Experimental and numerical studies on the proposed application of hollow electron beam collimation for the LHC at CERN

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Vince Moens, 11.04.2013

Personal Introduction

<u>Vince Moens</u>

Semester thesis 2012 @ CERN

"A quantitative comparison of the transverse damping and tune resonance crossing loss map techniques at the LHC"

Master thesis 2013 @ CERN & Fermilab

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Introduction & Concept

- Hollow Electron Beam Collimation
- HEBC experience at Tevatron
- Focus of this work

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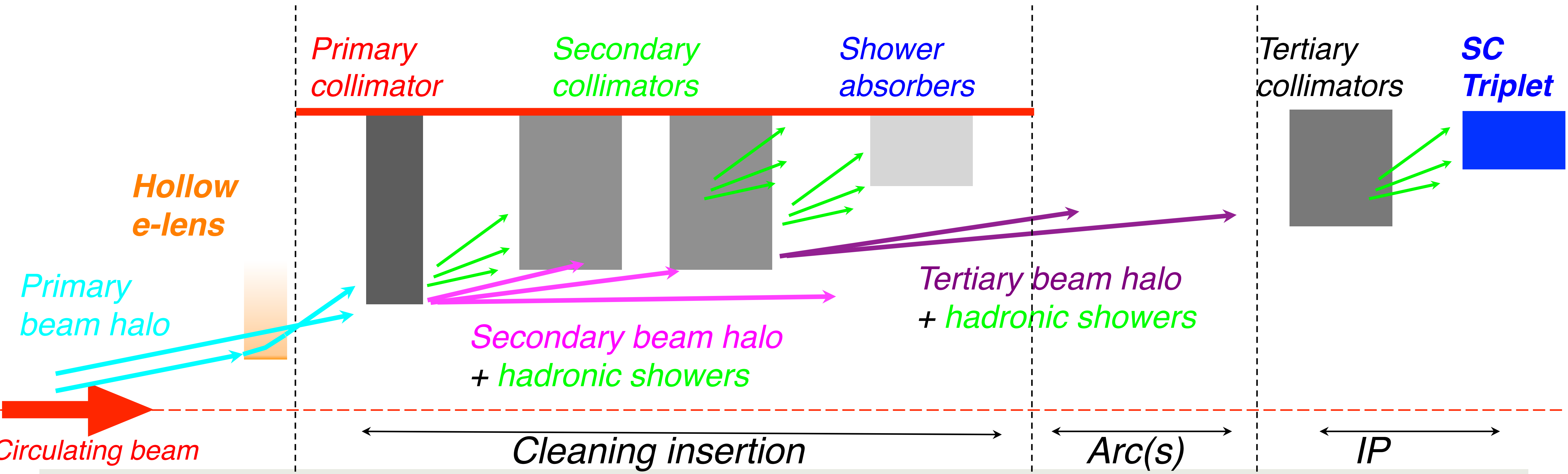
http://anim3d.web.cern.ch/

Hollow Electron Beam Collimation

- Hollow electron beam studies for LHC collimation part of US-LARP since 2009:

Hollow Electron Beam Collimation is the enhancement of diffusion of halo particles through the use of the transverse electric fields of a hollow electron beam.

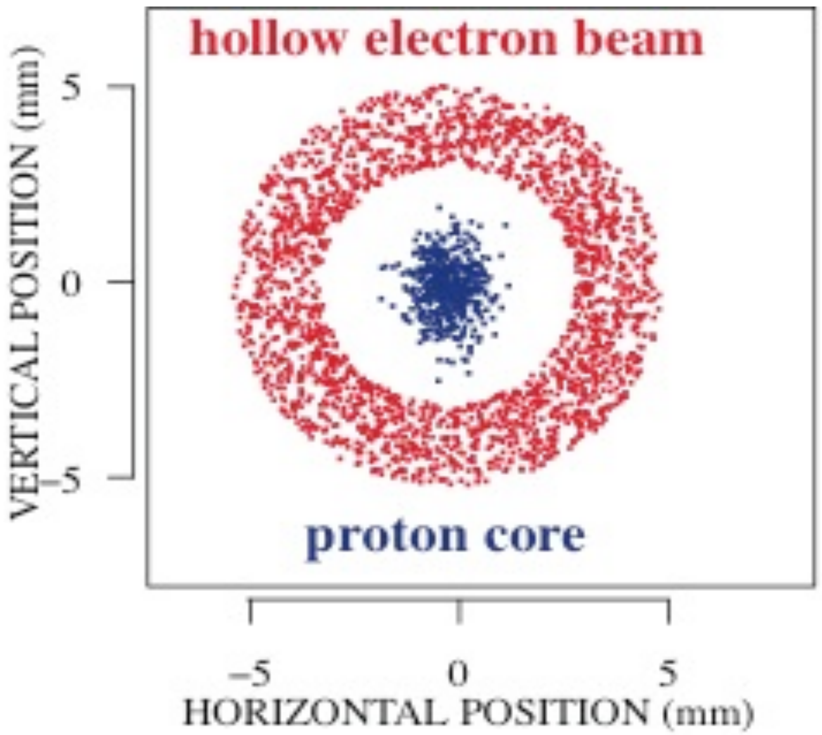
- Technique aimed at improving current system (hierarchy remains)
  - Fully compatible with present and future systems
- Installation point is flexible

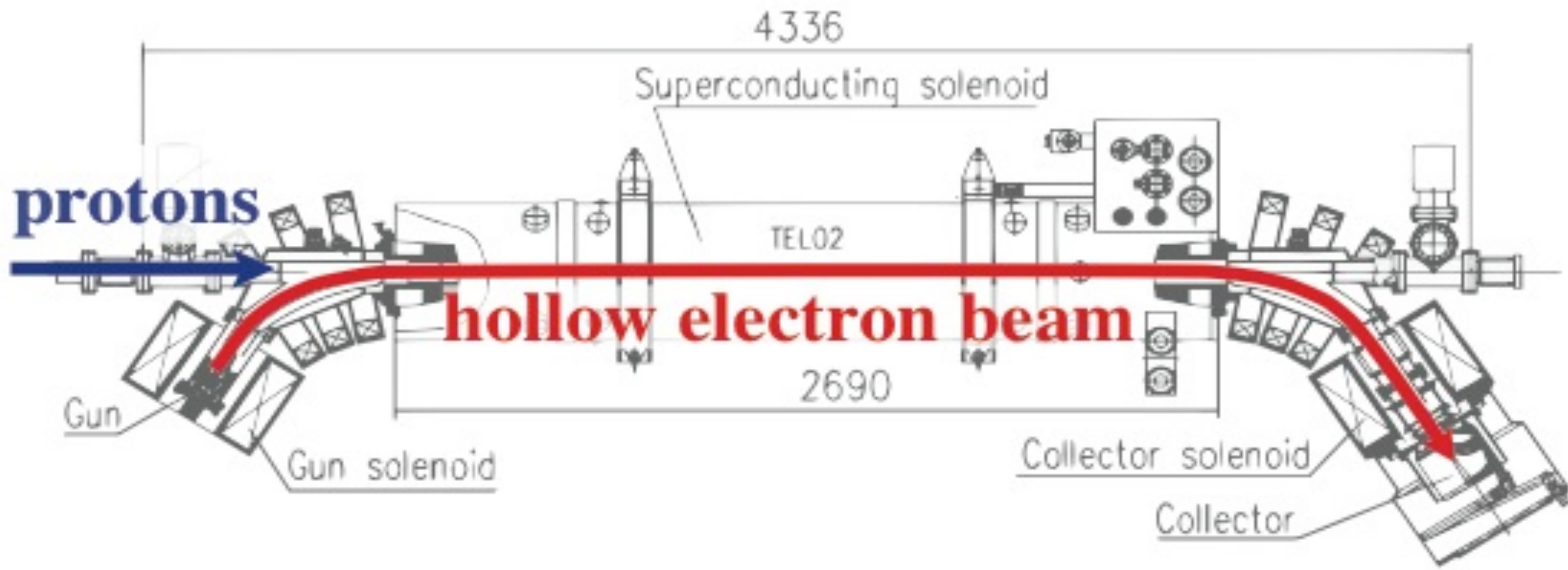


Illustrative scheme form Stefano redaelli

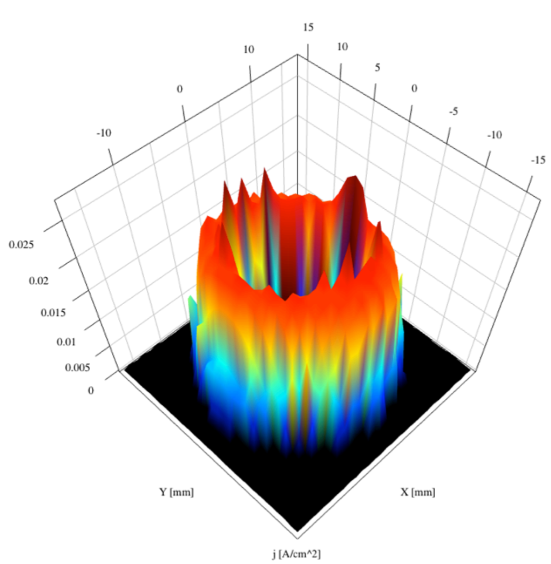
Hollow Electron Beam Collimation

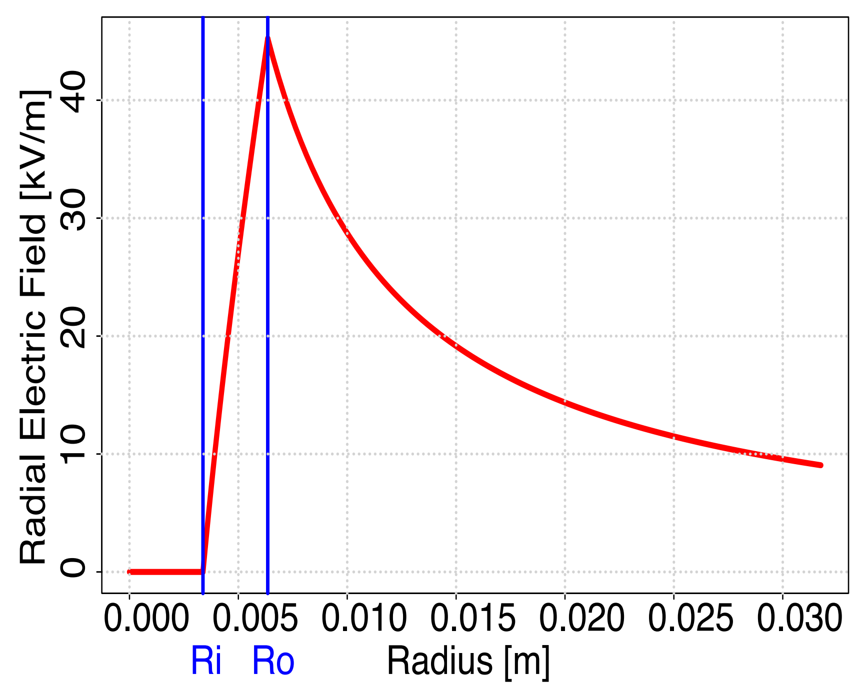
- Align hollow electron beam coaxial with beam core





- Hollow electron beam creates transverse electric field



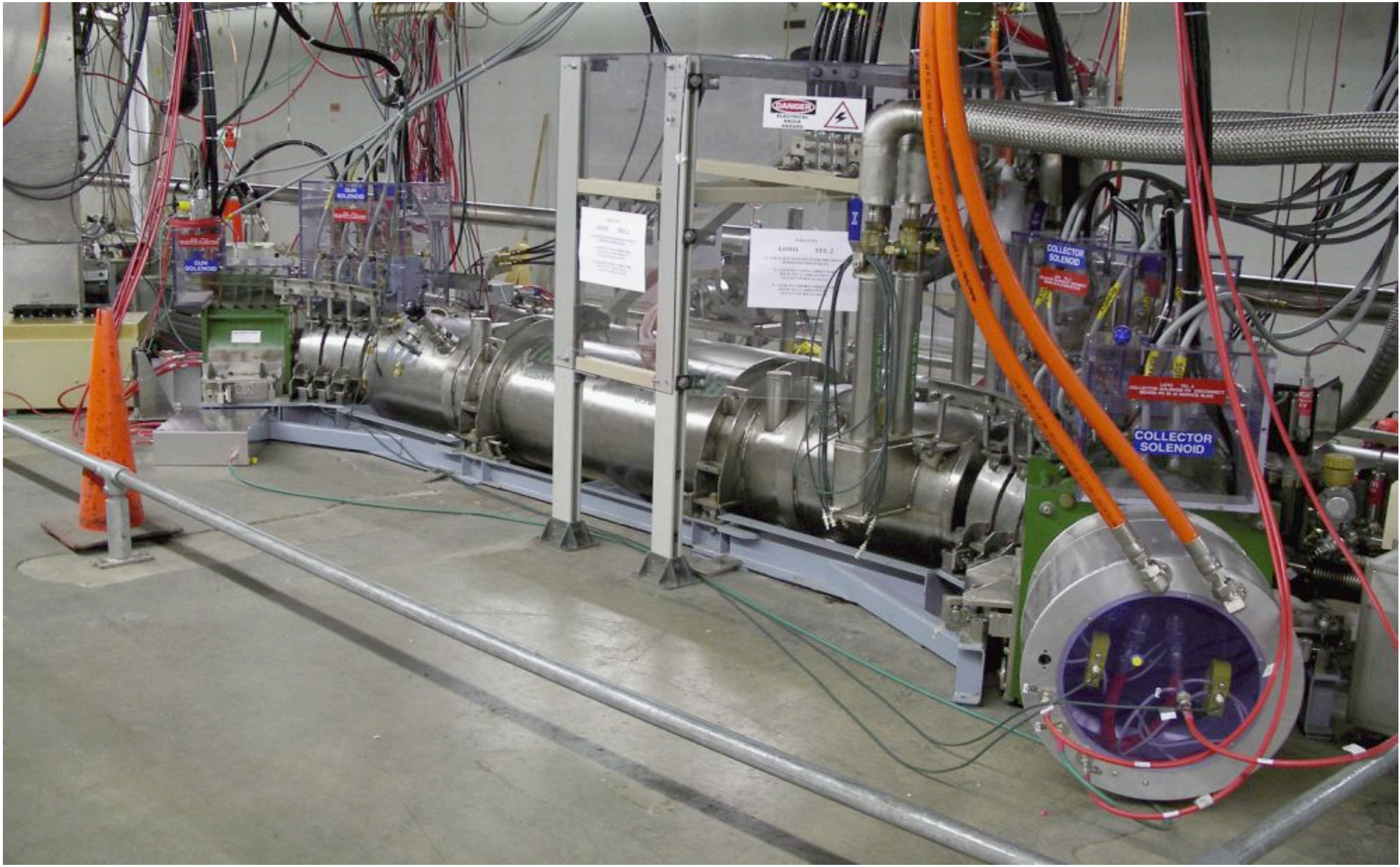


$$r \leq R_o \quad E = 0$$

$$R_i \geq r \leq R_o \quad E(r) \propto r$$

$$R_o \geq r \quad E(r) \propto \frac{1}{r}$$

Tevatron Electron Lens 2

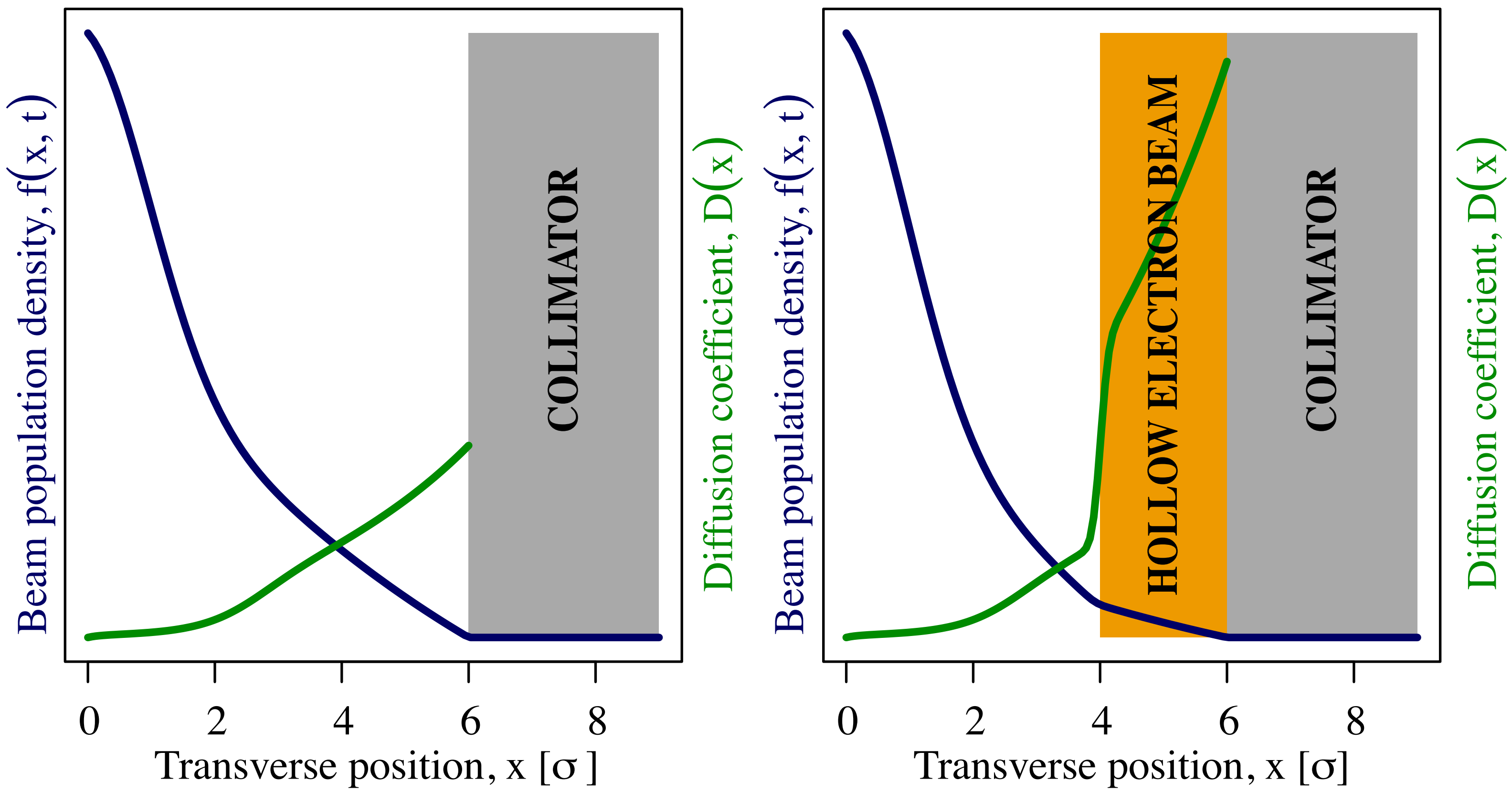


Hollow Electron Beam Collimation

- Transverse kick on halo particles with $R_i < r < R_o$

$$\Theta = \frac{1}{2\pi\varepsilon_0} \frac{I_r L(1 \pm \beta_e \beta_p)}{r \beta_e \beta_p c^2 (B\rho)_p}$$

- Enhances diffusion rate of halo particles -> Deplete tails



- Actual cleaning done by standard collimators
  - HEBC creates buffer zone between core and collimators
  - Control over when tails are cleaned
  - HEBC tunes impact parameter slightly

Source: FERMILAB-CONF-11-506-AD-APC

HEBC Experience at the Tevatron

- Approx. 10 years of stable Tevatron Electron Lens operation for abort gap cleaning
- HEBC Experiments at Tevatron from 2010-2011 for LHC collimation studies
- Observations:
  - Effects on beam core were negligible
    - Curcial for luminosity production in the collider
  - Control of scraping of beam halo possible
  - Loss-spike fluctuations due to beam jitter reduced
- Rely on Tevatron experience
- 2 new designs for LHC
  - Implementation studies
  - Conceptual Design Report (November 2013)

Focus of this work

- My task: Characterizes a new 1-inch Hollow Electron Gun (HG1b) for use at LHC (1-1 implementation)
  - Optimal operation parameters
  - Yield studies
  - Beam evolution
  - Transverse fields
- Completed first full 3D simulations of HG1b in Tevatron electron lens test stand
- Input for Conceptual Design Report in November 2013

Electron Gun & Test Stand

- 1 inch Hollow Electron Gun
- Tevatron Electron Lens Test Stand
- Thermionic Emission

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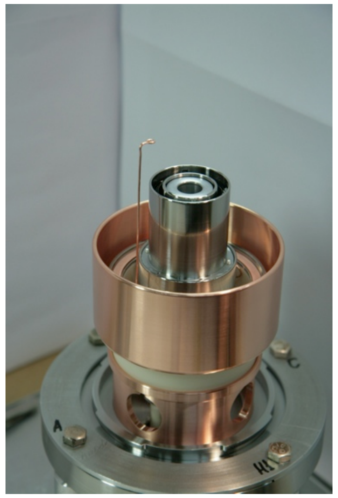
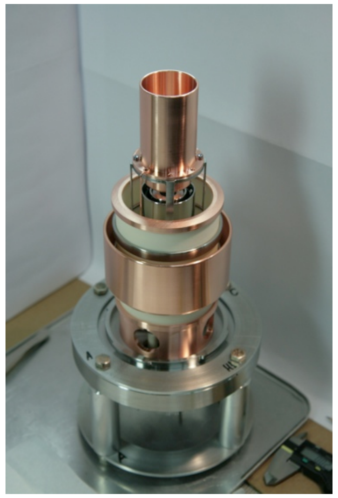
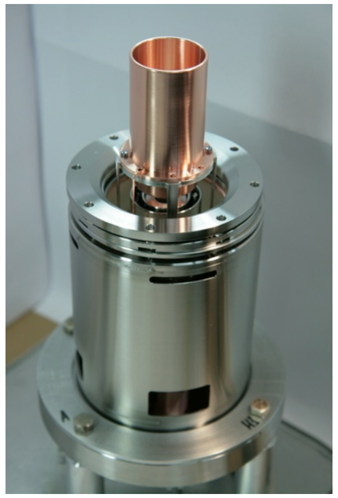
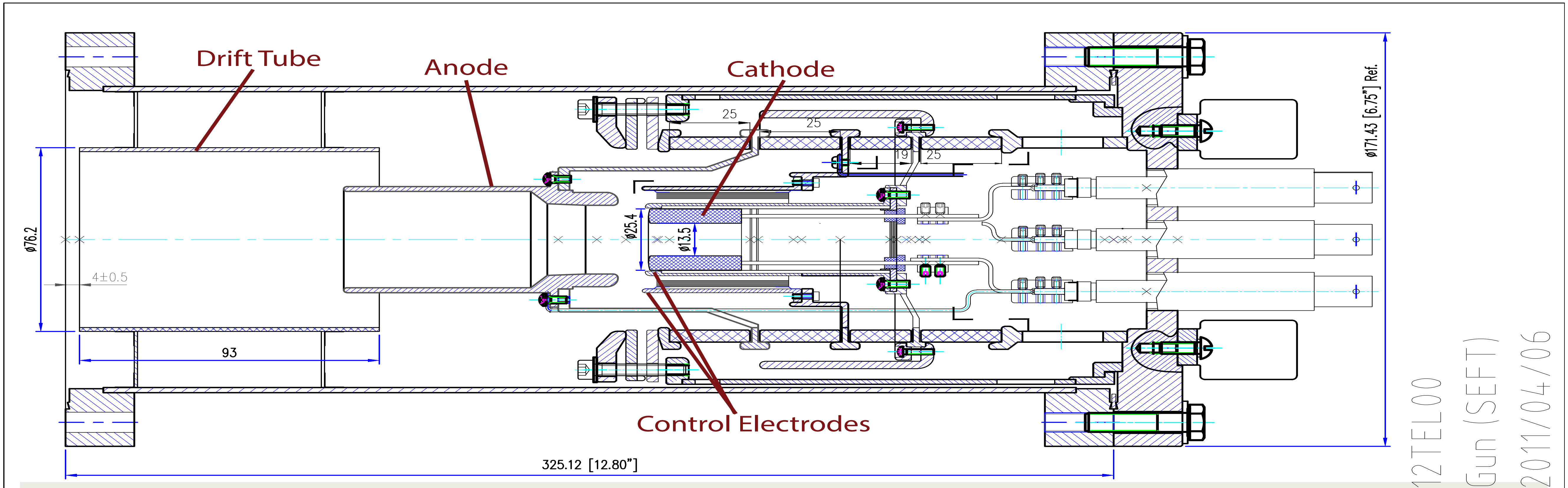
1 inch Hollow Electron Gun (HG1b)

- Bigger gun for higher beam currents
- Hollow cathode: Tungsten impregnated with $3BaO{:}1CaO{:}1Al_2O_3$
- $\varnothing_o$ = 25.4 mm, $\varnothing_i$ = 13.5 mm

$V_{cathode}$	0.5-8 kV
$\frac{R_i}{R_o}$	0.53 mm
I_{fill}	9.25 A



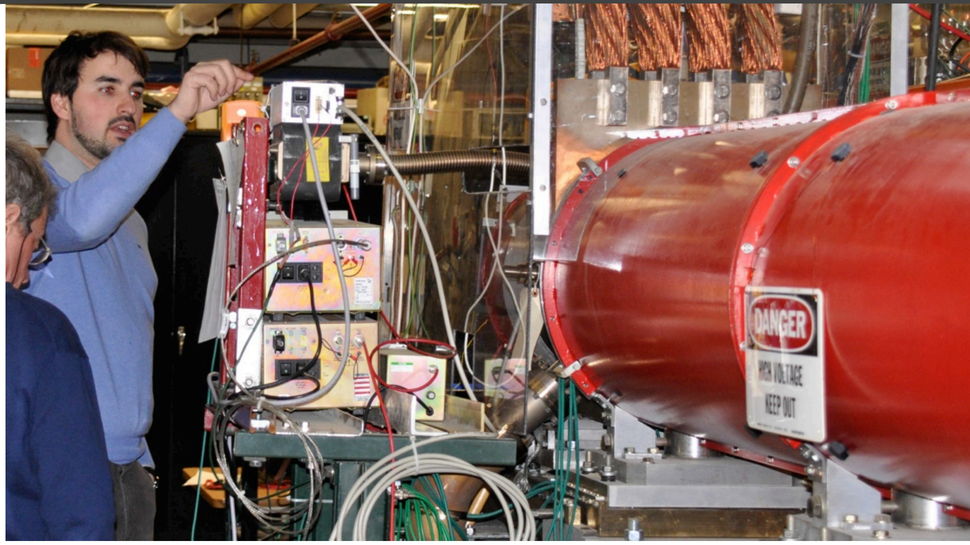
Source: Alexander Didenko

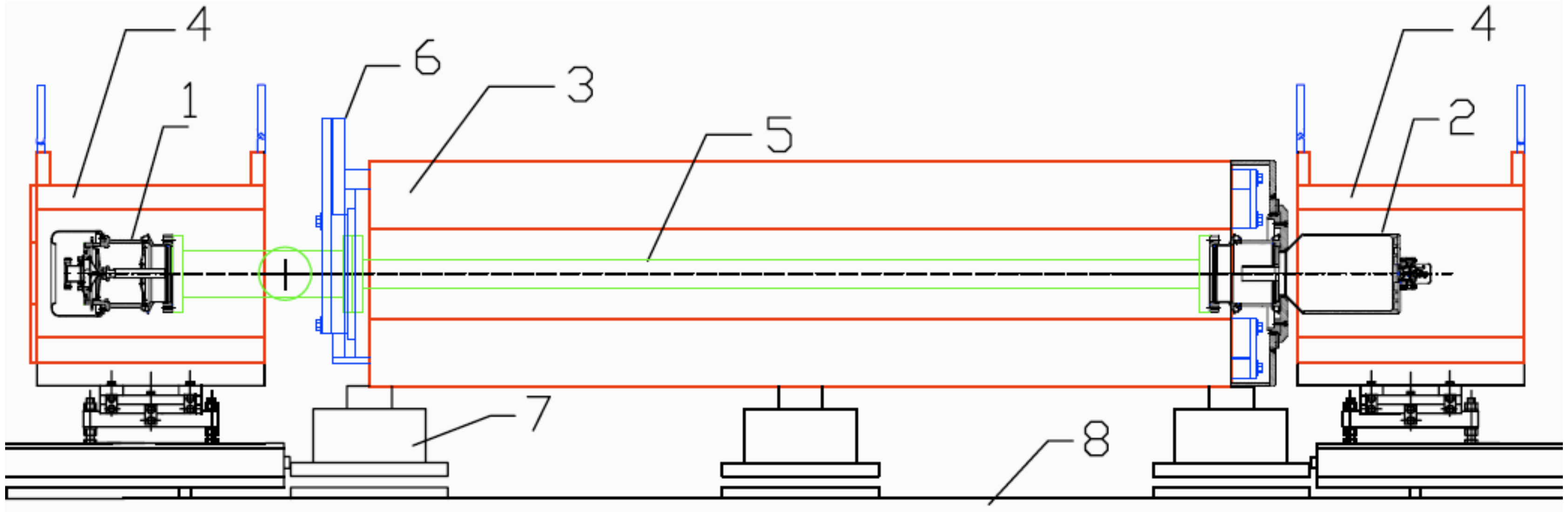
Tevatron Electron Lens Test Stand (TELTS)

- Used for all measurements part of this work

- Data collection:
  - Pinnhole collector
  - Toroids & oscilloscope

- Similar to TEL2
  - No bends
  - No superconducting main solenoid

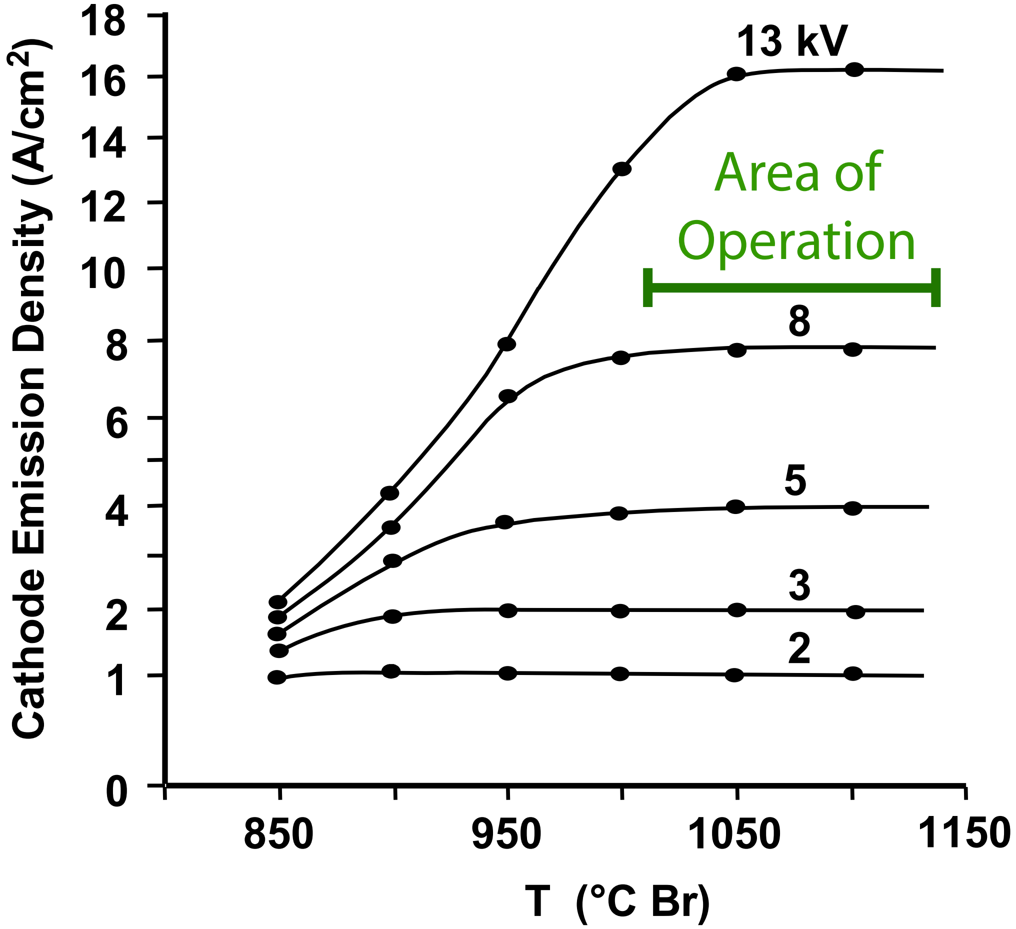


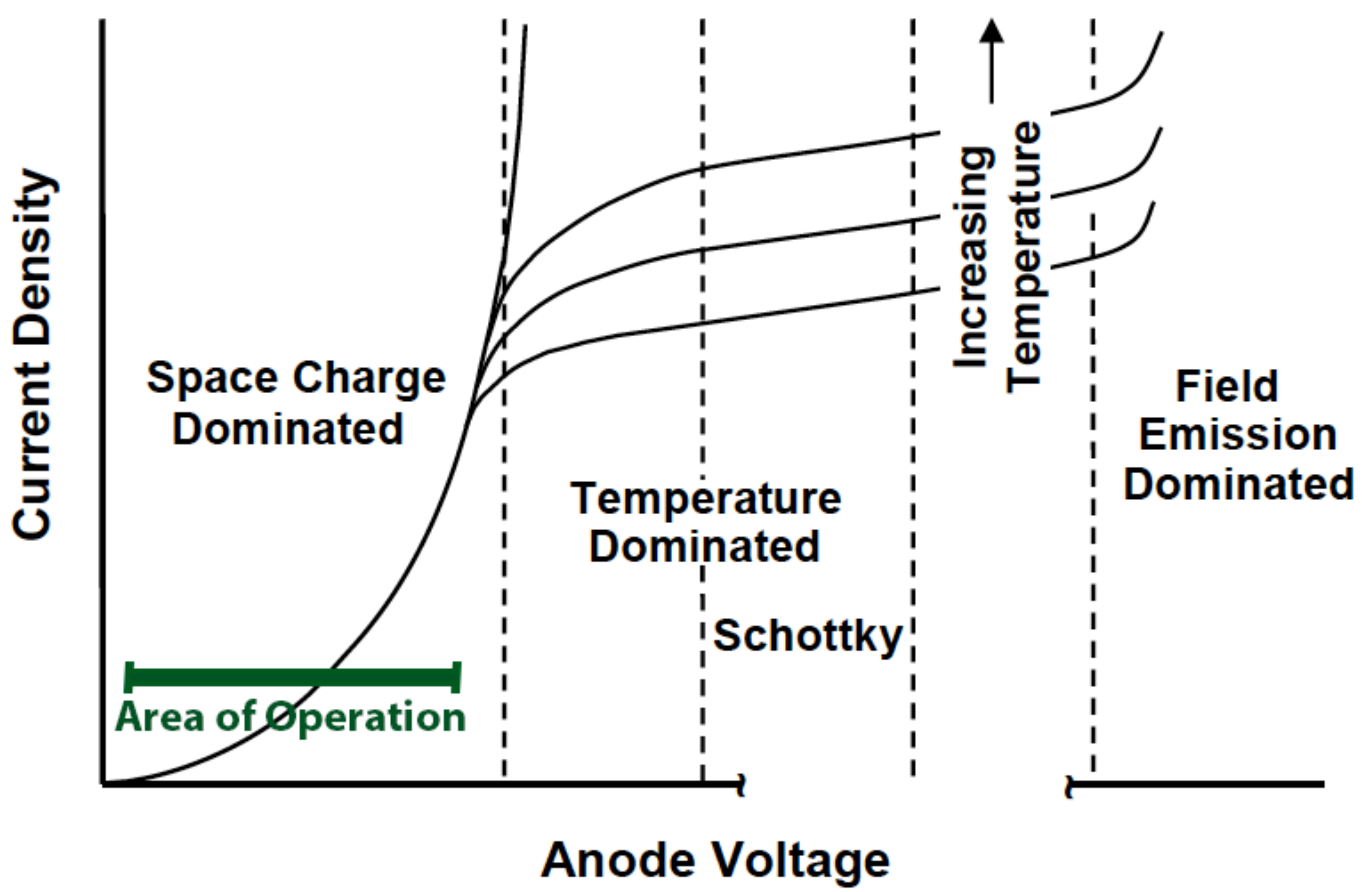


1. Gun
2. Collector
3. Main Solenoid
4. Small Solenoids
5. Beam tube
6. Magnetic Corrector controls

Source: 10.1109/PAC.1999.792290

Thermionic Emission





- Aim: Operate in Space Charge Limited Emission Regime
- Emission type depends on filament current and cathode potential
- Space Charge Limited Emission:

$$I_{beam} = PV_a^{\frac{3}{2}} = 1.67 \times 10^{-3}\pi \left(\frac{q}{mc^2}\right)^{\frac{1}{2}} \frac{V_a^{\frac{3}{2}}}{d^2} \left(r_{ext}^2 - r_{int}^2\right) \quad [A]$$

- Yield measured in perv: $P = \frac{I}{V_a^{\frac{3}{2}}} \quad [perv]$

Results

- Optimal operation parameters for LHC
- Yield measurements
- Beam evolution
- Rough Upper Estimate of Emittance Growth
- 3D simulations

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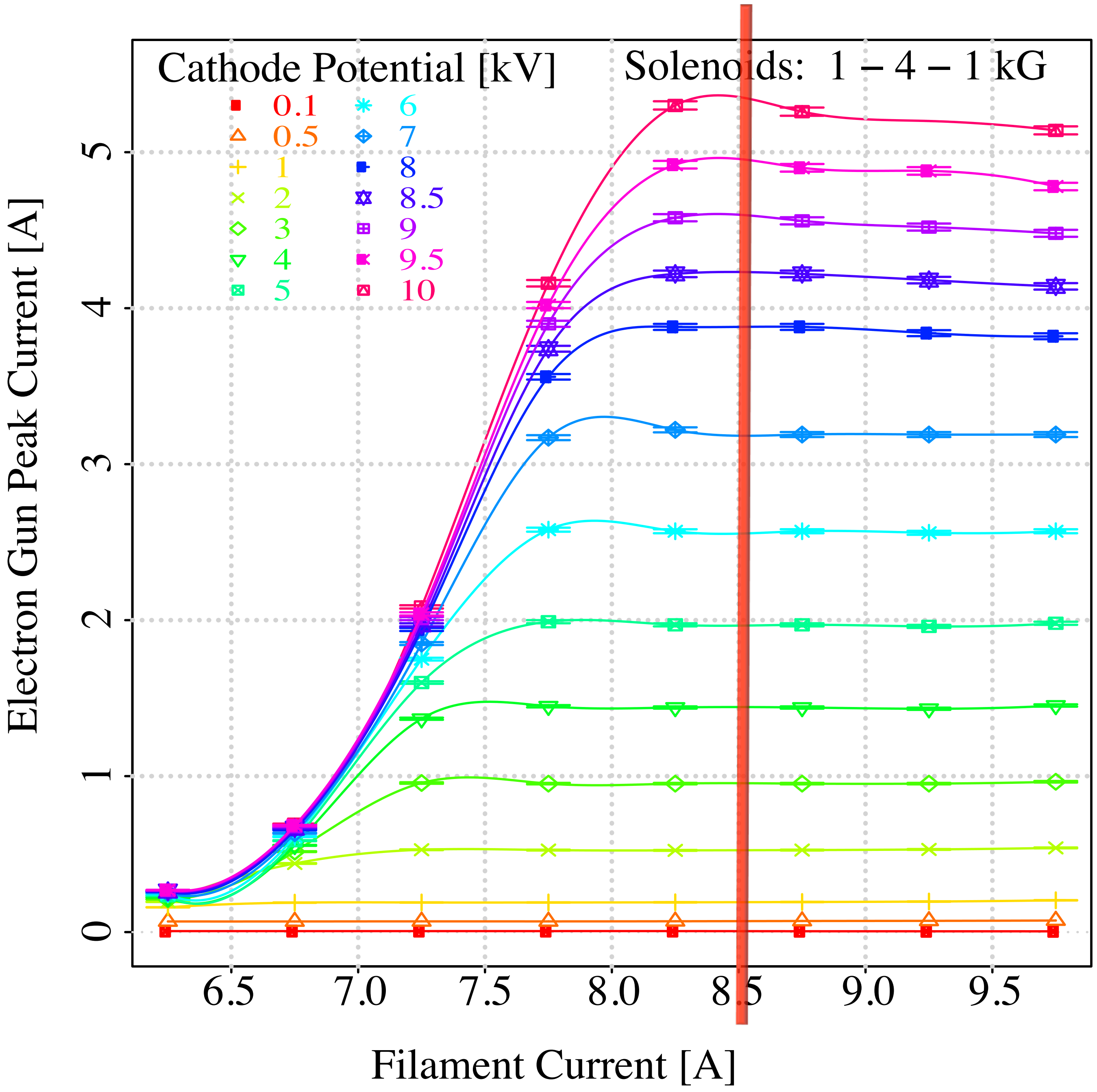
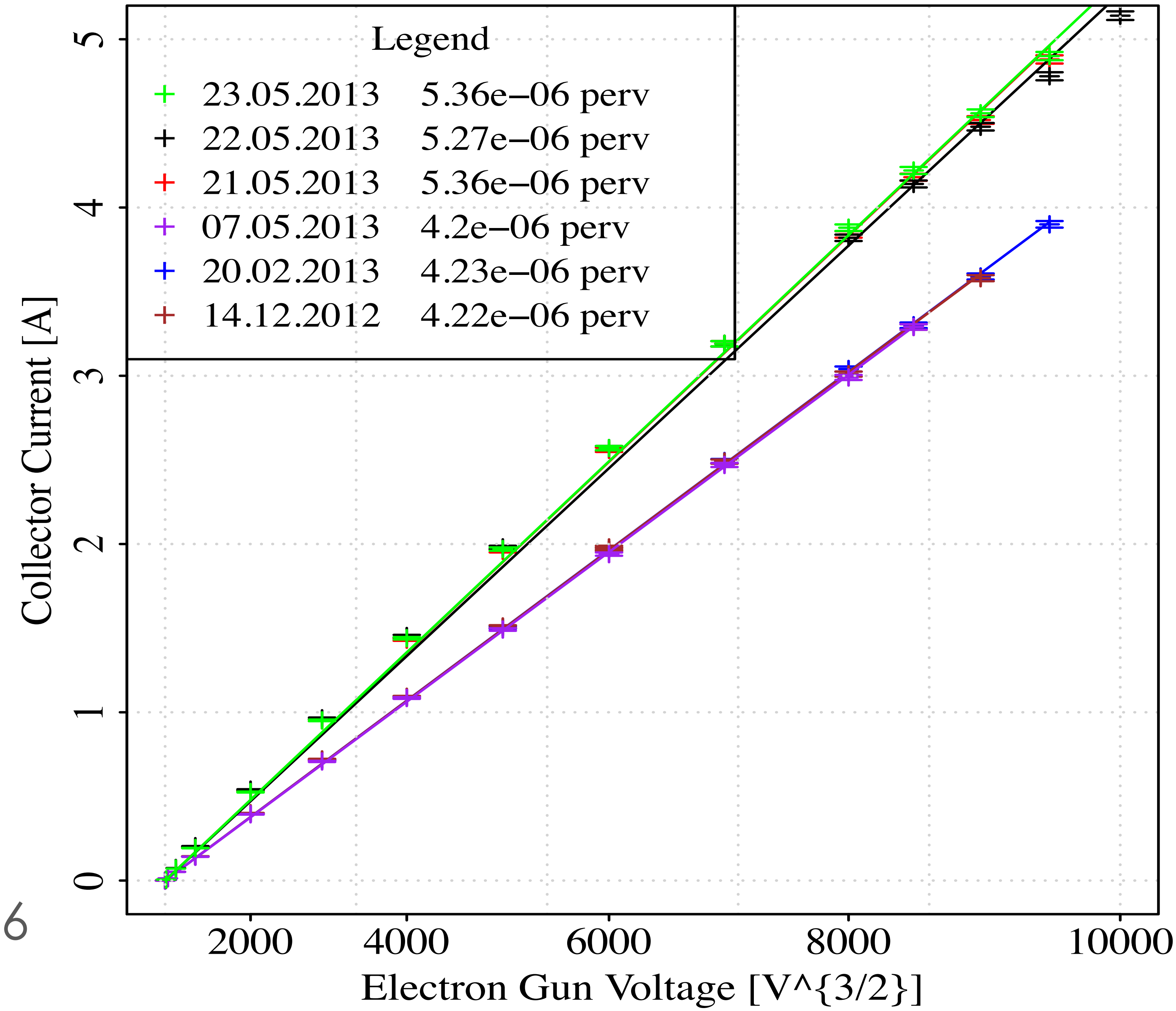
Optimal Operating Parameters

- Inner radius 3 σ < R_i < 6 σ (σ=4.7×10^{-4} m)
- Magnetic compression (R_i=4σ)
  - Factor **11.5**
  - B=0.43-5-0.43 T
- Cathode potential of HG1b
  - **3-4 kV** for similar current as Tevatron experiments
- Optimal filament current
  - Up to now: 9.25 A
  - Can be reduced to ≈ **8.5 A**



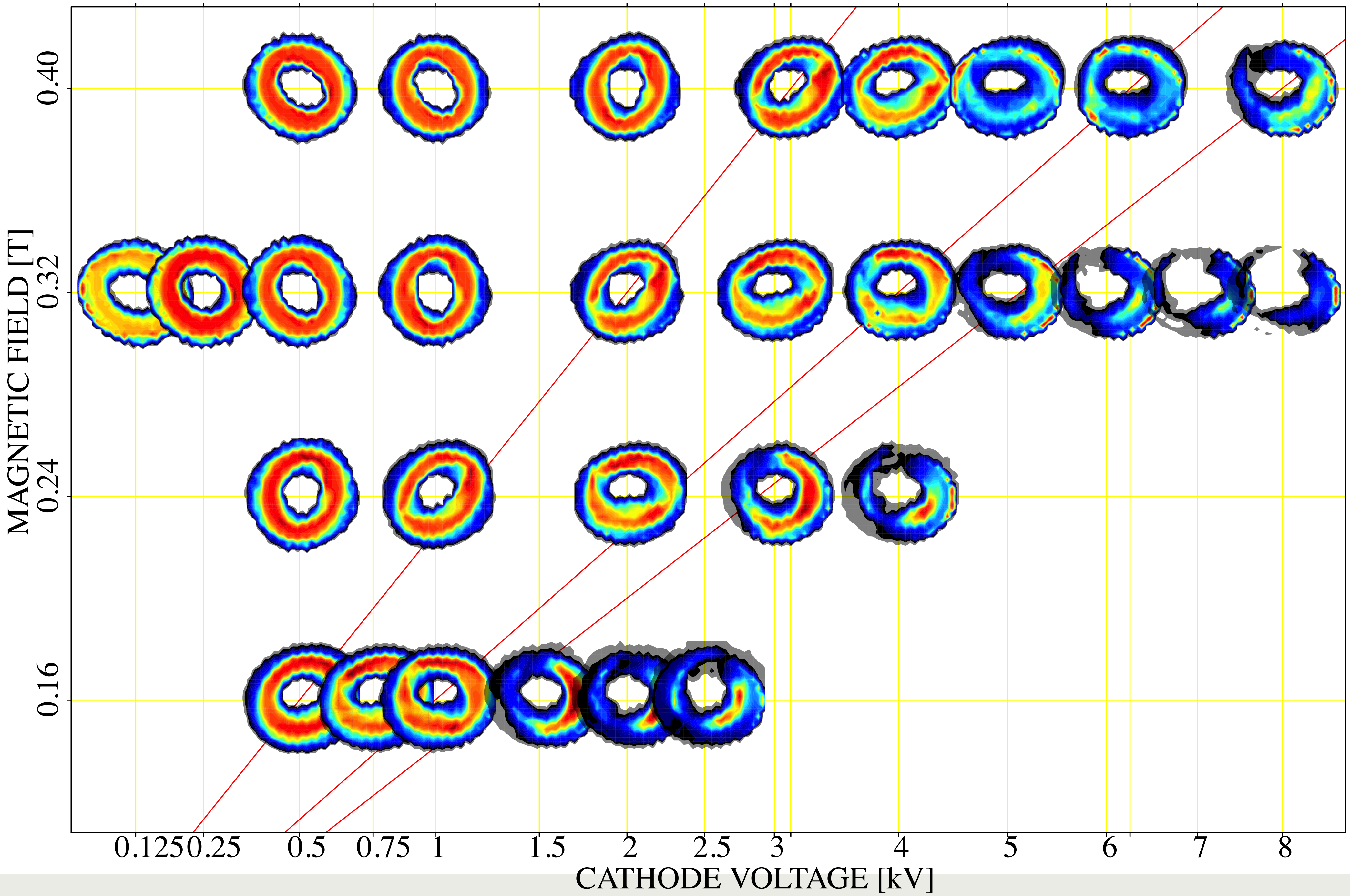
HG1b Yield

- Before transport improvement:
  - Yield: $4.22(3)\times10^{-6}$ perv
  - Consistent with previous measurements
  - Slow degradation of gun
- Yield at collector 70% of gun
  - Biggest Gun yet!
- After transport improvement:
  - Yield: $5.3(1)\times10^{-6}$ perv
    - Produces 5 A at 10 kV
  - 15% of SAM simulations
  - 65% more yield than HG06



Transverse Profiles

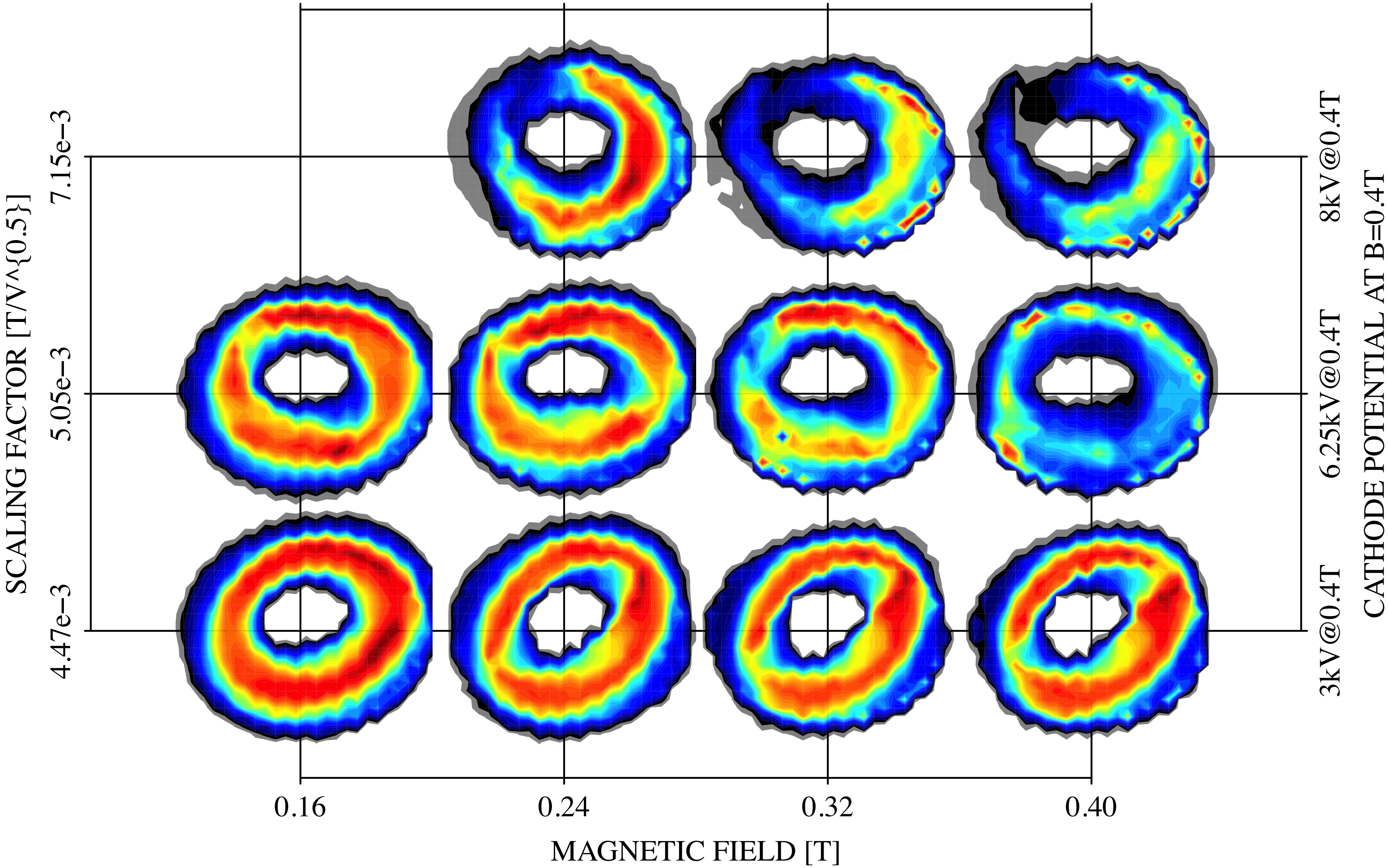
- Current density profiles by moving beam over pinhole
- Profiles injected into 3D simulation
- Profiles sorted by B_{main} and V_a
- Red lines: scaling lines



Beam Scaling

- Scaling law ➔ angle of rotation must be constant

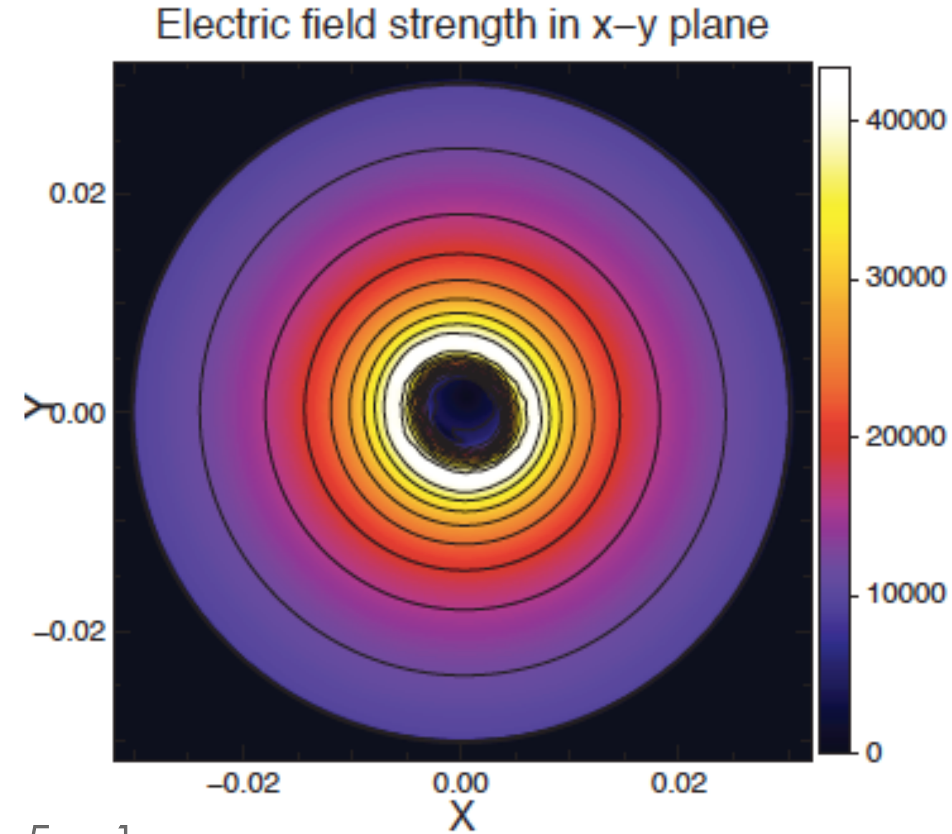
$$B \propto \sqrt{V}$$



Rough Emittance Growth Estimates

- Calculation of electric fields using WARP
- Emittance growth given by:

$$\Delta\varepsilon = \beta\theta^2 = \beta\left(\frac{E_{tot}qE_rL}{E_{tot}^2 - E_0^2}\right)^2 \quad \left[\frac{m}{turn}\right]$$



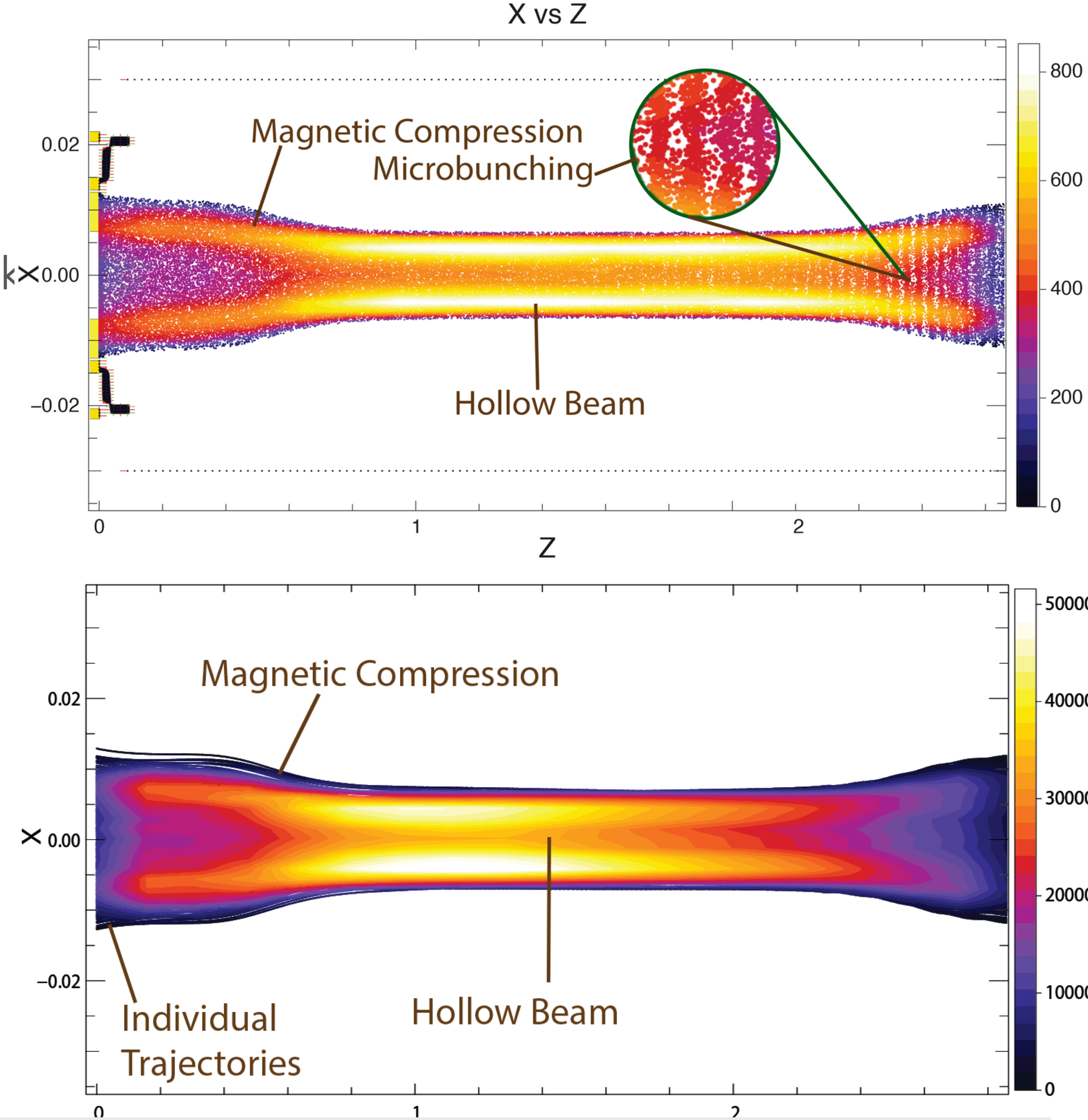
- Rough estimate through mean Gaussian weighted RMS field in center of beam
- Current LHC emittance growth rate ≈ 1 ×10^-5 s^-1

EGR $[\times 10^{-5}\,\frac{1}{s}]$		Cathode Voltage [kV]			
Radius [mm]	**B_{max} [kG]**	**500**	**1000**	**2000**	**3000**
4 σ	4	0.089	0.246	1.11	97.8 (3125 V)
	3.2	0.025	0.093	29.3	48.7
	2.4	0.010	4.59	18.9	227
	2.4	1.34	4.54	144	-

- Indication of no extra emittance growth -> Luminosity

First Full 3D simulations

- First 3D simulation of HEBL using WARP
- Aimed at extracting kick map for SixTrack or Lifetrack simulations
- Two injection methods implements
- Issues to be solved:
  - Implementation of TEL2 bends
  - Heavy computing power needed
  - Further diagnostics tools need to be implemented
- Continued by myself for conceptual design report



Conclusions

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Conclusions

- Useful technique for enhancing current collimation systems
  - **Active control of losses**
  - **Less dependent on loss spikes**
  - **Increases impact parameter**
- Determined optimal operating parameters for LHC
  - **Factor 11 compression**
  - **8.5 A Filament Current**
  - **3-4 kV Cathode Potential**
- Transmission upgrade through magnetic compression in TELTS
- Significant yield improvement of HG1b: $5.3(1)\times10^{-6}$ perv
- Transverse profile scaling $\propto \frac{\sqrt{V_a}}{B}$
- Emittance growth rates are acceptable compared to current growth rates
- First Full 3D simulations

Questions

Thank You!

Availability:

- Fermilab Library: FERMILAB-MASTERS-2013-02 (www.inspirehep.net)
- CERN Library: CERN-THESIS-2013-126 (www.cds.cern.ch)

Acknowledgements

• **Prof. Leonid Rivkin**	Master Thesis Director
• **Dr. Giulio Stancari**	Fermilab Supervisor
• **Dr. Stefano Redaelli**	CERN Supervisor
• **Dr. Moses Chung**	WARP advisor
• **Dr. Alexander Valishev**	HEBL collaborator
• **Dr. David Grote**	WARP author

CERN

LHC Collimation Project

LARP

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Backup Slides

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Backup Contents

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- Tevatron Electron Lens 2
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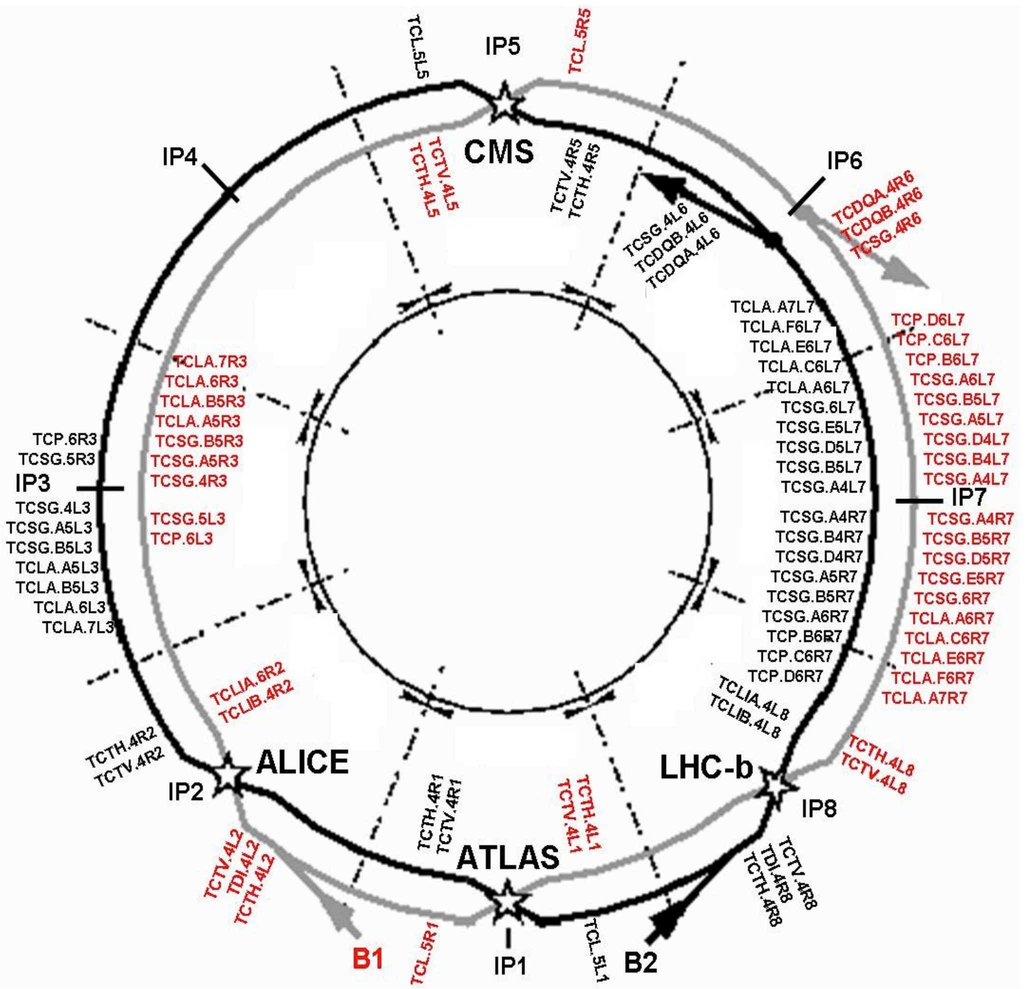
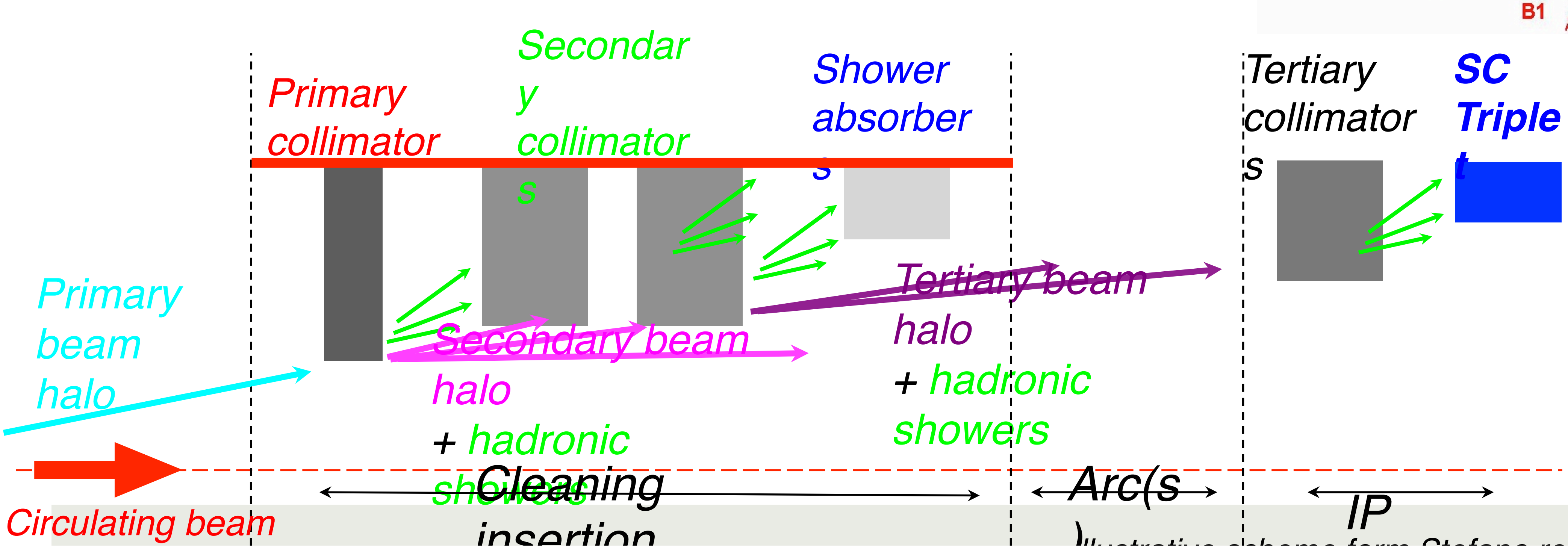
- Cathode Temperature
- Time Structures
- Generalized Perveance
- SAM Simulations
- Background Gases
- Transverse Profiles
- Beam Evolution
- Transverse Electric Fields at 500 V
- Transverse Electric Fields at 8 kV
- Derivation – Angle of Rotation
- Derivation – Electric Field Equations
- Derivation – Emittance Growth Rate
- WARP – Implemented Gun
- WARP – Potential Fields
- WARP – Electric Fields

LHC & Collimation System

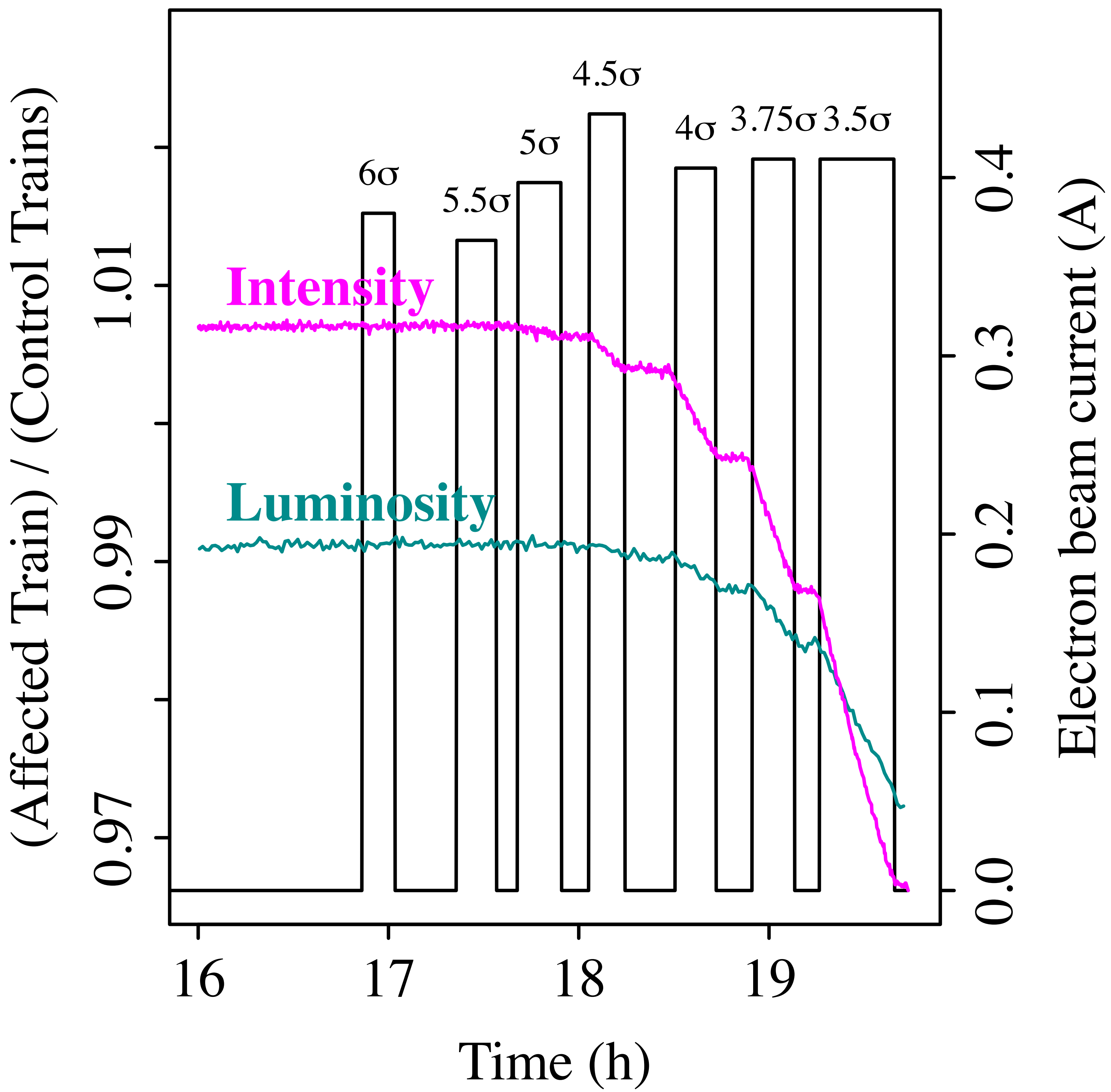
- Beam continually cleaned through multi-stage collimation system
- Approximately 100 collimators
- 4 colliding IR & 4 non interacting IR
- Affected by electromagnetic impedance, beam jitter, increased loss rates when moving collimators

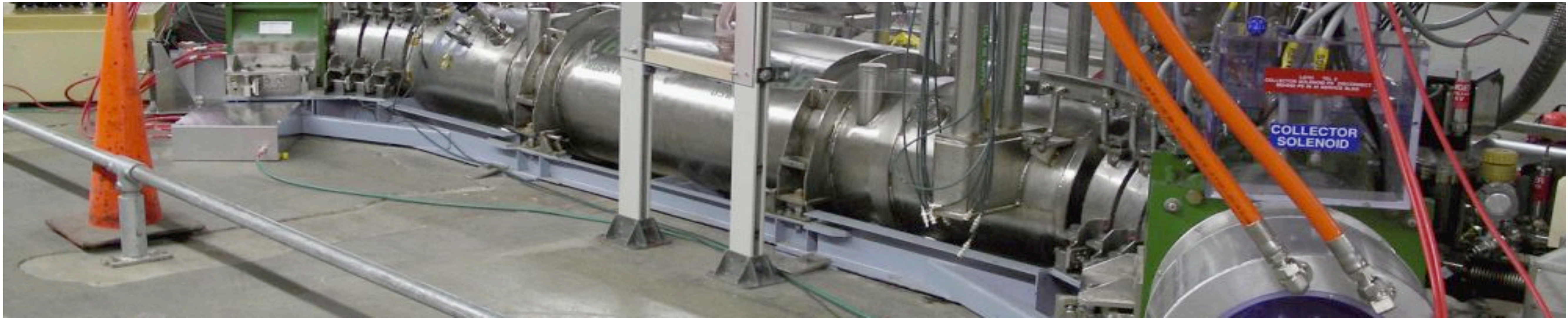




Illustrative scheme form Stefano redaelli

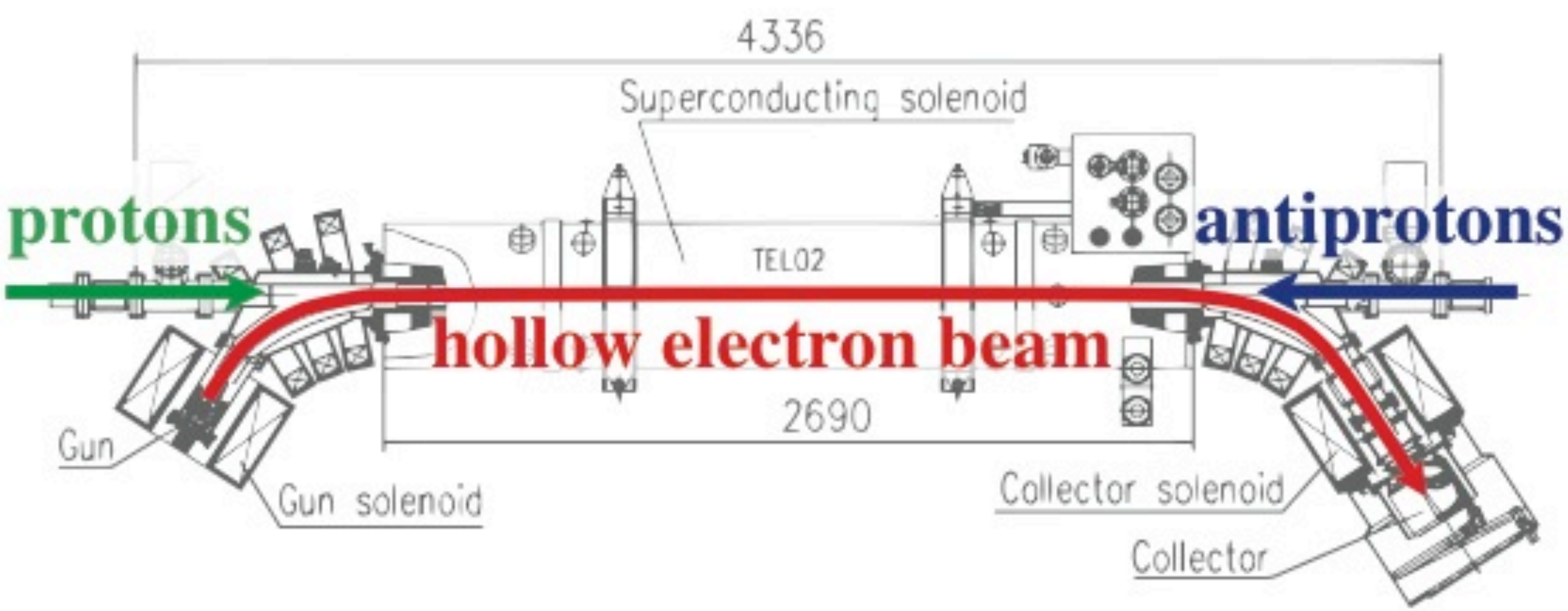
Tevatron Intensity

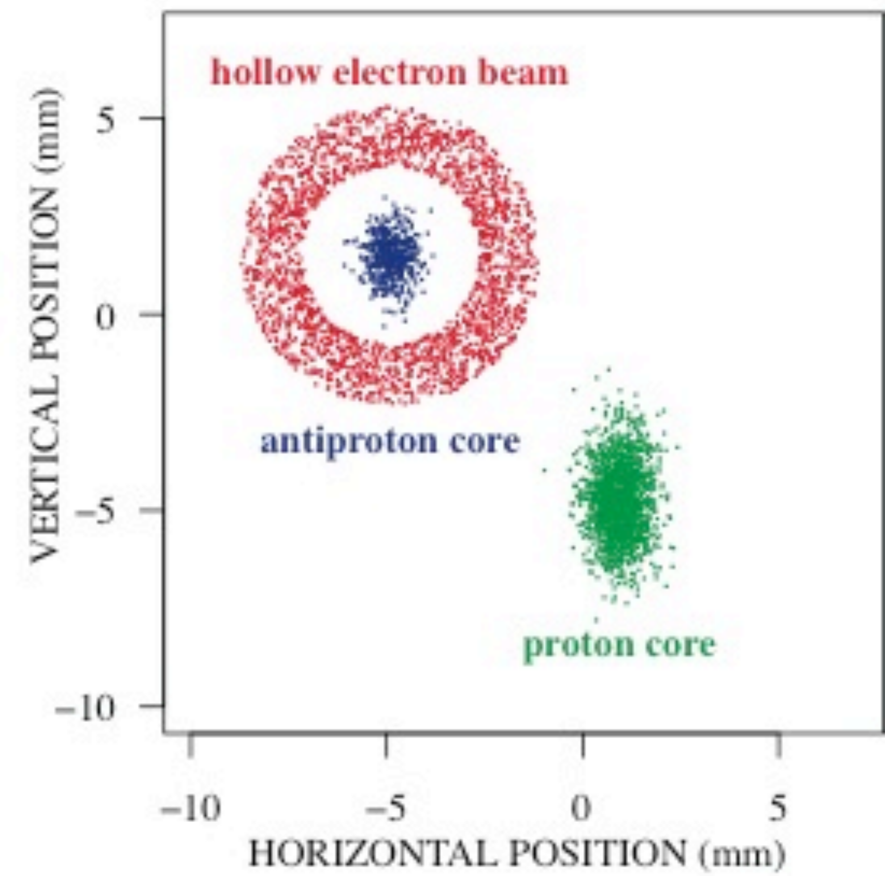




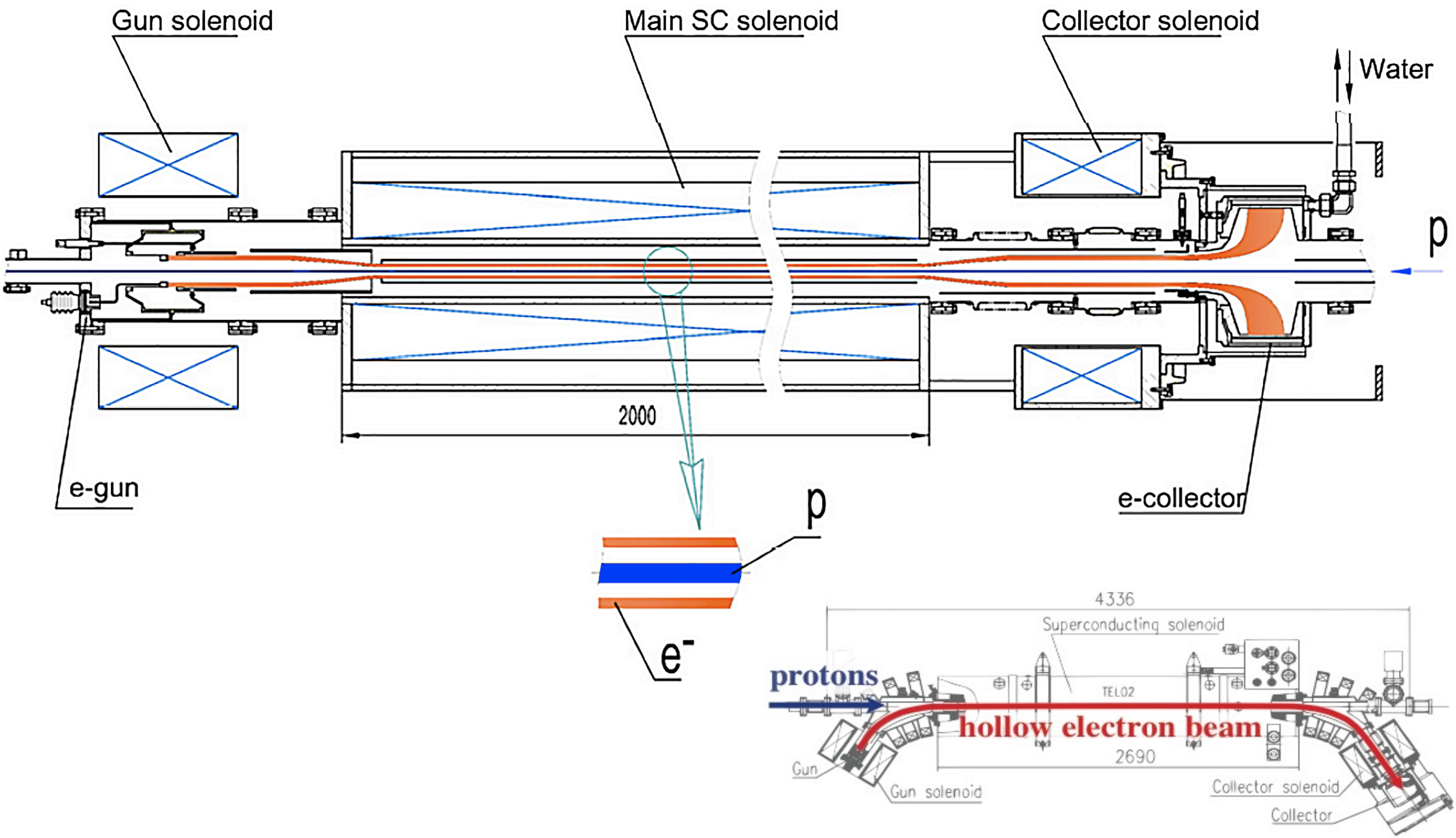
Tevatron Electron Lens 2

- Gun & collector outside tube
- 3 main solenoids
- Only one beam
- Pierce through edge



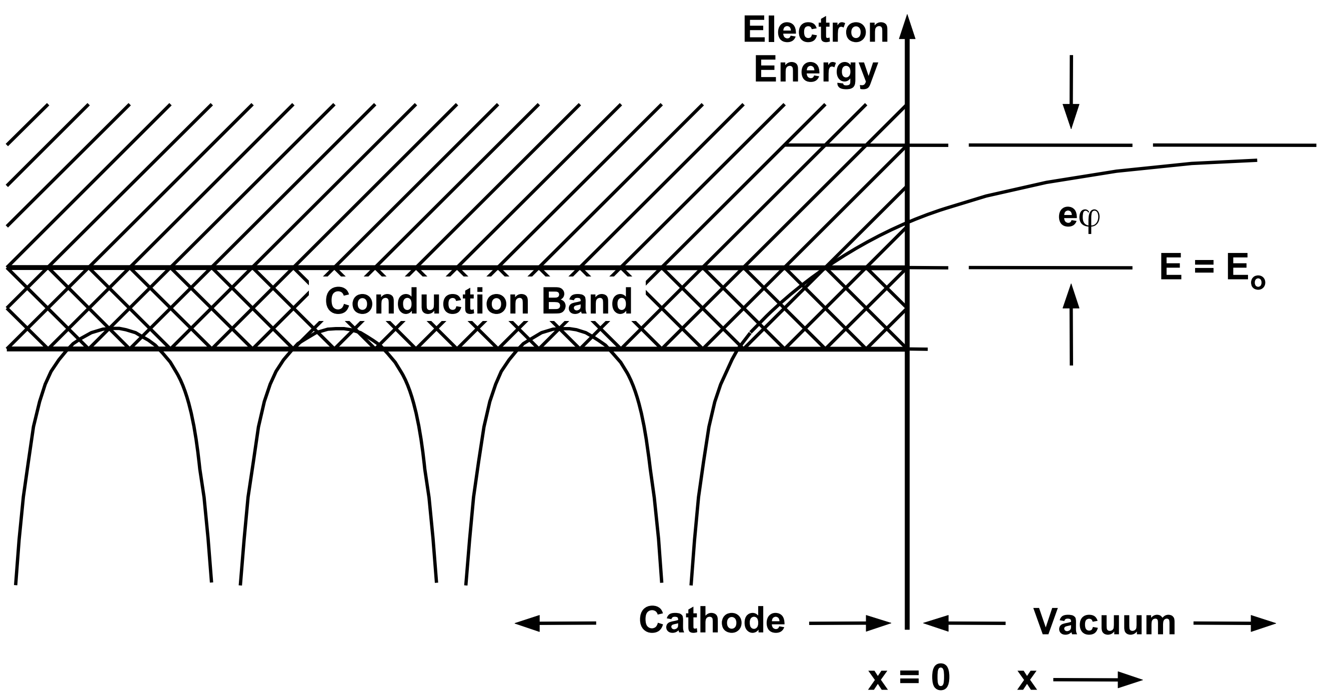


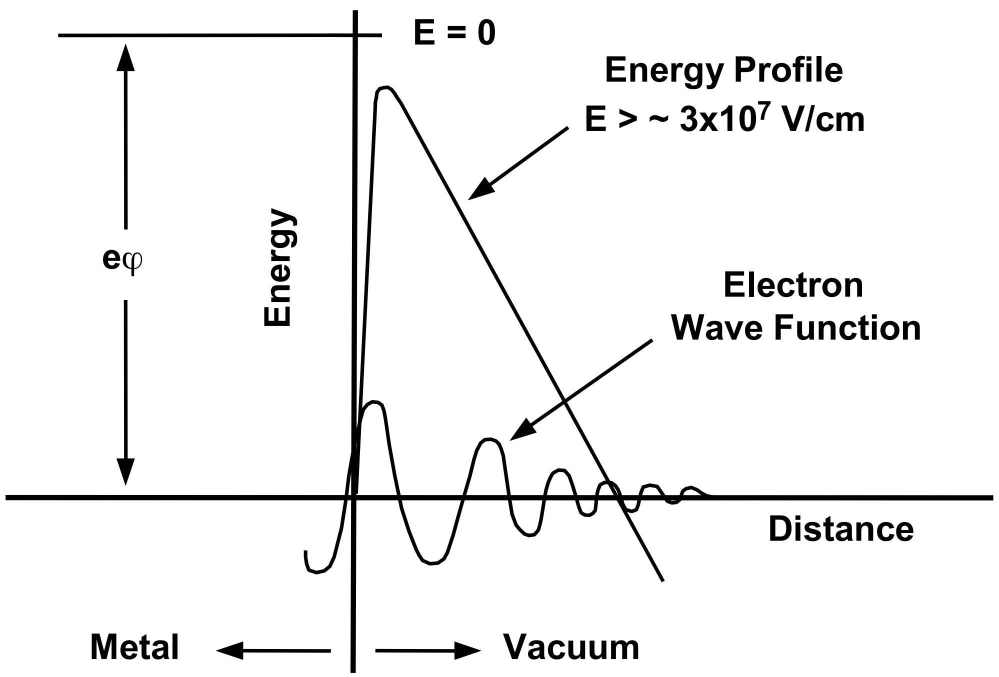
Conceptual Straight HEBL Design

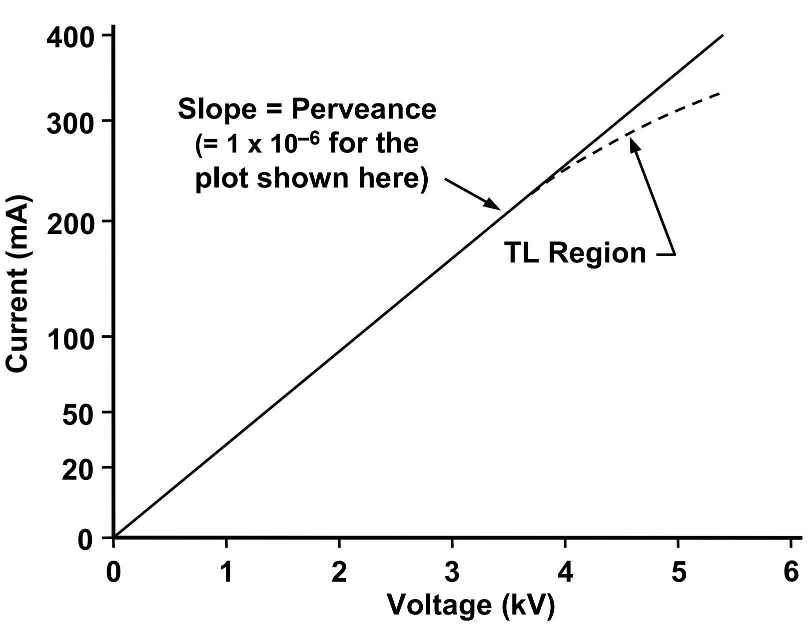


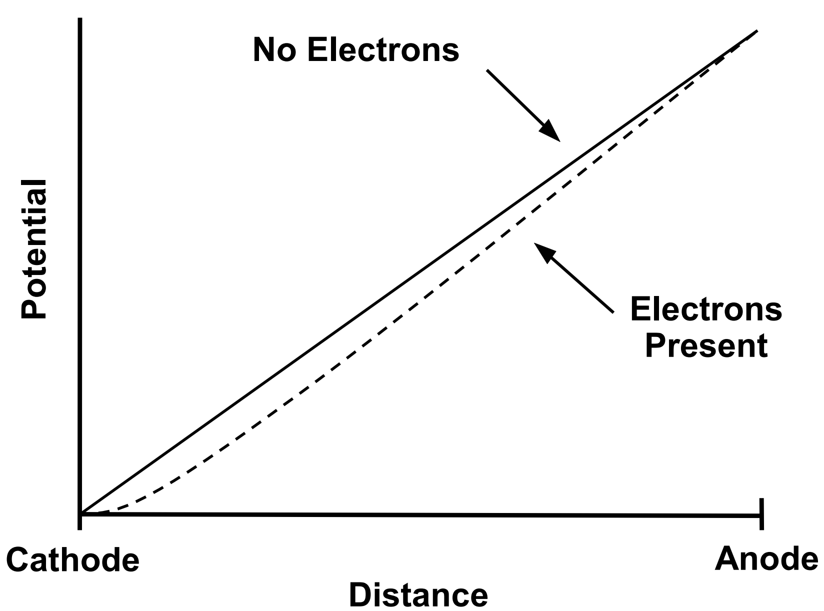
Source: Gennady Kuznetsov

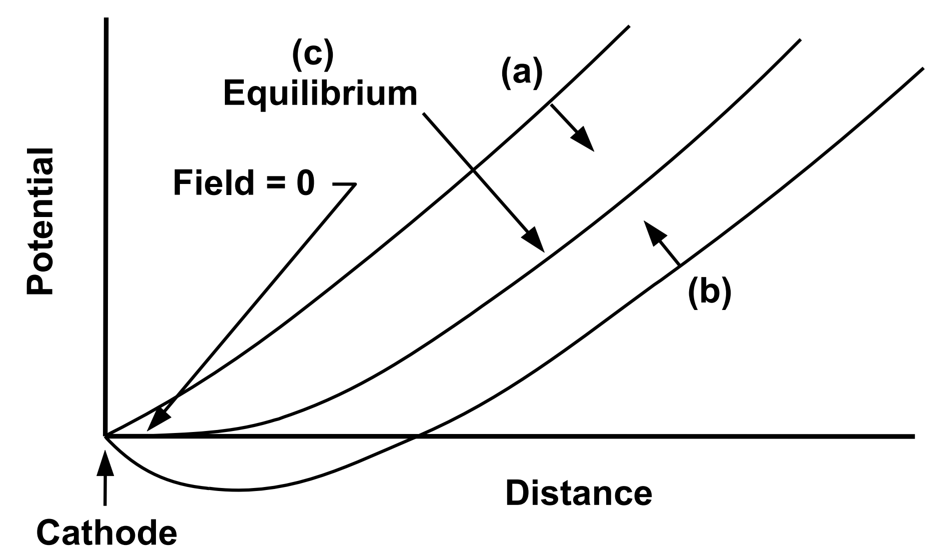
Thermionic Emission



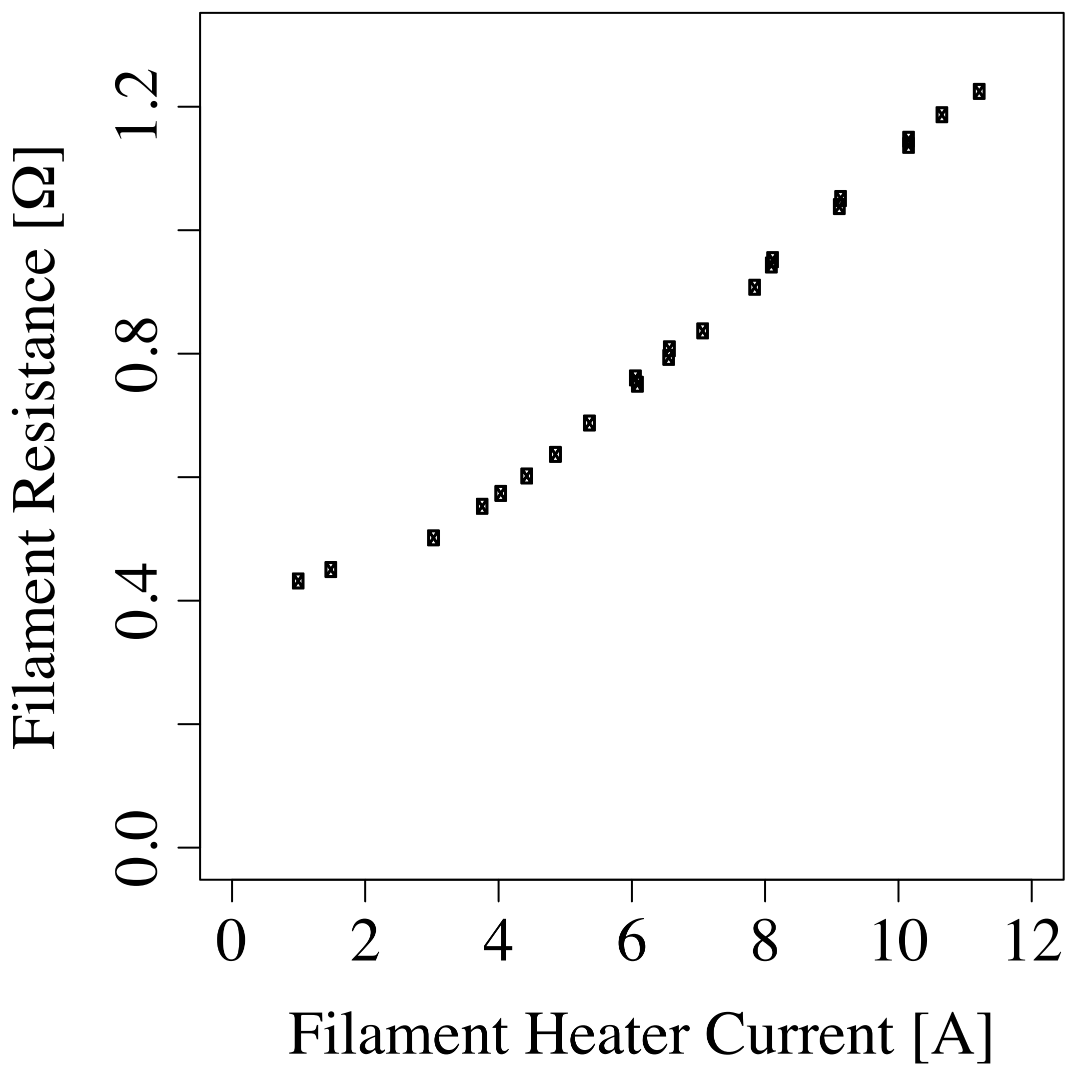


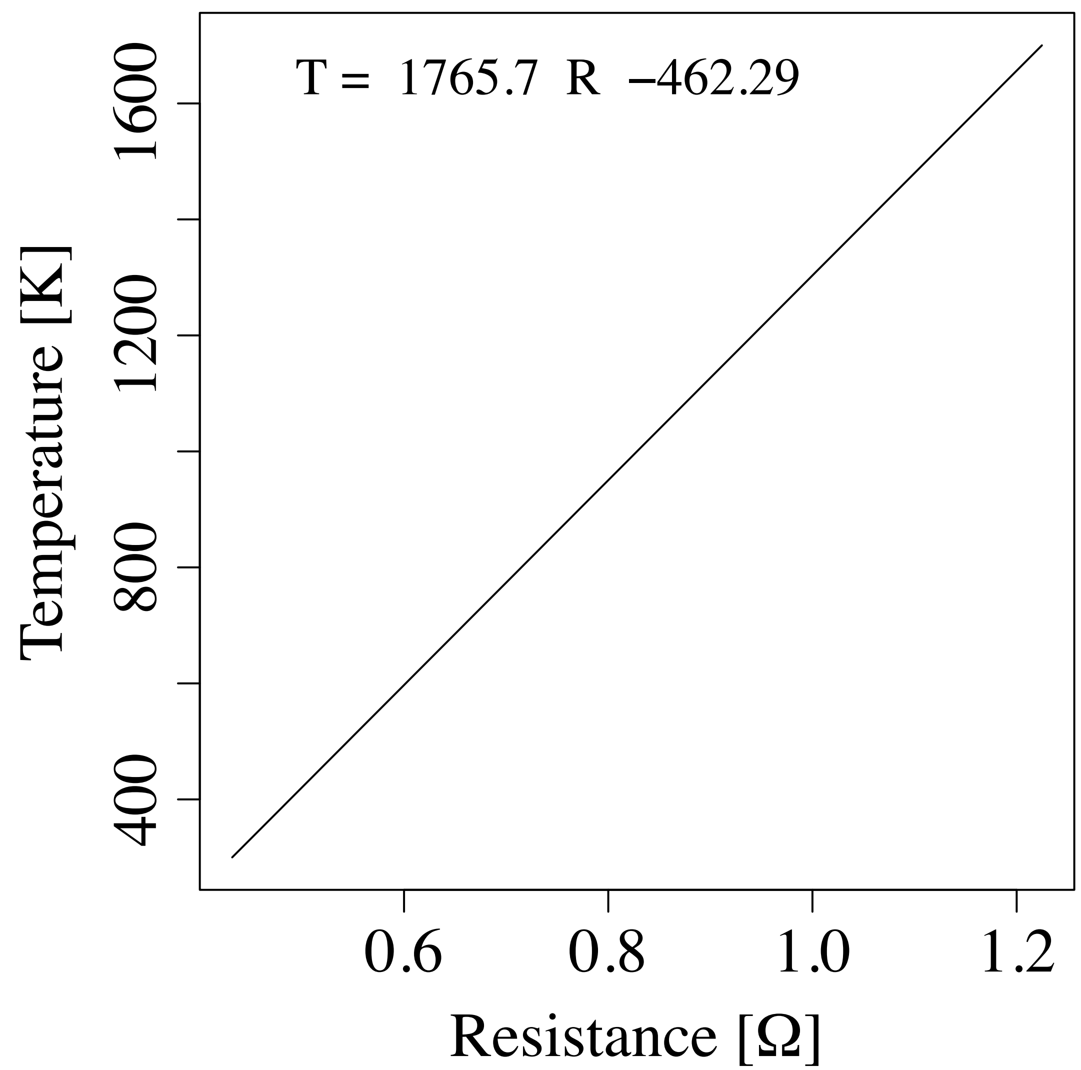






Cathode Temperature





β=1770 K Ohm^{-1}

$T=\beta R+T_0$

T_0=-462 °C

Time Structures

- Rise Time: 200 ns
- Bunch spacing Tevatron: 400 ns
- Bunch spacing LHC: 25 ns
- Possible to obtain bunch by bunch manipulation in LHC.
- Aim is to obtain turn-by-turn excitation.

- Valentina achieved 75% cleaning in 20s using AC beam mode

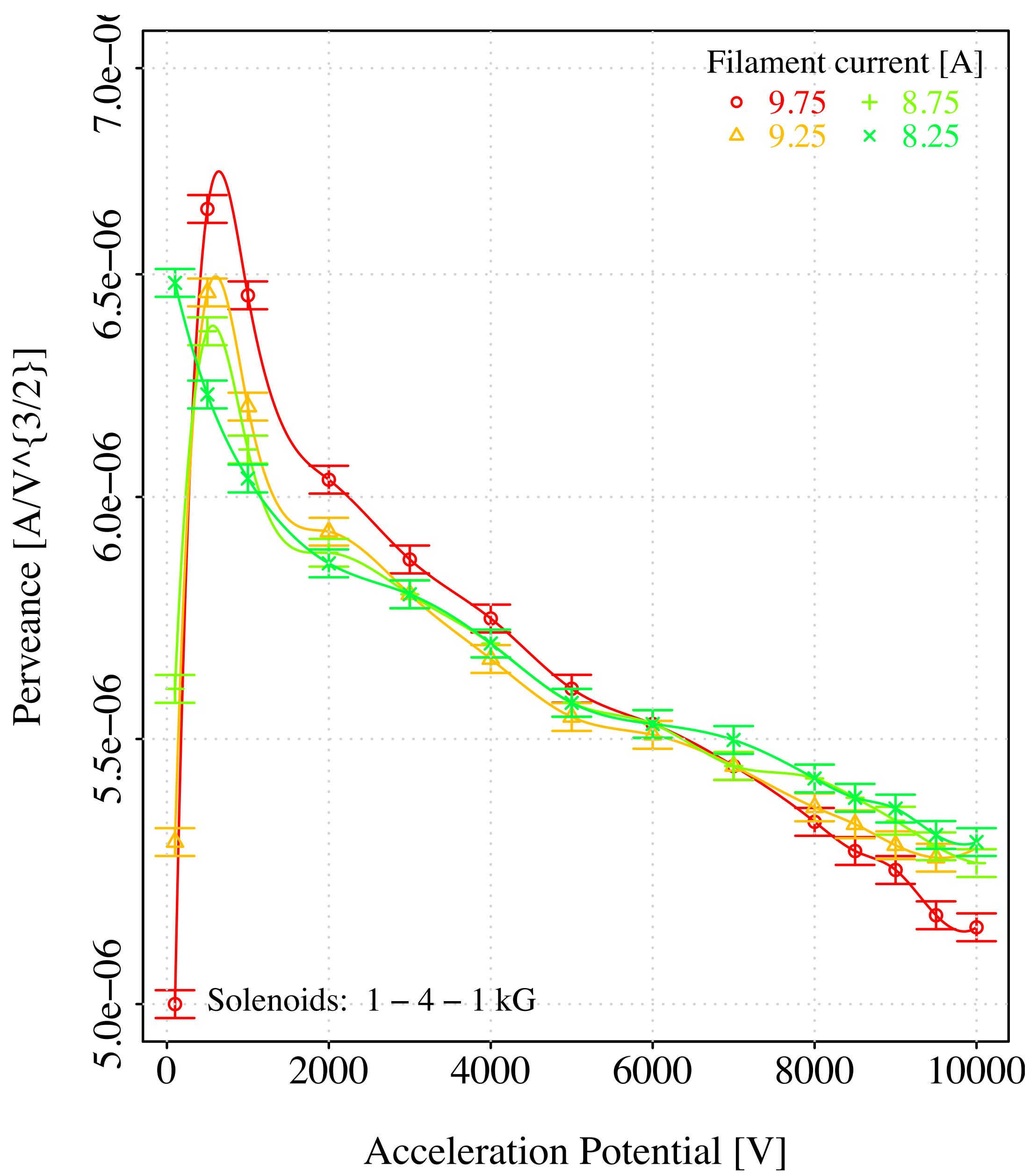
Generalized Perveance

$$K = \frac{I}{I_0}\frac{2}{(\beta\gamma)^3}(1-\gamma^2 f_e) \qquad I_0 = \frac{4\pi\varepsilon_0 mc^3}{q} = 17kA$$

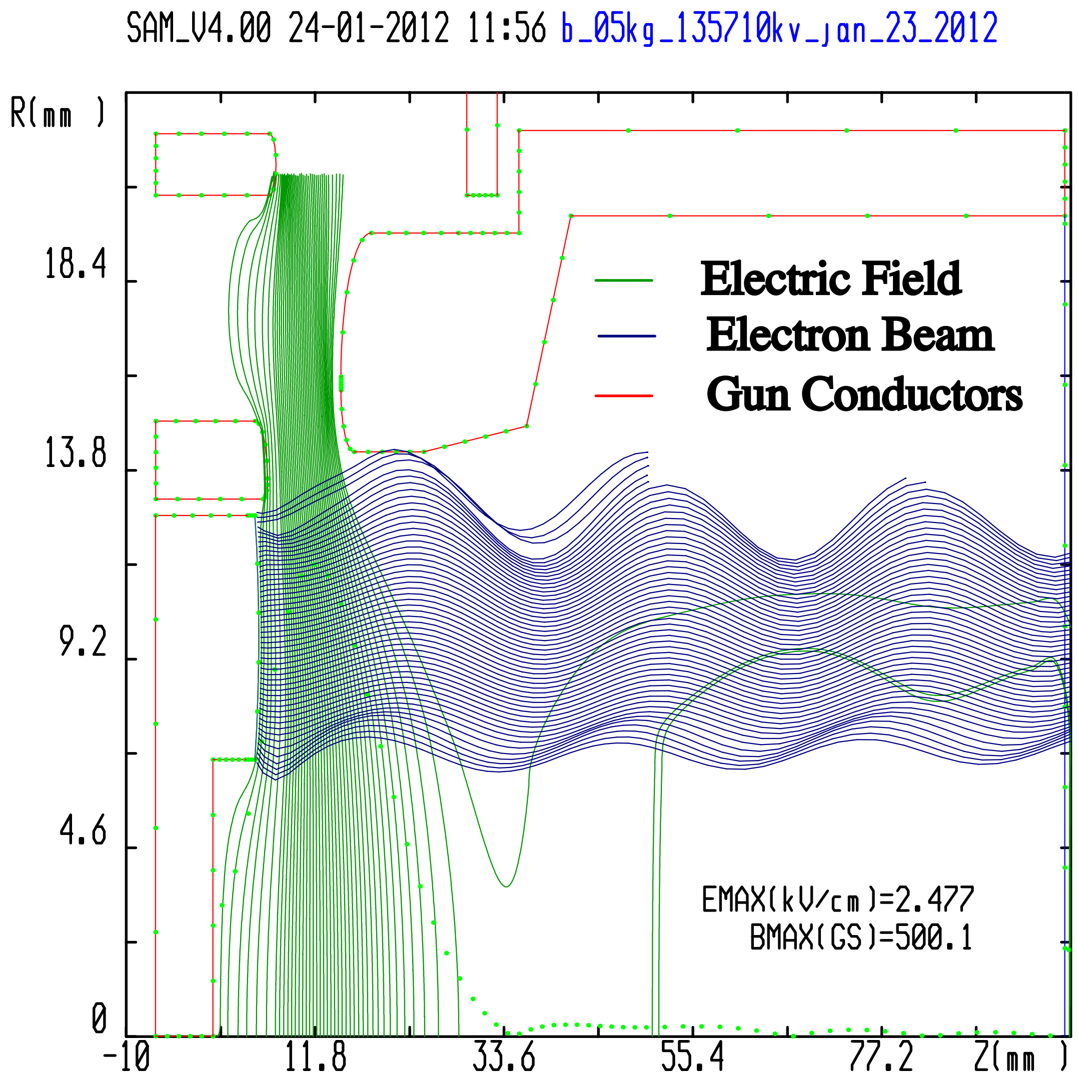
$$\beta = \frac{v}{c} \text{ and } v = \left(\frac{2qV}{m}\right)^{\frac{1}{2}}$$

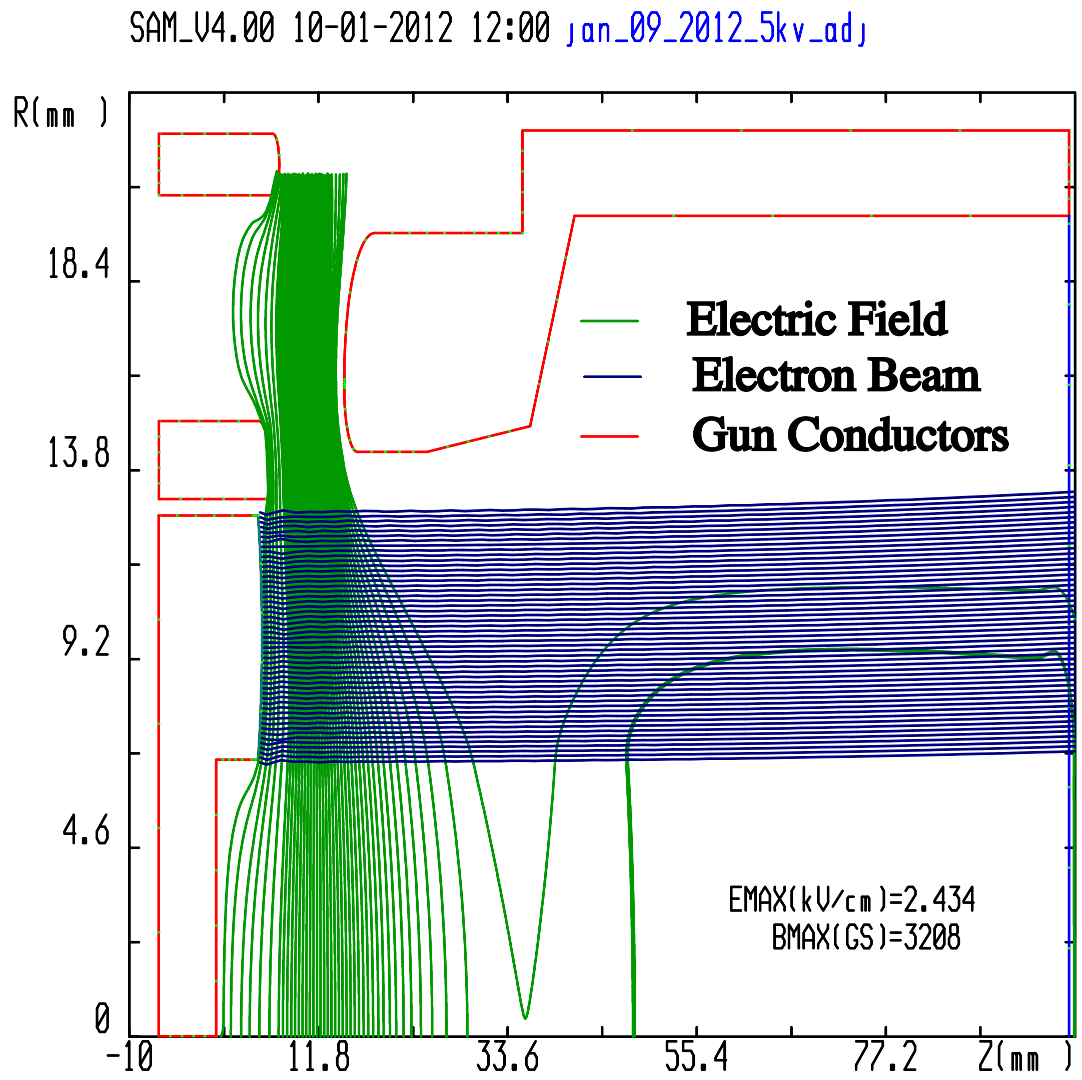
$$K = P \times \left[\frac{(1-\gamma^2 f_e)}{4\pi\varepsilon_0\gamma^3(2q/m)^{1/2}}\right]$$

$$\frac{K}{(1-f_e)} = P \times \left[\frac{m^{1/2}}{4\pi\varepsilon_0(2q)^{1/2}}\right] = P \times 1.515 \times 10^4$$



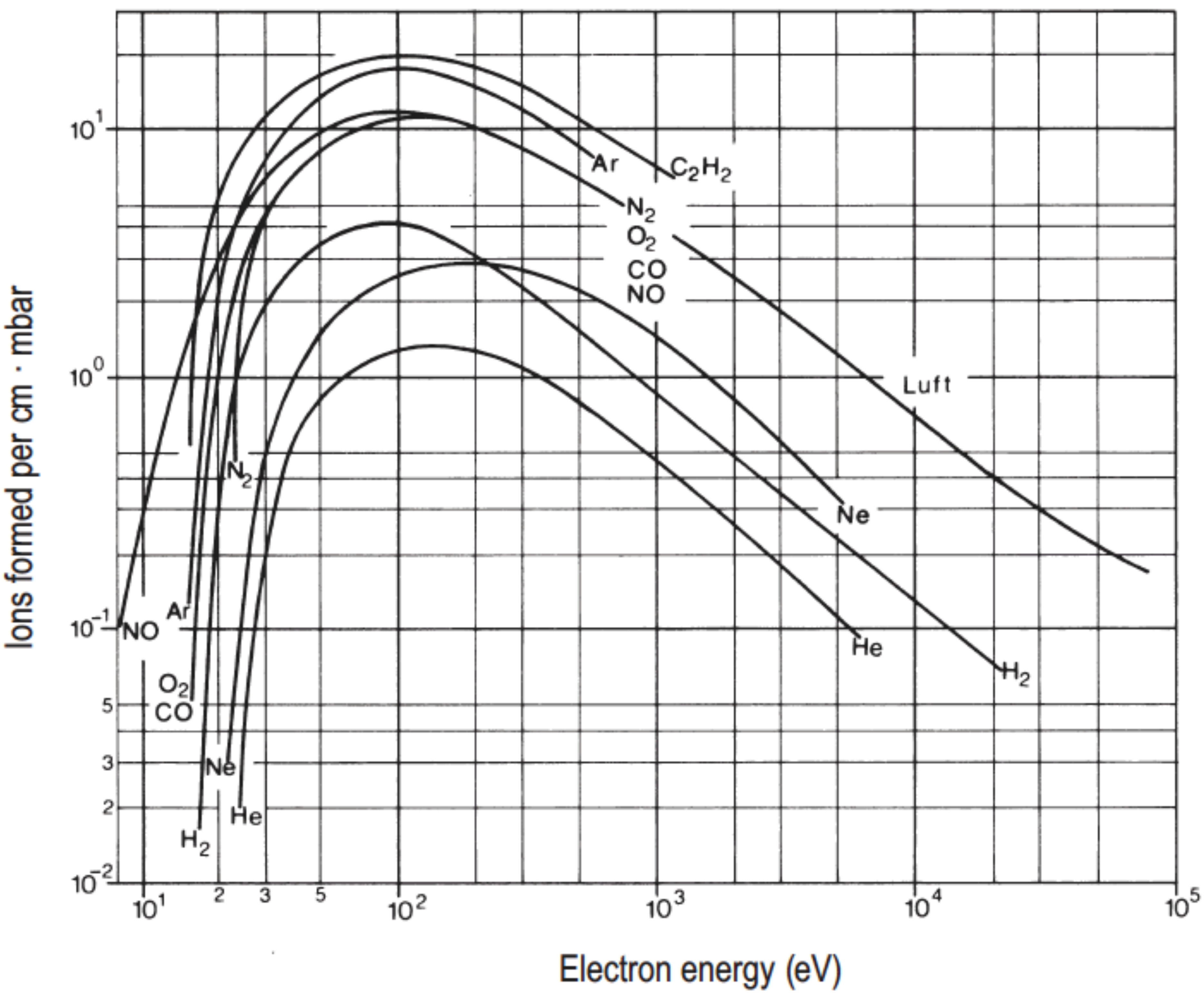
SAM Simulations





B = 0.05 T V=5 kB B = 0.5 T

Background Gases



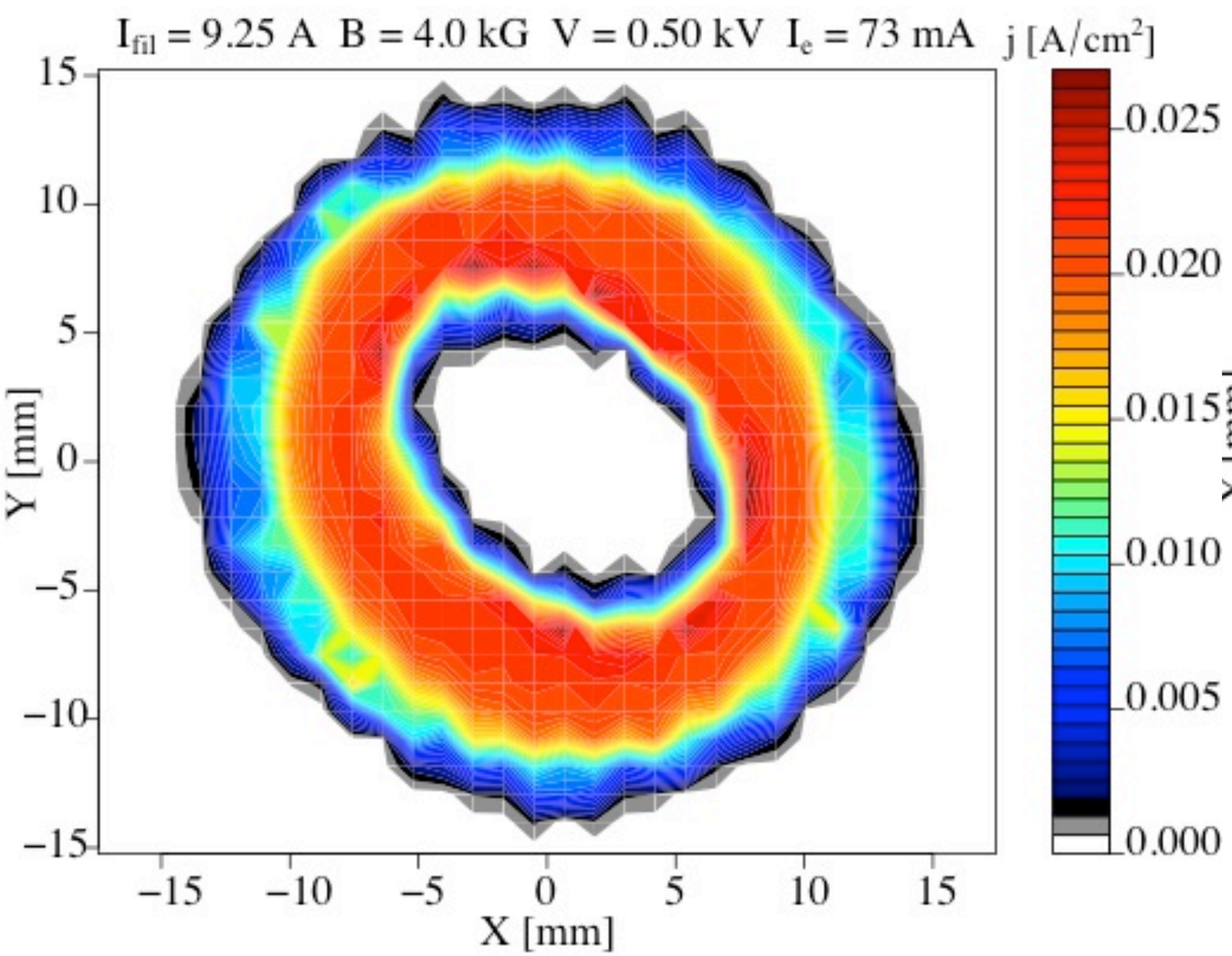
Background Gas of Test Stand

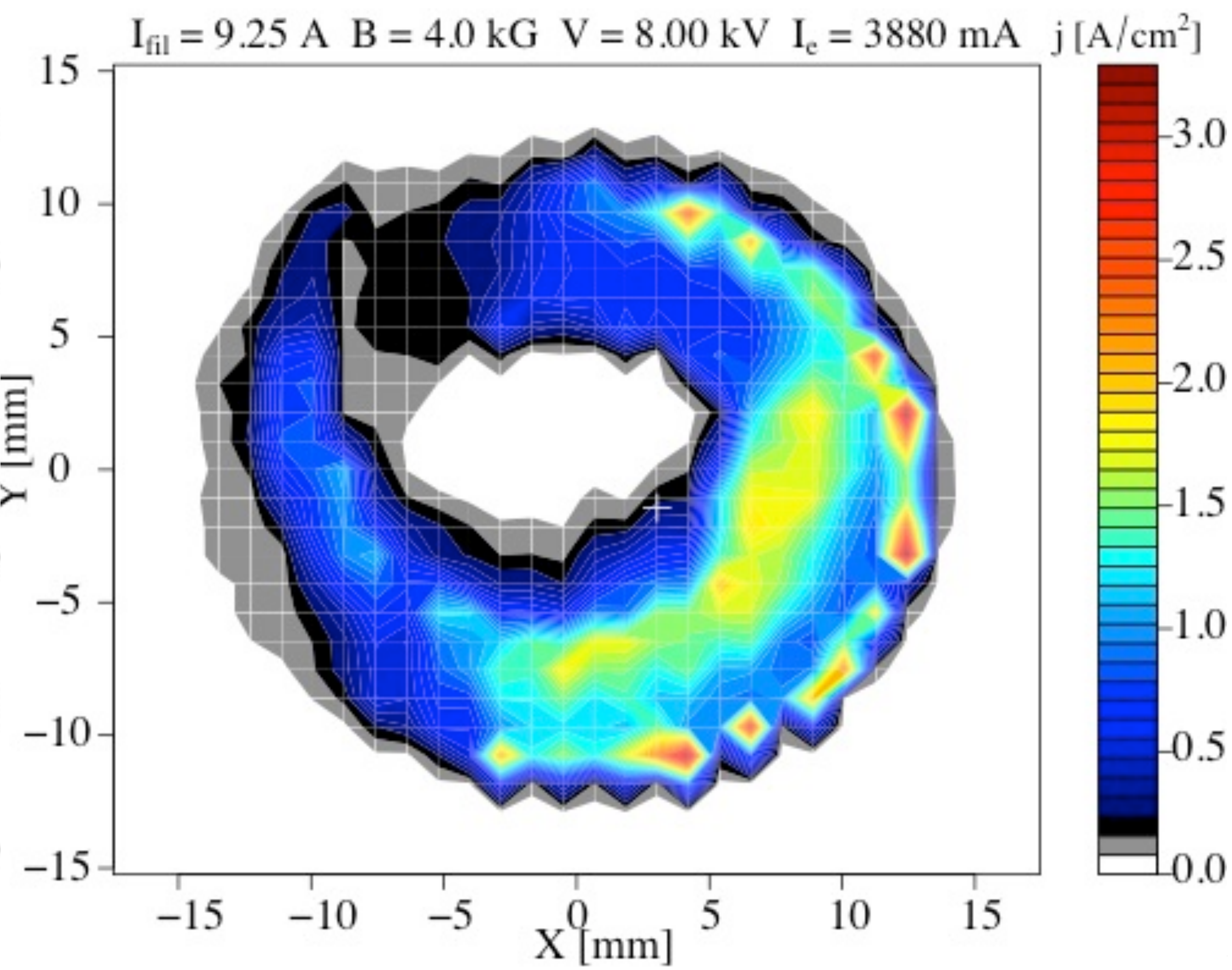
Hydrogen gas at
1×10^{-8} mbar

Transverse Profiles

- $V_a = 500$ V
- $I_{peak} = 73$ mA
- B = 1 - 4 - 1 kG

- $V_a = 8$ kV
- $I_{peak} = 3.88$ A
- B = 1 - 4 - 1 kG





Beam Evolution

- Angle of rotation around beam axis (derived from dioctron frequency)

$$\varphi = \frac{PE_0L\sqrt{V_a}}{4\pi\varepsilon_0 ec^2(R_o^2 - R_i^2)B}\left(1 - \left(\frac{R_i}{r}\right)^2\right) \quad [rad]$$

- Dependence on r ➔ slippage
- Scaling law ➔ angle of rotation must be constant

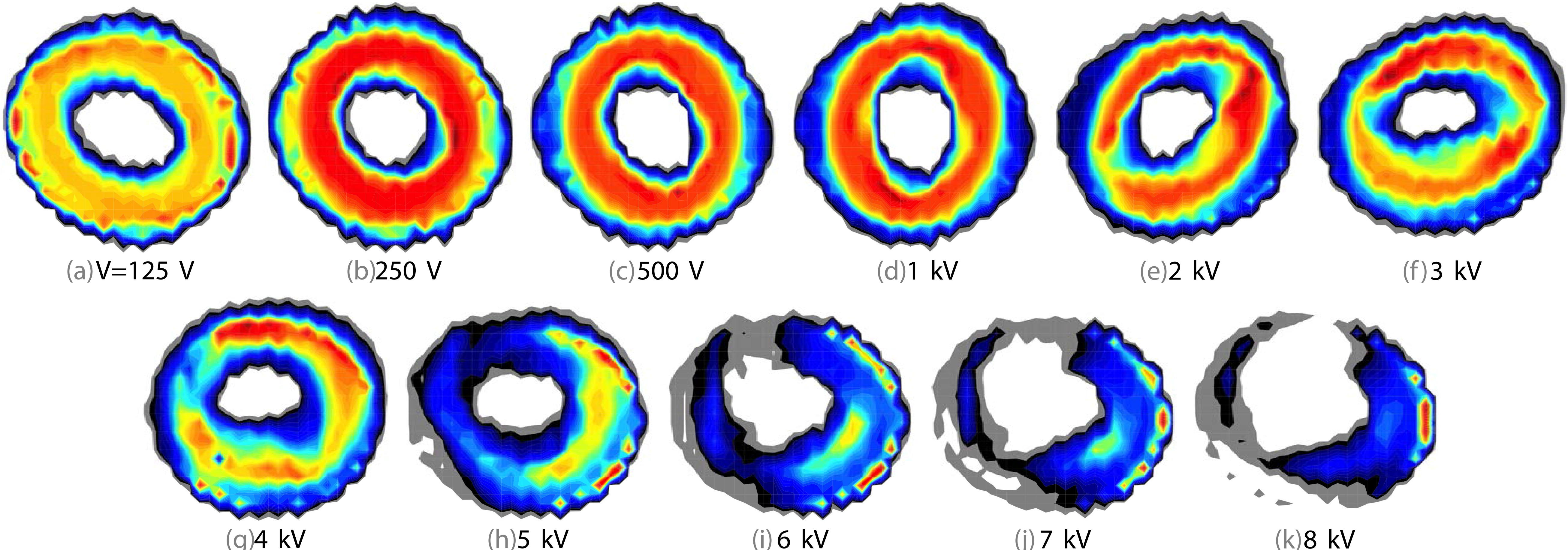
$$B \propto \sqrt{V}$$

- Angle of rotation at outer cathode radius

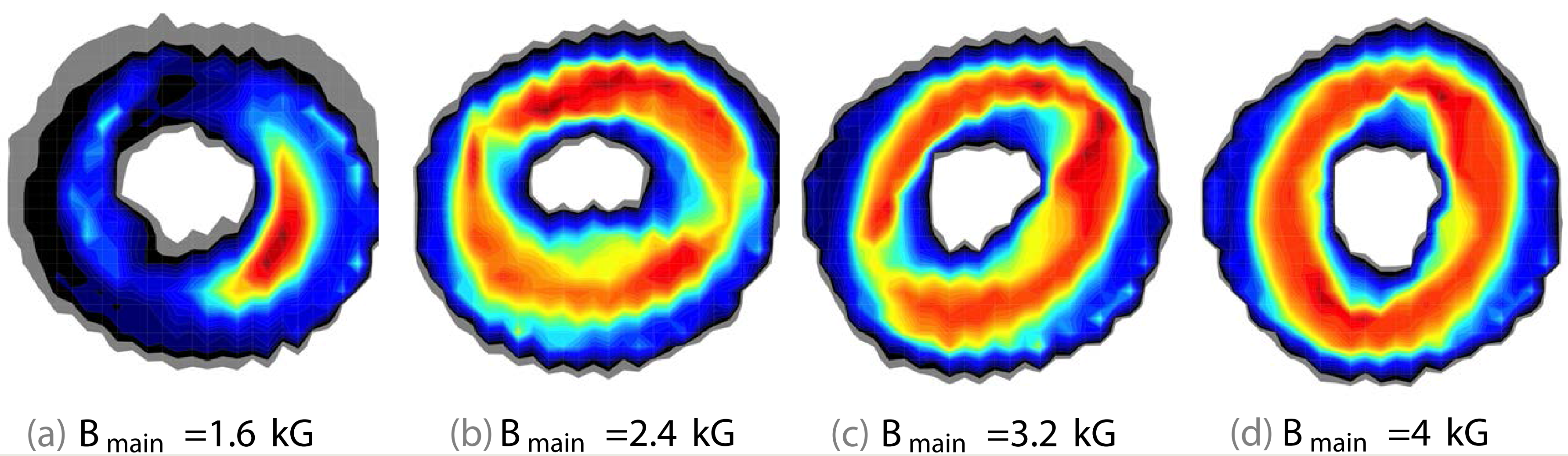
Angle of rotation [°]	Acceleration Potential [kV]							
Magnetic Field [T]	1	2	3	4	5	6	7	8
0.40	72	101	124	143	160	175	189	202
0.32	89	127	155	179	200	219	237	253
0.24	120	169	207	239	267	292	316	337
0.16	179	253	310	358	400	438	473	506

Beam Evolution

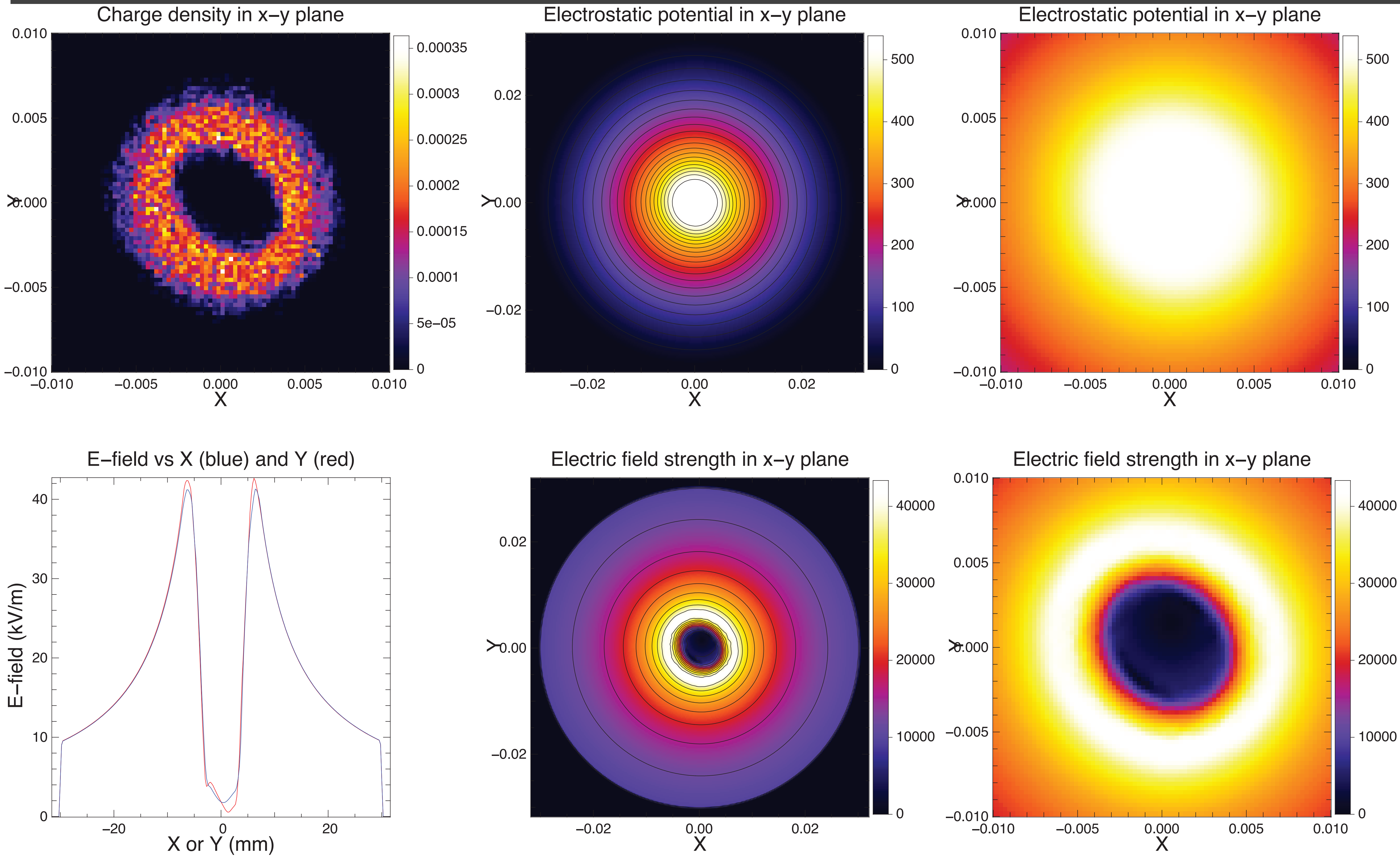
- Profile evolution with V at B= 0.8-3.2-0.8 kG



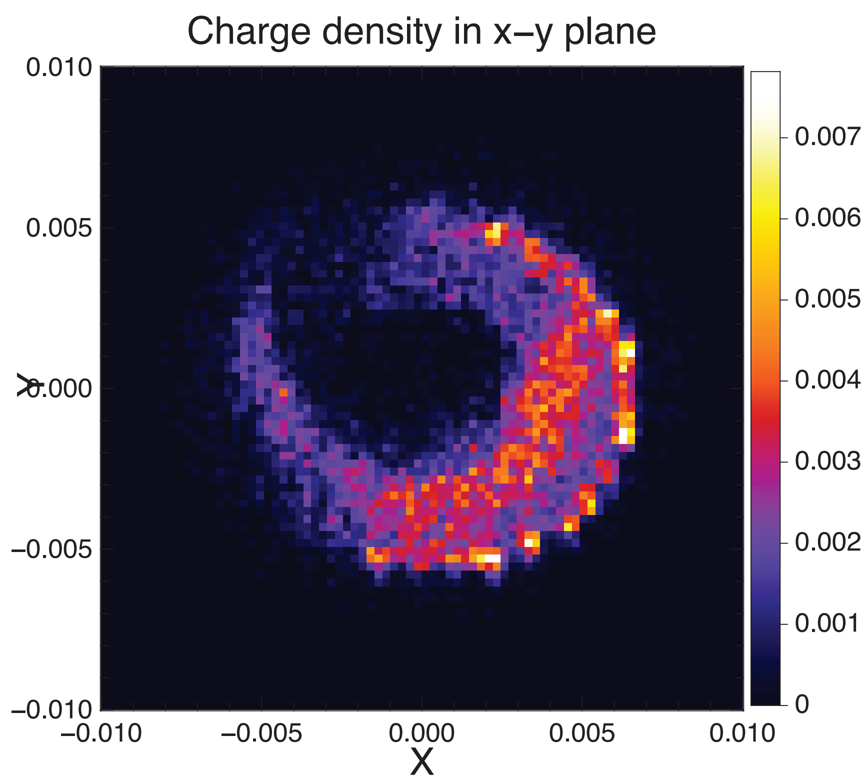
- Profile evolution with V at B= 0.8-3.2-0.8 kG

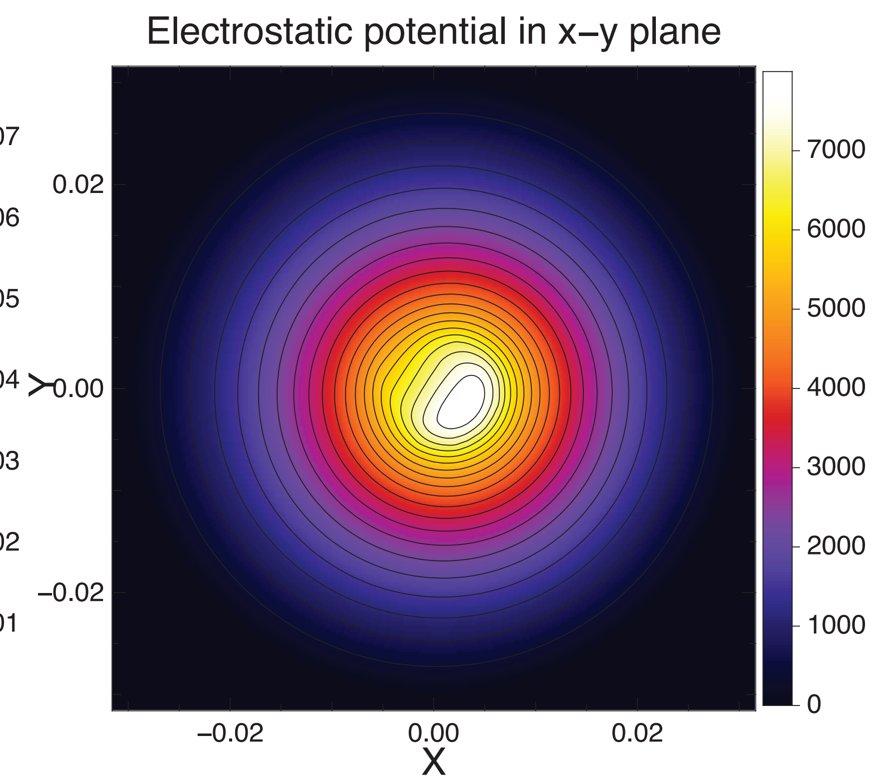


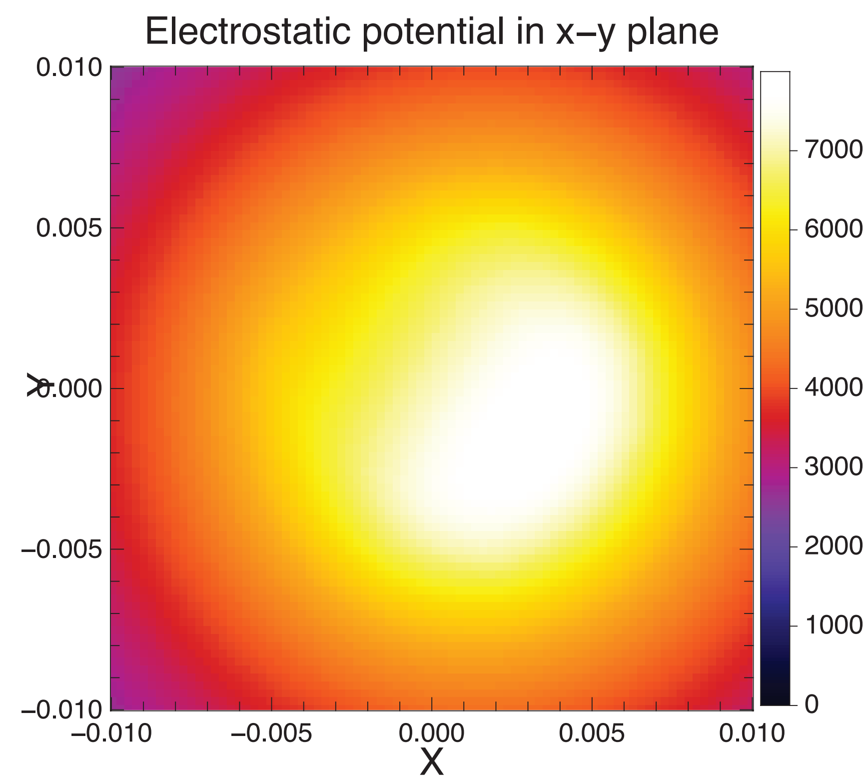
Transverse Electric Fields at 500 V

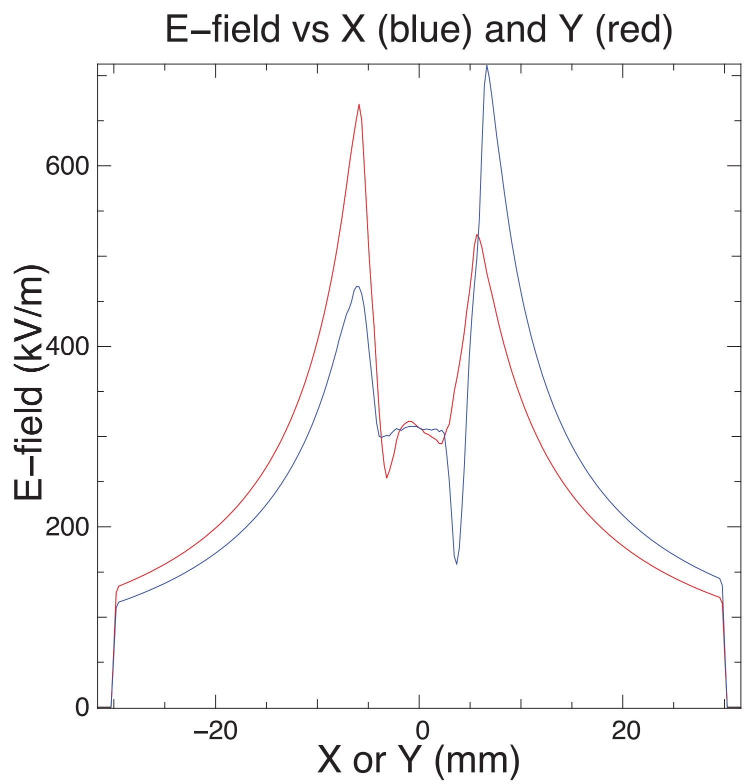


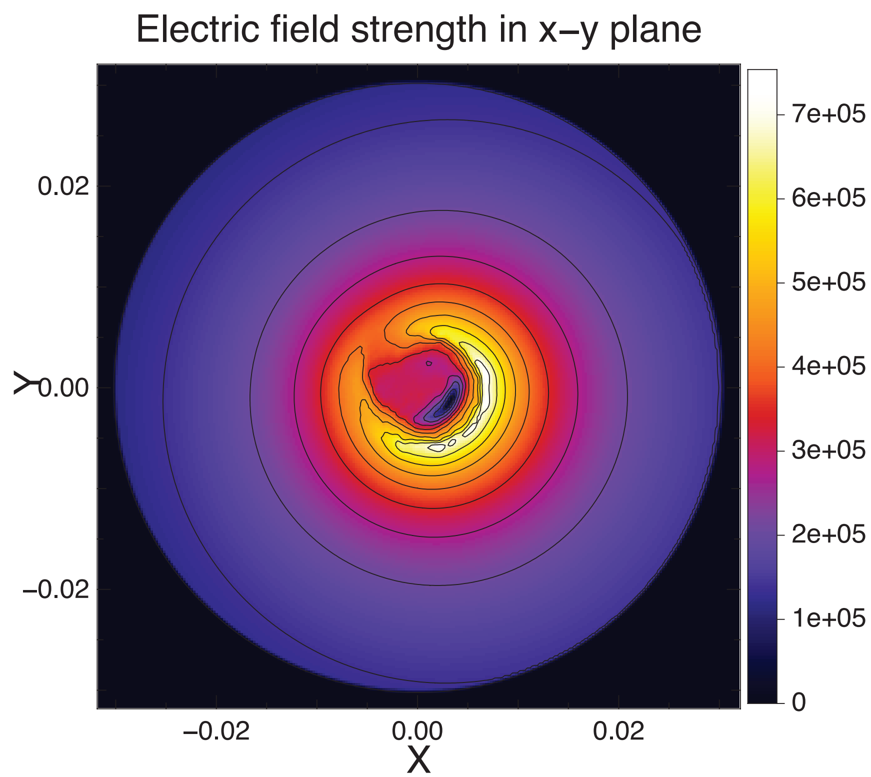
Transverse Electric Fields at 8 kV

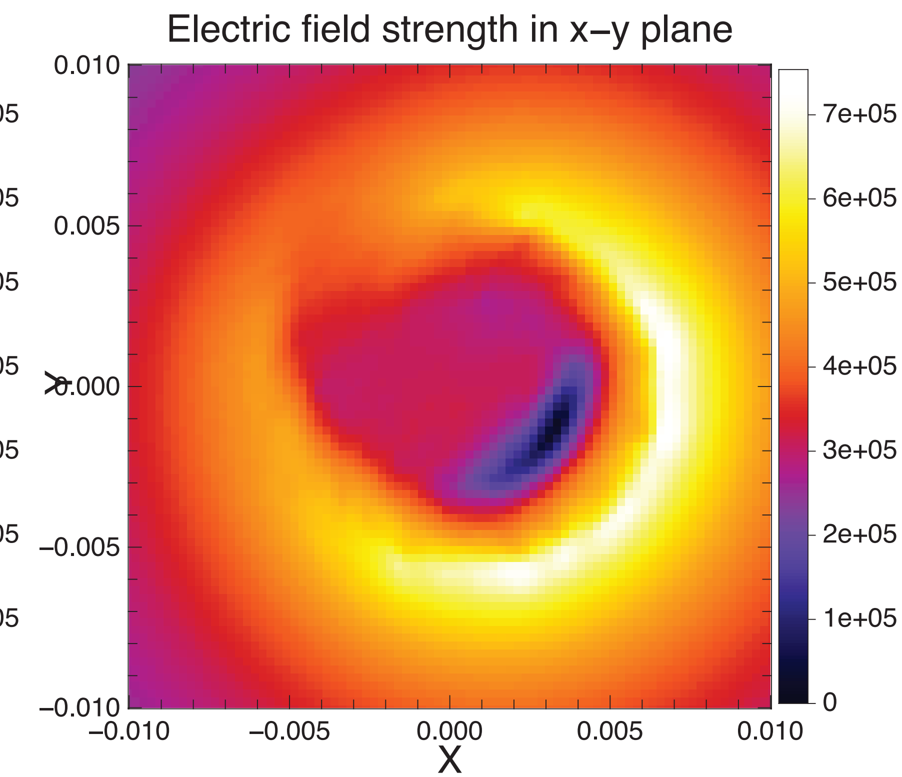












Derivation – Angle of Rotation

$$\omega_p^2 = \frac{q^2 n}{\varepsilon_0 \gamma^3 m}\left(1-\gamma^2 f_e\right) \qquad \omega_r = \omega_D = \frac{\omega_p^2}{2\omega_c} = \frac{ne}{2\varepsilon_0 B} \tag{1}$$

$$\omega_r = \omega_D(1-f-\beta_z^2)\left[1-\left(\frac{R_i}{r}\right)^2\right], \quad \forall R_i \le r \le R_o \tag{2}$$

$$\varphi_r = \frac{\omega_D L}{v_z}\left[1-\left(\frac{R_i}{r}\right)^2\right] = \frac{n_e e L}{2\varepsilon_0 B v_z}\left[1-\left(\frac{R_i}{r}\right)^2\right], \quad \forall R_i \le r \le R_o \tag{3}$$

$$\varphi_r = \frac{IL}{2\pi\varepsilon_0 B(R_0^2-R_i^2)v_z^2}\left[1-\left(\frac{R_i}{r}\right)^2\right] \tag{4}$$

$$= \frac{IL}{2\pi\varepsilon_0 B(R_0^2-R_i^2)c^2 eV_a\left(\frac{(2E_0+eV_a)}{(E_0+eV_a)^2}\right)}\left[1-\left(\frac{R_i}{r}\right)^2\right], \quad \forall R_i \le r \le R_o \tag{5}$$

$$\varphi = \frac{IE_0L}{2\pi\varepsilon_0 B(R_0^2-R_i^2)2c^2 eV_a}\left[1-\left(\frac{R_i}{r}\right)^2\right], \quad \forall R_i \le r \le R_o \tag{6}$$

$$\varphi = \frac{PE_0L}{4\pi\varepsilon_0 c^2(R_0^2-R_i^2)e} \times \frac{\sqrt{V_a}}{B}\left[1-\left(\frac{R_i}{r}\right)^2\right] \tag{7}$$

$$= 2.7\times 10^{-2}\frac{\sqrt{V_a}}{B}\left[1-\left(\frac{R_i}{r}\right)^2\right], \quad \forall R_i \le r \le R_o \tag{8}$$

Derivation – Electric Field Equations

$$\oiint_{\partial\Omega} E \cdot \mathrm{d}S = \frac{Q_{\text{encl},\Omega}}{\varepsilon_0} \tag{1}$$

$$E \cdot 2\pi r L = \frac{\int_0^R \rho(r')2\pi r' L \mathrm{d}r'}{\varepsilon_0} \tag{2}$$

$$E = \frac{\int_0^R \rho(r') r' \mathrm{d}r'}{\varepsilon_0 r} \tag{3}$$

$r \leq R_o$ $$E = 0 \tag{4}$$

$R_i \geq r \leq R_o$ $$E(r) = \frac{\rho(r^2 - R_i^2)}{2\varepsilon_0 r} = \frac{IL(r^2 - R_i^2)}{2\pi v_z \varepsilon_0 r(R_o^2 - R_i^2)} \tag{5}$$

$R_o \geq r$ $$E(r) = \frac{\rho(R_o^2 - R_i^2)}{2\pi\varepsilon_0 r} = \frac{IL}{2\pi v_z \varepsilon_0 r} \tag{6}$$

Derivation – Emittance Growth Rate

$$\frac{\mathrm{d}}{\mathrm{d}t}p_r = F_y = q\vec{E}_r \tag{1}$$

$$p_r = q\vec{E}_r t \tag{2}$$

$$p_z \tan(\theta) = q\vec{E}_r \tag{3}$$

$$\rightarrow \tan(\theta) = \frac{q\vec{E}_r t}{p_z} \tag{4}$$

$$\rightarrow \tan(\theta) = \frac{q\vec{E}_r L}{p_z v_z} \tag{5}$$

$$\rightarrow \tan(\theta) = \frac{\gamma E_0 q\vec{E}_r L}{p_z^2} \tag{6}$$

$$\rightarrow \tan(\theta) = \frac{E_{tot} q\vec{E}_r L}{(E_{tot}^2 - E_0^2)} \tag{7}$$

$$\Rightarrow \vartheta = \frac{E_{tot} q E_r L}{E_{tot}^2 - E_0^2} \tag{8}$$

Derivation – Emittance Growth Rate

$$\begin{pmatrix} x_{n+1} \\ x'_{n+1} \end{pmatrix} = M \begin{pmatrix} x_n \\ x'_n \end{pmatrix} \tag{1}$$

$$\varepsilon = \gamma x_{n+1}^2 + 2\alpha x_{n+1} x'_{n+1} + \beta x'^2_{n+1} = \gamma x_n^2 + 2\alpha x_n x'_n + \beta x'^2_n \tag{2}$$

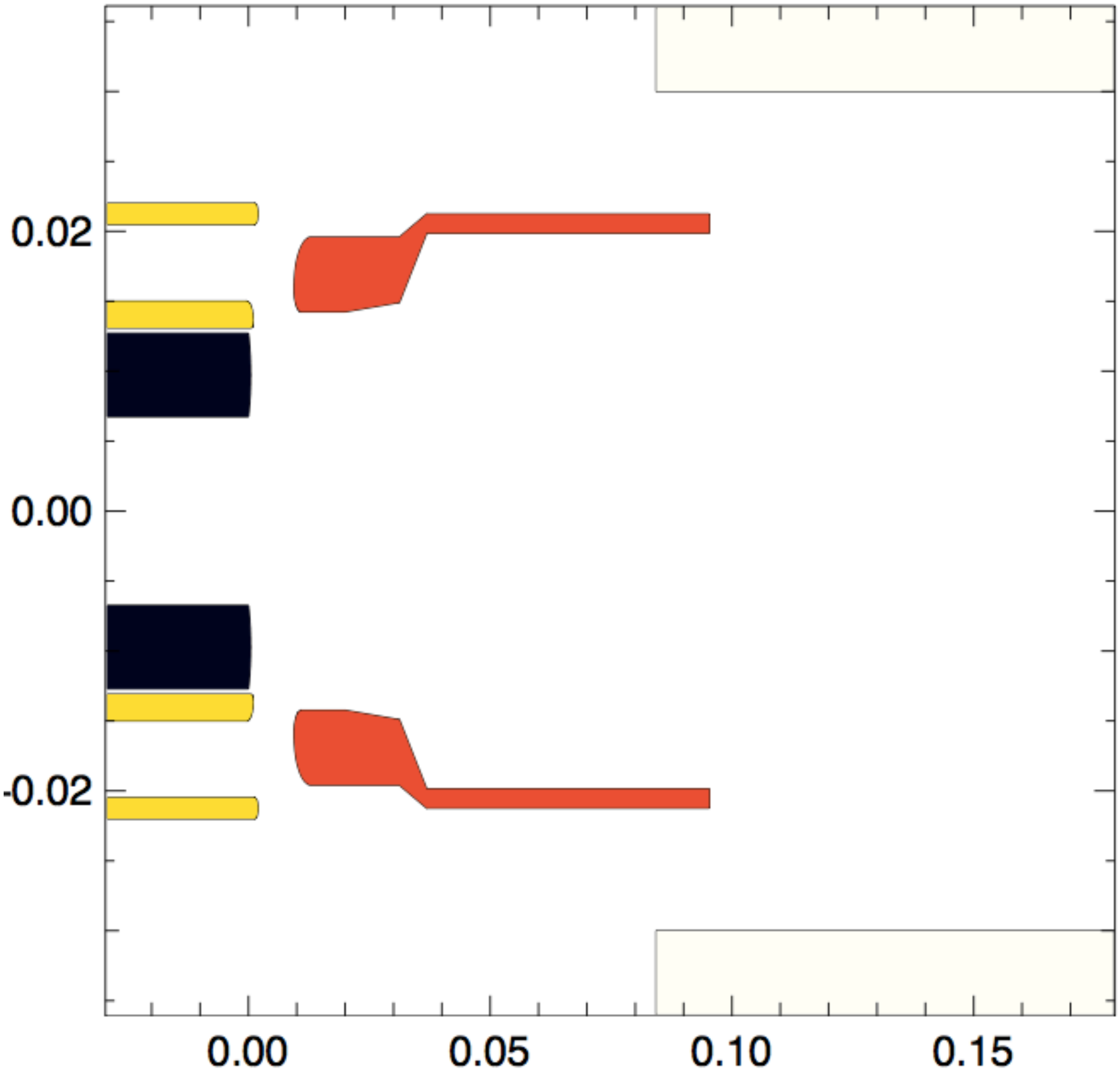
$$\begin{pmatrix} \tilde{x}_{n+1} \\ \tilde{x}'_{n+1} \end{pmatrix} = M \begin{pmatrix} x_n \\ x'_n \end{pmatrix} + \begin{pmatrix} 0 \\ \vartheta \end{pmatrix} \tag{3}$$

$$\varepsilon = \gamma \tilde{x}_{n+1}^2 + 2\alpha \tilde{x}_{n+1} \tilde{x}'_{n+1} + \beta \tilde{x}'^2_{n+1} = \gamma x_{n+1}^2 + 2\alpha x_{n+1}(x'_{n+1} + \vartheta) + \beta (x'_{n+1} + \vartheta)^2 \tag{4}$$

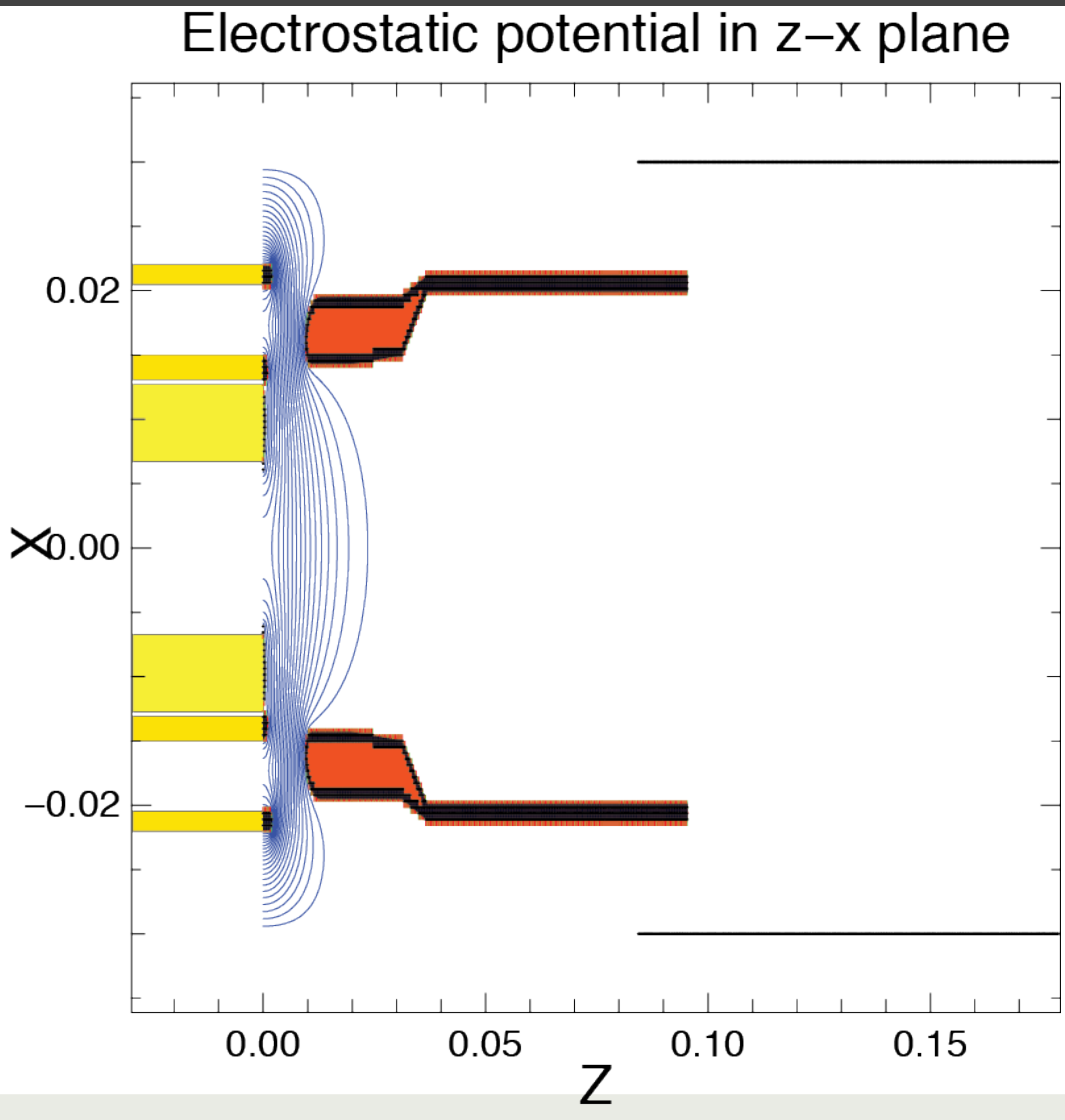
$$\Delta\varepsilon = 2\vartheta(\alpha x_{n+1} + \beta x'_{n+1}) + \beta\vartheta^2 \tag{5}$$

$$\Delta\varepsilon = \beta\vartheta^2 = \beta \left(\frac{E_{tot} q E_r L}{(E_{tot}^2 - E_0^2)} \right)^2 \tag{6}$$

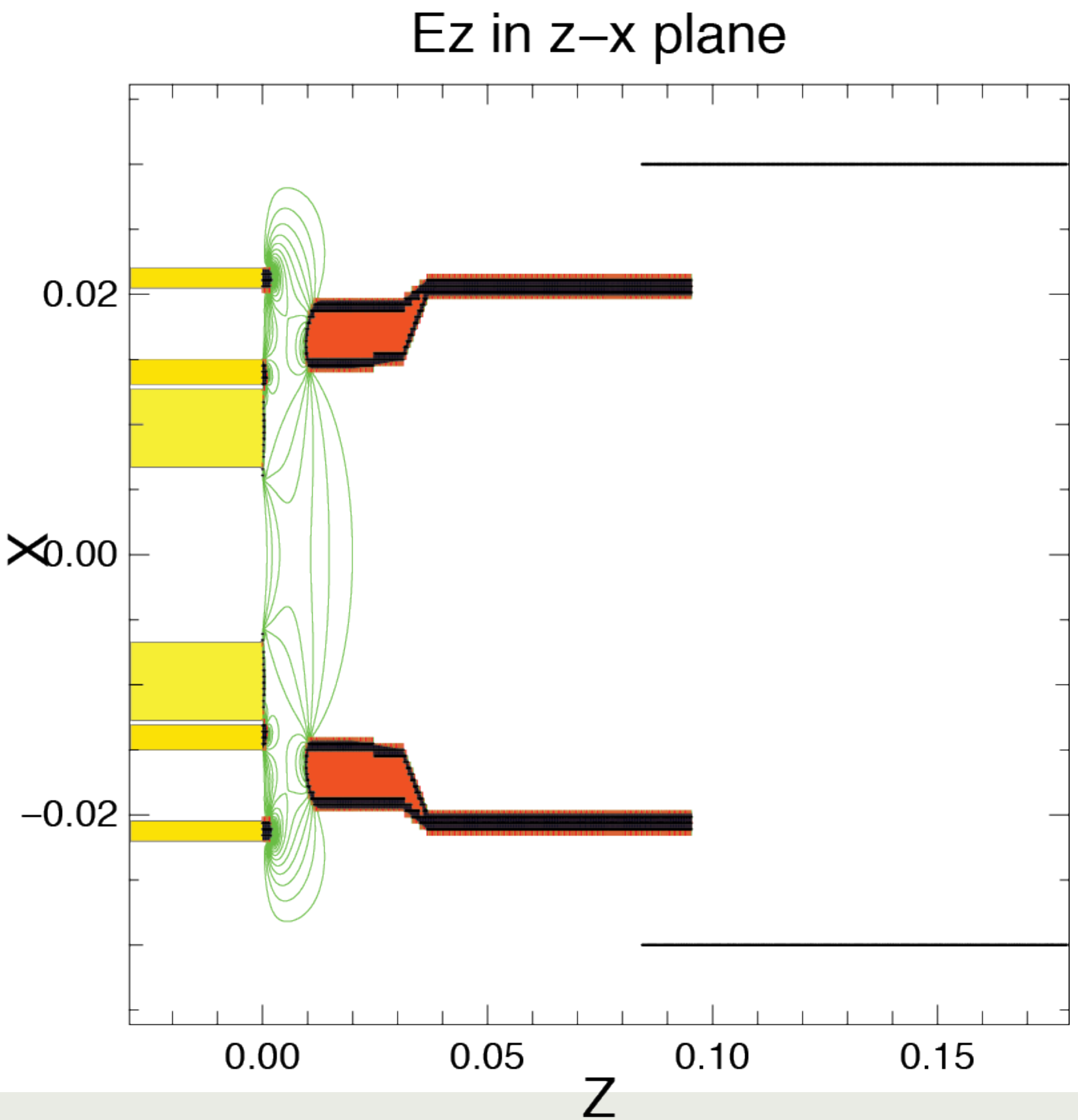
WARP – Implemented Gun



WARP – Potential Fields



WARP – Electric Fields



WARP – Electric Fields