Studies on collimation with hollow electron beams

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In collaboration with

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- G. Kuznetsov, A. Romanov (BINP Novosibirsk)
- J. Smith (SLAC)
Concept of hollow electron beam collimator (HEBC)

Cylindrical, hollow, magnetically confined, pulsed electron beam overlapping with halo and leaving core unperturbed

Halo experiences nonlinear transverse kicks

Shiltsev, BEAM06, Yellow Report CERN-2007-002
Shiltsev et al., EPAC08
Hollow-beam collimation concept

Advantages

- electron beam can be placed close to core ($\sim 3–4\sigma$)
- no material damage
- low impedance, no instabilities
- position controlled by magnetic field, no motors or bellows
- gradual removal, no loss spikes due to beam jitter
- no ion breakup
- transverse kicks are not random in space or time
  $\rightarrow$ resonant excitation tuned to betatron frequency is possible
- abundance of theoretical modeling, technical designs, and operational experience on interaction of keV–MeV electrons with MeV–TeV (anti)protons
  - electron cooling
  - Tevatron electron lenses
Existing Tevatron electron lenses

- TEL1 used for abort-gap clearing during normal operations
- TEL2 used as TEL1 backup and for studies

Typical parameters

- Peak energy: 10 keV
- Peak current: 3 A
- Max gun field $B_g$: 0.3 T
- Max main field $B_m$: 6.5 T
- Length $L$: 2 m
- Rep. period: 21 $\mu$s
- Rise time: <200 ns

TEL2 timing example

- **abort gap**
- **bunch train**
- **collector current**
- **cathode current**
- **pickup signal**
- **proton bunch**
- **antiproton bunch**
- **revolution marker**

G. Stancari (Fermilab)
Total losses show large fluctuations
Abort-gap losses are smooth (TEL1 clearing)
Example of HEBC at TEL2 location in Tevatron

- **Lattice:**
  - $\beta_x = 66$ m, $\beta_y = 160$ m
  - $D_x = 1.18$ m, $D_y = -1.0$ m

- **Protons:**
  - $\epsilon = 20$ $\mu$m (95%, normalized)
  - $\Delta p/p = 1.2 \times 10^{-4}$
  - $x_{co} = +2.77$ mm, $y_{co} = -2.69$ mm
  - $\sigma_x = 0.46$ mm, $\sigma_y = 0.71$ mm

- **Antiprotons:**
  - $\epsilon = 10$ $\mu$m (95%, normalized)
  - $\Delta p/p = 1 \times 10^{-4}$
  - $x_{co} = -2.77$ mm, $y_{co} = +2.69$ mm
  - $\sigma_x = 0.32$ mm, $\sigma_y = 0.50$ mm

- **Electrons:**
  - $I = 2.5$ A
  - $B_g = 0.3$ T, $B_m = 0.74$ T
  - $r_1 = 4.5$ mm, $r_2 = 7.62$ mm at gun
  - $r_{min} = 2.9$ mm $= 4\sigma_y$, $r_{max} = 4.9$ mm in main solenoid
Requirements and constraints

- Placement: $\sim 4-5\sigma +$ field line ripple ($\sim 0.1$ mm)
- Transverse compression controlled by field ratio: $r_m/r_g = \sqrt{B_g/B_m}$
  - fields must provide efficient transport
  - instability threshold $< B_m \lesssim 10$ T (technology)
- Large amplitude functions ($\beta_x$, $\beta_y$) to translate transverse kicks into large displacements
- If proton beam is not round ($\beta_x \neq \beta_y$), separate horizontal and vertical scraping is required
- Cylindrically symmetric current distribution ensures zero electric field on axis; if not, mitigate by:
  - segmented control electrodes near cathode
  - crossed-field ($E \times B$) drift of guiding centers
  - tuning kicks to halo tune ($\neq$ core tune)?
Hollow-beam collimation concept

Disadvantages

- kicks are small, large currents required
- alignment of electron beam is critical
- hollow beams can be unstable
- cost: $\approx 5 \text{ M$} (2 \text{ M$ material and supplies, 3 M$ salaries)
Transverse kicks for protons

In cylindrically symmetrical case,

\[
\theta_{\text{max}} = \frac{2 l}{L} \frac{1 \pm \beta_e \beta_p}{r_{\text{max}} \beta_e \beta_p c^2 (B\rho)_p} \left( \frac{1}{4\pi\epsilon_0} \right)
\]

\[-: \mathbf{v}_p \cdot \mathbf{v}_e > 0 \]

\[+: \mathbf{v}_p \cdot \mathbf{v}_e < 0 \]

**Example \((\mathbf{v}_p \cdot \mathbf{v}_e > 0)\)**

- \(l = 2.5 \text{ A}\)
- \(L = 2.0 \text{ m}\)
- \(\beta_e = 0.19 \text{ (10 kV)}\)
- \(r_{\text{max}} = 3.5 \text{ mm (5\sigma in TEL2)}\)

<table>
<thead>
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<th>(p) energy (TeV)</th>
<th>0.150</th>
<th>0.980</th>
<th>7</th>
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<tbody>
<tr>
<td>kicks ((\mu)rad):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hollow-beam max</td>
<td>2.4</td>
<td>0.36</td>
<td>0.051</td>
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<tr>
<td>collimator rms (Tevatron)</td>
<td>110</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>collimator rms (LHC)</td>
<td></td>
<td></td>
<td>4.5</td>
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</tbody>
</table>
Modeling

kick maps
in overlap region

- analytical form
  ideal case
- 2D from measured profiles
  Poisson solver
- 3D particle-in-cell warp code,
effects of
  - TEL2 bends
  - profile evolution
  - alignment

⇒ tracking software
with lattice and apertures

- STRUCT
- lifetrac
- SixTrack
- DMAD
Simulation of HEBC in Tevatron

- STRUCT code, complete description of element apertures, helices, rf cavities, sextupoles
- Halo defined as \[5\sigma < x < 5.5\sigma, 0.2\sigma < y < 0.5\sigma\] or \[0.2\sigma < x < 0.5\sigma, 5.5\sigma < y < 6\sigma\]
- Hollow beam \(5\sigma < r < 6.4\sigma\)
- Effect of resonant excitation

![Graph showing particle decay over turn number with different strengths and parameters](image-url)
Simulation of HEBC in Tevatron

- Lifetrac code with fully-3D beam-beam, nonlinearities, chromaticity
- Simplified aperture: single collimator at $5\sigma$
- Halo particles defined as ring in phase space with $3.5\sigma < x, y < 5\sigma$
- Hollow beam $3.5\sigma < r < 5\sigma$
- No resonant pulsing

Halo losses vs turn number for maximum kick of 0.5 $\mu$rad and 3.0 $\mu$rad
Simulation of HEBC in LHC

Smith et al., PAC09, SLAC-PUB-13745

- First impact (1D) and SixTrack codes
- Collimator at $6\sigma$
- Beam halo defined as ring $4\sigma < x < 6\sigma$
- Hollow beam at $4\sigma < r < 6\sigma$

Cleaning $\equiv 95\%$ hits collimator

Significant increase in impact parameter
Collimation scenarios

- HEBC probably too weak to replace collimators
  → ‘staged’ collimation scheme: HEBC + collimators + absorbers
- HEBC can act as ‘soft’ collimator to avoid loss spikes generated by beam jitter
- HEBC as scraper for intense beams
- increase in impact parameter is significant
- HEBC may allow collimators to be retracted (probably not relevant for LHC)
- resonant kicks are very effective
- tune shifts too small to drive lattice resonances
- effects should be detectable in Tevatron
Design of 15-mm-diameter hollow gun

- Convex tungsten dispenser cathode with BaO:CaO:Al₂O₃ impregnant
- 7.6-mm outer radius, 4.5-mm-radius bore
- Electrode design based upon existing 0.6-in SEFT (soft-edge, flat-top) gun previously used in TEL2

Calculations with SAM code  L. Vorobiev
Mechanical design  G. Kuznetsov
Test bench at Fermilab

Built to develop TELs, now used to characterize electron guns and to study plasma columns for space-charge compensation

- High-perveance **electron guns**: ∼amps peak current at 10 kV, pulse width ∼µs, average current <2.5 mA
- Gun / main / collector **solenoids** (<0.4 T) with magnetic correctors and pickup electrodes
- Water-cooled **collector** with 0.2-mm pinhole for profile measurements

G. Stancari (Fermilab)
Performance of hollow cathode vs voltage and temperature

Perveance is 4 µperv
Profile measurements

- Horizontal and vertical magnetic steerers deflect electron beam
- Current through 0.2-mm-diam. pinhole is measured vs steerer strength
HOLLOW GUN
October 21, 2009

Vacuum: 2x10^{-8} mbar
Filament: 66 W (7.75 A)
Cathode voltage: -0.5 kV
HV PS current: 1.0 mA
Pulse width: 6 us
Rep. period: 0.6 ms
Peak current: 44 mA
Solenoids: 3-3-3 kG
HOLLOW GUN
October 26, 2009

Vacuum: 2x10^{-8} mbar
Filament: 66 W (7.75 A)
Cathode voltage: -9.0 kV
HV PS current: 1.43 mA
Pulse width: 6 us
Rep. period: 80 ms
Peak current: 2.5 A
Solenoids: 3-3-3 kG

Measured profile: 9.0 kV 2.5 A 0.3 T
Profile evolution with increasing current and voltage
Hollow-beam instabilities

- Profiles measured 2.8 m downstream of cathode
- In previous plots, magnetic field kept constant at 0.3 T
- If current density is not axially symmetric, neither are space-charge forces
- Guiding-center drift velocities $\mathbf{v} \propto \mathbf{E} \times \mathbf{B}$ depend on $r$ and $\phi$
- Electron beam behaves like incompressible, frictionless 2D fluid
- Typical nonneutral plasma slipping-stream (‘diocotron’) instabilities arise, vortices appear

Kyhl and Webster, IRE Trans. Electron Dev. 3, 172 (1956)
Levy, Phys. Fluids 8, 1288 (1965)

Current-density distribution evolves as the beam propagates

$$(\text{evolution time}) \propto \frac{(\text{current})}{(\text{magnetic field}) \times (\text{voltage})}$$
G. Stancari (Fermilab)
Hollow beam collimation
LHC CWG : 15 Mar 2010
Profile reproducibility

0.5 kV  2 kV  7.5 kV

Oct 2009

(Filament heater was turned off and on between measurements)
Recent studies in Recycler Ring

A. Shemyakin and A. Valishev, Beams-doc-3554-v1 (19 Feb 2010)

- Can a helical electron beam approximate the effect of a hollow beam?
- Need integer number of turns, short pitch compared to amplitude functions
- Preliminary study with 8-GeV protons in electron cooler a few weeks ago
- Helical electron trajectory generated by upstream correctors

- Very short lifetimes (not fully understood)
- Indications of scraping: core has longer lifetime than halo
- Work in progress...
Planned Tevatron studies

Experimental goals

- verify hollow-beam alignment procedures
- evaluate effect on core lifetime
- measure losses at collimators, absorbers and detectors vs HEBC parameters: position, angle, intensity, pulse timing, excitation pattern
- assess improvement of loss spikes

Hardware/software improvements in TEL2

- Stacked-transformer modulator (faster, complex waveforms)
- BPM system

Alignment based upon BPMs, bunch-by-bunch losses, Schottky power, tunes. Studies with Gaussian gun under way.
Next steps

- **Modeling:**
  - 2D and 3D kick maps from measured distributions
  - performance vs lattice parameters
  - effect of misalignments, field-line ripple, bends

- **Test bench:**
  - Evolution of hollow beam
  - Time stability of current density within each pulse
  - Design and test 25-mm cathode (∼7 A)?

- **Recycler Ring:**
  - More measurements with helical beam in electron cooler?

- **Tevatron:**
  - Gaussian gun currently installed in TEL2
    - study of nonlinear head-on beam-beam compensation:
      - bunch-by-bunch lifetimes, tunes, tune spreads
  - Install 15-mm hollow gun in TEL2 (July shutdown?)
  - Start parasitical and dedicated studies on collimation

*Thank you for your attention*