Plans for deployment of hollow electron lenses at the Large Hadron Collider for enhanced beam collimation

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• Introduction: Need for halo control in the LHC

• Halo control using hollow electron lens

• Design of a hollow electron lens for the LHC

• Present status and timeline

• Summary
LHC collimation challenge

- LHC: 27 km ring, designed to collide 7 TeV proton beams
- Huge stored energy per beam: 362 MJ for nominal configuration, 675 MJ for planned upgrade HL-LHC
- Several MJ found above 3σ (7 MJ for Gaussian, in reality more)
- Beams could be highly destructive if not controlled well => collimation plays an essential role to prevent dangerous losses

675 MJ = kinetic energy of USS Harry S. Truman cruising at 7 knots
LHC collimation worked very well in Run I at 4 TeV (2010-2013)

Routinely stored ~140 MJ beams over hours
Run 1 lifetime drops

- Operation sometimes perturbed by sudden losses => beam dumps
Halo removal

- Halo scraped on collimators when orbit moves
- Expect higher losses in the future (higher stored energy)
- HL-LHC: phase failure of crab cavity => beam gets a ~1-σ kick which causes scraping
- Possible mitigation: limit peak loss by actively depleting halo in controlled way
Methods for halo control

- **Hollow electron lens**
  - Subject of this talk
  - Requires new hardware

- **Alternatives under parallel study:**
  - Put halo on resonance using a tune ripple or transverse damper
  - Relies on very good knowledge of tune and detuning with amplitude – not evident!
  - Does not require new hardware
**Principle of hollow e-lens**

- Main beam travelling inside a hollow electron beam (cylindrical shell) over a short distance
- Halo particles kicked to higher amplitudes by electromagnetic field of electron beam (slow process)
  - Eventually hit collimators
- Electron beam hollow => core not affected (in field-free region)
Experimental studies at Tevatron

- Operating the e-lens at inner radius 4-4.5σ has no effect on luminosity while the intensity goes down => halo is scraped

- Loss spikes due to beam jitter and tune adjustments suppressed

See also
Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08
Tevatron electron lens layout

- Pulsed, magnetically confined, low-energy electron beam
- Tunable transverse halo kicks ~0.1 μrad

Electron lens (TEL-2) in the Tevatron tunnel

- Electron gun
- Superconducting solenoid
- Collector
• Should be integrated in existing collimation system
**Proposed location in the LHC**

- Best place found: IP4
  - Space available and $\beta_x \approx \beta_y$
Required parameters

- Kick given by electron lens

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

- Keeping the Tevatron hardware, kicks given to protons would be factor \(\sim 7\) less from magnetic rigidity
  - Increase electron current to compensate (or length – less attractive)

- Halo removal rate depends not only on kick but also on lattice non-linearities
  - Simulations (LifeTrack and SixTrack) demonstrate desired halo depletion with 5A current and stochastic excitation mode

Hollow electron gun (1)

- New gun needed for higher current and adjusted electron beam size
- First prototype built and tested at Fermilab.
- Tungsten dispenser cathode with BaO:CaO:Al2O3 impregnant, 1400 K

Prototype yields 5 A at 10 kV
**Hollow electron gun (2)**

- **Powering**
  - 10 kV modulator used to power the gun
  - If we want to act on a subset of bunches: Need fast rise time of 200 ns

- **Next gun to be built at CERN**
  - Test stand planned to be set up at CERN
Superconducting solenoid

- 3 m long, 250 A current, 5T field, cooled with He to 4.2 K
- Includes 6 correction coils for alignment of electron beam and pickup coil for quench protection
Technical design

- S-shaped to compensate for the asymmetric electron beam distributions seen by the main beam
- Gun and collector stick out in *vertical plane* to fit in tunnel
Instrumentation

• Detailed design of instrumentation not yet started
• Need to monitor position of electron beam and proton beam
  – Requirement: About 20 µm accuracy (0.1 σ of proton beam), good accuracy for fast (proton) and slow (electron) signals
• Need to monitor electron current at cathode and collector
• Need to monitor electron beam profile
• In addition: need halo monitor for the LHC proton beam to study halo population in various scenarios
## Summary of main parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value or range</th>
</tr>
</thead>
<tbody>
<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 transverse scraping range [$\sigma$]</td>
<td>4–8</td>
</tr>
<tr>
<td>Inner/Outer cryostat diameter [mm]</td>
<td>132 / $\approx$ 500</td>
</tr>
<tr>
<td>Inner vacuum chamber diameter [mm]</td>
<td>100 (80)</td>
</tr>
<tr>
<td><strong>Magnetic fields and magnet parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Gun and collector solenoid, $B_g$ [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>Compression factor, $\sqrt{B_m/B_g}$</td>
<td>2.2–5.5</td>
</tr>
<tr>
<td>Maximum current in main solenoid [A]</td>
<td>250–300</td>
</tr>
<tr>
<td><strong>Electron gun</strong></td>
<td></td>
</tr>
<tr>
<td>Inner/outer cathode radius [mm]</td>
<td>6.75/12.7</td>
</tr>
<tr>
<td>Peak yield at 10 kV, $I$ [A]</td>
<td>5</td>
</tr>
<tr>
<td><strong>Cryogenic requirements</strong></td>
<td></td>
</tr>
<tr>
<td>Static heat load [W]</td>
<td>$\leq$5</td>
</tr>
<tr>
<td>Dynamic heat load from electric powering [W]</td>
<td>$\leq$0.5</td>
</tr>
<tr>
<td>Dynamic heat load from beam effects</td>
<td>negligible</td>
</tr>
<tr>
<td><strong>High-voltage modulator</strong></td>
<td></td>
</tr>
<tr>
<td>Cathode-anode voltage [kV]</td>
<td>10</td>
</tr>
<tr>
<td>Rise time (10%–90%) [ns]</td>
<td>200</td>
</tr>
<tr>
<td>Repetition rate [kHz]</td>
<td>35</td>
</tr>
</tbody>
</table>
Conceptual design

- Collaboration between US LHC Accelerator Research Program (LARP), LHC collimation team, and HL-LHC Project

- Conceptual design report finished in 2014
Strategy

- Collimation needs can only be defined in detail after gaining operational experience at 6.5 TeV (end of 2015)
  - Uncertainties: cleaning efficiency, lifetimes, quench limits, impedance
  - Final decision on installation to be taken based on Run II experience
- Meanwhile, proceed with the completion of a design for the construction of 2 devices.
  - Estimated time needed: about 3 years
  - If technical design is finalized in 2015, could aim at installation during long shutdown in 2018
• **Hollow electron lenses** could be used at the LHC to **deplete the beam halo** in a controlled way, avoiding sharp loss spikes
  – Successfully tested at Tevatron

• **Conceptual design finished** for e-lens with LHC requirements
  – Design of key components profiting from FNAL (gun) and CERN (solenoid) experience.

• **Technical design and integration studies ongoing**
  – Could aim at installing 1 device per beam in 2018

• **Final decision to be based on LHC beam experience at 6.5 TeV**
  – Will actively monitor the LHC tails and beam lifetimes in 2015 to establish adequate action plan
Some references

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- LHC Collimation Review 2013, http://indico.cern.ch/event/251588,
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- H. Rafique et al., TUPTY069, IPAC15