# COLLIMATION WITH HOLLOW ELECTRON BEAMS: A PROPOSED DESIGN FOR THE LHC UPGRADE*

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## *Abstract*

Collimation with hollow electron beams is a technique for halo removal in high-power hadron beams. The concept was tested experimentally at the Fermilab Tevatron collider using a hollow electron gun installed in one of the Tevatron electron lenses. Within the US LHC Accelerator Research Program and the European HiLumi LHC Design Study, we are investigating the applicability of this technique to the Large Hadron Collider and a conceptual design is being developed. We review some of the main topics related to this study: motivation; halo removal processes; development of hollow electron guns; effects on the proton beam core; and integration in the LHC machine.

## INTRODUCTION

Hollow electron beam collimation is a new technique for beam collimation and halo scraping [1, 2, 3]. In a hollow electron beam collimator, a magnetically confined, pulsed, low-energy (a few keV) electron beam with a hollow current-density profile overlaps with the circulating beam over a short section of the ring. If the electron distribution is axially symmetric, the beam core is unperturbed, whereas the halo experiences smooth and tunable nonlinear transverse kicks. The electron beam is generated by a hollow cathode and transported by strong solenoidal fields. The size, position, intensity, and time structure of the electron beam can be controlled over a wide range of parameters.

The technique still relies on robust conventional collimators to absorb particles, but it has several features that can complement a classic multi-stage collimation system. In the case of high-power proton beams, for instance, scraping is smooth, controllable, and the issues of material damage and electromagnetic impedance of the collimator jaws are mitigated. In addition, a depletion zone is generated between the proton beam core and the collimator edges, making local energy deposition less sensitive to beam jitter, collimator movements, orbit and tune adjustments, or fast failures in the case of crab-cavity operation. In the case of ion collimation, it may be possible to reduce uncontrolled losses due to fragmentation. Hollow electron beam collimation is also being evaluated in comparison with other halo scraping techniques, such as tune modulation [4].

Hollow electron beam collimation is based on the technology of electron cooling and electron lenses. Electron lenses were developed for beam-beam compensation in colliders [5], enabling the first observation of long-range beam-beam compensation effects [6]. They were used for many years during regular Tevatron collider operations for cleaning uncaptured particles from the abort gap [7]. 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 [8], and for exploring hollow electron beam collimation in 2010–2011 [2, 3]. Electron lenses for beam-beam compensation were built for the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory and are currently being commissioned [9].

The Tevatron experiments on hollow electron beam collimation were conducted on antiprotons, mainly at the end of regular collider stores. In some cases, the electron beam was turned on for the whole duration of the fill. Because of the flexible pulsing pattern of the high-voltage modulator [10], the electron beam could be synchronized with a subset of bunches, providing a direct comparison with the unaffected beam.

The technique may provide a unique option to complement the LHC collimation system, but extending it from one machine to another is not trivial. To study these issues, a conceptual design of hollow electron beam collimation for the LHC upgrade is being developed within the US LHC Accelerator Research Program (LARP) and the European FP7 HiLumi LHC Design Study. If approved by the CERN management, this may then develop into a technical design in 2014, with the goal to build the devices in 2015–2017 and install them during the next long LHC shutdown, currently scheduled for 2018. In case of a resource-limited timeline, installation during the following long shutdown in 2022 is also an option.

## HALO SCRAPING

For scraping the halo of a 7-TeV proton beam, we envision the inner radius of the electron beam to be placed between about $4\sigma$ and $6\sigma$ of the LHC proton rms beam size $\sigma = 0.32$ mm. This size is derived from the nominal normalized rms emittance $\varepsilon = 3.75\ \mu$m and the typical amplitude function at the candidate locations, $\beta = 200$ m. Scraping of elliptical proton beams is possible by displac-

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ing the electron beam, but for simplicity we focus on round beams.

For stability and for transport efficiency, the field in the guiding solenoids should be as large as possible. Based upon previous experience and technical feasibility, we consider configurations where the gun, main (superconducting), and collector solenoids have fields in the ranges $0.2\ \mathrm{T} \leq B_g \leq 0.4\ \mathrm{T}$, $2\ \mathrm{T} \leq B_m \leq 6\ \mathrm{T}$, and $0.2\ \mathrm{T} \leq B_c \leq 0.4\ \mathrm{T}$, respectively. This implies magnetic compression factors $k \equiv \sqrt{B_m/B_g}$ in the range $2.2 \leq k \leq 5.5$, which sets the required sizes of the cathode inner and outer radii. The 1-inch electron gun cathode built for this purpose, for instance, has inner radius $r_{ci} = 6.75$ mm and an outer radius $r_{co} = 12.7$ mm. After magnetic compression, these radii translate to $1.2\ \mathrm{mm} = 3.9\sigma \leq r_{mi} \leq 9.5\sigma = 3.0\ \mathrm{mm}$ and $2.3\ \mathrm{mm} = 7.3\sigma \leq r_{mo} \leq 18\sigma = 5.7\ \mathrm{mm}$ in the interaction region inside the main solenoid. The LHC primary collimators will be placed at around $6\sigma$ from the beam axis.

The scraping experiments at the Tevatron with 0.98 TeV antiprotons were done with peak electron beam currents up to 1.2 A, and halo removal times ranged between seconds and minutes, depending upon the radius and intensity of the electron beam.

The transverse kicks generated by the hollow electron beam are nonlinear and have a small random component due to noise in the electron beam current. These kicks interact with the lattice nonlinearities and with the sources of noise in the machine. Therefore, the kicks needed to obtain a given halo removal rate may not be directly proportional to the magnetic rigidity of the circulating beam — a linear machine with low noise may require larger electron beam intensities.

Tracking simulations in the Tevatron lattice with the Lifetrac code showed that relatively small electron currents can significantly enhance halo removal [11]. The removal rates are sensitive to the shape of the electron beam and to the distribution of the halo population. In the absence of experimental data, tracking codes can give rough but conservative estimates of the removal rates. Numerical simulations of the LHC lattice with the SixTrack code indicated that, in the absence of beam-beam interactions and of diffusion processes, removal of 7-TeV protons with a 1-A electron beam current would be slow [12]. Higher electron yields and different pulsing schemes were therefore pursued to extend the capabilities of the technique.

A 1-inch-diameter hollow electron gun based on a tungsten dispenser cathode was developed and characterized at the Fermilab electron-lens test stand [13, 14]. The perveance of this gun is 5.3 $\mu$perv. This implies a peak yield of over 5 A at 10 keV. This yield should be sufficient to have a detectable effect on 7-TeV protons.

One can also exploit the flexibility of the electron beam pulsing pattern. Most of the Tevatron scraping experiments were done with the same turn-by-turn excitation intensity on the bunches of interest, but, for beam-beam compensation purposes, the high-voltage modulator was designed to handle bunch-by-bunch adjustments, with 10%–90% rise times of 200 ns [10]. Fast abort-gap cleaning was achieved by turning on the electron beam every 7th turn, in resonance with the betatron oscillations of the uncaptured beam.

In the LHC, one could certainly change the electron beam current turn by turn, synchronizing the voltage change with the abort gap, for instance. (Bunch-by-bunch adjustments every 25 ns or 50 ns are probably unnecessary.) This flexibility opens up the possibility to operate the hollow electron lens in different pulsing modes: *continuous* — the same voltage is applied every turn; *resonant* — the voltage is changed turn by turn according to a sinusoidal function (possibly including a frequency sweep to cover the tune spread of the halo), or with the same amplitude, but skipping a given number of turns (as in the Tevatron abort-gap cleaning mode); *stochastic* — the voltage is turned on or off every turn according to a random function, or a random component is added to a constant voltage amplitude. These modes of operation were simulated with tracking codes [12]. Both the resonant and the stochastic mode give significant and tunable halo removal rates. While the first is sensitive to the details of the tune distribution (lattice nonlinearities, beam-beam parameter), the stochastic mode is much more robust.

Using collimator scans, it was possible to measure the effects of collisions and of the hollow electron lens on halo diffusion in the Tevatron as a function of betatron amplitude [15, 16]. Diffusivities in action space with and without collisions were also measured at the LHC [17]. Halo suppression is the main consequence of the drift and diffusion enhancement by the electron beam, but we intend to further investigate other important aspects, such as the increase in impact parameters and its effect on collimation efficiency.

## UNDESIRED EFFECTS ON THE CORE

The core of the circulating beam is unaffected if the distribution of the electron charge is axially symmetric. One possible cause of asymmetry is the space-charge evolution of the electron beam. Other sources of asymmetry are the bends that are used to inject and extract the electron beam from the interaction region.

The electron beam was turned on for several hours during some Tevatron collider stores. With aligned beams and continuous operation, no deterioration of the core lifetimes or luminosities were observed. Only a limited number of experiments were done in resonant mode (by skipping turns).

The current-density profiles generated by the hollow electron guns were measured in the Fermilab electron-lens test stand as a function of beam current and axial magnetic field. Space-charge evolution of the electron beam profiles is mitigated by increasing the guiding magnetic fields. For main fields above 2 T and beam currents up to a few amperes, we estimate that transverse current-density profiles are practically frozen.

The calculation of the electric fields from the measured current density profiles and the generation of the kick maps caused by the bends is described in a separate paper [18]. These fields are being used as inputs for tracking simulations to estimate beam lifetimes and emittance growth rates. For the Tevatron lattice and working point, the only azimuthal asymmetry seen to cause extra losses in the core was the quadrupole component in a particular resonant mode (pulsing every 6th turn) [11].

## FURTHER CONSIDERATIONS

The bunch structure in the LHC is very different from the one in the Tevatron. This translates into tighter requirements on the electromagnetic impedance of the electron-lens hardware. Another aspect being considered is the possible extension of this technique to different operational scenarios, such as scraping during the acceleration ramp, which do not present impediments in principle, but have never been tested experimentally.

Diagnostic instrumentation includes accurate beam position monitoring of the long electron pulses and measurement of the electron beam profiles with wires or with fluorescent screens, as done at RHIC. A sensitive local loss monitor is also required to verify relative beam alignment. A direct measurement of the halo population, although not strictly necessary, would greatly benefit this project.

The construction cost of each of 2 electron lenses (one per beam) for the LHC is estimated to be 2.5 M$ in materials and 3.0 M$ in labor. Construction of 2 devices would take about 3 years. Reuse of some of the Tevatron equipment, such as superconducting coils, is possible. Each electron lens occupies about 6 m of tunnel length. Installation time is dominated by cryogenic integration (similar to a stand-alone magnet) and requires at least 3 months for warm-up, connections, and cool-down. The Tevatron devices had static heat loads of 12 W for the helium vessel at 4 K and 25 W for the liquid nitrogen shield.

## CONCLUSIONS

Experimental and numerical studies are being conducted to support the conceptual design of a hollow electron beam collimator for the LHC, a promising technique for controlled scraping of very intense beams. A hollow electron gun with geometrical features and peak current yields appropriate for the LHC was built. Several electron beam pulsing modes were studied in numerical simulations to extend the achievable halo removal rates. No effects on the beam core are expected in the continuous mode of operation. The effect of imperfections in the resonant and stochastic modes is being evaluated with tracking codes using kick maps generated from measured and calculated electron beam charge distributions. Options for instrumentation and diagnostics were considered. No major obstacles were identified in the integration of the devices in the LHC ring from the point of view of electromagnetic impedance, mechanical engineering, or cryogenics.

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