HiLumi
HL-LHC PROJECT

Electron lens test bench

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BI-TB, 22.02.18, CERN

CERN

Outline

- Context: electron beam applications
- Brief description of electron lenses and electron beam dynamics
- Electron lens test bench at CERN:
  - Motivation
  - Description
  - Current status
  - Plans for upgrade
- Summary and outlook

Context: electron beam applications

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

- Electron cooling (for ex. at CERN LEIR, AD, ELENA, GSI SIS18),
- Space charge compensation (GSI SIS18 *, FNAL IOTA)
- Beam-beam compensation (at FNAL Tevatron and BNL RHIC)
- Halo diffusion enhancement (at FNAL Tevatron)
- #Beam generation with EBIS (Electron Beam Ion Source) (RexEBIS at CERN)

- At HL-LHC e-lenses are being studied for:
  - BBLR for Beam-Beam Long-Range compensation
  - BBHO for Beam-Beam Head-On compensation
  - HEL for Halo diffusion enhancement

* under study with the ARIES project (Accelerator Research and Innovation for European Science and Society)

Electron beam applications

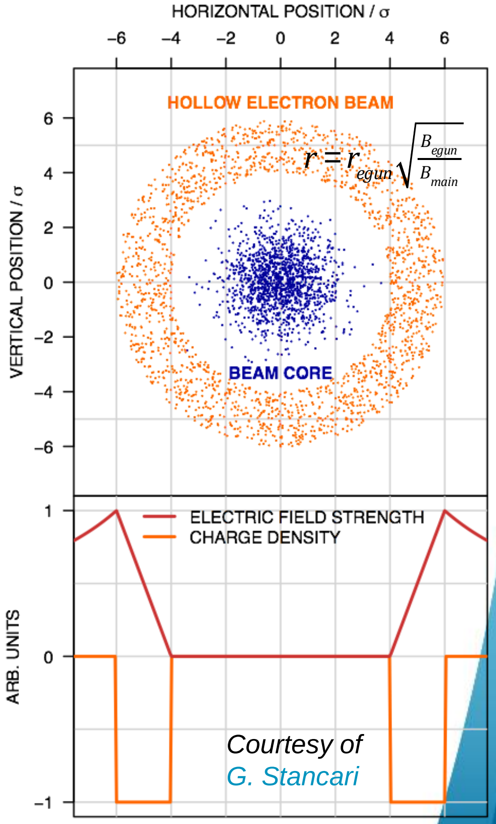
- **Space charge compensation** : electric field generated by electron beams (Gabor lenses) used to focus ion/proton beams, whose space charge would otherwise cause emittance blow-up.
  - Electron beam with transverse and longitudinal distribution plus current intensity ~ matching beam to be focused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

- **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.
  Beam-beam tune spread might be reduced by:
  - for Long-Range Beam-Beam (parasitic encounters)
    - compensation with e-beam wire
    - at HL-LHC required electron beam ~ 200Am (for 2 wires per HL IP)
    - ~ 60Am (=20A x 3m) × 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
    - at RHIC ~0.2A proton beam with beam-beam parameter 0.007 used total of 2 e-lenses with ~2Am (=1A × 2m) × 5kV (2 IPs)
    - HL-LHC ~1.1A proton beam with beam-beam parameter 0.033 ~ 10Am (scaling with current and e-energy plus 2 e-lenses per HL IP) × 15-20kV

Electron beam applications

- **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).

- 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



Courtesy of G. Stancari

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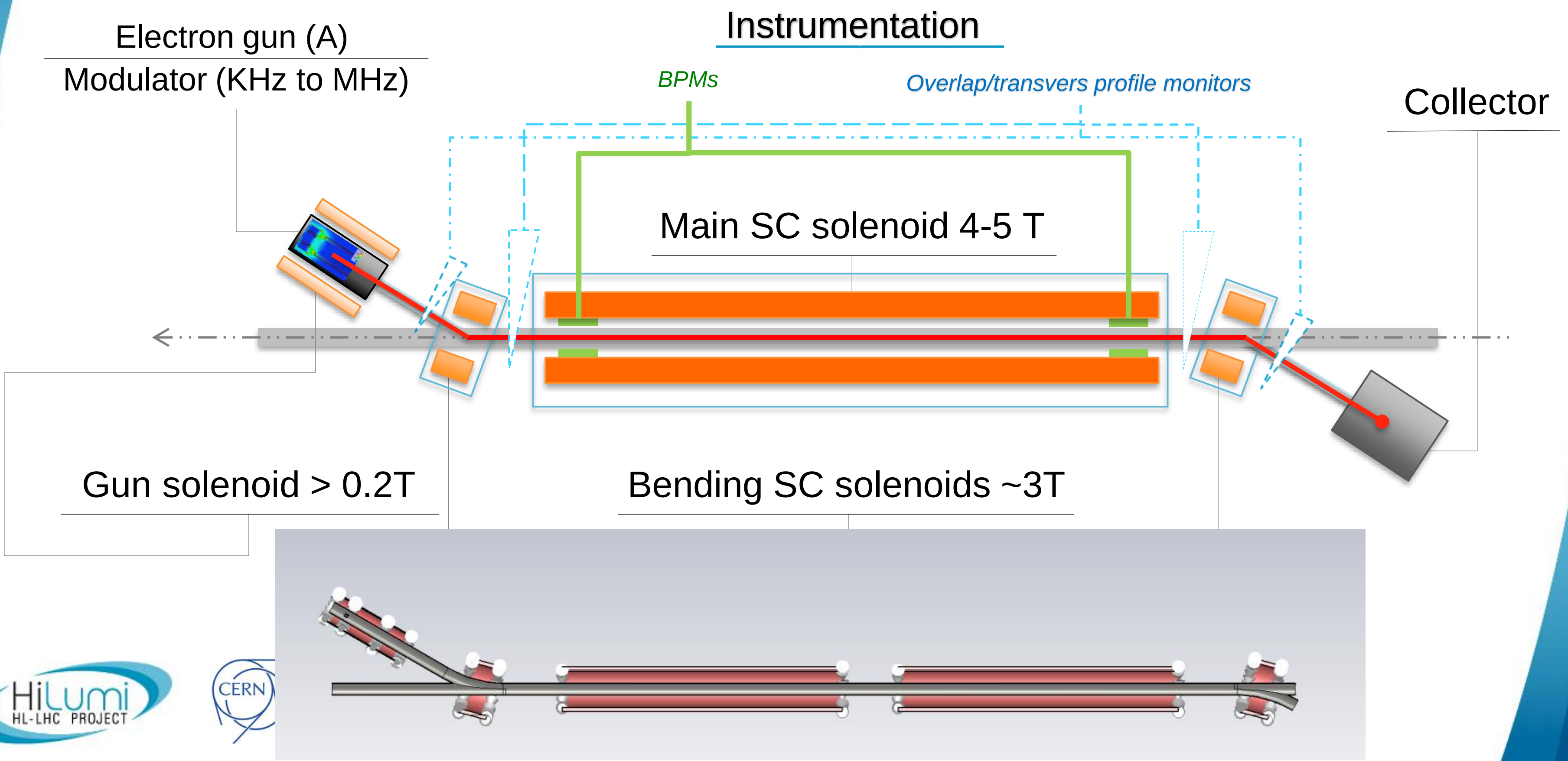
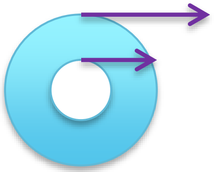
Electron Lens shcematics

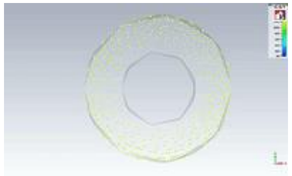


Electron beams

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

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

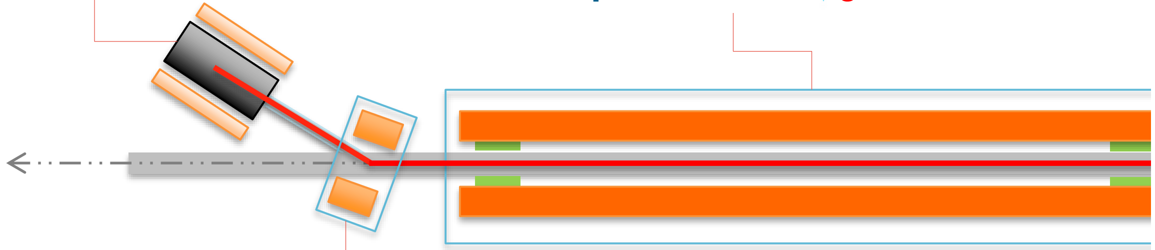




Electron beam in electron lens

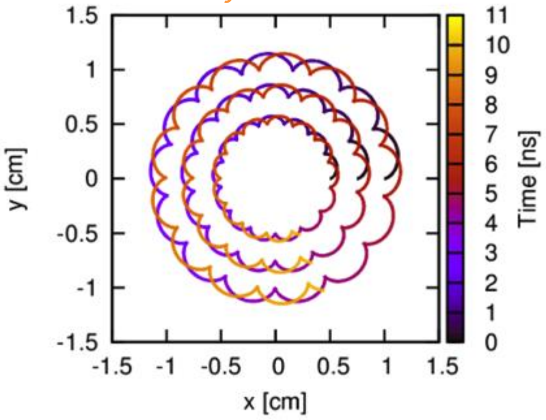
several A e-beam
~10mm @ cathode

Beam is further
compressed: stronger SC



Beam is bent and
compressed

Courtesy of Daniel Noll



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

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

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

Effective length 2.9 m

Current 3A at 12 kV (5A at 15 kV)

Hollow shape of the beam

HEL@HL-LHC has

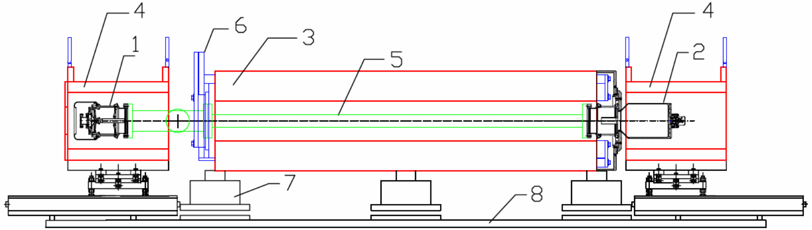
- higher current,
- higher energy,
- higher current density
- longer effective length

comparing to implemented electron lenses

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

E-lenses test stands in the world: overview

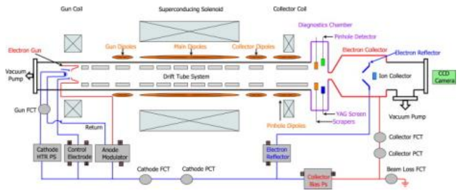
FERMILAB - Tevatron



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

Operational, E of e-beam up to 10 kV, will be used for testing guns for space-charge compensation at IOTA ring

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

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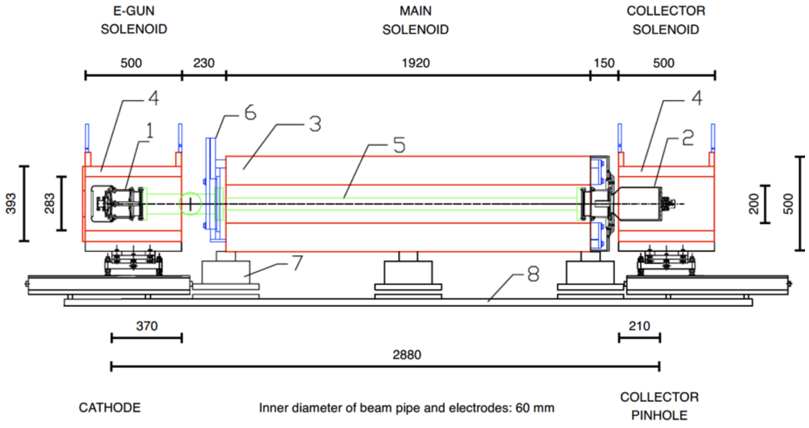
E-lens test stand at FNAL

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



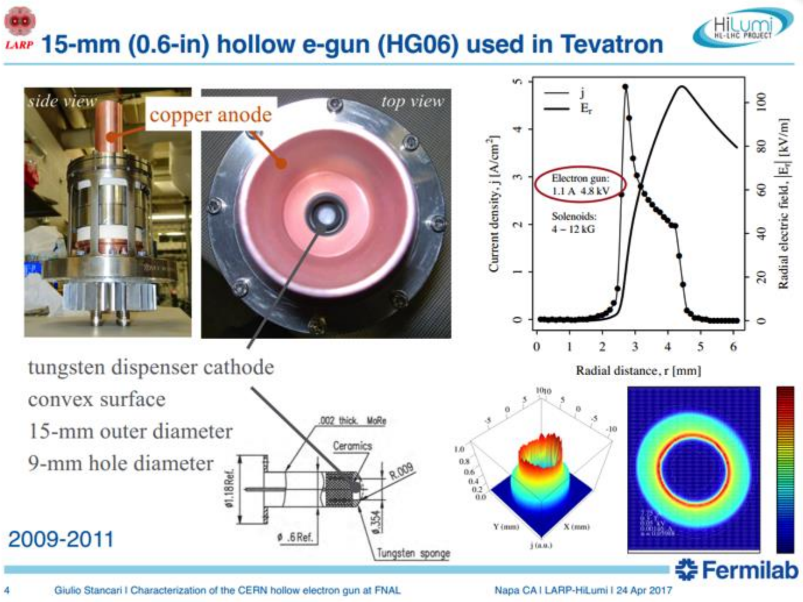
Operational, up to 10 kV, 8μs x 1Hz pulses (or higher at < 5A)

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.

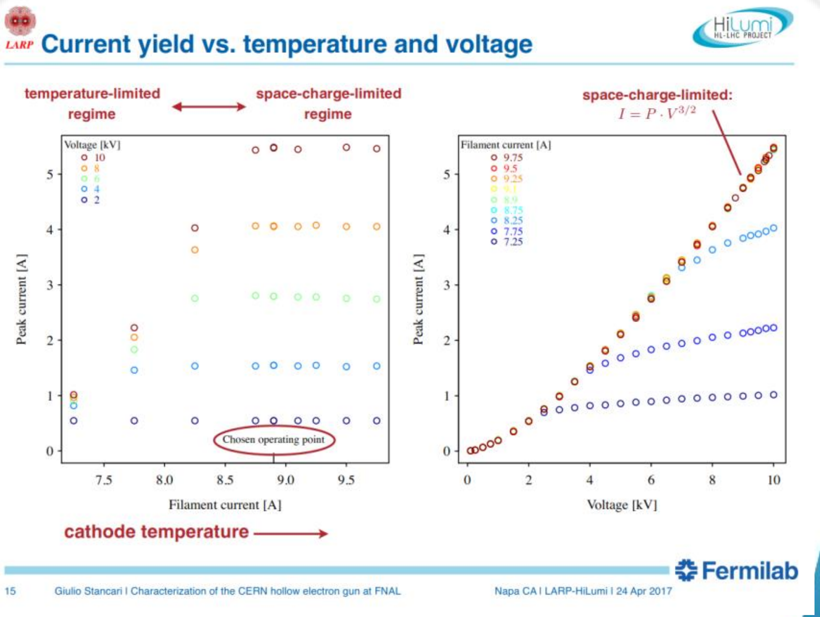
Diagnostics: pin-hole FC in collector

FNAL test stand: measurements

- Electron gun characterization



G. Stancari FNAL

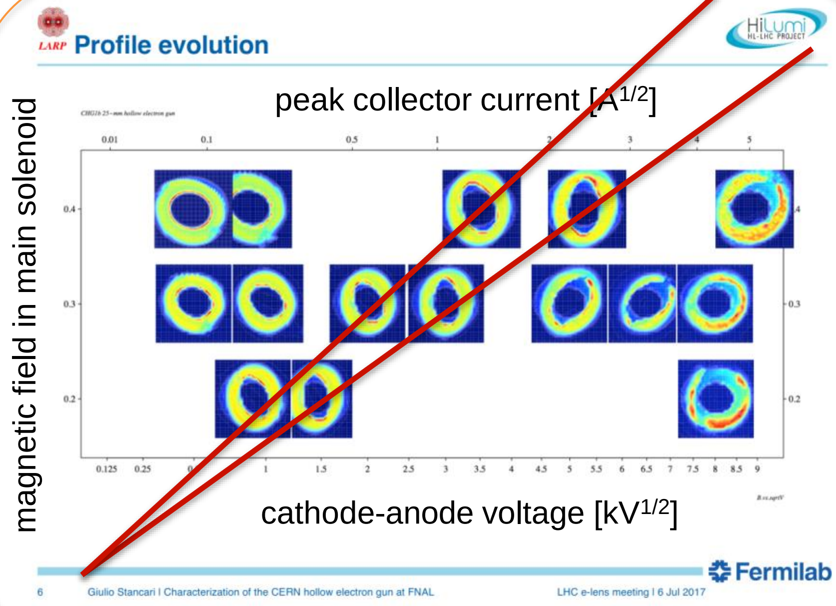


G. Stancari FNAL

FNAL test stand: measurements

- Beam dynamics

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

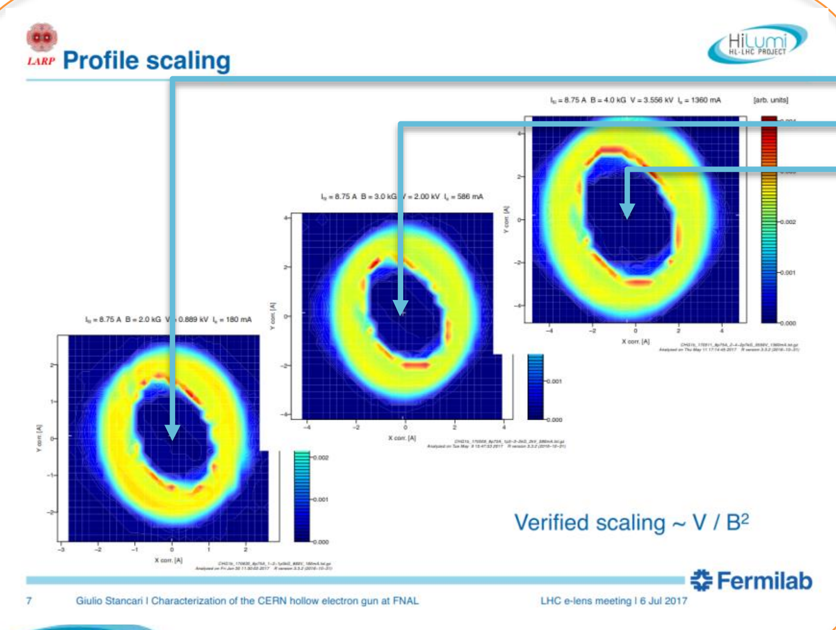


G. Stancari FNAL

- Current profiles scaling with $\approx \sqrt{V}/B$ indicate that we are in space charge dominated regime
- Measurement 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 cause the electron beam profile to ovalise and tilt.
- Studies ongoing with 5T and 3 to 5A, and reduced beam pipe diameter (60mm)

FNAL test stand: measurements

- Beam dynamics



G. Stancari FNAL

- Profiles looks similar on the V/B^2 curve
  - 0.2T 0.889 kV 180mA
  - 0.3T 2.000 kV 586mA
  - 0.4T 3.556 kV 1360mA
  - *0.5T 6.000 kV 3000mA (scaled)*

- Deformation at low current (<0.5A) and low magnetic field <0.4T is observed

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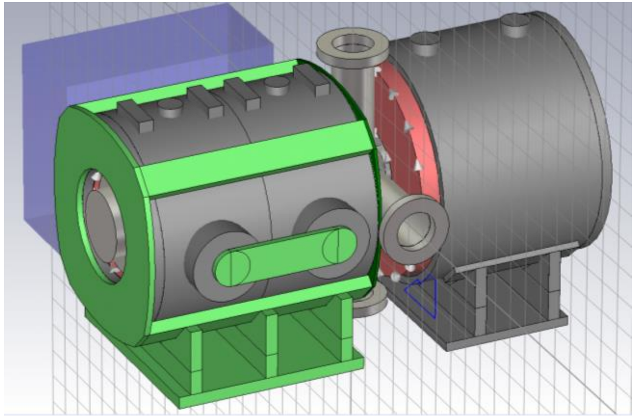
Test facility at CERN

- Foreseen for ARIES studies WP16 – **Intense, RF modulated E-beams (IRME):**
  - Design and build a test stand for testing 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

  [50x70mm oval e-beam, 5-10A, 22kV for the ion beam at the Heavy Ion Synchrotron SIS18 (to be used as injector to SIS100) for **Space Charge Compensation** matched transversally and longitudinally]
- Foreseen to test high intensity e-gun for **Beam-Beam Long Range compensation:**
  - Few mm round e-beam, up to 20A, **20-35kV**
  - Modulation at 40MHz for BPM measurements
- Foreseen to test Gas Curtain Monitor
- If **HEL-HL-LHC** becomes baseline:
  - Characterise e-guns
  - Validate, commission modulators
  - Test beam instrumentation, modulators, interlocks,
  - Learn safety and technical aspects of e-lenses operation
  - Prepare infrastructure for test and commissioning of components of HEL@HL-LHC

Test-stand development at CERN:

Basic configuration – stage 1



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

Purpose of this 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
  - Electron gun: anode modular

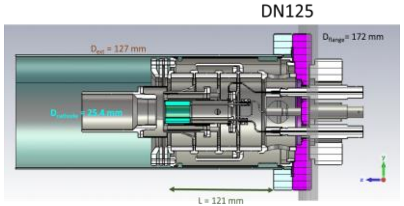
- Preparation for Stage 2 in parallel
  - Design diagnostic box/collector

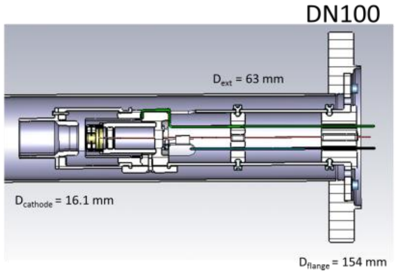
*Detalization of next stages depends on HEL@HL-LHC

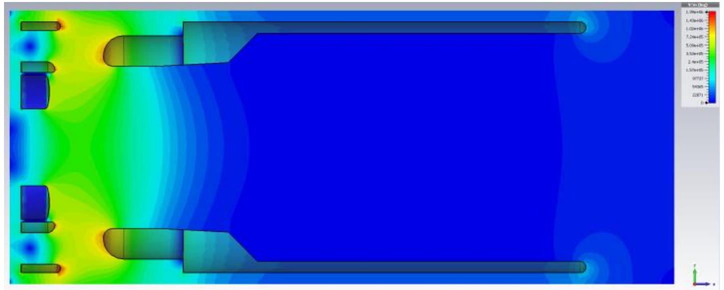
Stage 1: measurements

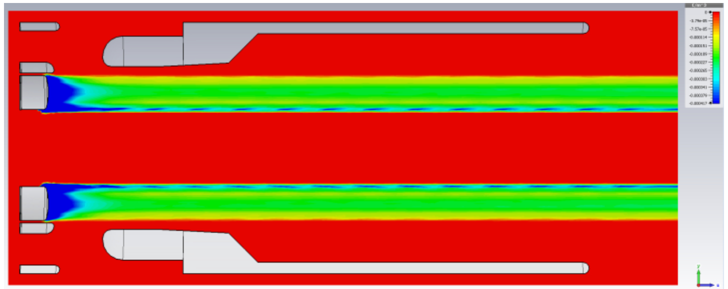
- Gun characterization
  - Measurements like in FERMILAB, but without 2 m drift for 25.4/16.1mm guns
  - Comparison experimental results with CST/WARP/TRAK/UltraSAM (to use output beam profile distribution as inputs for beam dynamics simulation)

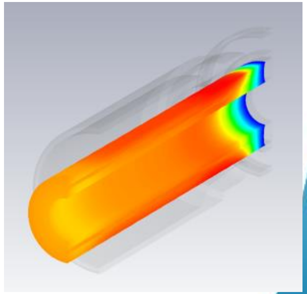
- Anode modulator
  - 33 kHz at full range (0 V – -10kV), 200pF at 10kV at 33 kHz…
  - ~MHz at % level (beam modulation for BPM)
  - **Test modulator but not the beam/BPM*





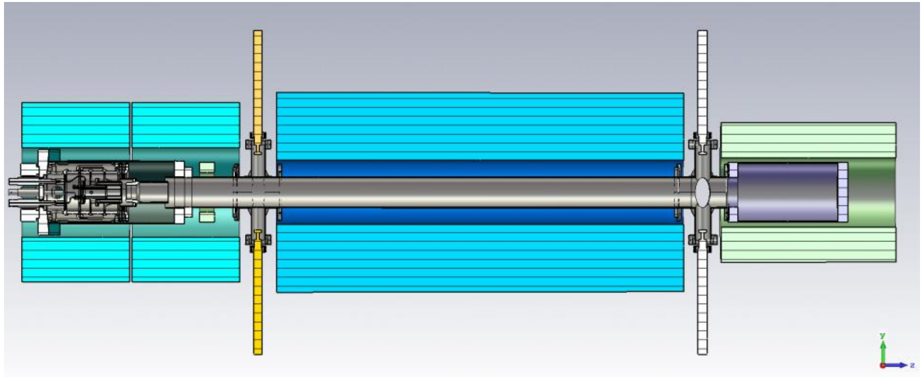






Test-stand development at CERN. Upgrade.

Addition of main solenoid – stage 2



Main warm solenoid (can be recuperated) could achieve 0.4-0.5T at 1.2m. Upgrade of the building in terms of heat exchanger and power grid will be needed.

(dry SC solenoid may be cheaper and would expand range of investigation)

Purpose and measurements of stage 2:

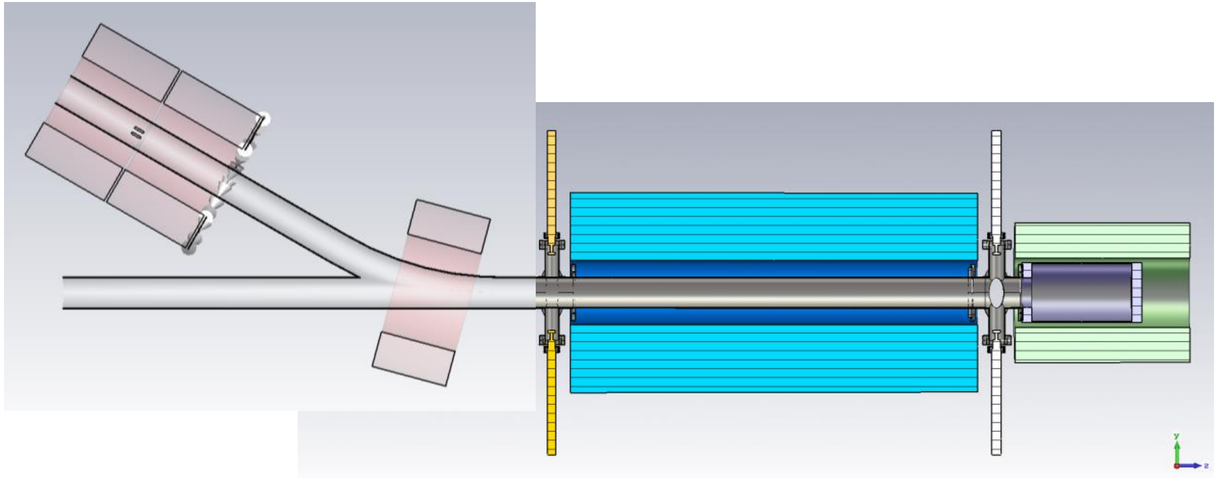
- Allow drift and see beam deformations/rotations/… computer model validation
- Study electron beam dynamics in regime close to virtual cathode
- Study electron beam dynamics with compression

- 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
- Stress design of the gun + modulator for BPM for HEL (stochastic HEL operations on/off turn by turn)

- Design and test extracting electrodes for electrons created at the gas curtain (cooling needed)

Test-stand development at CERN. Upgrade 2.

Addition a bend – stage 3



Purpose of this stage:

- Measure effect of B x gradB on deformation of beam with high current density
- Computer model validation

Test stand as infrastructure for HEL@HL-LHC

- Several components can be prototyped, tested and commissioned at test-stand at stage 2:
  - Diagnostics:
    - BPM
    - YAG screen
    - Pin-Hole Faraday Cup
  - Anode modulator (LF/HF)
  - Collector
  - Machine protection system
- Test stand is compact and can be transported to the SM18 for test with SC solenoids (bending, main) and commissioning of HEL@HL-LHC components:
  - Software control (correctors, etc.)
  - Interlocks

Simulations and computer codes

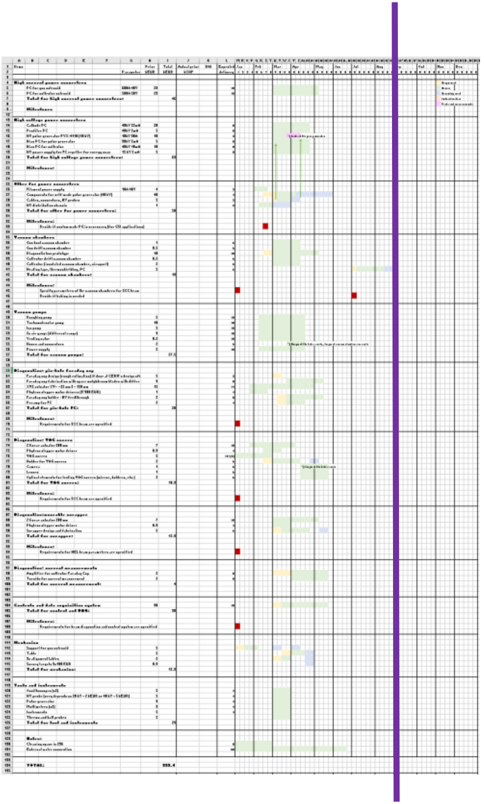
- Reliable and verified simulation technics and models are required
- Computer codes that will be used for simulation for electron gun and beam dynamics:
  - CST particle studio
  - WARP
  - Results of gun simulations using TRACK and UltraSAM (2D codes) are available
  - BENDER

Planning for stage 1

#WeHavePlan

Work to do…
Items to buy…
Items to design…
Items to manufacture…

#AndIssues
Water cooling
Electrical power



September 2018

Cooling?

Current status

- "Long delivery" components (14-16 weeks) are ordered
- There are still some items to design and order
- Issues:
  - Cooling water in the building 236
    - Building is close to LINAC3, but cooling water is cut. Installation of heat exchanger/chiller is needed. Bottleneck for stage 1. Solenoids can work in pulsed mode (for stage 2) depending on heat exchanger power.
  - Electrical power in the building 236
    - Electrical power consumption on stage 2 can be 170 kWt, if warm drift solenoid is used (using solenoids in pulsed mode will reduce average power, but peak current will remain 450A) – electrical grid upgrade in the building is needed (already discussed for 50kCHF, tbd asap).

- September 2018 to start commissioning looks reasonable if cooling water is available.

Costs estimation

Summary and outlook

- A test stand at CERN is being constructed in a phased approach:
  - Stage 1 (Gun Solenoid – Diagnostic box – Collector solenoid) can be used for:
    - E-gun characterization both for HL-LHC HEL (in parallel or after FNAL) and SIS18 SCC lens;
    - Benchmark simulation codes (CST, WARP, TRAK, UltraSAM)
    - E-gun studying for BBLR compensation;
    - Test anode modulator
    - Test and commission BGC
  - Stage 2 (+ drift solenoid) is needed to:
    - Test RF modulation for SIS18 SCC lens;
    - Test BPM for electrons (HF or LF modulation);
    - Investigate electron beam dynamics and benchmark simulation codes (CST, WARP, …)
- Stage 1: start commissioning in September 2018