# Beam dynamics simulations in electron lens test stand

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in collaboration with G. Stancari, FNAL

*8th HL-LHC Collaboration Meeting*
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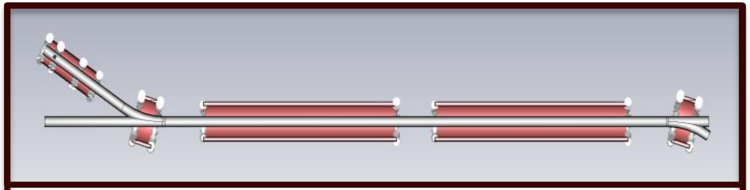
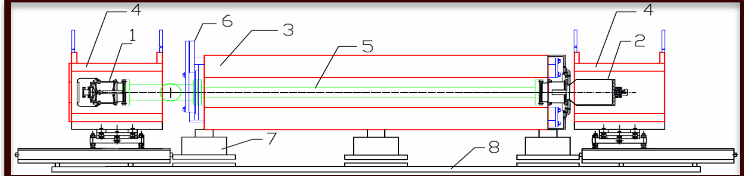
# Outline

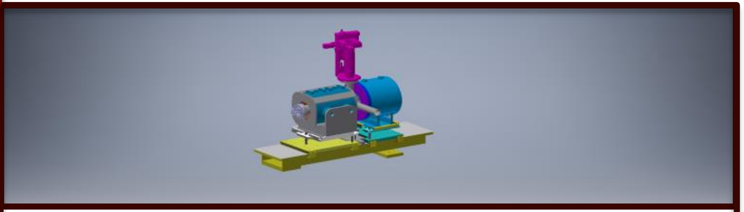


HEL @ HL-LHC

Simulations:
- Benchmarking
- Image analysis




E-lens test stand at FNAL



E-lens test stand at CERN

# Existing electron lenses and HEL@HL-LHC

## Tevatron, FERMILAB

Table 1: Electron Lens and Tevatron collider parameters.

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| *Tevatron Electron Lens* | | | |
| Electron energy (oper./max) | $U_e$ | 5/10 | kV |
| Peak electron current (oper./max) | $J_e$ | 0.6/3 | A |
| Magnetic field in main/gun solenoid | $B_{main}$ / $B_{gun}$ | 30 / 3 | kG |
| Radii: cathode/*e*-beam in main solenoid | $a_c$ / $a_e$ | 7.5 / 2.3 | mm |
| *e*-pulse period/width, "0-to-0" | $T_0$ / $T$ | 21 / ≈0.6 | µs |
| Interaction length | $L_e$ | 2.0 | m |
| *Tevatron Collider Parameters* | | | |
| Circumference | $C$ | 6.28 | km |
| Proton/antiproton beam energy | $E$ | 980 | GeV |
| Proton bunch intensity | $N_p$ | 250 | $10^9$ |
| Antiproton bunch intensity | $N_a$ | 50-100 | $10^9$ |
| Emittance proton, antiprot. (norm., rms) | $\varepsilon_p$ / $\varepsilon_a$ | ≈2.8 / ≈1.4 | µm |
| Number of bunches, bunch spacing | $N_B$ / $T_b$ | 36 / 396 | ns |
| Initial luminosity | $L_0$ | 1.5-2.9 | $10^{32}$ cm$^{-2}$s$^{-1}$ |
| Beta functions, TEL2 | $\beta_y / \beta_x$ | 150/68 | m |
| Beta functions, TEL1 | $\beta_y / \beta_x$ | 29/104 | m |
| Proton/antiproton head-on tuneshift | $\xi^p$ / $\xi^a$ | ≈0.008 / ≈0.011 | max., per IP |
| Proton/antiproton long-range tuneshift | $\Delta Q^p$ / $\Delta Q^a$ | ≈0.003 / ≈0.006 | max. |

V. Kamerdzhiev, Progress with Tevatron electron lenses, Proceedings of COOL 2007, Bad Kreuznach, Germany

## RHIC, BNL

TABLE I. The parameters for the RHIC electron lenses.

| Parameter | Unit | Value | Value |
|---|---|---|---|
| *Proton beam parameters* | | *Design* | 2015 *operated* |
| Total proton energy $E_p$ | GeV | 250 | 100 |
| Relativistic factor $\gamma_p$ | | 266.4 | 106.8 |
| Bunch intensity $N_p$ | $10^{11}$ | 3.0 | 2.25 |
| $\beta^*_{x,y}$ at IP6, IP8 (p-p) | m | 0.5 | 0.85 |
| $\beta^*_{x,y}$ at IP10 (p-e) | m | 10.0 | 15.0 |
| Lattice tunes ($Q_x$, $Q_y$) | | (0.695, 0.685) | (0.695, 0.685) |
| Phase advance (IP8–IP10) | Degree | 180 | 180 |
| rms emittance $\varepsilon_n$, initial | mm mrad | 2.5 | 2.8 |
| rms beam size at IP6, IP8, $\sigma^*_p$ | $\mu$m | 70 | 150 |
| rms beam size at IP10, $\sigma^*_p$ | $\mu$m | 310 | 630 |
| rms bunch length $\sigma_s$ | m | 0.50 | 0.70 |
| Beam-beam parameter $\xi$/IP | | 0.0147 | 0.0097 |
| Number of beam-beam IPs | | 2 + 1 | 2 + 1 |
| *Electron lens parameters* | | | |
| Distance of center from IP | m | 1.5 | 1.5 |
| Effective length $L_e$ | m | 2.1 | 2.1 |
| Kinetic energy $E_e$ | kV | 5 | 5 |
| Relativistic factor $\beta_e$ | | 0.14 | 0.14 |
| Relativistic factor $\gamma_e$ | | 1.0002 | 1.0002 |
| Current $I_e$ | A | 1.0 | 0.43/0.60 |
| Electron beam size at interaction | $\mu$m | 350 | 650 |
| Linear tune shift | | 0.0147 | 0.01 |

X. Gu, Electron lenses for head-on beam-beam compensation in RHIC, Physical review accelerators and beams 20, 023501 (2017)

## HL-LHC, CERN

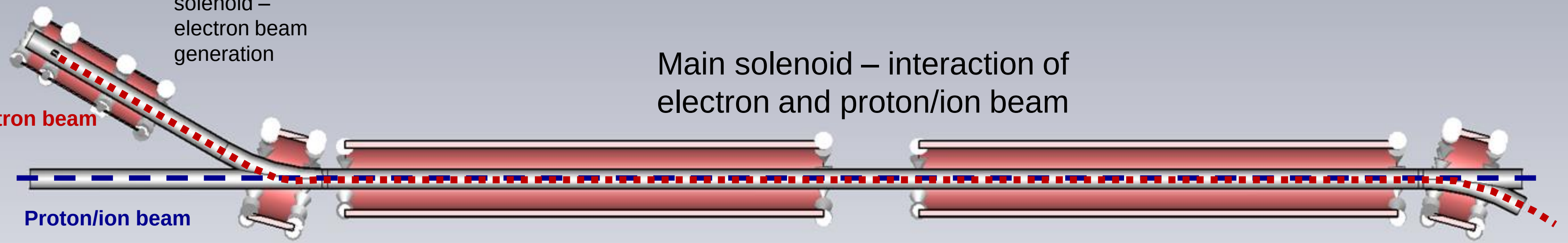
| | |
|---|---|
| Current | 5A at 15kV |
| Beam shape | Hollow beam |
| Effective length | 2.9 m |

HEL@HL-LHC has
- higher current,
- higher current density
- longer effective length

comparing to implemented electron lenses

HEL components (gun, diagnostics, modulator, etc.) are unique.

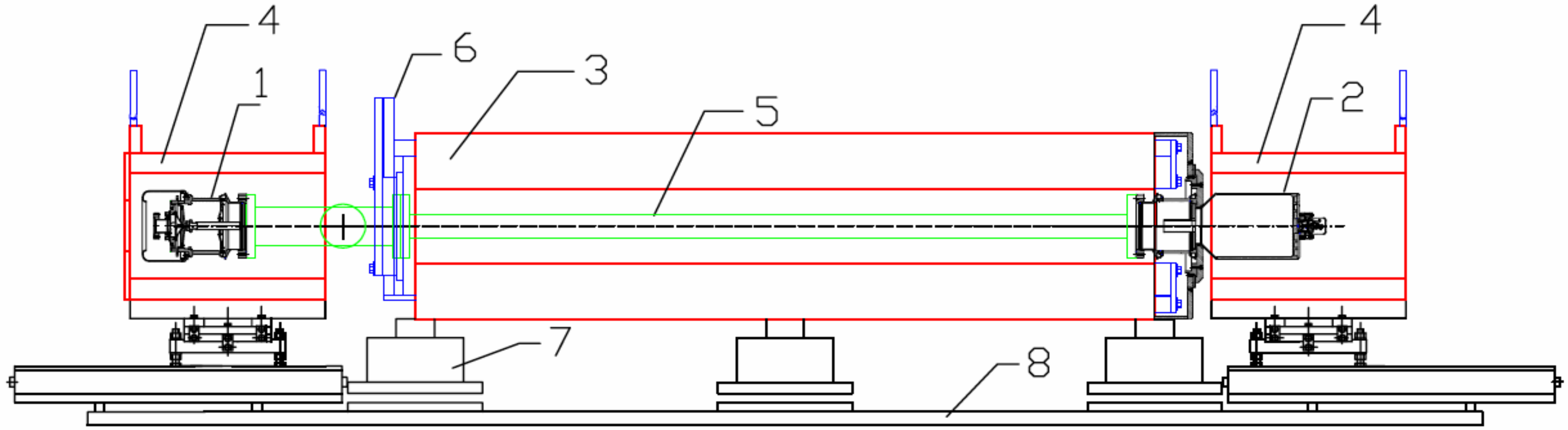
# Beam dynamics in electron lens (short overview)

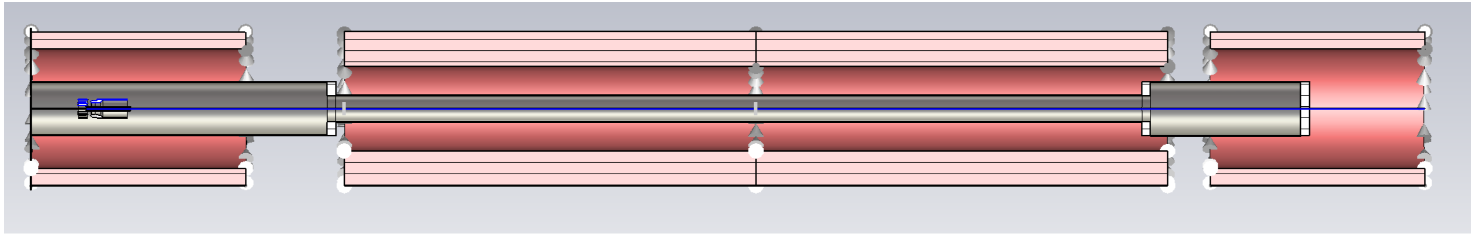



$$\frac{d\mathbf{r}_{\text{guiding centre}}}{dt} = v_{\parallel}\frac{\mathbf{B}}{|B|} + \frac{\mathbf{E}_{\perp}\times\mathbf{B}}{B^2} + v_{\perp}\frac{\mathbf{B}\times\nabla\mathbf{B}}{B^2} - \frac{v_{\parallel}^2}{\omega_c}\frac{\mathbf{R}_c\times\mathbf{B}}{R^2|B|}$$

- In the presence of drift tube – possible formation of virtual cathode
- Intensity modulation – possible change of longitudinal profile
- Reliable simulation tool and test stand is required for development/ studying and optimization of the hollow electron lenses for HL-LHC.

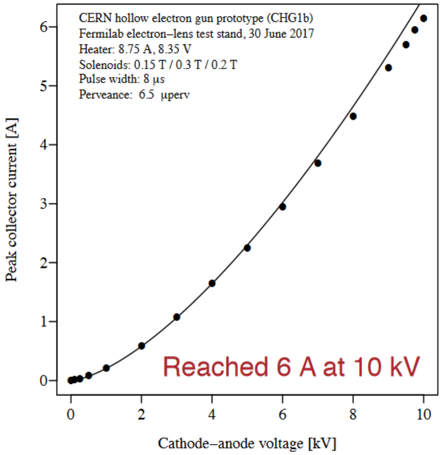
# FNAL test stand – model in CST® Particle Studio

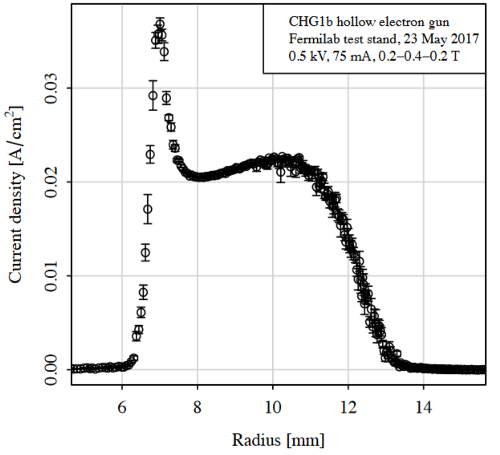


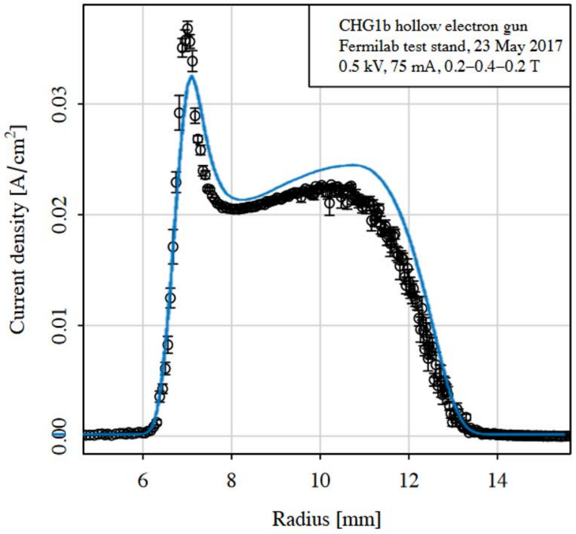
# FNAL test stand – electron gun

## Measured performance of CHG1b 25-mm e-gun



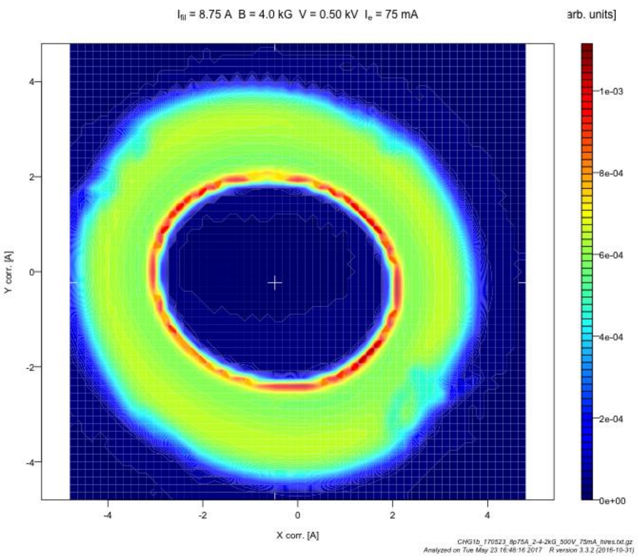

*Data file: CHG1b_170523_8p75A_2–4–2kG_500V_75mA_hires.txt.gz*

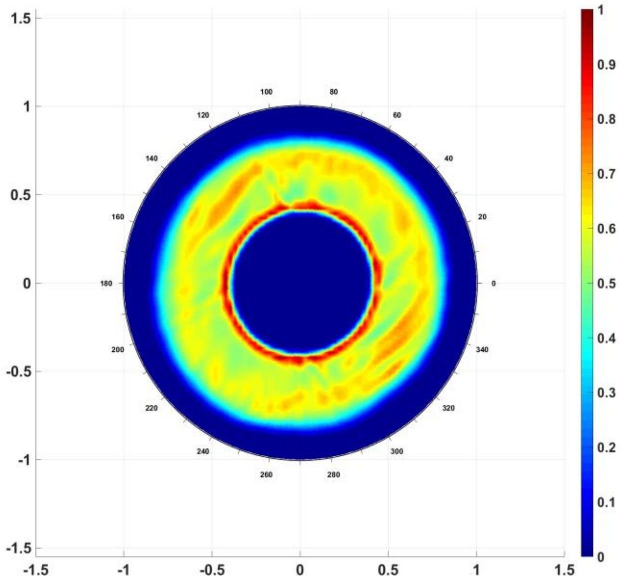



Courtesy of Giulio Stancari, FNAL

4 Giulio Stancari I Electron-gun emission and calculation of residual fields LHC ColUSM I 9 Mar 2018 Fermilab

# Image comparison



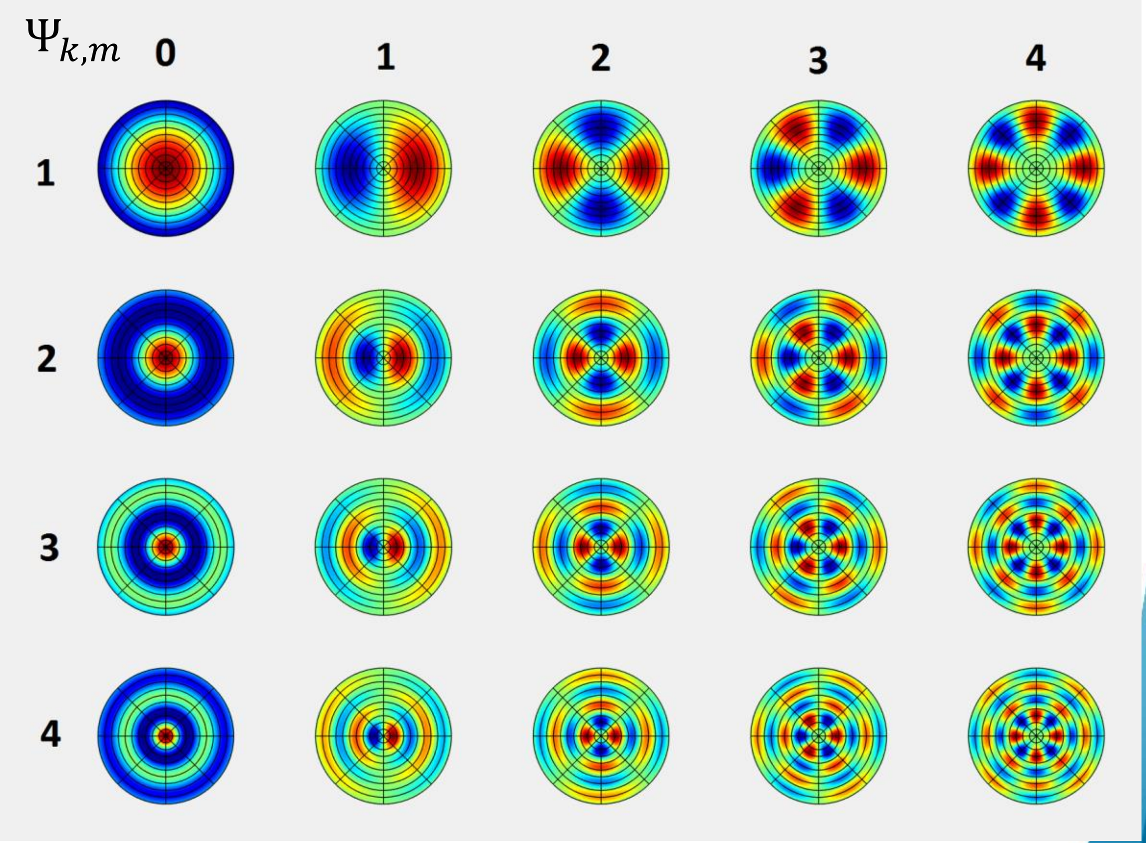
Comparison pixel by pixel can not be used

# Image comparison – Polar Fourier Transform

$$f(r,\varphi) = \int_0^{\infty} \sum_{m=-\infty}^{\infty} P_{k,m} \Psi_{k,m}(r,\varphi) k \, dk$$

$\Psi_{k,m}$ - basis function

$P_{k,m}$ - polar Fourier coefficients

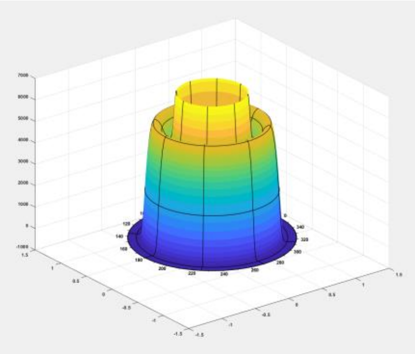


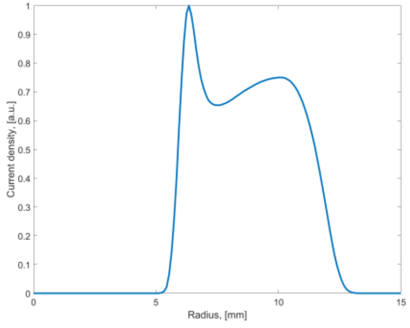
# Image comparison – test pulse

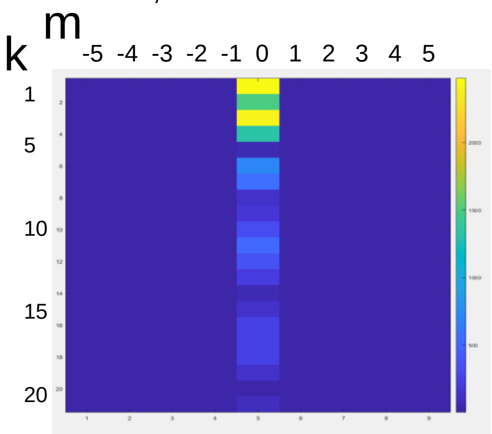
Beam profile in 3D

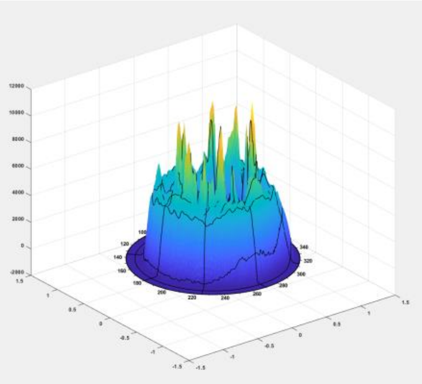
Beam profile in 2D

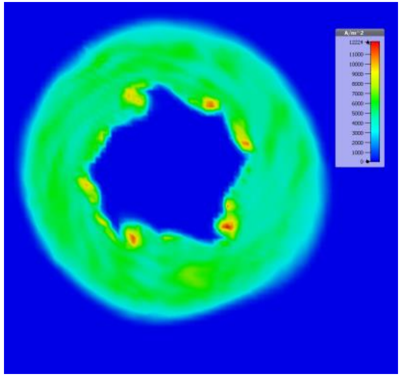
$P_{k,m}$ from PFT

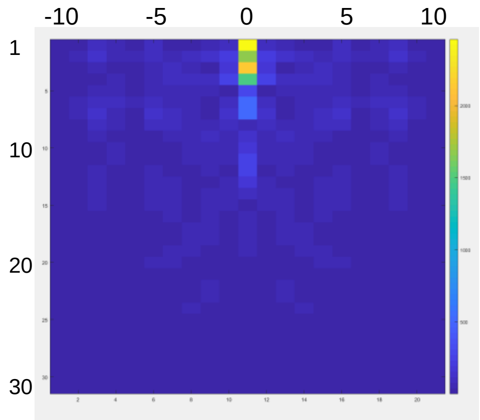









HiLumi HL-LHC PROJECT

# Profile evolution (results from FNAL test stand)

Total rotation phase $\varphi$ of the hollow electron beam

$$\varphi \approx \Omega_D \Delta T \propto \frac{n_{e0}}{B}\frac{L}{v_z}$$

$\Omega_D$ – diocotron frequency = $\frac{\omega_{pe}^2}{2\omega_{ce}} \propto \frac{n_{e0}}{B}$

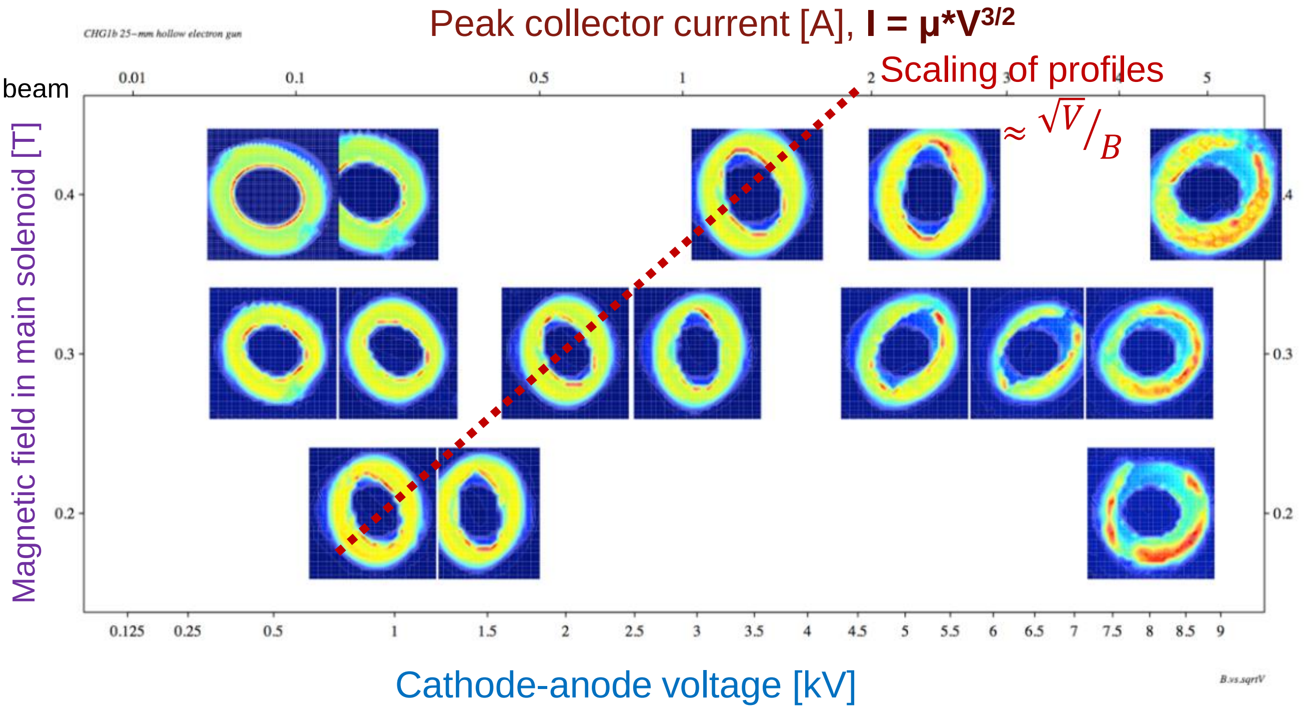
$\Delta T$– transient time $\approx \frac{L}{\vartheta_z}$

$$\vartheta_z \approx \sqrt{\frac{2eV}{m_e}} \propto \sqrt{V}$$

$$J = n_{e0} e \vartheta_z \propto V^{3/2}$$

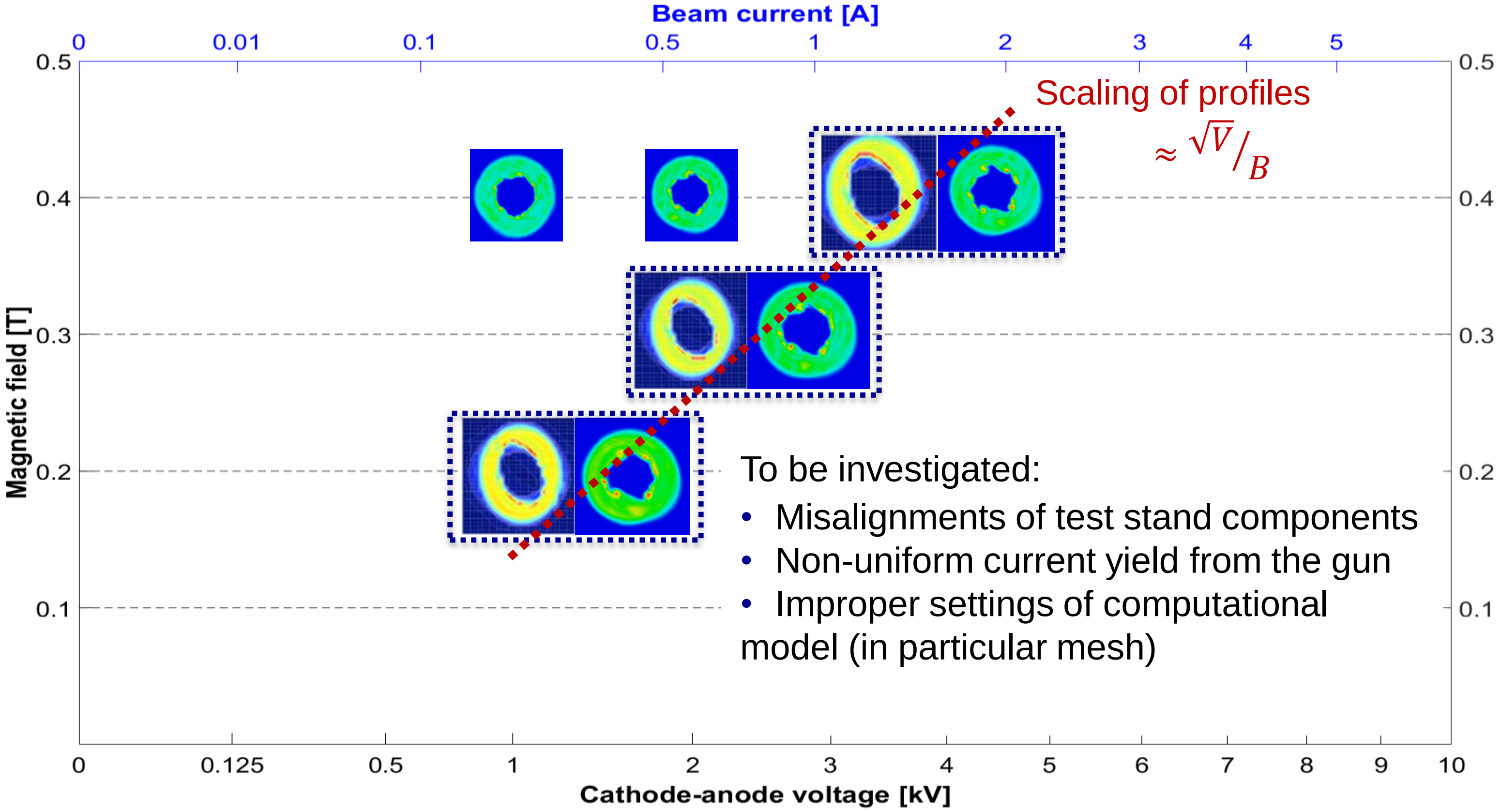
*Child-Langmuir law*

$$\varphi \approx const \times \frac{\sqrt{V}}{B} L$$




Courtesy of Giulio Stancari, FNAL

# Profile evolution - simulation

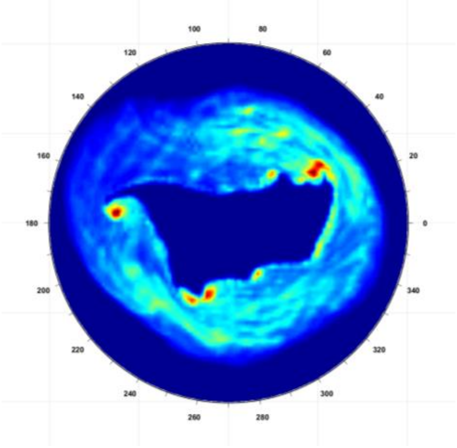



To be investigated:

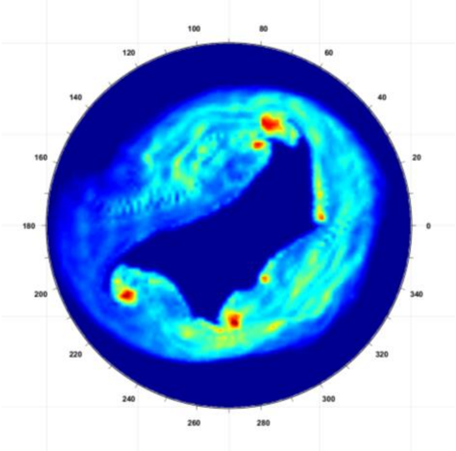
- Misalignments of test stand components
- Non-uniform current yield from the gun
- Improper settings of computational model (in particular mesh)

# Profiles of the beam with tilted gun

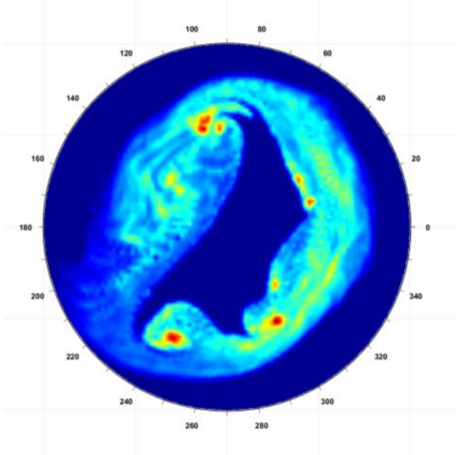
**2 kV** / 0.4T / **2700 mm**




**4kV** / 0.4T / **2700 mm**




**6kV** / 0.4T / **2700 mm**

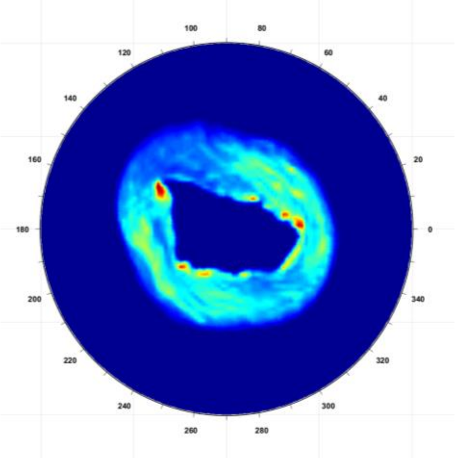



*In simulations gun is tilted by 2$^{o}$ and then aligned by steerers.

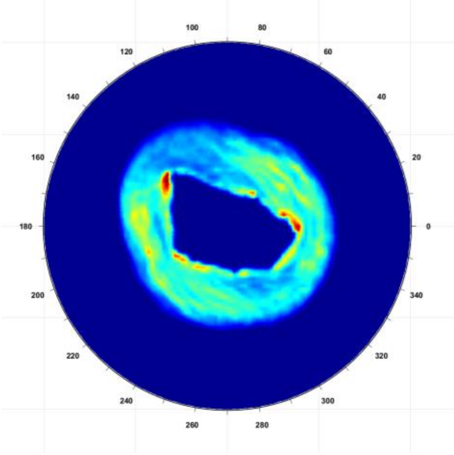
$$\varphi \approx const \times \frac{\sqrt{V}}{B} L$$

# Scaling of profiles vs Length (simulation)

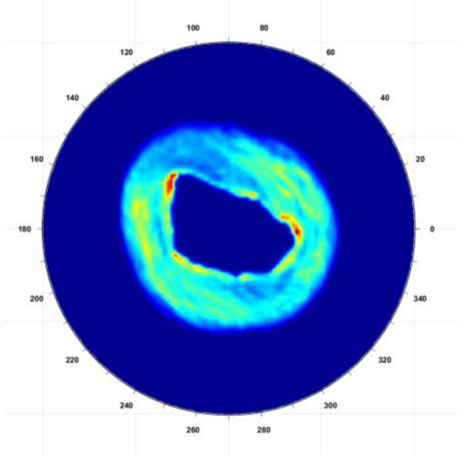
**2 kV** / 0.4T / **2000 mm**




**4kV** / 0.4T / **1414 mm**



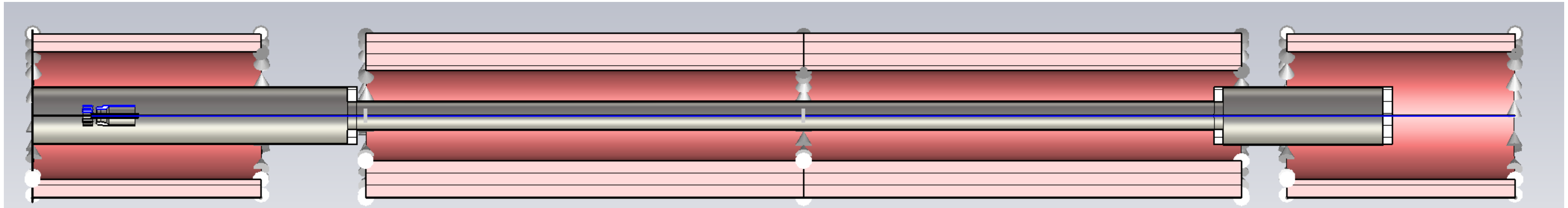

**6kV** / 0.4T / **1155 mm**

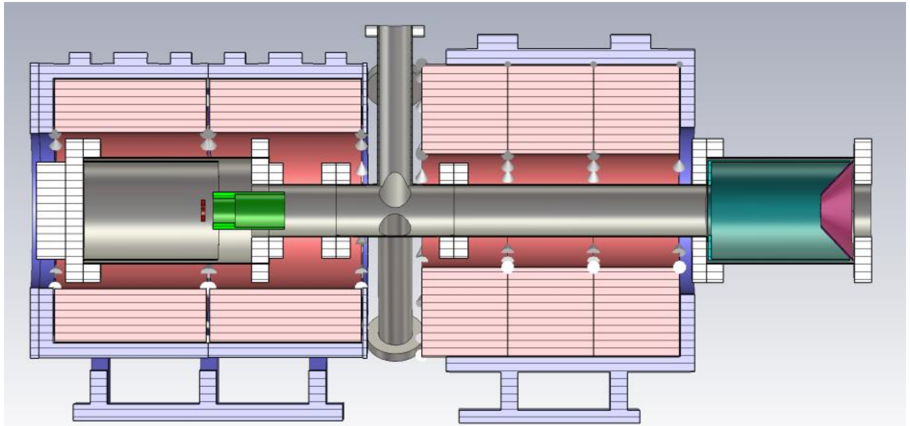



*In simulations gun is tilted by 2$^{o}$ and then aligned by steerers.

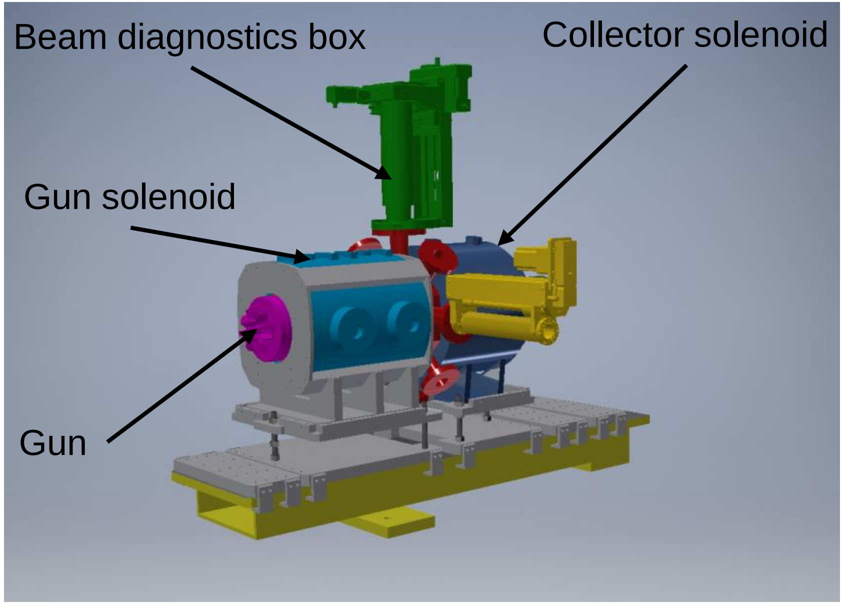
$$\varphi \approx \frac{\sqrt{V}}{B} L \qquad \frac{\sqrt{2}\,[kV]}{0.4\,[T]} 2000\,[mm] \approx \frac{\sqrt{4}\,[kV]}{0.4\,[T]} 1414\,[mm] \approx \frac{\sqrt{6}\,[kV]}{0.4\,[T]} 1155\,[mm]$$

# E-lens test stand at CERN


E-lens test stand at FNAL


E-lens test stand at CERN

# Electron lens test stand at CERN: stage 1




Purpose of first stage:

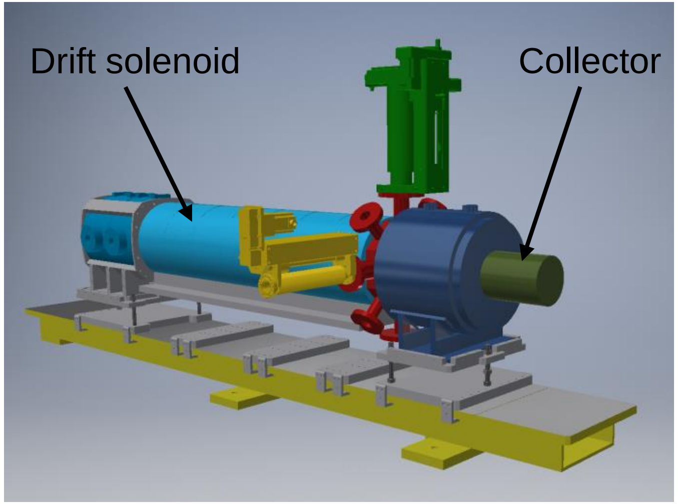
- Preparation:
  - Commissioning hardware (magnets, vacuum, HV system, control, etc.)
  - Safety and technical aspects of operation
  - Commissioning diagnostic procedures (current, profile, position)
- Measurements:
  - Electron gun tests: characterization (profile measurements)
  - Electron gun: anode modular

Covered by HL-LHC

# Conclusions

- Measurements at FNAL electron lens test stand were simulated using CST® Particle Studio:
  - Perveance of the gun and initial beam profile are in good agreement
  - Beam profiles from experimental measurements are more distorted comparing to results from simulation
  - Possible reasons of such discrepancies should be investigated:
    - Misalignments of test stand components
    - Non-uniform current yield from the gun
    - Improper settings of computational model (in particular mesh)
- E-lens test bench at CERN will give additional capabilities for gun characterization.
- Comparison of profiles based on Fourier decomposition in polar coordinates was introduced for data analysis.

# Test stand: stage 2.



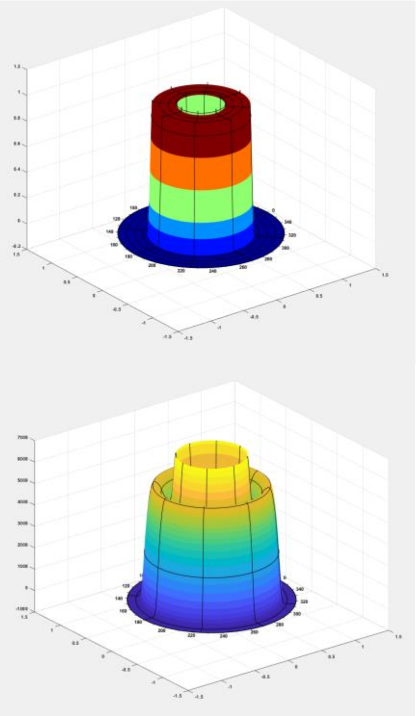

Purpose and measurements of stage 2:

- Allow drift and see beam deformations/rotations/… computer model validation
- Study electron beam dynamics in regime close to virtual cathode
- Study electron beam dynamics with compression

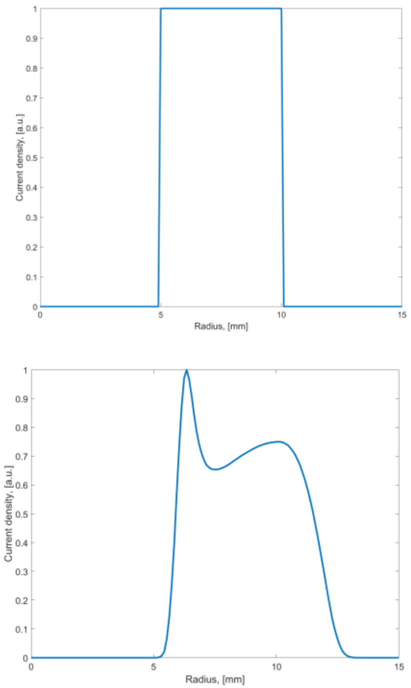
- Test Beam Position Monitor ‘shoe-box’ or ‘strip-line’ with very HF modulation
- Test effect of very HF modulation (<10% current) on beam dynamics (microbunching?) for HEL

# Image comparison – test pulse

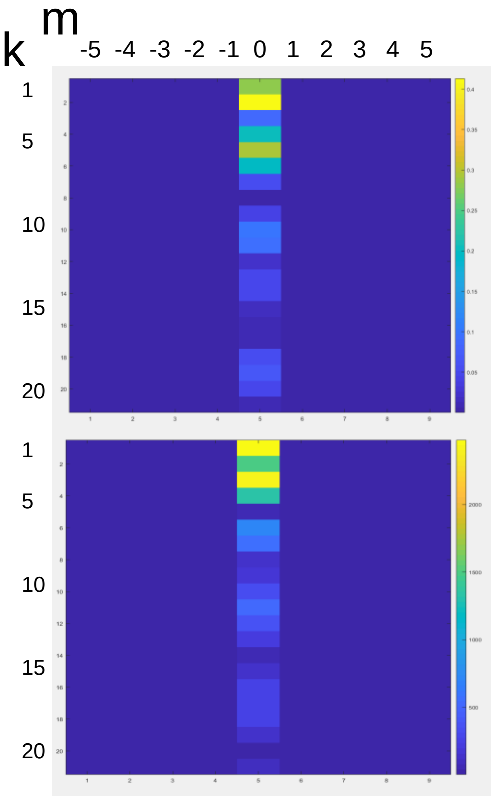
Beam profile in 3D



Beam profile in 2D




$P_{k,m}$ from PFT



# Image comparison – distorted beam