BGC as profile diagnostics for Electron Lenses in HL-LHC (Halo Depletion and Beam-Beam Long Range Compensation)

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Beam Gas Curtain Instrument Review – Cockcroft Institute – 27-28 June 2017

Outline

- Hollow Electron Lens motivations and principles
- HEL current design
- BGC requirements for HEL

- Long-Range Beam-Beam effect and ‘wire’ compensation
- LRBB compensation with electron lens
- Current design status
- BGC requirements for LRBB

- TIMELINE

LHC collimation challenge

- Large Hadron Collider: 27 km ring, designed to collide 7 TeV proton beams
- Huge stored beam energy per beam : 362 MJ for nominal configuration, 675 MJ for planned upgrade HL-LHC

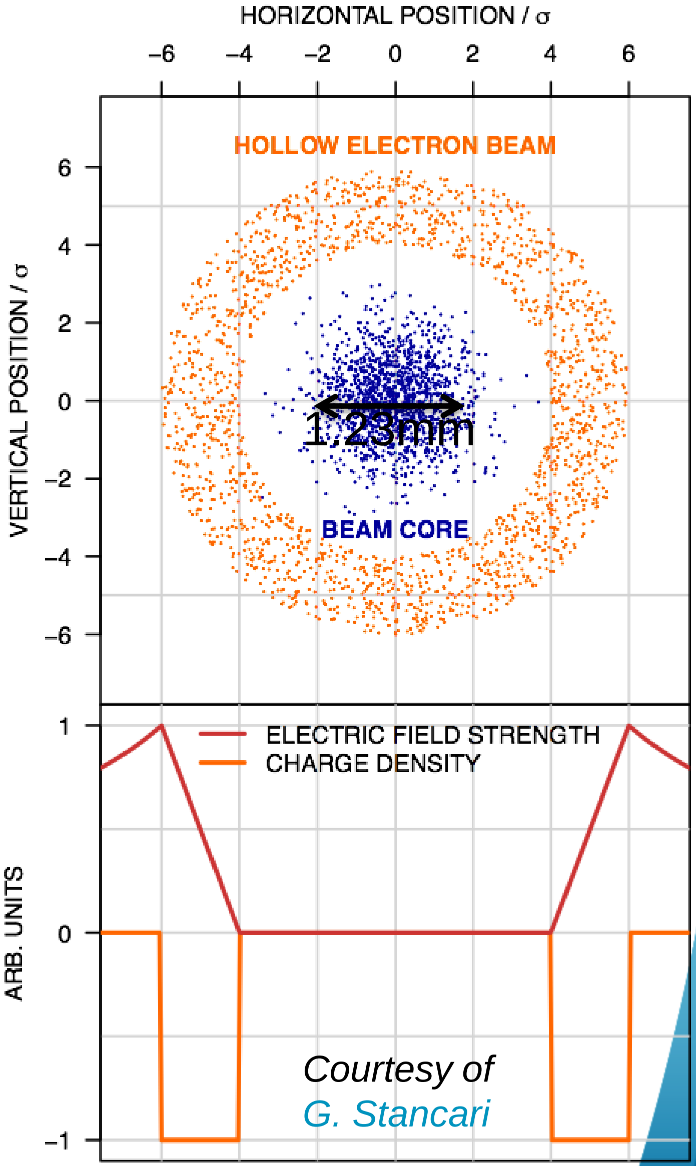
675 MJ = kinetic energy of USS Harry S. Truman cruising at 7 knots

- Beams could be highly destructive if not controlled well => collimation plays an essential role to prevent dangerous losses

Courtesy of
A. Bertarelli

Principle of hollow e-lens

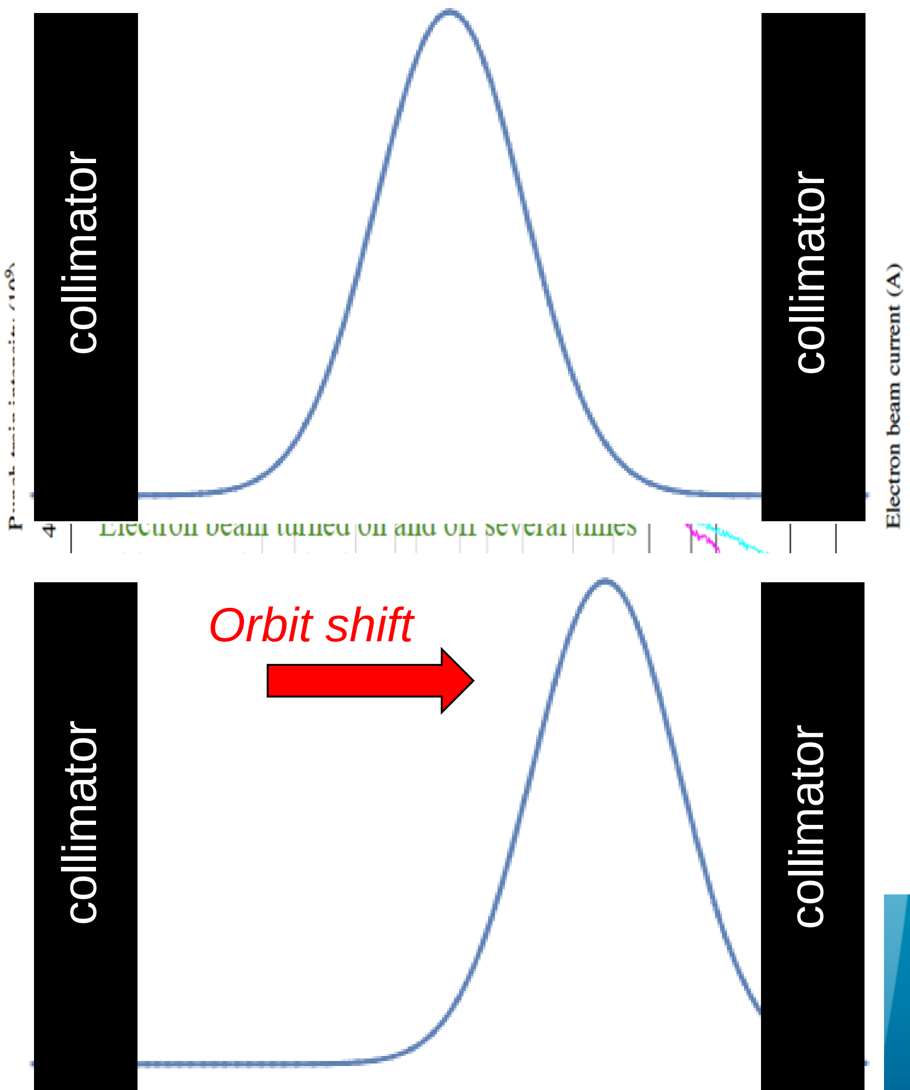
- Main beam travelling inside a hollow electron beam over a short distance (~3m), can act on the halo particles at transverse amplitudes below primary collimators
- Halo particles kicked to higher amplitudes by electromagnetic field of electron beam (slow process)
- Axisymmetric electron beam hollow =>
  core not affected (in field-free region)
  + no effects on impedance



1σ≈3.06μm

Review of the need for hollow e-lenses for the HL-LHC (CERN, 6-7 October 2016)

- https://indico.cern.ch/event/5678
- Successfully demonstrated at Tevatron (Stancari et al.)
- Review conclusions:
  - A hollow e-lens will mitigate CC failures (large betatron oscillations) if < 1 to 2 σ
  - HL-LHC less sensitive to transients due to small variations of orbit, tune and other parameters
  - **Implement active beam halo control using a hollow e-lens**



Required parameters

- Kick given by electron lens

+ counter, − co-propagating

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

$$r = r_{egun} \sqrt{\frac{B_{egun}}{B_{main}}}$$

- Keeping the Tevatron hardware, kicks given to protons would be factor ~7 less from magnetic rigidity
  - Increase electron current to compensate (or length – less attractive)
- Halo removal rate depends not only on kick but also on lattice non-linearities
  - Simulations (LifeTrack and SixTrack) demonstrate desired halo depletion with 5A current and stochastic excitation mode

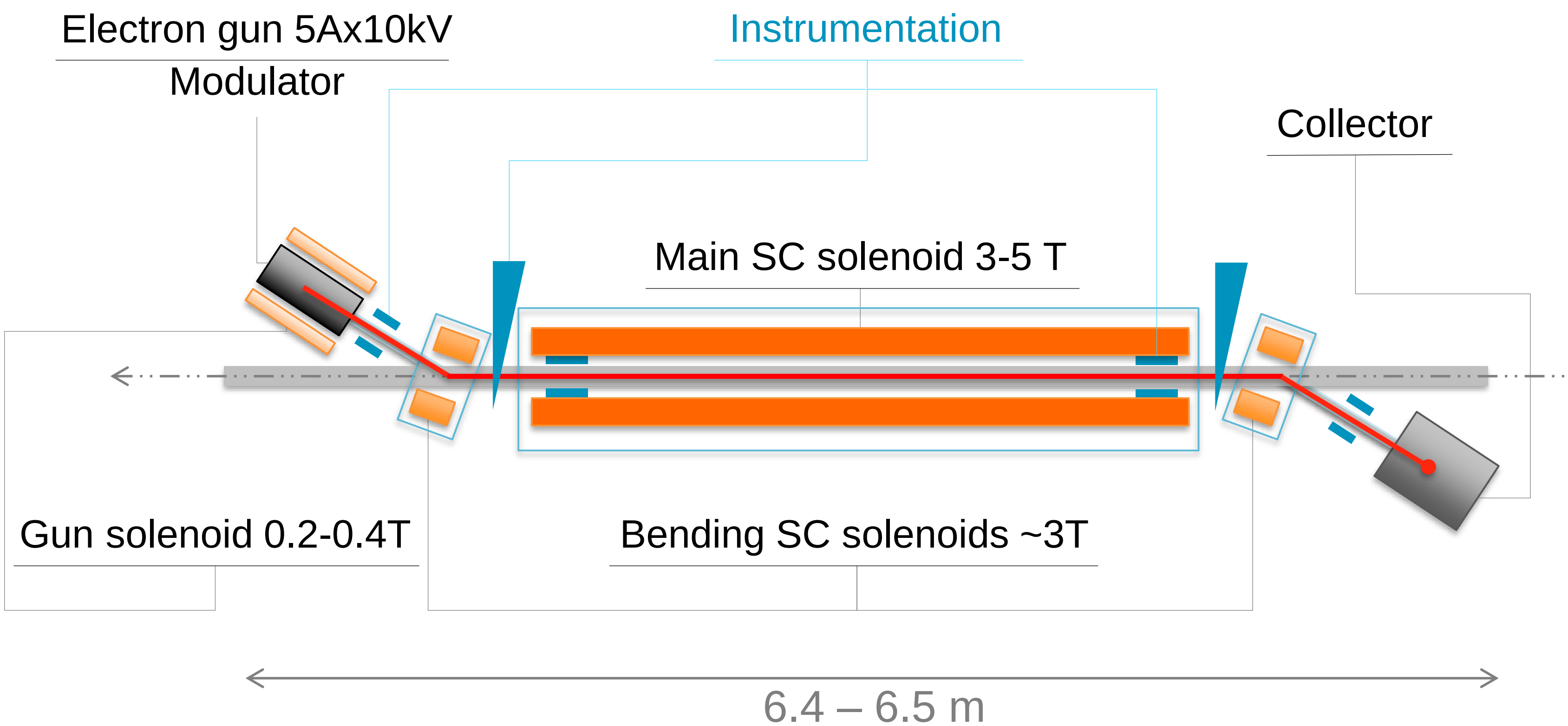
A. Valishev, FERMILAB-TM-2584-AP (2014)

- 10kV to transport through the e-lens structure

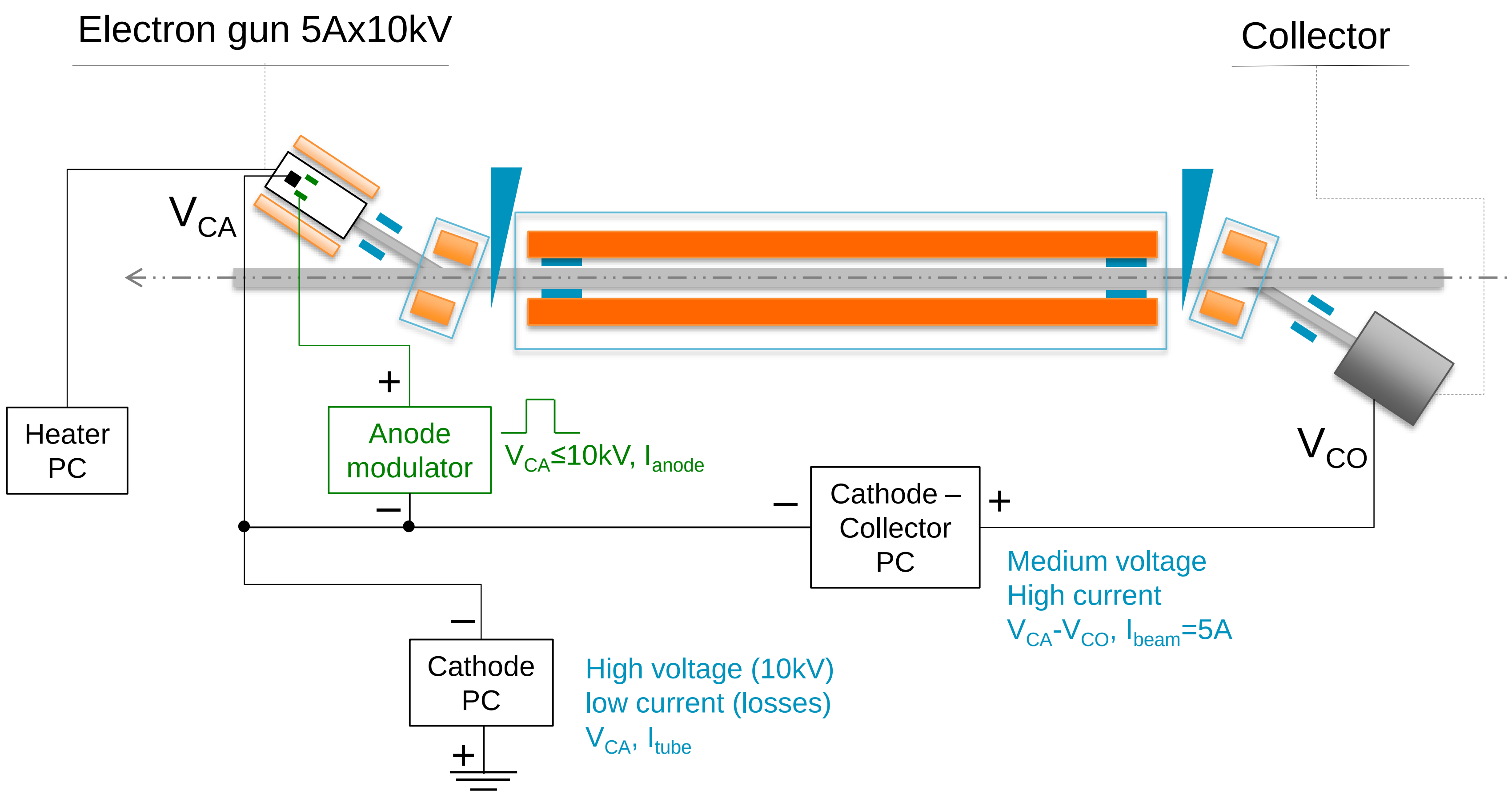
Instrumentation

- Need to monitor position of electron beam and proton beam
  - Requirement: ~ 30 µm accuracy (0.1 σ of proton beam), time resolution of 1 ns (protons) and 100 ns (electrons).
- Need to monitor electron current at cathode and collector
- Need to monitor electron beam profile
  - Requirement: $d_{4\sigma} \approx 6.93$ mm and $d_{6\sigma} \approx 10.4$ mm
    ~ 48÷50µm resolution
- Sensitive loss monitors can be placed downstream
- In addition: need halo monitor for the LHC proton beam to study population in various scenarios, independently of e-lens

Hollow Electron Lens

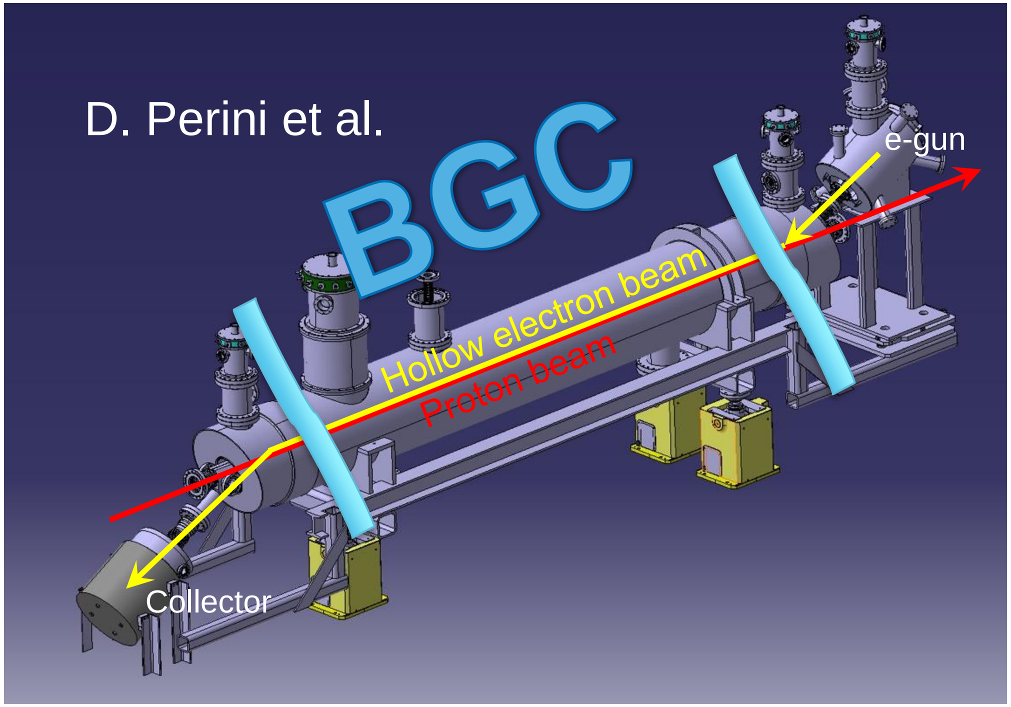


Hollow Electron Lens



Technical design

- S-shaped to compensate for the asymmetric electron beam distributions seen by the main beam
- Gun and collector stick out in vertical plane to fit in LHC tunnel



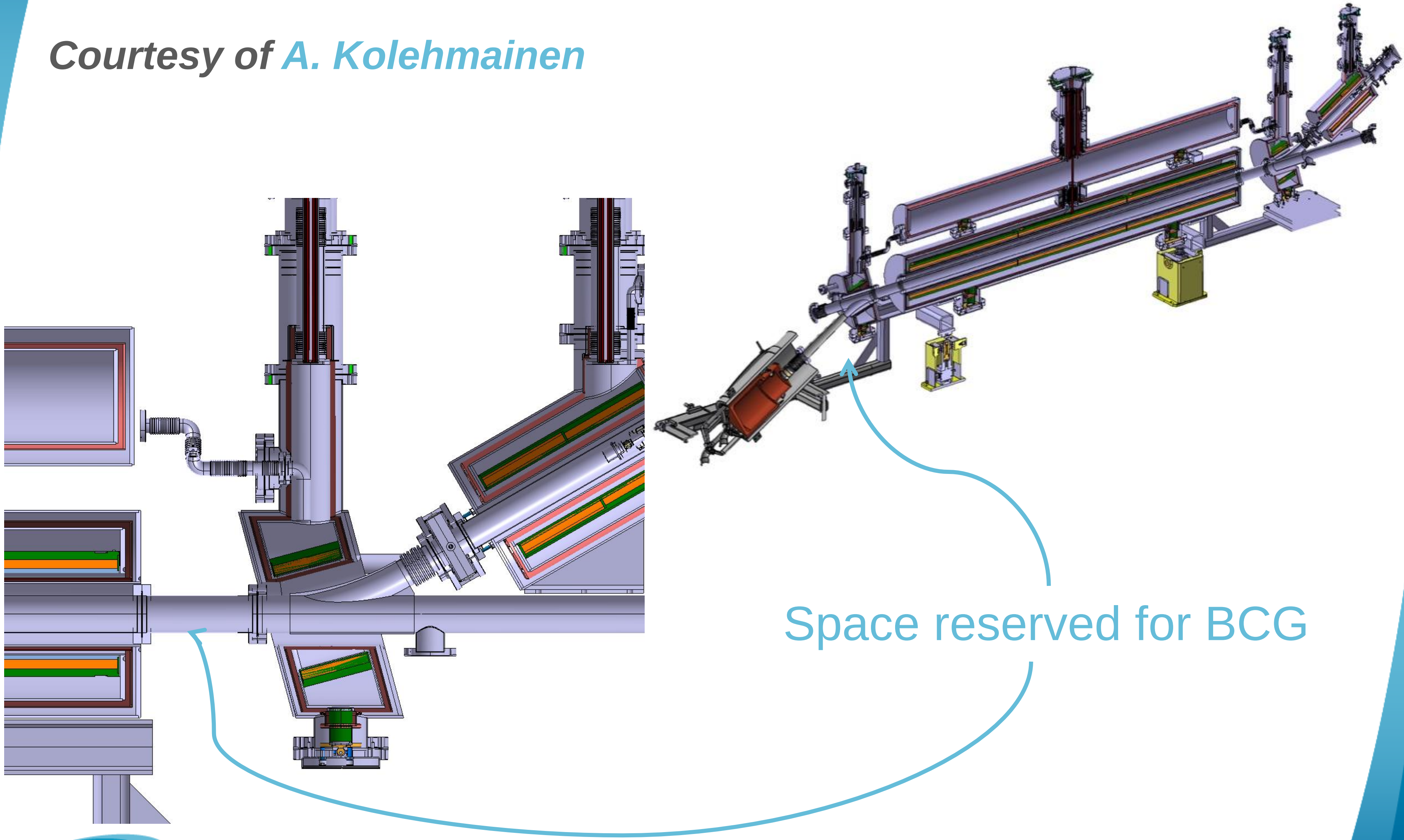
Candidate locations for the electron lenses are RB-44 and RB-46 at Point 4, on each side of the interaction region IR4.

The beam to beam distance is 420 mm.
The longitudinal available space is limited

- Proton beam ~ round

Technical design

Courtesy of A. Kolehmainen

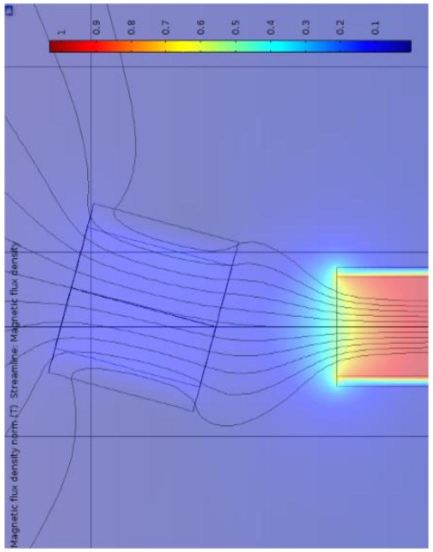


BGC requirements for HEL

- Proton beam (±2σ) ~ 1.23 mm
  - ~ 30 µm resolution (0.1 σ of proton beam)
- Electron beam (from 4 to 6σ)
  - $d_{4\sigma} \approx$ 6.93 mm and $d_{6\sigma} \approx$ 10.4 mm

    @ 0.5T in the gap

    ~ 48÷50µm resolution



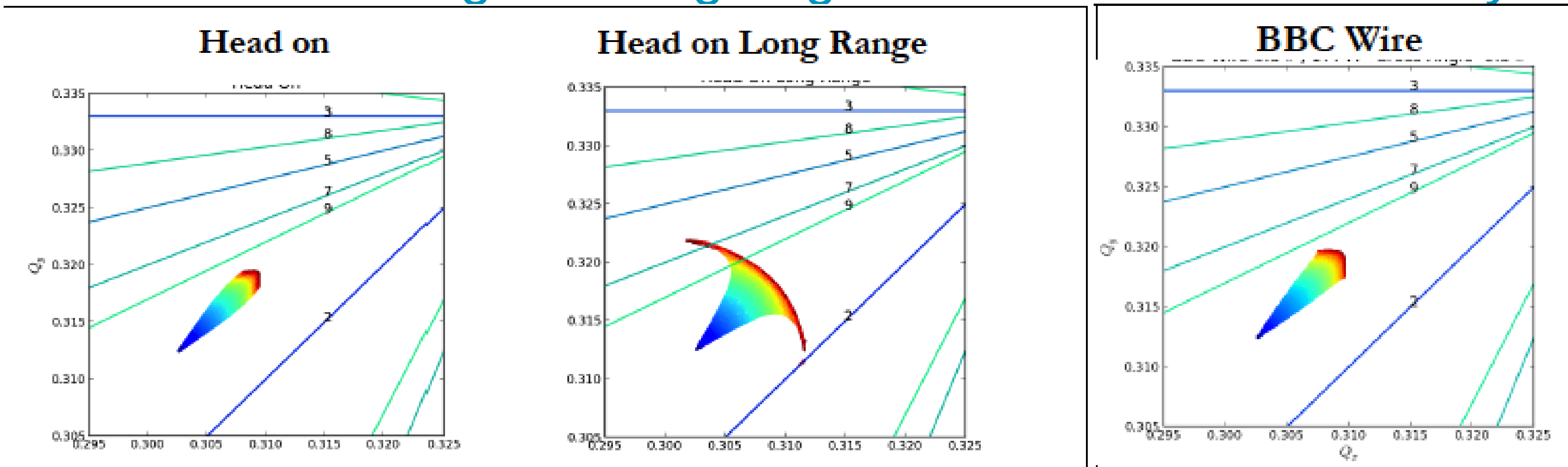
- Low impedance for p+ beam
- As smooth as possible for e- beam (see later LRBB)

Timeline

- October 2017: Conceptual readiness review
- Test stand at CERN 2018?
- LS2 (end 2018) Technical Design Report
- LS3 (end 2023) Installation

Long-Range Beam-Beam

- LRBB interactions limit accelerator performance
  - perturb motion at large betatron amplitudes, where particles come close to opposing beam
  - produce beam blow-up and deterioration of beam lifetime
  - causes amplitude dependent detuning
  - limit closing crossing angle and therefore luminosity



Tune spread by T. Rijoff

LRBB Wire compensation

- Beam-beam (LR) kick (round Gaussian beams + crossing in both planes)

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

≈1 for large separation

with (beam separation)

$$\Rightarrow X = x + x_c \quad , \quad Y = y + y_c$$

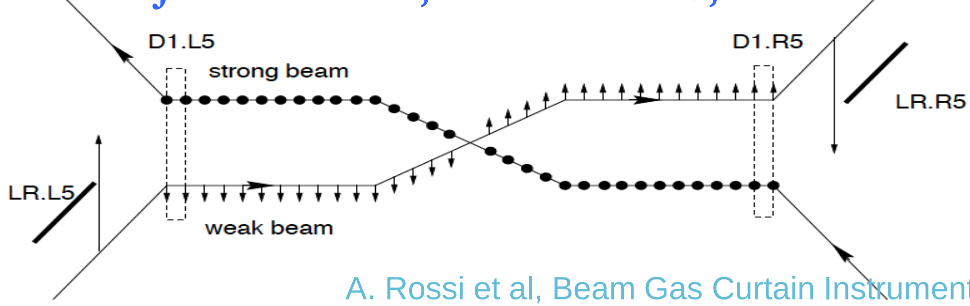
- Can be approximated by an "infinite" wire

$$\Delta\{x',y'\}_w = -\frac{\mu_0}{2\pi}\frac{I_w L_w}{B\rho}\frac{\{X_w,Y_w\}}{X_w^2+Y_w^2}$$

wire separation

$$\Rightarrow X_w = x + x_w \quad , \quad Y_w = y + y_w$$

J.P.Koutchouk, LHC Note 223, 2000



Courtesy of Y.Papaphilippou

LRBB compensation with e-lenses

- Total electron beam current @ HL-LHC for LRBB compensation *S.Fartoukh in PhysRevSTAB.18.121001*
  - $(I_w L_w)_{eq}$= 10.56Am per encounter ➔ ~ 200Am per IP side

$$\mathrm{D}r_w = - \frac{\mathrm{m}_0}{2\mathrm{p}} \frac{I_w L_w}{r_w} \frac{1}{B\mathrm{r}}$$

!

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

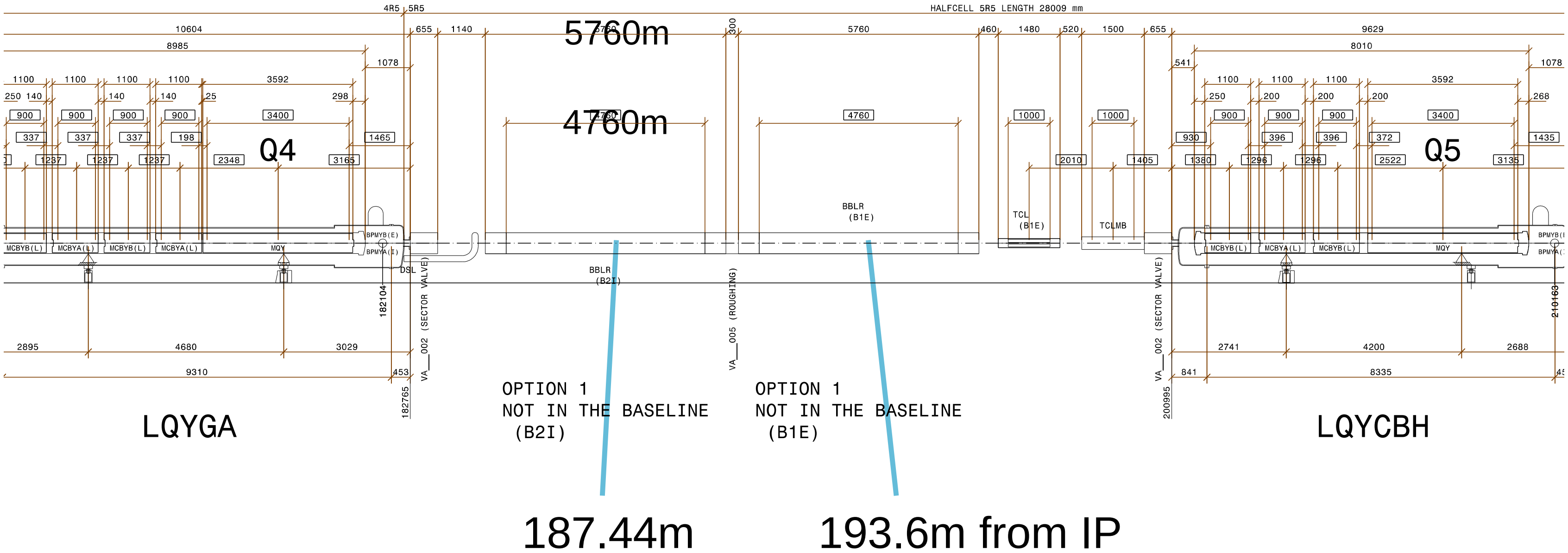
$$\beta_p \simeq 1, \qquad \frac{1+\beta_e}{\beta_e} = 4 \text{ to } 6$$

- Current assumption 20A e-beam x 3m length
- At an aspect beam ratio of $\frac{b_X}{b_Y}$ = 2 and ½.

Constraints from layout

- ~ optimal beam aspect ratio in matching section
- Beam inter-axis 194 mm

Current layout (latest from HL-WP15)



- Region getting shorter and crowded

Assumptions for e-lens simulations so far

- Proton beam dimension important only in the crossing plane
- For HL IP5 (reverse plane for IP1) B2, symmetric for B1

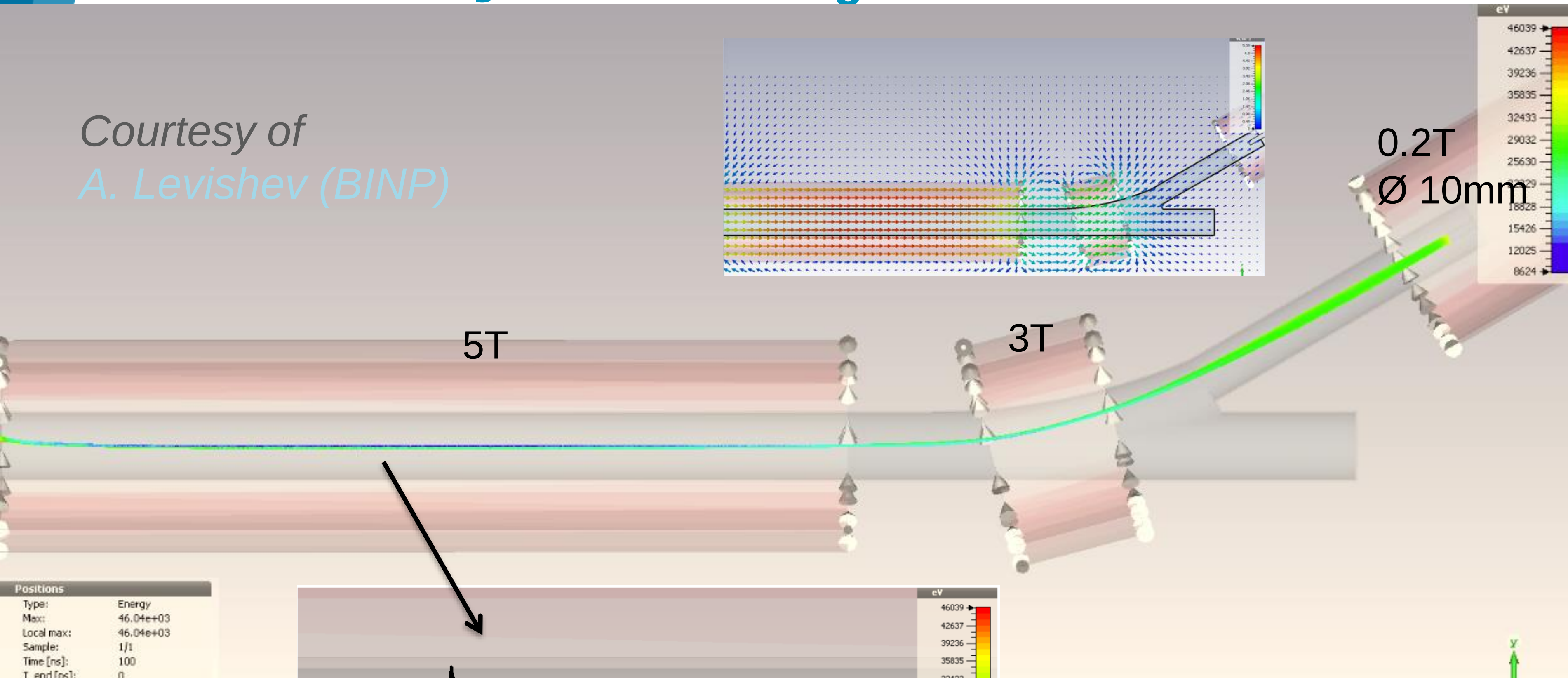
		β_x (m)	σ_x (mm)	β_y (m)	σ_y (mm)
Round	left	1000	0.58	2000	0.82
	right	2000	0.82	1000	0.58
Flat	left	500	0.41	4000	1.16
	right	1000	0.58	2000	0.82

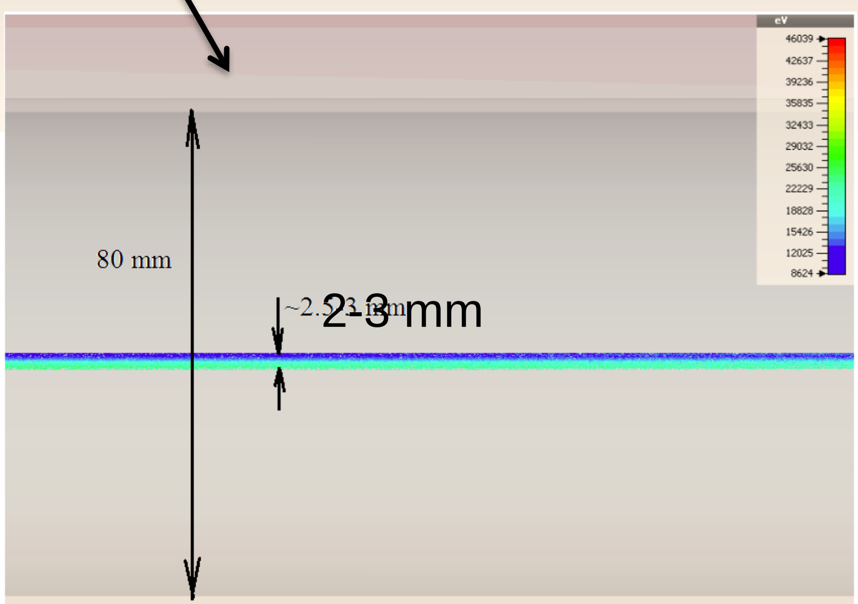
- In the simulations presented today by A. Levichev it was assumed an electron beam of Ø 2 mm given space available if electron beam wire placed at 10 σ_x

HiLumi HL-LHC PROJECT

Beam dynamics I_e=20 A, V=35 kV

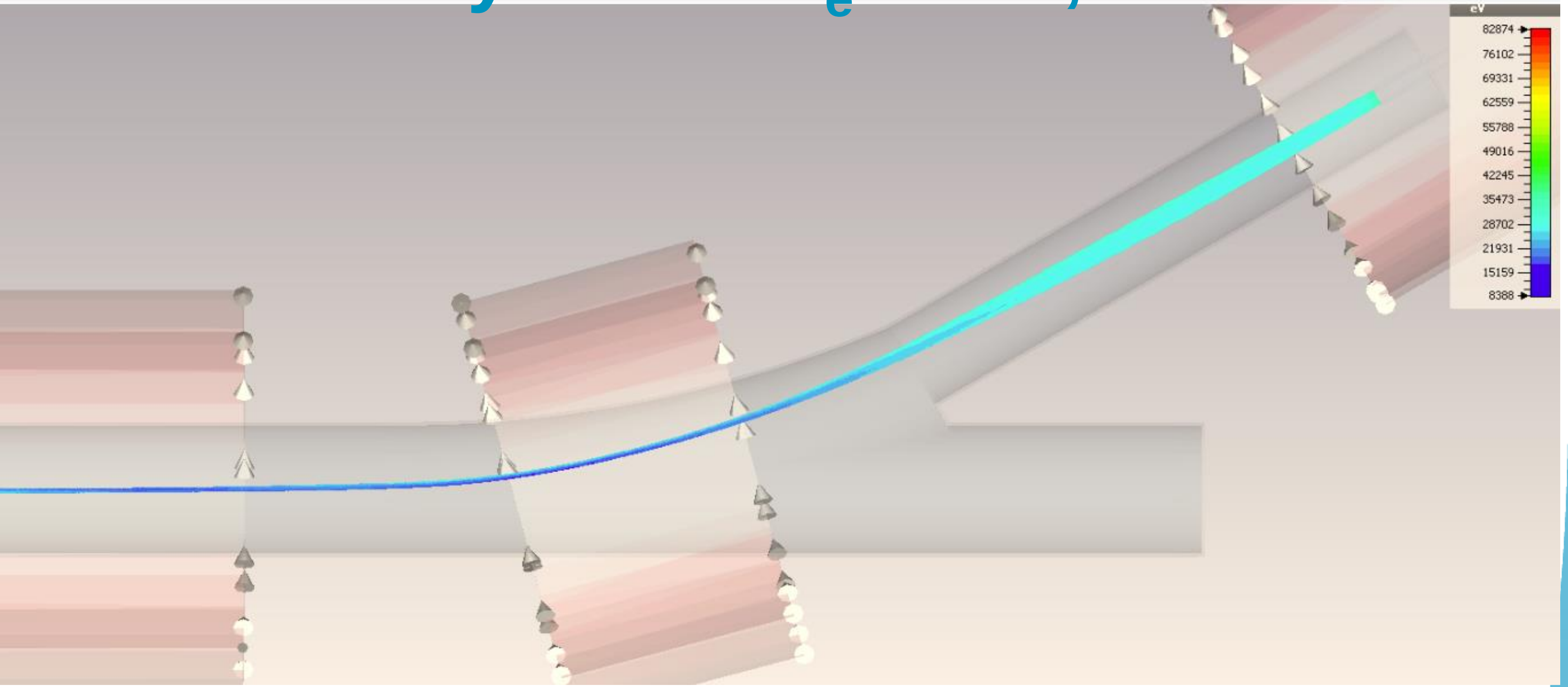
Courtesy of
A. Levishev (BINP)





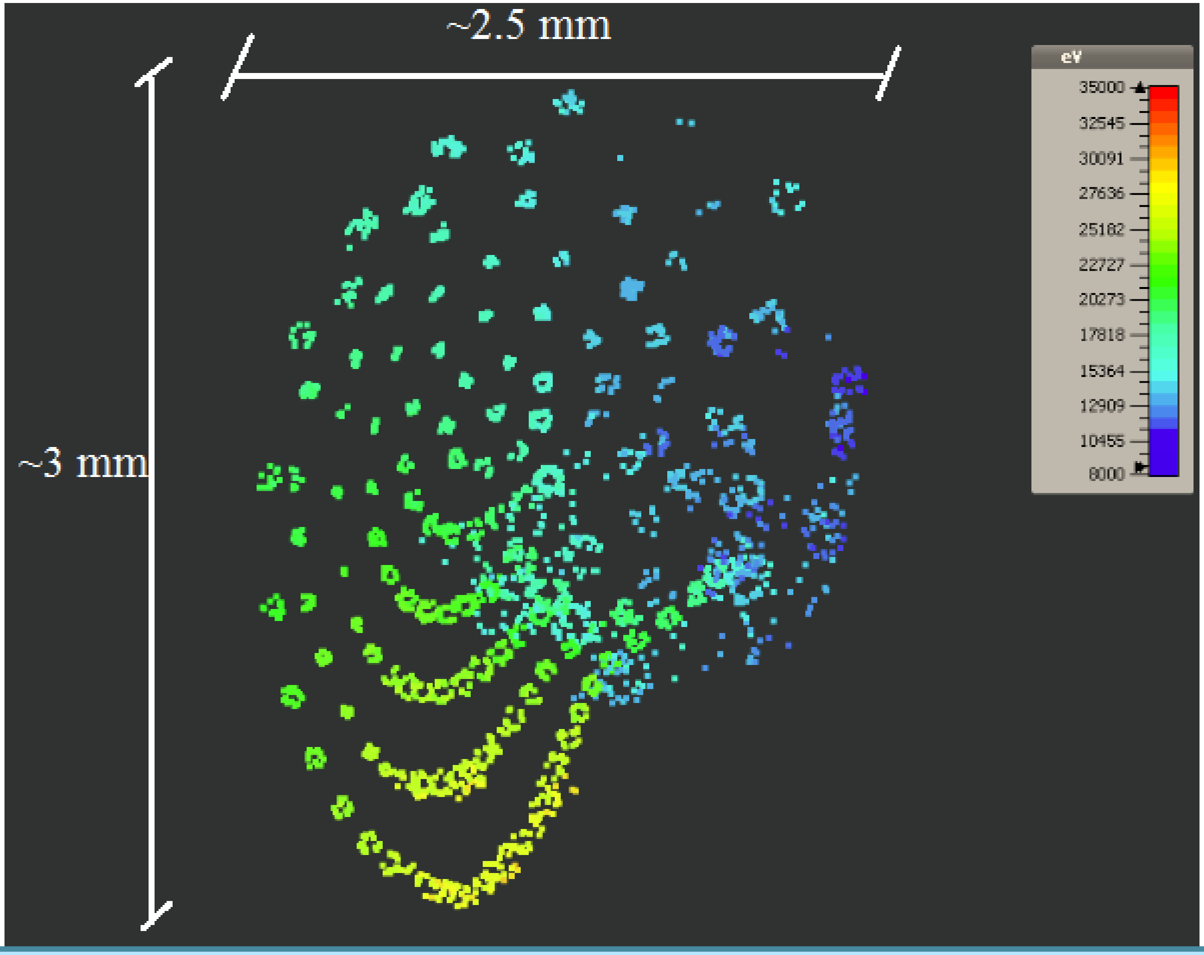
@ **35kV**, 20 A can propagates through the electron lens

Beam dynamics I_e=20 A, V=35 kV



e-beam potential decreases when the beam is compressed and injected into the p-beam vacuum chamber with large aperture of the bending solenoid. Due to the asymmetric vacuum chamber the beam potential becomes also asymmetric and particles get different velocities.

Beam dynamics I_e=20 A, V=35 kV: transverse beam

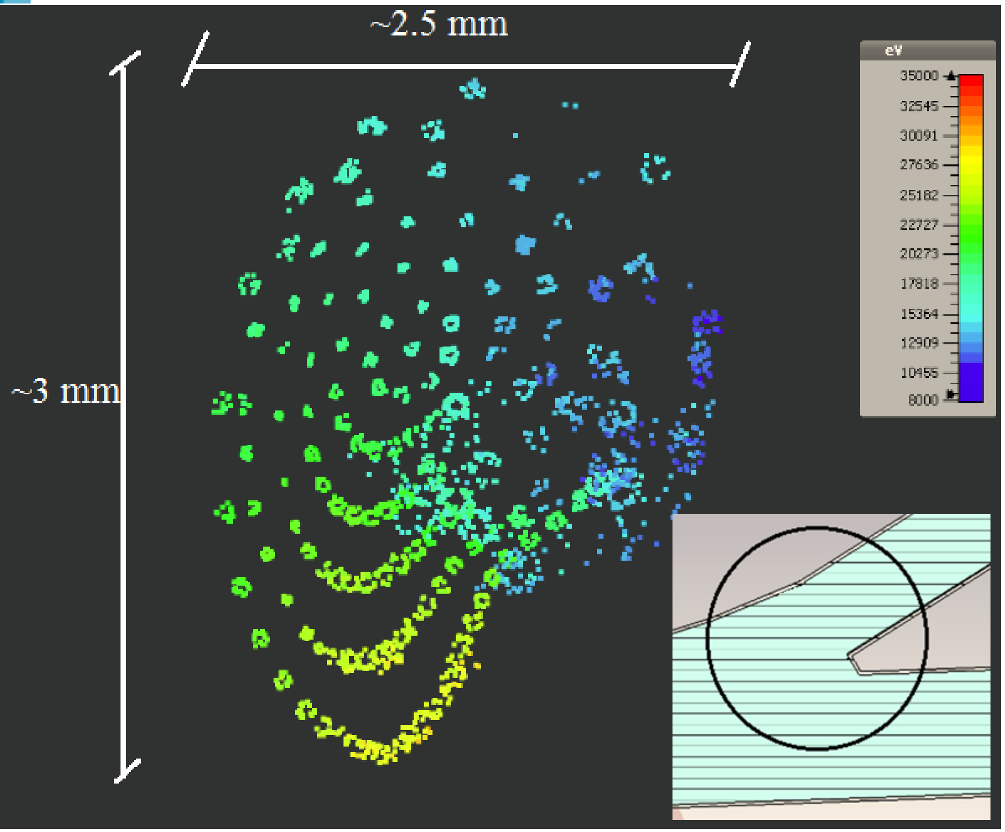


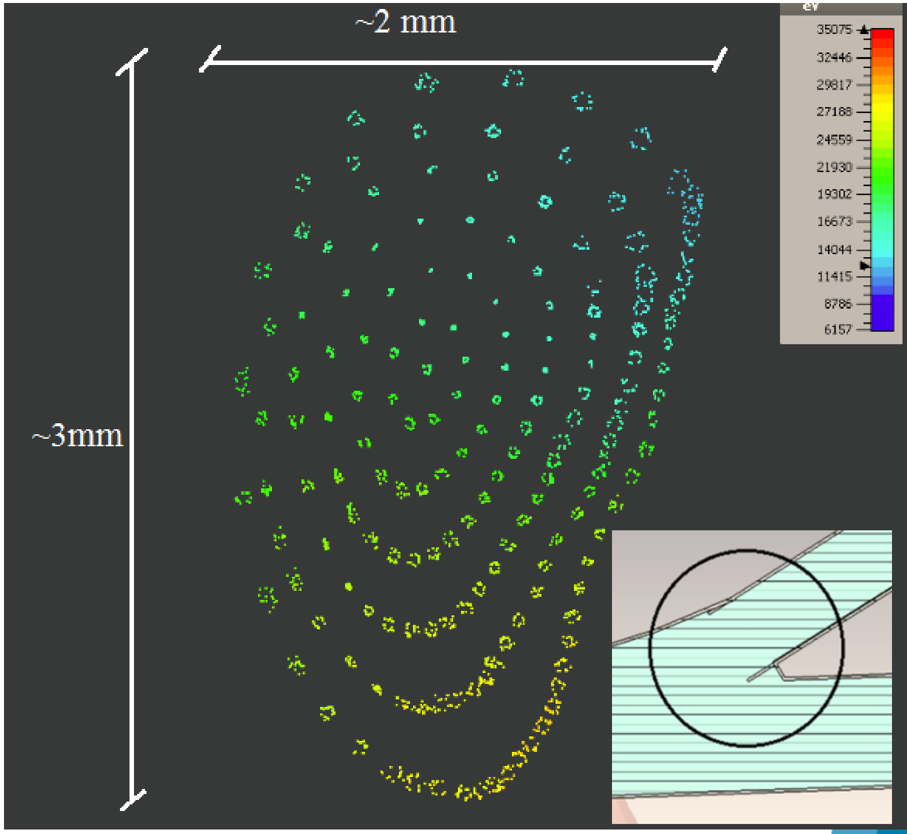
e-beam profile results asymmetric, due to asymmetric vacuum chamber. For particles with different potential the Lorenz radius are differed. Besides the individual particle rotation, due to the magnetic field on the cathode the beam is rotated as a whole and therefore the potential distribution along the radius changes with time.

Beam dynamics I_e=20 A, V=35 kV

Attempt to symmetrized vacuum chamber

Transverse beam space





BGC requirements for LRBB

- Proton beam (±2σ) ~ 2.8 mm
  - ~ 50 µm resolution (0.1 σ of proton beam)
- Electron beam smallest ~ 2mm,
  - ~ 50µm resolution
- Low impedance for p+ beam
- As smooth as possible for e- beam (see later LRBB)

Timeline

HEL

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BBLR

- 2017 first demonstration test with wire collimator
- 2018 new demonstration test

Conclusions

- BGC can be used as profile and overlap monitor for electron lenses in HL-LHC
- Design to be adapted for integration
- To be taken into account in next iterations:
  - Low impedance for proton beam
  - High perveance for electron beam

Thank you for your attention

Effect on halo distribution

- Controlled increase of diffusion speed of halo particles
- Still need existing collimators to absorb the extracted halo particles