Simulation studies for the e-dynamics and discussion on the range of interesting e-currents (4-5A) and solenoid fields (4-6T), summary of BINP studies and range of required parameters

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With contributions from G. Stancari (FNAL) and A. Pikin (BNL)

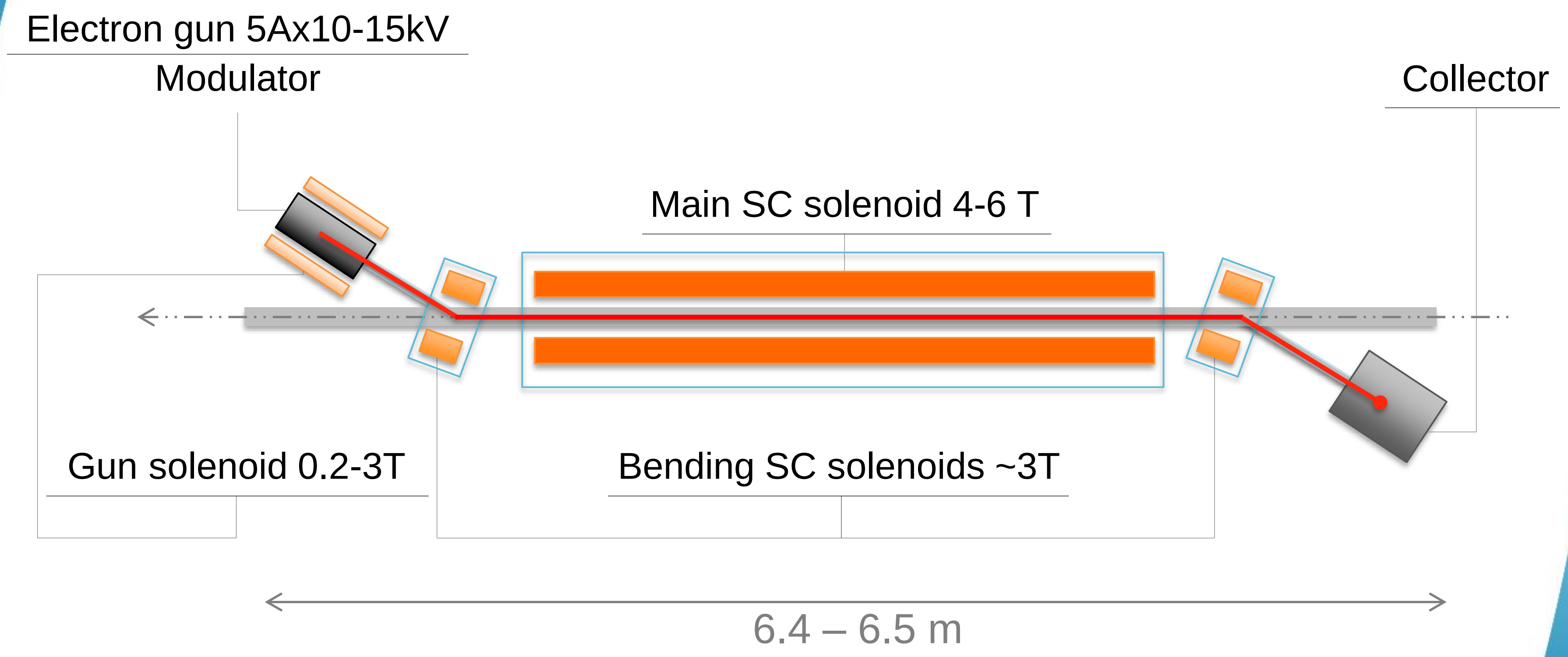
Context

- HEL e-beam has different regime (highly space-charged limited) from existing e-lenses
- Simulations: UltraSAM (Track) CST (WARP)
  - Not yet a direct comparison between different codes, but indications points towards a need for a higher accelerating voltage and magnetic field
  - Need of increasing statistics
- Experimentally we have performed measurements at FNAL test facility
  - Limitations: no bend, ratio beam pipe/beam very far from perveance limit, no compression
  - RHIC e-lens or CERN tests stands
- Need to be confidence in the choice of parameters

Outline of this talk

- Electron gun simulations (UltraSAM and CST)
- Simulations of electron transport through the HEL:
  - 'Virtual cathode' (or Pierce instability)
  - Effect of asymmetries of the vacuum chamber
  - Effect of change of geometry for diagnostics
  - Transverse beam profile and longitudinal velocities
  - Effect of drift velocity
  - Diocotron instability?
- Conclusions and future studies

Hollow Electron Lens

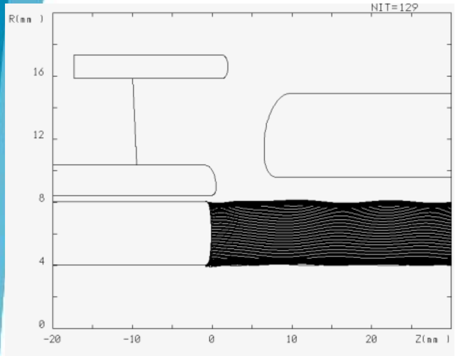


See Diego Perini for design and Marian Gonzalez for integration

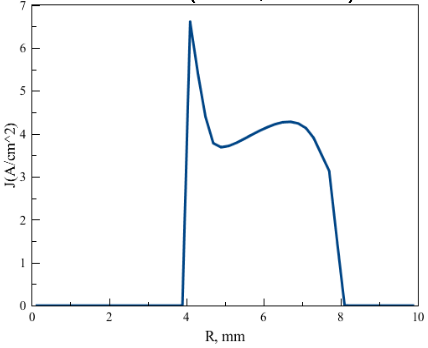
Gun simulations

Gun with small curve cathode

Renormalized Fermilab's gun with curve cathode

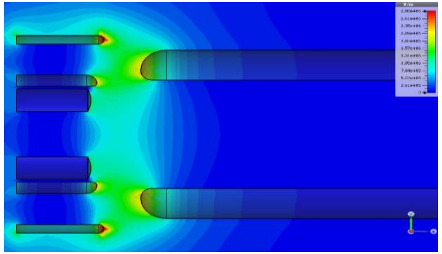


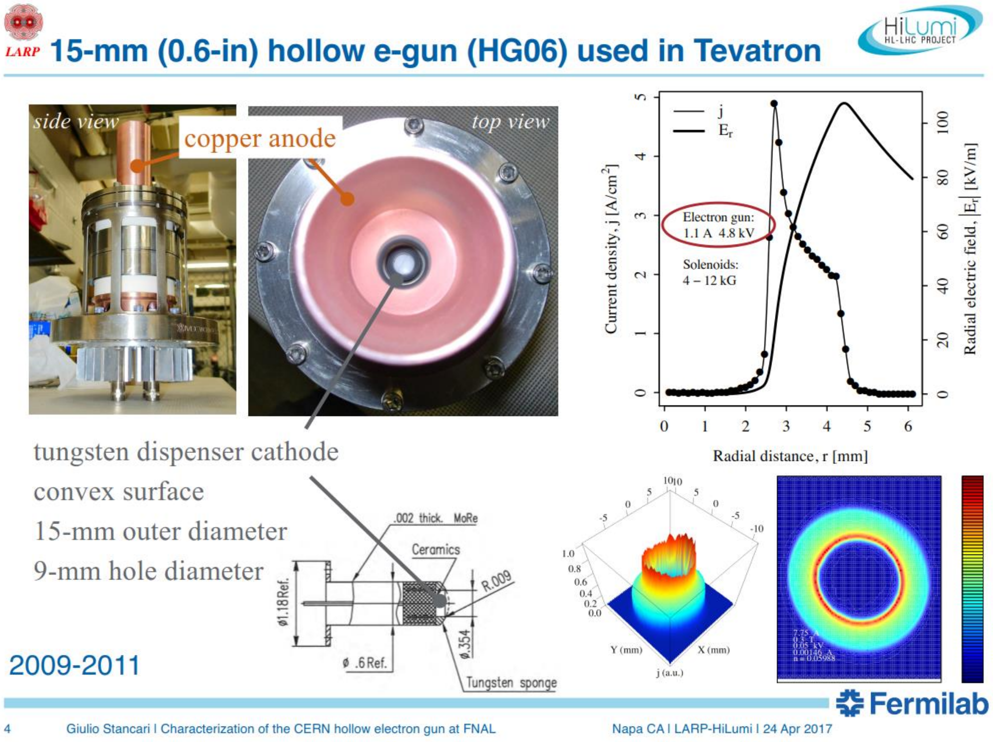
Transverse profile on the distance of 30 mm from the cathode (5.9 A, 9.8 kV)



Extracted current	**5.9 A**
Applied voltage	**10 kV**
Mag. field on the cathode	**0.18 T**

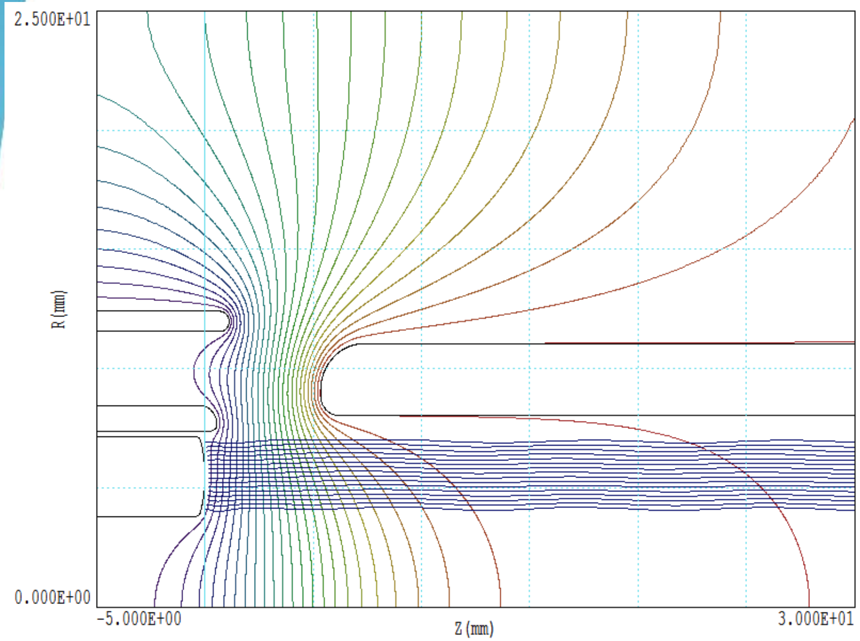
Code: UltraSAM



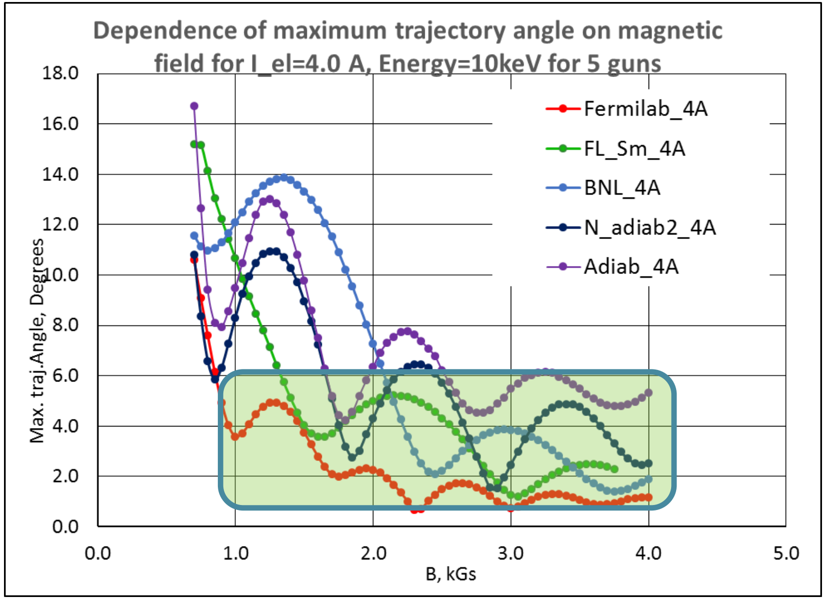


A. Pikin: gun comparison

Fermilab gun scaled down to
r_{in}=4.0mm, P=6.4x10^{-6} A/$V^{3/2}$

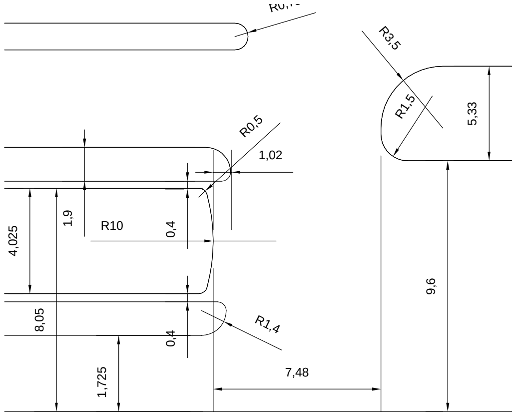


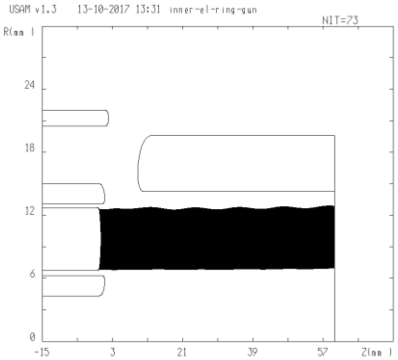
Cumulative angles:

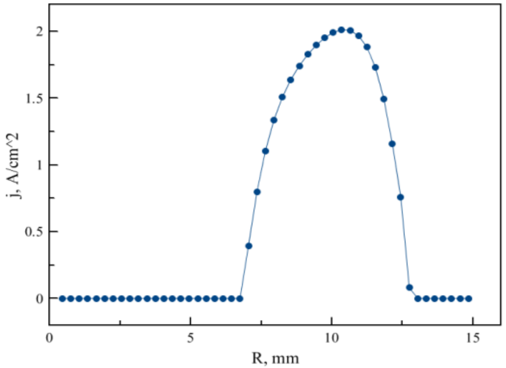


Proposal to change gun emission profile

- If deemed necessary to have a smother emission profile, it is proposed to add an inner electron to the FNAL gun design

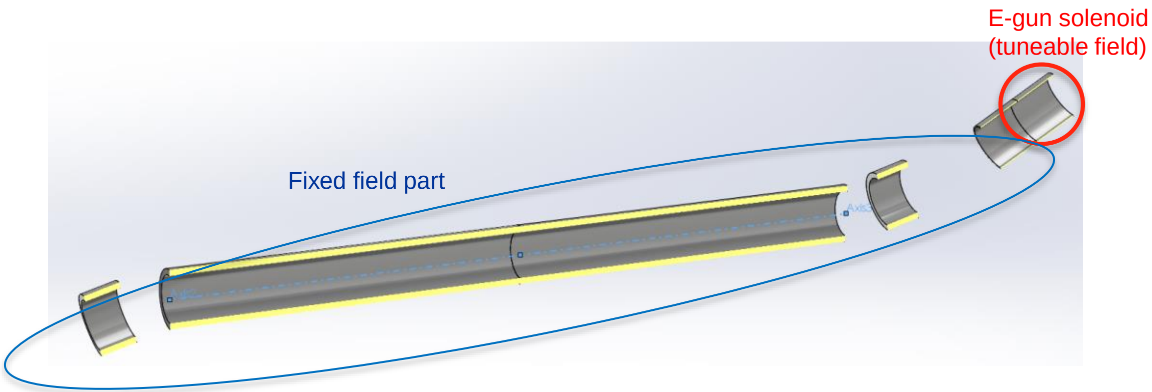






Electron transport simulations: parameters

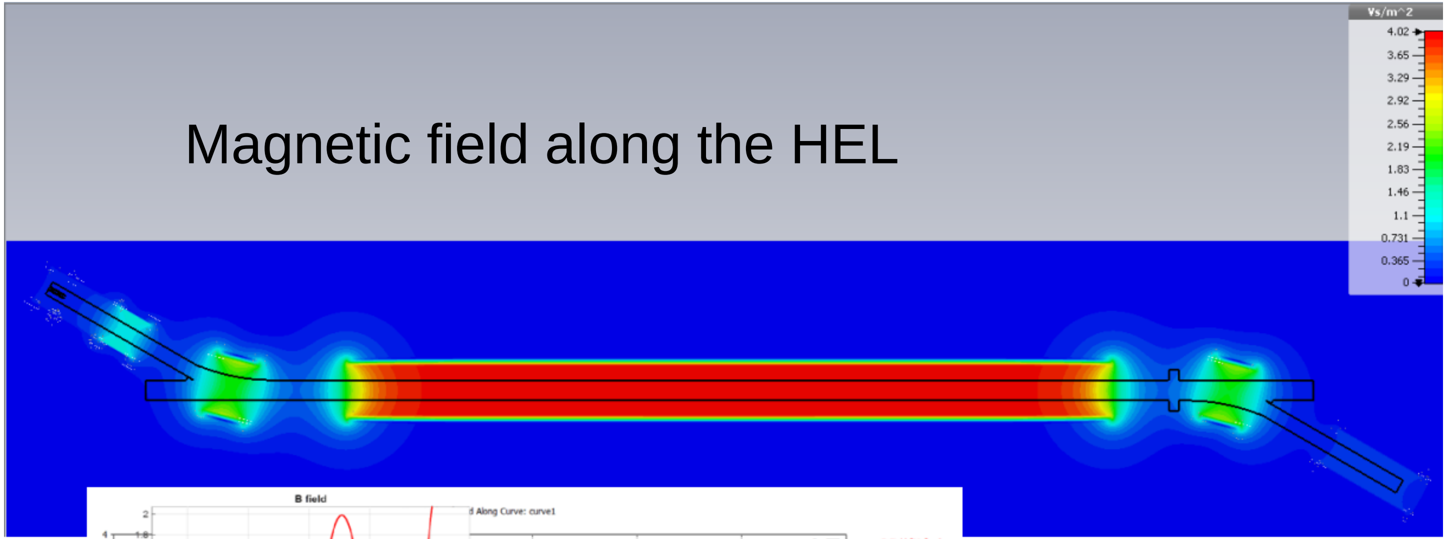
Geometry and magnetic field as from current baseline

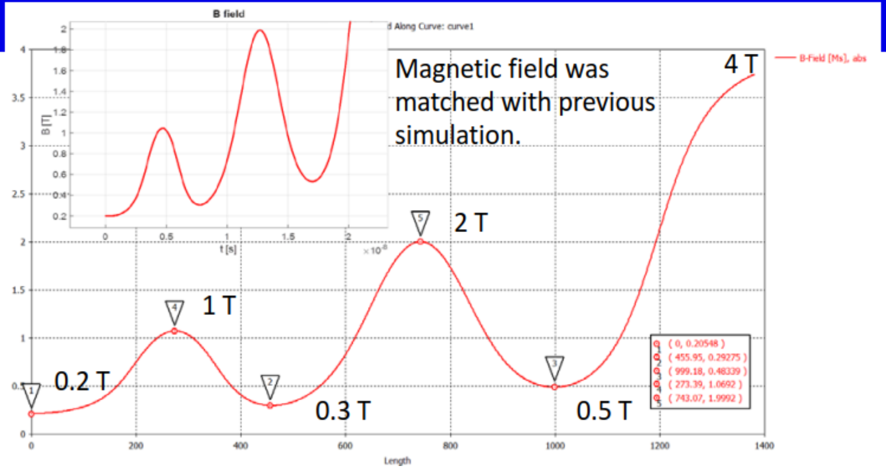


Courtesy of Diego Perini

Nominal magnetic field of the main solenoid	**4 T**
Nominal magnetic field in the e-gun cathode	0.2 T
Inner radius of the hollow electron beam @ nominal fields	0.9 mm (3 σ)
Outer radius of the hollow electron beam @ nominal fields	1.8 mm (6 σ)
Inner diameter of the cathode	8.05 mm
Outer diameter of the cathode	16.10 mm
Nominal current at the cathode	5 A

Magnetic field along the HEL





Perveance . . .

- For non-relativistic beams, $E=U+K$
- U = potential of the pipe walls (ground) – potential of the beam

- The pipe **perveance P_p** defines the minimum potential difference with which the beam can be transported through the pipe, and depends on geometrical factors (pipe and beam size), beam current and kinetic energy (initially beam velocity $v = \sqrt{(2 \cdot e \cdot U_o/m)}$ with U_o accelerating potential).

- Analytical estimate for P_p (cylindrical capacitance, assuming round e-beam)

$$P_p = \frac{\sqrt{2e/m_e}}{3\sqrt{3}} \frac{4\pi\varepsilon_0}{\ln\left(r_{pipe}/r_{beam}\right)}$$

… and critical electron current

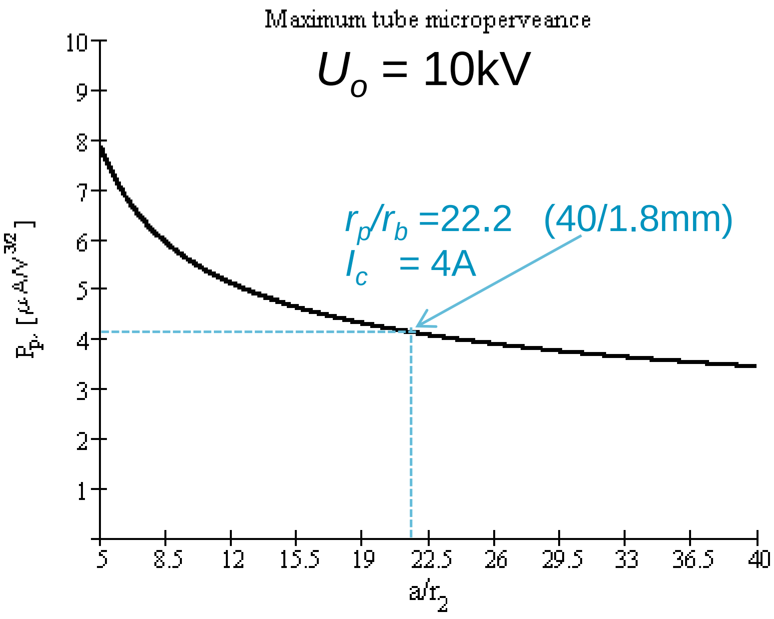
- Maximum current trough a pipe for a given accelerating potential U_o

$$I_c = P_p U_o^{3/2}$$

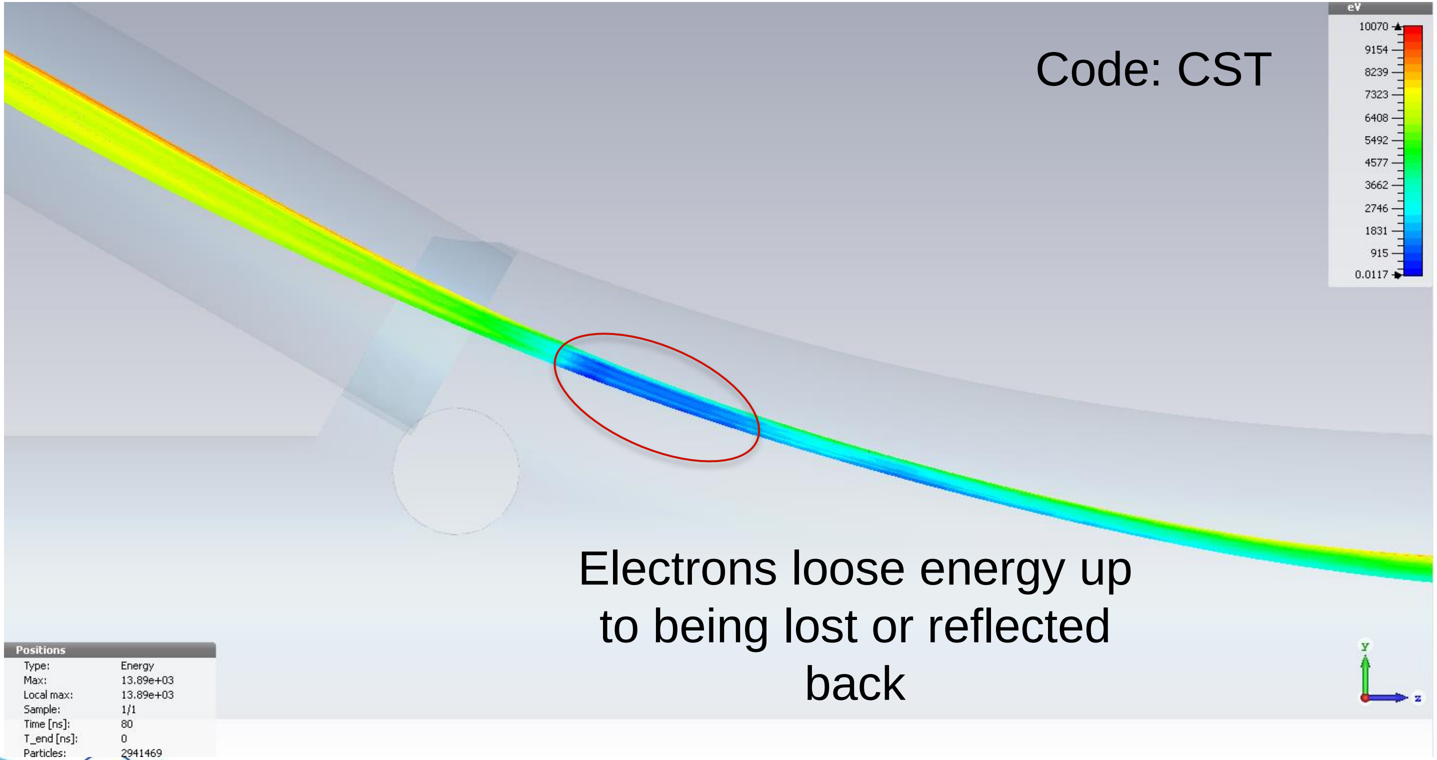
- For $I \sim I_c$, the minimum beam energy in the pipe will be $\sim U_o/3$

U_o = 10kV $\rightarrow$ I_c = 4A, and U_{min} ~3keV

$U_o \geq$ 12kV $\rightarrow$ I_c = 5A, and U_{min} ~4keV



Effect of compression and virtual cathode: 10 kV accelerating voltage and 5A current

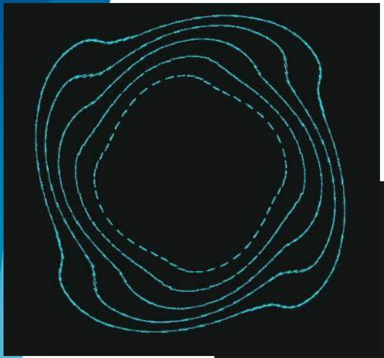


Regime near the 'virtual cathode'

- The regime of the virtual cathode (or near virtual cathode) is characterized by different phenomena such as
  - Radio frequency radiation (like in VIRCATOR – VIRtual CAthode oscillaTOR),
  - Distortion of the beam shape,
  - Particle losses,
  - Diocotron instability etc.

  We should therefore work as far as possible from the critical regime.
- In stable regime, the beam energy decrease is smaller and depends non-linearly on the particle radius.

Overcurrent regime

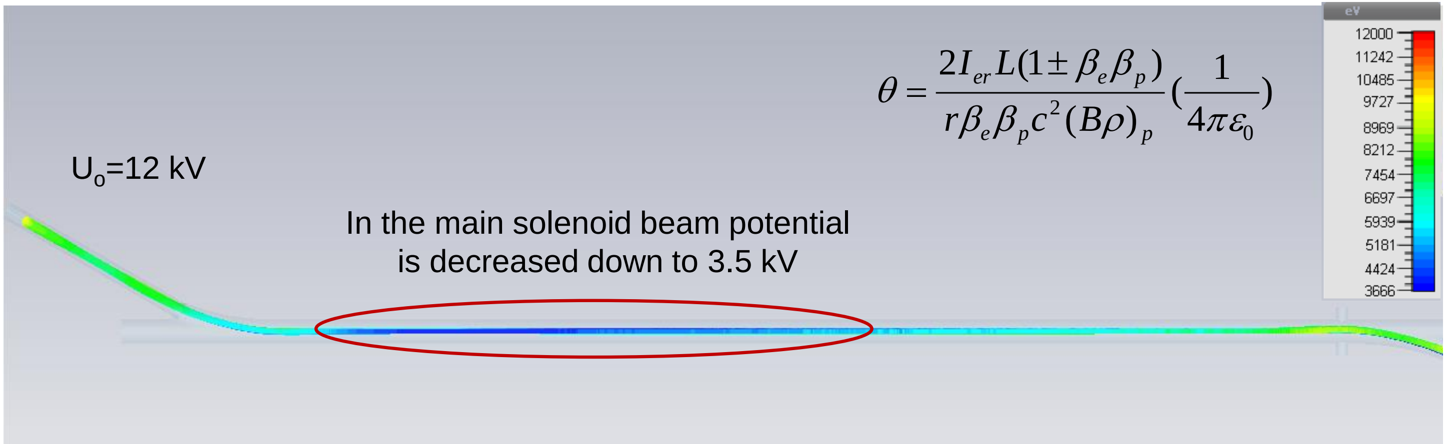


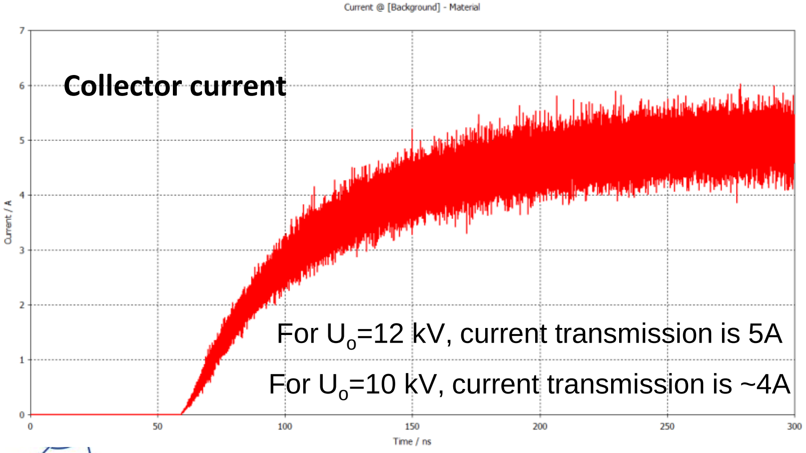
Initiation of the overcurrent regime instability

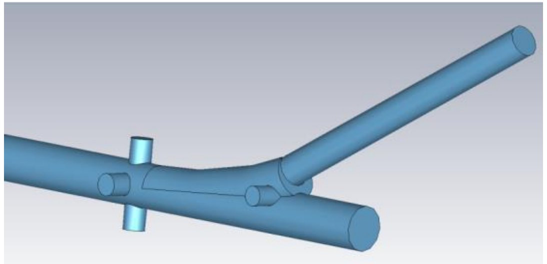
NOTE: the 'square shape' is an artefact of this simulations

Movie made with increasing beam current

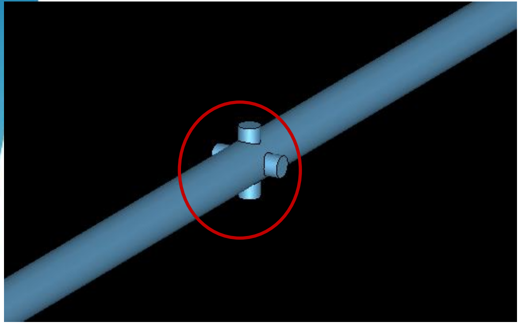
Beam potential along the HEL





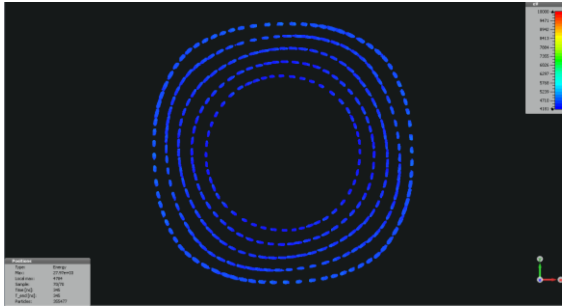


Beam potential along the HEL with ports for diagnostics

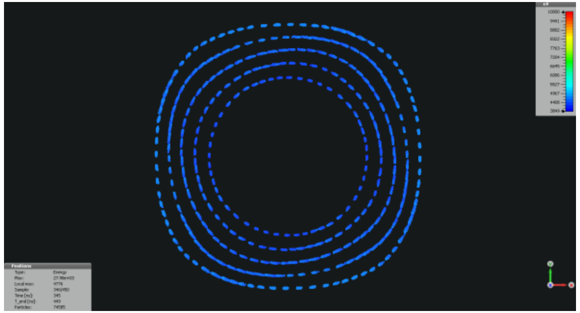


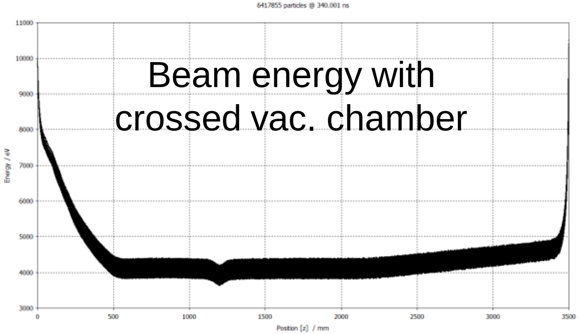
Additional ports for diagnostics do not seem to influence beam dynamics

Cross section of the beam in fixed point with crossed vac. chamber

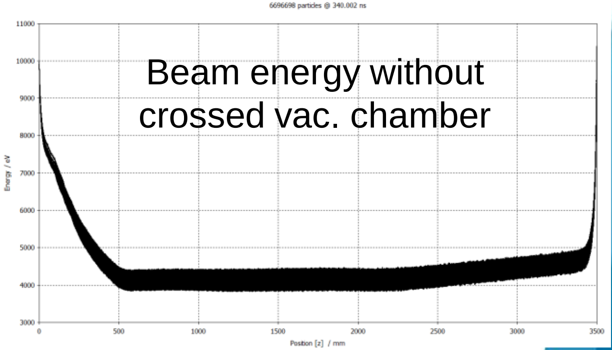


Cross section of the beam in fixed point without crossed vac. chamber





Beam energy with crossed vac. chamber



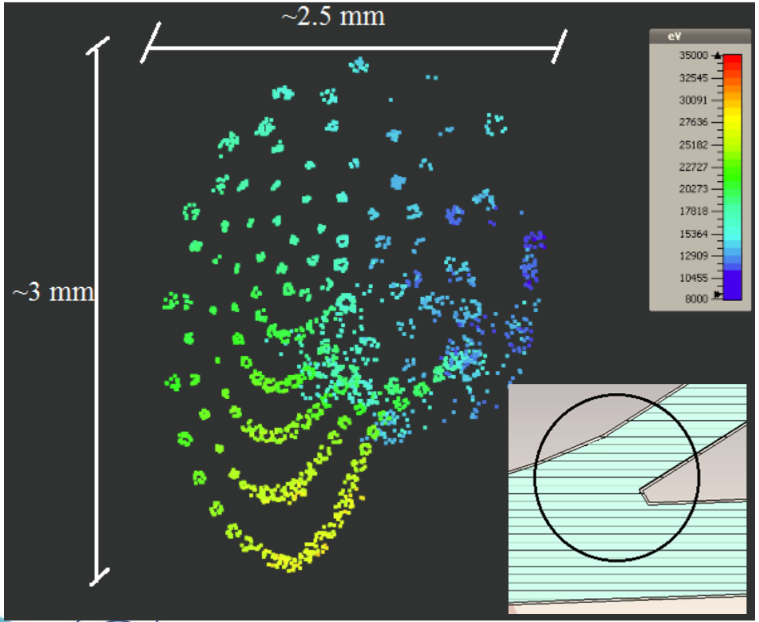
Beam energy without crossed vac. chamber

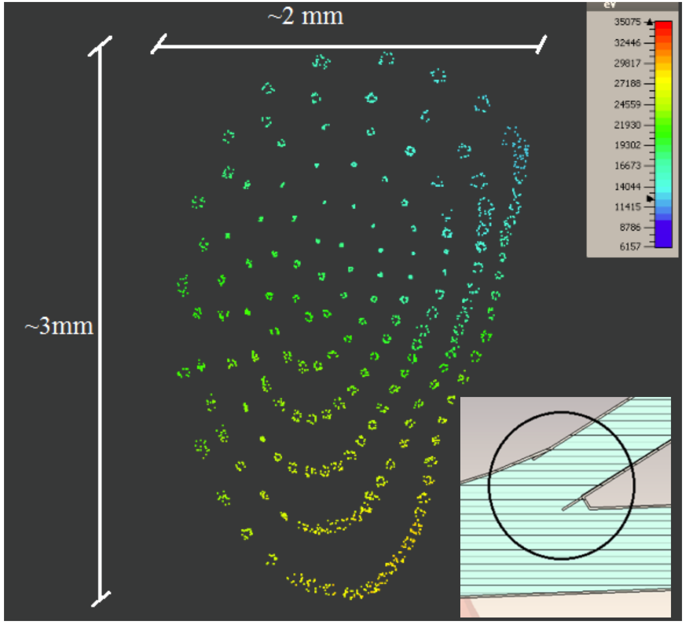
Magnetic field of 6 T, initial energy is 10 kV, beam current is 4 A

Beam dynamics I_e=20 A, U_o=35 kV (LRBB compensation)

Attempt to symmetrized vacuum chamber

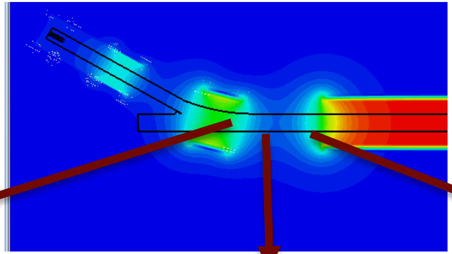
Transverse beam space





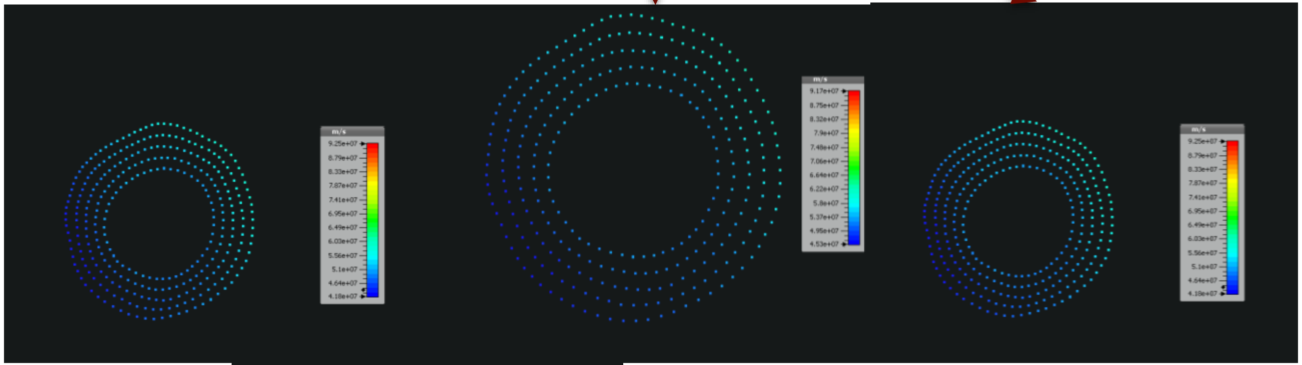
Transverse beam profile and longitudinal velocities

Minimum velocity is 4.2x10^7 (β=0.14)



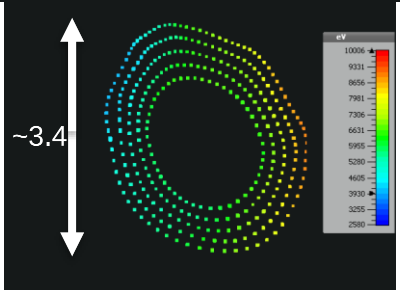
Maximum velocity is 7x10^7 (β=0.23)

5A x 12kV



Maximum velocity is 5.6x10^7 (β=0.19)

Minimum velocity is 3.7x10^7 (β=0.12)



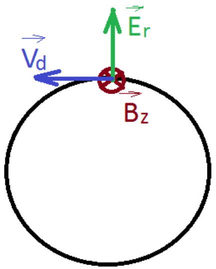
In the main solenoid

In the main solenoid the beam external diameter is about 3.4 mm, inner diameter is about 1.7 mm, minimum beam potential is about 4 kV, maximum is about 9 kV, relative velocities are 0.12 and 0.19 correspondingly

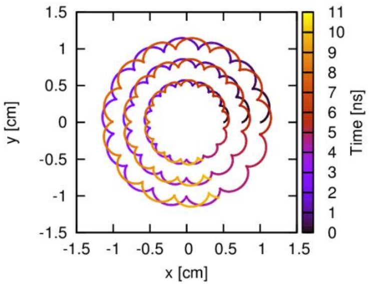
Effect of drift velocity

- Larmor motion: electrons rotating along the magnetic line with longitudinal velocity $v = \sqrt{2e/m_e U}$

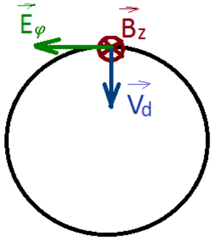
- Drift velocity derives from the ExB (e-beam electric field significant for large e-currents) $\vec{v}_d = \frac{\left|\vec{E} \times \vec{B}\right|}{B^2}$



Rotation velocity, larger at larger radius



Courtesy of Daniel Noll

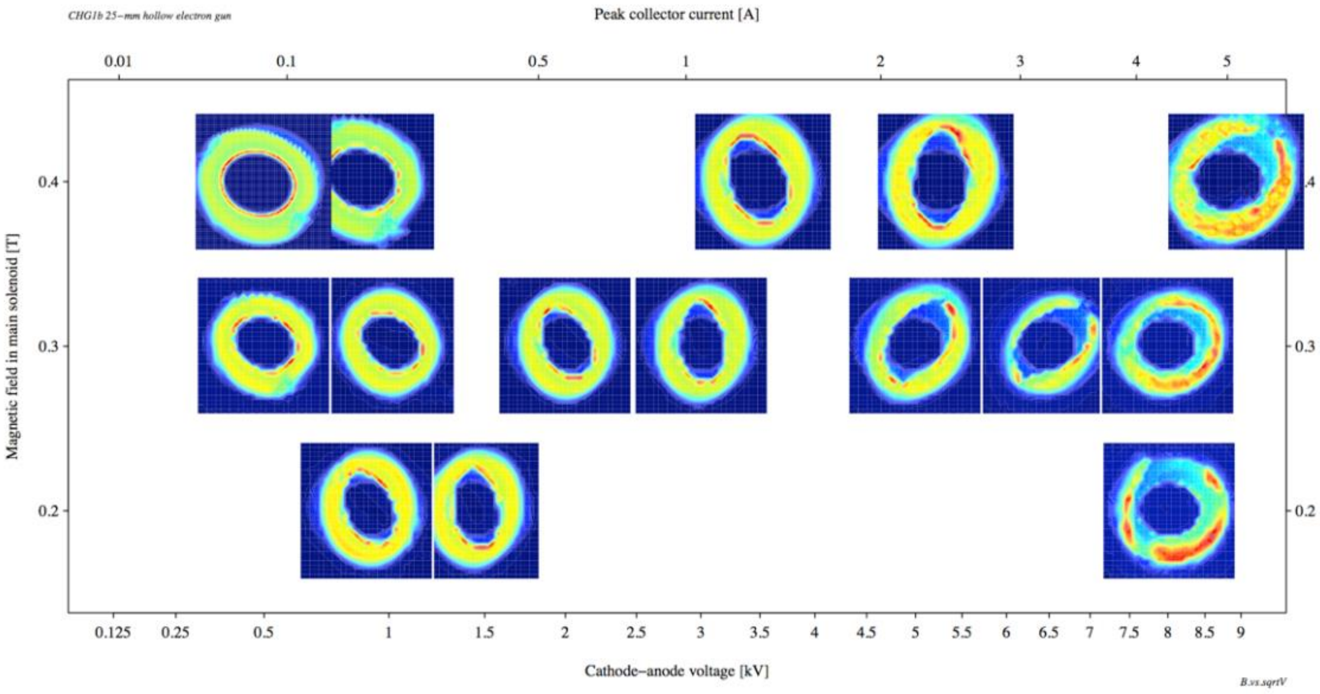


$\omega = v_d / r$ Circular beam frequency

$$\Phi(z,r) = \frac{z \cdot v_d}{r \cdot \sqrt{2\eta U}}$$

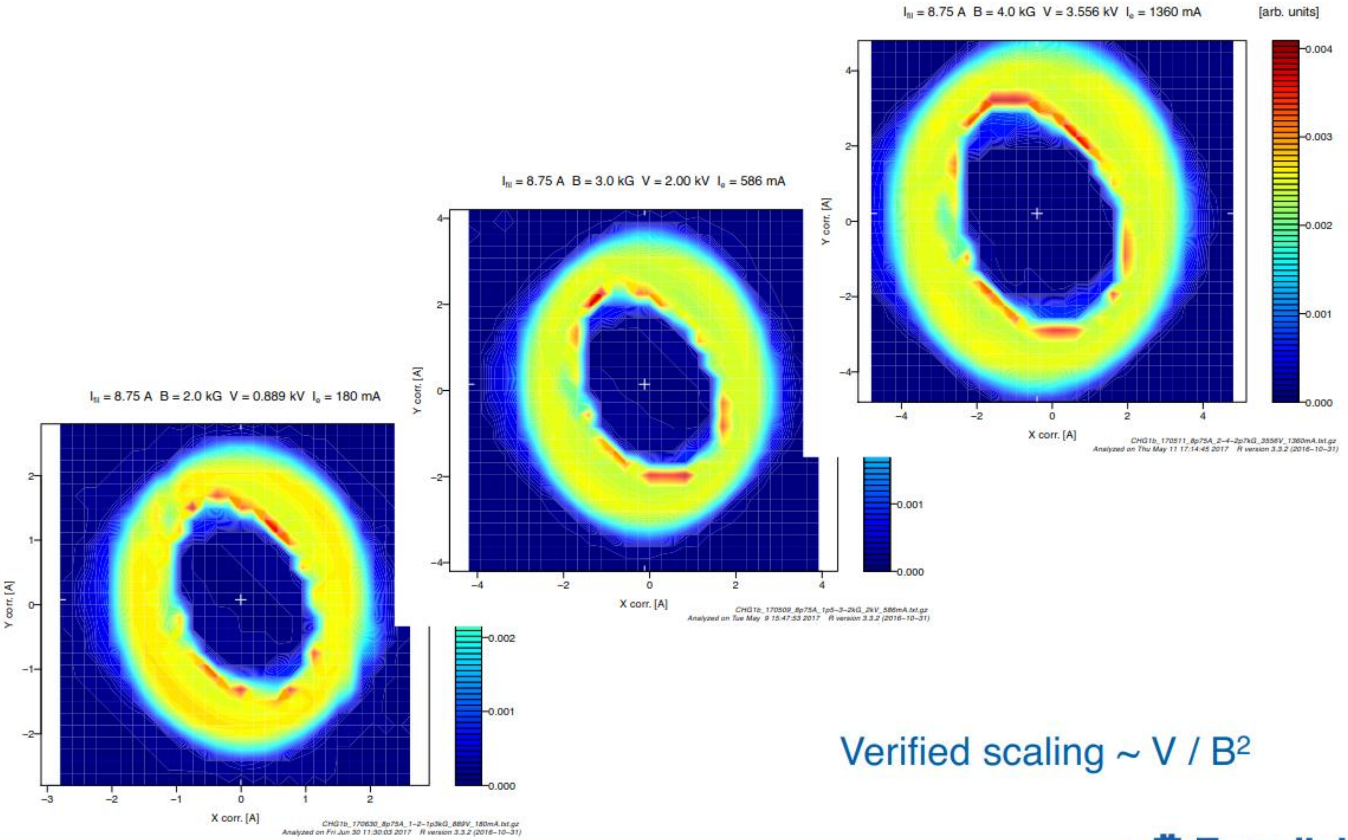
In case of non azimuthally uniform beam there could be an angular component of the electric field causing beam to tilt by Φ.

Profile evolution



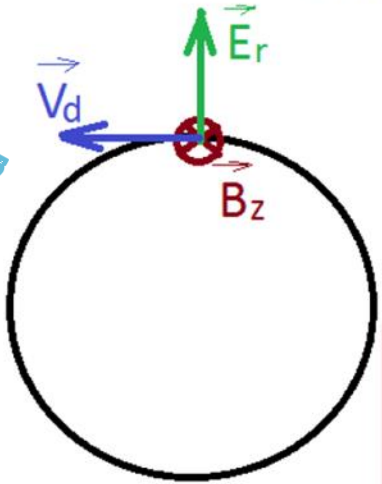
Profile scaling

$$\vec{v}_d = \frac{\lfloor \vec{E} \times \vec{B} \rfloor}{B^2}$$



Verified scaling ~ V / B²

Drift velocities. Radial beam field



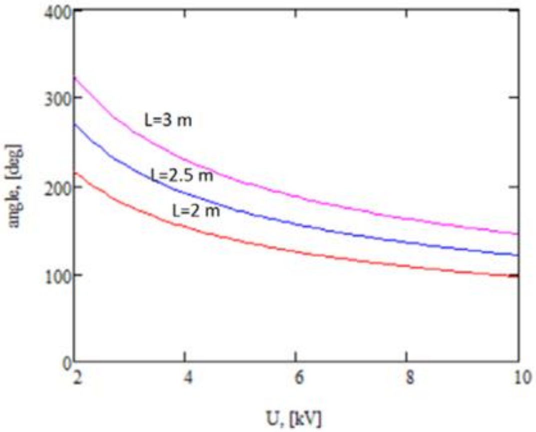
$$Vd = \frac{Er}{Bz}$$ -drift velocity

$$\lambda = \frac{2\pi}{\omega}Vz = \frac{2\pi R}{Vd}Vz$$ - wave length, R – beam radius, Vz – longitudinal velocity

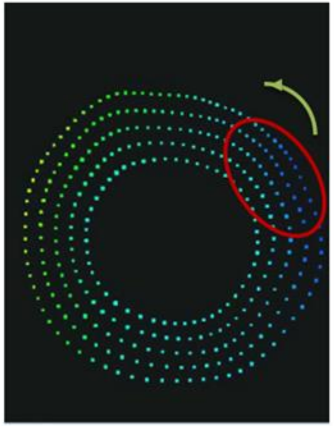
$$\varphi = 2\pi\frac{L}{\lambda}$$ - angle, L – length

According to the motion in the crossed beam electric field and the external magnetic field, particles move along the angle. Particles with different potential are shifted on the different angle. This leads to nonuniform charge distribution along the angle.

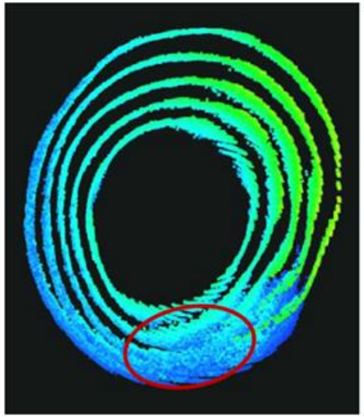
Simulation grid to be improved



Start



End



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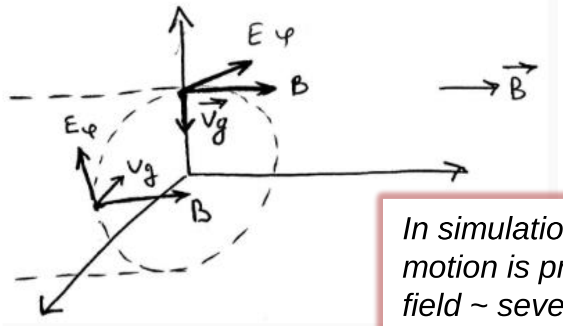
Drift velocities. Angular beam field

$$\overrightarrow{E_\varphi}||\overrightarrow{e_\varphi}, \vec{B}||\overrightarrow{e_z} \Longrightarrow \overrightarrow{v_d}||\overrightarrow{e_r}$$

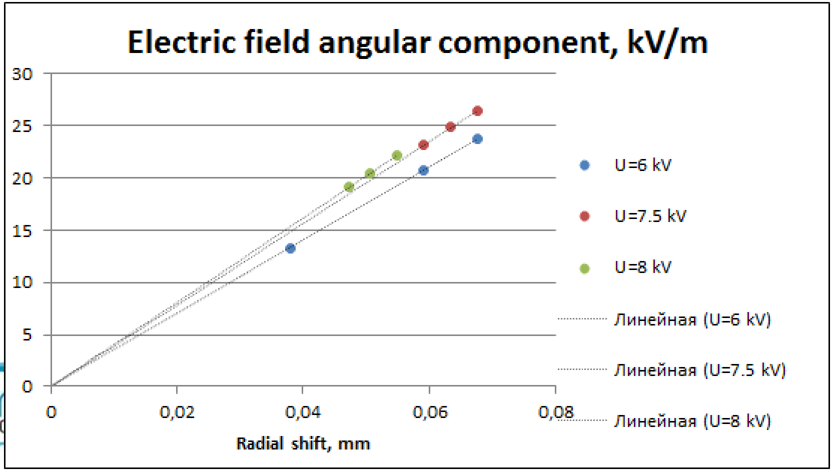
$$v_d = \frac{E_\varphi B}{B^2} = \frac{E_\varphi}{B}, \quad E_\varphi = v_d B = \frac{\Delta r B}{\Delta t} = \frac{\Delta r B}{L/v_{||}}$$

L – distance between two monitors
B – main solenoid field
$E\phi$ – electric field angular component
Δr – particle radial shift

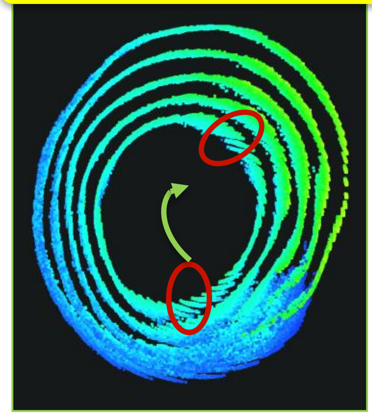
Simulation grid to be improved



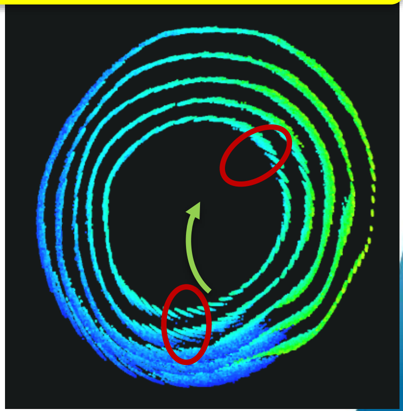
In simulations we saw some small drift shift of the particles to the beam center. This motion is probably caused by the angular electric field. Estimations showed that such field ~ several kV/m, and it must come from nonuniform charge distribution along the angle. Right now analysis of the electric field components is being continued.



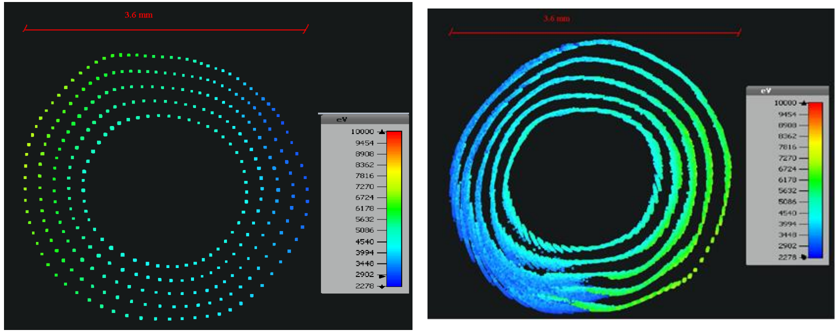
U_o= 10 kV



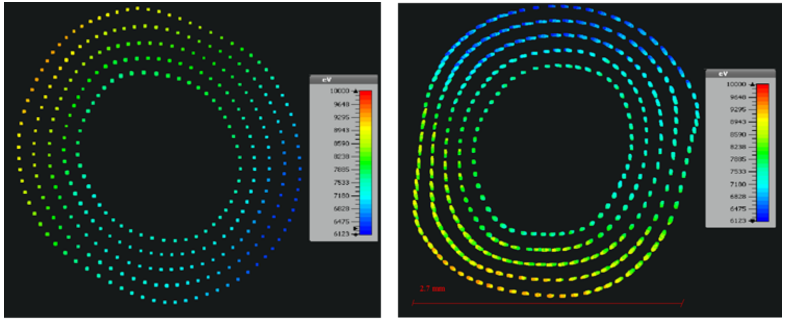
U_o= 12 kV



Effect of > U_0 and B



(I=4 A, U_0=10 kV) Beam profiles close to the beginning (left) of the main solenoid (4T) and the end (right)



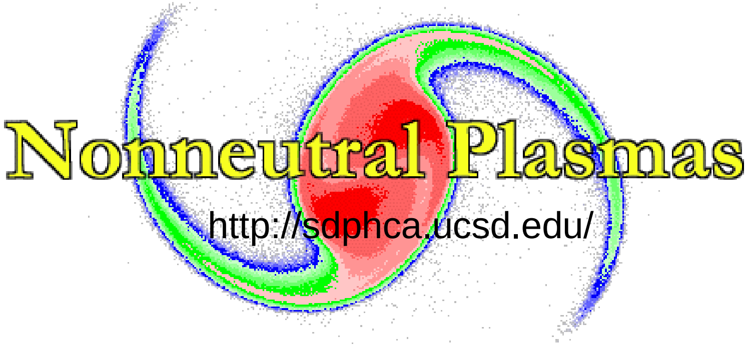
(I=4 A, U_0=12 kV) Beam profiles close to the beginning (left) of the main solenoid (6T) and the end (right)
Higher B = lower rotation velocity

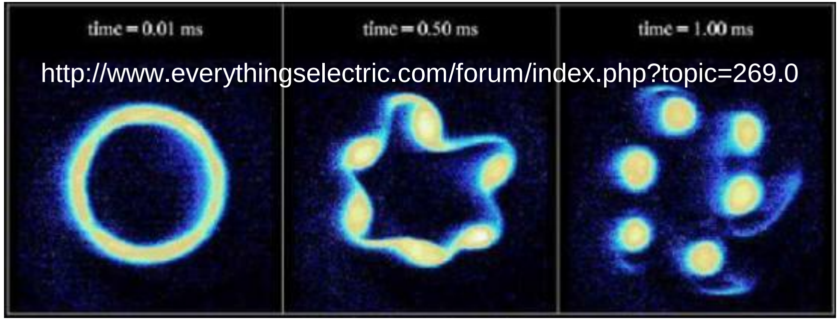
Higher accelerating potential (larger than the perveance limit) helps.
Larger main solenoid magnetic field stabilises the e-beam further.

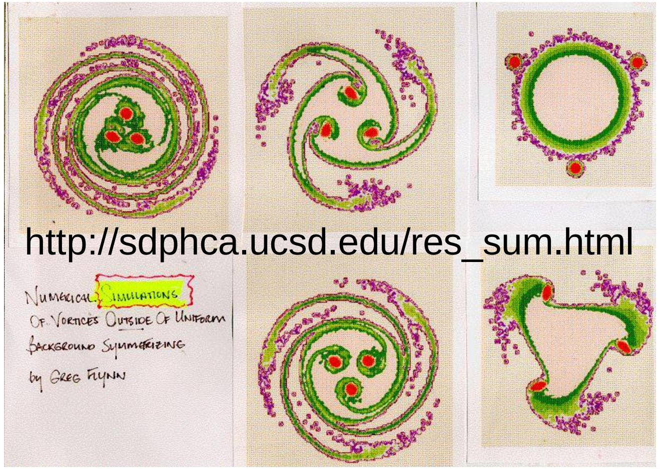
Diocotron instability

http://www.plasma-universe.com/index.php/Diocotron_instability

The diocotron instability (also called the slipping stream plasma instability), is "one of the most ubiquitous instabilities in low density nonneutral plasmas with shear in the flow velocity [.. that can ..] occur in propagating nonneutral electron beams and layers".[2] [3] It may give rise to electron vortices,[4], which resembles the Kelvin-Helmholtz fluid dynamical shear instability, and occurs when charge neutrality is not locally maintained.[5] The term diocotron derives from the Greek, meaning "pursue."[5]

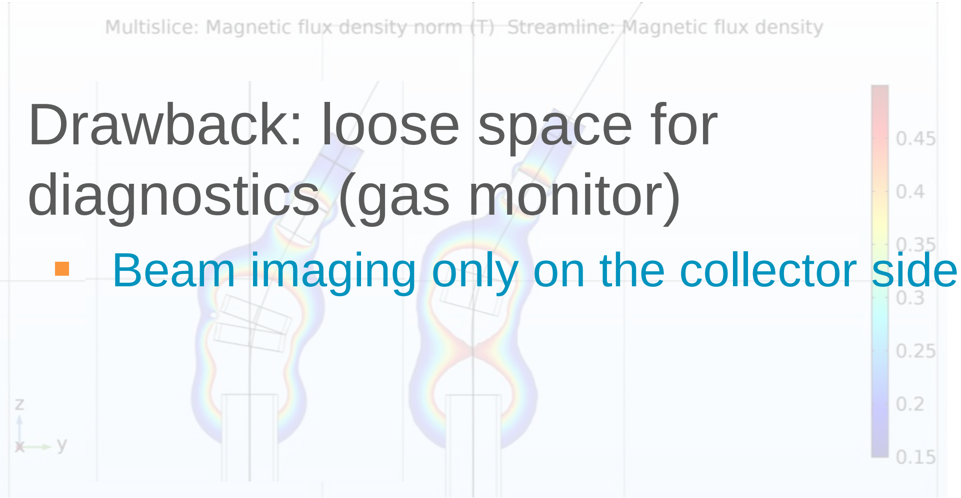






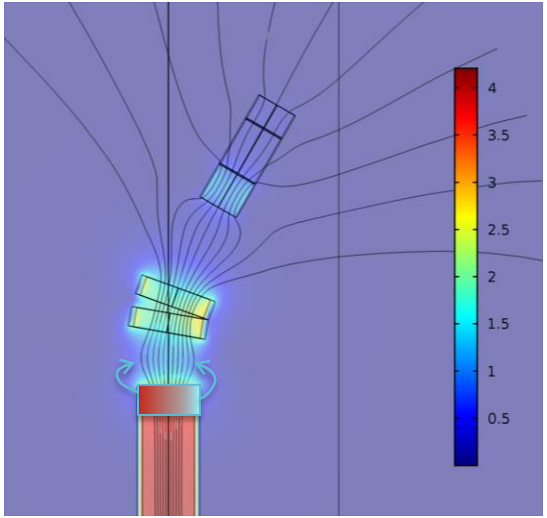
Improving magnetic field at injection

- Make the filed on the injection arm more uniform (to minimise deformations and transfer from longitudinal to transverse velocity)



- Drawback: loose space for diagnostics (gas monitor)
  - Beam imaging only on the collector side

Courtesy of Carlo Zanoni



White is off scale, high B

Main conclusions and feedback to design

- With 5A e-current min cathode-anode voltage $\geq$ 12 kV
- Working close the critical beam perveance (4 A, 10 kV or 5A, 12kV) may bring to instabilities or limit operational range
  - increase the cathode-anode voltage to at least 15kV (to be simulated)
  - if possible reduce the beam pipe size

- Increase the magnetic field of the main solenoid up to 6 T, would be of great advantage, if it is possible in term of construction. It allows reducing drift velocities and increasing the cathode radius. 5T still to be checked.

- Improve injection arm magnetic field (to be checked)

Future studies: Simulate . . .

- … present experimental set-up and compare to measurements
- … the full trajectory from gun to collector with CST studio improving statistics and:
  - Verify that gun dimensions + magnetic configuration can work with different design parameters:
    - Different beta function left and right of IP4
    - Different p-beam size at injection and top energy
  - Evaluate going to 15kV: could that compensate for a ‘low’ main field (4T)
  - How would dynamics improve at 5T?
  - How can we ensure ‘zero’ central field inside the HE beam = no distorsions? (insertion vacuum pipe + magnetic configuration)
  - By how much can we steer the e-beam in the main solenoid?
- … with PIC (particle-in-cell) simulators allowing to estimate margin to instability, including diocotron
- … effect of imperfections and operations with correctors
- … effect of modulation at high frequency (for BPM measurements)

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Thank you

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