



Status and plans for e-beam R&D

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7th HL-LHC Collaboration Meeting, 13-16 November 2017, CIEMAT Madrid

Context

Electron beams can be used in conjunction with proton/ion beams for

- Electron cooling (for ex. at CERN LEIR, AD, ELENA),
 - Space charge compensation (GSI SIS18, FNAL IOTA)
 - Beam-beam compensation (at FNAL Tevatron and BNL RHIC)
 - Halo diffusion enhancement (at FNAL Tevatron)
-
- At HL-LHC e-lenses are being studied for:
 - BBLR for Beam-Beam Long-Range compensation
 - HEL for Halo diffusion enhancement
 - BBHO for Beam-Beam Head-On compensation
 - Landau damping

Electron beam applications (1/3)

- **Electron cooling** is a method to shrink the emittance (size, divergence, and energy spread = lower the temperature) of a charged particle beam without removing particles from the beam. Electron are injected at the same velocity as the ion/proton beam, via Coulomb scattering they exchange momentum and at thermodynamic equilibrium (= same momentum), since the electrons are much lighter, they will have increased their velocity, and the opposite for the ions/protons.
 - Few tens of mA x 5-10 kV electrons
- **Space charge compensation**, where the electric field generated by electron beams (Gabor lenses) are 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

Electron beam applications (2/3)

- **Beam-beam compensation:** The strongly nonlinear beam-beam force excites high-order betatron resonances, particles diffuse into the tails of the transverse distributions causing emittance growth and beam losses.

$$D\{x', y'\} = -\frac{2N_p r_p}{g} \frac{\{X, Y\}}{X^2 + Y^2} \left(1 - e^{-\frac{X^2 + Y^2}{2s^2}} \right)$$

$$X = x + x_{ew}, \quad Y = y + y_{ew}$$

Beam-beam tune spread might be reduced by:

- **for Long-Range Beam-Beam (parasitic encounters)**

- compensation with e-beam wire (WP13)
- concept being tested in LHC with copper wires embedded in collimator (see G.Sterbini's talk, Wed.)
- at HL-LHC required electron beam $\sim 200\text{Am}$ (for 2 wires per HL IP)
 $\cong 60\text{Am} \times \text{several tens of kV}$ (2 e-lenses per HL IP) wire like

- **for Head-On Beam-Beam (IP collisions)**

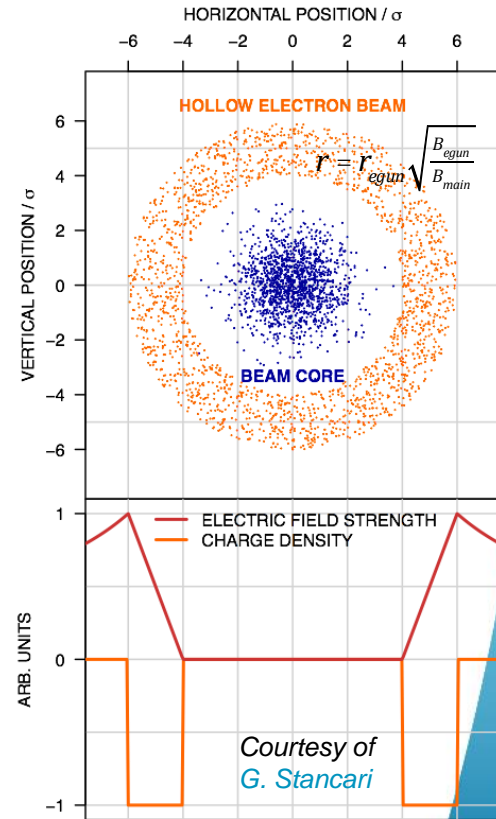
- collisions of the proton bunch with a space charge of a low energy e-beam, having the same Gaussian transverse distribution as the p-beam (WP13?)
- at RHIC $\sim 0.2\text{A}$ proton beam with beam-beam parameter 0.007
 used total of 2 e-lenses with $\sim 2\text{Am}$ ($=1\text{A} \times 2\text{m}$) $\times 10\text{kV}$ (2 IPs)
- HL-LHC $\sim 1.1\text{A}$ proton beam with beam-beam parameter 0.033
 $\rightarrow \rightarrow \cong 5.5\text{Am}$ (scaling with current plus 2 e-lenses per HL IP) $\times 15\text{-}20\text{kV}$

Electron beam applications (3/3)

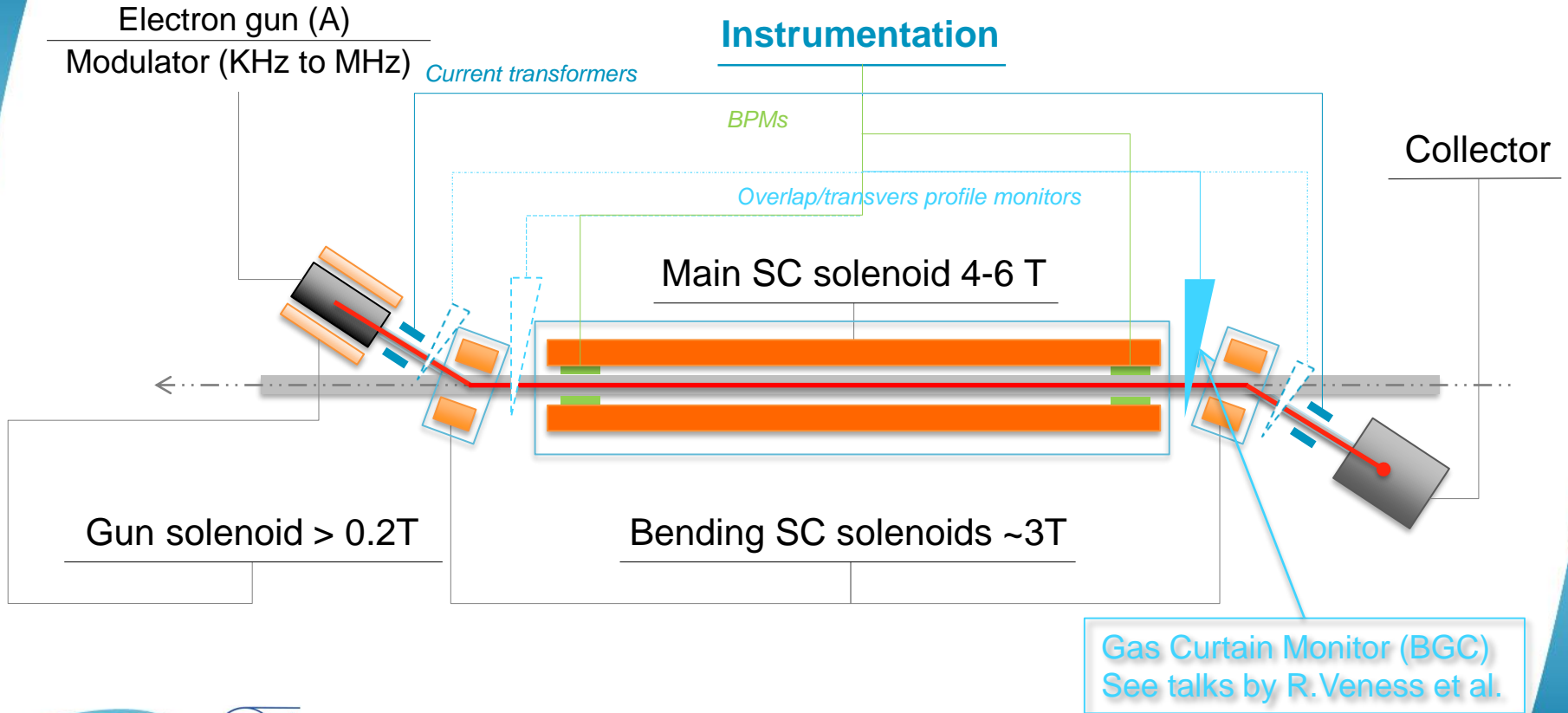
- **Halo diffusion enhancement:** Loss spikes have already affected the operation of the LHC, and control of beam losses is recognised as a critical concern for performance at HL-LHC due to the higher beam energies and intensities (for ex. for Crab Cavity failure).

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

- **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 (1×3m e-lens per beam) × 15-20kV



Electron Lens schematics (typical values)

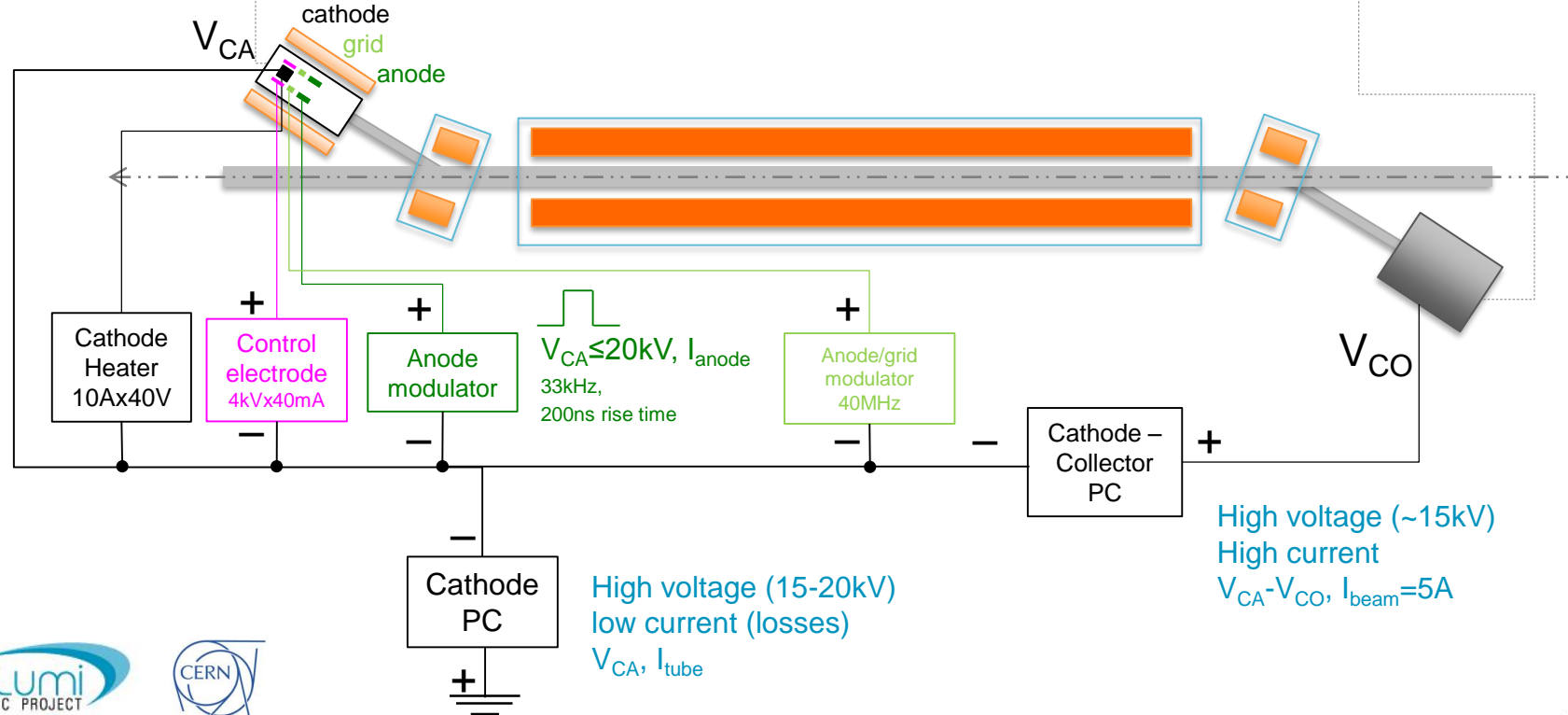


Gas Curtain Monitor (BGC)
See talks by R. Veness et al.

Hollow Electron Lens

Electron gun 5Ax15-20kV

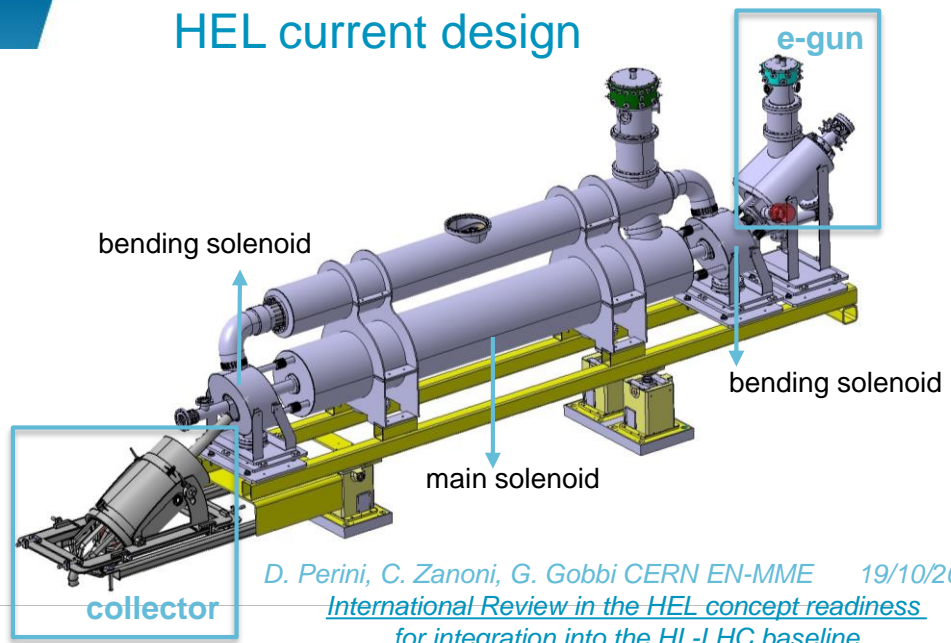
Collector



Outline

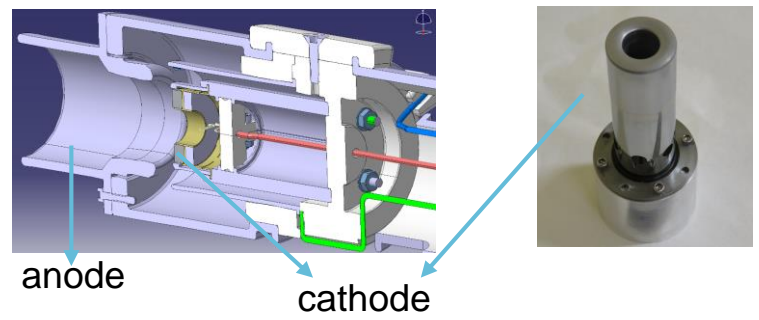
- Hollow Electron Lens
 - Current design
 - Electron beam studies
 - New campaign of simulations for HEL
- Brief Long-Range Beam Beam studies
- Experimental results: existing and future facilities
- Summary

HEL current design

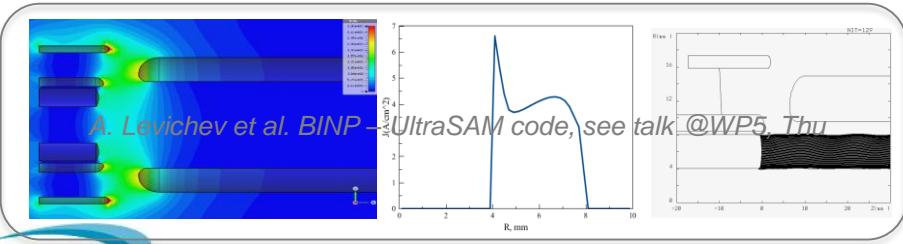
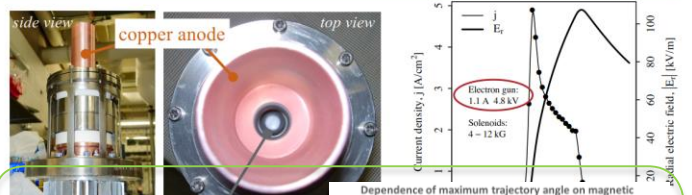


*D. Perini, C. Zanoni, G. Gobbi CERN EN-MME 19/10/2017
International Review in the HEL concept readiness
for integration into the HL-LHC baseline*

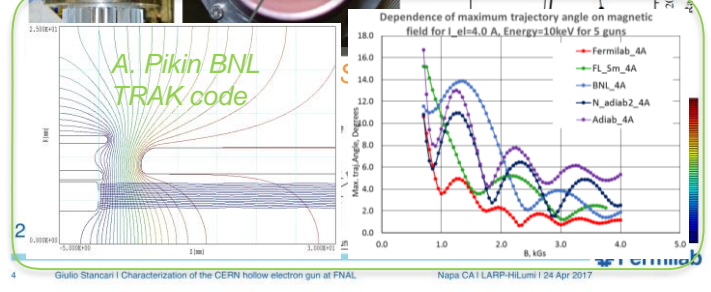
Gun (scaled design from FNAL)



LARP **15-mm (0.6-in) hollow e-gun (HG06) used in Tevatron** HiLumi



A. Levichev et al. BINP - UltraSAM code, see talk @WP5, Thu



Giulio Stancari | Characterization of the CERN hollow electron gun at FNAL Napsa CA1 LARP-HiLumi | 24 Apr 2017

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 $v = \sqrt{2 \cdot e \cdot U_0 / m}$ with U_0 accelerating potential).
- Analytical estimate for P_p (cylindrical capacitance, assuming round e-beam)

$$P_p = \frac{\sqrt{2e/m_e}}{3\sqrt{3}} \frac{4\pi\epsilon_0}{\ln(r_{pipe}/r_{beam})}$$

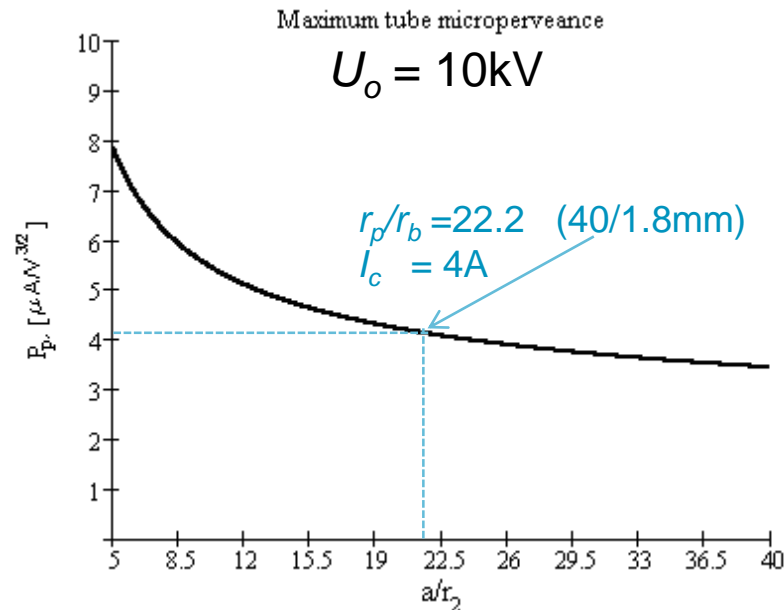
... and critical electron current

- Maximum current through a pipe for a given accelerating potential U_o
- For $I \sim I_c$, the minimum beam energy in the pipe will be $\sim U_o/3$

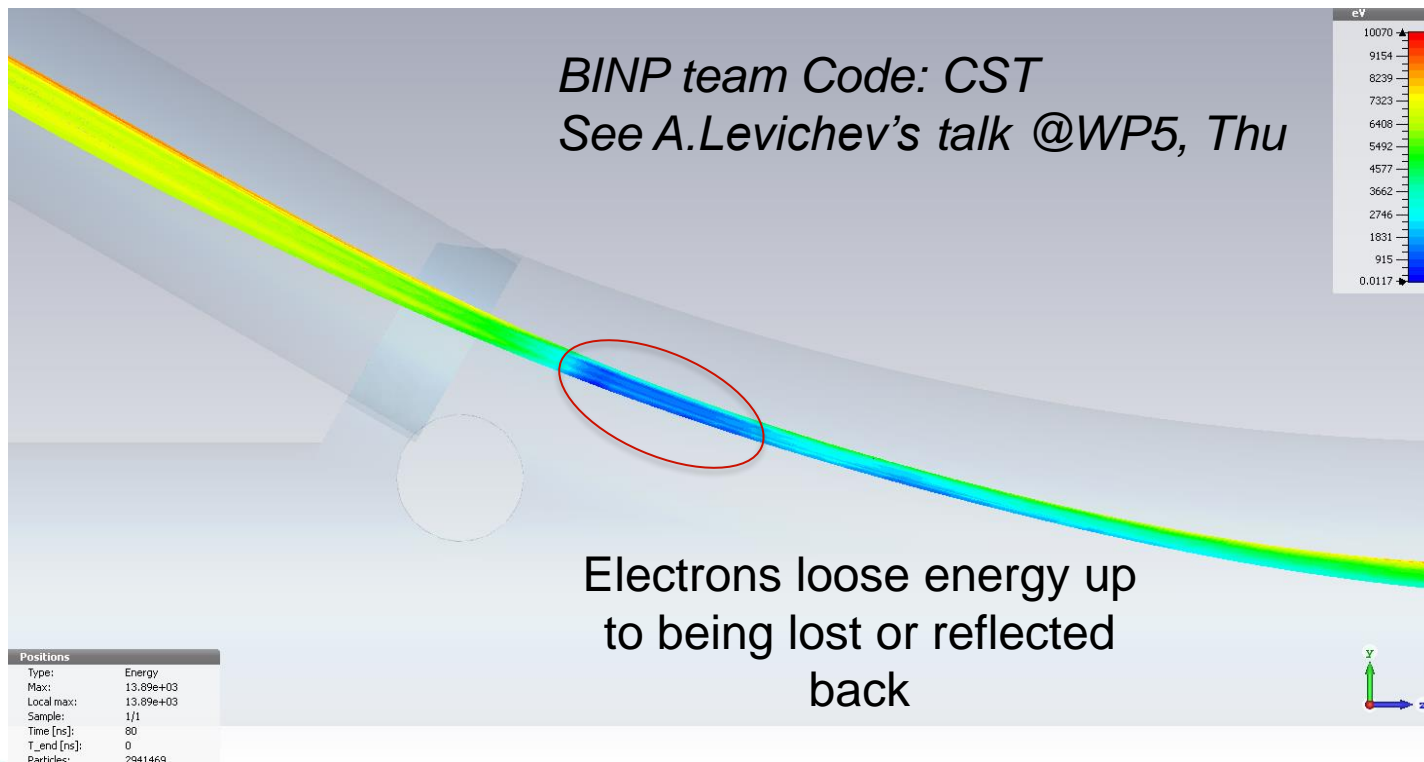
$$I_c = P_p U_o^{3/2}$$

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

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



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



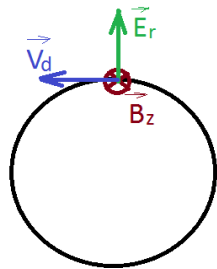
Effect of drift velocity

- Larmor motion: electrons rotating along the magnetic line

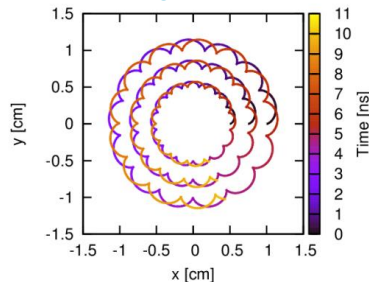
with longitudinal velocity $v = \sqrt{2e/m_e U}$

- Drift velocity derives from the ExB (e-beam electric field significant for large e-currents)

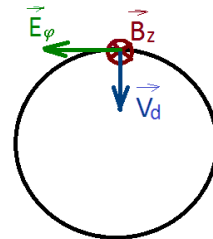
$$\vec{v}_d = \frac{\vec{E} \times \vec{B}}{B^2}$$



Rotation velocity, larger at larger radius



Courtesy of Daniel Noll



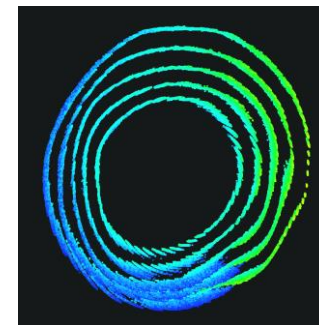
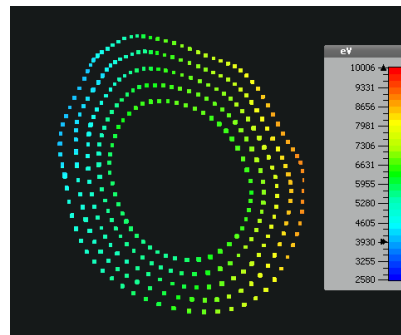
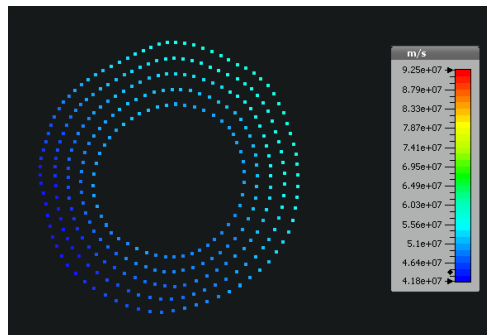
$\omega = v_d / r$ Circular beam frequency

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

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

Effect of drift velocity

CST simulation of a 5A beam deforming along the HEL (BINP)
See A. Levichev's talk
Thursday @WP5



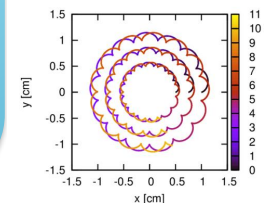
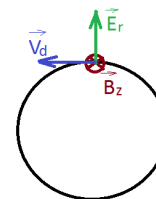
Figures of merit :

- Fraction of turn along the main solenoid
- Ratio between plasma and Larmor frequency

$$g = \frac{v_d \tau}{2\pi r_{\max}}, \quad g = \frac{\vartheta_{\max} (B\rho)_p \beta_p}{2\pi r_{\max} B\beta_e \cdot (1 + \beta_e \beta_p)} \leq 0.2$$

$$\frac{\omega_{\text{plasma}}}{\omega_e} = \frac{1}{B} \sqrt{\frac{m_e I_e}{\pi (r_{\max}^2 - r_{\min}^2) v_e \epsilon_0 e}} \leq 0.015$$

Courtesy of
G. Stancari



New campaign of simulations for HEL

- 5T, 2.9A ($\approx \cong 0.2$ urad kick to 7TeV protons), 15kV, 60mm vacuum chamber to get to a set of 'working' parameters for the C&S review March '18
- Validation of current simulations (codes and assumptions)
 - comparing with data taken at FNAL (next slides) with CST, WARP, PiC (BENDER),
 - in collaboration with FNAL (G.Stancary), BINP (A.Levichev's team), CERN (S.Sadovich)
- Review magnetic field and dimension of cathode

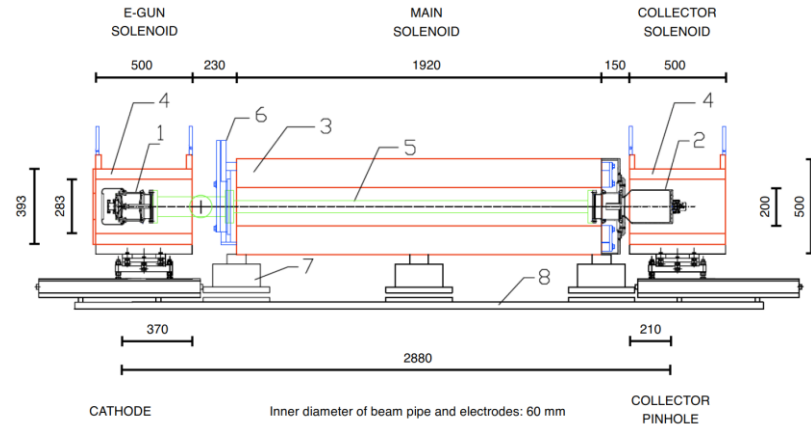
E-lenses experimental data: test stand

FERMILAB – Tevatron



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

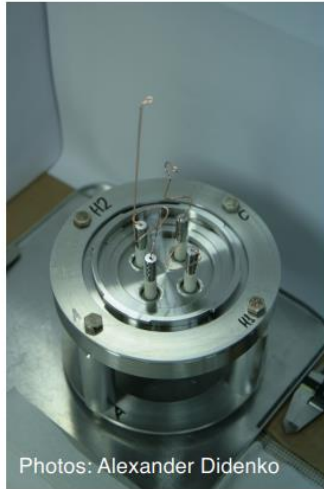
Operational, up to 10 kV, $8\mu\text{s} \times 1\text{Hz}$ pulses
(or higher at $< 5\text{A}$)
Used to test CERN guns, will be used for
testing guns for space-charge compensation
at IOTA ring. Could be used to test HF
modulators.





LARP

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



Photos: Alexander Didenko



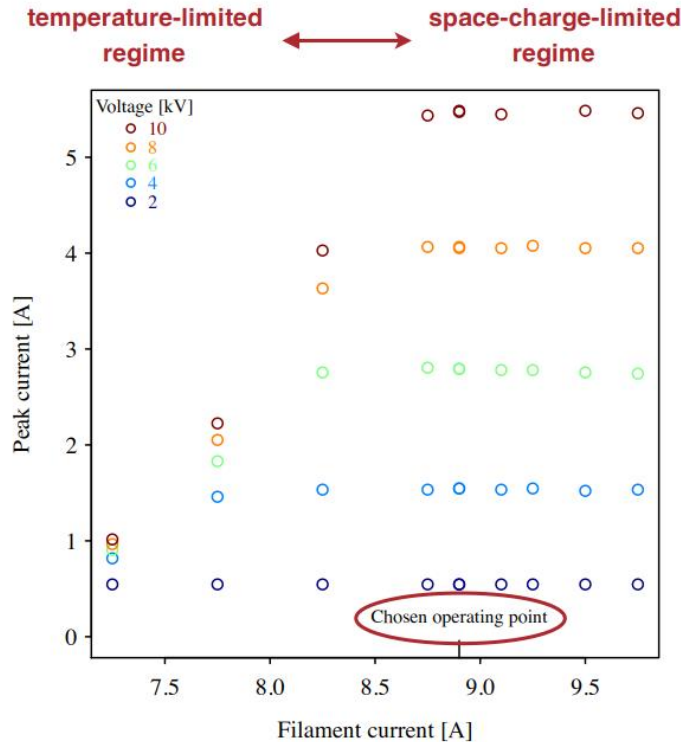
HG1: original design

HG1b: added cathode shield

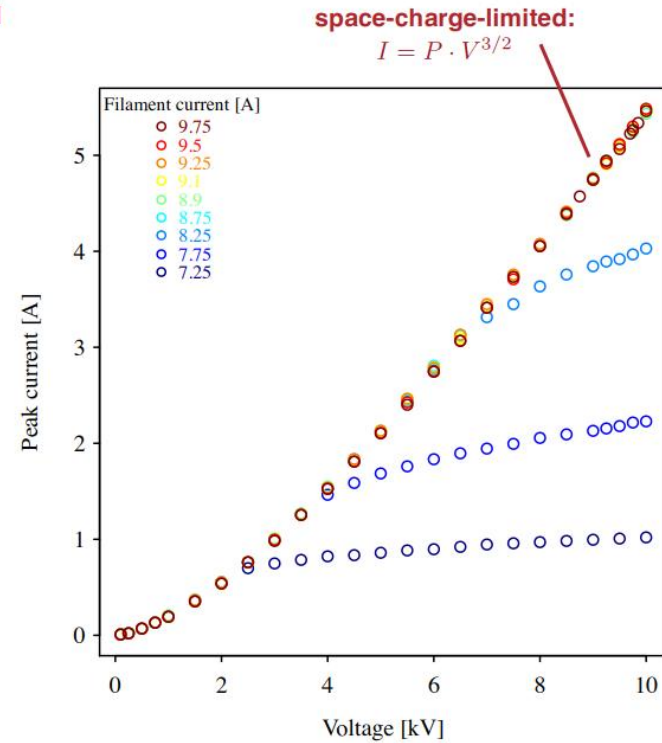
HG1c: replaced cathode

2011-present





cathode temperature \longrightarrow



Reached 5.2 A @ 10 kV

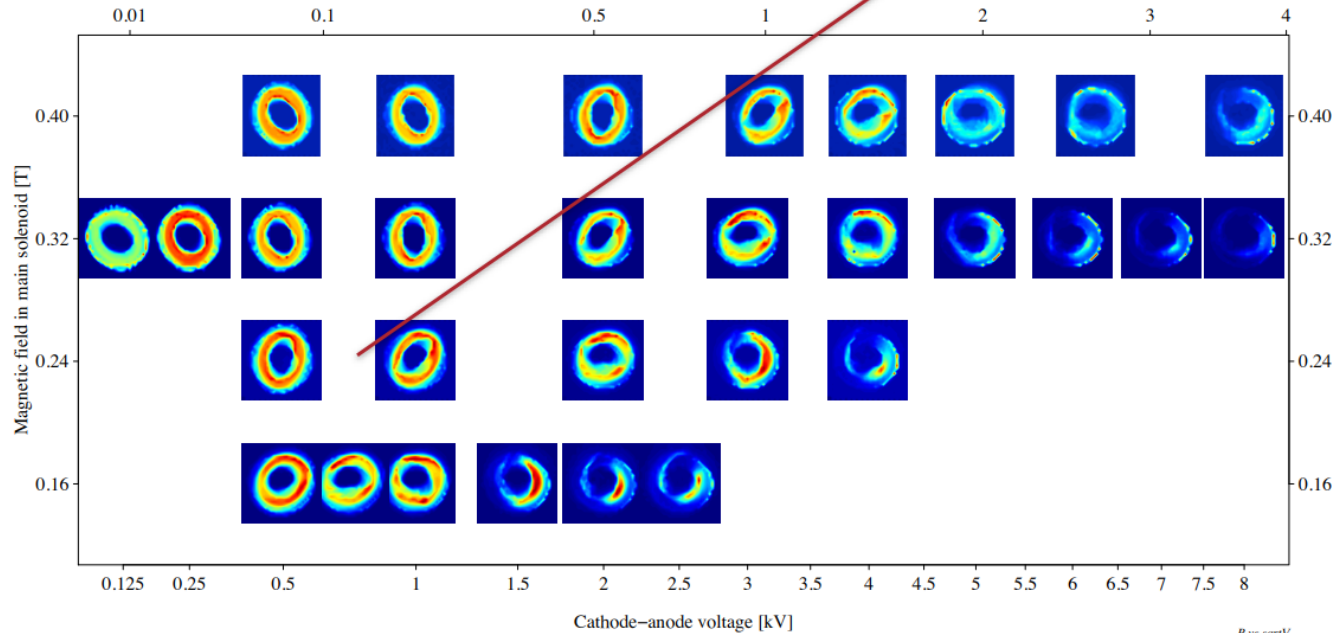
HG1B Ø25 cathode – Ø63 chamber

1-in hollow gun (HG1b)

Peak collector current [A]

Scaling of profiles

$$\approx \sqrt{V}/B$$



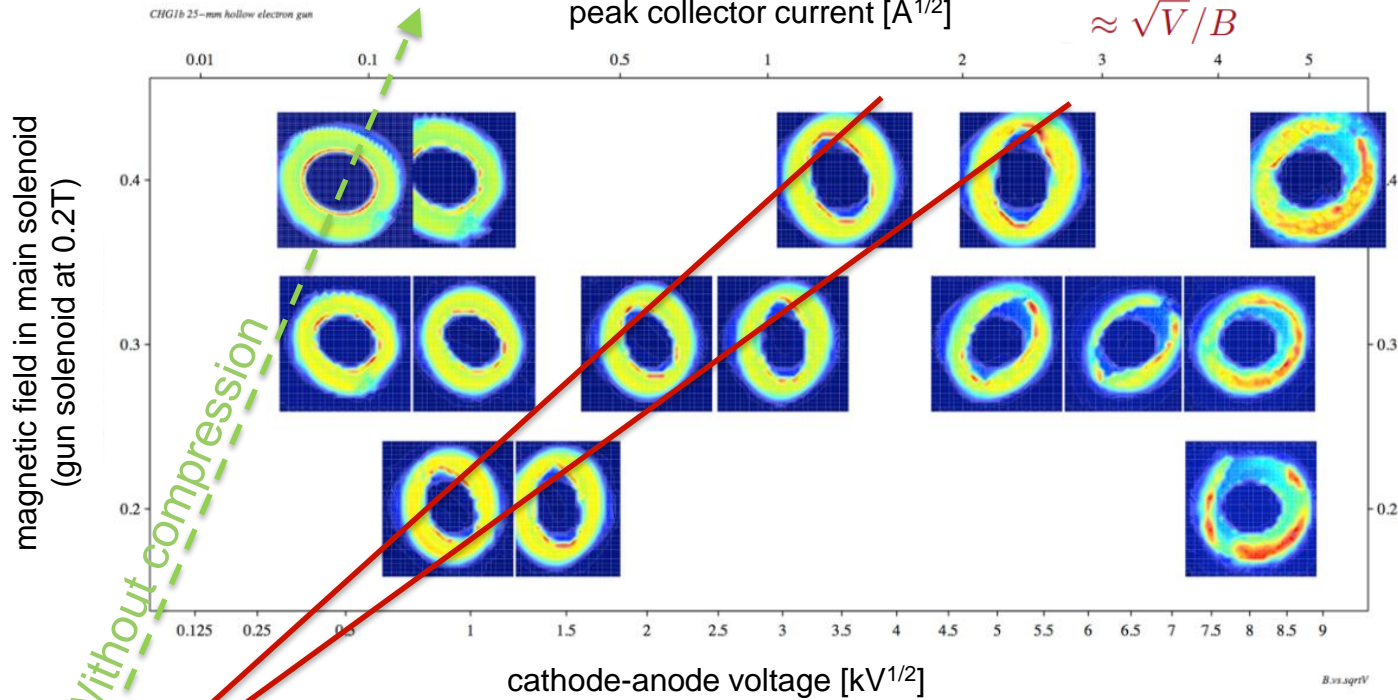
B vs. sqrt(V)



CHG1B Ø25 cathode – Ø63 chamber

Scaling of profiles

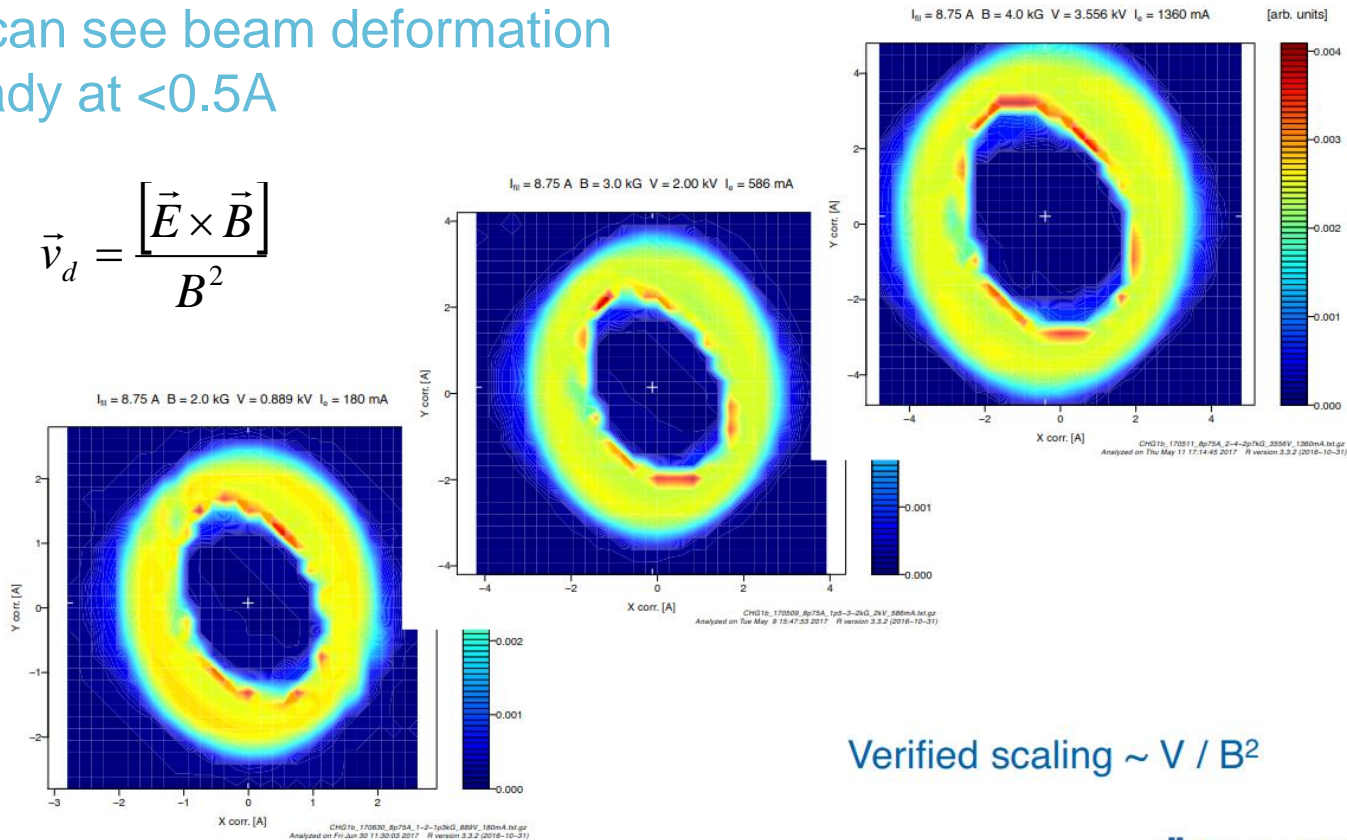
$$\approx \sqrt{V}/B$$





We can see beam deformation already at <0.5A

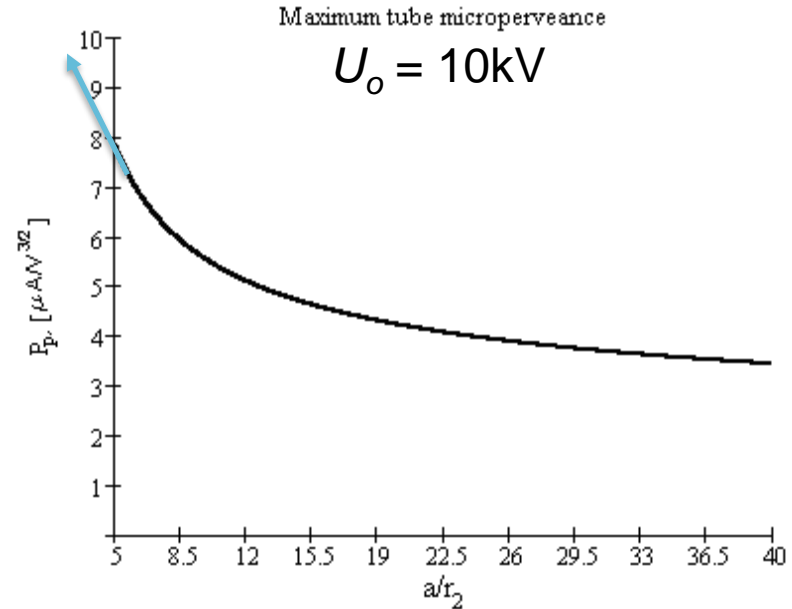
$$\vec{v}_d = \frac{[\vec{E} \times \vec{B}]}{B^2}$$



Verified scaling $\sim V / B^2$

Main differences with HEL

- Ratio between the pipe and beam size is ~ 3
→ pipe perveance $\sim 10A$
- Uniform pipe \emptyset
- No bends (we cannot see effect of drifts due to $B \times \text{grad}B$)



Test facility at CERN (1)

- Foreseen for ARIES studies WP16 – **Intense, RF modulated E-beams (IRME)**
 - Design and build a test stand for testing this gun including instrumentation suitable for measuring the transverse and longitudinal profiles of the RF modulated electron beam
 - Measure the properties of the RF modulated electron beam created by the gun using this test stand

Space Charge Compensation for the ion beam at the Heavy Ion Synchrotron SIS18 (to be used as injector to SIS100) → transversally and longitudinally matched e-beam of 50x70mm oval, 5(average)-10(peak) A, 22kV

Test facility at CERN (2)

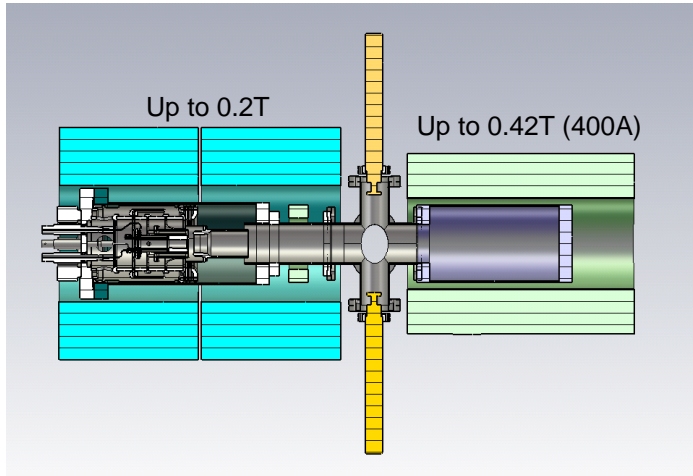
- Foreseen to test high intensity e-gun for **Beam-Beam Long Range compensation**
 - Few mm round e-beam, up to 20A, 20-35kV
 - Modulated at 40MHz for bunch by bunch
 - Could be modulated at 4MHz (**102nd HiLumi WP2 Meeting** <https://indico.cern.ch/event/662031/>)
- If **HEL** becomes baseline **tests at CERN**
 - beam instrumentation, modulators, interlocks,
 - understanding safety and technical aspects of e-lenses operation
 - preparation infrastructure for test and commissioning of components of HEL@LHC

Test-stand development at CERN:



Example of diagnostic box at RHIC e-lenses

Basic configuration – stage 1



Gun solenoid (twins), collector solenoid, diagnostic box (pin-hole Faraday cup + YAG screen monitor), HV system.



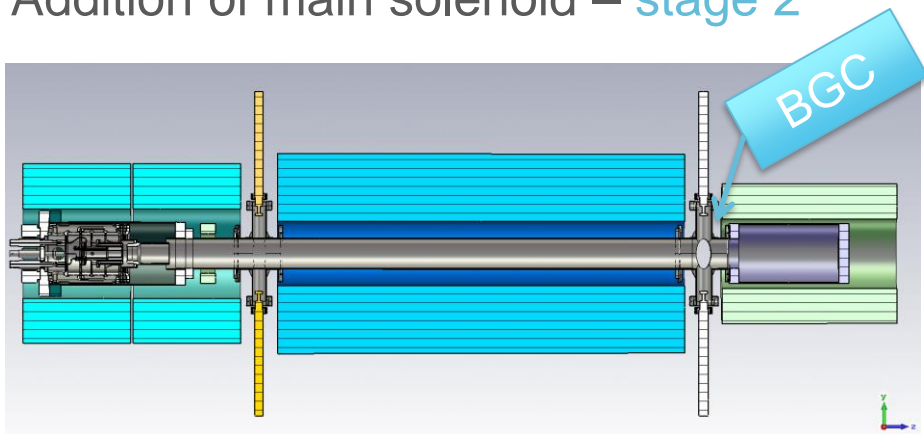
magnets at CERN

Purpose of this stage:

- Preparation:
 - Commissioning diagnostic procedures (current, profile, position)
 - Commissioning HV system
 - Safety and technical aspects of operation
- Electron gun tests: characterization & simulations
- Design diagnostic box
- Tests with Beam Gas Curtain monitor

Test-stand development at CERN. Upgrade

Addition of main solenoid – stage 2



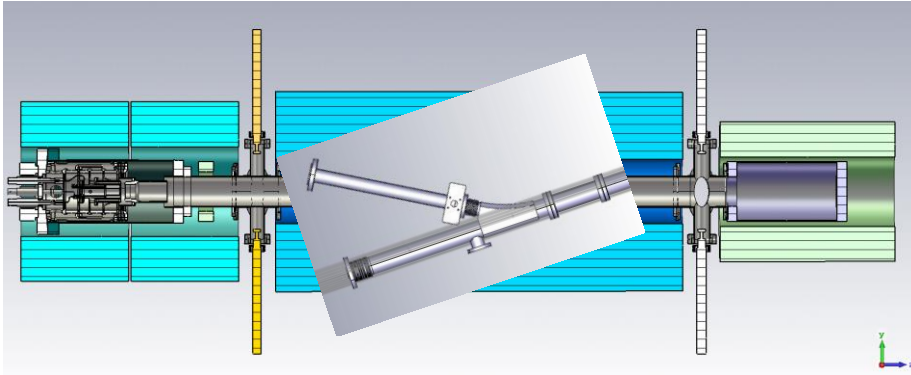
Main solenoid could be 0.4-0.5Tx1m or higher (in the latter case a dry SC solenoid may be cheaper and would expand range of investigation)

Purpose of this stage:

- Allow drift and see beam deformations/rotations/...
- Test Beam Position Monitor 'shoe-box' or stripline type with very HF modulation
- Test effect of very HF modulation (%current) on beam dynamics (microbunching?)
- Study electron beam dynamics in regime close to virtual cathode
- Computer model validation
- Study electron beam dynamics with compression (need at least 1-2T field)

Test-stand development at CERN. The future!

Addition a bend – stage 3



Purpose of this stage:

- Measure effect of $B \times \text{grad}B$ on deformation of beam with high current density
- Computer model validation

Summary

- Electron Lenses are currently studied at CERN for HEL and LRBB (HOBB?)
- HEL is being proposed as baseline to HL-LHC (IR4), studies to find 'working' e-beam parameters are ongoing.
- A test stand at CERN will allow:
 - Studying/characterisation e-lenses's modules:
 - E-gun (5A DC - 20A DC),
 - Modulator of electron beam
 - Beam diagnostics: profile, position, ...
 - Prototype of collector
 - * Compatibility with elliptical beams
 - Investigate electron dynamics
 - Testing computer models and studying beam dynamics
 - UltraSAM, Trak, CST, WARP
 - LHC e-lenses simulation
 - Understanding safety and technical aspects of e-lenses operation
 - Software control (correctors, etc.)
 - Interlocks
 - Preparation infrastructure for test and commissioning of components of HEL@LHC



Thank you

*Many thanks to Diego Perini, Stefano Redaelli, Giorgia Gobbi,
Carlo Zanoni*



Beam-Beam long range

$$D\{x', y'\} = -\frac{2N_p r_p}{g} \frac{\{X, Y\}}{X^2 + Y^2} \left(1 - e^{-\frac{X^2 + Y^2}{2s^2}} \right)$$

$$\Delta r' = -\frac{B_w L_w}{(B\rho)}$$

$$B_w = \frac{\mu_0 I_w}{2\pi r}$$

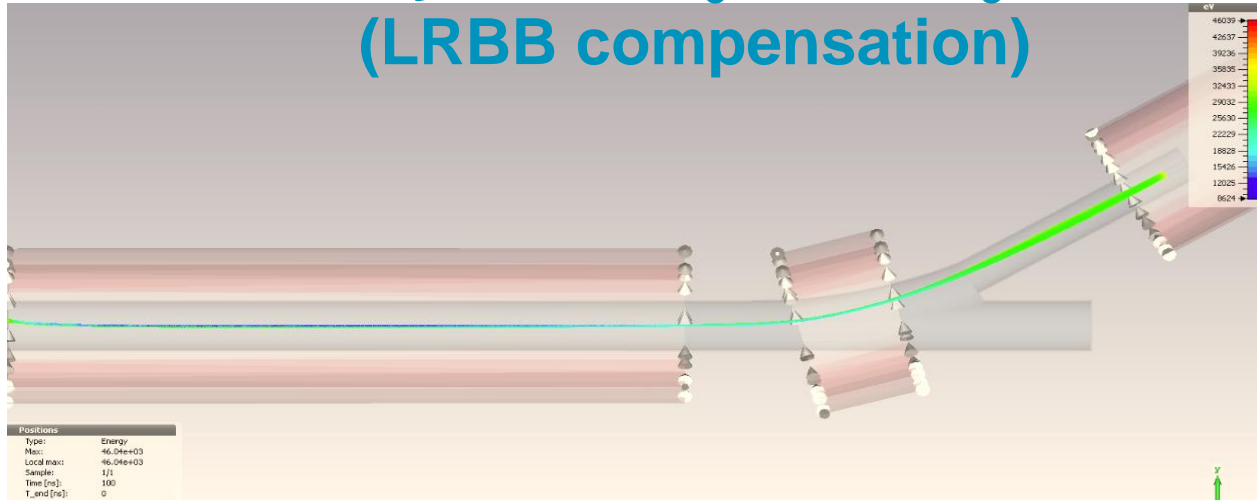
wire

$$X = x + x_w, \quad Y = y + y_w$$

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

E-lens

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



- Minimum potential = 35kV
- Due to the compression ($v \times B$) and asymmetry of vacuum chamber at insertion, the beam potential is decreased and becomes also asymmetric with particles at different velocities
- Alternatives are being studied + effects on LRBB compensations

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

Attempt to symmetrized vacuum chamber

Transverse beam space

