# Simulation Study of Hollow Electron Beam Collimation for LHC

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*Abstract*
In this note we describe the results of numerical simulations of hollow electron beam collimation for the nominal LHC machine. The halo cleaning rates for various operating scenarios are predicted. The impact of electron lens imperfections on the collider luminosity performance is estimated.

## Goals

1. Evaluate the halo cleaning efficiency for various operating scenarios: with and without beam-beam interactions; DC mode and random mode; the effect of electron lens bending sections; the effect of electron beam current.
2. Evaluate the effect of electron lens imperfections on the dynamics of core particles and impact of HEBC on luminosity performance.

## Simulation Parameters

All simulations were performed with LHC V6.503 lattice and nominal beam parameters: number of protons per bunch $N_p$=1.15×10$^{11}$, transverse normalized emittance $\varepsilon$=3.75 $\mu$m, bunch length $\sigma_z$=7.5 cm and momentum spread $\sigma_E$=0.00011. In the cases where beam-beam interactions were switched on, the beams collided at three main interaction points IP1, IP5, and IP8, and also at 94 long-range crossings corresponding to the longitudinal bunch spacing of 25 ns.

The hollow electron lens element was placed at the candidate location near IR4, where the horizontal and vertical beta-functions are equal ($\beta_x$=$\beta_y$=180 m, which corresponds to the proton rms beam size of $\sigma_p$=0.32 mm). The hollow electron beam inner radius was 4 $\sigma_p$, and the outer radius was 7.5 $\sigma_p$. Three values of electron beam current were studied: 1.2, 2.4, and 3.5 A. The lower value corresponds to the existing Tevatron Electron Lens setup, and the higher value of 3.6 A has been achieved in the prototype gun. The impact of electron beam bending sections was simulated with the use of thin kick approximation as described in [1].

The simulation studies were performed using the macroparticle tracking code *LIFETRAC*. Two types of initial particle distributions were used to assess the dynamics of core beam and of the halo particles. The core beam was represented by a 6-D Gaussian distribution with a 6 $\sigma$ cut-off. The halo beam had a Gaussian distribution in the z-Δp/p space, and uniform population between 4 and 6 $\sigma_p$ in z-y. The number of particle in each case was 10,000. A single collimator was placed at 6 $\sigma_p$ in x and y, to allow for the calculation of particle losses. The simulations were typically performed on the time scale of 5×10$^6$ turns, which corresponds to ~450 s of the real machine time. Since the simulation did not include any mechanism for particle transport from the core to the halo other than the beam-beam or HEBC-driven resonances, the results obtained do not represent a steady-state situation. Rather, they can be considered as the initial values of halo cleaning rates.



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## Results

*1. Establishment of baseline performance.*

First, a clean machine without HEBC was simulated in order to evaluate the intensity lifetime with and without beam-beam effects present. The luminosity lifetime was also computed. Without beam-beam interactions, no losses were registered for halo and core particles, as well as no emittance growth, which is to be expected for the nominal LHC lattice without magnetic imperfections. With beam-beam interactions turned on, the core beam did not exhibit any change in behavior, and the simulated luminosity lifetime was infinite. However, some losses of halo particles occurred, amounting to about 8% per hour (Fig. 1). Apparently, the beam-beam driven resonances impact large-amplitude particle diffusion. Along with the losses, the bunch length reduction is seen, which indicates the losses coming from off-momentum particles.

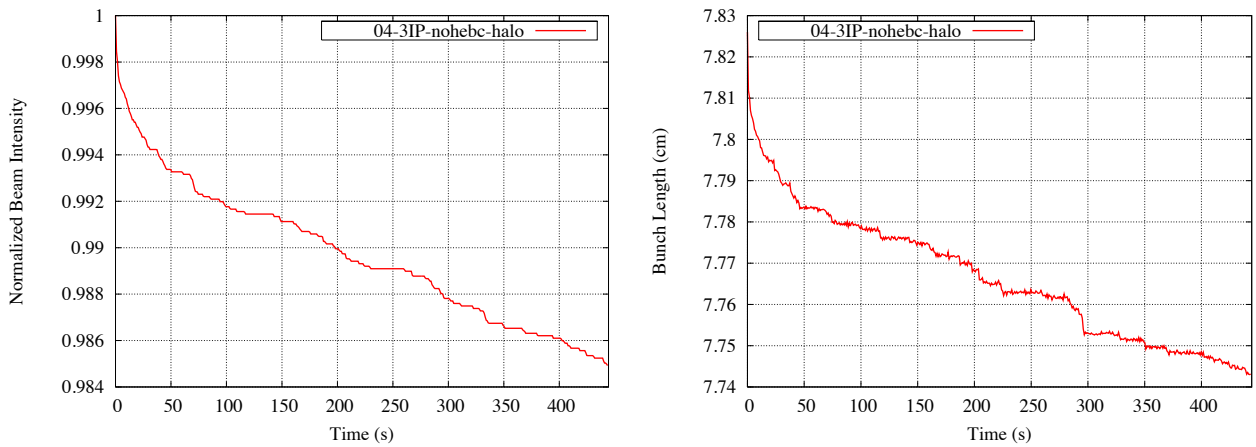


Figure 1. Halo particle losses with beam-beam on and HEBC off (left – intensity, right – bunch length).

*2. Halo removal rates in continuous mode*

Earlier results obtained with the SixTrack code and simplified halo model [2] suggest that the HEBC operated in continuous mode (when the electron lens current is constant turn-by-turn) is not very efficient for halo removal. Our simulations confirm this conclusion for the configuration without beam-beam effects. The halo removal rate is ~2%/hr at 1.2 A, 12%/hr at 2.4 A, and 40%/hr at 3.6 A of electron beam current. The effect of bending sections on removal rates is negligible.

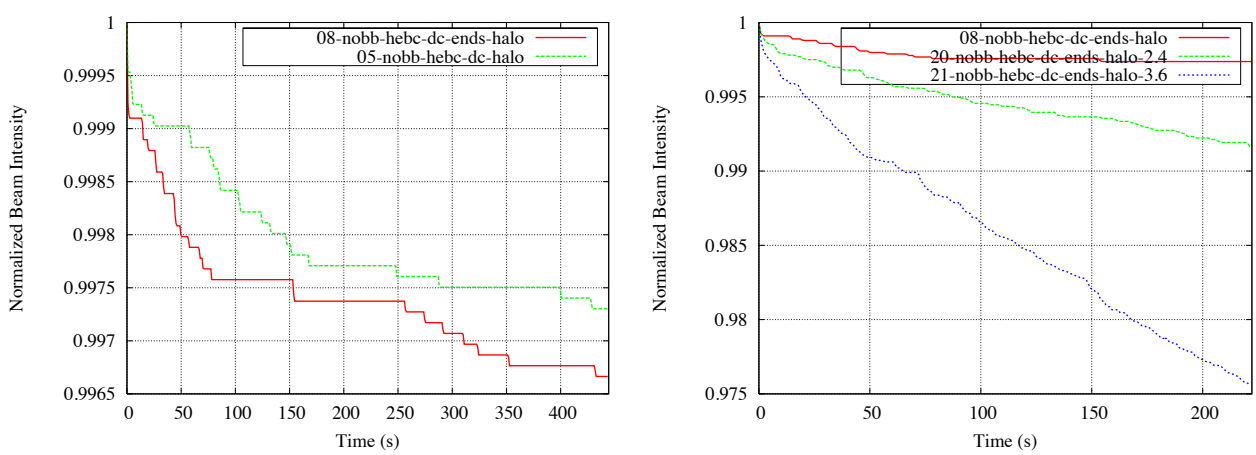


Figure 2. Halo removal with HEBC in continuous mode, no beam-beam interactions. Left – effect of $e^-$ bends at 1.2 A, right – effect of $e^-$ beam current.

The introduction of beam-beam interaction, however, drastically changes the situation. Fig. 3 presents the simulation results for HEBC in continuous mode with beam-beam on. Comparing Fig. 3 with the results in Fig. 1, one discovers that HEBC induces the halo losses of about 28% per hour with 1.2 A of current, 140%/hr (or 2.5% per minute) with 2.4 A, and 250%/hr (4%/min) with 3.6 A. The removal rate clearly depends on the particle's momentum as illustrated by Fig. 4. There, the intensity is plotted as a function of time for particles with different initial values of momentum deviation.

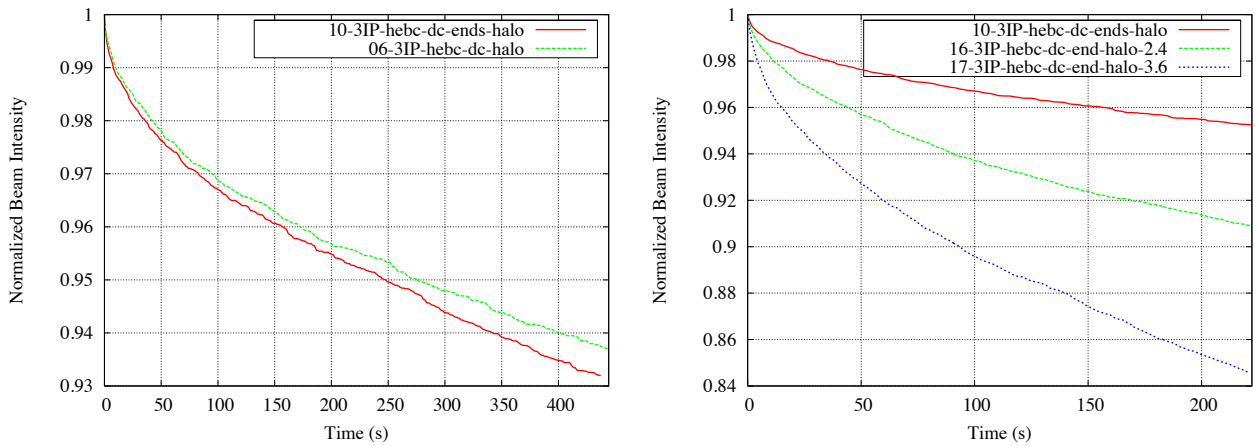


Figure 3. Halo removal with HEBC in continuous mode, with beam-beam interactions. Left – effect of $e^-$ bends at 1.2A, right – effect of $e^-$ beam current.

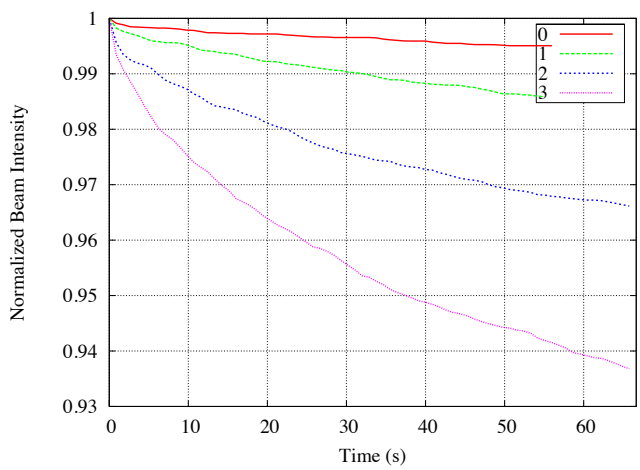


Figure 4. Halo removal rate for HEBC in continuous mode for different values of momentum deviation. Plot labels indicate the value of $\Delta p/p$ in units of $\sigma_E$.

### 3. *Halo removal rates in stochastic mode*

The introduction of random turn-by-turn modulation of the electron beam current significantly ehnances the halo cleaning efficiency, making HEBC the dominant loss mechanism. As illustrated by Figs. 5-6, the cleaning rates for the cases with and without beam-beam interactions do not differ as much as in the DC mode. In either case, 50% of halo is removed in 200 seconds with HEBC current at 1.2 A, and 80% at 3.6 A. The maximum cleaning rate attained in these simulations was approximately 100% per minute.

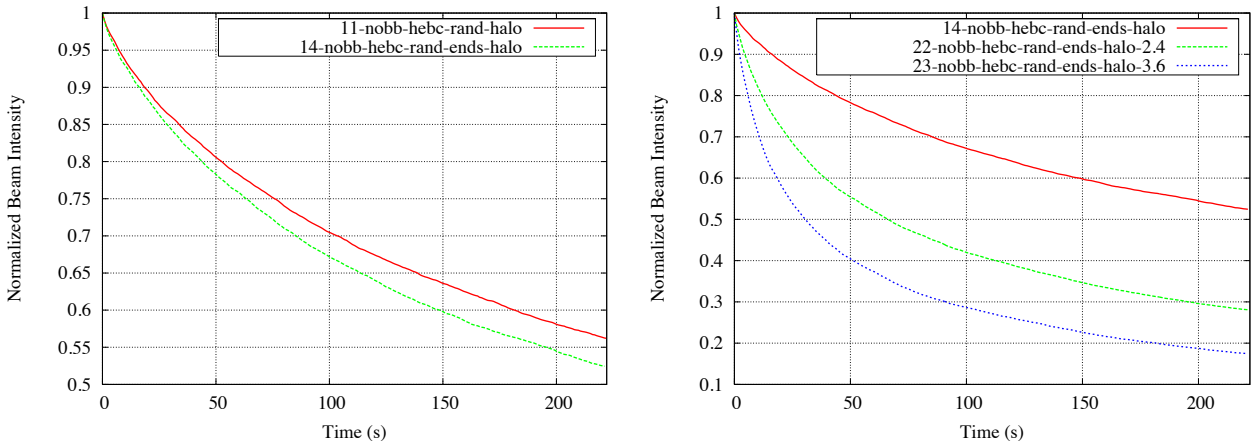


Figure 5. Halo removal with HEBC in stochastic mode, without beam-beam interactions. Left – effect of $e^-$ bends at 1.2 A, right – effect of $e^-$ beam current.

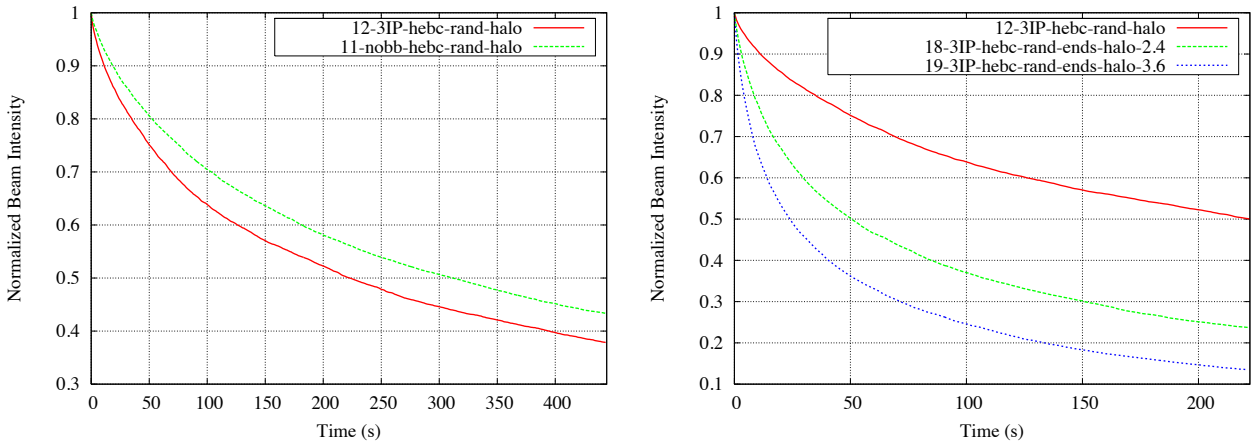


Figure 6. Halo removal with HEBC in stochastic mode, with beam-beam interactions. Left – comparison with no beam-beam case at 1.2 A, right – effect of $e^-$ beam current.

### *4. Effect of imperfections on the core*

The second major goal of the present study was to evaluate the impact of hollow electron lens on the dynamics of core particles, and consequently on the luminosity performance. Since the irregularities in azimuthal distribution of $e^-$ current can be minimized by carefull design of the cathode and of the transport system, we concentrated on the imperfection that is unavoidable in the present Electron Lens design – the bending sections, where the circulating beam has to "pierce" the wall of the hollow $e^-$ beam. The kicks from these bending sections were implemented in *LIFETRAC* according to [1]. As the simulation results in Fig. 7 suggest, in the continuous mode the bending sections do not produce any measurable effect on luminosity lifetime, which is also confirmed by the experimental results from the Tevatron [3].

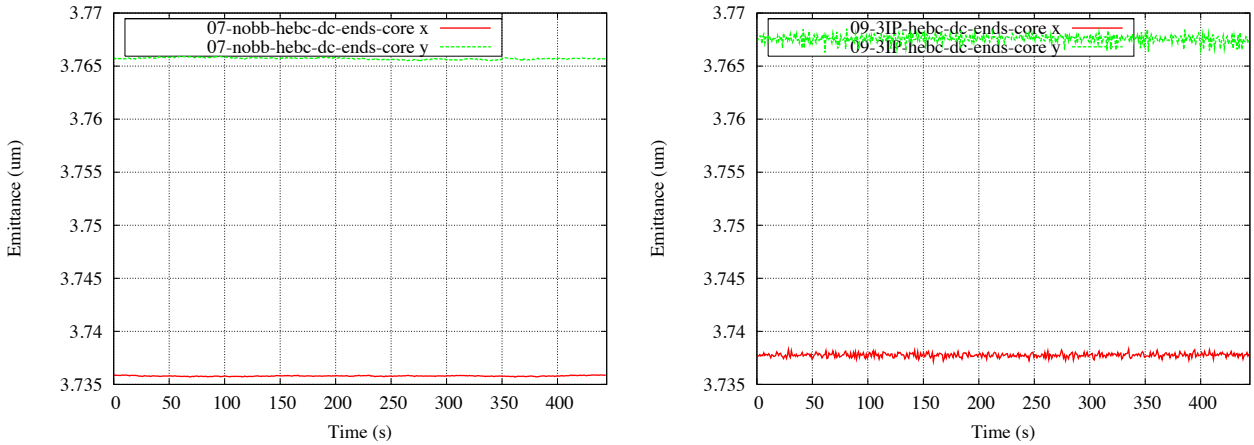


Figure 7. Emittance evolution with HEBC at 1.2 A in continuous mode, Left – beam-beam off, right – beam-beam on.

Our simulations suggest that for the stochastic mode, the uncompensated dipole component of the bending section kick may introduce emittance growth that depends on the electron lens design. Namely, the gun-side and collector-side bending sections of electron lens can be either on one side of the device (a-la Tevatron electron lenses, further we call this configuration "U-lens"), or on the opposite sides of the device with respect to the beam propagation (a-la RHIC electron lenses, "S-lens"). In the former case, the dipole components of horizontal kick from the bends add up, which leads to the horizontal emittance growth. In the latter case, the dipole components subtract leaving only higher order multipole harmonics, which are not found to be detrimental to the core dynamics. Figure 8 illustrates the comparison between the U-lens and S-lens configurations. There is no noticeable emittance growth for S-lens configuration, and the growth rate for U-lens scales approximately quadratically with the strength of modulation. A simulation with beam-beam interactions switched on (Fig. 9) allows to evaluate the luminosity performance. This is a very important simulation, representing the "worst-case scenario" for the effect of electron lens imperfections (bending sections) on the collider luminosity. Although the particle losses are not induced, and the beam lifetime remains almost perfect, the electron lens does contribute to the emittance growth, and the resulting luminosity lifetime is 90 hours (loss of ~1% per hour).

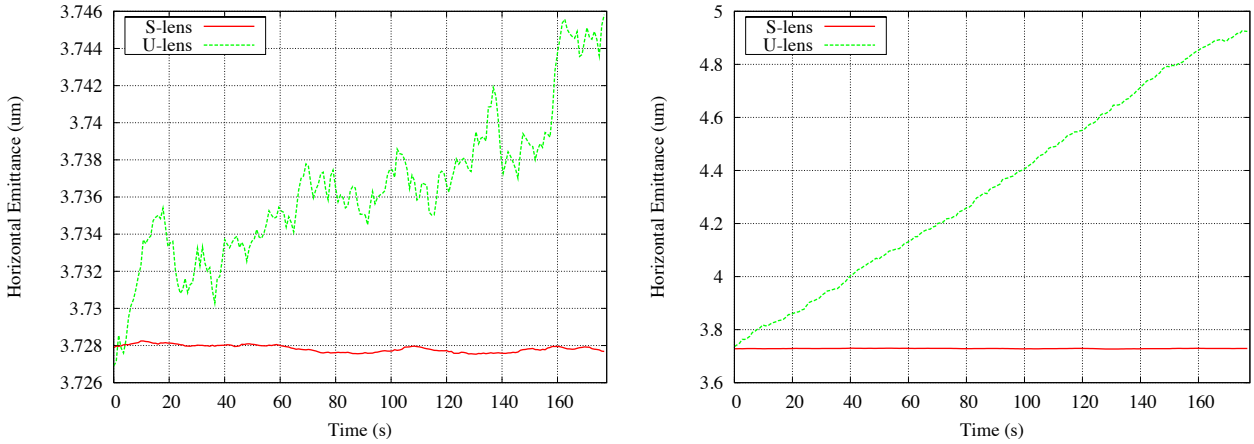


Figure 8. Evolution of horizontal emittance with time for S-lens and U-lens configurations with 10% $e^-$ current stochastic modulation (left), and 100% modulation (right). Beam-beam interactions off.

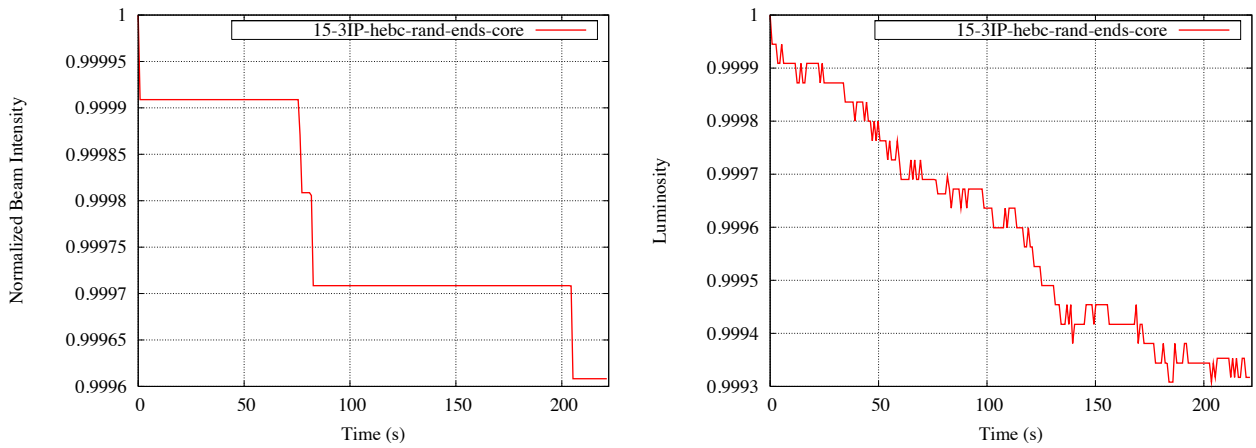


Figure 9. Evolution of beam intensity (left) and instantaneous luminosity (right) for HEBC in stochastic mode at 1.2 A, S-lens configuration.

## Conclusion

The tracking simulation study of hollow electron beam collimation applied to the nominal LHC machine predicts the halo removal rates ranging from a few percent per hour to a few percent per minute for the electron lens in continuous mode. Operating the lens in the so-called stochastic mode, when the current is randomly modulated on a turn-by-turn basis may significantly enhance the cleaning efficiency. In such a mode, the halo removal rates of up to 100% per minute are attainable.

The electron lens bending sections do not cause luminosity lifetime degradation in the continuous mode, but may affect the circulating beam core in the stochastic mode, and the S-lens configuration is preferred for such operation. The impact of bending sections on luminosity lifetime is estimated at about one percent per hour, however a further optimization of the bending sections is necessary in order to improve performance.

## References

[1] G. Stancari, FERMILAB-FN-0972-APC (2014).

[2] V. Previtali et al., FERMILAB-TM-2560-APC (July 2013).

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