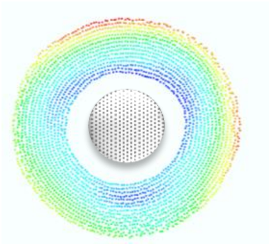
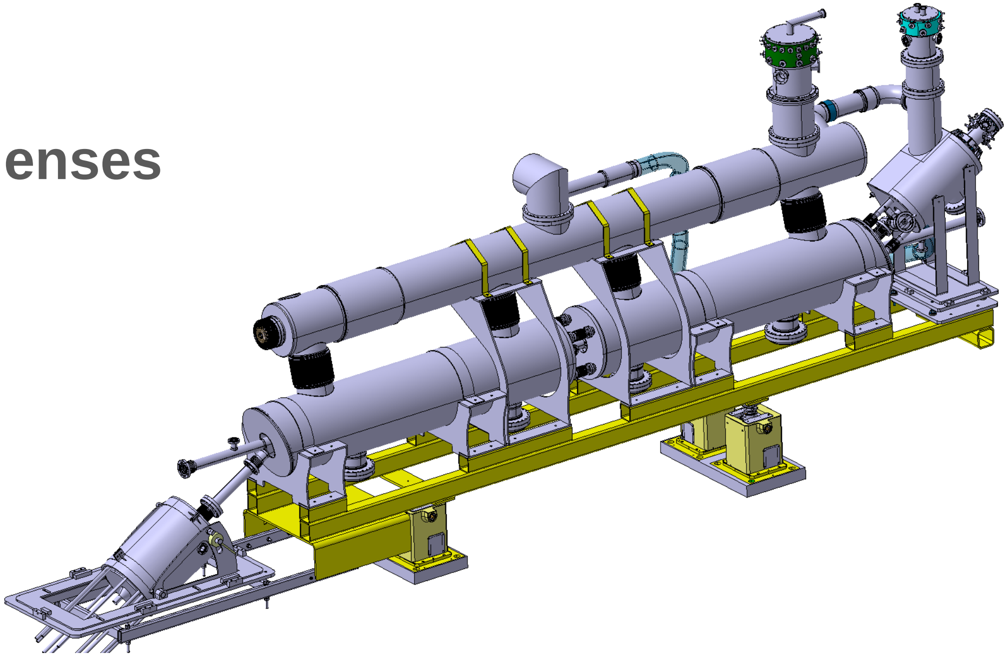
Review of hollow e-lenses





Acknowledgements:

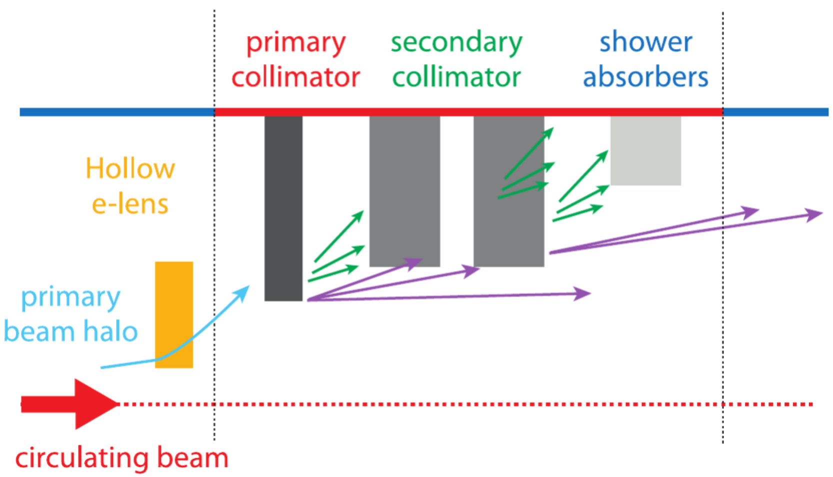
D. Perini, S. Redaelli, G. Gobbi, A. Kolehmainen, S. Sadovich – CERN

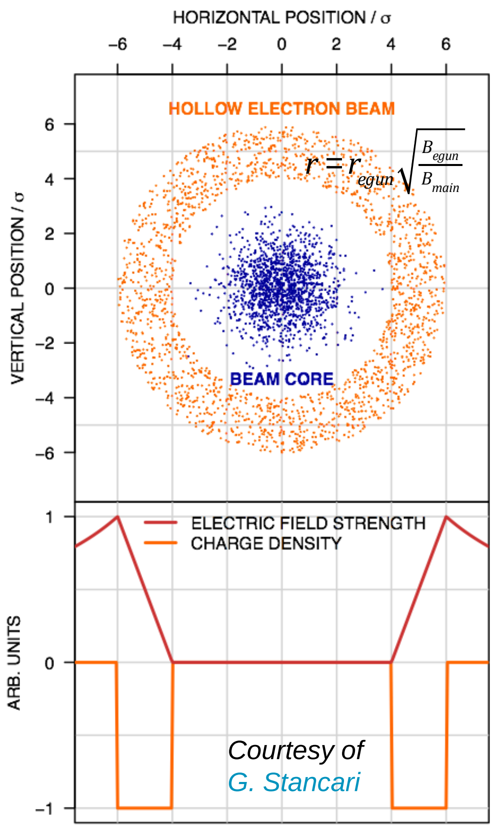
G. Stancari – FNAL

A. Levichev, M. Arsentyeva, A. Barnyakov, D. Nikiforov – BINP

Principle of Hollow Electron Lens

- Circulating beam travelling inside a hollow electron beam (cylindrical shell) over a short distance
- Halo particles kicked to higher amplitudes by electromagnetic field of electron beam (slow process)
- Eventually hit collimators





Courtesy of G. Stancari

- Circulating beam core not affected (in field-free region)

History and status

- First proposed for LHC in 2006 within CARE HHH [Vladimir Shiltsev]
- Initial LHC operation experience showed sharp loss spikes
  - additional motivation for e-lens as halo cleaner
- Operation experience in Run II show lower losses ⇒ need for electron-lens? ⇒ Review on the e-lens need for HL-LHC in 2016 @ CERN [chaired by Rüdiger Schmidt]
  - Strong recommendation to include e-lens for HL-LHC [≈ 35MJ stored beam energy in HL-LHC beam halo > 3σ]
- Study on technical design and preparation for integration into the HL-LHC baseline during 2016 and 2017 (encouraging comment from CMAC in 2017)
- Review on E-lens concept readiness for integration in the HL-LHC baseline in 2017 @ CERN [chaired by Wolfram Fischer]
- HL-LHC C&S review in 2018 supported the efforts by the project to integrate the HEL into its baseline and that the project is still working on a solution for financing the implementation within the fixed project budget

Motivations

General fill-by-fill overview

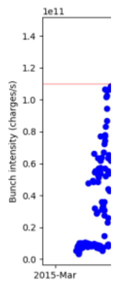
Total Intensity during Run 2 (2015 - 2018) at the START RAMP

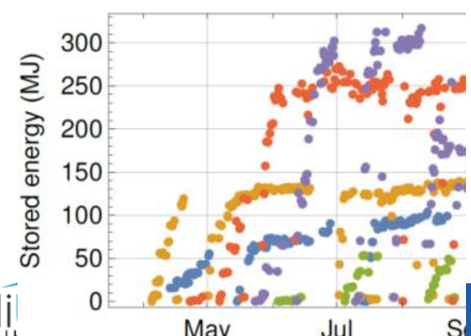
Reaching the 300MJ stored energy beginning 2017 and beginning 2018

Then lower to mitigate the 16L2

Bunch intensity during Run 2 at the STA

In **2018** with 2556 bunches at 1.1e11 p/b corresponding to **0.5 A of beam current**





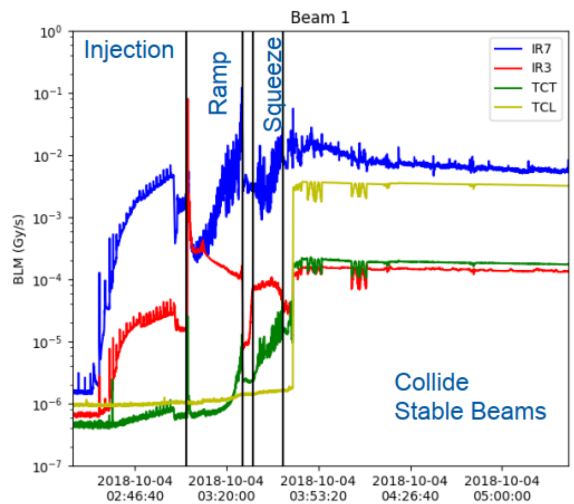
Losses during the cycle 2018

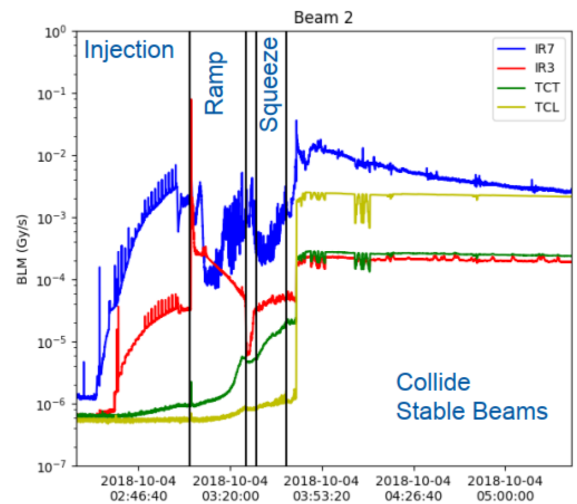
Standard Nominal fill in 2018 (fill number 7256)

Beam 1 and Beam 2 follow similar pattern, they are relatively low during run 2.

Beam 1 are on average higher than for Beam 2.

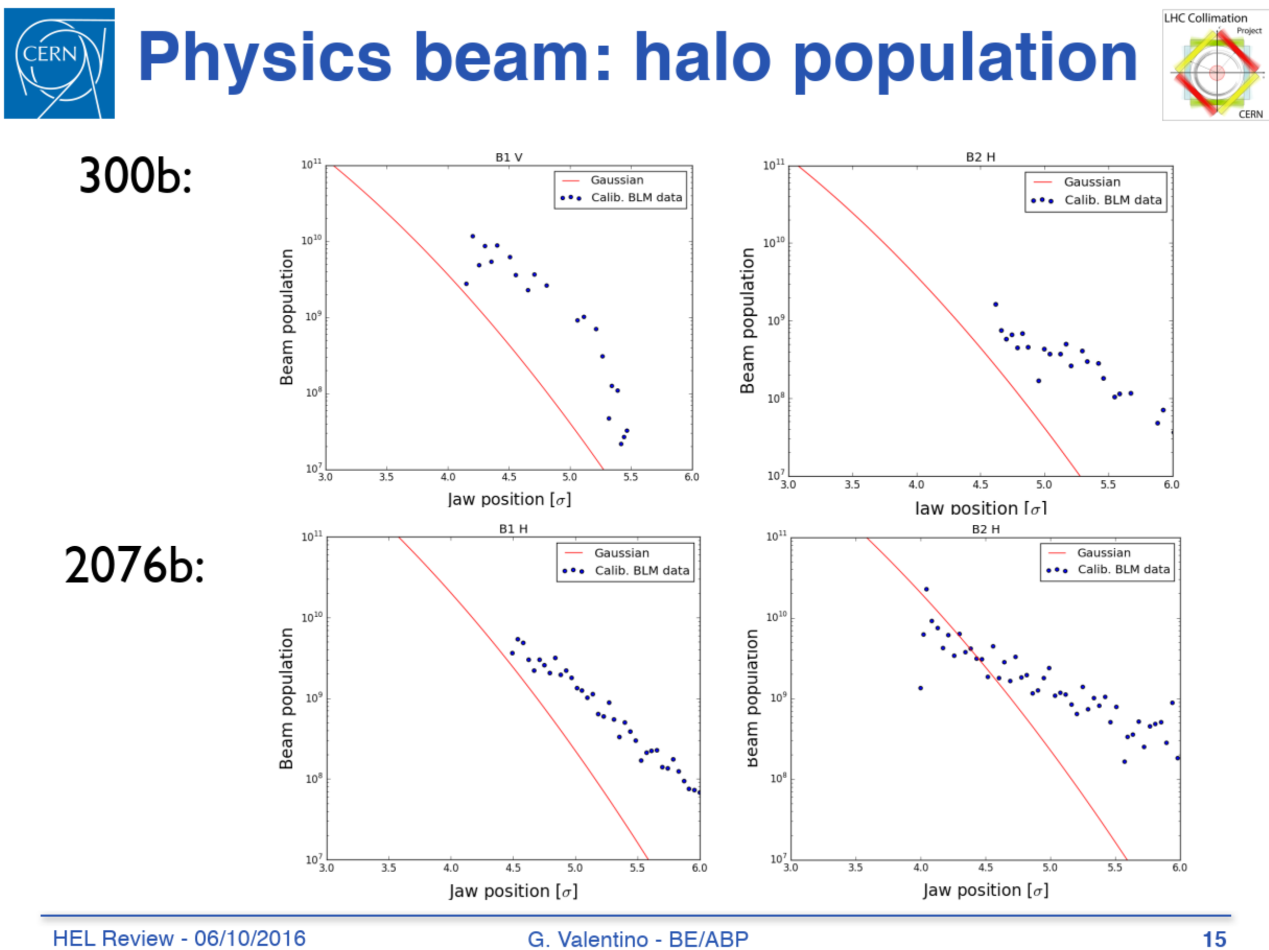
Very similar to previous years





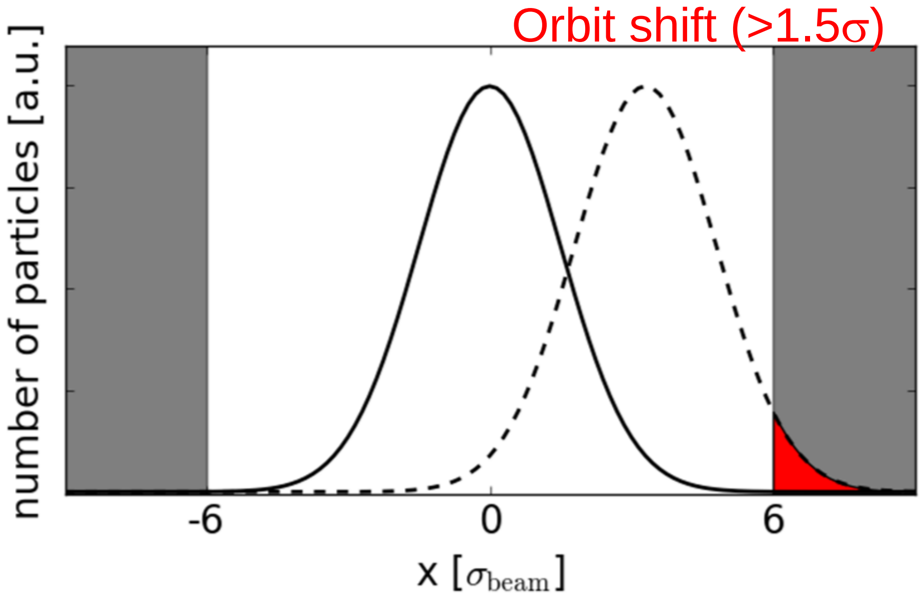
Motivations

- Around 5% of the beams is in the tails (> 3.5 sigma), compared to 0.22% for Gaussian
- Factor 22 difference: scaling to HL-LHC parameters = 33.6 MJ vs 1.48 MJ
- No apparent correlation with energy



Motivations

- Crab Cavity failure can induce fast (few turns) orbit shift or bunch rotation



- Small earthquakes (Geothermie2020)
- In 2012 and 2016 LHC operation sometimes sudden beam losses occurred => beam dumps in HL-LHC?
- Increase of operational margin (e.g. less sensitive to transients)

Summary by Gianluigi in 2016

- Halo control can open the way to tighter collimator settings and therefore reduced β^* with:
  - limited increases in integrated luminosity but a visible reduction on pile-up density
- For the HL-LHC nominal scenario we do not rely on tails for beam stabilization (as for the LHC) as experience tell us that they are not reproducible ➔ we rely on impedance reduction
- Halo control can provide more margin during all the operational phases and to handle ramp-up phases and configuration changes that inevitably HL-LHC will face.
- Synergies for other potential developments like long range and head on beam-beam compensation should be also considered

Issued raised at e-lens concept readiness review in 2017

- High current required from e-gun: shown possible with scandia-doped cathode (with prototype cathode measured at FNAL) *
- Change of cathode: possible with a valved-off volume and bake-out

- Aperture from 80 to 60 mm
- Change from 4 to 5 T main solenoid
- Accelerating field from 10 to 15 kV

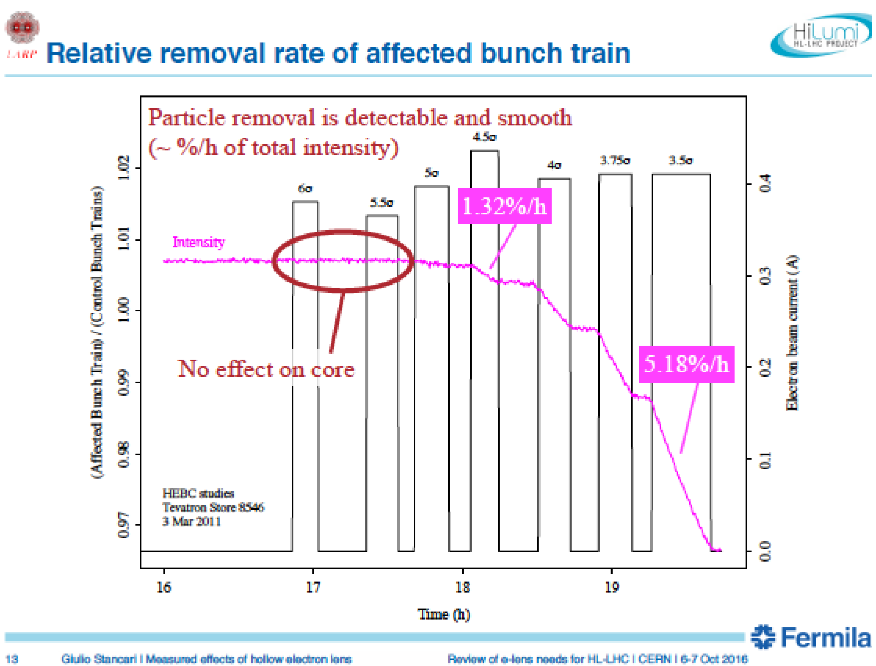
→ included in the design
→ proven with simulations

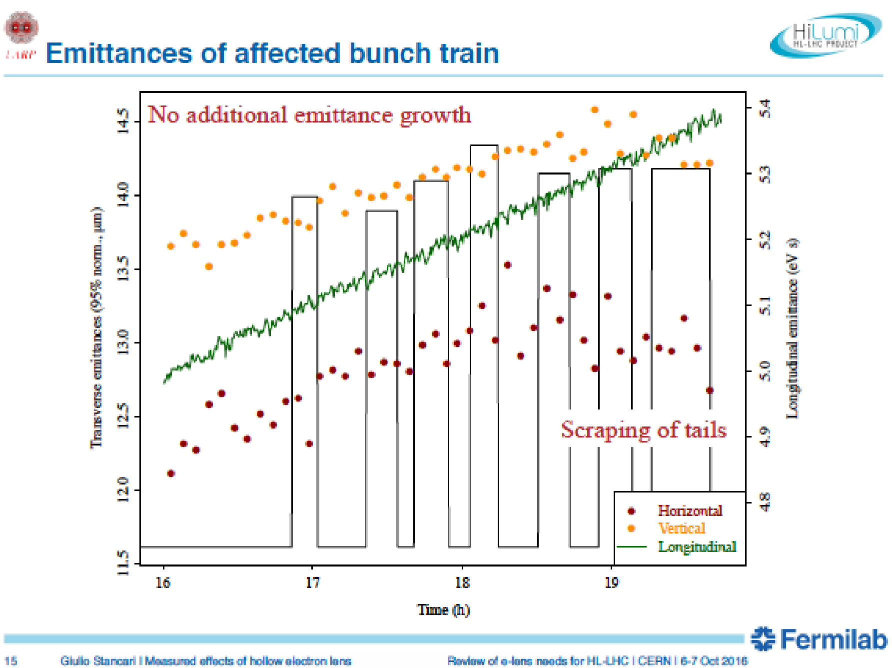
- *Beam Instrumentation for overlap diagnostics: good collaboration with UK for monitor development; one Gas Curtain Monitor in center of main solenoid rather than two monitors at the extremities*

* see G. Gobbi @ HL-LHC collaboration meeting 2018

Studies and proof of principle

- First proof of principle of hollow electron lens collimation at the Tevatron (G. Stancari, 2011)
- Experiments at the LHC to study effect on beam core in pulsed operation (M. Fitterer, 2016-2017)
- Further experiments at RHIC (X. Gu, 2018)





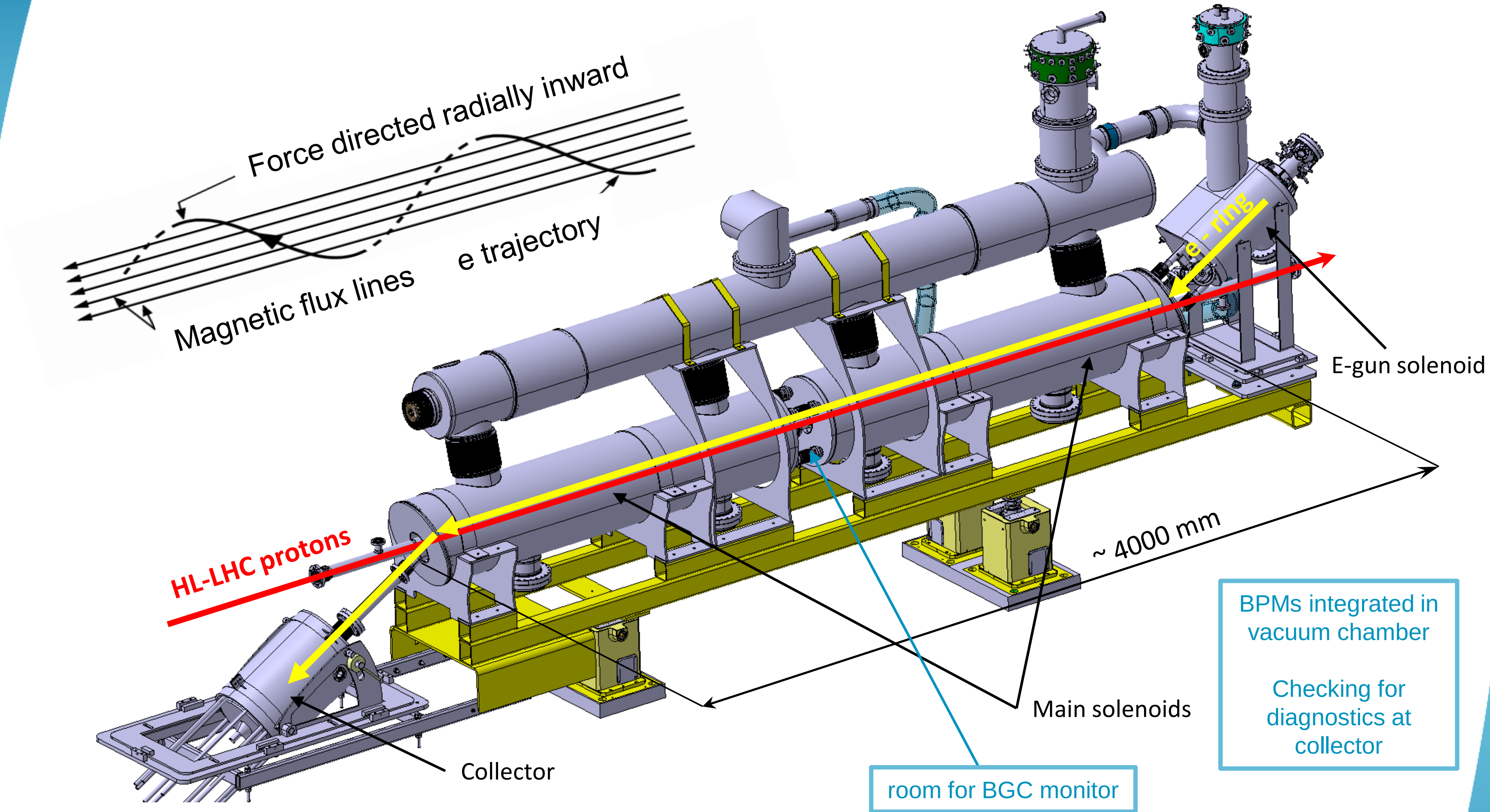
G. Stancari

HEL main parameters today

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

Parameter	Value or range
Proton beam optics at HEL, β [m]	280
Length of interaction, *L* [m]	3
Desired transverse scraping (3 to 6 beam σ), *r* [mm] (note that here geometric emittance = 3.5 umrad)	1.1 – 2.2 @ 7TeV 4.3 – 8.6 @ 450GeV
Electron beam current, *I* [A]	5
Cathode diameter [mm]	8 to 16
Gun extraction and modulation voltage [kV]	10
Cathode-ground voltage [kV]	15
Collector voltage [kV]	in study
Modulator rise time [ns]	200
Modulator repetition rate [kHz]	35
Magnetic field at gun [T]	0.35 @ 7TeV to 4 @ 450GeV
Magnetic field at bend [T]	3.5
Magnetic field at main [T]	3 @ 450GeV to 5 @ 7TeV

The system configuration

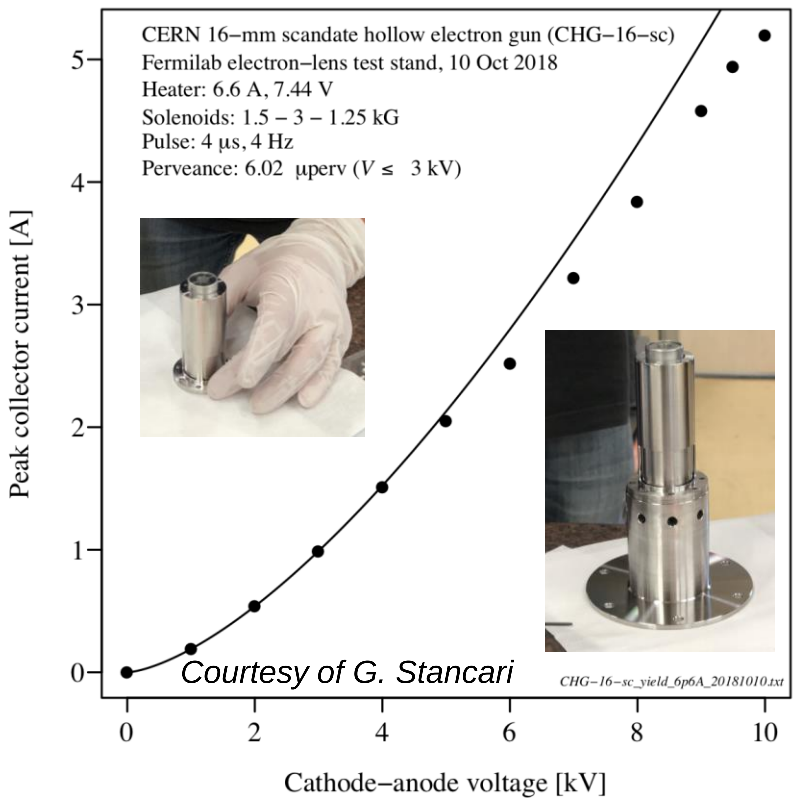


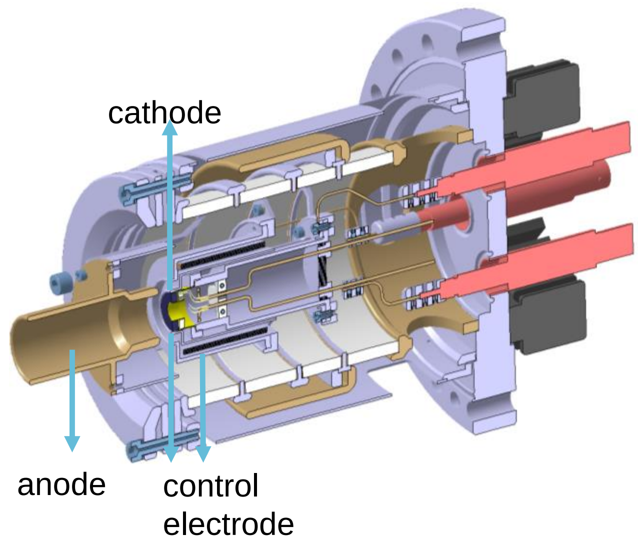
Electrons are produced by the cathode of an e-gun.
A system of superconducting solenoids cooled at 4.5K generates the magnetic field to tune de size and steer the trajectory of the electron ring.

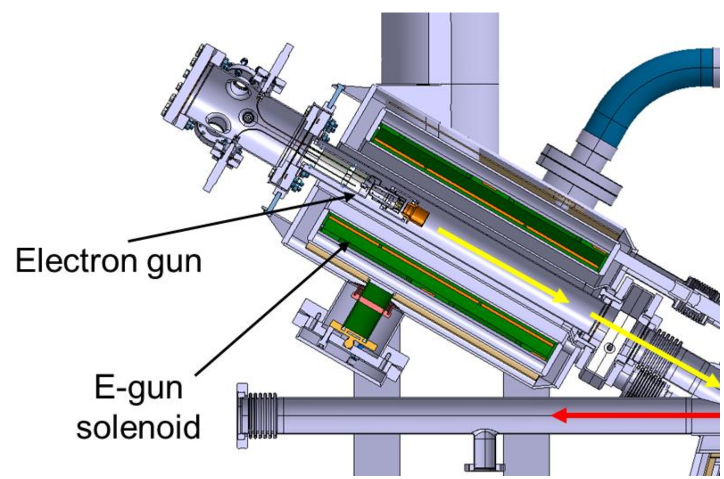
Scandia-doped cathode

- **Electron beam generated by hollow cathode**
- **Thermionic cathode→** electron emission T - activated

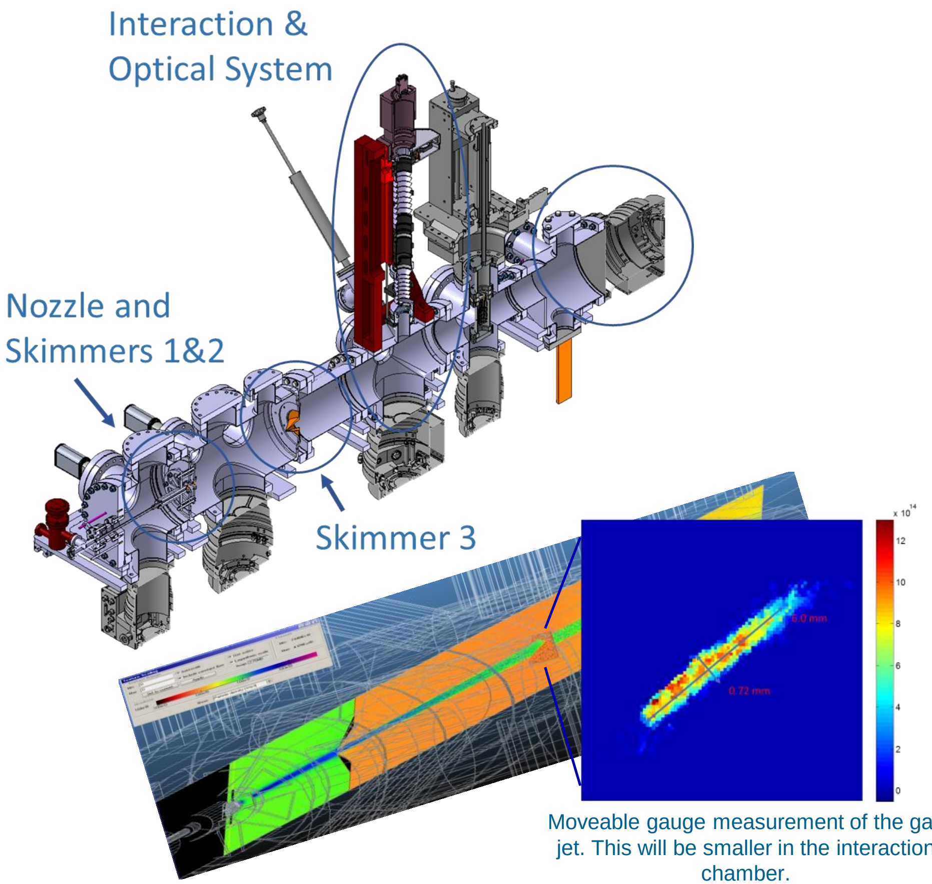
FNAL e-gun design with scaled electrode dimensions







Beam Gas Curtain Monitor

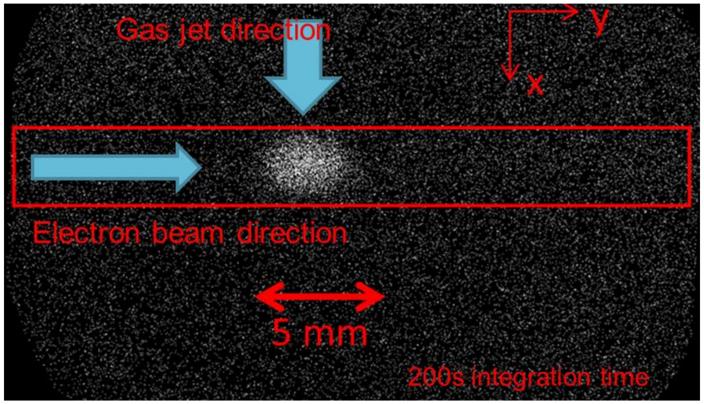


Moveable gauge measurement of the gas jet. This will be smaller in the interaction chamber.

Courtesy of R. Veness, T. Dodington, H. Zhang, S. Udrea and BGC collaboration
8th HL-LHC Collaboration meeting, 15-16 October 2018
IBIC 2017

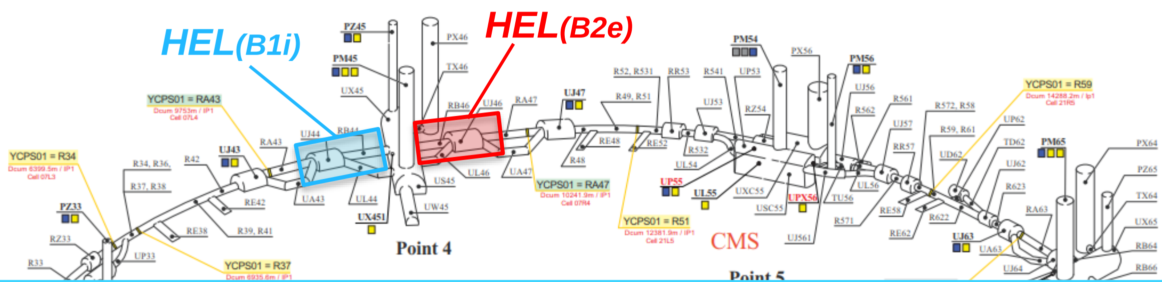
- Beam-Gas Fluorescence on target gas curtain
- Looking at Ne and Ar as gas
- Prototype to be installed in LHC

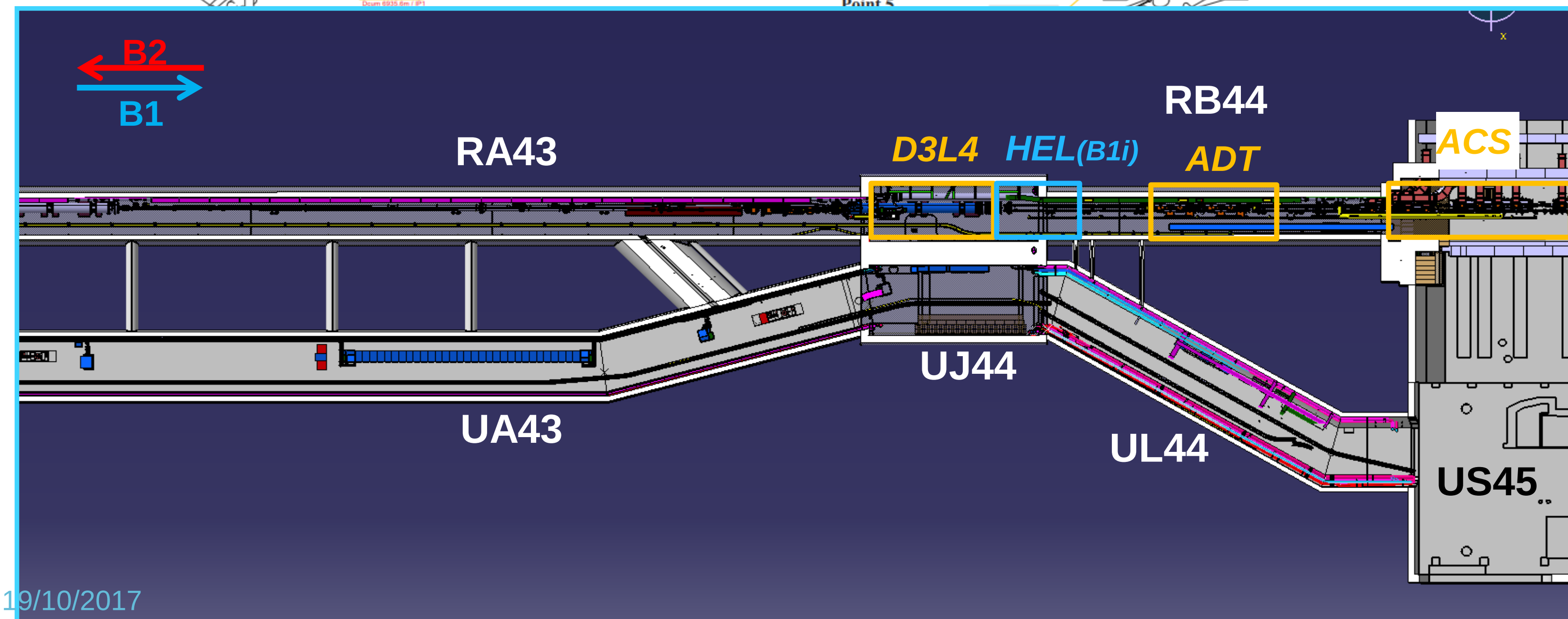
Nitrogen gas jet test



- Final design scaled to fit

Location of new HEL in LHC Ring (P4)

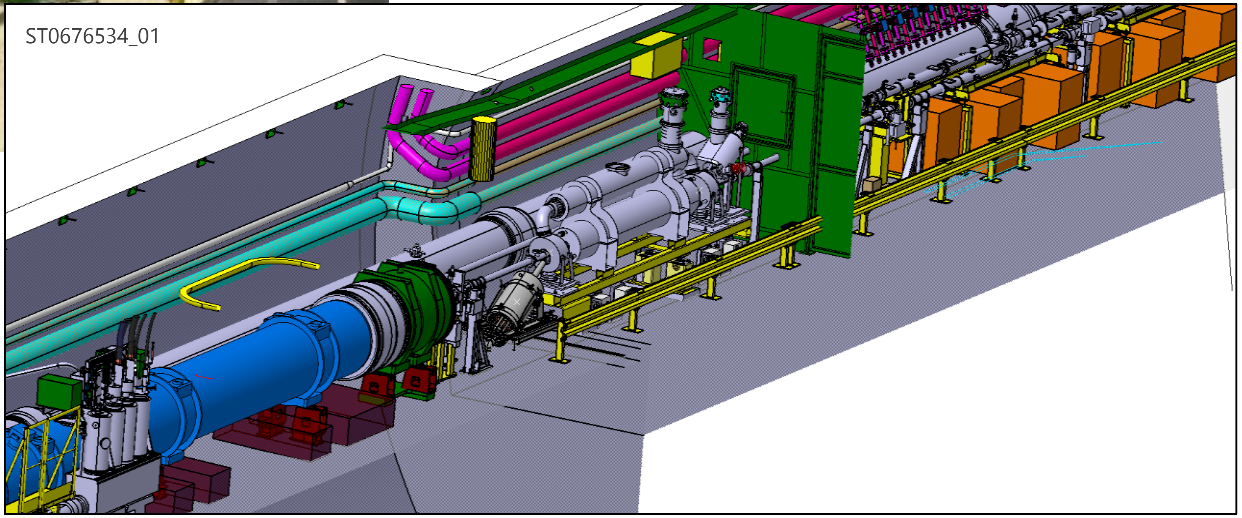




M. Gonzalez de la Aleja, Paolo Fessia

HEL integration in LHC

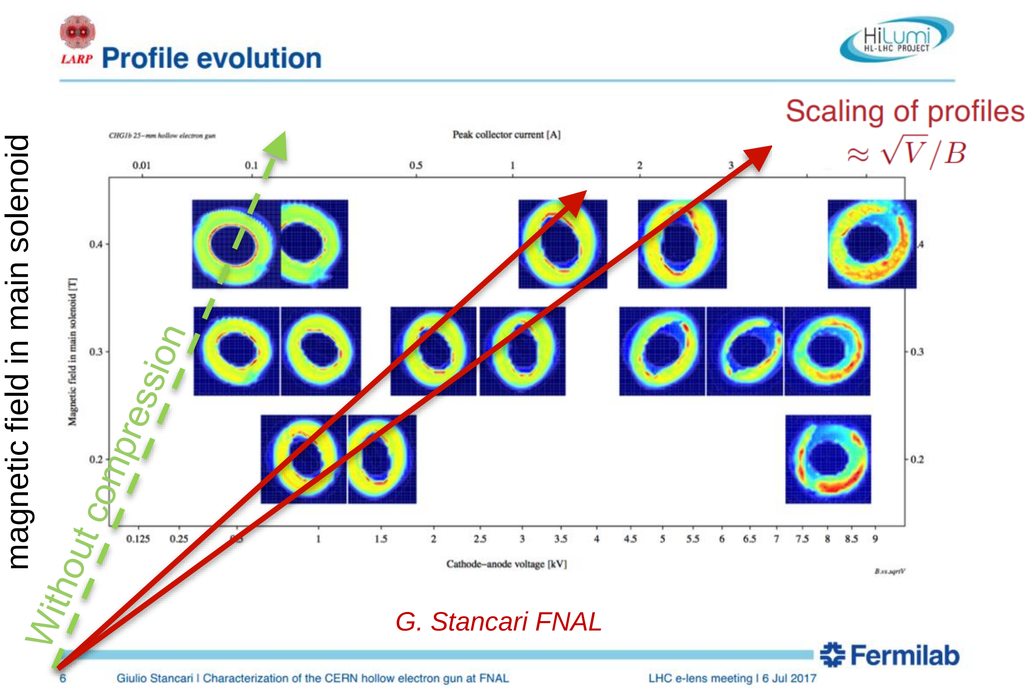
M. Gonzalez de la Aleja, Paolo Fessia



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

Space Charge driven Instabilities

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

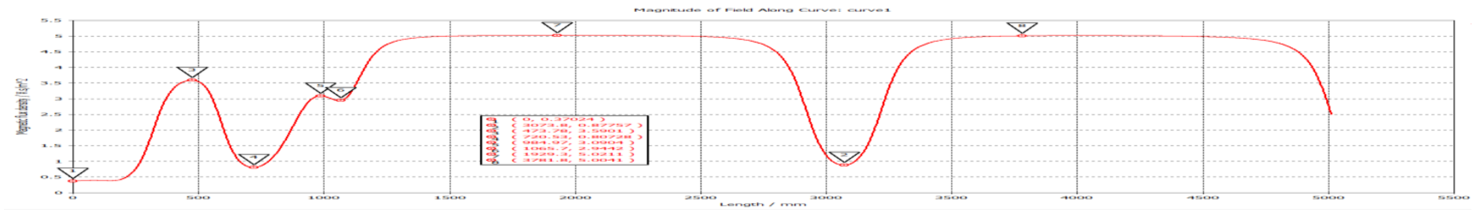


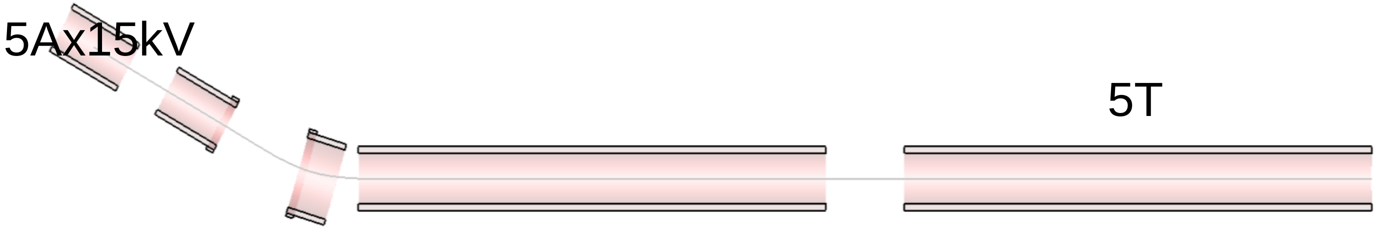
- Current profiles scaling with $\approx \sqrt{V}/B$ indicate that we are in space charge dominated regime
- Measurements show that at low current density we could operate at 5A (25mm outer radius) with 4T and a ~round beam
- Compression (5A to <4mm outer radius) will increase space charge and may cause the electron beam profile to ovalise and tilt.
- Studies with 5T / 5A, and reduced beam pipe diameter (60mm) show relative good results

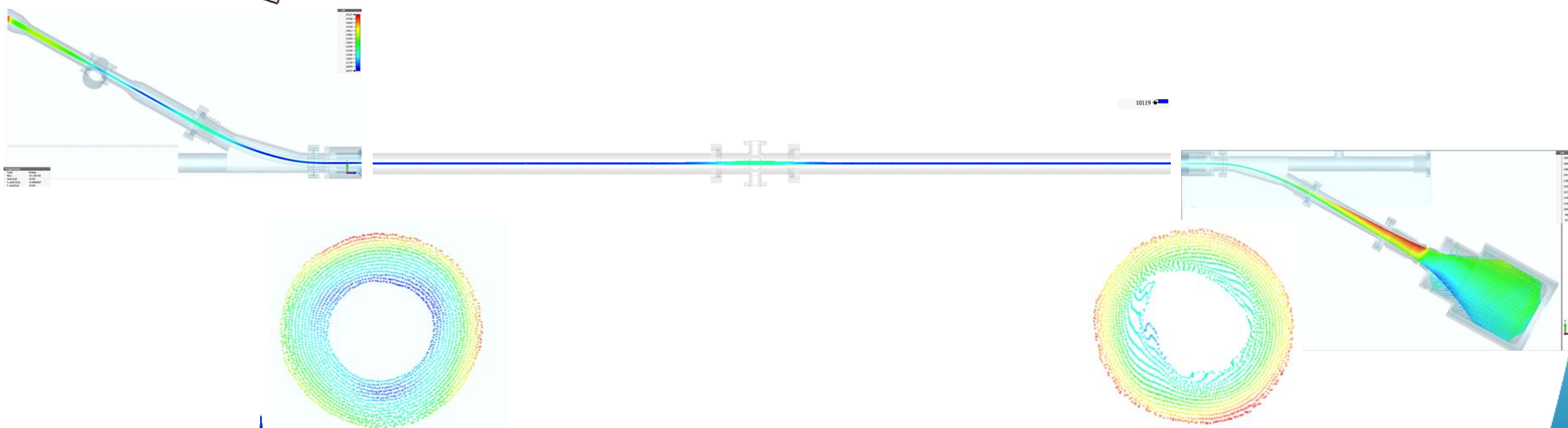
But space charge effects are not directly a show stopper! Rather, they might limit the maximum acceptable electron beam current and thus the cleaning efficiency

Hollow Electron Beam Simulations
Prof of HEL parameters

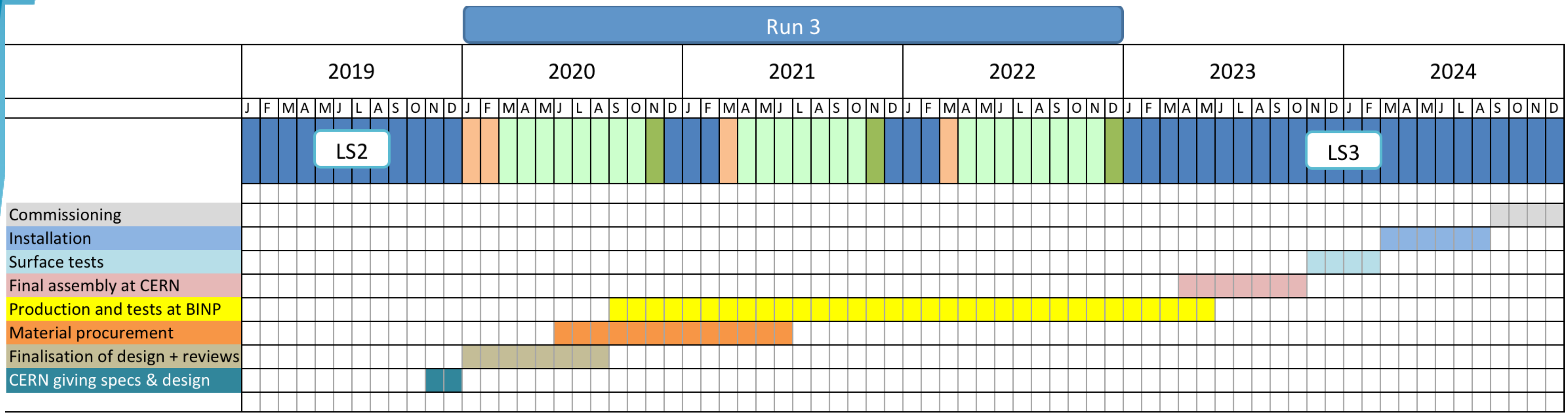
- CST Particle Studio simulation of the Hollow Electron Lens to feedback to thermomechanical design (here shown for 7TeV ops)







Schedule



- Assuming we want to operate the HEL in Run IV
- Assuming HEL built as in-kind

Conclusions

- The Hollow Electron Lens as beam halo control can provide more margin during all the operational phases and to handle ramp-up phases and configuration changes that inevitably HL-LHC will face
- Several dedicated reviews and the HL-LHC C&S review 2018 recommend its integration in the HL-LHC baseline
- Extensive design effort has been put to this purpose
- Now finalizing few details (corrector magnets and collector) in collaboration with BINP
- Will be ready to hand over design by end of 2019 if in-kind confirmed

Thank you from all the HEL team

Effect of pulsing (M. Fitterer)

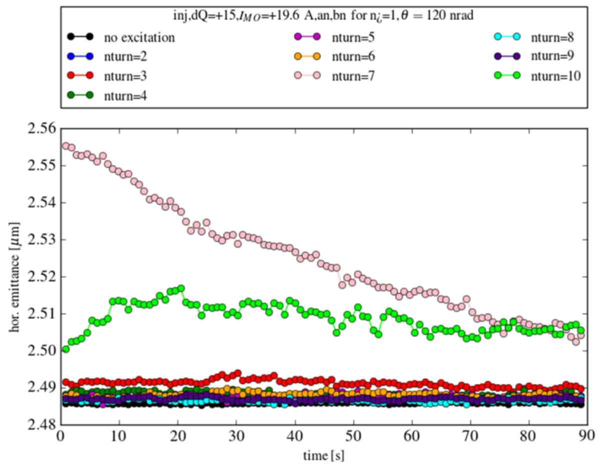
Experiment at the LHC – simulation results

expected kick from HEL: 15 nrad

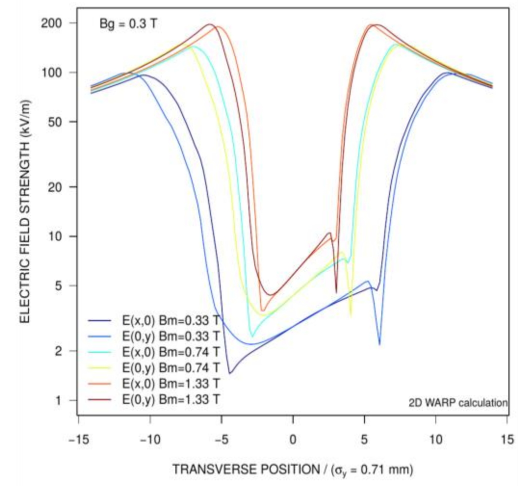
12 nrad H+V: no effect

120 nrad H+V: strongest effect for 7th and 10th turn pulsing

- losses
- constant or decreasing emittance due to change of transverse distribution over 10^4 turns caused by excitation of resonances



16 17/05/2017 M. Fitterer | Hollow Electron Beam Collimation for HL-LHC - Effects on the Beam Core | IPAC'17



Assumed e-beam kick (imperfections in beam profile)
G. Stancari

- e-lens could introduce noise on the p-beam core

HEL schematics