Collimation with hollow electron beams

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U.S. LHC Accelerator Research Program
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Fermilab

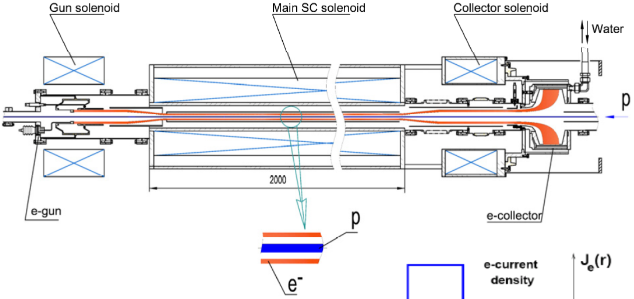
LARP

Motivation

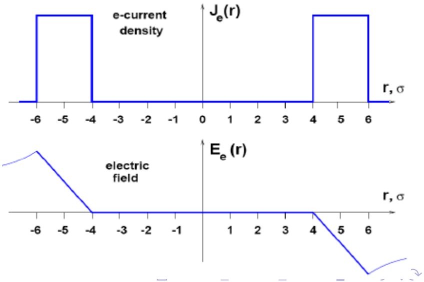
- LHC collimation system:
  graphite primaries at 6σ from core, secondaries at 7σ
- No beam scrapers in LHC: intolerable material damage below 5σ
- Great interest in investigating magnetized hollow electron beams as collimators/scrapers

Concept of hollow electron beam collimator (HEBC)

Cylindrical, hollow, magnetically confined, (pulsed or dc) 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

- electron beam can be placed close to core (~ 3–4σ), no material damage
- size of electron beam in overlap region r_{main} determined by 'compression ratio' of gun to main solenoid strength:

$$r_{\mathrm{main}} = r_{\mathrm{gun}} \sqrt{\frac{B_{\mathrm{gun}}}{B_{\mathrm{main}}}};$$

  range of available beam sizes determined by transport efficiency, instability thresholds, and magnet technology
- kicks are small and not random in space or time:
  - removal is gradual, no loss spikes due to beam jitter on hard-edge collimators
  - resonant excitation tuned to betatron frequencies is possible

Transverse kicks for protons

In cylindrically symmetrical case,

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

Example (TEL2, $\mathbf{v}_p \cdot \mathbf{v}_e > 0$): $I_r = 2.5$ A, $L = 2.0$ m, $\beta_e = 0.19$ (10 kV), $r = 3.5$ mm (5σ)

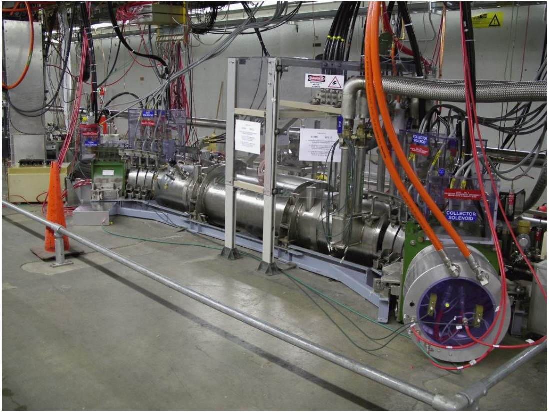
p energy (TeV)	0.150	0.980	7
kicks (μrad):			
hollow-beam max	2.4	0.36	0.051
collimator rms (Tevatron)	110	17	
collimator rms (LHC)			4.5

Hollow-beam collimation concept

- position controlled by magnetic correctors, no motors or bellows
- no ion breakup
- axial magnetic field ensures low impedance, stable beam; reducing the field allows greater range in radii, but may cause instability if residual electric field in hole is nonzero
- 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

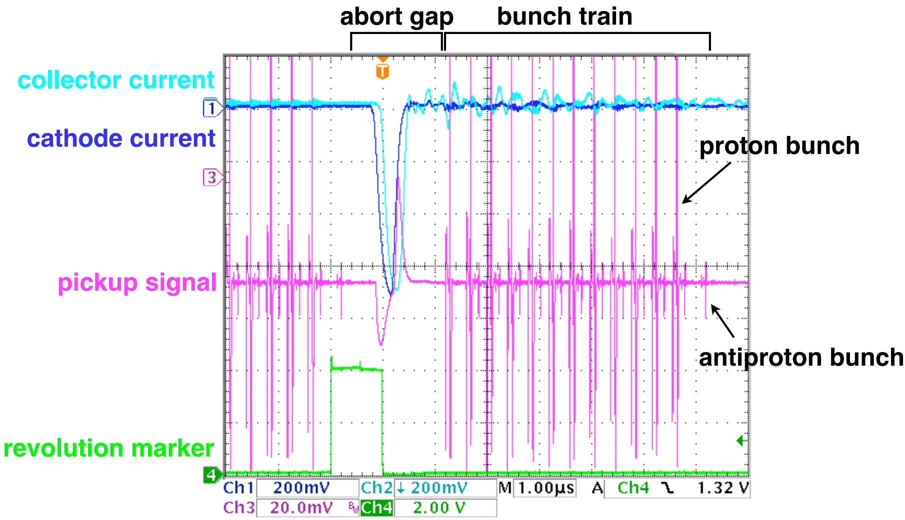


Shiltsev et al., Phys. Rev. ST AB **11**, *103501 (2008)*

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

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

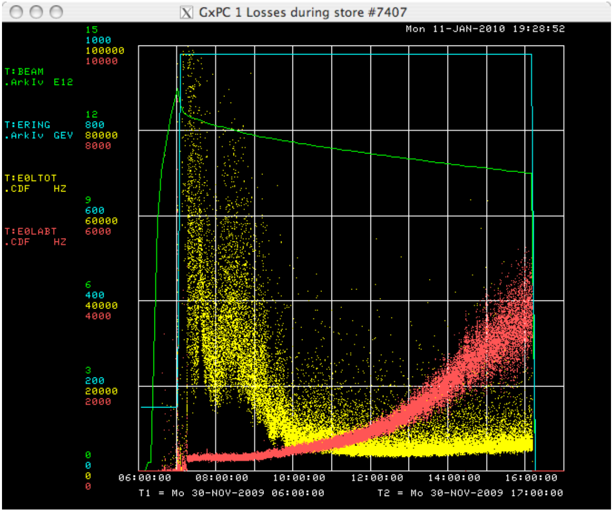
TEL2 timing example



Losses during store #7407

Beam intensity

Ring energy



Total losses show large fluctuations

Abort-gap losses are smooth (TEL1 clearing)

Hollow-beam collimation concept

- hollow beams can be unstable due to space charge forces
- alignment of electron beam is critical
- 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
- large amplitude functions at collimator preferred, 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
- cost: $\approx$ 5 M$ (2 M$ material and supplies, 3 M$ salaries)

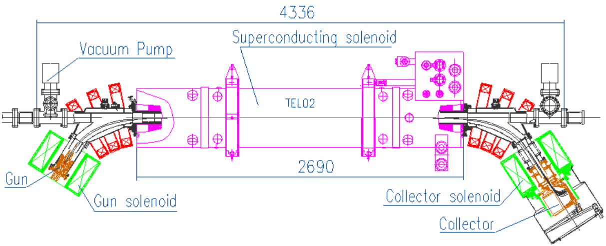
Modeling

kick maps
in overlap region

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

⇒ **tracking software**
with lattice and apertures

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



Simulations with ideal current distribution

Studied halo lifetimes, impact parameter, resonant excitation:

- 1D model (V. Shiltsev, FERMILAB-CONF-07-69)
- `STRUCT` model of Tevatron (A. Drozhdin)
- `lifetrac` model of Tevatron and LHC (A. Valishev)
- `SixTrack` model of LHC (Smith et al., PAC09, SLAC-PUB-13745)

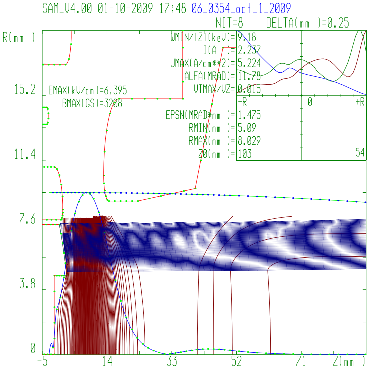
Conclusions of exploratory studies

- HEBC as 'soft-edge' scraper to complement/improve traditional collimation system
- Fast cleaning ('collimation') would require much higher electron currents
- HEBC may allow collimators to be retracted (probably not feasible in LHC)
- resonant kicks are very effective
- effects should be detectable in Tevatron

Design of 15-mm-diameter hollow gun

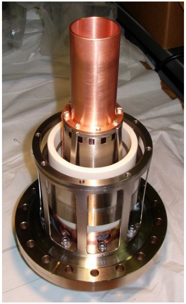
- Convex tungsten dispenser cathode with $BaO:CaO:Al_2O_3$ impregnant
- 7.6-mm outer radius, 4.5-mm-radius bore
- Electrode design based upon existing 0.6-in SEFT TEL2 gun

Calculations with SAM code
(L. Vorobiev)



Mechanical design *(G. Kuznetsov)*

Cathode
(w/o bore)



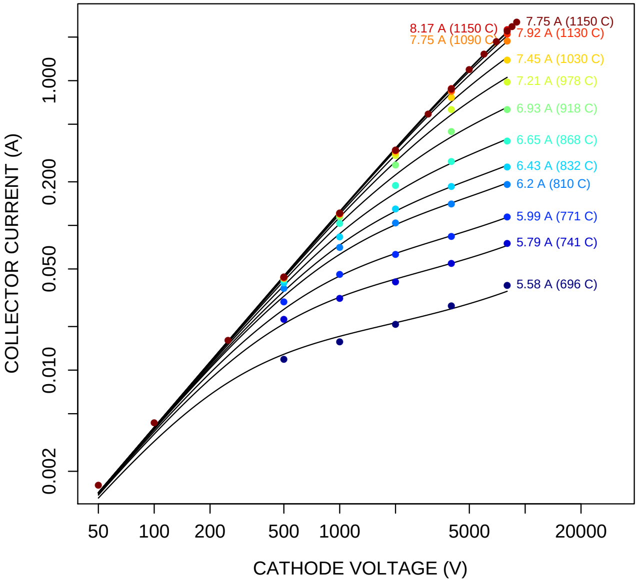
Assembled gun

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

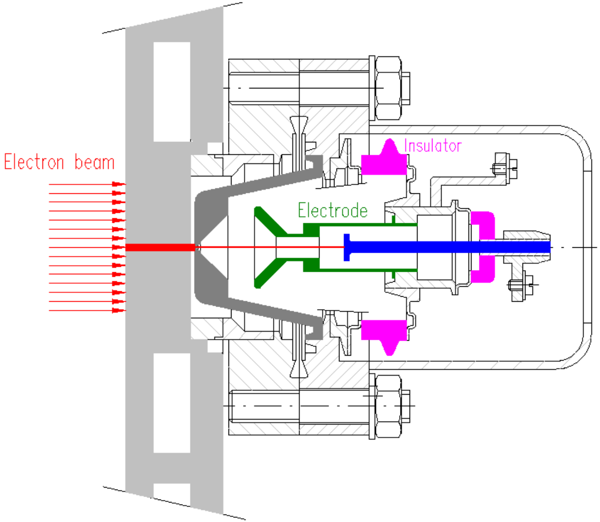
Performance of hollow gun vs voltage and temperature

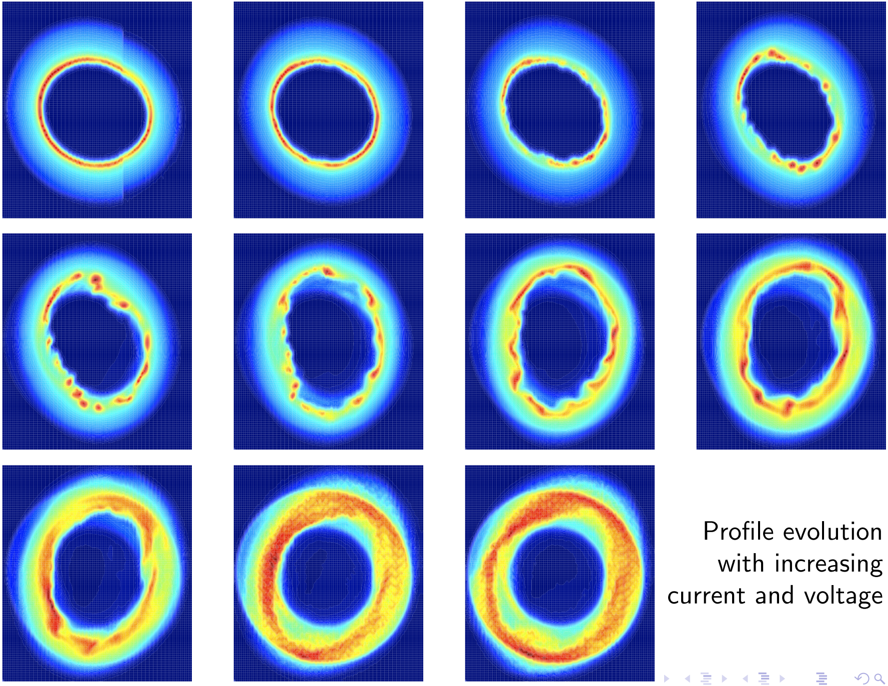


$P = 4\ \mu$perv

Profile measurements

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





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)*

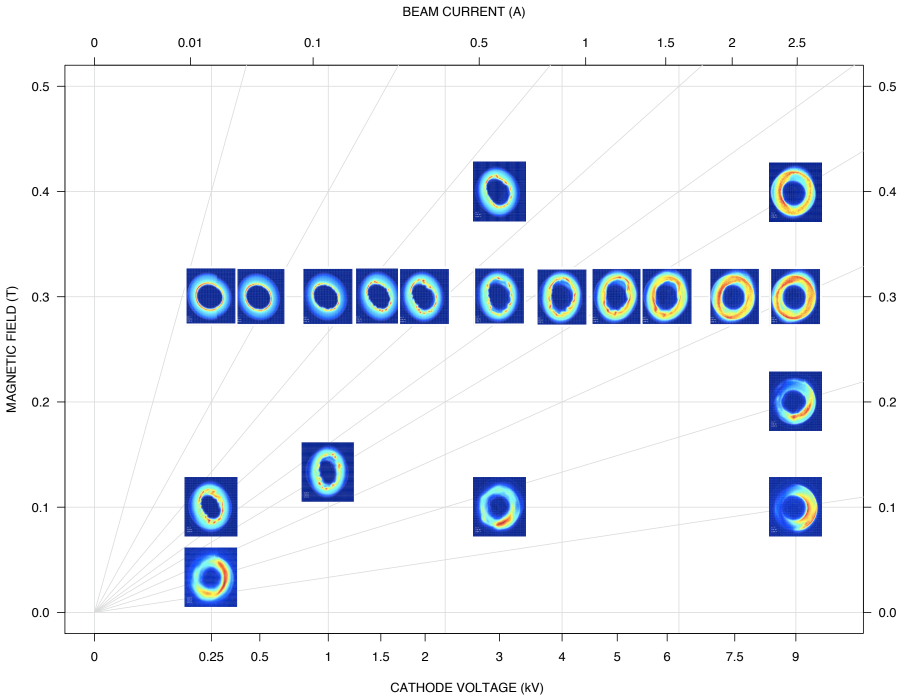
Kapatenakos et al., Phys. Rev. Lett. **30**, *1303 (1973)*

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

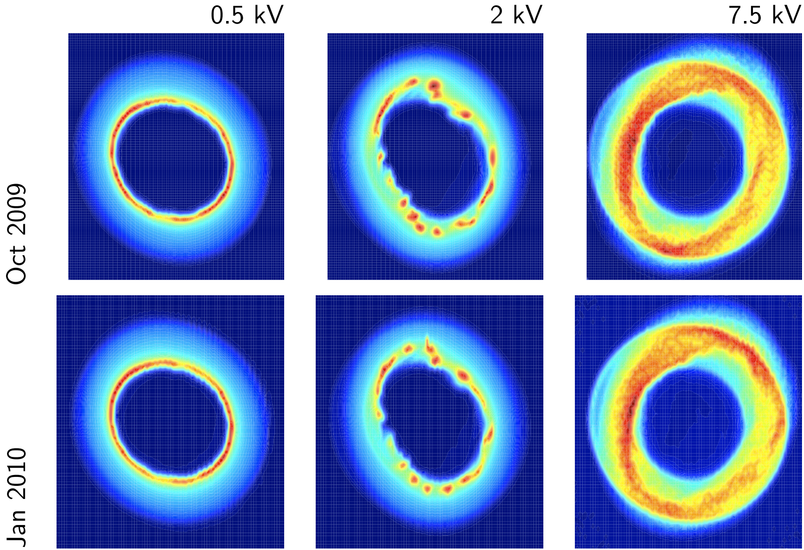
Perrung and Fajans, Phys. Fluids A **5**, *493 (1993)*

Current-density distribution evolves as the beam propagates

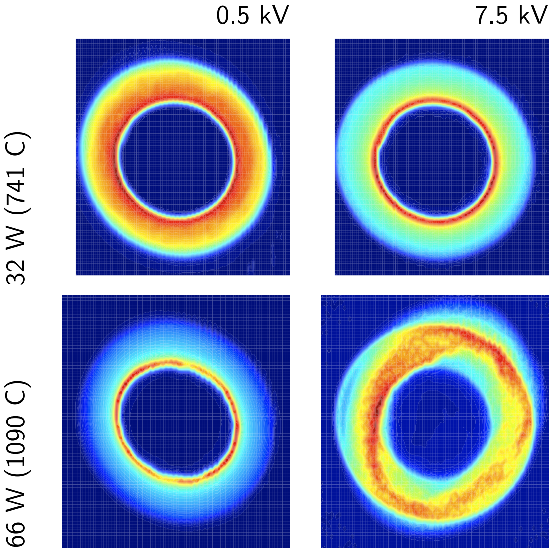
$$\text{(evolution time)} \propto \frac{\text{(current)}}{\text{(magnetic field)} \times \text{(voltage)}}$$


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

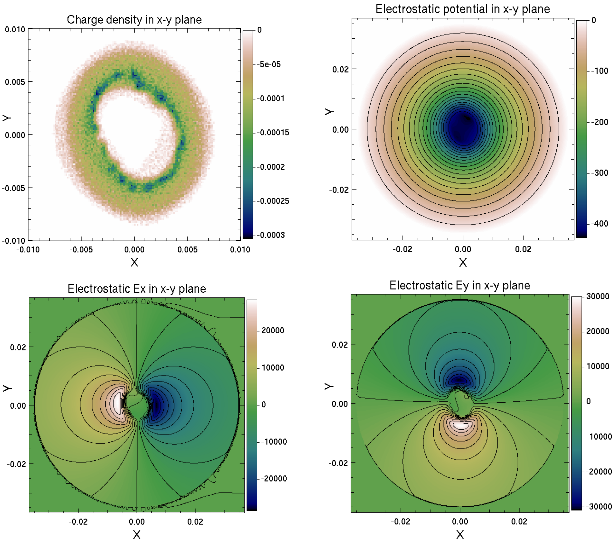
Profile reproducibility



Profiles vs temperature

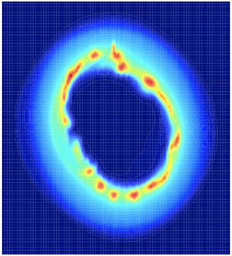


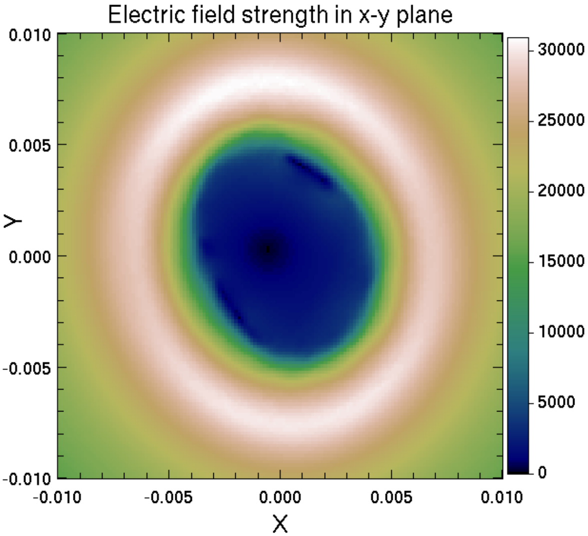
Warp calculation of 2D fields from measured profiles



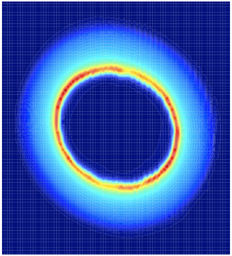
(thanks to D. Grote, J.-L. Vay, M. Venturini (LBNL) for kind support)

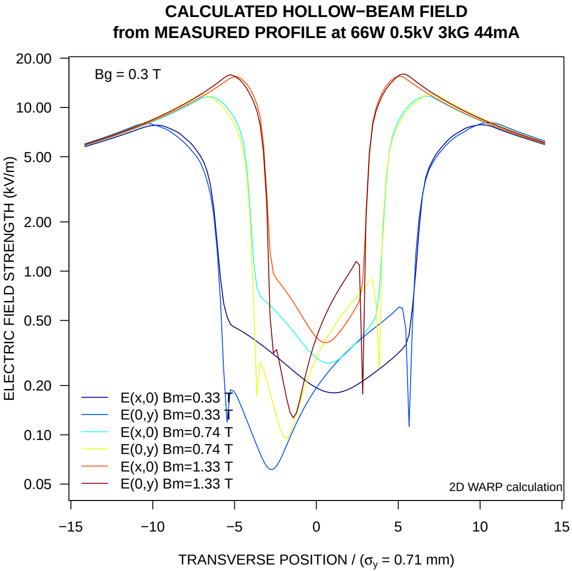
Electric field at 2 kV, 330 mA



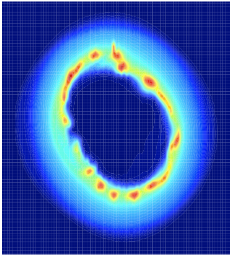


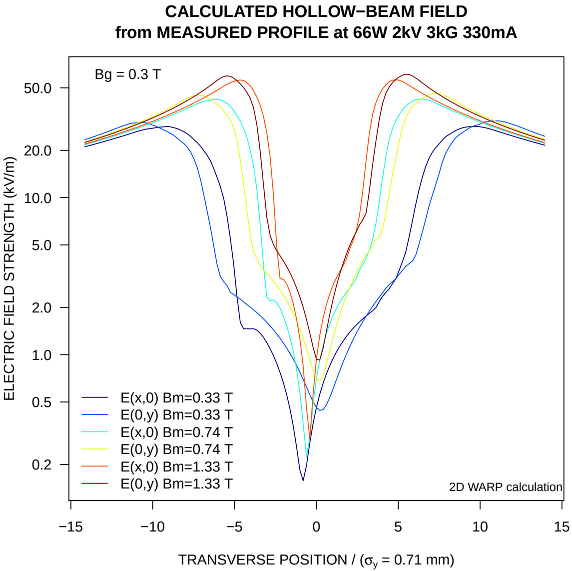
Electric fields at 0.5 kV, 44 mA



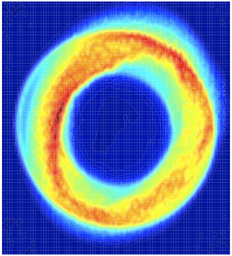


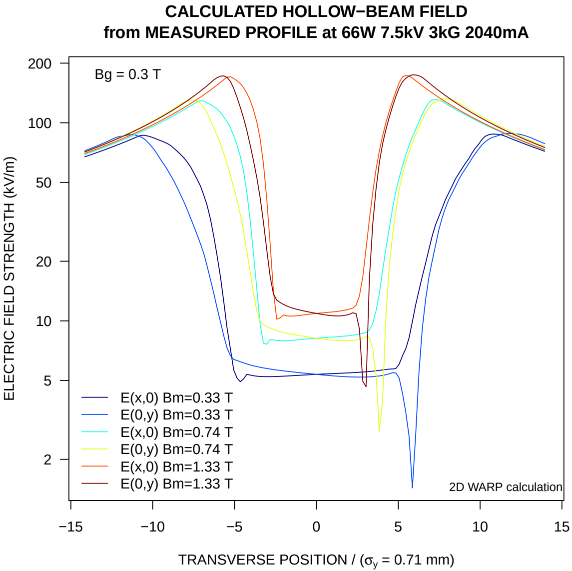
Electric fields at 2 kV, 330 mA



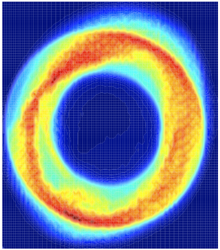


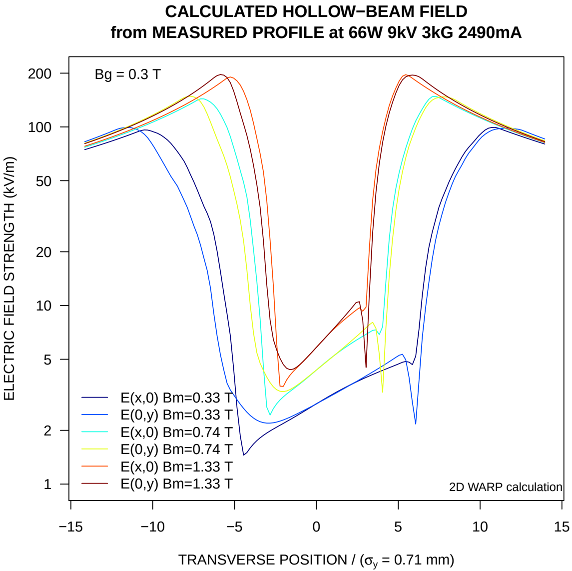
Electric fields at 7.5 kV, 2040 mA





Electric fields at 9 kV, 2490 mA

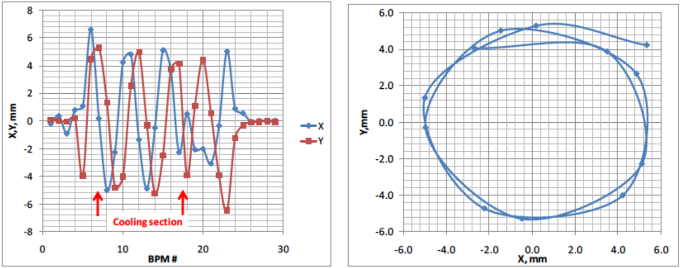




Helical-beam studies in Recycler Ring

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
- Helical electron trajectory generated by upstream correctors



- Indications of scraping: core has longer lifetime than halo
- Very short lifetimes (not understood), work in progress

Planned Tevatron studies with hollow electron beams

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

- Prefer 980 GeV over injection: stable orbits and emittances, collimation system in normal operating conditions (but effect is smaller)
- Take advantage of important TEL2 improvements:
  - Stacked-transformer modulator (faster, complex waveforms)
  - BPM system readout

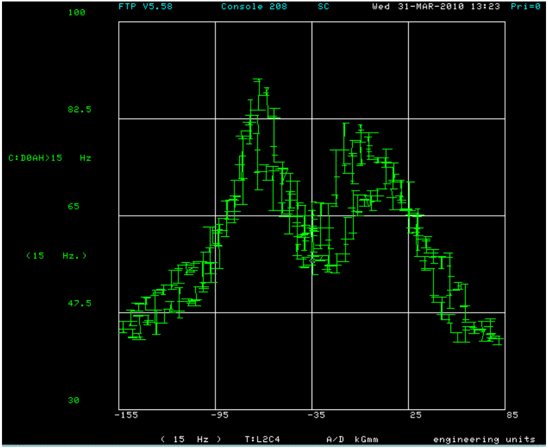
Alignment experiments

Procedure for aligning present TEL2 Gaussian gun:

- Align electrons with (anti)protons according to TEL2 BPMs
- Scan horizontally and vertically
- With nominal tunes, no increase in losses
- By moving lattice tunes closer to resonance, losses depend on position/angle, consistent with Gaussian lens tune shift and nonlinearity

Vertical scan of Gaussian beam on antiprotons

D0 losses for bunch A15

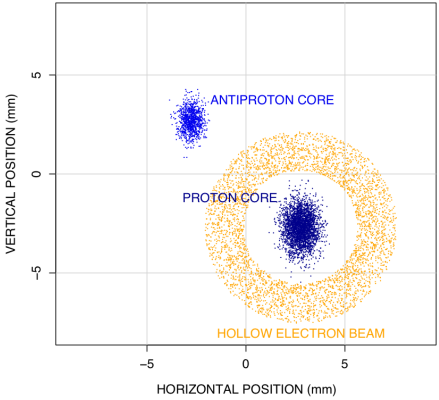


Vertical position (2 mm/div)

Center of loss curve coincides with BPM alignment to within 0.1 mm

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:
  - $\epsilon = 20$ μm (95%, normalized)
  - $\Delta p/p = 1.2 \times 10^{-4}$
  - $x_{\mathrm{co}} = +2.77$ mm, $y_{\mathrm{co}} = -2.69$ mm
  - $\sigma_x = 0.46$ mm, $\sigma_y = 0.71$ mm
- Antiprotons:
  - $\epsilon = 10$ μm (95%, normalized)
  - $\Delta p/p = 1 \times 10^{-4}$
  - $x_{\mathrm{co}} = -2.77$ mm, $y_{\mathrm{co}} = +2.69$ 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
  - $r_{\mathrm{min}} = 2.9$ mm $= 4\sigma_y^p$, $r_{\mathrm{max}} = 4.9$ mm in main solenoid



Next steps

- Modeling:
  - performance vs lattice parameters
  - effect of misalignments, field-line ripple, bends
  - 3D kick maps with bends and profile evolution
- Test bench:
  - time stability of current density within each pulse
  - scaling of hollow beam profiles with I, V, B
  - design and test 25-mm cathode ($\sim$7 A) with smoother profile
- Recycler Ring:
  - Continue 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