Collimation of high-energy hadrons with hollow electron beams

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In collaboration with

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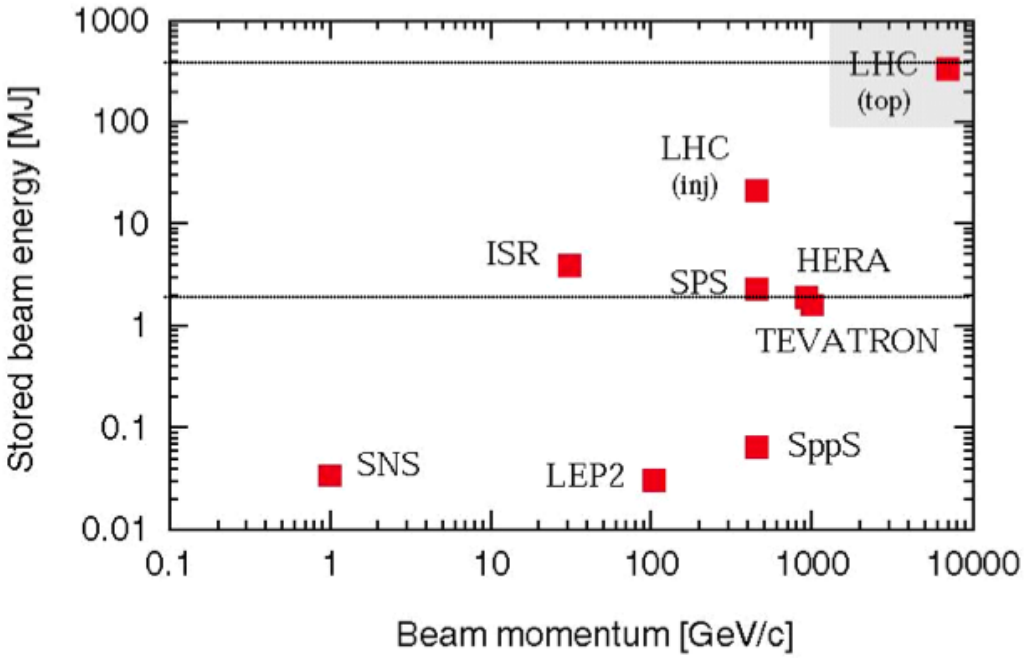
- G. Kuznetsov, A. Romanov (BINP Novosibirsk)
- J. Smith (SLAC)

Motivation

- In high-energy colliders, stored beam energy can be large:



R. Assmann et al., EPAC02

- Beam-beam collisions, intrabeam scattering, beam-gas scattering, rf noise, resonances, ground motion, etc. contribute to formation of beam halo
- Uncontrolled particle losses of even a small fraction of the circulating beam can damage components, quench superconducting magnets, produce intolerable experimental backgrounds

Motivation

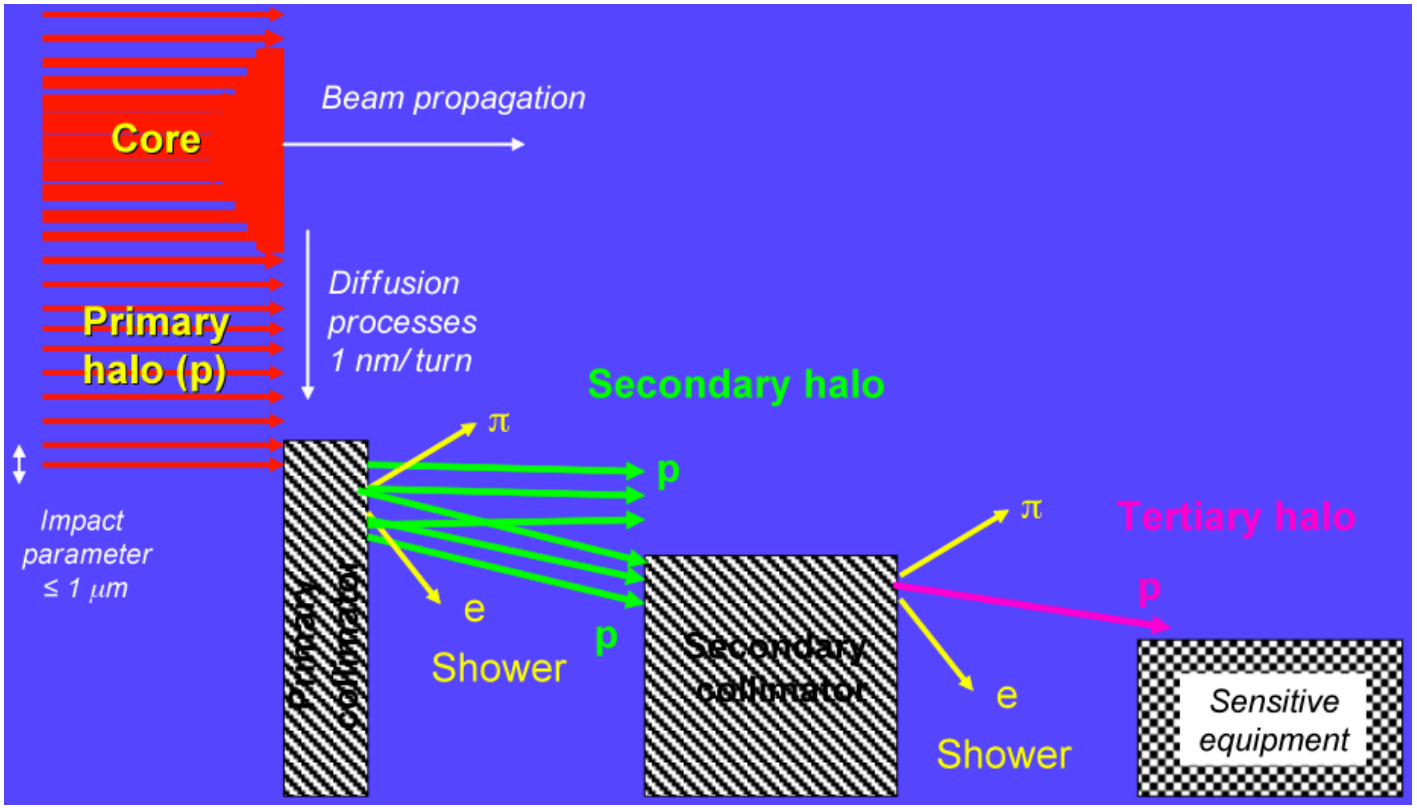
Goals of collimation:

1. reduce beam halo
2. concentrate losses in absorbers

Conventional schemes:

collimators (5-mm W at 5σ in Tevatron, 0.6-m carbon jaw at 6σ in LHC)

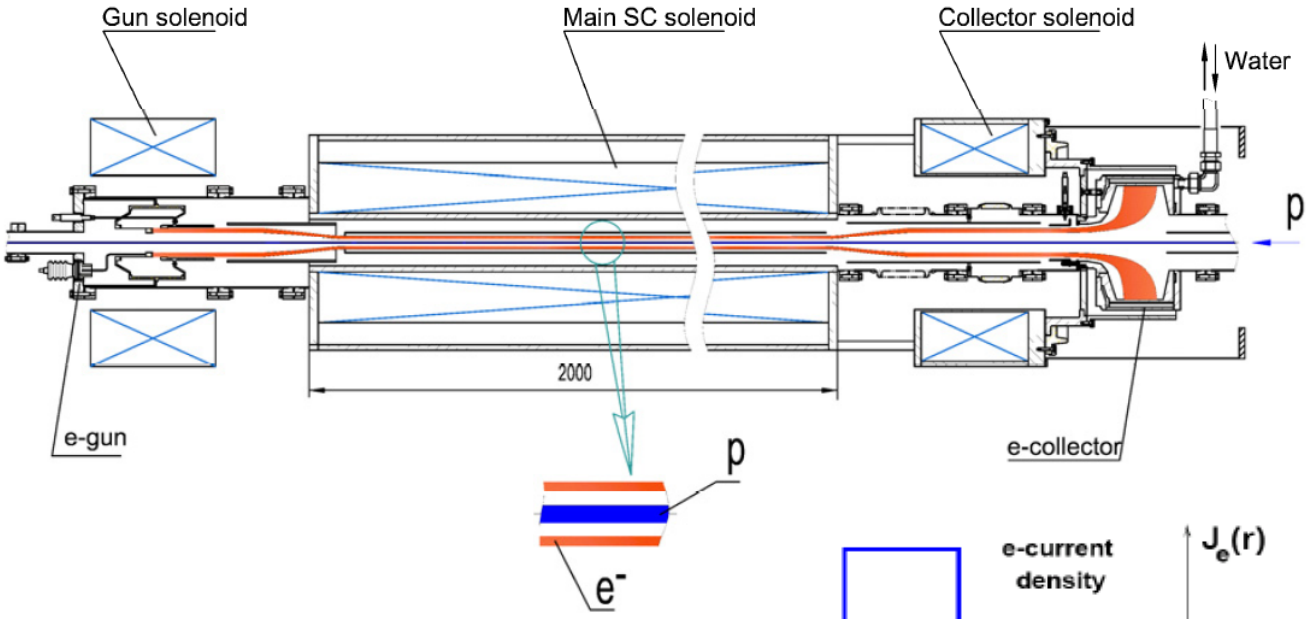
absorbers (1.5-m steel jaws at 6σ in Tevatron, 1-m carbon/copper at 7σ in LHC)



R. Assmann

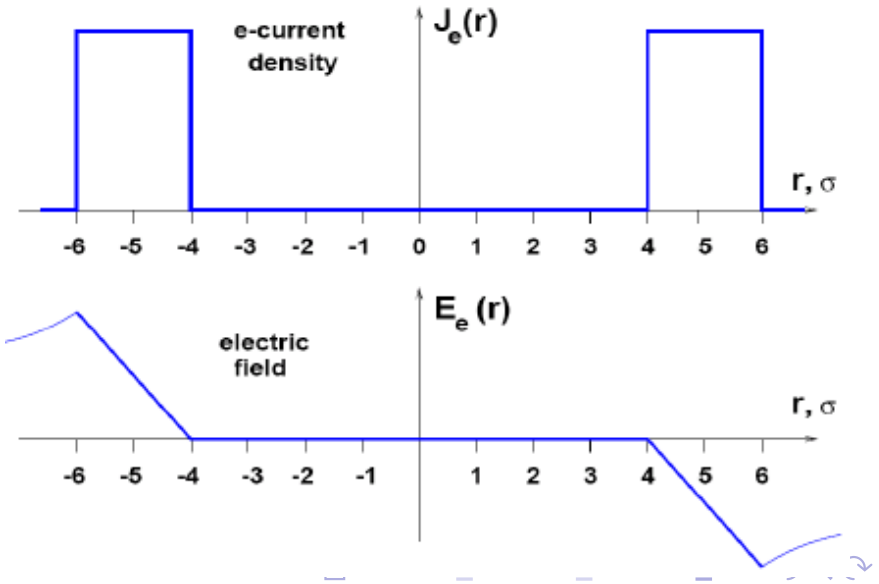
Concept of hollow electron beam collimator (HEBC)

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



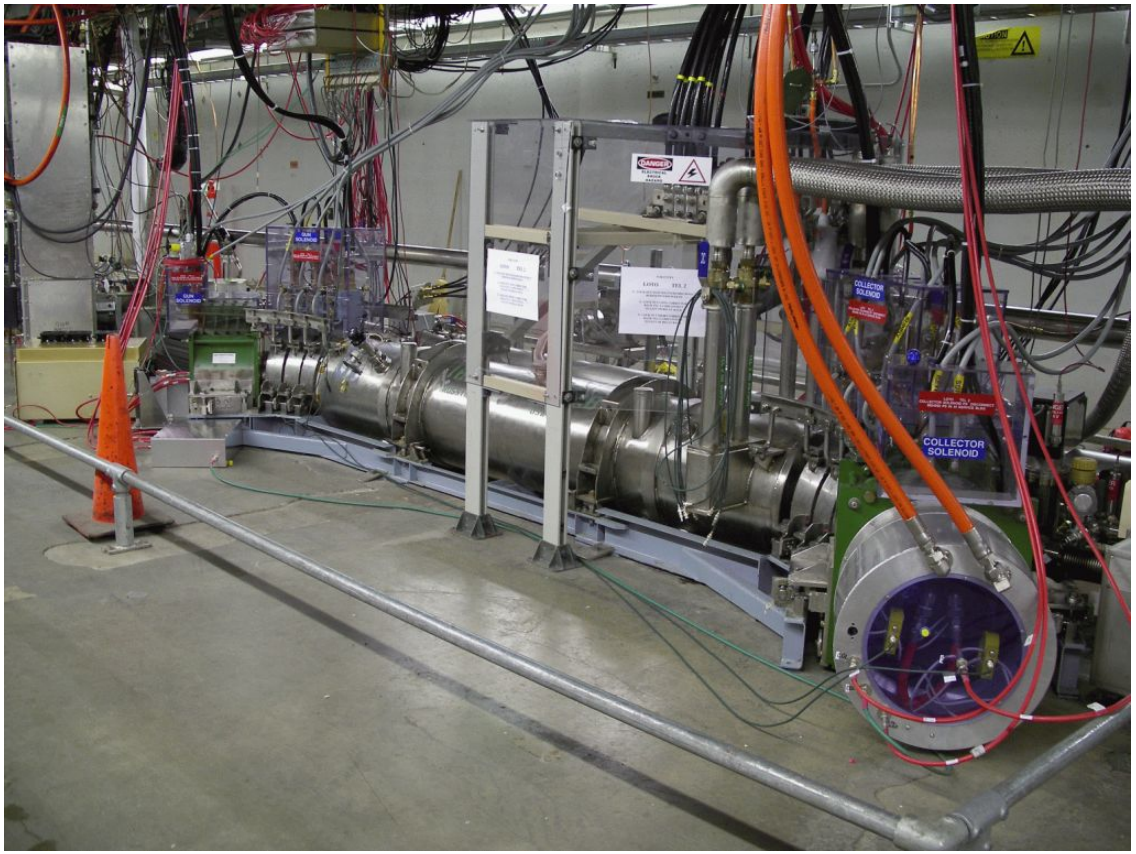
Hollow-beam collimation concept

Advantages

- electron beam can be placed closer to core ($\sim$ 3–4σ)
- no material damage
- lower impedance, no instabilities
- position controlled by magnetic field, no motors or bellows
- gradual removal, reduction in loss spikes
- no ion breakup
- transverse kicks are not random $\rightarrow$ resonant excitation tuned to betatron oscillation period
- estabilished technological and operational experience with electron cooling and Tevatron electron lenses

Existing Tevatron electron lenses

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

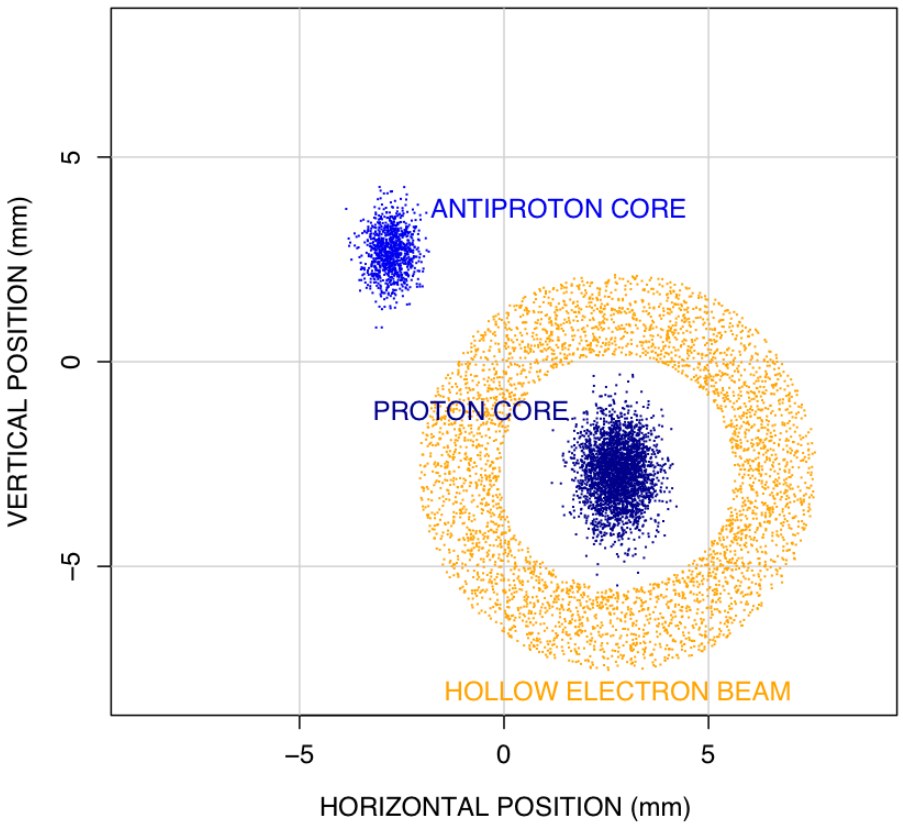


Typical parameters	
Peak energy	10 kV
Peak current	3 A
Max gun field B_g	0.3 T
Max main field B_m	6.5 T
Length L	2 m
Rep. period	21 μs
Rise time	<200 ns

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

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)
  - $\Delta p/p = 1.2 \times 10^{-4}$
  - $x_{\rm co} = +2.77$ mm, $y_{\rm co} = -2.69$ mm
  - $\sigma_x = 0.46$ mm, $\sigma_y = 0.71$ mm
- Antiprotons:
  - $\epsilon = 10$ μm (95%, normalized)
  - $\Delta p/p = 1 \times 10^{-4}$
  - $x_{\rm co} = -2.77$ 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: $\sim 4\sigma$ + field line ripple ($\sim$0.1 mm)
- Transverse compression controlled by field ratio B_m/B_g; limited by min B_g (sufficient for confinement) and max B_m ($\sim$ 10 T)
- 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

Transverse kicks for protons

$$\theta_{max} \simeq \frac{2\,I\,L\,(1 \pm \beta_e \beta_p)}{r_{max}\,\beta_e\,\beta_p\,c^2\,(B\rho)_p}\left(\frac{1}{4\pi\epsilon_0}\right) \qquad \begin{array}{ll} - & \text{copropagating} \\ + & \text{counterpropagating} \end{array}$$

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

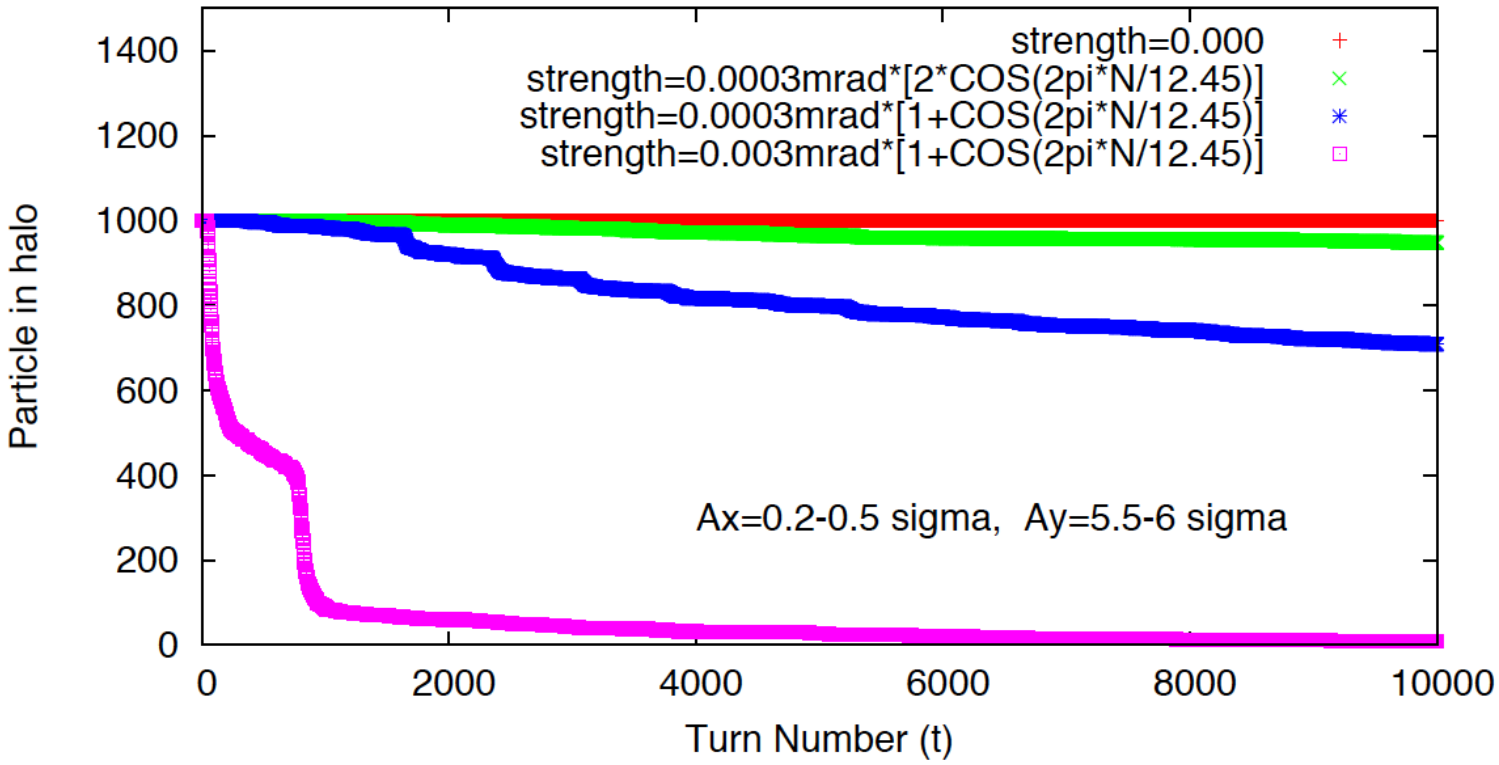
$I = 2.5$ A $\quad L = 2.0$ m $\quad \beta_e = 0.19$ (10 kV) $\quad r_{max} = 3.5$ mm (5σ in TEL2)

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

Simulation of HEBC in Tevatron

A. Drozhdin

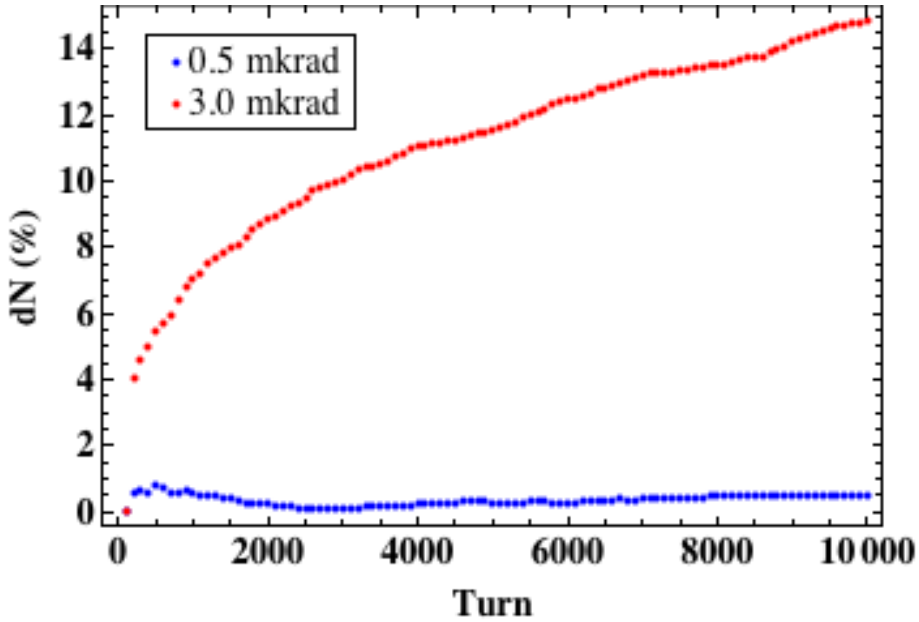
- STRUCT code, complete description of element apertures, helices, rf cavities, sextupoles
- Halo defined as $[5\sigma < x < 5.5\sigma, 0.2\sigma < y < 0.5\sigma]$ or $[0.2\sigma < x < 0.5\sigma, 5.5\sigma < y < 6\sigma]$
- Hollow beam $5\sigma < r < 6.4\sigma$
- Effect of resonant excitation



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



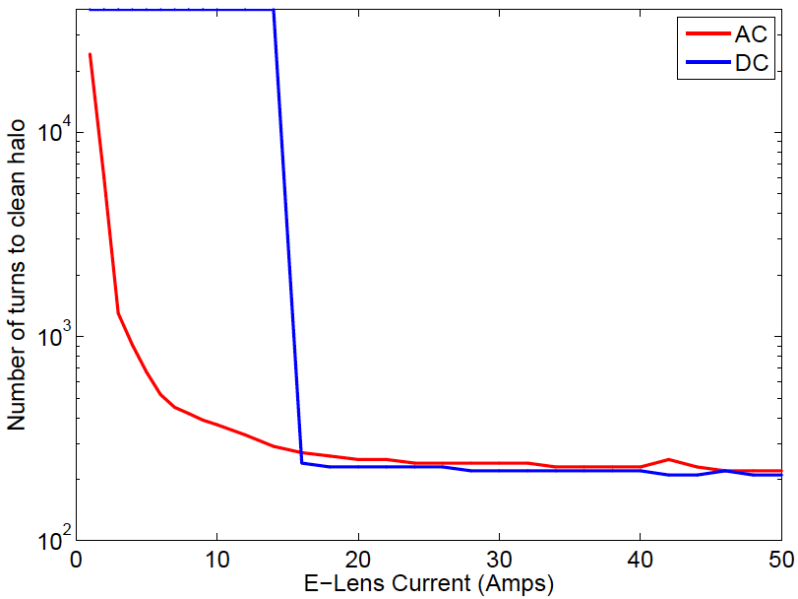
Halo losses vs turn number for maximum kick of 0.5 μrad and 3.0 μrad

Simulation of HEBC in LHC

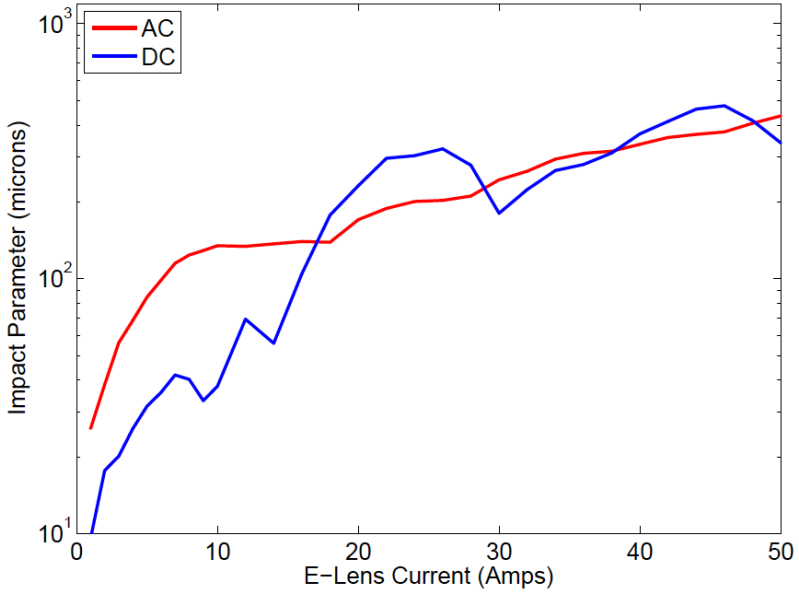
Smith et al., PAC09, SLAC-PUB-13745

- `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



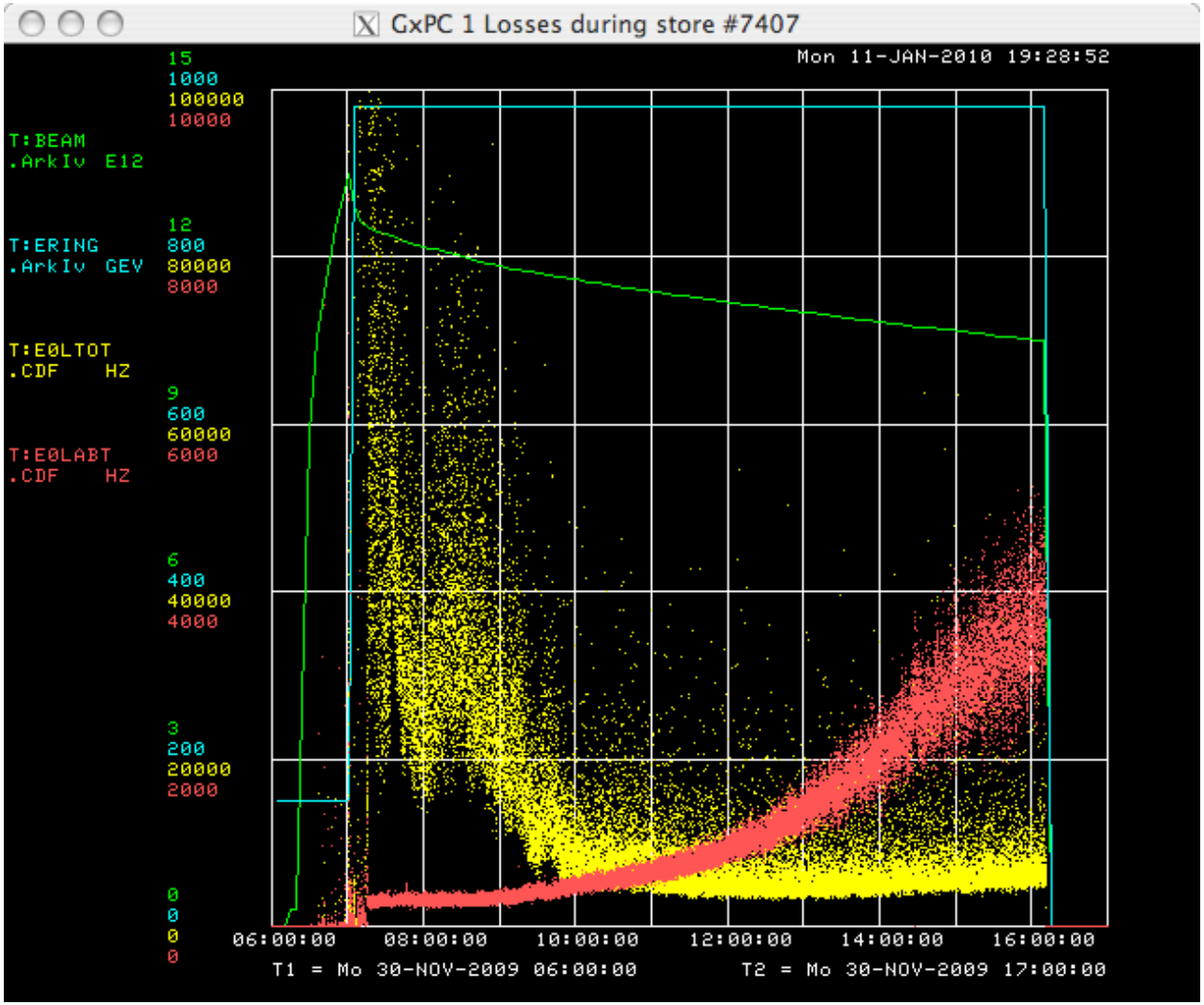
significant increase in impact parameter



Collimation scenarios

- HEBC probably too weak to replace collimators → 'staged' collimation scheme: HEBC + collimators + absorbers
- increase in impact parameter can be significant
- HEBC may allow collimators to be retracted
- resonant kicks are very effective
- tune shifts probably to small to drive lattice resonances
- effects should be detectable in Tevatron
- HEBC can act as 'soft' collimator to avoid loss spikes generated by beam jitter

Loss spikes during store #7407

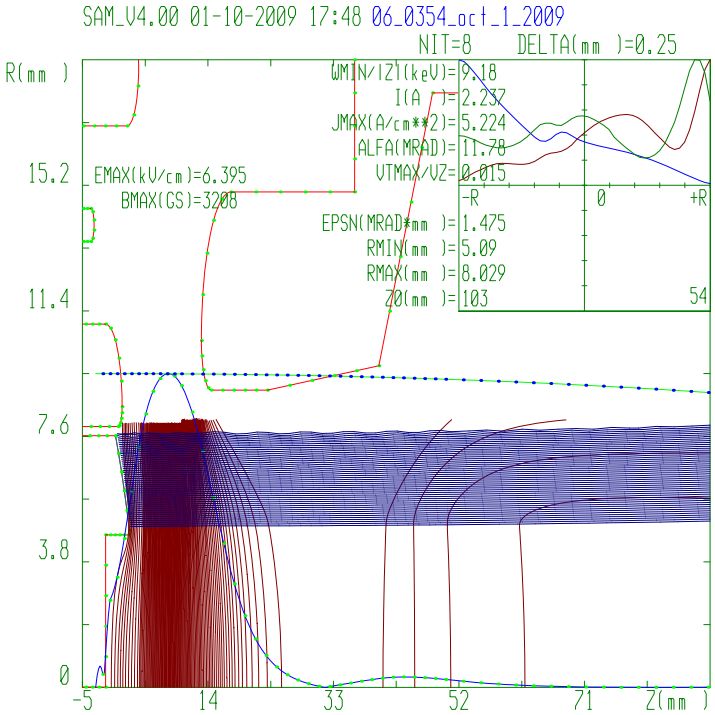


1) Beam intensity 2) Ring energy
3) E0 total losses 4) E0 abort-gap losses

Design of 15-mm-diameter hollow gun

- several approaches to high-perveance hollow-beam design, eg immersed Brillouin cathodes (magnetron injection guns)
- present design based upon existing 0.6-in SEFT (soft-edge, flat-top) convex gun used in TEL2

Calculations with SAM code:

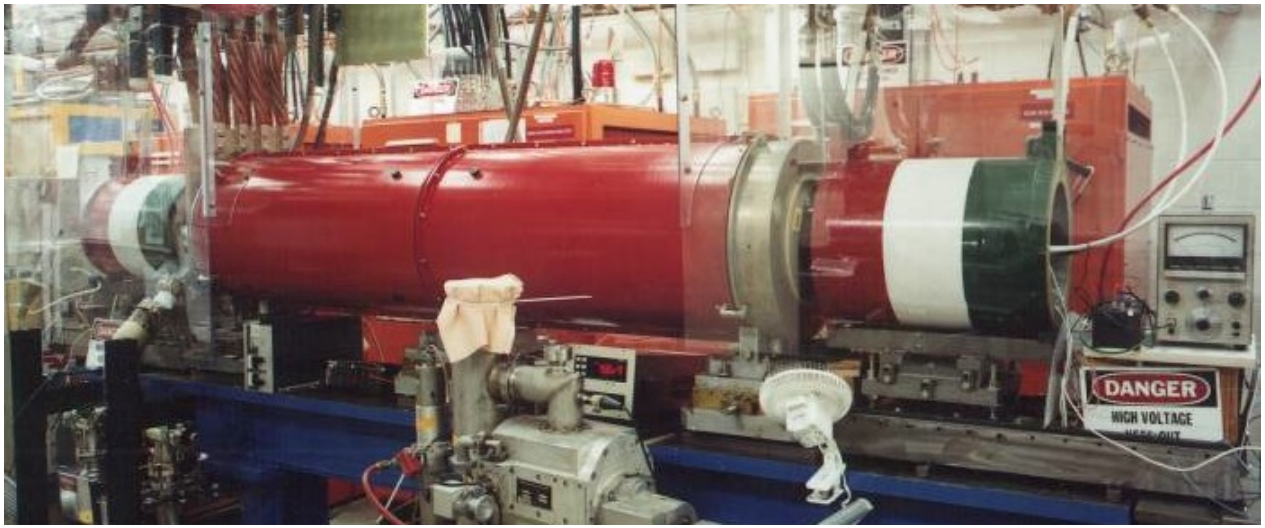


Mechanical design:

L. Vorobiev *G. Kuznetsov*

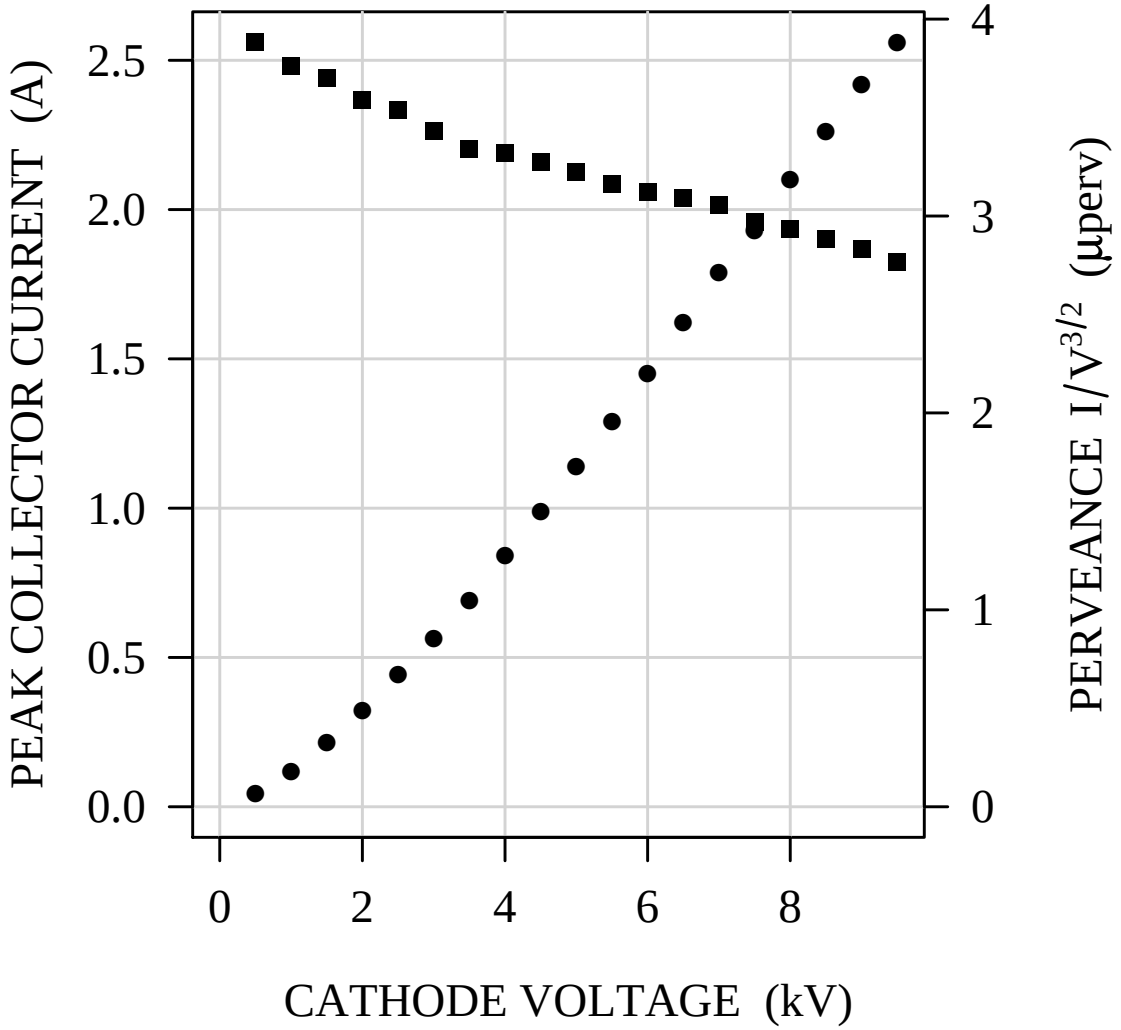
Test bench at Fermilab

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

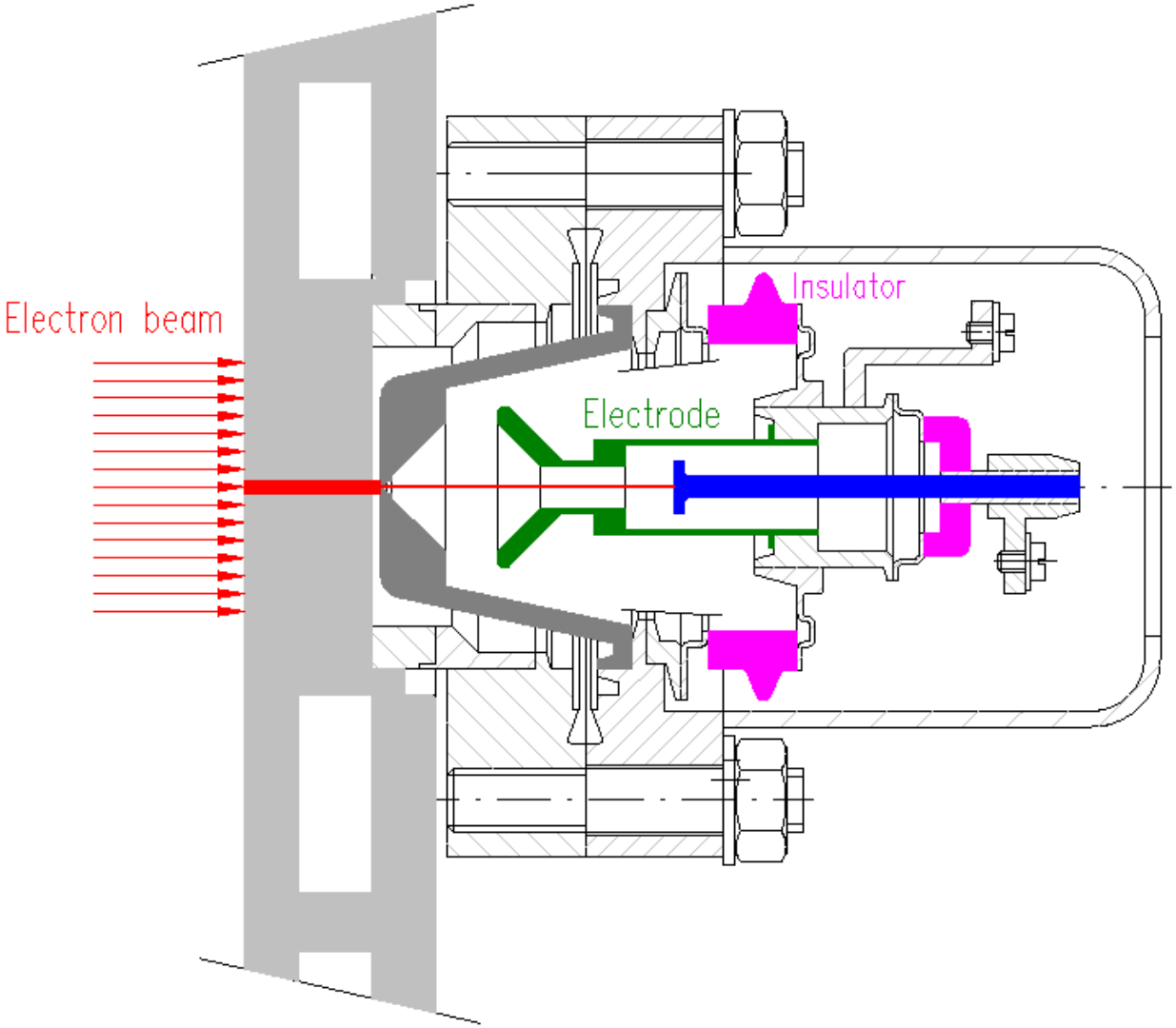
Current vs voltage of 15-mm hollow cathode



Filament heater: 66 W (1400 K)

Profile measurements

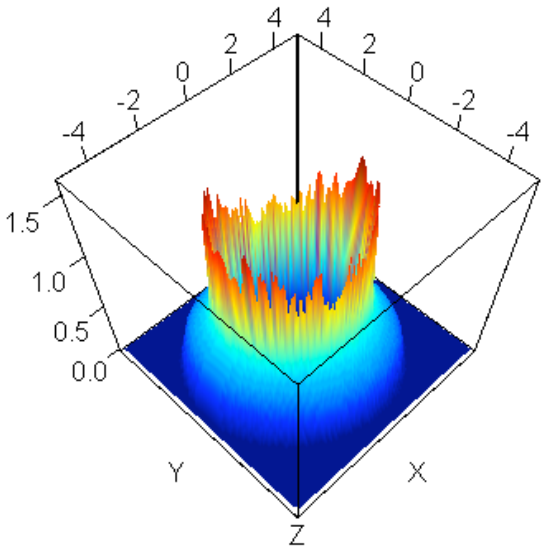
- Horizontal and vertical magnetic steerers deflect electron beam
- Current through 0.2-mm-diam. pinhole is measured vs steerer strength

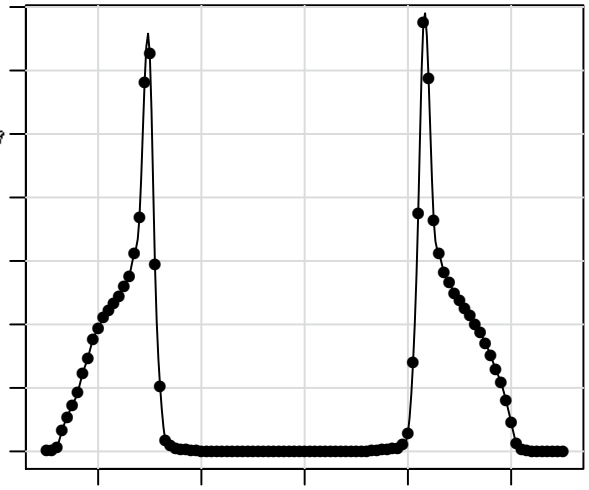


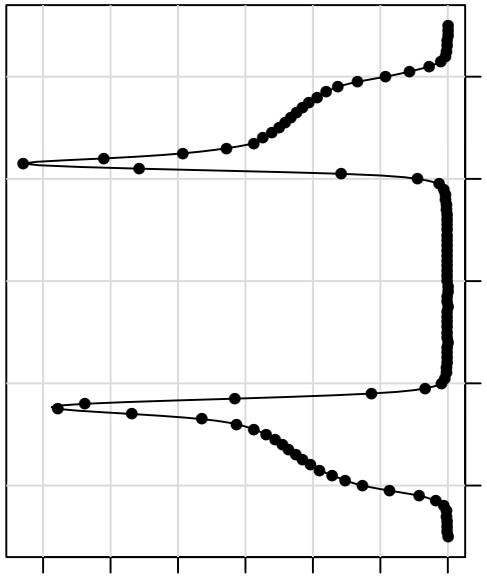
Measured profile: 0.5 kV 44 mA 0.3 T

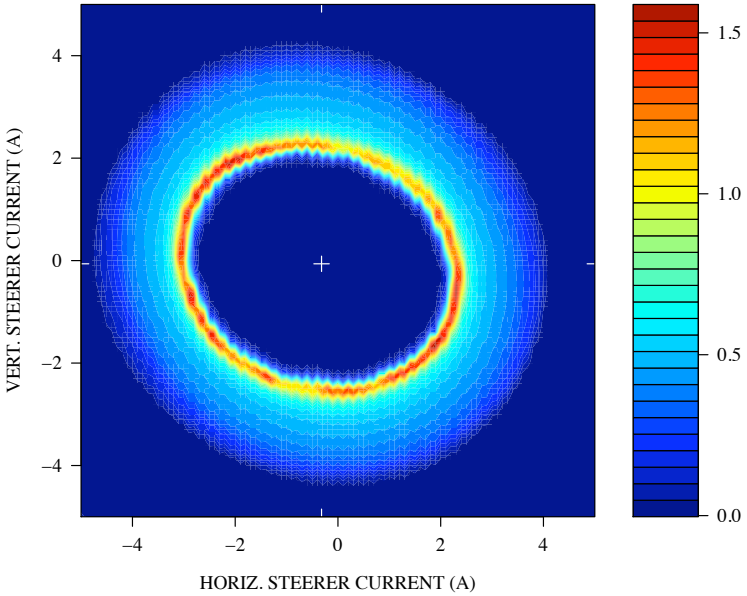
HOLLOW GUN
October 21, 2009

Vacuum: 2×10^{-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





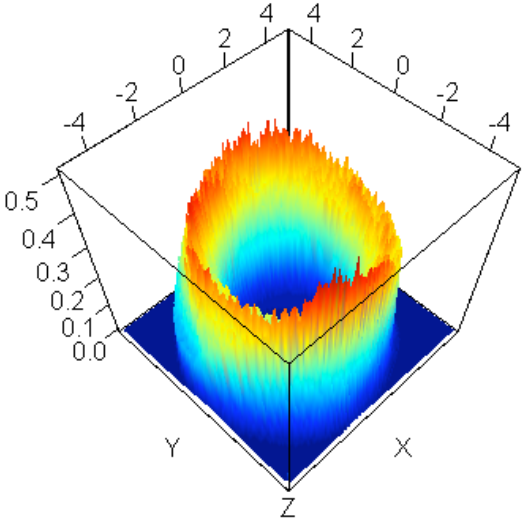


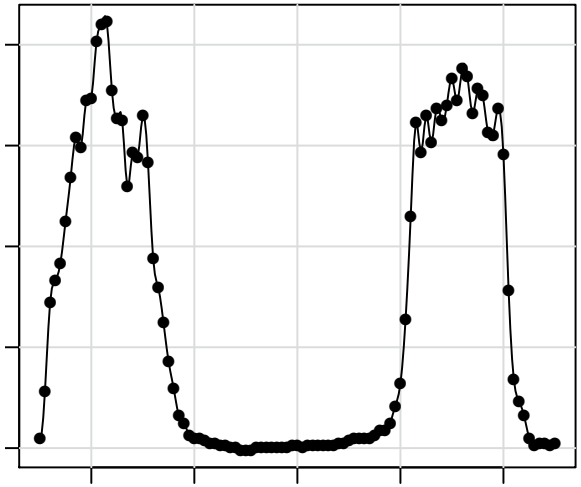


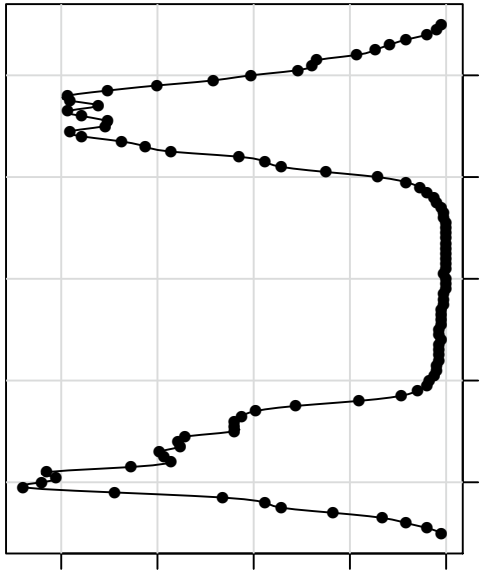
Measured profile: 9.0 kV 2.5 A 0.3 T

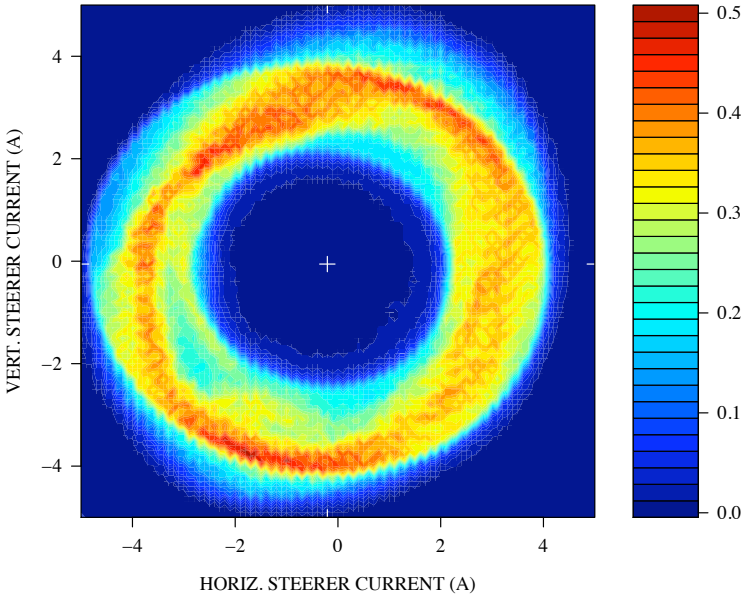
HOLLOW GUN
October 26, 2009

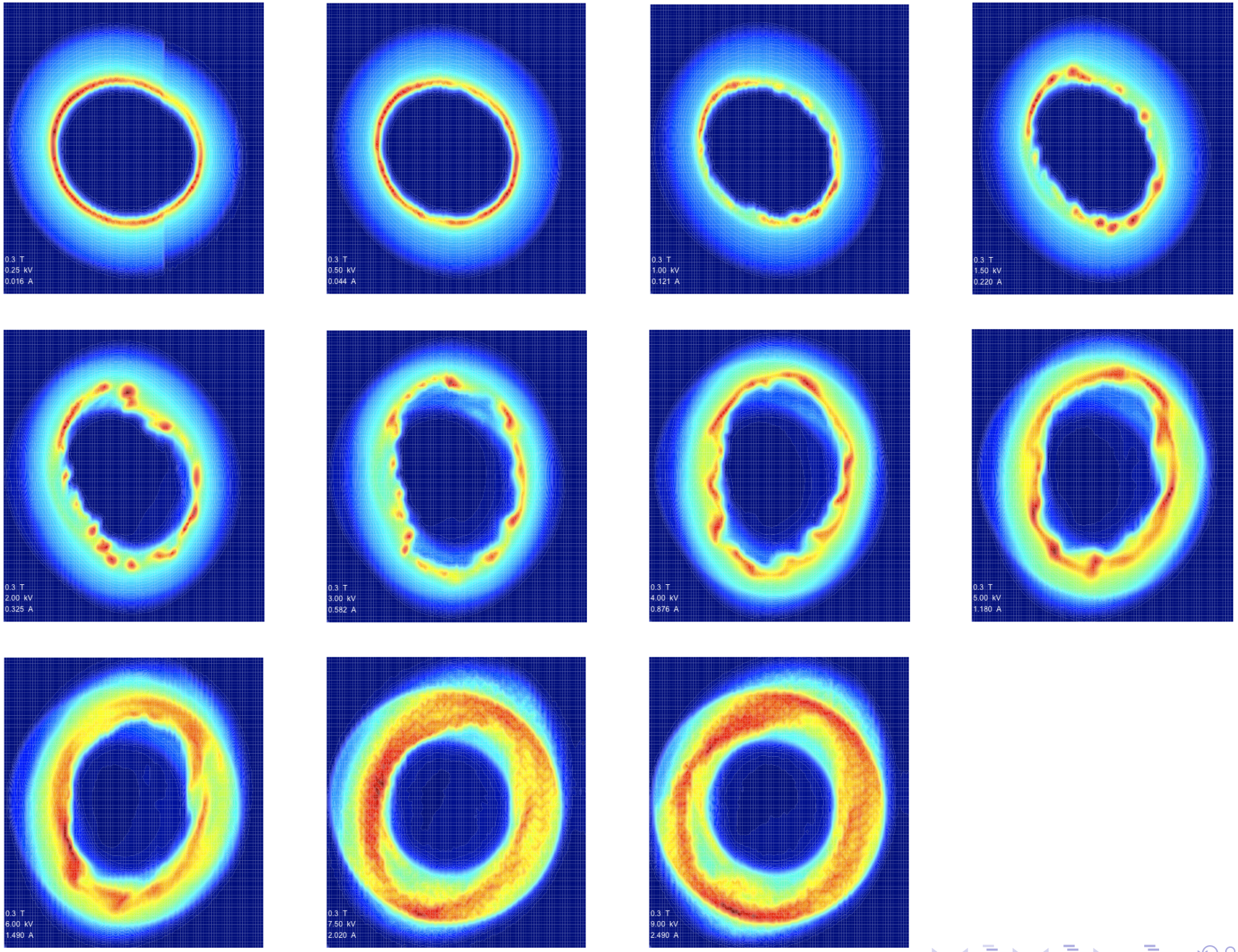
Vacuum: 2×10^{-8} mbar
Filament: 66 W (7.75 A)
Cathode voltage: -9.0 kV
HV PS current: 1.43 mA
Pulse width: 6 us
Rep. period: 80 ms
Peak current: 2.5 A
Solenoids: 3-3-3 kG










0.3 T
0.25 kV
0.016 A
0.3 T
0.50 kV
0.044 A
0.3 T
1.00 kV
0.121 A
0.3 T
1.50 kV
0.220 A
0.3 T
2.00 kV
0.325 A
0.3 T
3.00 kV
0.582 A
0.3 T
4.00 kV
0.876 A
0.3 T
5.00 kV
1.180 A
0.3 T
6.00 kV
1.490 A
0.3 T
7.50 kV
2.020 A
0.3 T
9.00 kV
2.490 A

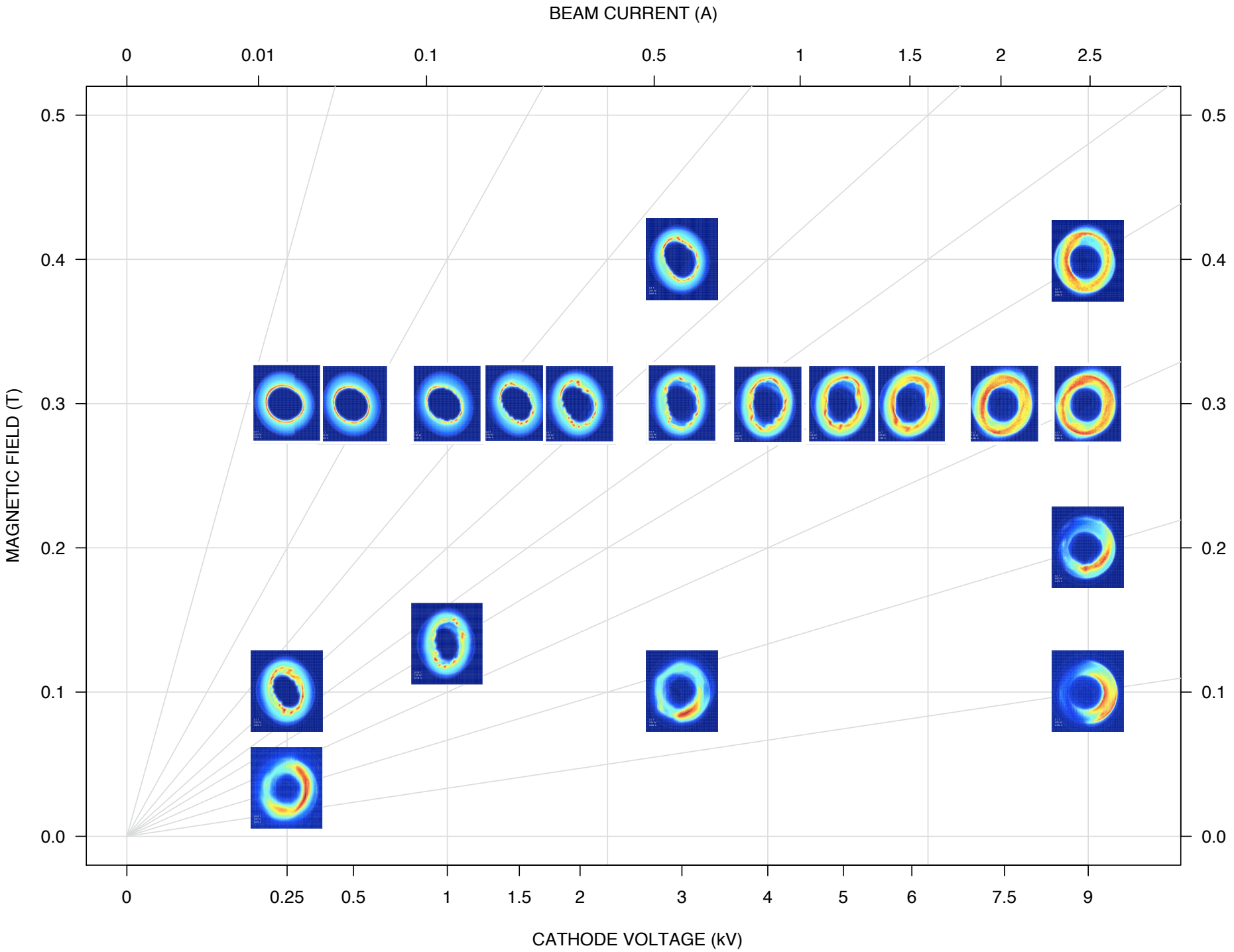
Hollow-beam instabilities

- Profiles measured 2.8 m downstream of cathode
- In previous plots, magnetic field kept constant at 0.3 T
- Space-charge forces are not uniform
- 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)

Properties of hollow profiles

- Interesting nonneutral plasma physics; all well known?
- For predicting profiles and electric field distributions in TEL2:
  - Simulation and modeling:
    Warp / Synergia / Dubin's code (UCSD) — work in progress
  - Experimental investigation of scaling properties of profiles in test bench:
    - from dimensional analysis of fundamental equations one expects $I \sim V^{3/2}$ (Child-Langmuir law)
    - to preserve transverse profiles ($\sim L$), one finds $B \sim V^{1/2} \sim I^{1/3}$


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

Next steps

- Simulations:
  - code comparison under common scenarios
  - performance vs lattice parameters
  - uneven B-field lines
  - realistic current profiles (smooth, asymmetric, . . .)
- Test bench:
  - Study evolution of hollow beam
  - Design and test 25-mm cathode to reach ∼7 A?
- Tevatron:
  - Test abort-gap clearing with Gaussian gun
  - Measure tune-spread changes with Gaussian gun (beam-beam compensation project)
  - Install 15-mm hollow gun in TEL2
  - Start parasitical and dedicated studies

Tevatron studies at 980 GeV

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

- Proton-only store sufficient for preliminary alignment
- Need colliding beams for bulk of study
- Will try to use available study time during Run II
- For dedicated run, foresee $\sim$5 8-hour shifts
- If other installations are planned during dedicated run, space shifts to allow for possible setup changes (e.g., try new gun = 1 4-hour access + 2 days of pumping)

Thank you for your attention