Experimental and numerical studies on the proposed application of hollow electron beam collimation for the LHC at CERN

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Thesis Director:
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Vince Moens

Semester thesis 2012 @ CERN

“A quantitative comparison of the transverse damping and tune resonance crossing loss map techniques at the LHC”

Master thesis 2013 @ CERN & Fermilab
Introduction & Concept

- Hollow Electron Beam Collimation
- HEBC experience at Tevatron
- Focus of this work

Electron Gun & Test Stand

- 1 inch Hollow Electron Gun
- Tevatron Electron Lens Test Stand
- Thermionic Emission

Results

- Optimal operation parameters for LHC
- Yield measurements
- Beam evolution
- Rough Upper Estimate of Emittance Growth
- 3D simulations

Conclusions
Introduction & Concept

- Hollow Electron Beam Collimation
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- Focus of this work
Hollow Electron Beam Collimation

- Hollow electron beam studies for LHC collimation part of US-LARP since 2009:

**Hollow Electron Beam Collimation is the enhancement of diffusion of halo particles through the use of the transverse electric fields of a hollow electron beam.**

- Technique aimed at improving current system (hierarchy remains)
  - Fully compatible with present and future systems

- Installation point is flexible

![Illustrative scheme form Stefano redaelli](image-url)
Hollow Electron Beam Collimation

- Align hollow electron beam coaxial with beam core

Hollow electron beam creates transverse electric field

\[ E(r) \propto \frac{1}{r} \]
Transverse kick on halo particles with $R_i < r < R_o$

Enhances diffusion rate of halo particles -> Deplete tails

Actual cleaning done by standard collimators

- HEBC creates buffer zone between core and collimators
- Control over when tails are cleaned
- HEBC tunes impact parameter slightly

\[ \Theta = \frac{1}{2\pi\varepsilon_0} \frac{I_r L (1 \pm \beta_e \beta_p)}{r \beta_e \beta_p c^2 (B\rho)_p} \]
HEBC Experience at the Tevatron

- Approx. 10 years of stable Tevatron Electron Lens operation for abort gap cleaning
- HEBC Experiments at Tevatron from 2010-2011 for LHC collimation studies

Observations:
- Effects on beam core were negligible
  - Crucial for luminosity production in the collider
- Control of scraping of beam halo possible
- Loss-spike fluctuations due to beam jitter reduced

- Rely on Tevatron experience
- 2 new designs for LHC
  - Implementation studies
  - Conceptual Design Report (November 2013)
Focus of this work

- My task: Characterizes a new 1-inch Hollow Electron Gun (HG1b) for use at LHC (1-1 implementation)
  - Optimal operation parameters
  - Yield studies
  - Beam evolution
  - Transverse fields

- Completed first full 3D simulations of HG1b in Tevatron electron lens test stand

- Input for Conceptual Design Report in November 2013
Electron Gun & Test Stand

- 1 inch Hollow Electron Gun
- Tevatron Electron Lens Test Stand
- Thermionic Emission
1 inch Hollow Electron Gun (HG1b)

- Bigger gun for higher beam currents
- Hollow cathode: Tungsten impregnated with $3\text{BaO}:1\text{CaO}:1\text{Al}_2\text{O}_3$
- $\varnothing_o = 25.4 \text{ mm}, \varnothing_i = 13.5 \text{ mm}$

<table>
<thead>
<tr>
<th>$V_{\text{cathode}}$</th>
<th>0.5-8 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{R_i}{R_o}$</td>
<td>0.53 mm</td>
</tr>
<tr>
<td>$I_{\text{fill}}$</td>
<td>9.25 A</td>
</tr>
</tbody>
</table>
Tevatron Electron Lens Test Stand (TELTS)

- Used for all measurements part of this work
- Data collection:
  - Pinhole collector
  - Toroids & oscilloscope
- Similar to TEL2
  - No bends
  - No superconducting main solenoid

Source: 10.1109/PAC.1999.792290
Thermionic Emission

- **Aim:** Operate in Space Charge Limited Emission Regime
- **Emission type** depends on filament current and cathode potential
- **Space Charge Limited Emission:**
  \[ I_{beam} = PV_a \frac{3}{2} = 1.67 \times 10^{-3} \pi \left( \frac{q}{mc^2} \right) \frac{1}{2} \frac{V_a^3}{d^2} (r_{ext}^2 - r_{int}^2) \]  
  \[ A \]
- **Yield measured in perv:** \[ P = \frac{I}{V_a^2} \]  
  \[ [perv] \]
Results

- Optimal operation parameters for LHC
- Yield measurements
- Beam evolution
- Rough Upper Estimate of Emittance Growth
- 3D simulations

Vince Moens, 11.04.2013
Inner radius $3 \sigma < R_i < 6 \sigma$ ($\sigma = 4.7 \times 10^{-4}$ m)

Magnetic compression ($R_i = 4\sigma$)
- Factor 11.5
- $B = 0.43-5-0.43$ T

Cathode potential of HG1b
- 3-4 kV for similar current as Tevatron experiments

Optimal filament current
- Up to now: 9.25 A
- Can be reduced to $\approx 8.5$ A
HG1b Yield

- **Before transport improvement:**
  - Yield: $4.22(3) \times 10^{-6}$ perv
  - Consistent with previous measurements
  - Slow degradation of gun

- **Yield at collector 70% of gun**
  - Biggest Gun yet!

- **After transport improvement:**
  - Yield: $5.3(1) \times 10^{-6}$ perv
  - Produces 5 A at 10 kV
  - 15% of SAM simulations
  - 65% more yield than HG06
Transverse Profiles

- Current density profiles by moving beam over pinhole
- Profiles injected into 3D simulation
- Profiles sorted by $B_{\text{main}}$ and $V_a$
- Red lines: scaling lines
 Beam Scaling

- Scaling law $\Rightarrow$ angle of rotation must be constant

$$ B \propto \sqrt{V} $$
Rough Emittance Growth Estimates

- Calculation of electric fields using WARP
- Emittance growth given by:
  \[ \Delta \varepsilon = \beta \theta^2 = \beta \left( \frac{E_{\text{tot}} q E_r L}{E_{\text{tot}}^2 - E_0^2} \right)^2 \left[ \frac{m}{\text{turn}} \right] \]
- Rough estimate through mean Gaussian weighted RMS field in center of beam
- Current LHC emittance growth rate \( \approx 1 \times 10^{-5} \text{ s}^{-1} \)

### Table

<table>
<thead>
<tr>
<th>EGR ( \times 10^{-5} \frac{1}{s} )</th>
<th>Cathode Voltage [kV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius [mm]</td>
<td>B(_{\text{max}}) [kG]</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>(4, \sigma)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>2.4</td>
</tr>
</tbody>
</table>

- Indication of no extra emittance growth \( \rightarrow \) Luminosity
- First 3D simulation of HEBL using WARP
- Aimed at extracting kick map for SixTrack or Lifetrack simulations
- Two injection methods implements
- Issues to be solved:
  - Implementation of TEL2 bends
  - Heavy computing power needed
  - Further diagnostics tools need to be implemented
- Continued by myself for conceptual design report
Conclusions

Vince Moens, 11.04.2013
Conclusions

- Useful technique for enhancing current collimation systems
  - Active control of losses
  - Less dependent on loss spikes
  - Increases impact parameter

- Determined optimal operating parameters for LHC
  - Factor 11 compression
  - 8.5 A filament current
  - 3-4 kV cathode potential

- Transmission upgrade through magnetic compression in TELTS

- Significant yield improvement of HG1b: $5.3(1) \times 10^{-6}$ perv

- Transverse profile scaling $\propto \frac{\sqrt{V_a}}{B}$

- Emittance growth rates are acceptable compared to current growth rates

- First full 3D simulations
Questions

Thank You!

Availabilty:

- Fermilab Library: FERMILAB-MASTERS-2013-02 (www.inspirehep.net)
- CERN Library: CERN-THESIS-2013-126 (www.cds.cern.ch)
Acknowledgements

- Prof. Leonid Rivkin, Master Thesis Director
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- Dr. Alexander Valishev, HEBL collaborator
- Dr. David Grote, WARP author
Backup Slides

Vince Moens, 11.04.2013

http://anim3d.web.cern.ch/
Backup Contents

- LHC & Collimation System
- Tevatron Intensity
- Tevatron Electron Lens 2
- Conceptual Straight HEBL Design
- Cathode Temperature
- Time Structures
- Generalized Perveance
- SAM Simulations
- Background Gases
- Transverse Profiles
- Beam Evolution
- Transverse Electric Fields at 500 V
- Transverse Electric Fields at 8 kV
- Derivation – Angle of Rotation
- Derivation – Electric Field Equations
- Derivation – Emittance Growth Rate
- WARP – Implemented Gun
- WARP – Potential Fields
- WARP – Electric Fields
LHC & Collimation System

- Beam continually cleaned through multi-stage collimation system
- Approximately 100 collimators
- 4 colliding IR & 4 non-interacting IR
- Affected by electromagnetic impedance, beam jitter, increased loss rates when moving collimators

Illustrative scheme form Stefano redaelli
Tevatron Intensity

Electron beam current (A)

(Affected Train) / (Control Trains)

Luminosity

Intensity

Time (h)

Electron beam current (A)
Tevatron Electron Lens 2

- Gun & collector outside tube
- Only one beam
- 3 main solenoids
- Pierce through edge

![Diagram of Tevatron Electron Lens 2](image)

- Hollow electron beam
- Antiprotons
- Protons
- Gun solenoid
- Collector solenoid
- Collector

Source: FERMILAB-CONF-11-506-AD-APC
Conceptual Straight HEBL Design

Source: Gennady Kuznetsov
Thermionic Emission

Electron
Energy

Conduction Band

Cathode

Vacuum

x = 0

E = E₀

eφ

E = 0

Energy Profile
E > ~ 3\times 10^7 \text{ V/cm}

Electron
Wave Function

Distance

Metal

Vacuum

Slope = Perveance
(\approx 1 \times 10^{-6} \text{ for the plot shown here})

TL Region

Current (mA)

Voltage (kV)

Potential

Cathode

Distance

Anode

Field = 0

Equilibrium

(c)

(a)

(b)
Cathode Temperature

\[ T = \beta R + T_0 \]

\[ \beta = 1770 \text{ K Ohm}^{-1} \]

\[ T_0 = -462 \text{ °C} \]
Time Structures

- Rise Time: 200 ns
- Bunch spacing Tevatron: 400 ns
- Bunch spacing LHC: 25 ns
- Possible to obtain bunch by bunch manipulation in LHC.
- Aim is to obtain turn-by-turn excitation.

- Valentina achieved 75% cleaning in 20s using AC beam mode
Generalized Perveance

\[ K = \frac{I}{I_0} \frac{2}{(\beta \gamma)^3} (1 - \gamma^2 f_e) \]

\[ I_0 = \frac{4 \pi \varepsilon_0 mc^3}{q} = 17 kA \]

\[ \beta = \frac{v}{c} \text{ and } v = \left( \frac{2qV}{m} \right)^{\frac{1}{2}} \]

\[ K = P \times \left[ \frac{(1 - \gamma^2 f_e)}{4 \pi \varepsilon_0 \gamma^3 (2q/m)^{1/2}} \right] \]

\[ \frac{K}{(1 - f_e)} = P \times \left[ \frac{m^{1/2}}{4 \pi \varepsilon_0 (2q)^{1/2}} \right] = P \times 1.515 \times 10^4 \]
SAM Simulations

- Electric Field
- Gun Conductors
- Electron Beam

\[ B = 0.05 \text{ T} \quad V = 5 \text{ kV} \quad B = 0.5 \text{ T} \]
Background Gases

Background gas of test stand:

Hydrogen gas at $1 \times 10^{-8}$ mbar.
Transverse Profiles

- $V_a = 500 \text{ V}$
- $I_{\text{peak}} = 73 \text{ mA}$
- $B = 1 - 4 - 1 \text{ kG}$
- $V_a = 8 \text{ kV}$
- $I_{\text{peak}} = 3.88 \text{ A}$
- $B = 1 - 4 - 1 \text{ kG}$
Beam Evolution

- Angle of rotation around beam axis (derived from dioctron frequency)
  \[
  \varphi = \frac{P \varepsilon_0 L \sqrt{V_a}}{4\pi\varepsilon_0 ec^2 (R_o^2 - R_i^2) B} \left(1 - \left(\frac{R_i}{r}\right)^2\right) \quad [\text{rad}]
  \]

- Dependence on \( r \) ➔ slippage

- Scaling law ➔ angle of rotation must be constant
  \[ B \propto \sqrt{V} \]

- Angle of rotation at outer cathode radius

| Angle of rotation \[^{\circ}\] | Acceleration Potential \[\text{kV}\] |
|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Magnetic Field \[\text{T}\] | 1    | 2    | 3    | 4    | 5    | 6    | 7    | 8    |
| 0.40              | 72   | 101  | 124  | 143  | 160  | 175  | 189  | 202  |
| 0.32              | 89   | 127  | 155  | 179  | 200  | 219  | 237  | 253  |
| 0.24              | 120  | 169  | 207  | 239  | 267  | 292  | 316  | 337  |
| 0.16              | 179  | 253  | 310  | 358  | 400  | 438  | 473  | 506  |
Beam Evolution

Profile evolution with $V$ at $B=0.8-3.2-0.8$ kG

- (a) $V=125$ V
- (b) $250$ V
- (c) $500$ V
- (d) $1$ kV
- (e) $2$ kV
- (f) $3$ kV
- (g) $4$ kV
- (h) $5$ kV
- (i) $6$ kV
- (j) $7$ kV
- (k) $8$ kV

Profile evolution with $V$ at $B=0.8-3.2-0.8$ kG

- (a) $B_{\text{main}}=1.6$ kG
- (b) $B_{\text{main}}=2.4$ kG
- (c) $B_{\text{main}}=3.2$ kG
- (d) $B_{\text{main}}=4$ kG
Transverse Electric Fields at 500 V

Charge density in x–y plane

Electrostatic potential in x–y plane

Electrostatic potential in x–y plane

E–field vs X (blue) and Y (red)

Electric field strength in x–y plane

Electric field strength in x–y plane
Transverse Electric Fields at 8 kV

Charge density in x–y plane

Electrostatic potential in x–y plane

E–field vs X (blue) and Y (red)

Electric field strength in x–y plane

Electric field strength in x–y plane
Derivation – Angle of Rotation

\[
\omega_p^2 = \frac{q^2 n}{\varepsilon_0 \gamma^3 m} (1 - \gamma^2 f_e) \quad \omega_r = \omega_D = \frac{\omega_p^2}{2\omega_c} = \frac{ne}{2\varepsilon_0 B} \tag{1}
\]

\[
\omega_r = \omega_D (1 - f - \beta_z^2) \left[ 1 - \left( \frac{R_i}{r} \right)^2 \right], \quad \forall R_i \leq r \leq R_o \tag{2}
\]

\[
\varphi_r = \frac{\omega_D L}{v_z} \left[ 1 - \left( \frac{R_i}{r} \right)^2 \right] = \frac{n_e e L}{2\varepsilon_0 B v_z} \left[ 1 - \left( \frac{R_i}{r} \right)^2 \right], \quad \forall R_i \leq r \leq R_o \tag{3}
\]

\[
\varphi_r = \frac{IL}{2\pi \varepsilon_0 B (R_0^2 - R_i^2) v_z^2} \left[ 1 - \left( \frac{R_i}{r} \right)^2 \right] \tag{4}
\]

\[
= \frac{IL}{2\pi \varepsilon_0 B (R_0^2 - R_i^2) c^2 e V_a (2E_0 + e V_a ) ^2 (E_0 + e V_a )^2} \left[ 1 - \left( \frac{R_i}{r} \right)^2 \right], \quad \forall R_i \leq r \leq R_o \tag{5}
\]

\[
\varphi = \frac{IE_0 L}{2\pi \varepsilon_0 B (R_0^2 - R_i^2) 2c^2 e V_a} \left[ 1 - \left( \frac{R_i}{r} \right)^2 \right], \quad \forall R_i \leq r \leq R_o \tag{6}
\]

\[
\varphi = \frac{PE_0 L}{4\pi \varepsilon_0 c^2 (R_0^2 - R_i^2) e} \times \frac{\sqrt{V_a}}{B} \left[ 1 - \left( \frac{R_i}{r} \right)^2 \right] \tag{7}
\]

\[
= 2.7 \times 10^{-2} \frac{\sqrt{V_a}}{B} \left[ 1 - \left( \frac{R_i}{r} \right)^2 \right], \quad \forall R_i \leq r \leq R_o \tag{8}
\]
Derivation – Electric Field Equations

\[ \iiint_{\partial \Omega} E \cdot dS = \frac{Q_{\text{encl}, \Omega}}{\varepsilon_0} \]  
(1)

\[ E \cdot 2\pi r L = \frac{\int_0^R \rho(r') 2\pi r' L \, dr'}{\varepsilon_0} \]  
(2)

\[ E = \frac{\int_0^R \rho(r') r' \, dr'}{\varepsilon_0 r} \]  
(3)

\[ r \leq R_o \quad E = 0 \]  
(4)

\[ R_i \geq r \leq R_o \quad E(r) = \frac{\rho(r^2 - R_i^2)}{2\varepsilon_0 r} = \frac{IL(r^2 - R_i^2)}{2\pi v_z \varepsilon_0 r (R_o^2 - R_i^2)} \]  
(5)

\[ R_o \geq r \quad E(r) = \frac{\rho(R_o^2 - R_i^2)}{2\pi \varepsilon_0 r} = \frac{IL}{2\pi v_z \varepsilon_0 r} \]  
(6)
Derivation – Emittance Growth Rate

\[
\frac{d}{dt} p_r = F_y = q \vec{E}_r
\]  \hspace{1cm} (1)

\[ p_r = q \vec{E}_r t \] \hspace{1cm} (2)

\[ p_z \tan(\theta) = q \vec{E}_r \] \hspace{1cm} (3)

\[ \rightarrow \tan(\theta) = \frac{q \vec{E}_r t}{p_z} \] \hspace{1cm} (4)

\[ \rightarrow \tan(\theta) = \frac{q \vec{E}_r L}{p_z v_z} \] \hspace{1cm} (5)

\[ \rightarrow \tan(\theta) = \frac{\gamma E_0 q \vec{E}_r L}{p_z^2} \] \hspace{1cm} (6)

\[ \rightarrow \tan(\theta) = \frac{E_{tot} q \vec{E}_r L}{(E_{tot}^2 - E_0^2)} \] \hspace{1cm} (7)

\[ \Rightarrow \vartheta = \frac{E_{tot} q E_r L}{E_{tot}^2 - E_0^2} \] \hspace{1cm} (8)
Derivation – Emittance Growth Rate

\[
\begin{pmatrix}
  x_{n+1} \\
  x'_{n+1}
\end{pmatrix}
= M
\begin{pmatrix}
  x_n \\
  x'_n
\end{pmatrix}
\]

(1)

\[
\epsilon = \gamma x_{n+1}^2 + 2\alpha x_{n+1} x'_{n+1} + \beta x'_{n+1}^2 = \gamma x_n^2 + 2\alpha x_n x'_n + \beta x'_n^2
\]

(2)

\[
\begin{pmatrix}
  \tilde{x}_{n+1} \\
  \tilde{x}'_{n+1}
\end{pmatrix}
= M
\begin{pmatrix}
  x_n \\
  x'_n
\end{pmatrix}
+ \begin{pmatrix}
  0 \\
  \vartheta
\end{pmatrix}
\]

(3)

\[
\epsilon = \gamma \tilde{x}_{n+1}^2 + 2\alpha \tilde{x}_{n+1} \tilde{x}'_{n+1} + \beta \tilde{x}'_{n+1}^2 = \gamma x_{n+1}^2 + 2\alpha x_{n+1} (x'_{n+1} + \vartheta) + \beta (x'_{n+1} + \vartheta)^2
\]

(4)

\[
\Delta \epsilon = 2\vartheta (\alpha x_{n+1} + \beta x'_{n+1}) + \beta \vartheta^2
\]

(5)

\[
\Delta \epsilon = \beta \vartheta^2 = \beta \left( \frac{E_{tot} q E_r L}{E_{tot}^2 - E_0^2} \right)^2
\]

(6)
WARP – Implemented Gun
WARP – Potential Fields

Electrostatic potential in z–x plane
WARP – Electric Fields

Ez in z–x plane
WARP – Electric Fields

Emagnitude in z–x plane