Studies on collimation with hollow electron beams

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LHC Collimation Working Group Meeting
15 March 2010

Fermilab

LARP

In collaboration with

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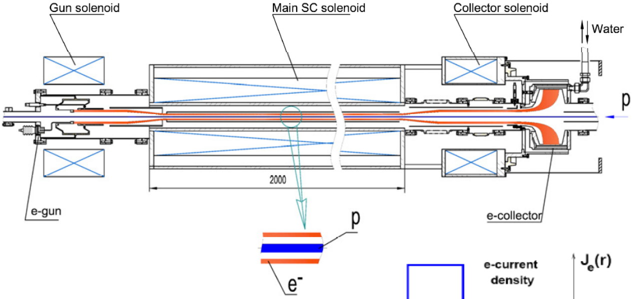
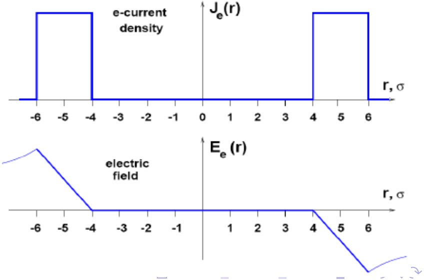
- G. Kuznetsov, A. Romanov (BINP Novosibirsk)
- J. Smith (SLAC)

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

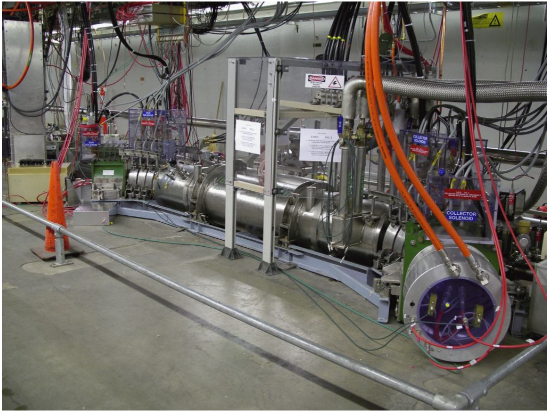
Hollow-beam collimation concept

Advantages

- electron beam can be placed close to core ($\sim$ 3–4σ)
- 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

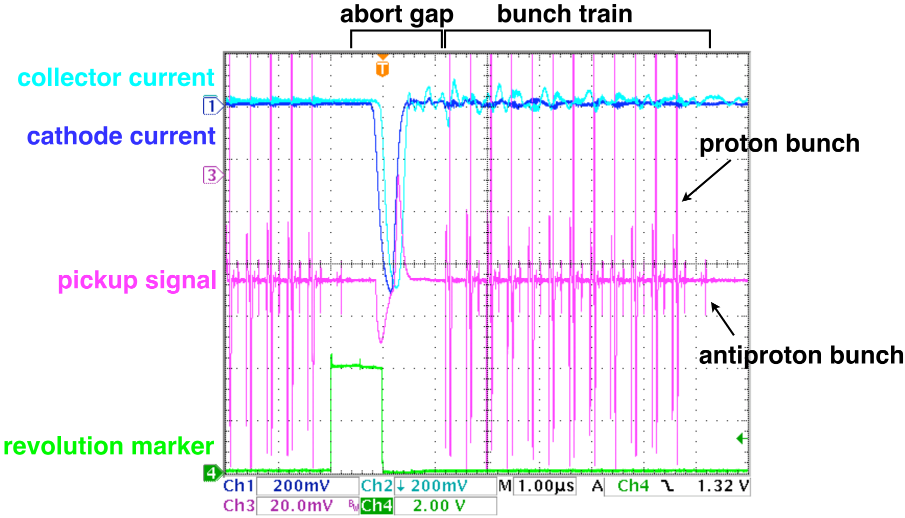


Typical parameters	
Peak energy	10 keV
Peak current	3 A
Max gun field B_g	0.3 T
Max main field B_m	6.5 T
Length L	2 m
Rep. period	21 μs
Rise time	$<$200 ns

Shiltsev et al., Phys. Rev. ST AB **11**, *103501 (2008)*

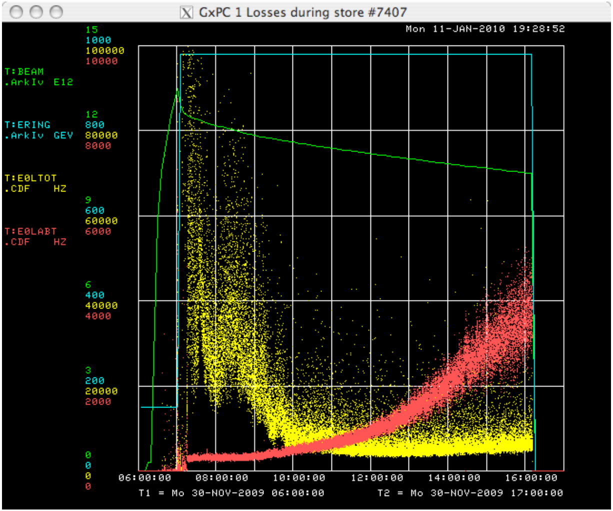
Shiltsev et al., New J. Phys. **10**, *043042 (2008)*

TEL2 timing example



Losses during store #7407

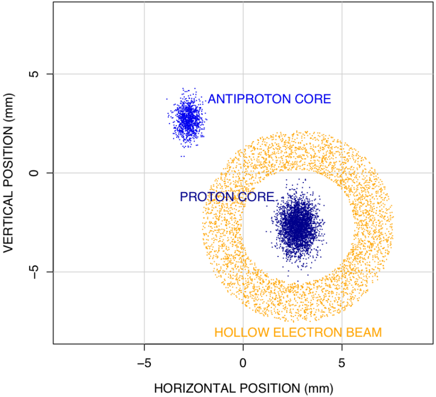
Beam intensity
Ring energy



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)
  - $\Delta p/p = 1.2 \times 10^{-4}$
  - $x_{\rm co} = +2.77$ mm, $y_{\rm co} = -2.69$ mm
  - $\sigma_x = 0.46$ mm, $\sigma_y = 0.71$ mm
- Antiprotons:
  - $\epsilon = 10\ \mu$m (95%, normalized)
  - $\Delta p/p = 1 \times 10^{-4}$
  - $x_{\rm co} = -2.77$ mm, $y_{\rm co} = +2.69$ 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
  - $r_{\rm min} = 2.9$ mm $= 4\sigma_y^p$, $r_{\rm max} = 4.9$ mm in main solenoid



Requirements and constraints

- Placement: $\sim$ 4–5σ + 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 (β_x, β_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 ($\mathbf{E} \times \mathbf{B}$) 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 M$ (2 M$ material and supplies, 3 M$ salaries)

Transverse kicks for protons

In cylindrically symmetrical case,

$$\theta_{max} = \frac{2\, I\, L\, (1 \pm \beta_e \beta_p)}{r_{max}\, \beta_e\, \beta_p\, c^2\, (B\rho)_p} \left(\frac{1}{4\pi\epsilon_0} \right) \qquad \begin{array}{ll} - : & \mathbf{v}_p \cdot \mathbf{v}_e > 0 \\ + : & \mathbf{v}_p \cdot \mathbf{v}_e < 0 \end{array}$$

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

$I = 2.5$ A $\quad L = 2.0$ m $\quad \beta_e = 0.19$ (10 kV) $\quad r_{max} = 3.5$ mm (5σ in TEL2)

p energy (TeV)	0.150	0.980	7
kicks (μrad):			
hollow-beam max	2.4	0.36	0.051
collimator rms (Tevatron)	110	17	
collimator rms (LHC)			4.5

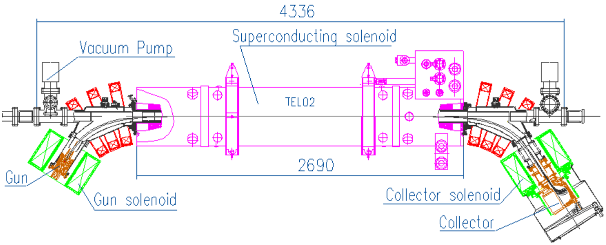
Modeling

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

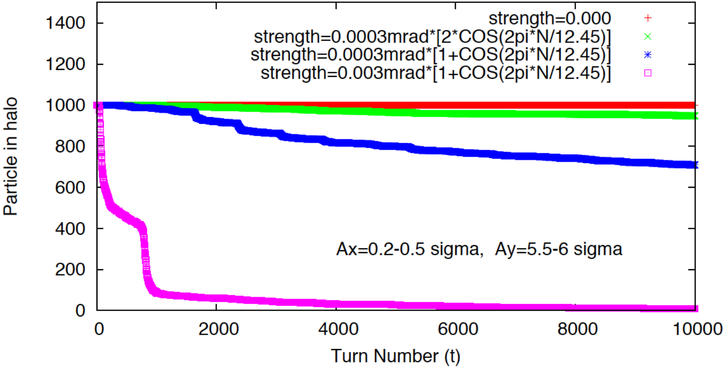
⇒ **tracking software**
with lattice and apertures

- `STRUCT`
- `lifetrac`
- `SixTrack`
- `DMAD`



A. Drozhdin

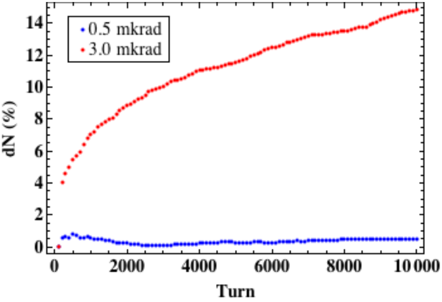
- `STRUCT` code, complete description of element apertures, helices, rf cavities, sextupoles
- Halo defined as $[5\sigma < x < 5.5\sigma, 0.2\sigma < y < 0.5\sigma]$ or $[0.2\sigma < x < 0.5\sigma, 5.5\sigma < y < 6\sigma]$
- Hollow beam $5\sigma < r < 6.4\sigma$
- Effect of resonant excitation



Simulation of HEBC in Tevatron

A. Valishev

- `Lifetrac` code with fully-3D beam-beam, nonlinearities, chromaticity
- Simplified aperture: single collimator at 5σ
- 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



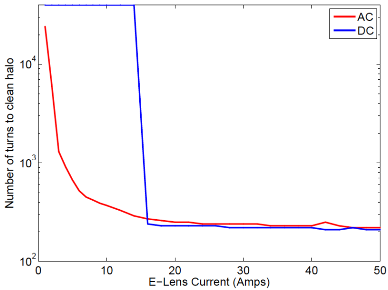
Halo losses vs turn number for maximum kick of 0.5 μrad and 3.0 μrad

Simulation of HEBC in LHC

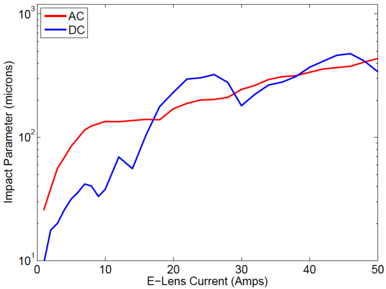
Smith et al., PAC09, SLAC-PUB-13745

- `first_impact` (1D) and `SixTrack` codes
- Collimator at 6σ
- 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



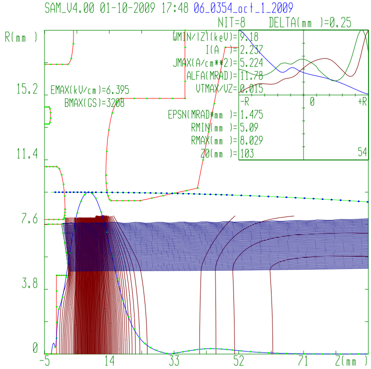
Collimation scenarios

- HEBC probably too weak to replace collimators
  $\rightarrow$ '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

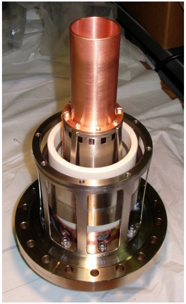
- Convex tungsten dispenser cathode with $BaO:CaO:Al_2O_3$ impregnant
- 7.6-mm outer radius, 4.5-mm-radius bore
- Electrode design based upon existing 0.6-in SEFT (soft-edge, flat-top) gun previously used in TEL2

Calculations with SAM code *L. Vorobiev*



Mechanical design *G. Kuznetsov*

Cathode (w/o bore)



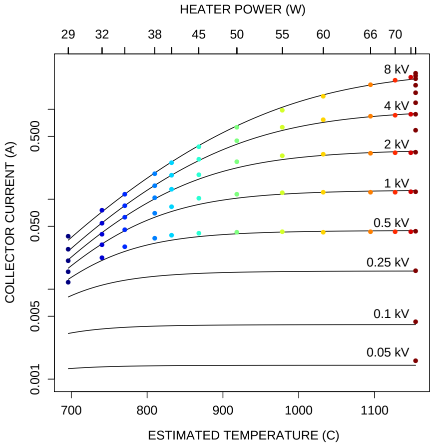
Assembled gun

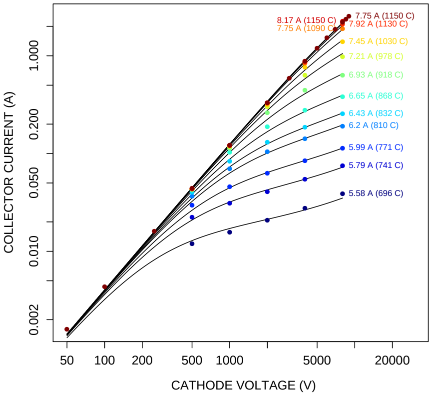
Test bench at Fermilab

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

- High-perveance **electron guns**: $\sim$amps peak current at 10 kV, pulse width $\sim\mu$s, 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

Performance of hollow cathode vs voltage and temperature

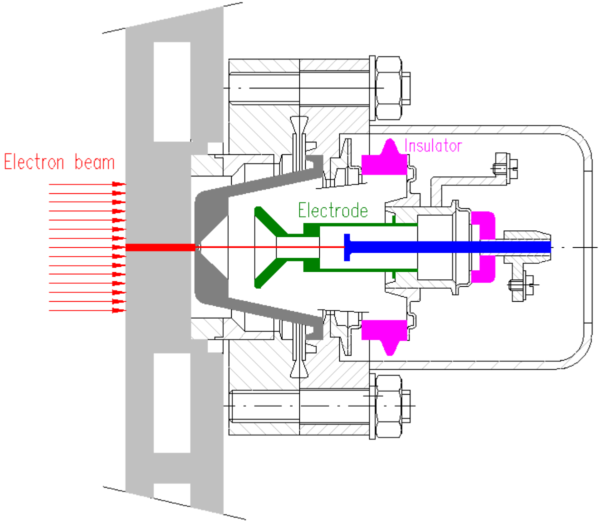




Perveance is 4 μperv

Profile measurements

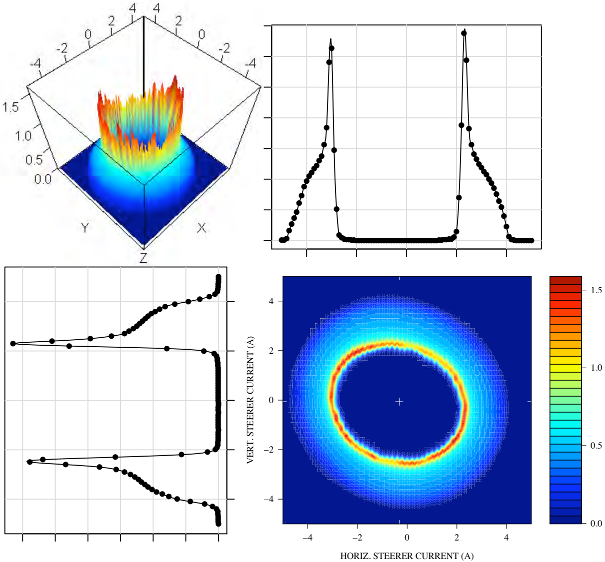
- Horizontal and vertical magnetic steerers deflect electron beam
- Current through 0.2-mm-diam. pinhole is measured vs steerer strength



Measured profile: 0.5 kV 44 mA 0.3 T

HOLLOW GUN
October 21, 2009

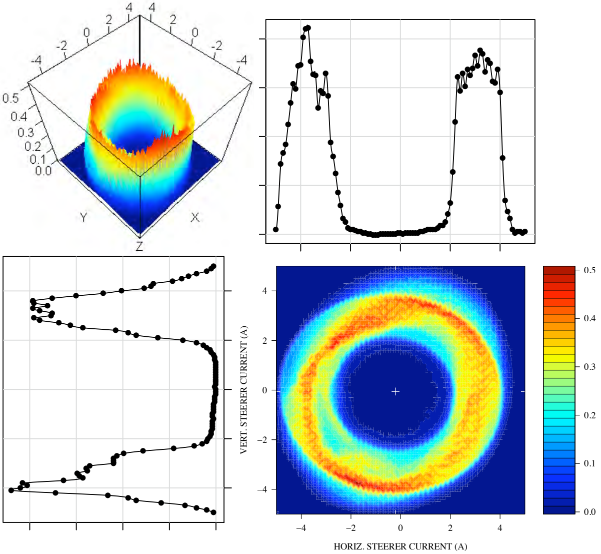
Vacuum: 2x10^{-8} mbar
Filament: 66 W (7.75 A)
Cathode voltage: -0.5 kV
HV PS current: 1.0 mA
Pulse width: 6 us
Rep. period: 0.6 ms
Peak current: 44 mA
Solenoids: 3-3-3 kG

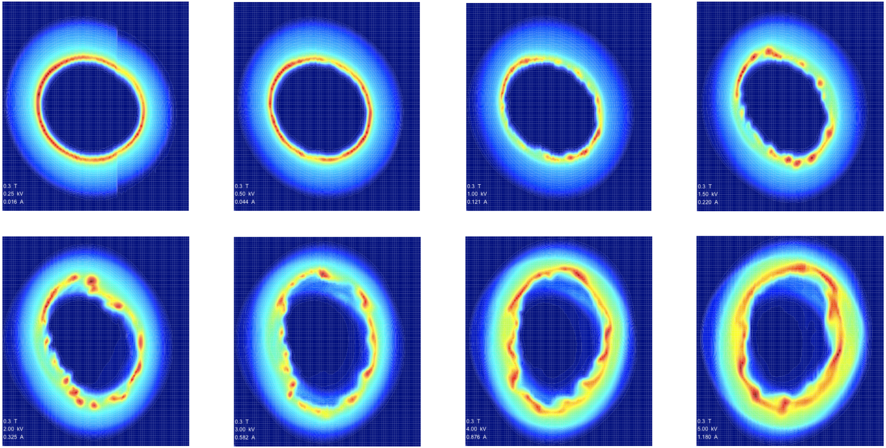


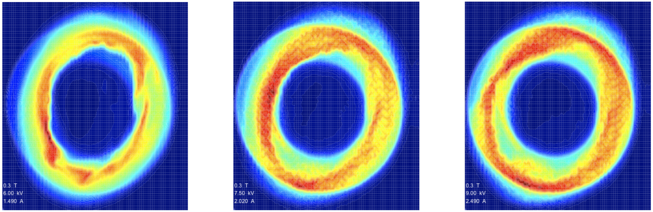
Measured profile: 9.0 kV 2.5 A 0.3 T

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







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 ϕ
- 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)*

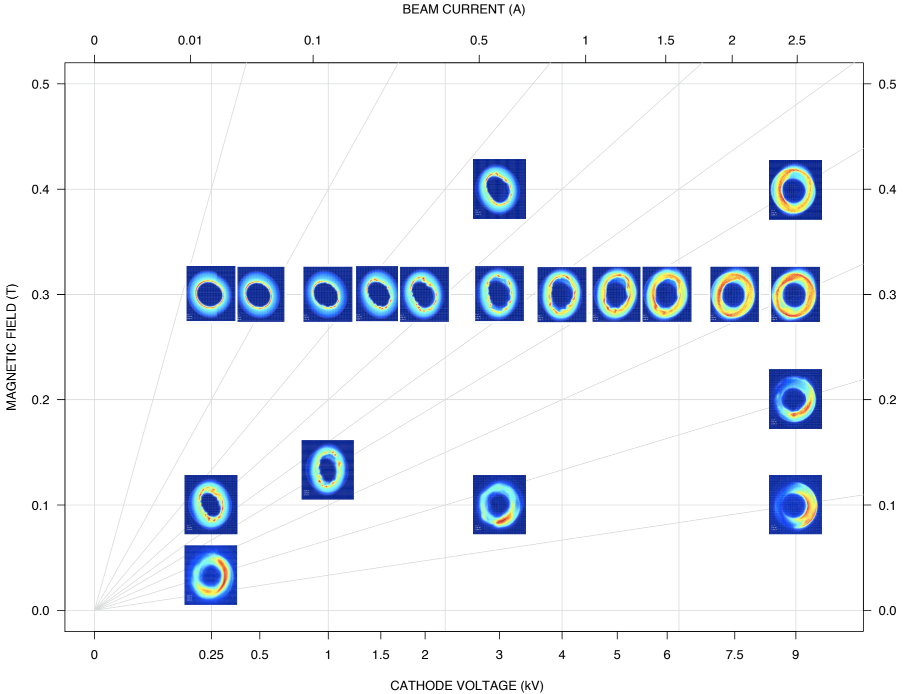
Kapatenakos et al., Phys. Rev. Lett. **30**, *1303 (1973)*

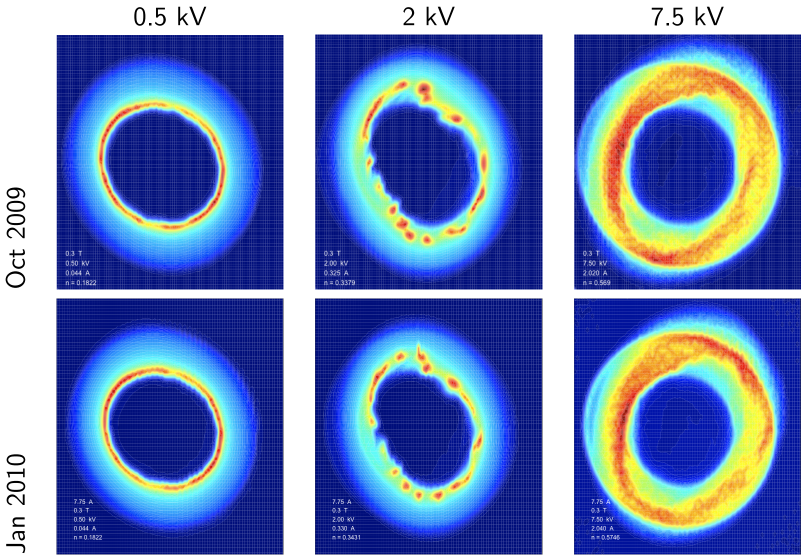
Driscoll and Fine, Phys. Fluids B **2**, *1359 (1990)*

Perrung and Fajans, Phys. Fluids A **5**, *493 (1993)*

Current-density distribution evolves as the beam propagates

$$\text{(evolution time)} \propto \frac{\text{(current)}}{\text{(magnetic field)} \times \text{(voltage)}}$$


BEAM CURRENT (A)
0
0.01
0.1
0.5
1
1.5
2
2.5
MAGNETIC FIELD (T)
0.0
0.1
0.2
0.3
0.4
0.5
CATHODE VOLTAGE (kV)
0
0.25
0.5
1
1.5
2
3
4
5
6
7.5
9

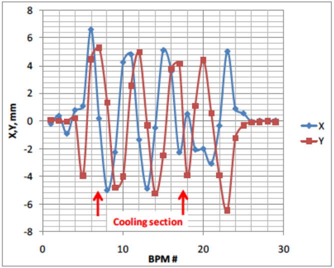


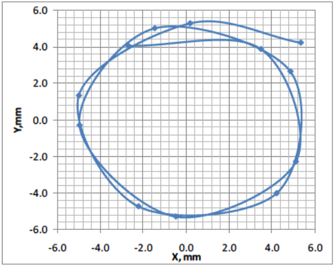
(Filament heater was turned off and on between measurements)

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 ($\sim$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