LHC Electron Lenses: What Are They Good For?

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What Is Electron Lens?

- It is very stable and very well controlled (~frozen) electron cloud

Can control current, diameter, length, position, timing, velocity, shape, angle, direction

$\sim 10^{12} \text{e}^-$
What is it good for?

- **IT CAN KILL**
  - blow up emittances in controlled fashion
  - drive particles out – randomly or via resonance drive
  - remove unwanted particles, bunches, e.g.:
    - only in between bunches
    - just 1 out of 3000
    - only satellites
    - only those with $a > 5 \times \text{Sigma}$, etc., etc.
What is it good for?

- **IT CAN HEAL**
  - reduce emittance blowup caused by other processes:
    - space-charge forces
    - beam-beam forces, etc
  - reduce beam loss rates by moving particles away from dangerous resonances
  - selective resonant extraction
  - introduce incoherent tune spread to stabilize beams
How strong is it?

- **Figure of merit - tuneshift dQ:**
  - Similar to space-charge and beam-beam

\[
dQ_{x,y} = \pm \frac{\beta_{x,y}}{2\pi} \cdot \frac{1 \pm \beta_e}{\beta_e} \cdot \frac{J_e \cdot L_e \cdot r_p}{e \cdot c \cdot a_e^2 \cdot \gamma_p}
\]

For many applications, electron beam size needs to be \( n \times \sigma \) protons

- e.g. \( n=1 \) for head on BBC

This product is \( \text{const}(E) \)

\( \rightarrow \) RHIC

\( \rightarrow \) Tevatron

\( \rightarrow \) LHC
Tuneshift $dQ_{\text{hor}} = +0.009$ by TEL

$J_e = 2A, a = 1.7\text{mm} \ L = 2m \ E = 980\text{GeV} \ \beta_e = 0.2$

- Three p-bunches in the Tevatron, the TEL acts on one of them
Can that “beast” be safe for operation?

- Yes!– look at the Tevatron:

  - **TEL-1 is used for abort gap cleaning**
    - 5 years in 24/7 operation (since 2002)
    - >1000 HEP stores
    - No store lost because of TEL – best record
    - Only 8-hr accesses (over 5 yrs) to the tunnel required to replace failed TEL components

  - **TEL-2 used for Beam-Beam Compensation**
    - Installed in June’06, commissioned for operation in August

  - used for studies in ~15 HEP stores for few (upto 8) hours, almost every store in Sep
    - No quenches/problems/complaints
Is Technology Available?

TEL-1 (2001)
- 3.65m (143.6”)
- Superconducting solenoid
- e-gun
- Collector solenoid
- Collector

TEL-2 (2006)
- 600ns
- 50kHz
- 1-2A

+ Marx HV Modulator, SEFT gun, 2 Cryo bypasses, 4-plate BPMs & Cables
Possible e-Lens Configurations
TEL-2 Parameters for Vert. LR-BBC

- Generates $dQ \sim 0.004$
  - Compensates b-by-b vert tune spread
  - $J_e = 1-2\,A$
  - pulsed, $dt = 600\,\text{ns}$, rep.rate = 50 kHz $\times$ Nb
  - $\beta_y = 136$, $\beta_x = 50\,\text{m}$
  - “flattop+smooth edge” distribution
  - $a_e = 2.5\,\text{mm}$ at 980 GeV
  - $L_e = 2\,\text{m}$, $U_e = 5\,\text{kV}$
  - $B_{\text{gun}} = 3\,\text{kG}$, $B_{\text{main}} = 31\,\text{kG}$
LHC Electron Lenses Can:

#1: LEL as Head-On Compensator at design intensities and with x(2…4?)Np/bunch

#2: LEL as Beam Stabilizer (Tune Spreader) to help octupoles @ design Np=1.15e11

#3: LEL as soft hollow collimator

#4: LEL as soft “beam conditioner”
LHC footprint (design)
LHC footprint (x2 Np/bunch)
Head-on beam-beam compensation

- If beam sizes and shapes are matched \((e=p)\)

- for LHC \(N_p=1.1\times10^{11}, N_{ip}=4\), for 10kV electrons \((\beta=0.2)\) one needs \(N_e=4.4\times10^{11}\) or

\[ J_e=1.2 \text{ A in } L=3 \text{ m long e-beam} \]

\[ N_e = \frac{N_{IP}N_p}{(1 + \beta_e)}. \]

- approx Gaussian e-current distribution with rms = 0.3-0.5 mm

... or donut shape?
50% Head-On Compensation by LEL
LEL Parameters for Job #1:

- To compensate 1.15e9 head-on:
  - will help 1x and 2xNp operation
  - $J_e = 1.2A$
  - DC
  - $\beta_x = \beta_y = 200$ m
  - Gaussian or optimized distribution
  - $a_e = 0.3$ mm rms at 7TeV
  - $L_e = 3$ m, $U_e = 10kV$
  - $B_{gun} = 2kG$, $B_{main} = 65kG$
  - One eLens/beam
Stability of LHC Beams

Design approach:
→ Use octupoles before collisions
→ Hope for head-on tunespread

Issues:
→ Collimators too close to beam → extra impedance
→ Octupoles limit DA

BackUp solution:
→ Feedback (noise?)
#2: LEL as Beam Stabilizer

- Such tune spreader does not limit DA → can replace octupoles before collisions
- Note that p-p beam-beam tune spread by itself does not help stability much in multibunch regime because of both beams are movable and many coherent modes outside incoherent spectrum (Tevatron, Yu.Alexahin) - in contrast, e-beam does not move (= NL lens).
Example: TEL as Tune Spreader

980 GeV protons
extra tune spread $dQ \sim 0.003$
Tune shift $\sim 0.004$
LEL Parameters for Job #2:

To generate $dQ \sim 0.004$:

- will suffice for 2xNp operation
- $J_e = 0.5-1A$
- DC
- $\beta_x = \beta_y = 200\ m$
- Gaussian or bell-shape distribution
- $a_e = 0.3\ mm\ rms\ at\ 7\ TeV$
  - $= 0.9\ mm\ rms\ at\ 0.45\ TeV$
- $L_e = 2\ m, U_e = 10kV$
- $B_{gun} = 2kG, B_{main} = 65kG$
#3: Hollow Electron Beam as Collimator

Diffusion enhanced by Non-linear fields and/or resonant pulsing Structure (e.g. every 13th turn)
"LEL-Combo" Collimation

Phase I Collimation

LEL-Combo Collimation:
LEL drives particles from 4 to 6 sigma,
Collimators 2 sigma
FARTHER
Multi-A Hollow Electron Beams Generated

Tunable profile

A. Bubley, et al. PTE, 49(1), 2006

Ring cathode

A. Shemyakin, et al. NIM A, 1996
LEL Parameters for Job #3:

To clean 4-6 sigma protons:

- Will allow collimators ~50% farther
- $J_e = 0.5-3 \, A$
- DC or pulsed resonantly (10\textsuperscript{th} or 13\textsuperscript{th} turn)
- $\beta_x = \beta_y = 200 \, m$
- Hollow beam distribution
- $r_{\text{min}} = 1.2 \, mm$ at 7 TeV
- $r_{\text{max}} = 1.8 \, mm$ at 7 TeV
- $L_e = 2 \, m$, $U_e = 10 \, kV$
- $B_{\text{gun}} = 2kG$, $B_{\text{main}} = 65kG$
#4: Killing Satellites

- Easier to do at 450GeV
- But more time at 7TeV
- Drive resonantly
LEL Parameters for Job #4:

- **To kill all satellites in ~1 hr:**
  - Will allow collimators ~50% farther
  - $J_e = (n \sim 300 \text{ pulses/turn}) \times 2A$
  - Varied resonantly (10th or 13th turn)
  - $\beta_x = \beta_y = 200 \text{ m}$
  - Flat beam distribution
  - $r_e = 0.6 \text{ mm} \quad \text{at 7TeV}$
  - $L_e = 2 \text{ m}, U_e = 80kV$
  - $B_{\text{gun}} = 4kG, B_{\text{main}} = 32kG$
Gridded e-Gun for Fast 5ns Modulation

Shape of the grid and the cathode

- 0.3mm grid-to-cathode
- Convex cathode for max perveance
# RHIC and Tevatron as Testbeds

<table>
<thead>
<tr>
<th>Possible to Test at</th>
<th>RHIC</th>
<th>TeV</th>
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<tbody>
<tr>
<td>#1 head-on compensation</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>#2 Q-spreader/stabilizer</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>#3 soft hollow collimator</td>
<td>+</td>
<td>tested</td>
</tr>
<tr>
<td>#4 satellite killer</td>
<td>+</td>
<td>tested</td>
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In addition to:

| #5 wire bblr compensation | +    | -   |
| #6 bunch-by-b dQ comp | -    | +   |
Proposed Action Path

- Form an LHC eCompensation Task Force with a charge to perform feasibility study in ~1 year (FNAL, RHIC, KEK, LHC)
- Goal is to explore parameter space and effectiveness of head-on BBC in LHC and RHIC
- Same for jobs #2,3,4 (spreader, collimator, satellite-killer)

In case of positive outcome, next steps may include:

- Design of the TEL for RHIC 2008
- Modification of TEL for RHIC 2009-2010
- Demonstrate head-on compensation 2010-2011
- Install ELs in LHC and commission 2011-2012
First Step: Theory and Simulations

- Will Gaussian or truncated Gaussian e-current density distribution work (improve lifetime and reduce diffusion rates)?
  - Straightforward tracking with a weak-strong code
  - Is partial distribution helpful?
- Is there a better distribution?
  - from first principles, theory, analytical consideration
  - Effects are $\beta_{LEL}/\beta^*/\sigma_z$; or $dP/P$
  - check in numerical tracking
- Importance of e-p interaction in bending sections
  - Which of three configurations is better?
  - Is the choice tune dependent?
- Lifetime deterioration due to e-p misalignment:
  - e-beam straightness tolerances
  - relative e-p displacement, angle
- Effect of low-frequency variations $dJ$, $dX$ on beam lifetime
- Ion cleaning efficiency tolerances
- Cross-interaction with wires in LHC - if there is any
- e-beam effect on coherent stability or strong-strong beam-beam effects
...finally – a hint for LHC:

up-to-date experience tells us that only hadron colliders which employ electron lenses can achieve luminosities above $2.3e32$ cm$^{-2}$ s$^{-1}$