigma when operating in AC mode and in DC mode the stability is much better. Also, the transverse current density of a DC beam would be much more stable versus AC. The proton beam core cannot experience much force while passing through the electron beam and so the DC beam again may be the preferred solution.

FURTHER STUDIES AND CONCLUSIONS

The simulations performed so far have been with an ideal electron beam. Misalignments and electron current errors will inevitably degrade the performance of the e-lens. Future studies must include these realities. There also will inevitably be some field leakage into the center of the hollow beam affecting the proton beam core. A proposal has been written to design and build a low current hollow electron gun for use with one of the Tevatron electron lenses. This device would provide details on the stability and current distribution in a hollow electron beam. Additionally, the impedance contributions of such a device must be confirmed to be within acceptable levels if installed in the LHC.

In conclusion, it has been demonstrated that a hollow electron lens with realistic parameters can effectively clean out the LHC beam halo. Even though an AC lens results in faster cleaning time and at a lower current, a DC lens with sufficient, yet still practical, current can clean out the beam halo just as effectively and within a fraction of a second.

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