Electron lenses for the Large Hadron Collider

Giulio Stancari
Fermilab
Contributors

R. Bruce, S. Redaelli, A. Rossi, B. Salvachua Ferrando (CERN)
A. Valishev (Fermilab)

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Outline

- Introduction
  - What’s an electron lens? What can it be used for?
- Hollow electron beam collimation
  - Concept and experimental demonstration at the Tevatron
  - Proton halo in the LHC
  - A design of hollow electron beam scraper for the LHC
    - parameters, simulations, hardware, integration
- Conclusions
What’s an electron lens?

- Pulsed, magnetically confined, low-energy electron beam
- Circulating beam affected by electromagnetic fields generated by electrons
- Stability provided by strong axial magnetic fields

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

3-m overlap region

superconducting solenoid
1–6 T

6 m total length

conventional solenoids
0.1–0.4 T

Electron lens (TEL-2) in the Tevatron tunnel

- Electron gun
- Superconducting solenoid
- Collector
First main feature: 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
Second main feature: pulsed electron beam operation

Beam synchronization in the Tevatron

Pulsed electron beam could be synchronized with any group of bunches, with a different intensity for each bunch.
Applications of electron lenses

In the Fermilab Tevatron collider

› long-range beam-beam compensation (tune shift of individual bunches)
› abort-gap cleaning (for years of regular operations)
› studies of head-on beam-beam compensation
  • Stancari and Valishev, FERMILAB-CONF-13-046-APC
› demonstration of halo scraping with hollow electron beams

Presently, being commissioned in RHIC at BNL
› head-on beam-beam compensation

Current areas of research

› generation of nonlinear integrable lattices
  in the Fermilab Integrable Optics Test Accelerator
› hollow electron beam scraping of protons in LHC
› long-range beam-beam compensation
  as charged, current-carrying “wires” for LHC
› to generate tune spread for Landau damping
  of instabilities before collisions in LHC
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Concept of hollow electron beam collimator or scraper

- **Beam core** is unaffected (field-free region)
- **Halo** experiences nonlinear, tunable, possibly pulsed transverse kicks:

\[ \theta_r = \frac{2 I_r L (1 \pm \beta_e \beta_p)}{r \beta_e \beta_p c^2 (B \rho)_p} \left( \frac{1}{4\pi \epsilon_0} \right) \]

No metal close to the high-power beam: no material damage or impedance

Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08
Hollow beam collimation with Tevatron electron lenses

protons

Hollow Electron Beam

ANTIPROTON CORE

HORIZONTAL POSITION [mm]

Vacuum Pump

Superconducting solenoid

4336

Gun
gun solenoid

2690

Collector

Collector solenoid

Tunable transverse halo kicks ~0.1 \( \mu \text{rad} \)

electrons

antiprotons

collector

0.6-in hollow electron gun
1.2 A at 5 kV
Hollow electron beam collimation studies in the Tevatron

- Tevatron studies (Oct. ‘10 - Sep. ’11) provided experimental foundation
- Main results:
  - compatible with collider operations
  - beam alignment is reliable and reproducible
  - halo removal is controllable, smooth, and detectable
  - negligible particle removal or emittance growth in the core
  - loss spikes due to beam jitter and tune adjustments are suppressed
  - effect of electron beam on halo fluxes and diffusivities vs. amplitude can be directly measured with collimator scans

Stancari et al., IPAC11 (2011)
Collimation and beam halo are critical for LHC

- LHC and HL-LHC represent **huge leaps in stored beam energy**

<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>LHC 2012</th>
<th>LHC nominal</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stored energy per beam</td>
<td>2 MJ</td>
<td>140 MJ</td>
<td><strong>362 MJ</strong></td>
<td><strong>692 MJ</strong></td>
</tr>
</tbody>
</table>

- **No scrapers exist** in LHC for full beam at top energy
- The collimation system has performed very well so far (6σ half gaps, 140 MJ @ 4 TeV): efficiency, robustness
- About 40 **fills lost** in 2012 due to **instabilities** (interplay of *collimator impedance* and beam-beam effects?)
- **Minimum design HL-LHC lifetimes** (e.g., slow losses during squeeze/adjust) are close to **plastic deformation** of primary and secondary collimators: 
  \[
  \frac{692 \text{ MJ}}{0.2 \text{ h}} = 1 \text{ MW}
  \]
- Significant program of collimation system upgrades under way
Collimation and beam halo are critical for LHC

- **Halo populations** (e.g., 4\(\sigma\) to 6\(\sigma\)) in LHC are poorly known. Collimator scans and van-der-Meer luminosity scans indicate 0.1%-2% of total energy, which translates to 0.7 MJ to 14 MJ at 7 TeV.

- **Quench limits, magnet damage**, or even **collimator deformation** will be reached with fast crab-cavity failures (~2\(\sigma\) orbit shift) or other fast losses
  
  see also R. Schmidt, IPAC14; B. Yee-Rendon, IPAC14

- Hence the **need to measure and monitor the halo, and to remove it at controllable rates**. Beam halo monitoring and control are one of the major risk factors for HL-LHC and for safe operation with crab cavities

- **Hollow electron lenses** are the most established and flexible tool for controlling the halo of high-power beams
Halo population measurements in LHC at 4 TeV with collimator scans

1 bunch per beam

Gaussian core from wire scans and sync light

Intensity loss from current transformer

Integrated loss rate from calibrated beam loss monitors

Halo estimates:
- above Gaussian core
- beyond 4σ
A plan for electron lenses and halo control in LHC

- Developed with **LHC collimation team, US LHC Accelerator Research Program (LARP)** and **HL-LHC Project**
- Final **collimation needs and decisions** can only be defined after gaining operational experience at 7 TeV (end of 2015)
  - uncertainties: cleaning efficiency, lifetimes, quench limits, impedances
- Meanwhile, proceed with **design** of 2 electron lenses, 1 per beam:
  - conceptual design completed (arXiv:1405.2033)
  - technical design in 2014-2015
- **Construction** 2015-2017, if needed; **installation** during 2018 long shutdown (2022 if limited by resources)
- Investigate proposed **alternative schemes** (R. Bruce). Cheaper, available sooner?
  - transverse damper excitation (W. Hofle)
  - both work in tune space, halo not necessarily separated
- Exchange electron lens **hardware/software expertise** with CERN; synergies with ELENA electron cooler (G. Tranquille) and e-wire compensators (H. Schmickler)
- Develop noninvasive, direct **halo diagnostics**: synchrotron light (A. Fisher); backscattered electrons in e-lens (à la RHIC) (P. Thieberger)?
- If possible, extend Tevatron experience with **beam tests** at RHIC
The conceptual design report

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

G. Stancari,† V. Previtali, and A. Valishev
Fermi National Accelerator Laboratory, PO Box 500, Batavia, Illinois 60510, USA

R. Bruce, S. Redaelli, A. Rossi, and B. Salvachua Ferrando
CERN, CH-1211 Geneva 23, Switzerland
(Dated: May 9, 2014)

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.

Available as FERMILAB-TM-2572-APC and as arXiv:1405.2033, soon also as CERN Note
Electron beam size is matched to proton beam size by solenoids

Electron beam size is matched to proton beam size by solenoids...
Proton rms size
Inner radius
Outer radius
Accelerating voltage
Velocity
Peak current
Linear current density

Example of numerical parameters for the LHC

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 $	heta_{rms} = 1.3 \mu$rad
Pulsed operation of the electron lens in the LHC

Current state of the art of electron-lens modulator rise time (10%-90%) is 200 ns at 5 kV

Pfeffer and Saewert, JINST 6, P11003 (2011)

This enables

- **turn-by-turn current modulation** 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 (25 ns or 50 ns) is not necessary for collimation
### Summary of specifications in conceptual design report

<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), $\varepsilon_p$ [(\mu)m]</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, $P$ [(\mu)perv]</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>

All technical parameters are currently achievable
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

HG1b 1-inch hollow electron gun
Fermilab electron-lens test stand
22 May 2013
Filament heater: 9.75 A, 11.02 V
Solenoids: 0.1–0.4–0.1 T
Pulse width 8 µs, rep. rate 4 Hz
Average perveance: 5.3 µperv

Yields 5 A at 10 kV
Numerical simulations: goals

‣ 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.

‣ Which modes of operation would be useful?
  ▶ 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

‣ 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?

Previtali et al., FERMILAB-TM-2560-APC (2013)
Numerical simulations: tools

Particle-in-cell codes for electron beam dynamics with space charge
- charge, fields, proton kicks

Lifetrac and SixTrack for numerical tracking
- LHC (V6.503) and HL-LHC lattices with errors, with or without collisions
- electron lens at RB-46 (near IP4), 3.6 A max. current
- single aperture restriction at $6\sigma$
- Uniform halo population 4-6$\sigma$
  - no replenishing mechanisms, but halo diffusion was measured in both Tevatron and LHC
    Stancari et al., FERMILAB-CONF-13-054-APC, arXiv:1312.5007

- Ideal electron lens and imperfections
  - profile asymmetries
  - simplified model of injection/extraction bends

Previtali et al., FERMILAB-TM-2560-APC (2013)
Dynamics of the magnetically confined electron beam

3D simulation of electron beam propagation in electron lens with Warp particle-in-cell code

- 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
  - tests on multi-core laptops
  - parallel version on Fermilab Accelerator Simulations Wilson Cluster

First use of particle-in-cell codes for electron-lens design

Moens, CERN-THESIS-2013-126
Stancari, NA-PAC13, IPAC14
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/extration


2. azimuthal asymmetries in overlap region

Morozov et al., IPAC12
Azimuthal asymmetries in overlap region from measured profiles

Fermilab electron-lens test stand

Pinhole for current-density measurements

Calculated electric field [kV/m] for 1-A current, inner radius $4\sigma_p$

Example of measured profile

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

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

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*
Design and simulation of bends and kick maps with space charge

Figure 1: Geometric parameters of the initial electron lens bend design.

Figure 2: Parameters of the solenoids required for the initial electron lens bend design.

Figure 3: Schematic of an initial bend design for the IOTA electron lens.

Example of electron-lens bend for the Fermilab IOTA ring (D. Noll)
Lifetrac calculation of frequency maps vs. amplitude

Frequency map shows new resonances and tune jitter for particles in the halo.
Lifetrac calculations of halo removal rates vs. electron current

A wide range of removal rates is possible
Continuous mode useful for smooth cleaning
Stochastic mode can be used for faster scraping
Lifetrac calculation of the effect of injection/extraction bends

- In continuous mode, no impact on emittances or luminosity

- In stochastic mode, with U-layout (gun and collector on same side), dipole kick generates emittance growth (e.g., 10% modulation, 0.3 um/h)

- In stochastic mode, with S-layout (gun and collector on opposite sides of ring), small contribution to luminosity lifetime (90 h, or 1%/h)

If pulsed operation is required, then S-layout is necessary
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
Round beams, $\beta \sim 200$ m, low dispersion
Integration studies

- Preliminary studies on cryogenics, electronics, vacuum, diagnostics, impedance
- Cryogenics will be main effort
- No major obstacles so far
Mechanical design of an LHC electron lens

Perini, Riekki, CERN EN/MME
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\textsubscript{2} shield
• Tevatron magnet string liquid He flux was 90 l/s
• N\textsubscript{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
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

Design needs to be reviewed according to LHC specifications
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
- Electron beam diagnostics, following BNL designs
  - Overlap with protons: backscattered electrons; also as sensitive halo monitor?
  - Profiles with screens (low current), pinhole (high current), gas fluorescence?
The rate of electrons backscattered towards the gun by Coulomb collisions is a **sensitive probe of the overlap** between electron and circulating beam.

High dynamic range, promising for **continuous nondestructive halo monitoring**

Thieberger et al., IBIC 2014
Backscattered electron detector tested with ions in RHIC

Counting rate vs. electron beam position in overlap region

Thieberger et al., IBIC 2014
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
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
- Preliminary modular proposal for US-HL-LHC scope
  - electron guns
  - superconducting solenoids
  - backscattered electron detector
Summary and outlook

- **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.
  - Expected performance based upon experimental data and numerical simulations.
  - Technical parameters are achievable.
- **Next steps** and topics for discussion:
  - Technical design.
  - Electron-lens test stand at CERN.
  - Beam halo in LHC: machine studies and monitoring techniques.
  - Electron lens and diagnostic studies at RHIC.
  - Alternative schemes.
  - Collaborations, personnel exchanges.

(Thank you for your attention!)
Backup slides
Relative scraping of 1 pbar bunch train vs. electron hole radius

Particle removal is detectable and smooth

No effect on core

HEBC studies
Tevatron Store 8546
3 Mar 2011
Long-range compensation is essential for HL-LHC flat optics schemes

- A possible HL-LHC luminosity scheme:
  - flat optics at collisions: (10, 50) cm $\beta^*$ ⇒ no IP1/5 compensation
  - no crab cavities required (crab crossing/kissing improve performance)
  - a long-range beam-beam compensation scheme is needed to achieve luminosity

- Wire compensator devices at 10σ to be tested after current shutdown: technically challenging (378 A required) and a risk for collimation and machine protection

- Electron lenses for long-range beam-beam compensation may be a safer, less demanding alternative, with pulsing option
  - $(21 \text{ A}) \times (3 \text{ m})$ required for HL-LHC, any transverse shape

Valishev and Stancari, arXiv:1312.1660
Long-range beam-beam compensation with electron lenses

Preliminary work proceeding in parallel:

- **beam physics**: expected performance, sensitivity to location
  - 2 options under study:
    - between D1 and D2 dipoles (challenging layout and integration)
    - beyond D2 dipole

- **energy deposition** (superconducting solenoid) and **radiation to electronics** (anode high-voltage modulator) in both locations
- **integration**