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HOLLOW ELECTRON-LENS ASSISTED COLLIMATION AND PLANS FOR THE LHC

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Abstract

The hollow electron lens (e-lens) is a very powerful and advanced tool for active control of diffusion speed of halo particles in hadron colliders. Thus, it can be used for a controlled depletion of beam tails and enhanced beam halo collimation. This is of particular interest in view of the upgrade of the Large Hadron Collider (LHC) at CERN, in the framework of the High-Luminosity LHC project (HL-LHC). The estimated stored energy in the tails of the HL-LHC beams is about 30 MJ, posing serious constraints on its control and safe disposal. In particular, orbit jitter can cause significant loss spikes on primary collimators, which can lead to accidental beam bump and magnet quench. Successful tests of e-lens assisted collimation have been carried out at the Tevatron collider at Fermilab and a review of the main outcomes is shown. Preliminary results of recent experiments performed at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven, put in place to explore different operational scenarios studies for the HL-LHC, are also discussed. Status and plans for the deployment of hollow electron lenses at the HL-LHC are presented.

INTRODUCTION

The present LHC collimation system [1] has achieved excellent performance with cleaning inefficiency of about 1×10^{-4} and ensured safe operation without quenches from circulating beam losses with stored beam energies up to 270 MJ at 6.5 TeV [2–4]. Although this performance is very satisfactory, further improvements are deemed necessary for the High-Luminosity upgrade (HL-LHC) of the LHC [5–8] that aims at achieving stored energies of about 700 MJ. In this framework, the installation of hollow electron-lens (HEL) is considered as a possible option to improve various aspects of beam collimation. In particular, one of the main concerns come from the estimated stored energy in the beam tails. Various measurements have been carried out at the LHC, which show overpopulated tails with respect to usual gaussian assumption [9]. The scaling to HL-LHC beams lead to an estimation of about 30 MJ of stored energy in the beam tails. This large amount of energy can cause unforeseen beam dump in case of orbit jitter and fast failure scenarios related to crab cavities, due to the high losses that would take place on primary collimators. Moreover, the deposited energy during these events can lead to magnet quench on beam loss peak around the machine, together with permanent damages to collimators. Thus, a controlled and safe disposal of overpopulated beam tails has been recommended by two international reviews carried out in recent years [10, 11].

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LHC COLLIMATION SYSTEM AND ITS UPGRADE FOR HL-LHC

An illustrative picture of the working principle of the present collimation system is given in Fig. 1. The present LHC system [1, 2] is composed by 44 movable ring collimators per beam, placed in a precise multi-stage hierarchy that must be maintained in any machine configuration to ensure optimal cleaning performance. Two LHC insertions (IR) are dedicated to collimation: IR3 for momentum cleaning, i.e. removal of particles with a large energy offset (cut from $\delta p/p \sim 0.2$ % for zero betatron amplitude); and IR7 for betatron cleaning, i.e. continuous controlled disposal of transverse halo particles. Each collimator insertion features a three-stage cleaning based on primary collimators (TCP), secondary collimator (TCSG) and absorber (TCLA). In this scheme, the energy carried by the beam halo intercepted by TCPs is distributed over several collimators (e.g. 19 collimators are present in the betatron cleaning insertion). Dedicated collimators for protection of sensitive equipment (such as TCTP for the inner triplets), absorption of physics debris (TCL) and beam dump protection (TCSP) are present at specific locations of the machine. A detailed description of these functionalities goes beyond the scope of this paper and can be found in [1].

The main upgrades of the present collimation system in the present HL-LHC baseline [6] are the replacement of one 8.3 T dipole in the IR7 Dispersion Suppressor with two 11 T dipoles and a collimator in-between, together with the replacement of present collimator jaws with low impedance material. Their aim is to improve the cleaning performance of the system, while reducing its contribution to the resistive wall impedance budget of the machine.

However, these upgrades go in the direction of improving the passive nature of the system and do not allow for an active control on overpopulated beam tails and their safe disposal. Several experimental tests are on-going in the LHC to study

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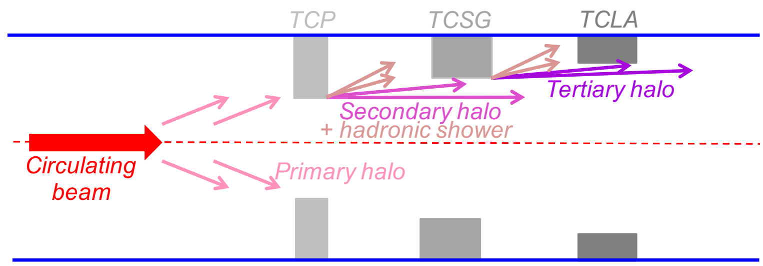

Figure 1: Working principle of the present collimation system.

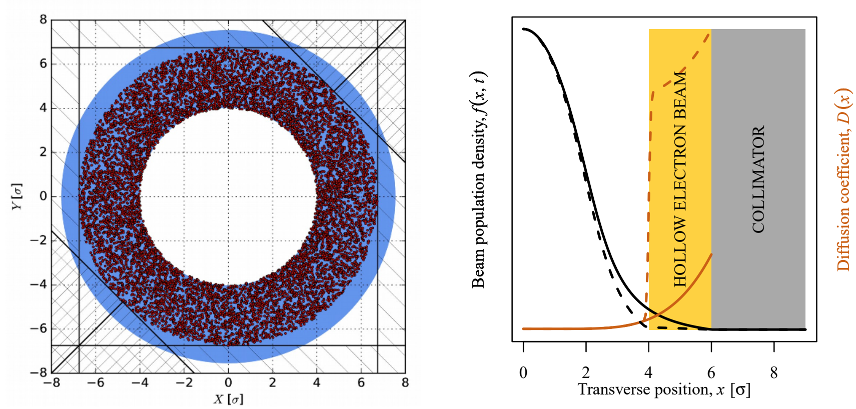

Figure 2: Concept of HEL assisted collimation: (left) the halo particles are shown by red dots, the geometrical cut performed by the horizontal–vertical–skew TCPs is represented by surrounding boxes and the hollow electron beam is depicted by the light blue ring overlapping with the halo particles and extending beyond the TCPs aperture; (right) qualitative illustration of diffusion coefficient and beam halo population with and without HEL shown by dashed and solid lines, respectively.

the possibility to perform such active control with present hardware [12–14]. Nevertheless, the installation of HEL represent one of the most promising option.

HEL Assisted Collimation

The concept of HEL assisted collimation consists of introducing an additional hierarchy layer represented by the hollow electron beam surrounding the proton beam for few meters, with the inner radius at a smaller aperture than TCPs [15]. An illustrative picture is reported in Fig. 2 (left), where beam halo particles are shown by red dots, the geometrical cut performed by the TCPs is represented by surrounding boxes and the hollow electron beam is depicted by the light blue ring overlapping with the halo particles and extending beyond the TCPs aperture. This allows to control the diffusion speed of halo particles with betatronic amplitude larger than the inner electron beam radius, depleting such halo between the beam core and TCPs. A qualitative illustration is reported in Fig. 2 (right).

In principle, the main benefit would be a loss spike free operation in the case of orbit jitter. Moreover, the control of halo population will help also in case of crab cavities fast failures. In particular, the worst accidental scenario is a phase slip that will induce a significant bunch rotation in the longitudinal plane [16]. Thus, a depleted halo population would reduce losses at TCPs also in this failure scenario. Additional benefits from a controlled diffusion speed would be a possible increase of impact parameters on TCPs with relative improvement of cleaning performance. If the impedance budget of the machine allows, collimator jaws could be closed at smaller transverse amplitude thanks to the depleted halo, allowing a β^* and crossing angle reduction at the high-luminosity experiments [17].

Nevertheless, possible drawbacks due to a depopulated halo can be the loss of Landau damping, which could be mitigated thanks to a tunable inner radius of the electron beam. Detection of unusual loss rates is one of the most important observables for machine protection purposes. Thus, a depleted halo could jeopardize the performance of the present machine protection strategy. A solution could be the presence of witness bunch trains on which the HEL does not act. Perturbation to the circulating beam could come from residual field and imperfections of the magnets used to guide the electron beam and from the hollow electron beam itself. To minimize these effects, the preferred operation mode is DC on selected bunch trains, together with an "S" shape design to self-compensate edge effects. Perturbations from the electron beam itself are minimized ensuring its symmetric shape. Possible concerns are also the complexity of the device that includes many superconducting magnets. However, the operational experience at Tevatron and RHIC give us the required confidence on the high availability and low failure rate of the entire apparatus.

FERMILAB EXPERIENCE

Two e-lenses were installed in the Tevatron collider, which were used in operations for long range beam-beam compensation and abort gap cleaning [18–20]. Studies were also

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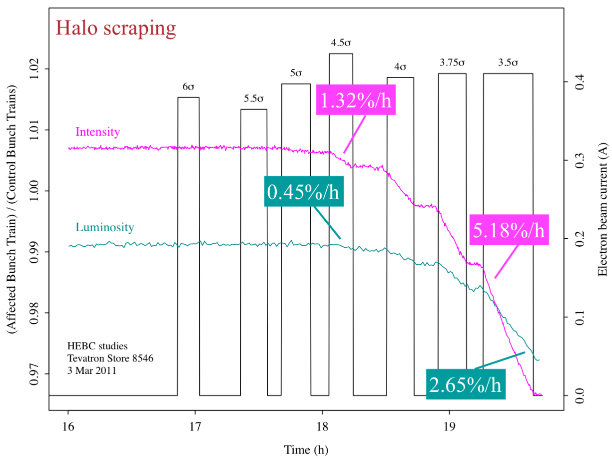

Figure 3: Normalized intensity and luminosity of the affected e-lens train with respect to the witness ones [21].

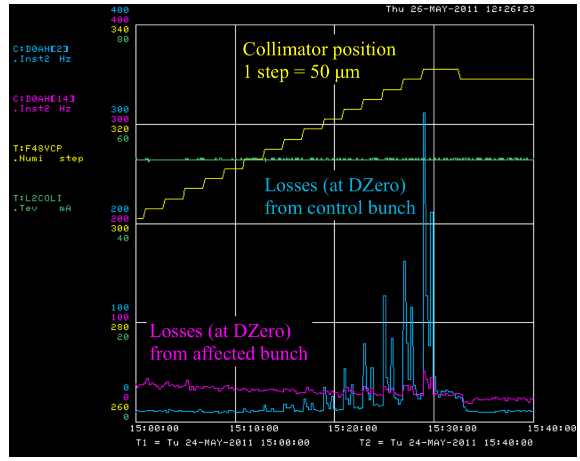

Figure 4: Loss spikes from affected and witness train during collimator scraping [15].

performed to demonstrate halo scraping with hollow electron beams [21, 22], which is of main interest in the context of this paper.

Several studies were performed to characterize the hollow electron beam as a function of magnetic field in the main solenoid and cathode-anode voltage [23]. This is crucial in order to provide the electron beam current required to enhance the halo diffusion speed, while ensuring its symmetry.

Another important milestone has been the demonstration of halo scraping without affecting the beam core. This evidence was obtained by injecting three trains of 12 antiproton bunches in the machine, with the HEL acting on only one of them. The bunch by bunch intensity and luminosity were monitored while changing the inner radius and current of the electron beam. Normalizing the intensity of the affected train with respect to the witness ones, it is possible to extrapolate if the loss rate is enhanced. On the other hand, the same normalization applied to the luminosity give us information regarding effects on the core. A decrease on normalized intensity at constant normalized luminosity, demonstrates that the loss rate of the affected train is enhanced acting on the diffusion speed of halo particles without any effect on the beam core. This is clearly visible in Fig. 3 [21].

As introduced previously, one of the main benefits of the installation in HL-LHC would be a loss spike free operation in the case of orbit jitter thanks to depleted beam halo. The reduced tail population thanks to HEL has been successfully proven by means of collimator scans, reported in Fig. 4 [24]. In particular, loss spikes coming from the affected train were observed about 300 µm after touching the tail of the witness train.

BROOKHAVEN EXPERIENCE

Two e-lenses are installed in the Yellow and Blue ring of the RHIC collider, which were used in p-p operations for head-on beam-beam compensation [25–32], where none of the 112 stores was aborted due to e-lens equipment failure. A gaussian beam overlapping to the proton beam is required for these purposes. Presently, and until the completion of the sPHENIX detector upgrade, only heavy ions are used in operation, which do not require head-on beam-beam compensation. Thus, it was agreed to change the electron gun of the e-lens in the Yellow ring in order to provide an hollow electron beam. Being the only active e-lens in the world, this provides a unique opportunity to explore different operational scenarios studies for the HL-LHC.

Different tests have been performed and are still on-going. One of the main achievements was the successful demonstration that back-scattered electrons can be used to centre the electron beam around the circulating one. The electron beam is kept stable while the circulating beam is moved by means of a local 4-correctors bump. When the main beam intercepts the electrons some of them are back-scattered and detected [33]. Due to the fact that back scattered electrons are guided by the solenoidal fields in the e-lens, they are deflected upward making impossible measurements on the bottom part of the electron beam. To overcome this limitation, different scans in the horizontal plane are performed for different vertical position. The main beam is then centered in the position that minimizes the rate of back-scattered electrons for different vertical positions. In principle, this operation should be repeated also for different angles of the main beam. However, this procedure was skipped for these first tests due to the significant time needed and good confidence obtained by varying the beam angle for fixed transverse positions.

Similar measurements as done at Tevatron were repeated with 100 Z GeV Ru and 13.6 Z GeV Au beams. In particular, two trains of 28 Ru bunches were injected in the two RHIC rings, with the e-lens acting only on one train in the Yellow ring. First the electron beam inner radius (r) was changed with a fixed electron beam current (I), while monitoring bunch-by-bunch losses and integrated loss rate in the two beams. As second test, r was fixed and I was changed. Measured bunch-by-bunch losses were integrated for each train and losses from the affected train were normalized with respect to the witness one. Normalized bunch-by-bunch

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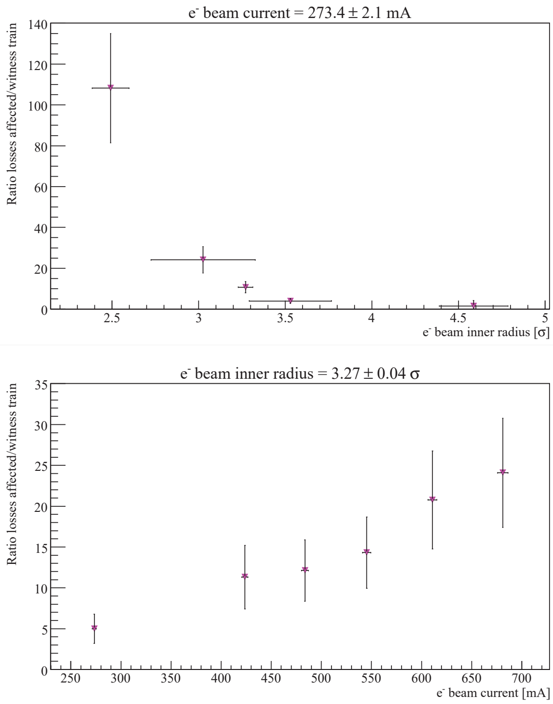

Figure 5: (top) Normalized bunch by bunch losses varying inner electron beam radius and (bottom) electron beam current.

losses during the two measurements are shown in Fig 5. As clearly visible a $1/r$ trend is observed in the losses while changing r, while a linear trend as a function of I is observed when varying I.

Similar tests were performed with 13.6 Z Au beams, in which scans of octupoles and chroma were also performed with fixed radius and current of the electron beam. Moreover, bunch by bunch luminosity were also available allowing to study effects on the circulating beam core. Encouraging results were observed on-line, the detailed off-line analysis is on-going.

LHC PLANS

Two international reviews [10, 11] were carried out to asses the need, cost and readiness for the installation of the HEL in the LHC tunnel, in particular for operations in the HL-LHC era. Although they are not yet part of the HL-LHC baseline, their installation was recommended and final integration studies are on-going.

HEL Design

The candidate locations for the HELs installation in the LHC tunnel are at both sides of the interaction region IR4. This location provides the required distance between the two beams and the longitudinal space. The main requirements are: compact design, reasonable magnetic fields in the solenoids, smooth and high magnetic fields in the transition regions, technically feasible dimensions and current density of the cathode, adjustable inner radius of the electron beam to be adapted to the beam size for different energies. The present design [34] that fulfill all these requirements is shown in Fig. 6 and functional specifications are reported in Table 1. The main components are the main solenoid that ensures 3 m of overlap between the circulating and electron beams, two bending solenoids for the injection and extraction of the electron beam, electron gun solenoid to adjust the inner radius of the electron beam. Several corrector coils are also present. All the magnets involved are superconducting and the “S” shape of the entire assembly allow to self-compensate edge effects. Thermal and structural verification were performed by means of numerical simulations for all the components, from the electron gun to the collector [35].

Table 1: Design Parameters for the HL-LHC HEL [36]

Parameter	**Value or range**
Magnetic field main solenoid [T]	5
Magnetic field cathode [T]	0.2 - 2
Inner radius electron beam [mm]	0.9 - 5.67
Outer radius electron beam [mm]	1.8 - 11.34
Inner diameter cathode [mm]	8.05
Outer diameter cathode [mm]	16.10
Nominal current cathode [A]	5

Cryogenics

As described above, all the magnets in the HEL are superconducting. Thus, a solid connection to the cryogenic system is required. Upgrades of the cryogenic system in IR4 are foreseen in the framework of HL-LHC, aiming at providing cooling capacity and distribution to match the needs with efficient solutions without making it the weakest sector, allowing to connect future users such as the HEL. The present concept could be integrated to the cryogenic system of the LHC without any showstopper [37].

Beam Instrumentation

Beam instrumentation concepts are based on experience in FNAL and BNL. The main requirements to allow reliable HEL operations are: alignment of proton and electron beams with resolution < 60 µm, profile and current measurements of the electron beam, beam loss monitoring for solenoid quench protection. The preliminary baseline detectors are: beam position monitors for general alignment of proton and electron beams, gas jet curtain combined with luminescence detection for characterization of the electron beam and relative alignment with respect to circulating beam, standard LHC ionization chamber for beam loss monitoring [38]. Possible options could be also back-scattered electron detector and YAG Screen in the case of problems with gas jet curtain combined with luminescence.

Operational Aspects

Several operational aspects were taken into account [39]. A round pipe of 60 mm radius is foreseen, in order to avoid issues in terms of available aperture for the circulating beam.

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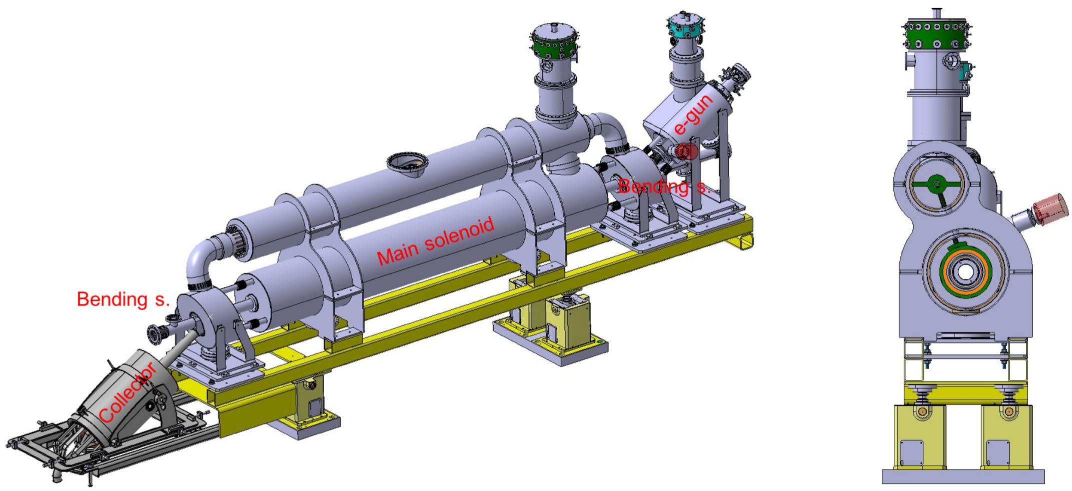

Figure 6: (left) Side and (right) front view of the present HL-LHC hollow electron lens design.

Effect of linear coupling from solenoidal fields show a negligible effect. In case of quench, missing dipole kick could cause losses and a proper interlock strategy is needed. Impedance calculations on pipe were performed using CST Particle Studio [40], which show good performance and negligible impact to total machine impedance budget. The "S" shape of e-lens is conceived so that the effect on the proton beam core from the two electron beam crossings cancels out. However, dipolar kicks from bending solenoids add up. Thus, a dedicated orbit corrector connected in series with the bending solenoids is foreseen. Moreover, also imperfections on the bends or electron beam profile can induce a non-zero kick at the center of the beam. All these effects, except dipolar kick from bending solenoids, are negligible in DC operations but can become significant for pulsed modes. Thus, several simulation and experimental studies were carried out in 2016 and 2017 [41, 42] in order to find possible pulsing operation mode that would enhance the HEL effect without jeopardizing machine performance and its protection.

CONCLUSIONS

A wide overview of HEL assisted collimation tests done in different laboratories has been reported, together with plans for the LHC and its upgrade HL-LHC. Their installation in the LHC tunnel can lead to several benefits for operations in the HL-LHC era, in particular for an active control of the about 30 MJ of expected stored energy in the beam tails. Possible drawbacks have been studied and appropriate solutions have been found. Experimental and operational experiences at Tevatron and RHIC show results in agreement with expectations, with an extremely high hardware reliability despite their complexity. Although HEL are not yet part of the HL-LHC baseline, their integration has been recommended by two international reviews. All the relevant aspects for HEL installation have been studied and its design is considered mature for a possible installation. Final and detailed tracking simulation studies are on-going to define optimal operational scenario.

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