Hollow Electron Beam Collimation Progress

Is the hollow-beam ‘soft scraper’ a viable complement to collimation systems for high-intensity machines?

G. Stancari, A. Valishev, G. Annala, T. Johnson, G. Saewert, V. Shiltsev, D. Still, L. Vorobiev

Fermilab

Thanks to AD Operations, AD Tevatron, CDF and DZero for support and study time

- Project status
- Tevatron results
- Outlook

All Experimenters Meeting, Fermilab, July 25, 2011
Concept of hollow electron beam collimator (HEBC)

Halo experiences nonlinear transverse kicks:

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

About \(0.2 \mu\text{rad}\)
in TEL2 at 980 GeV

For comparison:
multiple scattering in Tevatron collimators

\[
\theta_{\text{rms}} = 17 \mu\text{rad}
\]

Shiltsev, BEAM06, CERN-2007-002
Shiltsev et al., EPAC08
The 15-mm hollow electron gun

Copper anode

top view

Tungsten dispenser cathode with convex surface
15-mm diameter, 9-mm hole

Yield: 1.1 A at 4.8 kV
Profile measurements

CURRENT DENSITY (a.u.)

0.8
0.6
0.4
0.2
0.0

-10
-5
0
5
10

X (mm)

1.1 A
4.8 kV

Yield: 1.1 A at 4.8 kV
Profile measurements
Layout of the beams in the Tevatron

Protons → electrons → Antiprotons

Antiproton collimators:
- Primary (F49)
- Secondary (F48)
- Secondary (D17)

CDF
DZero

Tevatron electron lens
Transverse separation is 9 mm at TEL

Pulsed electron beam can be synchronized with any group of bunches
The conventional two-stage collimation system

- **Goals of collimation:**
  - reduce beam halo
  - direct losses towards absorbers

- **Conventional schemes:**
  - **primary collimators**
    - Tevatron: 5-mm W at 5\(\sigma\)
    - LHC: 0.6-m carbon jaws at 6\(\sigma\)
  - **secondary collimators**
    - Tevatron: 1.5-m steel jaws at 6\(\sigma\)
    - LHC: 1-m carbon/copper at 7\(\sigma\)
1-dimensional diffusion cartoon of collimation

Local loss rate (flux)

\[ R \propto -D \cdot \left[ \frac{\partial_x f}{x=x_c} \right] \]

Beam population density, \( f(x,t) \)

Transverse position, \( x [\sigma] \)

Diffusion coefficient, \( D(x) \)

Collimator
1-dimensional diffusion cartoon with hollow electron beam

Beam population density, $f(x, t)$

Diffusion coefficient, $D(x)$

Transverse position, $x$ [$\sigma$]
A good complement to a two-stage system for high intensities?

› Can be close to or even overlap with the main beam
  › no material damage
  › continuously variable strength ("variable thickness")
› Works as "soft scraper" by enhancing diffusion
› Low impedance
› Resonant excitation is possible (pulsed e-beam)
› No ion breakup
› Position control by magnetic fields (no motors or bellows)
› Established electron-cooling / electron-lens technology
› Critical beam alignment
› Control of hollow beam profile
› Beam stability at high intensity
› Cost
Tevatron beam studies

- Started in October 2010
- 19 experiments so far: parasitic and dedicated
- Measured many **observables** vs. main **factors**: beam **current**, relative **alignment**, **hole size**, **pulsing pattern**, **collimator configuration**:
  - overall particle **removal rate**
  - **effects on the core** and on unaffected bunches
  - **removal rate vs. particle amplitude**
  - enhancement of transverse beam **diffusion**
  - **collimation efficiency**
  - **fluctuations** in loss rates
- Removal rates and halo scraping shown in February
- A few examples of diffusion and fluctuation effects shown here
Electrons acting on 1 antiproton bunch train (#2, A13-A24)

Hole radius

Control Bunch Train #1 (A1–A12)
Affected Bunch Train #2 (A13–A24)
Control Bunch Train #3 (A25–A36)

Electron beam current (A)

Bunch train intensity \((10^9)\)

HEBC studies
Tevatron Store 8546
3 Mar 2011
Diffusion rate vs. amplitude from collimator scans

Vertical secondary collimator scan

Keeping loss spikes below quench limit constrains collimator settings

local losses

collimator position

Tails repopulate faster at large amplitudes (higher diffusion rate)
New gated loss monitors during collimator scan

Electrons (0.9 A) on pbar train #2, 4.25σ hole
Example of **vertical collimator step out**, 50 μm

- Diffusion rate enhanced by factor \( \sim 10 \)
- Halo population reduced
- Periodic losses suppressed

*HEBC studies*
Tevatron Store 8749
20 May 2011, 8:18:42

![Graph showing loss rate over time](image-url)
Fourier analysis of losses

Losses due to beam jitter are suppressed
Correlation of steady-state losses

- Hollow beam eliminates correlations among trains
- Interpretation: larger diffusion rate, lower tail population, less sensitive to jitter


- Control trains strongly correlated
- Losses from beam jitter much larger than statistical fluctuations
Summary and outlook

‣ Scraping with hollow electron beams appears to be a viable option for storage rings and colliders
‣ Many new observations at the Tevatron: halo removal rates, effects on core, diffusion, fluctuations in losses, collimation efficiencies, ...
‣ A few more studies planned (now - end of August)
‣ New 1-inch gun assembly and test in September (A. Didenko, contractor engineer)
‣ Validate Tevatron simulations (I. Morozov, guest scientist)
‣ TEL2 hardware (2 M$) will become available after Tevatron shutdown
‣ Transfer experimental program to CERN? Support from DOE LARP Review and LHC Collimation Review (June 2011).
‣ Study applicability to LHC in collaboration with CERN: needed? feasible? (V. Previtali, new Toohig fellow). Possible key improvements: scraping before collisions and collimator setup, efficiency for ions.

Thanks for your attention
Removal rate: affected bunch train relative to other 2 trains

Particle removal is detectable and smooth

No effect on core

Electron beam current (A)

(Affected Bunch Train) / (Control Bunch Trains)

HEBC studies
Tevatron Store 8546
3 Mar 2011

Intensity

1.32%/h

5.18%/h

Particle removal is detectable and smooth

No effect on core

Electron beam current (A)
Is the core affected? Are particles removed from the halo?

Several strategies:

- **No removal** when e-beam is shadowed by collimators (previous slide)
- Check **emittance** evolution
- Compare **intensity** and **luminosity** change when scraping antiprotons:

\[
\mathcal{L} = \left( \frac{f_{\text{rev}} N_b}{4\pi} \right) \frac{N_p N_a}{\sigma^2} \quad \frac{\Delta \mathcal{L}}{\mathcal{L}} = \frac{\Delta N_p}{N_p} + \frac{\Delta N_a}{N_a} - 2 \frac{\Delta \sigma}{\sigma}
\]

- same fractional variation if other factors are constant
- luminosity decreases **more** if there is emittance growth or proton loss
- luminosity decreases **less** if removing halo particles (smaller relative contribution to luminosity)

- **Removal rate** vs. amplitude (collimator scan, steady state)
- **Diffusion rate** vs. amplitude (collimator scan, time evolution of losses)
Emittances of affected bunch train

No additional emittance growth

Scraping of tails

Transverse emittances (95% norm., µm)

Longitudinal emittance (eV·s)

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>Transverse (Horizontal)</th>
<th>Transverse (Vertical)</th>
<th>Longitudinal</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td></td>
<td></td>
<td>11.5</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td>12.0</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
<td>12.5</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td></td>
<td>13.0</td>
</tr>
</tbody>
</table>
Luminosity of affected bunch train relative to other 2 trains

Halo scraping

Electron beam current (A)

Time (h)

HEBC studies
Tevatron Store 8546
3 Mar 2011

Intensity

Luminosity

(Affected Bunch Train) / (Control Bunch Trains)

Intensity

Luminosity

0.45%/h

1.32%/h

5.18%/h

2.65%/h

HEBC studies
Tevatron Store 8546
3 Mar 2011
Relative decay rates

![Graph showing relative decay rates vs. hole radius (σ)]

- Intensity
- Luminosity

Relative decay rate (%/h)

Hole radius (σ)
Electrons (0.15 A) on pbar train #2, 3.5σ hole (1.3 mm at collimator)
Vertical scan of primary collimator (others retracted)

E-beam shadowed, no effect on core!

E-beam turn-on
down towards beam axis
Diffusion rate vs. amplitude from collimator scans

Mess and Seidel, NIM A 351, 279 (1994)

time evolution of local losses after collimator step in

Distribution function

\[
D = R \cdot \frac{x_c^4}{\beta_c^2}
\]

small step in collimator position

evolution of tails of distribution function from diffusion equation

observed loss rate

\[
L(t) = a_1 \left( 1 + \frac{|\Delta x_c|}{x_c} \right) + a_0
\]

collimator step and position

normalization (intensity, efficiency, ...)

parameter related to diffusion rate

G. Stancari (Fermilab) Collimation with hollow electron beams AEM : 25 Jul 2011
First measurement of diffusion rates in Tevatron
Effect of e-lens is detectable, but need gated loss monitors
New gated antiproton loss monitors

- Scintillator paddles installed near F49 antiproton absorber
- Gated to individual bunch trains
- Logged at 15 Hz

For simultaneous measurements of **diffusion rates, collimation efficiency**, and **loss spikes** on affected and control bunch trains at maximum electron currents.
Design of larger (1-inch) hollow gun

- 25 mm outer diameter, 13.5 mm inner diameter
- Up to 3 A at 5 kV

- Goal: To test technical feasibility
- Characterization in Fermilab electron-lens test stand (September?)
- Installation in Tevatron unlikely