Beam dynamics simulations in electron lens test stand

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8th HL-LHC Collaboration Meeting
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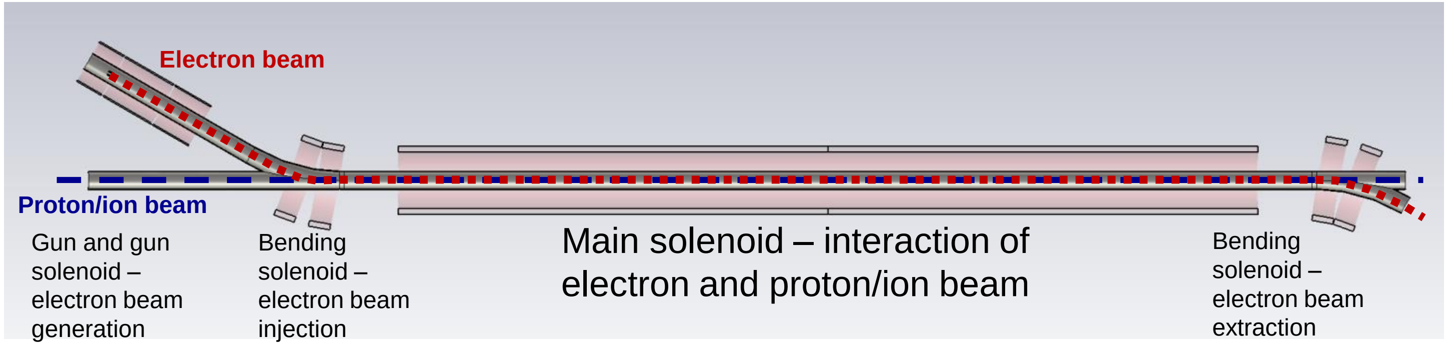
Beam dynamics in electron lense (short overview)



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

- In the presence of drift tube – possible formation of virtual cathode
- Intensity modulation – possible change of longitudinal profile

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)	ε_p ε_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	β_y / β_x	150/68	m
Beta functions, TEL1	β_y / β_x	29/104	m
Proton/antiproton head-on tuneshift	ξ^p ξ^a	≈0.008 ≈0.011	max., per IP
Proton/antiproton long-range tuneshift	ΔQ^p ΔQ^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 γ_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 ε_n, initial	mm mrad	2.5	2.8
rms beam size at IP6, IP8, σ^*_p	µm	70	150
rms beam size at IP10, σ^*_p	µm	310	630
rms bunch length σ_s	m	0.50	0.70
Beam-beam parameter ξ/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 β_e		0.14	0.14
Relativistic factor γ_e		1.0002	1.0002
Current I_e	A	1.0	0.43/0.6
Electron beam size at interaction	µm	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)

HEL @ HL-LHC

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

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

comparing to implemented electron lenses

Test of HEL components (gun, diagnostics, modulator, etc.) is required

Outline

- Simulation of the FNAL test stand in CST® Particle Studio
- Technique to compare beam profiles from experiments and simulations
- Electron lens test stand at CERN

Profile evolution (results from FNAL test stand)

Total rotation phase φ of the hollow electron beam

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

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

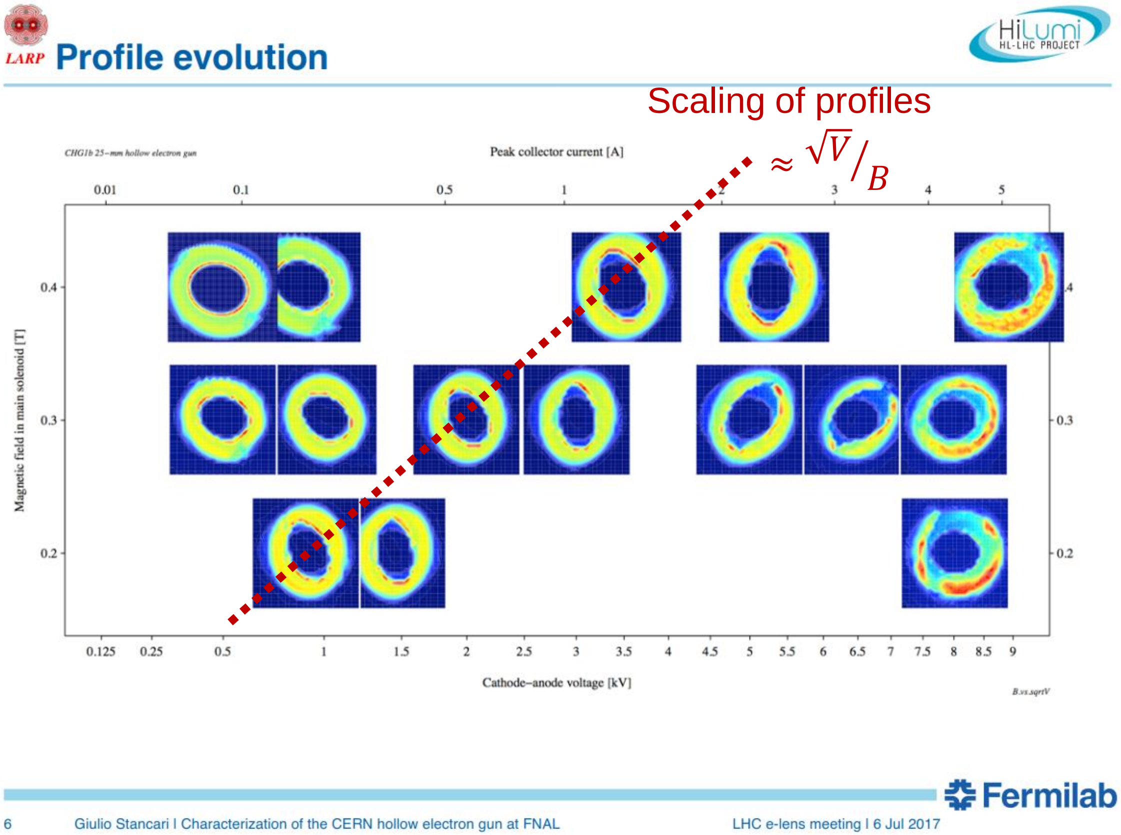
ΔT– transient time $\approx \frac{L}{\vartheta_z}$

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

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

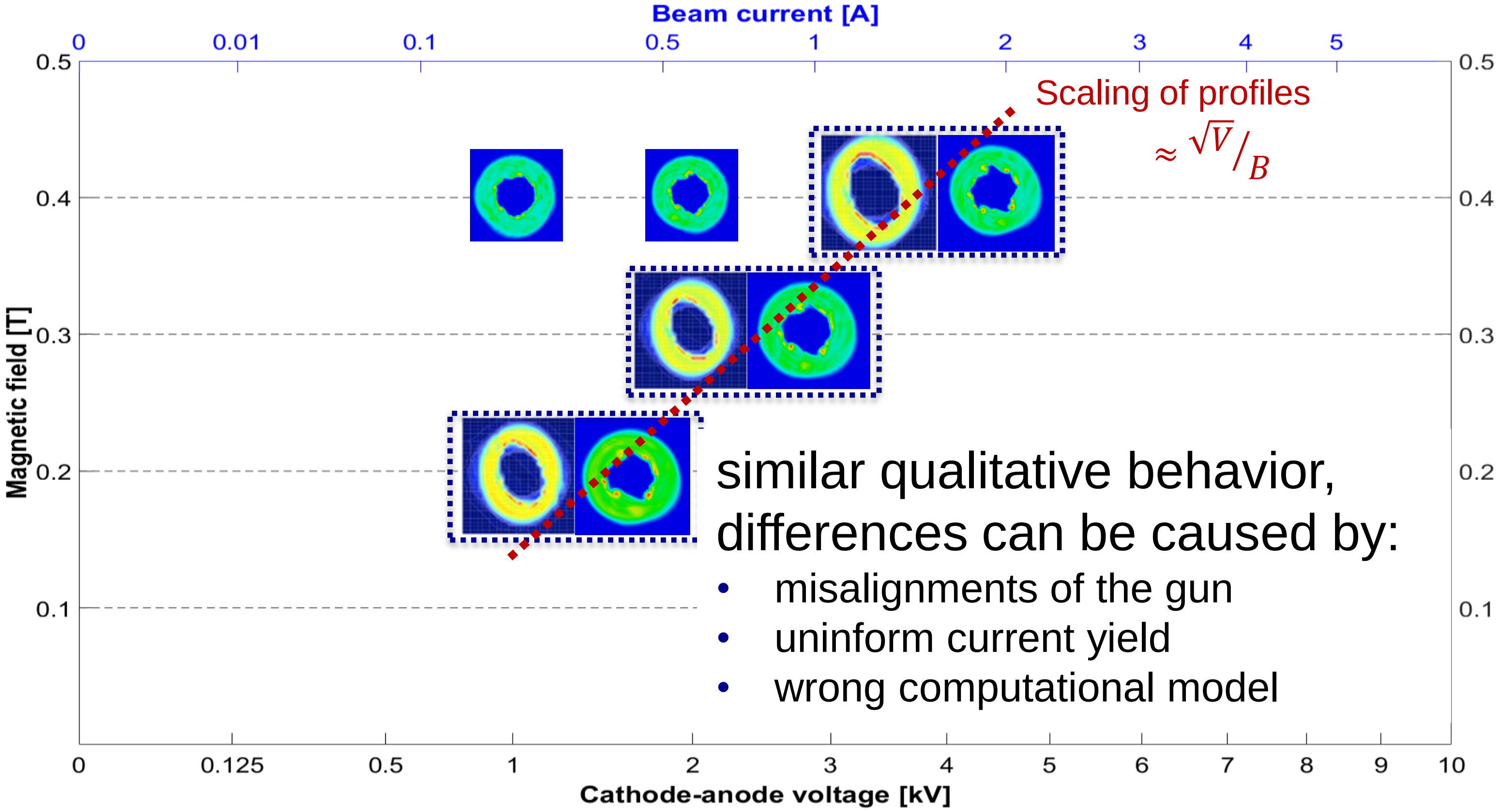
Child-Langmuir law

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



Courtesy of Giulio Stancari, FNAL

Profile evolution - simulation

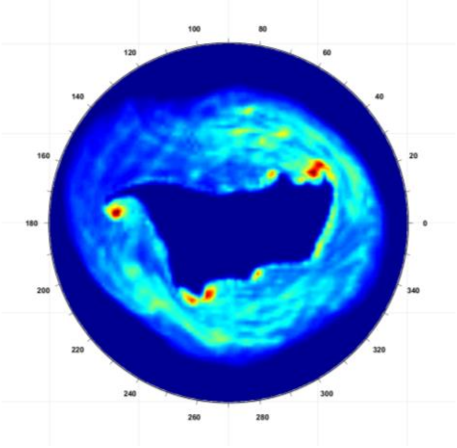


similar qualitative behavior, differences can be caused by:

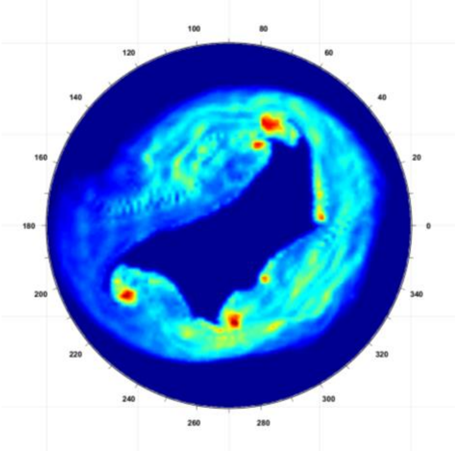
- misalignments of the gun
- uninform current yield
- wrong computational model

Profiles of the beam with tilted gun

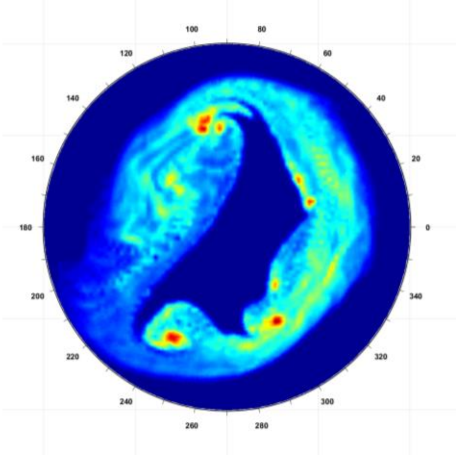
2 kV / 0.4T / **2700 mm**



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



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

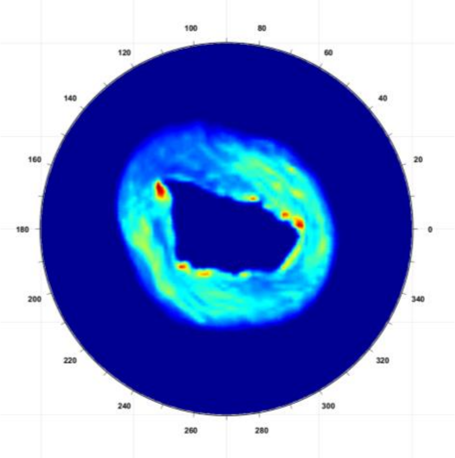


*In simulations gun is tilted by 2^o and then aligned by steerers.

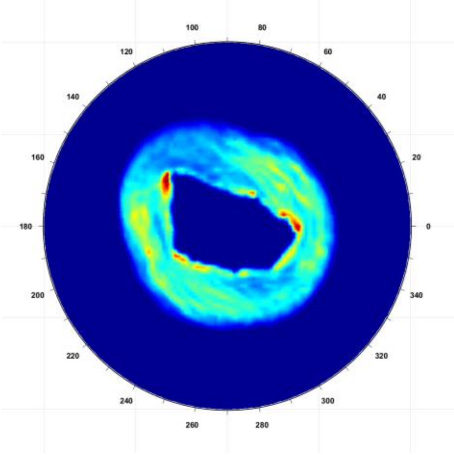
$$\varphi \approx const \times \frac{\sqrt{V}}{B} L$$

Scaling of profiles vs Length (simulation)

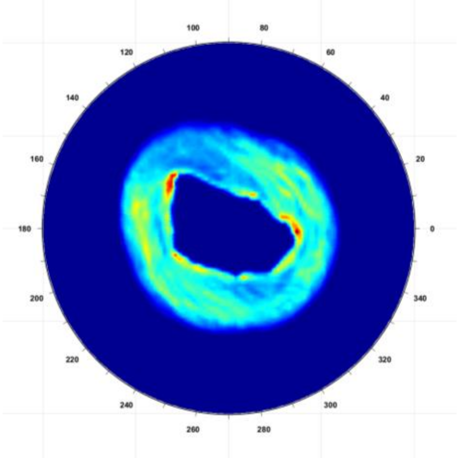
2 kV / 0.4T / **2000 mm**



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



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



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

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

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

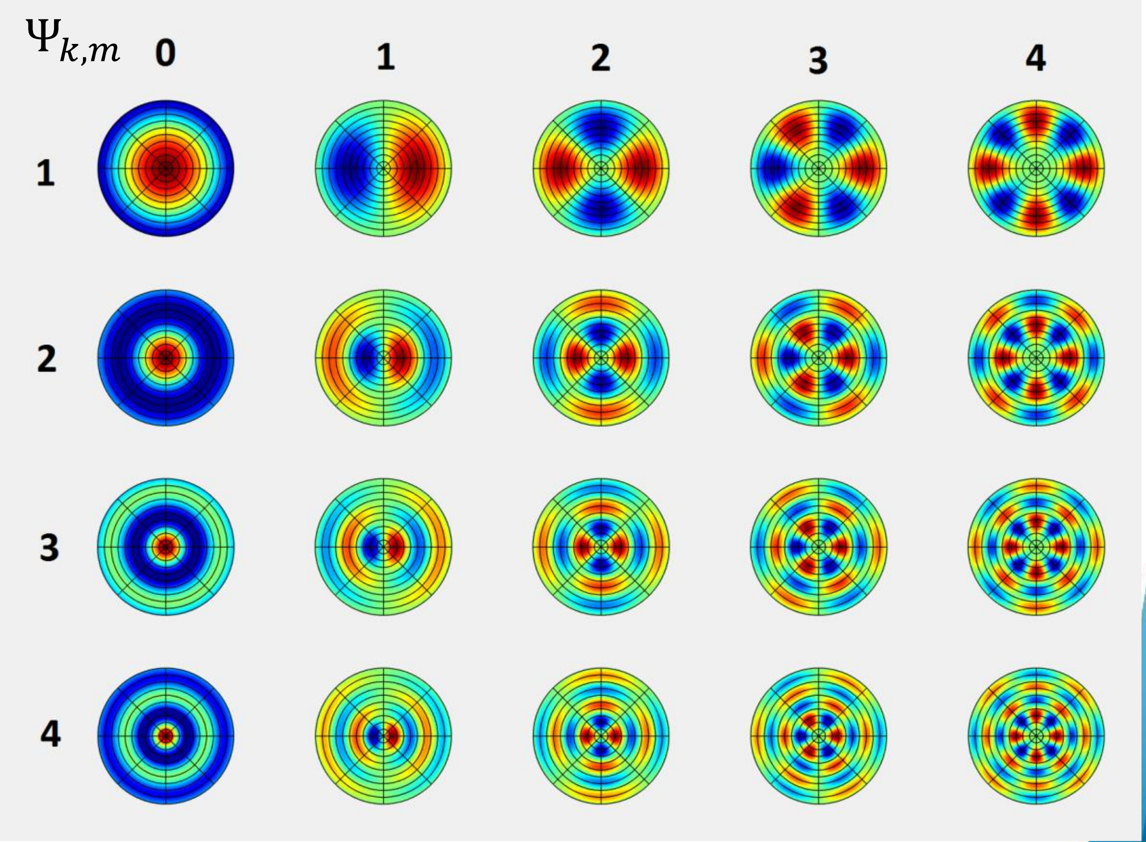
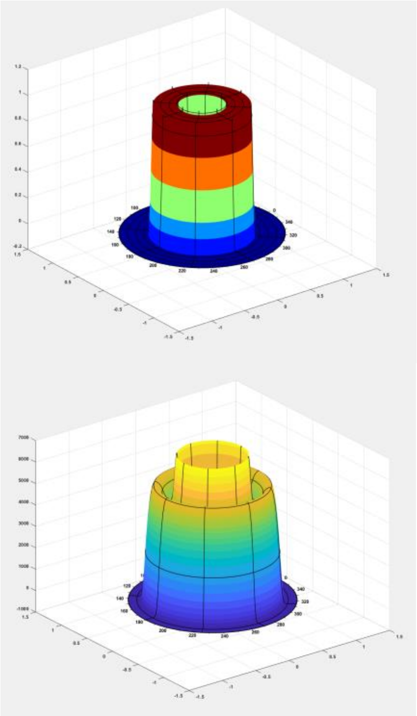
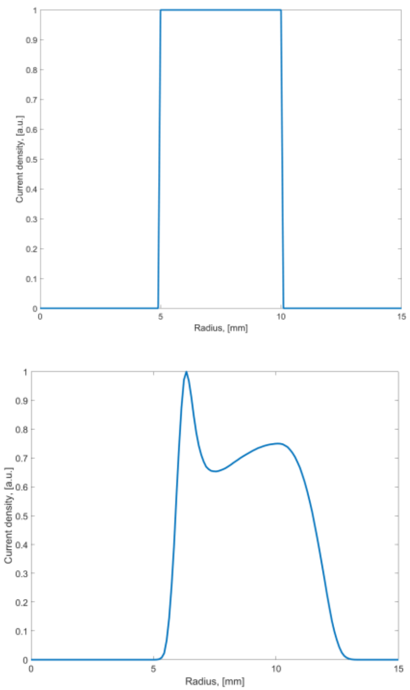


Image comparison – test pulse

Beam profile in 3D



Beam profile in 2D



$P_{k,m}$ from PFT

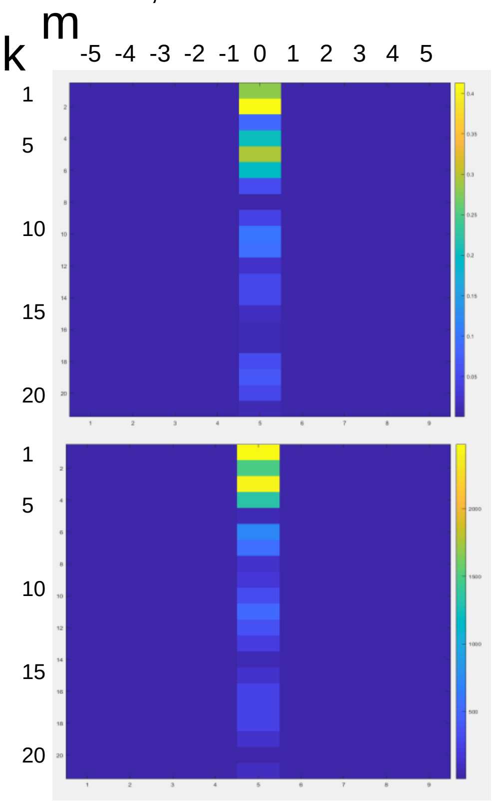
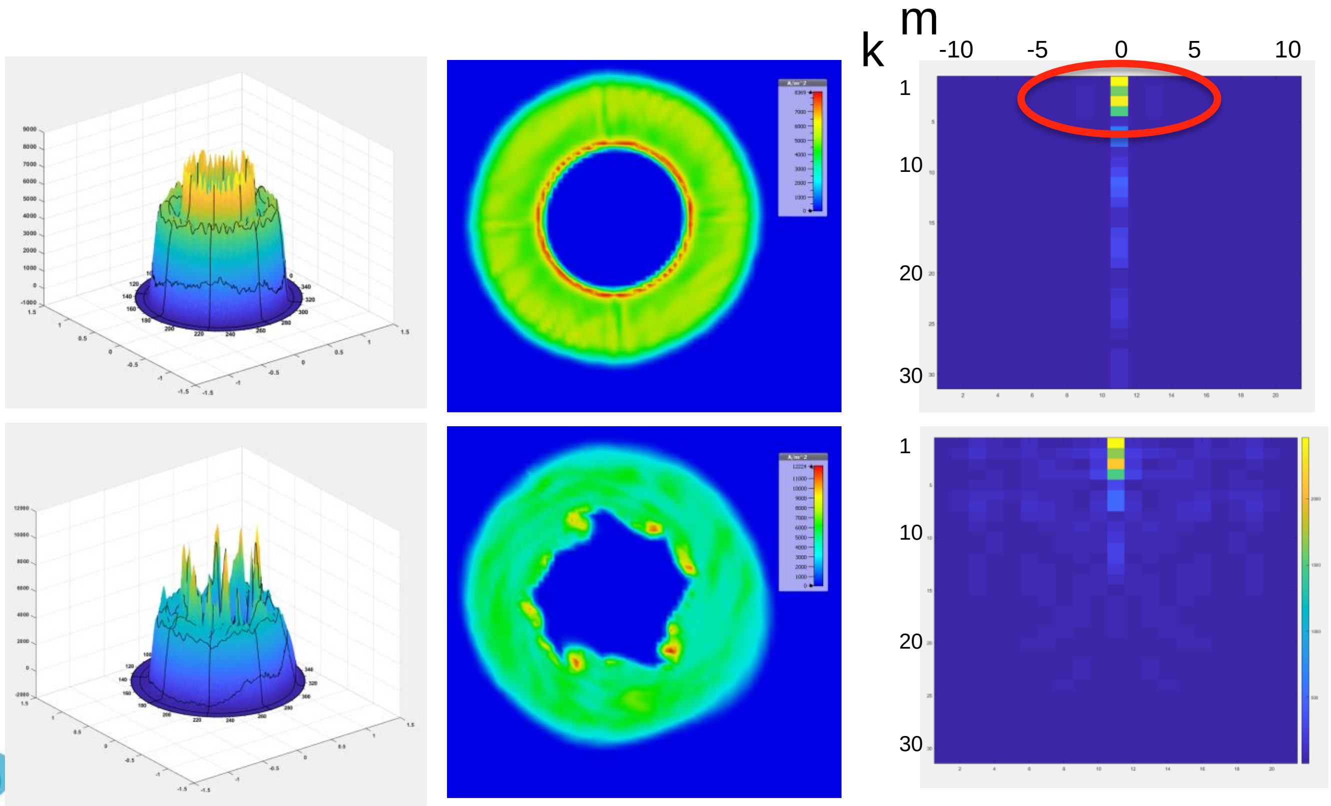
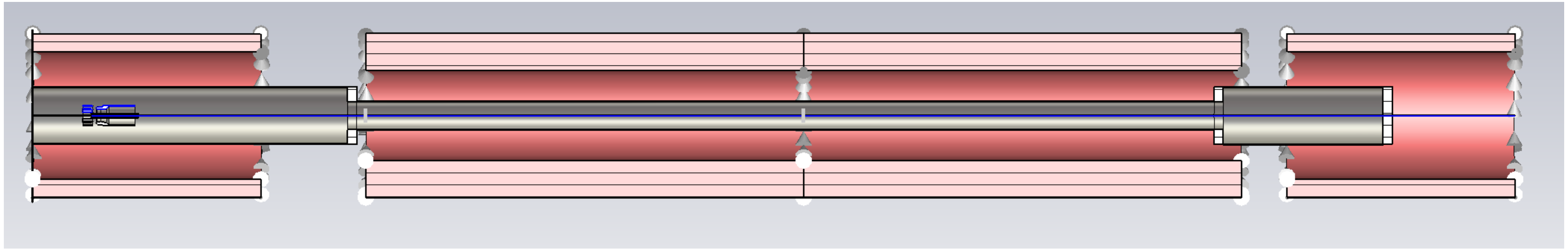


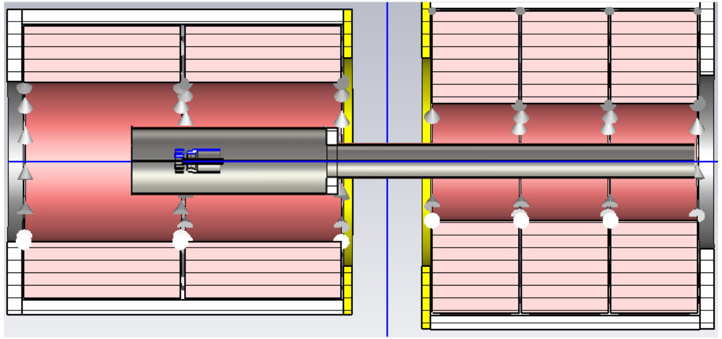
Image comparison – distorted beam

$P_{k,m}$ from PFT

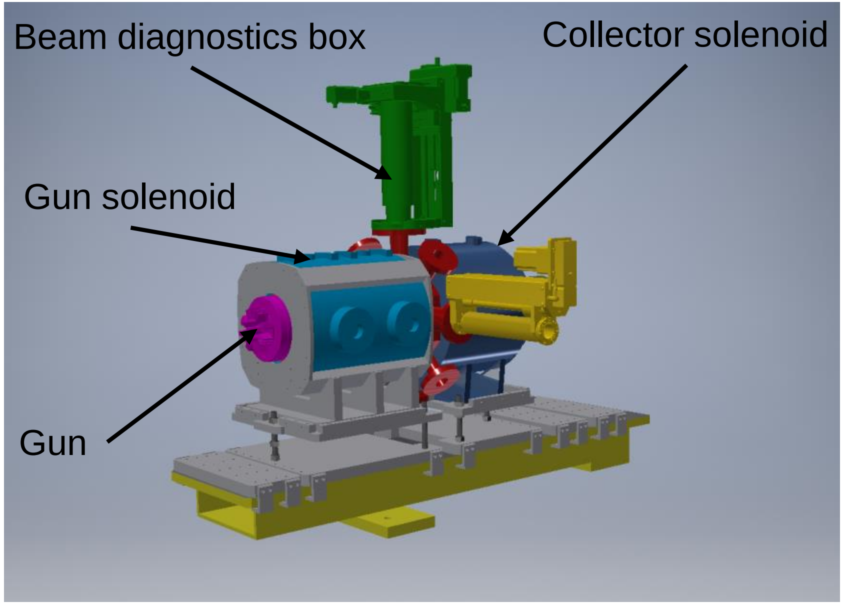


E-lens test stand at CERN





Electron lens test stand at CERN: stage 1

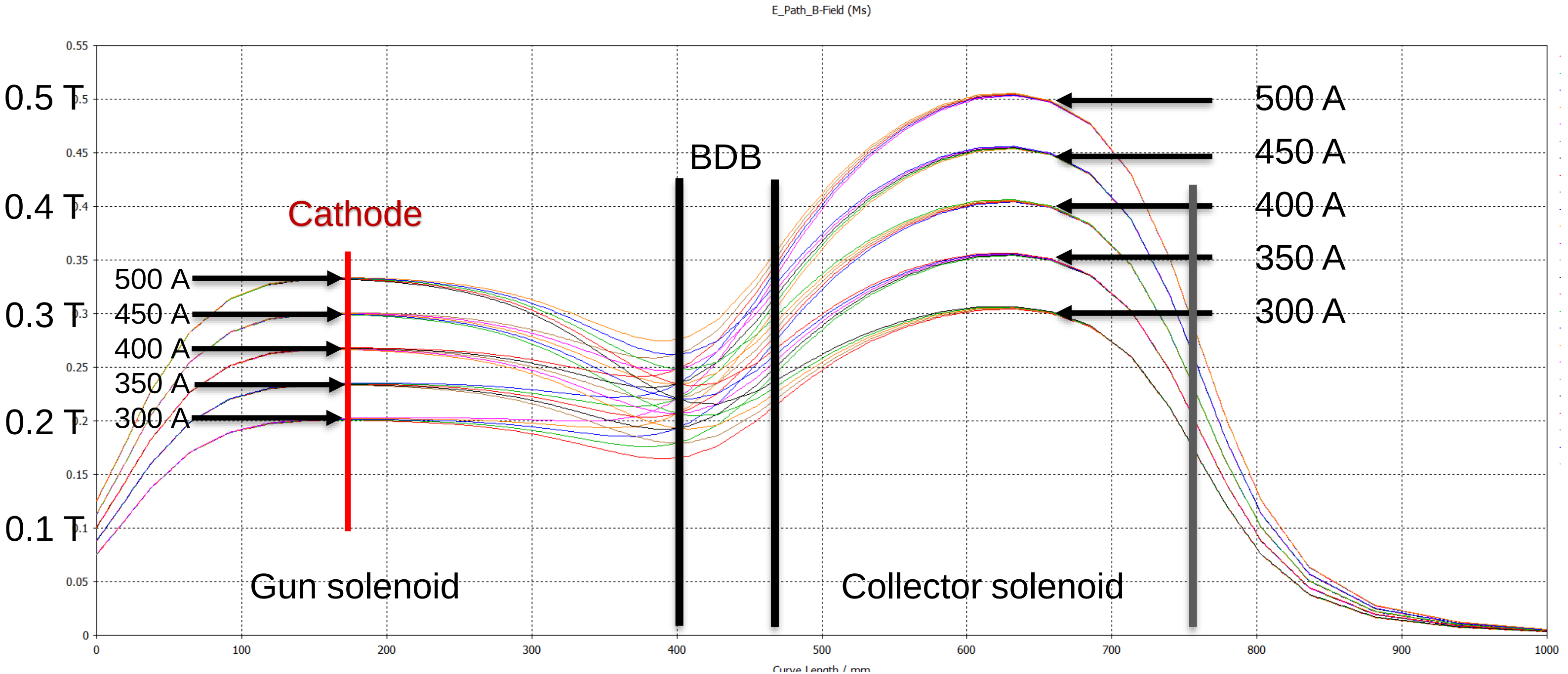


Purpose of first stage:

- 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

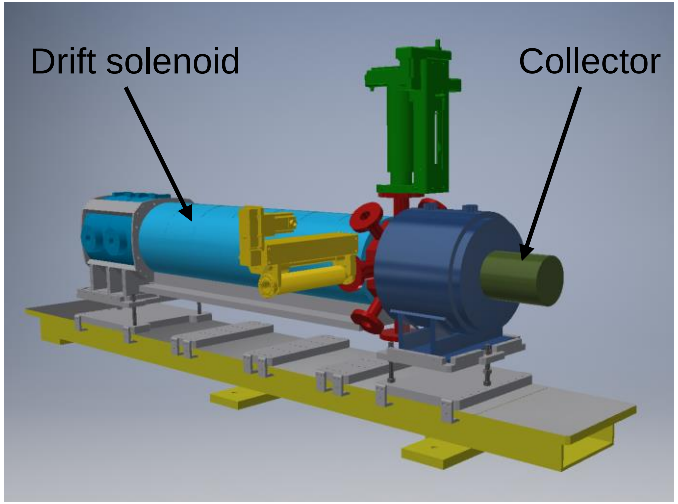
Magnetic field along Z axis for different currents in the solenoids



Conclusions

- Beam dynamics simulation in CST® PS and experiments in FNAL gives similar qualitative behavior, the differences can be caused by:
  - misalignments of the gun
  - uninform current yield
  - wrong computational model
- Comparison of profiles based on Fourier decomposition in polar coordinates was introduced for data analysis.
- E-lens test bench at CERN will give additional data required for validation of the simulations.

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

FNAL test stand – model in CST® Particle Studio