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ELECTRON LENSES FOR THE LARGE HADRON COLLIDER*

G. Stancari†, A. Valishev, Fermilab, Batavia, IL 60510, USA
R. Bruce, S. Redaelli, A. Rossi, B. Salvachua Ferrando, CERN, Geneva, Switzerland

Abstract

Electron lenses are pulsed, magnetically confined electron beams whose current-density profile is shaped to obtain the desired effect on the circulating beam. Electron lenses were used in the Fermilab Tevatron collider for bunch-by-bunch compensation of long-range beam-beam tune shifts, for removal of uncaptured particles in the abort gap, for preliminary experiments on head-on beam-beam compensation, and for the demonstration of halo scraping with hollow electron beams. Electron lenses for beam-beam compensation are being commissioned in RHIC at BNL. Within the US LHC Accelerator Research Program and the European HiLumi LHC Design Study, hollow electron beam collimation was studied as an option to complement the collimation system for the LHC upgrades. A conceptual design was recently completed, and the project is moving towards a technical design in 2014–2015 for construction in 2015–2017, if needed, after resuming LHC operations and re-assessing collimation needs and requirements at 6.5 TeV. Because of their electric charge and the absence of materials close to the proton beam, electron lenses may also provide an alternative to wires for long-range beam-beam compensation in LHC luminosity upgrade scenarios with small crossing angles.

INTRODUCTION

Electron lenses are pulsed, magnetically confined, low-energy electron beams whose electromagnetic fields are used for active manipulation of the circulating beam in high-energy accelerators [1, 2]. The first main feature of an electron lens is the possibility to control the current-density profile of the electron beam (flat, Gaussian, hollow, etc.) by shaping the cathode and the extraction electrodes. Another feature is pulsed operation, enabled by the availability of high-voltage modulators with fast rise times. The electron beam can therefore be synchronized with subsets of bunches, with different intensities for each subset. The main advantage of the use of electron lenses for high-power accelerators is the absence of metal close to the beam, therefore avoiding material damage and impedance.

Electron lenses were developed for beam-beam compensation in colliders [3], enabling the first observation of long-range beam-beam compensation effects by tune shifting individual bunches [4]. They were used for many years during regular Tevatron collider operations for cleaning uncaptured particles from the abort gap [5]. Thanks to the reliability of the hardware, one of the two Tevatron electron lenses could be used for experiments on head-on beam-beam compensation in 2009 [6], and for exploring hollow electron beam collimation in 2010–2011 [7, 8]. Electron lenses for beam-beam compensation were built for the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory and are being commissioned [9, 10]. Current areas of research on electron lenses include the generation of nonlinear integrable lattices in the Fermilab Integrable Optics Test Accelerator [11, 12] and applications for the LHC upgrades: as halo monitors and scrapers, as charged current-carrying ‘wires’ for long-range beam-beam compensation, and as tune-spread generators for Landau damping of instabilities before collisions.

In this paper, we focus on hollow electron beam scraping, which is the most mature of these concepts, following the experimental demonstration at the Tevatron and the conceptual design studies for the LHC. Preliminary considerations on long-range compensators based on electron beams are briefly discussed.

HALO CONTROL WITH HOLLOW ELECTRON BEAMS

Hollow electron beam collimation is based upon electron beams with a hollow current-density profile aligned with the circulating beam [7, 8, 13]. If the electron distribution is axially symmetric, the proton beam core is unperturbed, whereas the halo experiences smooth and tunable nonlinear transverse kicks. The size, position, intensity, and time structure of the electron beam can be controlled over a wide range of parameters.

The Tevatron experiments on hollow electron beam collimation can be summarized as follows [7, 8, 14, 15]: the use of the electron lens was compatible with collider operations during physics data taking; the alignment of the electron beam with the circulating beam was accurate and reproducible; the halo removal rates were controllable, smooth, and detectable; with aligned beams, there was no lifetime degradation or emittance growth in the core; loss spikes due to beam jitter and tune adjustments were suppressed; the local effect of the electron beam on beam halo fluxes and diffusivities was directly measured with collimator scans.

For the LHC and its luminosity upgrades (HL-LHC), beam halo measurement and control are critical, and this technique may provide unique capabilites. LHC and HL-LHC represent huge leaps in stored beam energy per beam, from 2 MJ at the Tevatron, to 140 MJ in the LHC in 2012, to 362 MJ in the nominal LHC, to 692 MJ for HL-LHC after 2022. Although the collimation system has performed well

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† Email: ⟨stancari@fnal.gov⟩.

so far in terms of efficiency and robustness, impedance limitations may already be surfacing in the several fills that were lost in 2012 due to instabilities. Moreover, the minimum design HL-LHC beam lifetimes (for instance, 0.2 h during squeeze and adjust) translate into slow losses that will be close to the plastic deformation of primary and secondary collimators. To address these and other issues, a significant program of collimation system upgrades is under way.

In particular, electron lenses may be the best option to tackle beam halo monitoring and control. Halo populations in the LHC are poorly known. Collimator scans and van-der-Meer luminosity scans indicate that between 0.1% and 5% of the total beam energy is in the tails, which will translate to 0.7 MJ to 35 MJ at 7 TeV for HL-LHC. Quench limits, magnet damage, or even collimator deformation will be reached with fast losses or fast crab-cavity failures (which result in orbit shifts of about 2 standard deviations of the proton beam size).

Beam halo monitoring and control are one of the major risk factors for HL-LHC and for safe operation with crab cavities. There is a need to measure and monitor the beam halo, and to remove it at controllable rates. Hollow electron lenses are the most established and flexible tool for this purpose.

In collaboration with the US LHC Accelerator Research Program and the HiLumi LHC Design Study, a plan for electron lenses in the LHC was developed, based on the decision that final collimation needs (not only for halo scraping) can only be defined after gaining operational experience at 7 TeV, presumably by the end of 2015, once uncertainties on cleaning efficiencies, beam lifetimes, quench limits, and impedances are reduced.

In the meantime, it was decided to proceed with the design of 2 hollow electron beam scrapers for the LHC, one per beam. A conceptual design was recently completed [16,17]. The expected performance is based upon experimental measurements and numerical simulations [18]. A wide range of halo removal rates is possible, from seconds to hours, using the electron lens in continuous mode (same electron current every turn for a given bunch) or in stochastic mode (by adding random noise turn by turn to the modulator voltage). The continuous mode is useful for smooth cleaning, whereas the stochastic mode can be used for faster scraping (e.g., before squeeze and adjust). No adverse effects on the proton beam core were observed or calculated in continuous mode. For stochastic operation, it is desirable to configure the electron lens in an S-shape (electron gun and collector on opposite sides of the beam axis) to cancel the dipole kicks due to the injection and extraction bends [19]. Currently available modulators [20] with rise times of about 200 ns not only enable stochastic or resonant operation, but also train-by-train or batch-by-batch customization of the electron current. This is useful to preserve the halo on a subset of bunches for machine protection (early loss detection) and to directly compare different electron-lens settings. The technical parameters of the electron lenses for the LHC (cathode size, current yield, magnetic fields, modulator, etc.) are within the present state of the art. No major integration issues were identified so far, although cryogenics will require a considerable effort.

The conceptual design will develop into a technical design in 2014–2015, with the goal to build the devices in 2015–2017, if needed. Installation during the next long LHC shutdown (LS2), currently scheduled for 2018, would be technically possible. In case of a resource-limited timeline, installation during the following long shutdown (in 2022) is also an option. In this case, more advanced solutions may be tested and included in the design. A close collaboration between Fermilab, Brookhaven, and CERN will ensure that both hardware and software expertise on electron lenses is transfered to CERN, and that more beam tests are conducted at RHIC, if possible.

At the same time, proposed alternative schemes for halo control should be investigated, as they may be cheaper than electron lenses, or they may become available sooner. These alternatives include excitations with the transverse damper, tune modulation with warm quadrupoles [21], and wire compensators. Both simulations and hardware tests are being conducted in preparation of beam studies after the startup of the LHC.

Noninvasive halo diagnostic methods, such as synchrotron-light monitoring with wide dynamic range, should be pursued with high priority. The electron lenses themselves, if they are installed, may provide a new sensitive way to measure halo populations with backscattered electron detectors, as is being demonstrated at RHIC [10,22].

ELECTRON ‘WIRES’ AS LONG-RANGE COMPENSATORS

Electron lenses may play an important role in HL-LHC luminosity schemes with flat beams and smaller crossing angles, where no crab cavities are necessary, but for which long-range beam-beam compensation is critical.

Conventional wire compensators will be tested after the current LHC shutdown. They are technically challenging and they present a risk for collimation and machine protection, because they involve water-cooled copper cables carrying 378 A at about 10 standard deviations of the proton beam size.

Electron lenses are considered as a safer, less demanding alternative to wire compensators, with the added benefit of pulsing [23]. About 21 A over a distance of 3 m would be required for HL-LHC, with any transverse shape.

Physics and integration studies were initiated. Candidate locations between the separation dipoles D1 and D2, and beyond D2 are under study. Simulations are used to calculate the expected performance and its sensitivity to location. Energy deposition in the superconducting solenoid, radiation to the high-voltage modulator, and integration issues are being addressed.

CONCLUSIONS

Electron lenses are unique devices for active beam manipulation in accelerators, with a wide range of applications. Halo scraping with hollow electron beams was demonstrated at the Fermilab Tevatron collider. Halo measurement and control is critical for LHC and its upgrades. A conceptual design of hollow electron beam scraper for the LHC was recently completed. The expected performance is based upon experimental data and on numerical simulations. Technical parameters are achievable. Electron lenses in the LHC are also a candidate for long-range beam-beam compensation (charged electron 'wire'). The concept was developed, and preliminary layout and integration studies were initiated. Magnetized low-energy electron beams are also relevant for the Fermilab program in the near future, for nonlinear integrable lattices in the Integrable Optics Test Accelerator at the Advanced Superconducting Test Accelerator facility.

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