Status of the Hollow Electron Lens e-beam

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BGC Collaboration Meeting at GSI - 19 March 2018

Outline

- Context
- Brief description of electron lenses and electron beam dynamics
- 2 phases test facility at CERN
- Summary and outlook

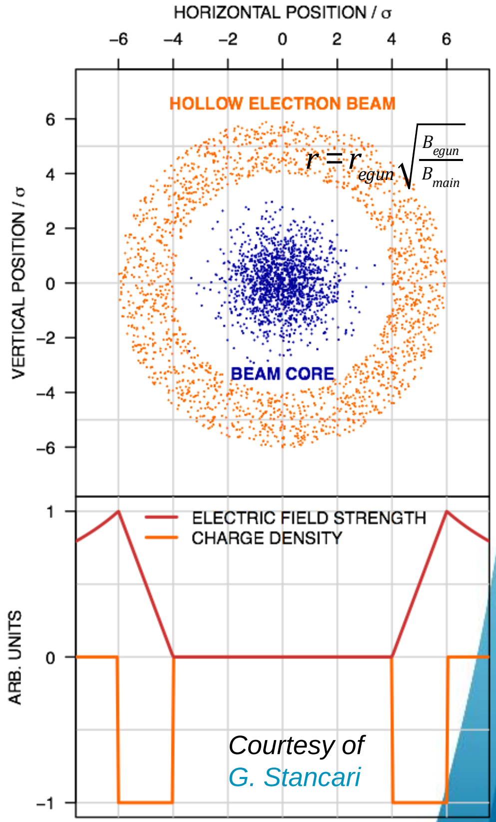
HiLumi HL-LHC PROJECT

Context: hollow electron lens

- **Halo diffusion enhancement:** Loss spikes have already affected the operation of the LHC, and control of beam losses is recognised as a critical concern for performance at HL-LHC due to the higher beam energies and intensities (for ex. for Crab Cavity failure).

$$\theta_r = \frac{2\, I_r\, L\, (1 \pm \beta_e \beta_p)}{r\, \beta_e\, \beta_p\, c^2\, (B\rho)_p} \left(\frac{1}{4\pi\epsilon_0} \right)$$

- **Hollow electron lenses** are being designed and (if approved as baseline) will be installed in IR4 (during LS3) as active mean to increase diffusion rate of halo particles. Halo
  - at HL-LHC required hollow electron beam ~ 15Am (3m e-lens per beam) 5A × 15kV
  - e-beam *Ø 1.9-3.8mm* at LHC top energy (7TeV)
    Ø 7.6-15.2mm at LHC injection energy (7TeV)



Courtesy of G. Stancari

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- **Brief description of electron lenses and electron beam dynamics**
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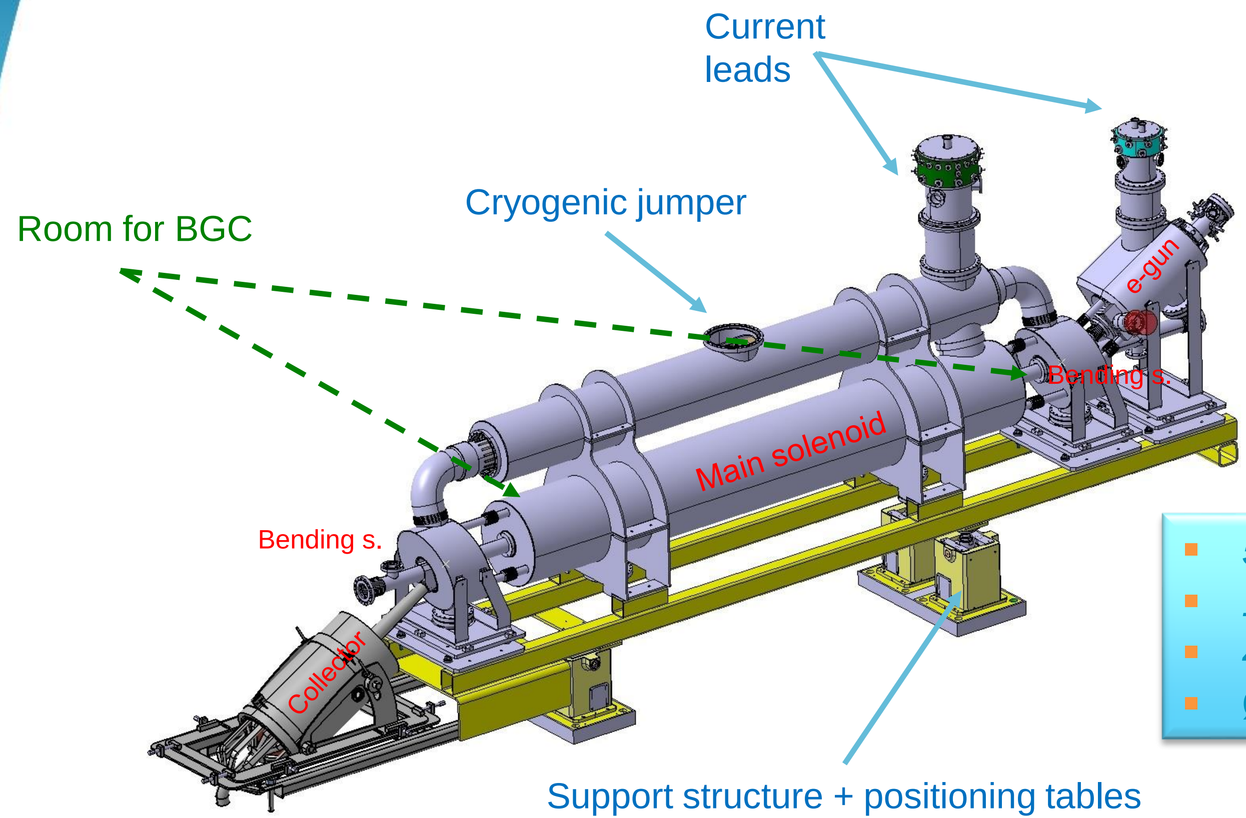
Reference Design of HEL for the Review in Oct. 2017

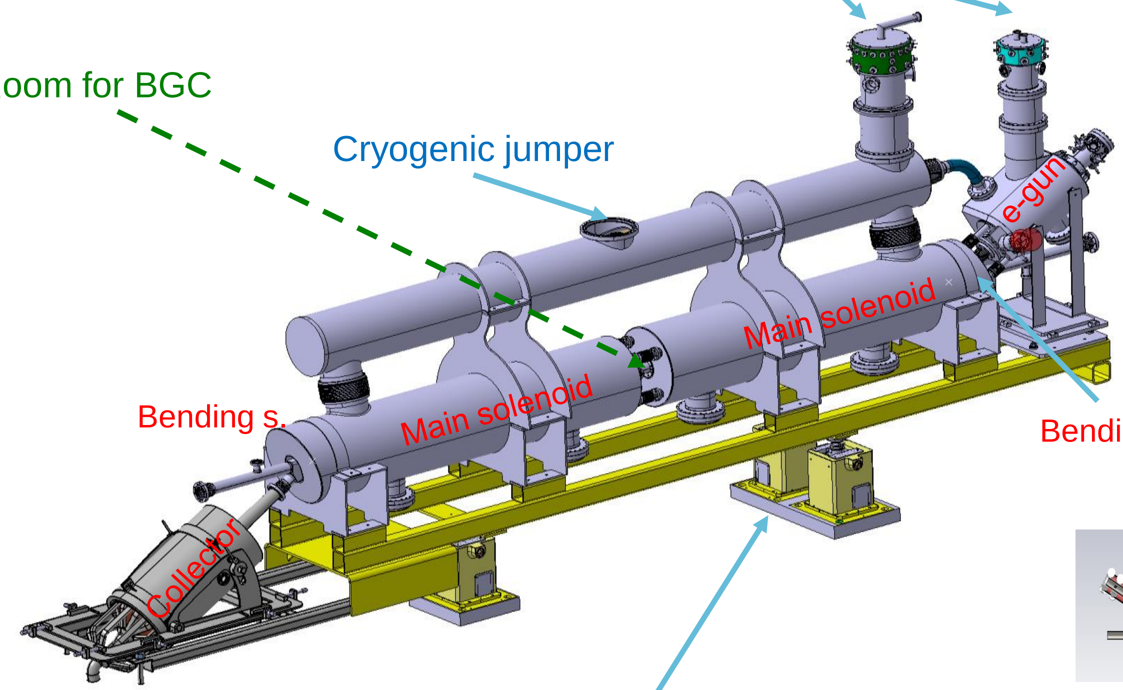


Support structure + positioning tables

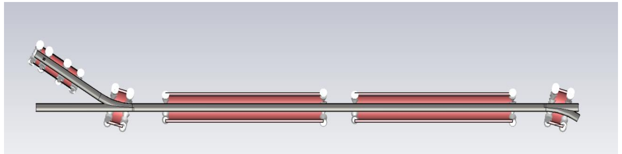
Discussions with the survey group to define the position of their targets.

- *5A hollow e-beam*
- *10kV*
- *4T main solenoid*
- *Ø 80mm vacuum chamber*

After review: Reference Design of HEL with central gap



- *5A hollow e-beam*
- *15kV*
- *5T main solenoid*
- *Ø 60mm vacuum chamber*



Support structure + positioning tables

Discussions with the survey group to define the position of their targets.

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	0.43/0.60
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 CERN

HEL Parameters

Current	(3A at 12 kV) 5A at 15 kV
Effective length	2.9 m

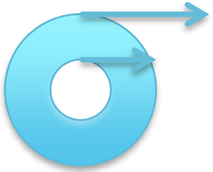
Hollow shaped beam with

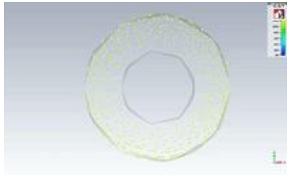
- higher current (5A),
- higher current density (~57A/cm^2 for 1.8-3.6mm hollow beam for protons at 7TeV)
- higher energy (15kV),
- longer effective length (2.9m)

Electron beams

- An electron in a uniform B field will gyrate along beam lines with
  - cyclotron frequency $$w_c = \frac{|qB|}{m}$$
  - gyroradius $$r_g = v_\perp / w_c = \left| \frac{m v_\perp}{qB} \right|$$
- In the presence of an electric field (self field of e-beam), assuming that the induced B field change is << w_c^{-1}

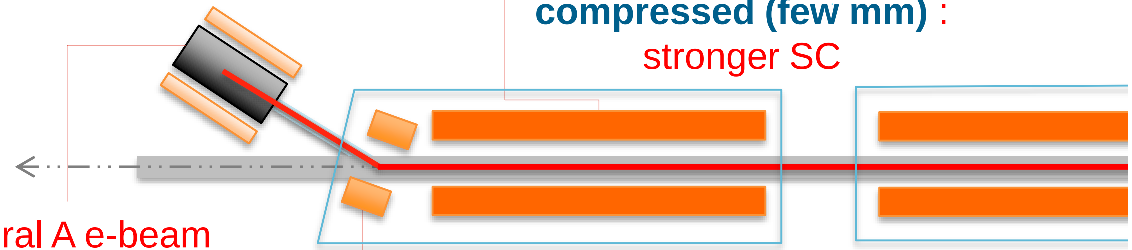
$$\frac{d\mathbf{r}_{\text{guiding centre}}}{dt} = v_{\parallel} \frac{\mathbf{B}}{|B|} + \frac{\mathbf{E}_{\perp} \times \mathbf{B}}{B^2}$$





Electron beam in electron lens

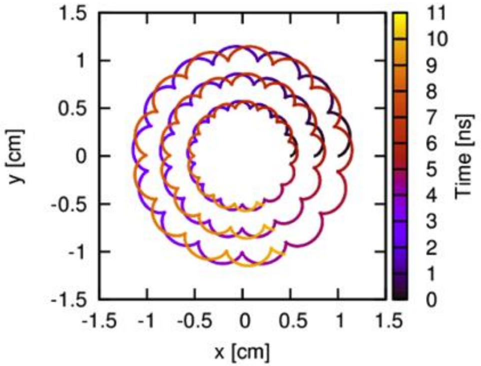
Beam is further **compressed (few mm)** : stronger SC



several A e-beam ~10mm @ cathode

Beam is **compressed** and **bent**

Courtesy of Daniel Noll



In case of azimuthally <u>non</u>-uniform beam there could be an angular component of the electric field causing further beam tilt.

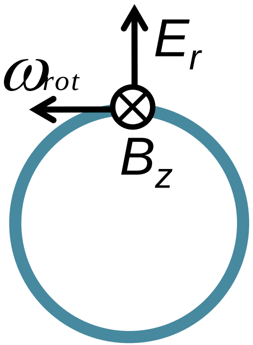
$$\frac{d\mathbf{r}_{\text{guiding centre}}}{dt} = v_{\parallel}\frac{\mathbf{B}}{|B|} + \frac{\mathbf{E}_{\perp} \times \mathbf{B}}{B^2}$$

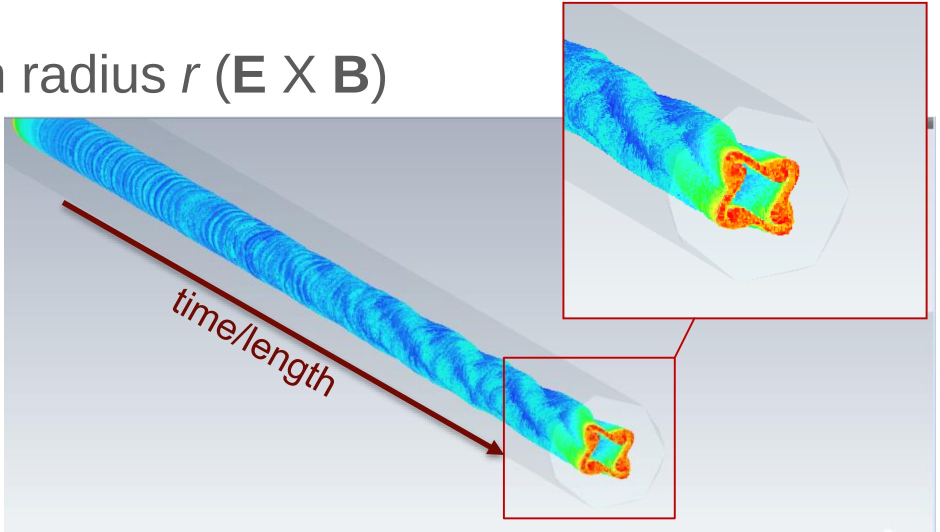
Origin of the diocotron instability

- Different angular velocities for different radii provide **relative motion of layers.** It **may** lead to the density equilibrium violation and cluster origin

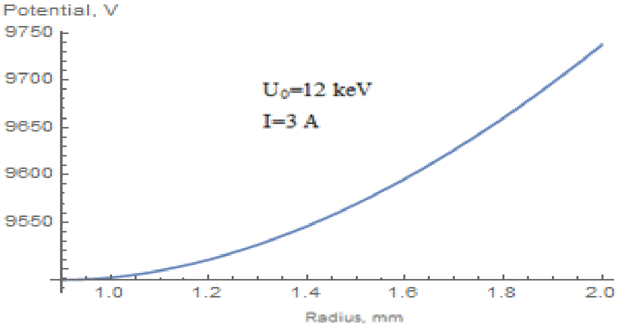
- Angular velocity for the given radius *r* (**E** X **B**)

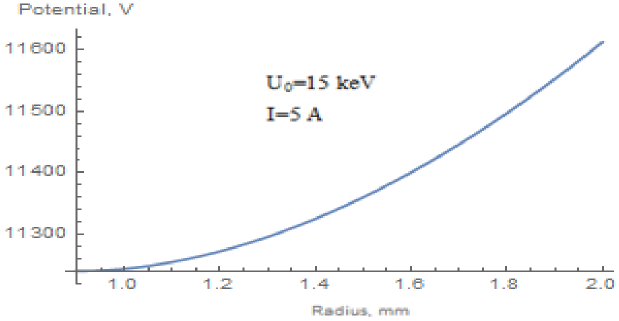
$$\omega_{rot}(r) = \frac{E_r(r)}{rB_z}$$



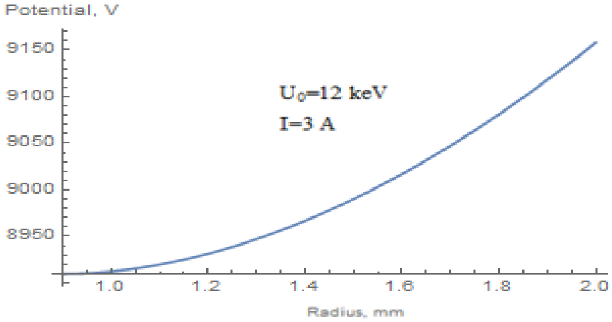


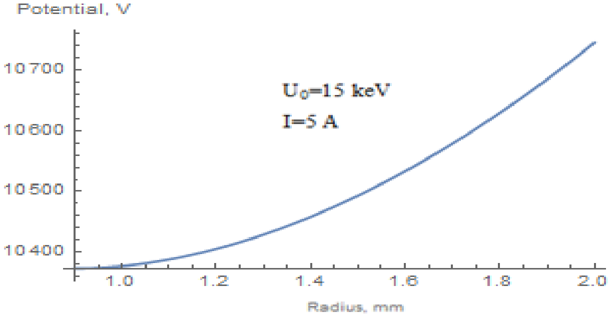
Estimation of potential sagging in chosen modes





In the vacuum chamber

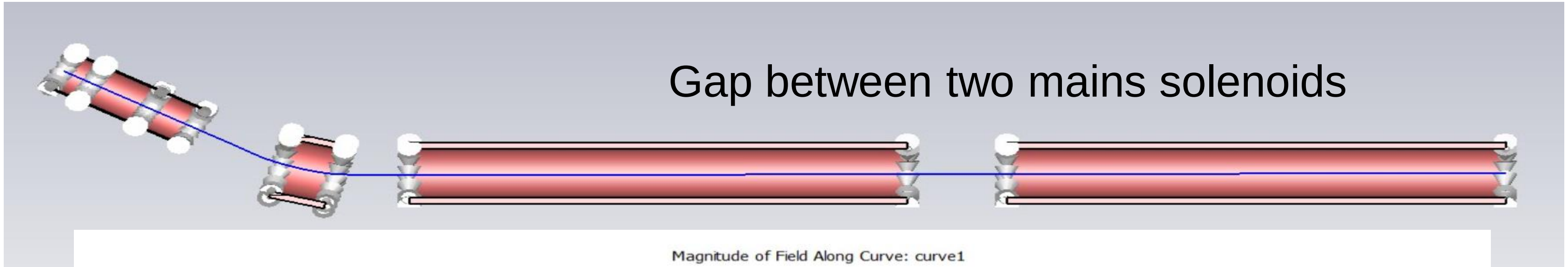


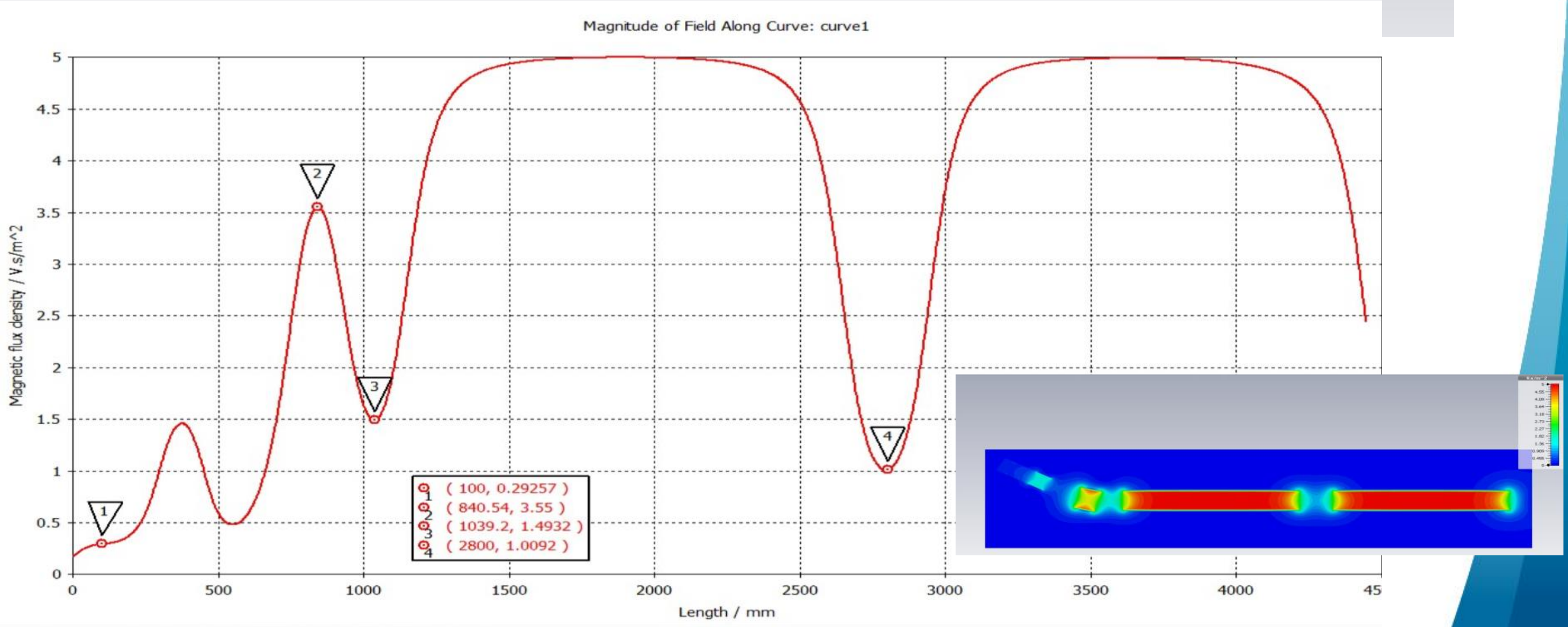


In the bending

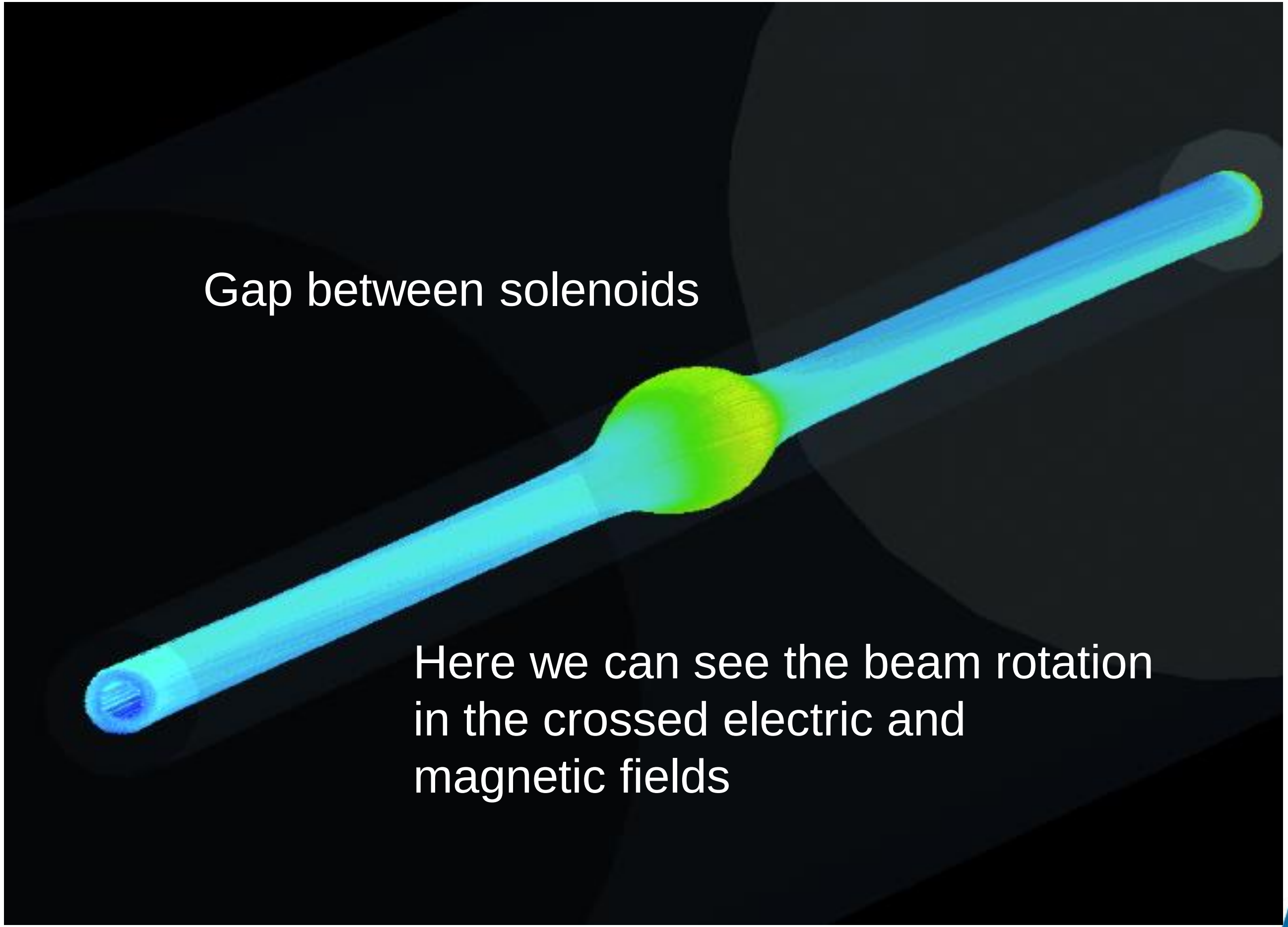
Barnyakov, A. Levichev, M. Maltseva, D. Nikiforov
BINP-CERN

E-lens magnetic system

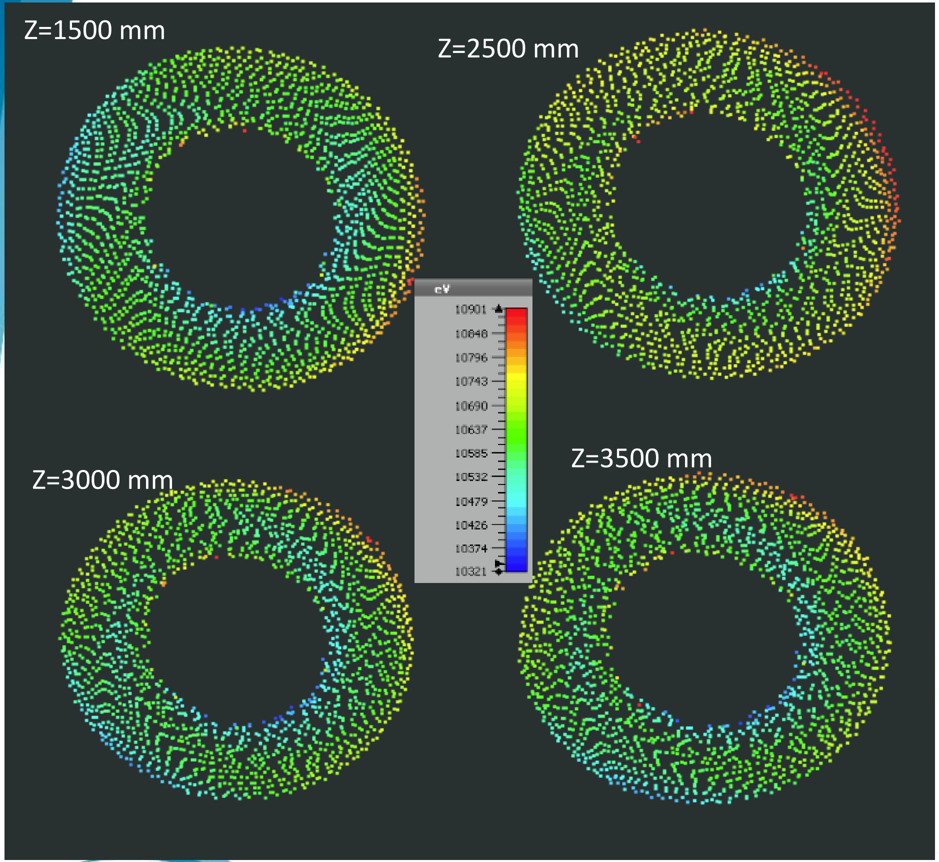




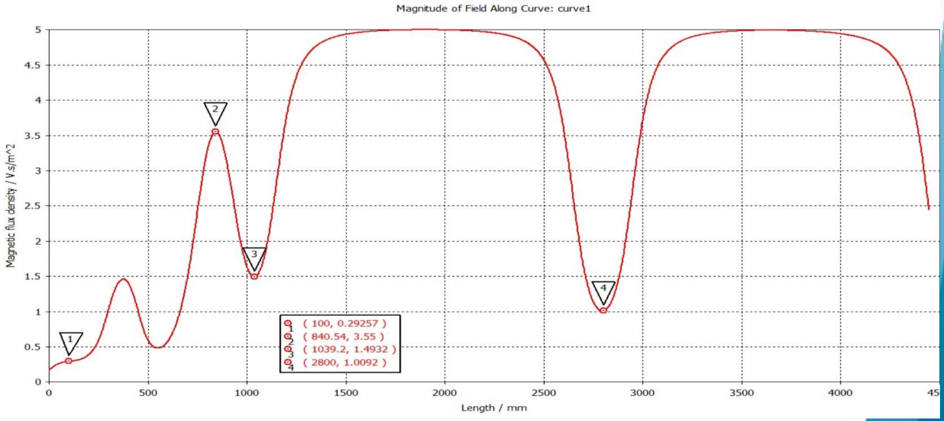
3 A and 12 kV: *trajectories in the main solenoid*



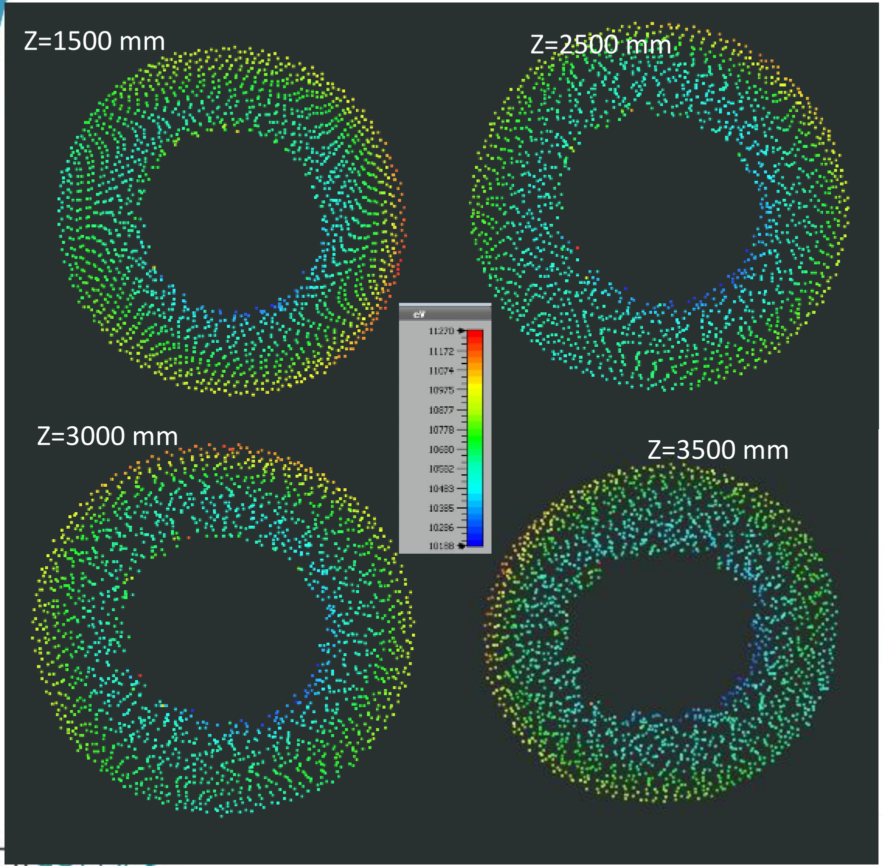
3 A and 12 kV: *cross sections in the main solenoid*



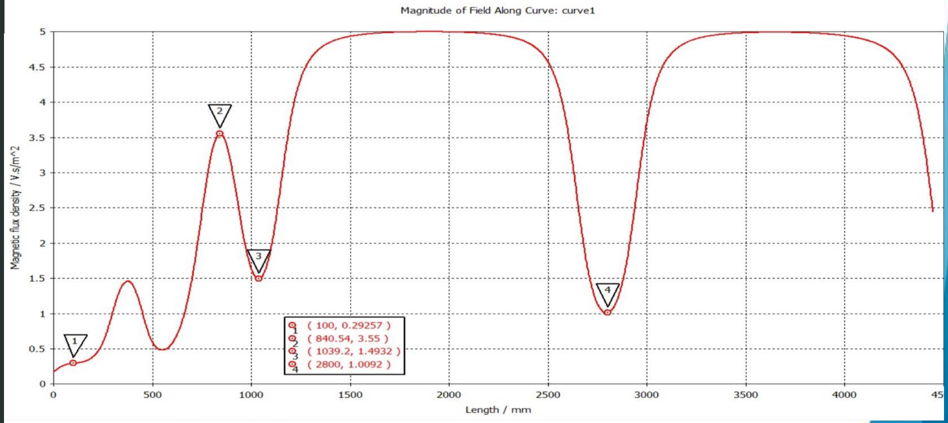
Beam rotation is about 100 degrees



5 A and 15 kV: *cross sections in the main solenoid*



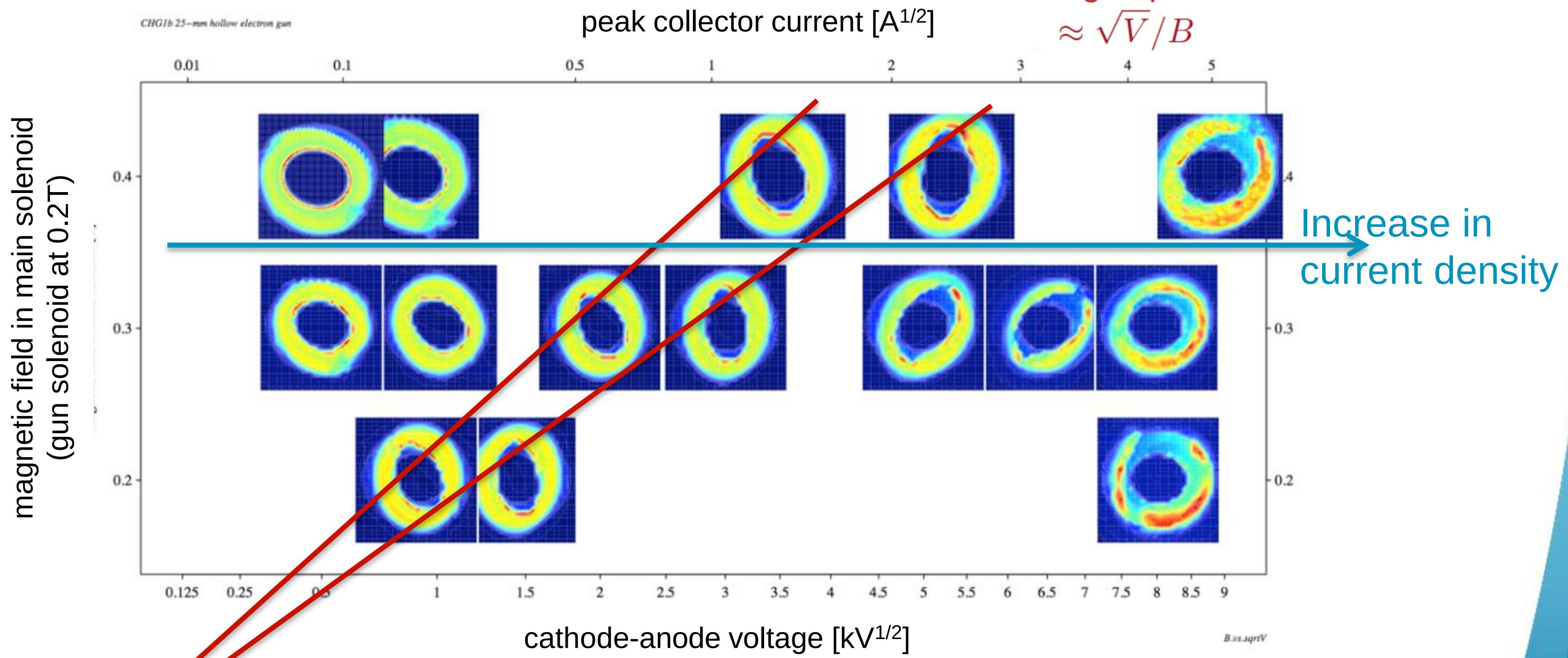
Beam rotation is about 170 degrees



Profile evolution

CHG1B Ø 25mm cathode – Ø 63mm chamber

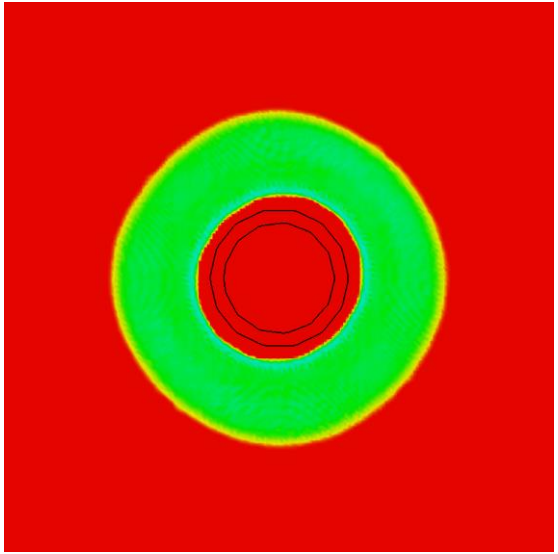
Scaling of profiles $\approx \sqrt{V}/B$

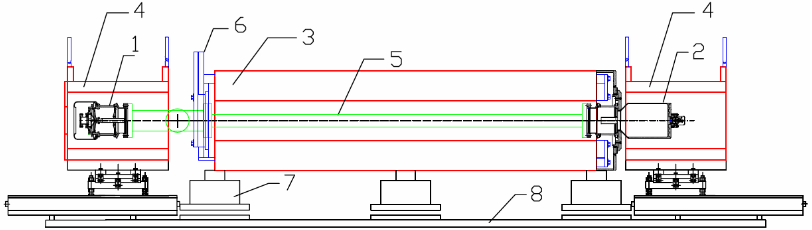


Courtesy of Giulio Stancari

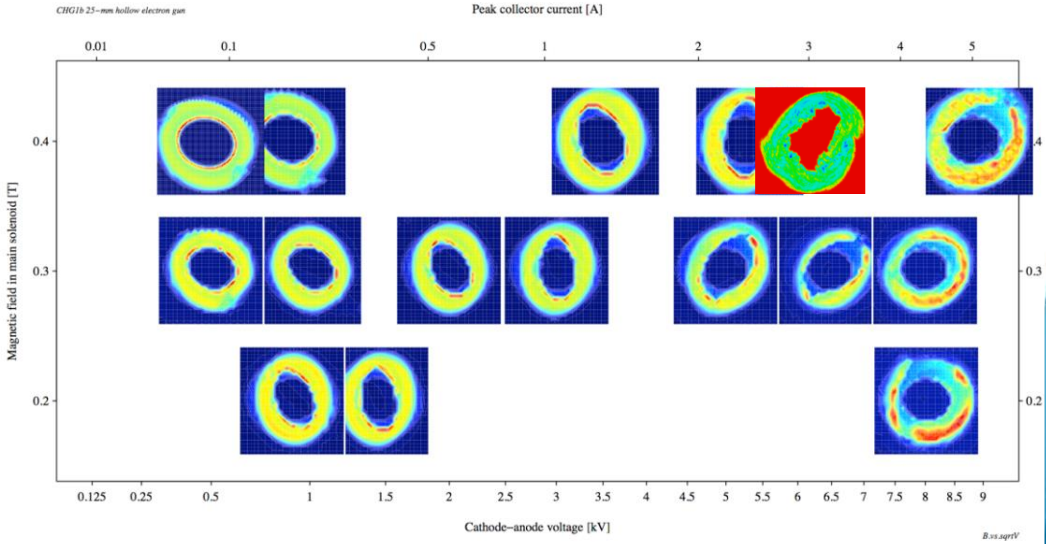
Preliminary CST simulation of FNAL measurements

3A with 0.2-0.4-0.2T
Real (measured) cathode emission





https://cdcvs.fnal.gov/redmine/projects/elens/wiki/Test_Stand



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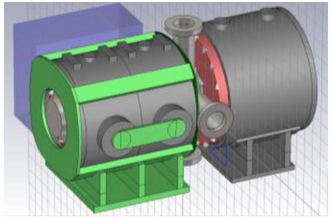
- Brief description of electron lenses and electron beam dynamics
- **2 phases test facility at CERN**
- Summary and outlook

Phase 1: description and purpose

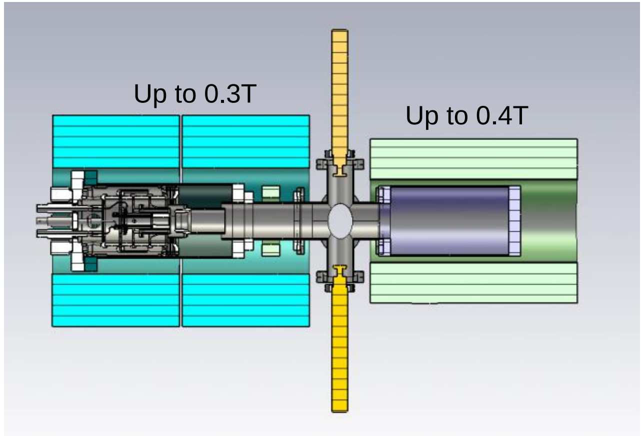


- Commissioning hardware (magnets, vacuum,
  HV system, control, etc.)
- Safety and technical aspects of operation
- Define diagnostic procedures

- Electron gun characterization
  current in temperature and space charge
  (anode voltage) limited emission
- Anode modular

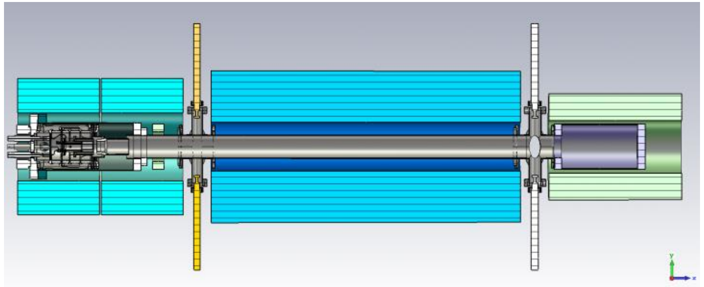
- Beam Gas Curtain monitor

- Gun and collector solenoids
- Diagnostic box
  - pin-hole Faraday cup with bias V
    [electron density distribution and energy]
  - YAG screen monitor
- 40 kV power converters



Phase 2: description and purpose

Addition of drift solenoid like at FNAL and RHIC

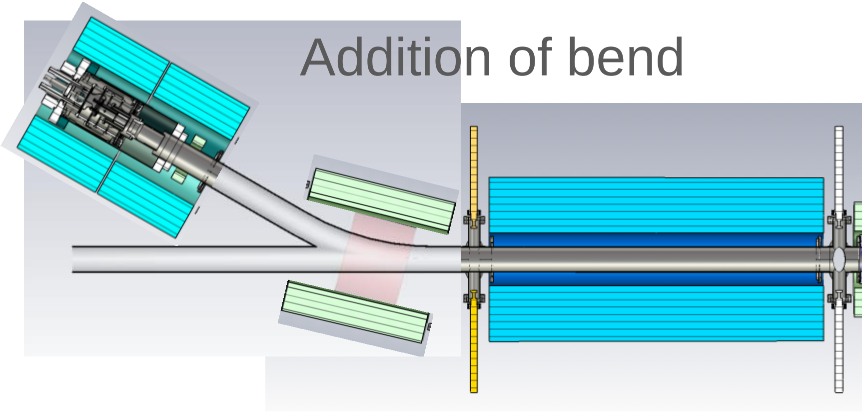


- Drift solenoid warm (recuperated) could achieve 0.4-0.5T over 1.2m.
  - Need upgrading **heat exchanger** and **power grid** in the building

- Dry SC drift solenoid (4T) may be cheaper and would expand range of investigation

- Validate BPM ‘shoe-box’ or ‘strip-line’ (with HEL or HF modulation) for electrons
- Test (improve) the modulators and check effects on electron position measurements as well as on electron beam dynamics
- Bench-mark our simulations and gain confidence on projection
- Design and test clearing electrodes for electrons created at the BGC
- Test BGC resolution and energy/density resolving

Phase 2 upgrade: description and purpose



- Measure effect of B x gradB on deformation of beam with high current density
- Computer model validation
- Fine tune parameters like the geometry of the vacuum chamber at injection of the electron beam (for example to avoid that the beam touches the chamber or deforms)

Summary and outlook

- A test stand at CERN is being constructed in a phased approached.
- Phase 1 it will be/ can be used to:
  - E-gun characterisation (in parallel or after FNAL).
  - Test and commission BGC [see ref.]
- Phase 2 needed to:
  - Test RF modulation.
  - Test BPM for electrons (HF or LF modulation).
  - Investigate electron beam dynamics and benchmark simulation codes like CST, WARP, UltraSAM, …
  - Test BGC resolution

HiLumi HL-LHC PROJECT

Tests for SIS18 space charge compensation

- **Space charge compensation** : electric field generated by electron beams (Gabor lenses) used to focus ion/proton beams, whose space charge would otherwise cause emittance blow-up.
  - Electron beam with transverse and longitudinal distribution plus current intensity ~ matching beam to be focused
  - 10 A average - 20 A peak current, 50x70 mm size, 25kV for GSI studies

HiLumi HL-LHC PROJECT

Thank you for your attention

References for Beam Gas Curtain (or Jet) monitor:

H. Zhang et al, DEVELOPMENT OF A SUPERSONIC GAS JET BEAM PROFILE MONITOR, IBIC2015

V. Tzoganis et al, EXPERIMENTAL RESULTS OF A GAS JET BASED BEAM PROFILE MONITOR, IPAC14

V. Tzoganis et al, Design and first operation of a supersonic gas jet based beam profile monitor, Phys. Rev. Accel. Beams 20, 062801, 12 June 2017

Spare slides

Electron Lens schematics (currently proposed)

Electron gun (5A 8-16mm cathode)

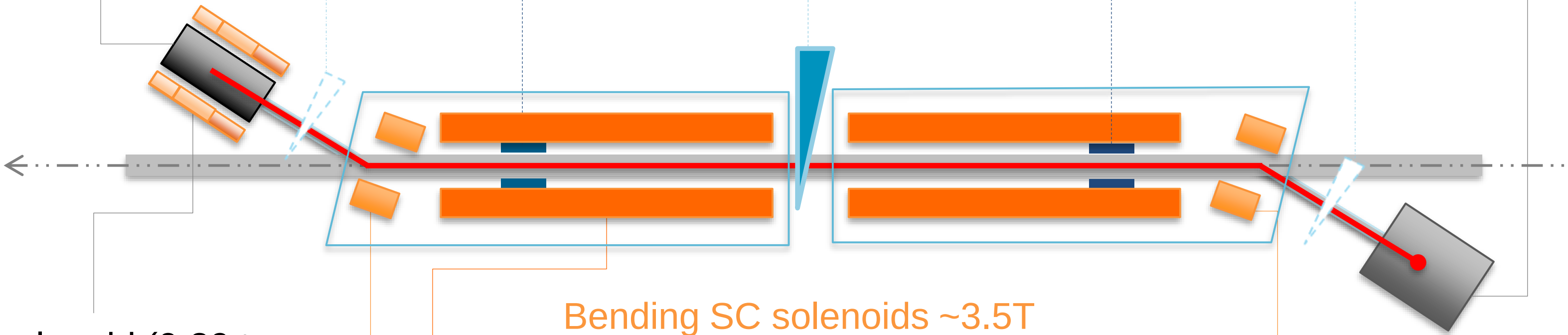
Modulator (KHz to MHz)

Instrumentation

BPMs

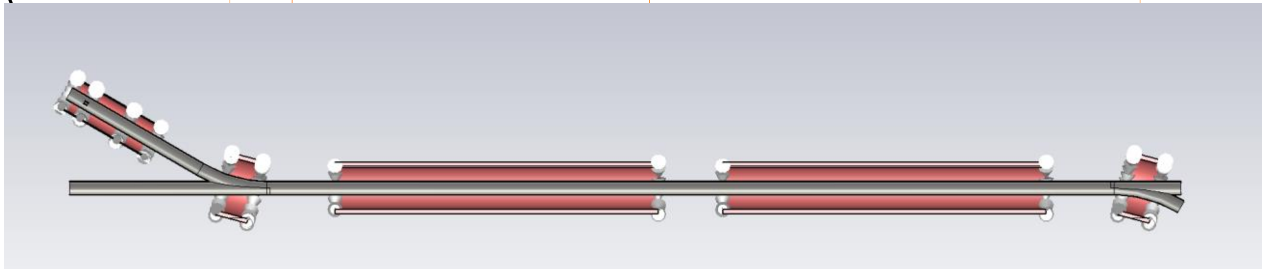
Overlap/transvers profile monitors

Collector



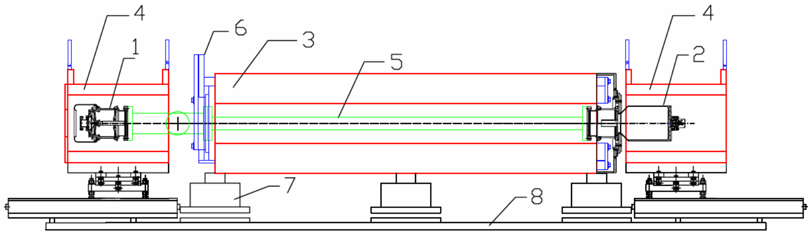
Bending SC solenoids ~3.5T

Gun solenoid (0.29 to 1÷1.5T)



E-lenses test stands in the world: overview

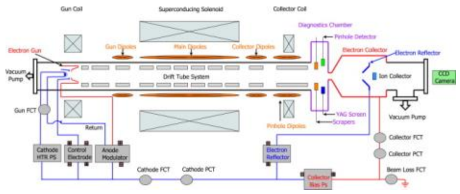
FERMILAB - Tevatron



https://cdcvs.fnal.gov/redmine/projects/elens/wiki/Test_Stand

Operational, up to 10 kV, 8μs x 1Hz pulses
Used to test CERN guns, will be used for testing guns for space-charge compensation at IOTA ring. Could be used to test HF modulators.

BNL- RHIC

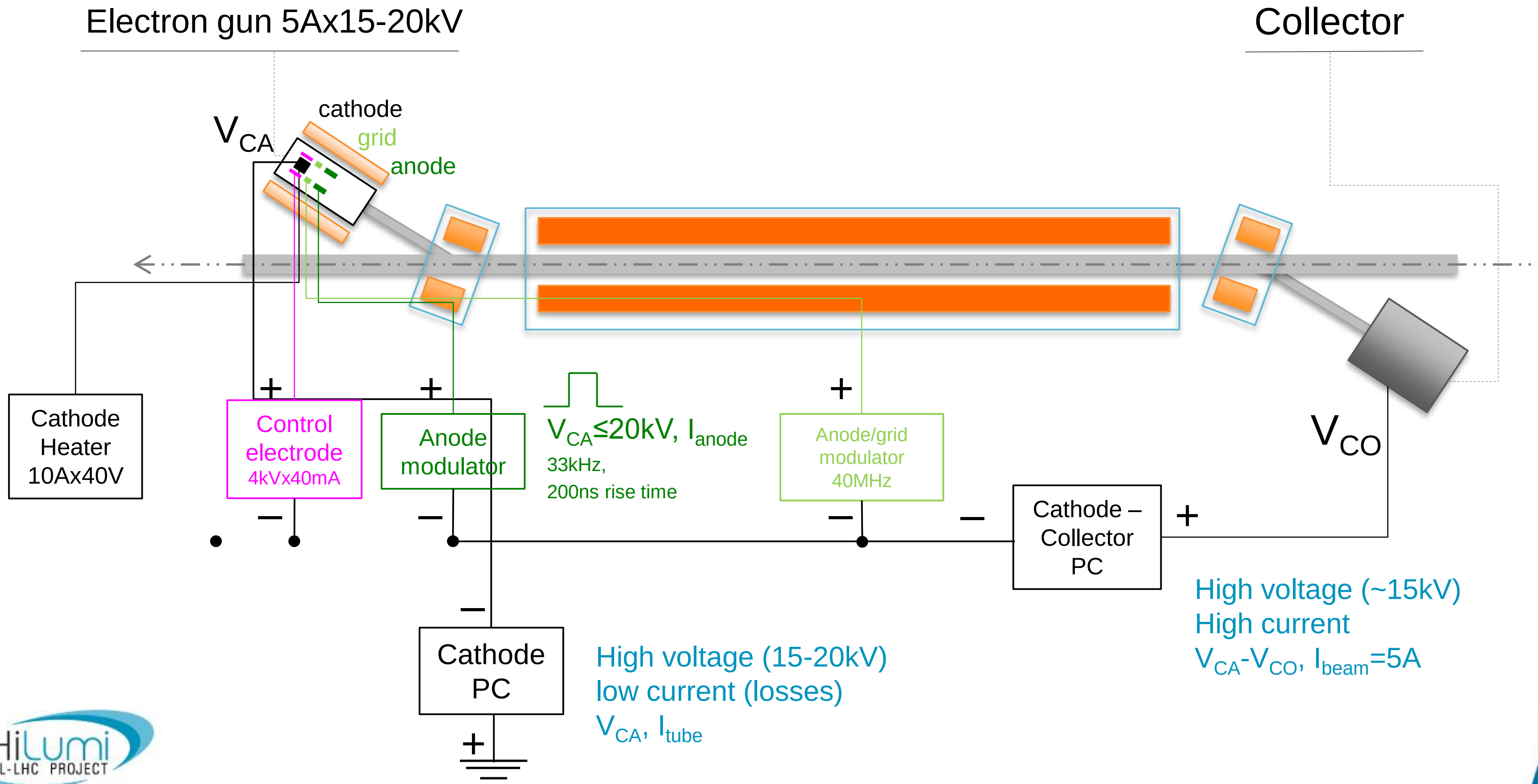


W. Fischer, et al. Construction progress of the RHIC electron lenses. IPAC 2012 - International Particle Accelerator Conference 2012. 2125-2127.

RHIC e-lenses test stand was converted to e-lenses at accelerator

Not all aspects important for HEL@HL-LHC can be tested
Available time for tests is very limited

Hollow Electron Lens



25-mm (1-in) Fermilab prototype for LHC (HG1)

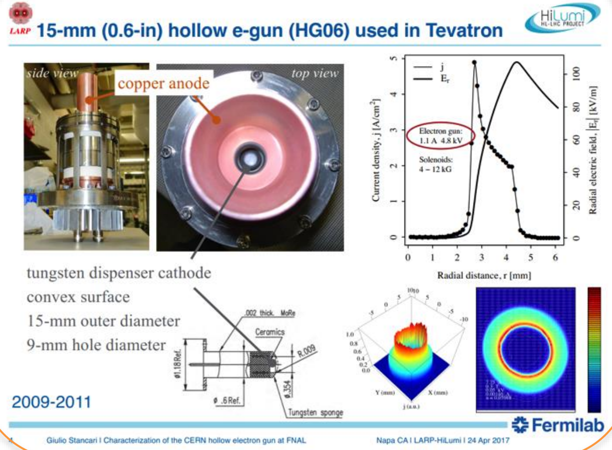
HG1: original design

HG1b: added cathode shield

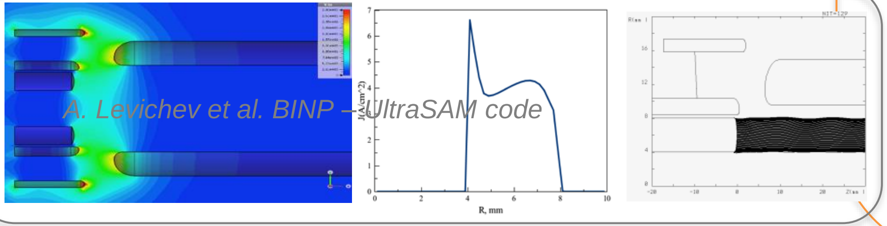
HG1c: replaced cathode

2011-present

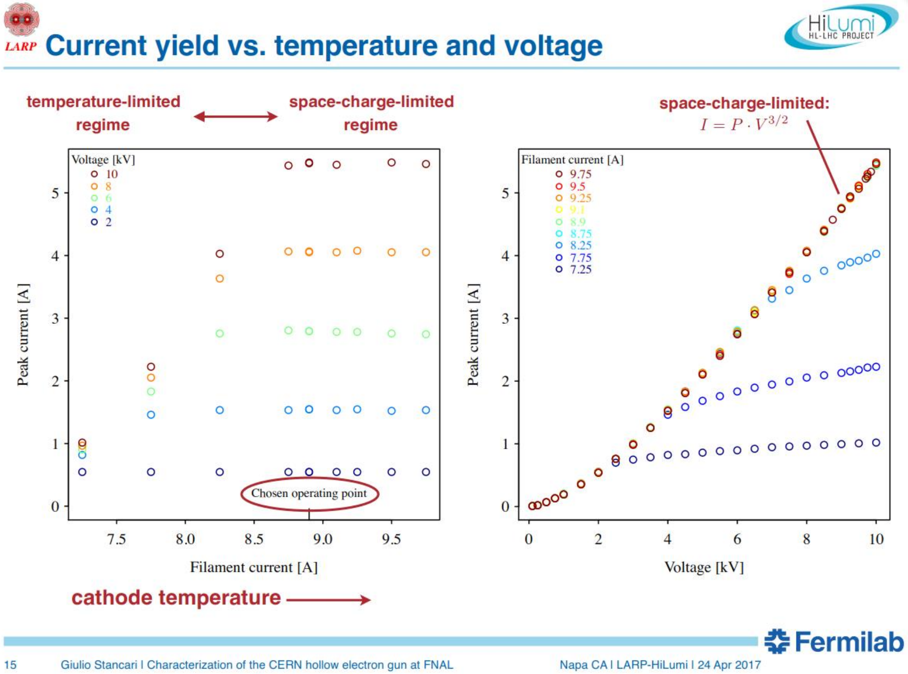
G. Stancari FNAL – WARP code



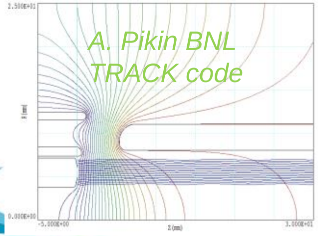
A. Levichev et al. BINP – UltraSAM code

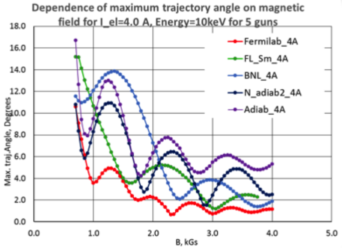


G. Stancari FNAL



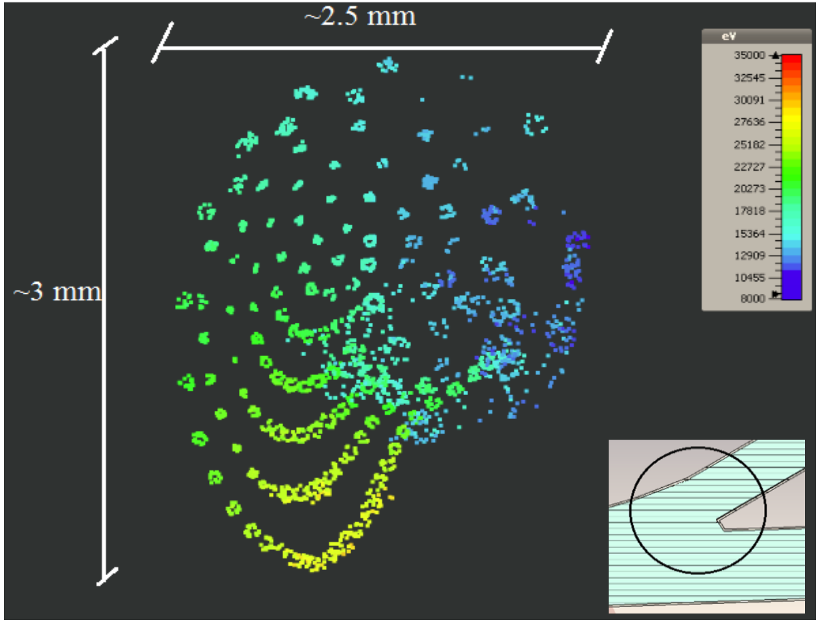
A. Pikin BNL
TRACK code

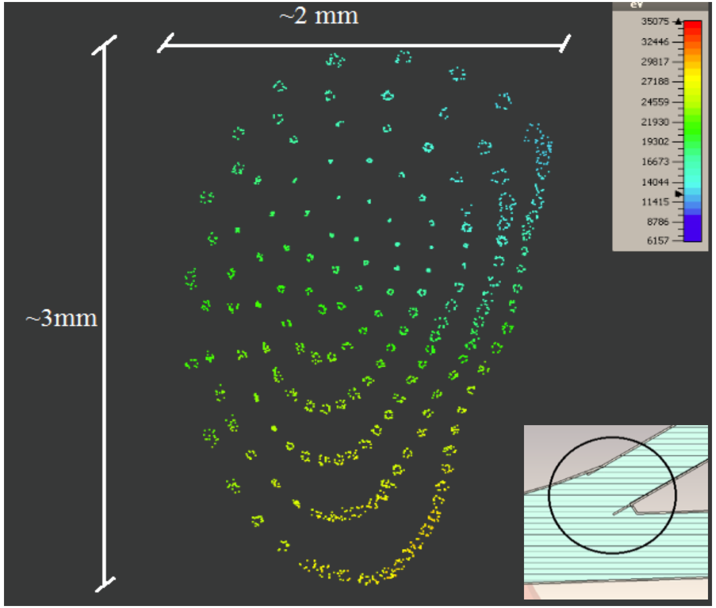




Electron gun characterisation

Preliminary electron studies
Effect of vacuum chamber geometry





Transverse electron profile for a 20A - 35 kV source (~1cm^2). The radial energy distribution and transverse dimensions are shown for 2 different pipe geometries.

Note: statistics/meshing probably too low/large to see full dynamics.

2017 – A. Levichev, D. Nikiforov, A. Barnyakov, BINP