Hollow electron lenses for the LHC: status of the conceptual design report

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LHC Collimation Upgrade Specification Meeting
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Contributors

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Many thanks to
The report

Conceptual design of hollow electron lenses for beam halo control in the Large Hadron Collider

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Collimation with hollow electron beams is a technique for halo control in high-power hadron beams. It is based on an electron beam (possibly pulsed or modulated in intensity) guided by strong axial magnetic fields which overlaps with the circulating beam in a short section of the ring. 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 (LARP) and the European FP7 HiLumi LHC Design Study, we are proposing a conceptual design for applying this technique to the Large Hadron Collider at CERN. A prototype hollow electron gun for the LHC was built and tested. The expected performance of the hollow electron beam collimator was based on Tevatron experiments and on numerical tracking simulations. Halo removal rates and enhancements of halo diffusivity were estimated as a function of beam and lattice parameters. Proton beam core lifetimes and emittance growth rates were checked to ensure that undesired effects were suppressed. Hardware specifications were based on the Tevatron devices and on preliminary engineering integration studies in the LHC machine. Required resources and a possible timeline were also outlined, together with a brief discussion of alternative halo-removal schemes and of other possible uses of electron lenses to improve the performance of the LHC.

Draft available at <https://cdcvs.fnal.gov/redmine/documents/683>
To be published as FERMILAB-TM-2572-APC, CERN document, and arXiv
Outline of the report

- Introduction
- Motivation and strategy
- Expected performance
  - principles, halo removal, effects on core, experimental studies
- Hardware specifications and integration studies
  - physical and mechanical features; hollow electron guns; vacuum; electrical; cryogenics; diagnostics; impedance
- Resources and schedule
- Alternative halo-removal schemes
  - tune modulation with warm quads, damper excitations, beam-beam wires
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Electron lens (TEL-2) in the Tevatron tunnel

- Electron gun
- Superconducting solenoid
- Collector
Electron lenses in the Fermilab Tevatron collider

- **long-range beam-beam compensation**

- **abort-gap cleaning during operations**

- **studies of head-on beam-beam compensation**
  - Stancari and Valishev, FERMILAB-CONF-13-046-APC

- **collimation with hollow electron beams**

Electron lenses for beam-beam compensation are currently being commissioned in the Relativistic Heavy Ion Collider at Brookhaven National Laboratory.
Control of electron beam profile

Current density profile of electron beam is shaped by cathode and electrode geometry and maintained by strong solenoidal fields.

Flat profiles for bunch-by-bunch betatron tune correction

Gaussian profile for compensation of nonlinear beam-beam forces

Hollow profile for halo scraping
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Hollow beam collimation with Tevatron electron lenses

Circulating beams affected by electromagnetic fields generated by electrons
Stability provided by strong axial magnetic fields

- Hollow beam collimation with Tevatron electron lenses

5-kV, 1-A electron gun
thermionic cathode
200-ns rise time

6 m total length

superconducting solenoid
1–6 T

conventional solenoids
0.1–0.4 T

Tunable transverse halo kicks ~0.1 μrad

Concept of hollow electron beam collimator or scraper

Beam core is unaffected (field-free region)

Halo experiences nonlinear transverse kicks:

\[ \theta_r = \frac{2 I_r L (1 \pm \beta_e \beta_p)}{r \beta_e \beta_p c^2 (B \rho)_p} \left( \frac{1}{4\pi \varepsilon_0} \right) \]

Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08
Electron beam size is matched to proton beam size by solenoids

- **Gun solenoid**: 0.4 T
- **Main solenoid**: 4 T
- **Collector solenoid**: 0.3 T

Distance along electron beam path [m]

Electron beam radius [mm]

Distance along electron beam path [m]

Electron beam size is matched to proton beam size by solenoids.
Example of numerical parameters for the LHC

Proton rms size
 Inner radius
 Outer radius
 Accelerating voltage
 Velocity
 Peak current
 Linear current density

Overlap region $L = 3$ m

Max. kick 0.3 $\mu$rad for 7-TeV protons

For comparison: multiple Coulomb scattering in LHC primaries generates random kicks with spread $\theta_{rms} = ...$ $\mu$rad
Beam optics at candidate locations (LHC v6.503)

Round beams, $\beta \sim 200$ m, low dispersion

Check HL-LHC lattices and evaluate impact on e-lens parameters
Pulsed operation of the electron lens in the Tevatron

Pulsed electron beam could be *synchronized* with any group of bunches
Pulsed operation of the electron lens in the LHC

Current state of the art of electron-lens modulator is a rise time (10%-90%) of 200 ns at 5 kV. Pfeffer and Saewert, JINST 6, P11003 (2011)

This enables
• turn-by-turn current modulation (stochastic or resonant) to enhance halo removal, if needed
• train-by-train (900 ns separation), or possibly batch-by-batch (225 ns), operation
  • to preserve halo on a subset of bunches for machine protection
  • to compare different electron-lens settings for diagnostics

Bunch-by-bunch operation is not necessary for collimation
## Summary of specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value or range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam and lattice</strong></td>
<td></td>
</tr>
<tr>
<td>Proton kinetic energy, $T_p$ [TeV]</td>
<td>7</td>
</tr>
<tr>
<td>Proton emittance (rms, normalized), $\varepsilon_p$ [µm]</td>
<td>3.75</td>
</tr>
<tr>
<td>Amplitude function at electron lens, $\beta_{x,y}$ [m]</td>
<td>200</td>
</tr>
<tr>
<td>Dispersion at electron lens, $D_{x,y}$ [m]</td>
<td>$\leq 1$</td>
</tr>
<tr>
<td>Proton beam size at electron lens, $\sigma_p$ [mm]</td>
<td>0.32</td>
</tr>
<tr>
<td><strong>Geometry</strong></td>
<td></td>
</tr>
<tr>
<td>Length of the interaction region, $L$ [m]</td>
<td>3</td>
</tr>
<tr>
<td>Desired range of scraping positions, $r_{mi} \sigma_p$</td>
<td>4–8</td>
</tr>
<tr>
<td><strong>Magnetic fields</strong></td>
<td></td>
</tr>
<tr>
<td>Gun solenoid (resistive), $B_g$ [T]</td>
<td>0.2–0.4</td>
</tr>
<tr>
<td>Main solenoid (superconducting), $B_m$ [T]</td>
<td>2–6</td>
</tr>
<tr>
<td>Collector solenoid (resistive), $B_c$ [T]</td>
<td>0.2–0.4</td>
</tr>
<tr>
<td>Compression factor, $k \equiv \sqrt{B_m/B_g}$</td>
<td>2.2–5.5</td>
</tr>
<tr>
<td><strong>Electron gun</strong></td>
<td></td>
</tr>
<tr>
<td>Inner cathode radius, $r_{gi}$ [mm]</td>
<td>6.75</td>
</tr>
<tr>
<td>Outer cathode radius, $r_{go}$ [mm]</td>
<td>12.7</td>
</tr>
<tr>
<td>Gun perveance, $P$ [µperv]</td>
<td>5</td>
</tr>
<tr>
<td>Peak yield at 10 kV, $I_e$ [A]</td>
<td>5</td>
</tr>
<tr>
<td><strong>High-voltage modulator</strong></td>
<td></td>
</tr>
<tr>
<td>Cathode-anode voltage, $V_{ca}$ [kV]</td>
<td>10</td>
</tr>
<tr>
<td>Rise time (10%–90%), $\tau_{mod}$ [ns]</td>
<td>200</td>
</tr>
<tr>
<td>Repetition rate, $f_{mod}$ [kHz]</td>
<td>35</td>
</tr>
</tbody>
</table>
Main goals of numerical simulations

- Would hollow electron beam collimation be effective in the LHC?
  - The kicks are nonlinear, with a small random component. Halo removal rates are expected to depend on magnetic rigidity of the beam, machine lattice, and noise sources. Nontrivial extrapolation from Tevatron to LHC.

- Would there be any adverse effects on the core, such as lifetime degradation or emittance growth?
  - No effects were seen in the Tevatron in continuous mode. Effects of asymmetries in resonant operation?

- Methods
  - Warp particle-in-cell code for electron beam dynamics
  - Lifetrac and SixTrack for numerical tracking
  - Machine models with nonlinearities
  - Uniform halo population, replenishing mechanisms to be implemented
    - Diffusion was measured in both Tevatron and LHC
  - Ideal electron lens, profile imperfections, injection/extraction bends
Dynamics of the magnetically confined electron beam

3D simulation of electron beam propagation in electron lens with Warp particle-in-cell code [V. Moens]:

- Injection: space-charge limited e-gun or arbitrary particle coordinates
- Layout: straight (test stand) or with bends (TEL-2 and LHC e-lens)
- Computing resources
  - up to 1 m propagation calculable on multi-core laptop
  - working parallel version installed on Fermilab cluster

Electron density in straight geometry
Results of numerical tracking simulations

- Flexibility of high-voltage modulator enables different modes of operation:
  - **continuous**: same electron current every turn
    - Most of Tevatron experiments done in this mode
  - **resonant**: current modulated to excite betatron oscillations (sinusoidal or skipping turns)
    - Used for clearing abort gap in Tevatron
  - **stochastic**: random on/off, or constant with random component
    - Observable effects in time scales of seconds/minutes
    - Smooth scraping with electron pulsed every turn
    - Enhanced removal rates with resonant or stochastic modes
      - Resonant mode depends on details of tune distribution
      - Stochastic mode is very robust
    - No adverse effects on core
      - in continuous mode, even with asymmetries/bends
      - in resonant mode in ideal case
      - effect of imperfections in resonant mode under study
Example of simulated halo scraping (SixTrack, LHC lattice)

Residual halo population vs. betatron amplitude after 18 s of resonant scraping

Previtali et al., FERMILAB-TM-2560-APC (2013)
Effect of asymmetries in electron distribution on circulating beam

No adverse effects were observed at the Tevatron in continuous operation, but application to the LHC may require higher beam currents and different pulsing patterns. We studied two sources of asymmetry:

1. bends for injection/extraction

2. azimuthal asymmetries in overlap region
Azimuthal asymmetries in overlap region from measured profiles

**Fermilab electron-lens test stand**

- Gun solenoid
- Electron gun
- Main solenoid
- Beam pipe
- Collector solenoid
- Collector
- Stands
- Platform

**Pinhole for current-density measurements**

**Calculated electric field [kV/m] for 1-A current, inner radius 4σp**

**Example of measured profile**

- X-axis: x/σp
- Y-axis: y/σp
- H. corrector setting [A]
- V. corrector setting [A]
Kick maps from injection and extraction bends: simplified approach

3D calculation of electric fields generated by a static, hollow charge distribution inside cylindrical beam pipes using Warp particle-in-cell code

Electrostatic potential on the plane of the bend for 1 A, 5-keV electron beam (red = -1.2 kV, blue = 0 V)

Symplectic kick maps are calculated by integrating electric fields over straight proton trajectories

\[ k_{x,y} \equiv \int_{z_1}^{z_2} E_{x,y}(x, y, z) \, dz \]

Kick maps from injection and extraction bends

Integrated fields ('kicks') [kV] vs. transverse proton position

For 7-TeV protons, 10 kV \(\Rightarrow\) 1.4 nrad
Core and halo beam dynamics including imperfections

Evaluation of core lifetimes, emittance growth rates, and frequency maps with Lifetrac tracking code [A. Valishev]

- LHC lattice V6.503 at 7 TeV, no multipole errors, collisions on
- 6D halo, 4-6σ transverse, Gaussian longitudinal
- Hollow e-lens 1.2 A at 4σ at IR4/RB46, continuous operation

Frequency-map analysis

- Negligible effects on core lifetimes, emittances, and luminosity
- Smooth halo scraping (4% of halo population / minute)
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Starting point for technical design
Candidate locations for electron lenses in the LHC

Upstream or downstream of Point 4:
- Available longitudinal space
- Separation of beam axes: 420 mm
- Cryogenic infrastructure
- Lattice functions
Candidate location RB-46
TEL2 dimensions for reference

Height (including current and cryo leads): 1.47 m

Weight: about 2 t
Mechanical integration studies for TEL2

- Rotation is necessary to avoid interference
- New design of cryostat for LHC is preferable
Hollow electron gun prototype for the LHC

- 25 mm outer diameter, 13.5 mm inner diameter
- Built and characterized at Fermilab electron-lens test stand
Performance of hollow electron gun prototype

Yields 5 A at 10 kV

- Build test stand at CERN to develop electron guns and study electron beam dynamics.
- Synergies with ELENA electron cooler?
Electrical systems

- Gun and collector solenoid power supplies: 340 A @ 0.4 T
- Main solenoid power supply: 1780 A @ 6.5 T
- High voltage supplies for cathode, profiler, anode bias, collector: 10 kV
- Stacked-transformer modulator, anode pulsing: 10 kV, 35 kHz, 200 ns rise time

No major challenges
Vacuum

- $10^{-9}$ mbar typical in TEL2 with 3 ion pumps + Ti sublim.
- Baking of inner surfaces
- LHC requires vacuum isolation modules on each side (0.8 m each): gate valves, NEG cartridges, pumps, gauges
- Surface certification
- E-cloud stability (enhanced with solenoids on)
- See also A. Rossi’s talk at e-lens review: [indico.cern.ch/event/213752](http://indico.cern.ch/event/213752)

Design needs to be reviewed according to LHC specifications
Cryogenics

- Cryogenics dominates installation time: at least 3 months required for warm-up, connections, cool-down
- Electron lenses may be treated as stand-alone magnets at 4.5 K
- May take advantage of dedicated rf refrigerator for HL-LHC at IR4
- TEL2 static heat loads: 12 W for He at 4 K and 25 W for liquid N$_2$ shield
- Tevatron magnet string liquid He flux was 90 l/s
- N$_2$ not available in LHC; use gaseous He at 20 bar?
- Integration of quench protection system
- See A. Rossi’s talk at e-lens review: indico.cern.ch/event/213752

Likely main integration effort
Diagnostics and instrumentation

- corrector magnets for position and angle in main solenoid
- accurate BPMs for both slow electron signals and fast proton signals
- pickup and ion-clearing electrodes
- sensitive (gated) loss monitors (scintillators, diamonds, ...) at nearest aperture
  - verify $e^-/p$ alignment
  - measure lifetimes, loss fluctuations, halo diffusivities vs. e-lens settings
- e-beam profiles with fluorescent screens (low current) and pinhole (high current), following BNL design
- direct noninvasive halo population measurement (synch. light, fluorescence, ...)?

Some state-of-the-art devices, some challenges
Would certainly benefit from test stand at CERN
Impedance

- Very different bunch structure in Tevatron and LHC
- Tight broad-band longitudinal impedance budget (90 mOhm)
- Preliminary studies suggest that
  - modifications of Tevatron vacuum chamber and electrodes may be required for longitudinal fields, such as rf shields to suppress trapped modes
  - transverse impedance is acceptable

More studies necessary, but no major obstacles so far
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Resources and schedule

- Construction cost of 2 devices for the LHC (1 per beam) is about 5 M$ in materials and 6 M$ in labor
- Construction in 2015-2017 and installation in 2018 is technically feasible
- Reuse of some Tevatron equipment is possible (superconducting coil, resistive solenoids, electron guns, ...)
- Contributions to design, construction, commissioning, numerical simulations, beam studies, project management to be specified in CERN / US LARP agreement
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Alternative halo removal techniques

- **Tune modulation** using warm quadrupoles
  - used at HERA to counteract power-supply ripple
- Excitation with **transverse dampers** (W. Hofle)
- Both methods **work in tune space**: halo not necessarily separated
- Beam-beam **wire compensator**
- **Emittance preservation** needs to be demonstrated
- **Simulations** of effects on halo and core were started
  - Previtali et al., FERMILAB-TM-2560-APC (2013)
Conclusions

- A concept for collimation and scraping of high-power hadron beams with hollow electron lenses was demonstrated at the Fermilab Tevatron collider.
- It may be the best option in cases where material damage, localized instantaneous energy deposition, or impedance limit the use of conventional collimators.
- A conceptual design of hollow electron beam scraper is being proposed for the LHC upgrades.
- Expected performance is based upon experimental data and numerical simulations.
- Further experimental tests may be possible at RHIC in 2015.
- No major obstacles so far for integration.
- Next steps:
  - initiate studies for technical design
  - build electron-lens experience at CERN
    - hardware: test stand operation and diagnostics, engineering, ...
    - modeling: electron beam dynamics, particle tracking, ...
  - compare with alternative schemes

Thank you for your attention!