Hollow Electron Lens Update

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Outline

• Introduction: Need for halo scraping in the LHC
• Halo scraping using hollow electron lens
• Design of a hollow electron lens for the LHC
• Present status and timeline
• Summary
LHC collimation challenge

- Large Hadron Collider: 27 km ring, designed to collide 7 TeV proton beams

- Huge stored beam energy per beam: 362 MJ for nominal configuration, 675 MJ for planned upgrade HL-LHC

- Beams could be highly destructive if not controlled well => collimation plays an essential role to prevent dangerous losses

\[ 675 \text{ MJ} = \text{kinetic energy of USS Harry S. Truman cruising at 7 knots} \]
LHC collimation worked very well in Run I at 4 TeV (2010-2013)
Routinely stored ~140 MJ beams over hours without accidental quenches
Run 1 lifetime drops

- However, operation sometimes perturbed by sudden losses correlated to fast orbit movements => beam dumps

Orbit at primary collimator
Courtesy of J. Wenninger

S. Redaelli
Halo removal

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

- **Hollow electron lens**
  - Solid experimental proof of principle at Tevatron
  - 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! may affect beam core
  - Does not require new hardware and shall be tested

See also
Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08
Principle of hollow e-lens

- Main beam travelling inside a hollow electron beam over a short distance (~3m), can act on the halo particles at transverse amplitudes below primary collimators.
- Halo particles kicked to higher amplitudes by electromagnetic field of electron beam (slow process).
- Electron beam hollow => core not affected (in field-free region) + no effects on impedance.
Effect on halo distribution

- Controlled increase of diffusion speed of halo particles
- Still need existing collimators to absorb the extracted halo particles

\[ R \propto -D \cdot [\partial_x f]_{x=x_c} \]
Tevatron electron lens layout

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

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

Superconducting solenoid
1–6 T

3-m overlap region

conventional solenoids
0.1–0.4 T

Electron lens (TEL-2) in the Tevatron tunnel
• Should be integrated in existing collimation system
Proposed location in the LHC

- Best place IR4:
  - Large intra beam distance
  - $\beta_x \approx \beta_y$
  - cryogenics
Required parameters

- Kick given by electron lens

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

- Keeping the Tevatron hardware, kicks given to protons would be factor ~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

First prototype of hollow cathode

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

- **Next gun** with slightly reviewed design to be built at CERN
  - **Test stand** planned to be set up at CERN (SM18) but initial tests at Fermilab

- **Powering**
  - 10 kV modulator used to power the gun
  - If we want to act on a subset of bunches: Need very fast rise time
  - 200 ns allows to switch on and off between bunch trains

- **Cathode**: one student to increase current
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 quench protection
- Possible modifications if profile monitor inserted (gas jet)
Instrumentation

• Need to monitor **position of electron beam and proton beam**
  – Requirement: About 20 µm accuracy (0.1 $\sigma$ of proton beam),
    time resolution of 1 ns (protons) and 100 ns (electrons).

• Need to monitor **electron current** at cathode and collector

• Need to monitor **electron beam profile**

• Sensitive loss monitors can be placed downstream

• In addition: need **halo monitor for the LHC proton beam** to study
  population in various scenarios, independently of e-lens

• Detailed design of instrumentation not yet started
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 LHC tunnel

**Heat loads (at 4.5 K for a 1-m long cryostat + anti cryostat)**

- Current leads (~250 A) 1 W
- Supports 0.5 W
- Thermal radiation 0.5 W / m (with superinsulation)
<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), $\varepsilon_r$ [\mu m]</td>
<td>3.75</td>
</tr>
<tr>
<td>Amplitude function at electron lens, $\beta_{xy}$ [m]</td>
<td>200</td>
</tr>
<tr>
<td>Dispersion at electron lens, $D_{xy}$ [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, rmi [$\sigma_p$]</td>
<td>4–8</td>
</tr>
<tr>
<td>Outer cryostat diameter</td>
<td>250</td>
</tr>
<tr>
<td>Inner cryostat diameter [mm]</td>
<td>154</td>
</tr>
<tr>
<td>Max. vacuum chamber flange OD [mm]</td>
<td>150</td>
</tr>
<tr>
<td>Inner vacuum chamber diameter [mm]</td>
<td>(?) (80)</td>
</tr>
<tr>
<td><strong>Temperatures</strong></td>
<td></td>
</tr>
<tr>
<td>Cold mass operating temperature [K]</td>
<td>4.2</td>
</tr>
</tbody>
</table>

**Magnetic fields and magnet parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value or range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun solenoid (resistive), $B_r$ [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>Main solenoid current [A]</td>
<td>200–250</td>
</tr>
<tr>
<td>Positioning solenoid current [A]</td>
<td>$25 \times 12$</td>
</tr>
<tr>
<td>Collector solenoid (resistive), $B_c$ [T]</td>
<td>0.2–0.4</td>
</tr>
<tr>
<td>Collector solenoid current [A]</td>
<td>(?) $50 \times 3 \times 2$</td>
</tr>
<tr>
<td>Compression factor, $k \equiv \sqrt{B_m/B_r}$</td>
<td>2.2–5.5</td>
</tr>
</tbody>
</table>

**Electron gun**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value or range</th>
</tr>
</thead>
<tbody>
<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, $I_p$ [A]</td>
<td>5</td>
</tr>
</tbody>
</table>

**High-voltage modulator**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value or range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode–anode voltage, $V_{oa}$ [kV]</td>
<td>10</td>
</tr>
<tr>
<td>Rise time (10%–90%), $T_{mod}$ [ns]</td>
<td>200</td>
</tr>
<tr>
<td>Repetition rate, $f_{mod}$ [kHz]</td>
<td>35</td>
</tr>
</tbody>
</table>
• 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 design of 2 devices (1 per beam)
  – Estimated time needed: about 3 years
  – If technical design is finalized in 2015, could aim at installation during long shutdown in 2018
Conclusions

- **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
  - New gun, new solenoid
- **Technical design and integration studies ongoing**
  - Could aim at installing 1 device per beam in 2018
- **Final decision on installation to be taken based on LHC beam experience at 6.5 TeV**
• Very high stored energy in LHC (nominal: 362 MJ, HL: 675 MJ). Maximum specified loss rate from nominal beam was 500 kW, while design quench limit was 8.5 W/m.

• Need a very efficient collimation system to intercept unavoidable beam losses that otherwise might quench superconducting magnets!

Challenge of nominal LHC
LHC Run 2 collimation system: > 100 movable devices

Betatron cleaning: IR7, momentum cleaning: IR3
• Highest losses in cold magnets: factor $\sim 10^4$ lower than losses on the primary collimator
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)