# Hollow e-lens layout and cathode development

52nd HL-LHC Technical Coordination Committee, 21.06.2018

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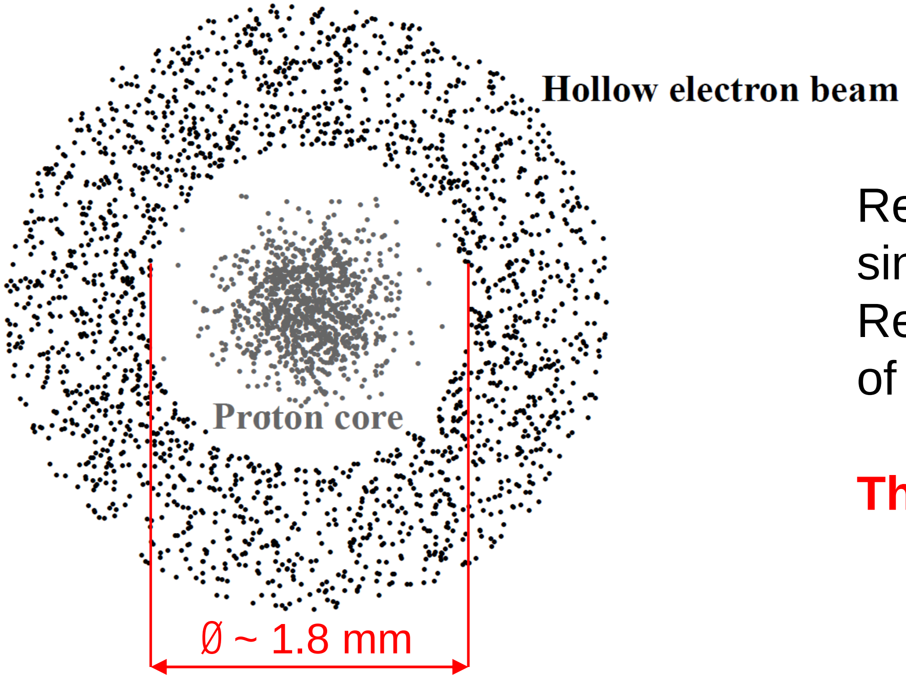
# Outline

- HEL configuration. Design choices.
- Changes / improvements from October 2017.
- Cathode programme.
- Conclusions.

Work carried out under the WP5 HL study

# What do we want to do?



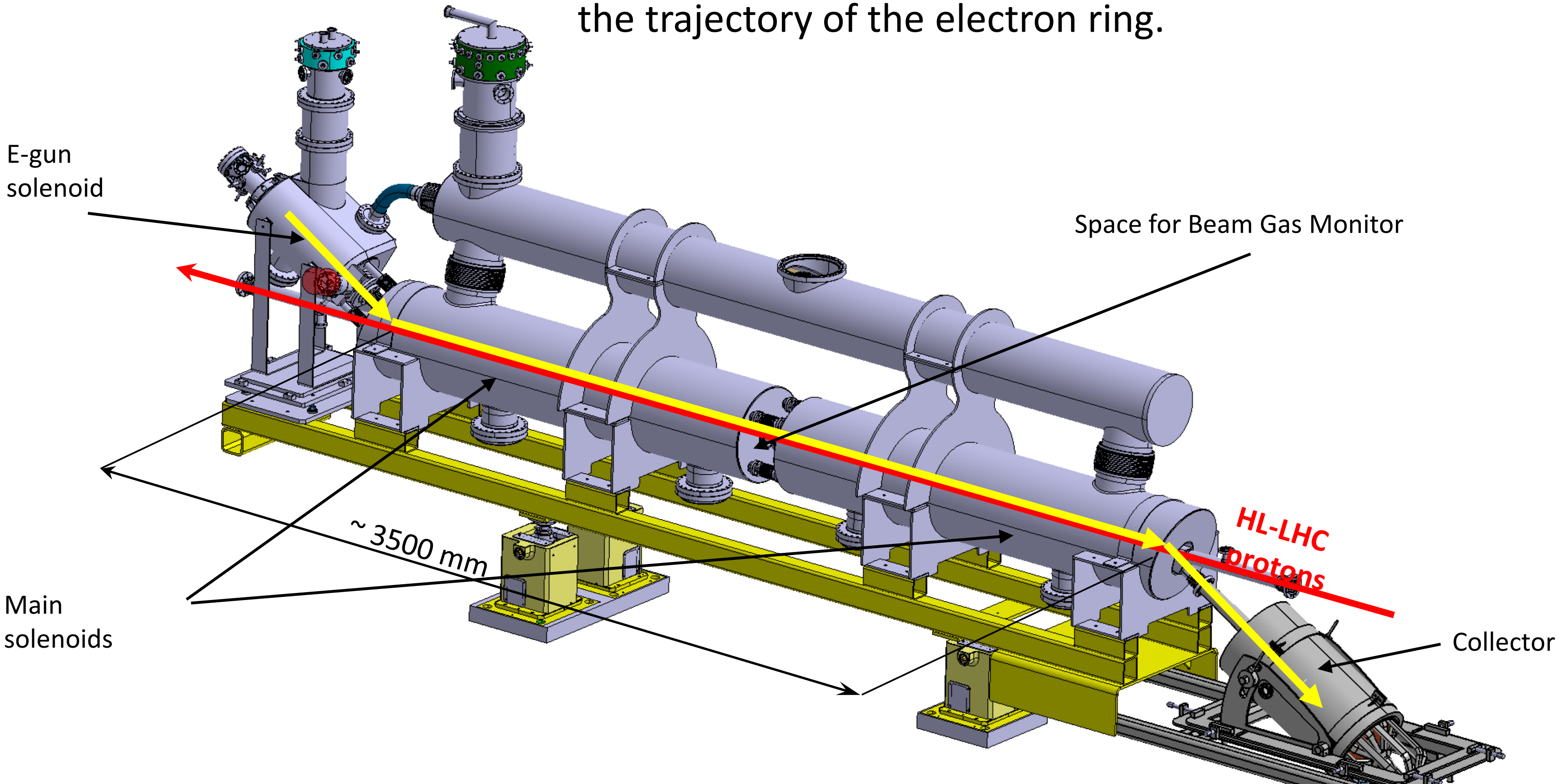
Off-centre of the ring ± 0.15 mm

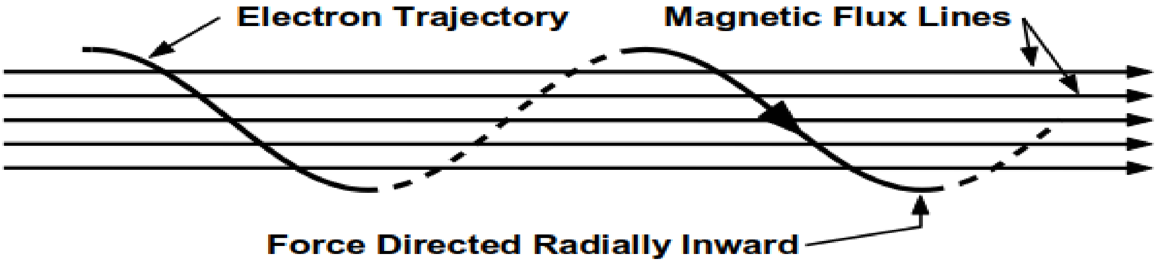
Reasonable precision of a middle size single component: ± 0.05 mm.
Reasonable precision of an assembly of many components: ± 0.2-0.5 mm.

**Therefore we need corrector coils.**

Beam-beam overlapping: ~3m , e current intensity: up to 5 A.
Use at injection and at collision level => different ring size

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.





# Existing electron lenses and HL-LHC hollow electron lenses.

| | RHIC EL | Tevatron EL | HL-LHC HEL |
|---|---|---|---|
| Effective length [m] | 2.1 | 2 | 3 |
| Current from cathode [A] | 1 | 0.6-1 | Up to 5 |
| Main solenoid field [T] | 6 | 3 | 5 |
| Solenoid inner bore [mm] | 200 | 160 | 180 |
| E-gun field [T] | 0.2-0.8 | 0.3 | 0.2-4 |
| Cathode radius [mm] | 4.1 @250GeV<br>7.5 @100GeV | 7.5 | 4 – 8.05<br>Hollow |
| Cathode surface [$cm^2$] | 0.53 @250GeV<br>1.77 @100GeV | 1.77 | 1.53 |
| Current density [$A/cm^2$] | 1.89 @250GeV<br>0.53 @100GeV | 0.6 | 3.27 |
| E-beam compression | 1.6-5.5 | 3.26 | 1.41-4.47 |

HL-LHC HEL is a new object.

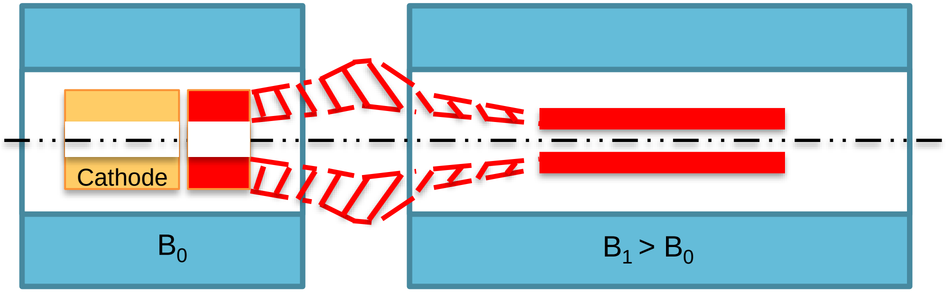
# Cathode size and magnetic fields

Use at injection and at collision level => different electron ring size

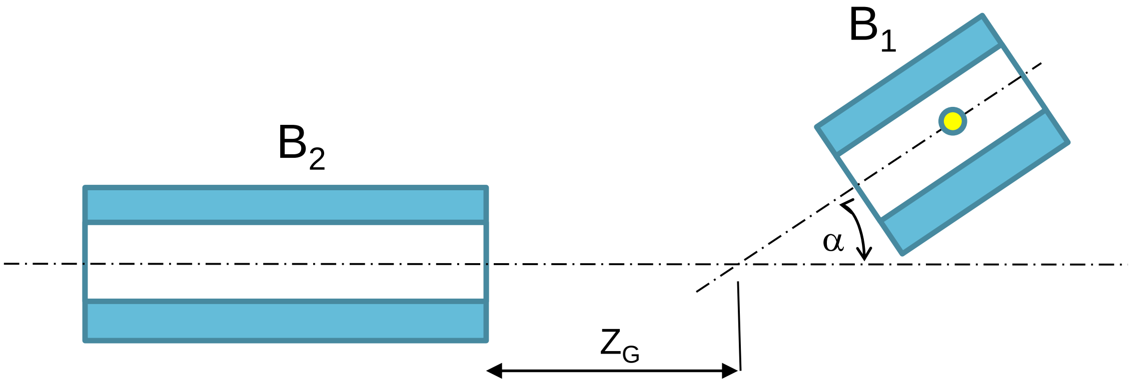
| | |
|---|---|
| **Nominal magnetic field of the main solenoid** | 5T |
| **Nominal magnetic field in the e-gun cathode** | 0.25 T – 4 T |
| **Inner radius of the hollow electron beam @ operation fields (5T, 0.25T)** | 0.9 mm |
| **Outer radius of the hollow electron beam @ operation fields (5T, 0,25T)** | 1.8 mm |
| **Inner diameter of the cathode** | 8.05 mm |
| **Outer diameter of the cathode** | 16.10 mm |
| **Inner radius of the hollow electron beam @ 5 T with 4 T @ cathode** | 3.6 mm |
| **Outer radius of the hollow electron beam @ 5 T with 4 T @ cathode** | 7.2 mm |
| **Nominal current at the cathode** | Up to 5 A |

$$\frac{r_0}{r_1} = \sqrt{\frac{B_1}{B_0}}$$

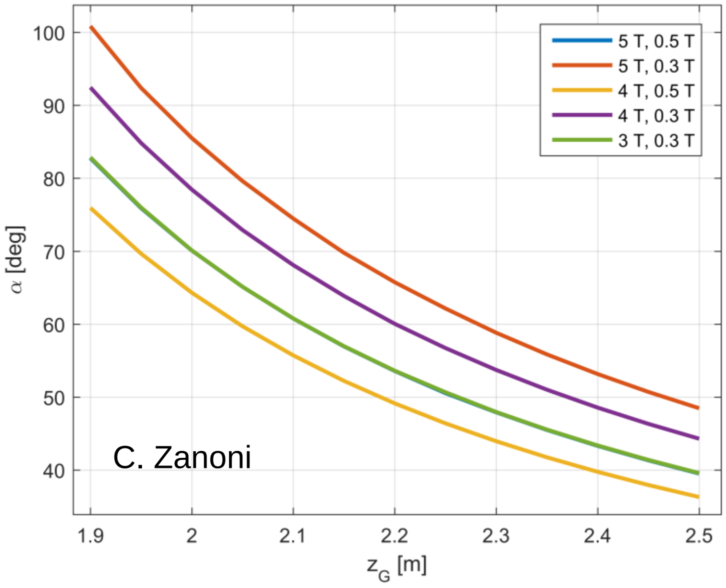
Where $r_0$ and $r_1$ are the radii of the electron beam in point 0 (cathode) and 1 (main solenoid) and $B_0$ and $B_1$ are the magnetic field in points 0 and 1 respectively.



# Trajectory in the bend

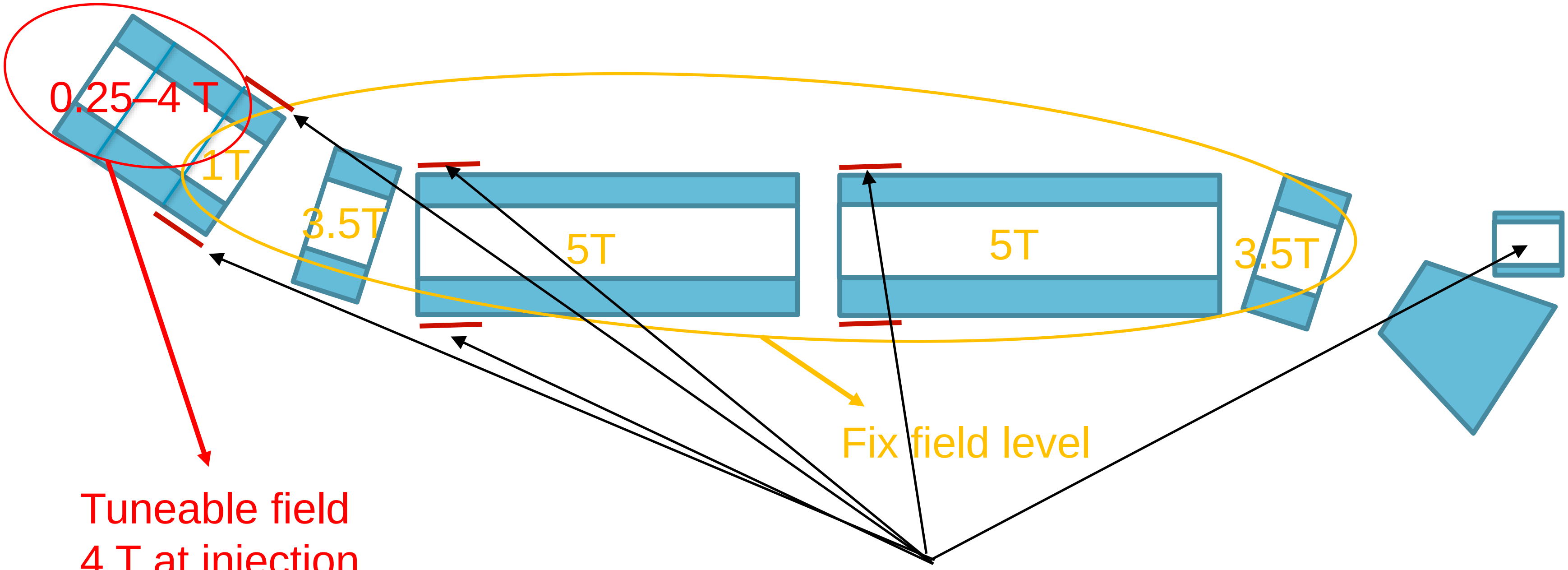


$Z_G$, $\alpha$, $B_1$ and $B_2$ are not independent parameters.
A change of the ratio $B_1/B_2$ calls for different $Z_G$ and $\alpha$



C. Zanoni

# Magnetic field configuration



Tuneable field
4 T at injection
0.25 T at collision

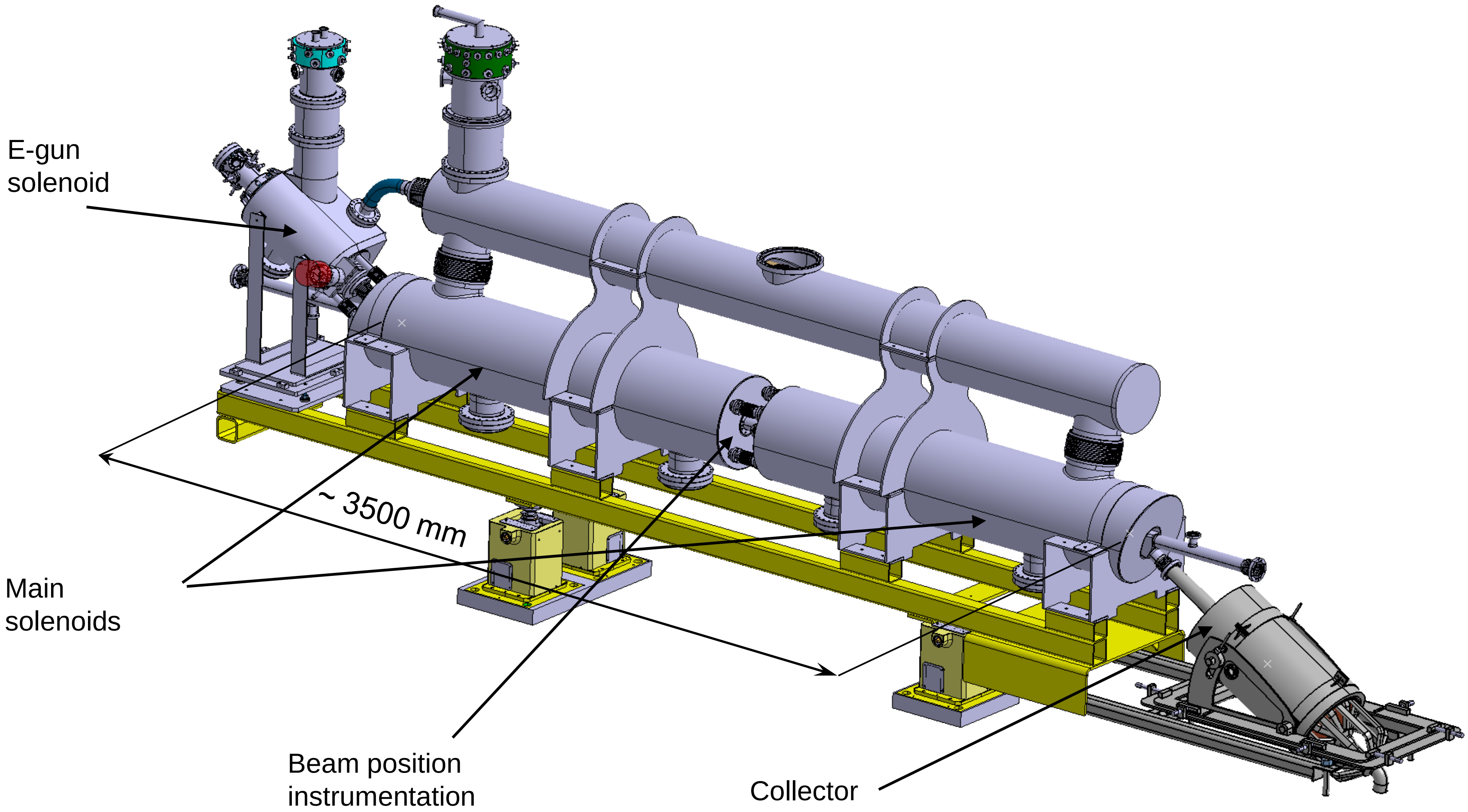
Correctors

## Minimum number of circuits

- 3 solenoids e-gun
- 1 bending solenoids
- 2 main solenoids

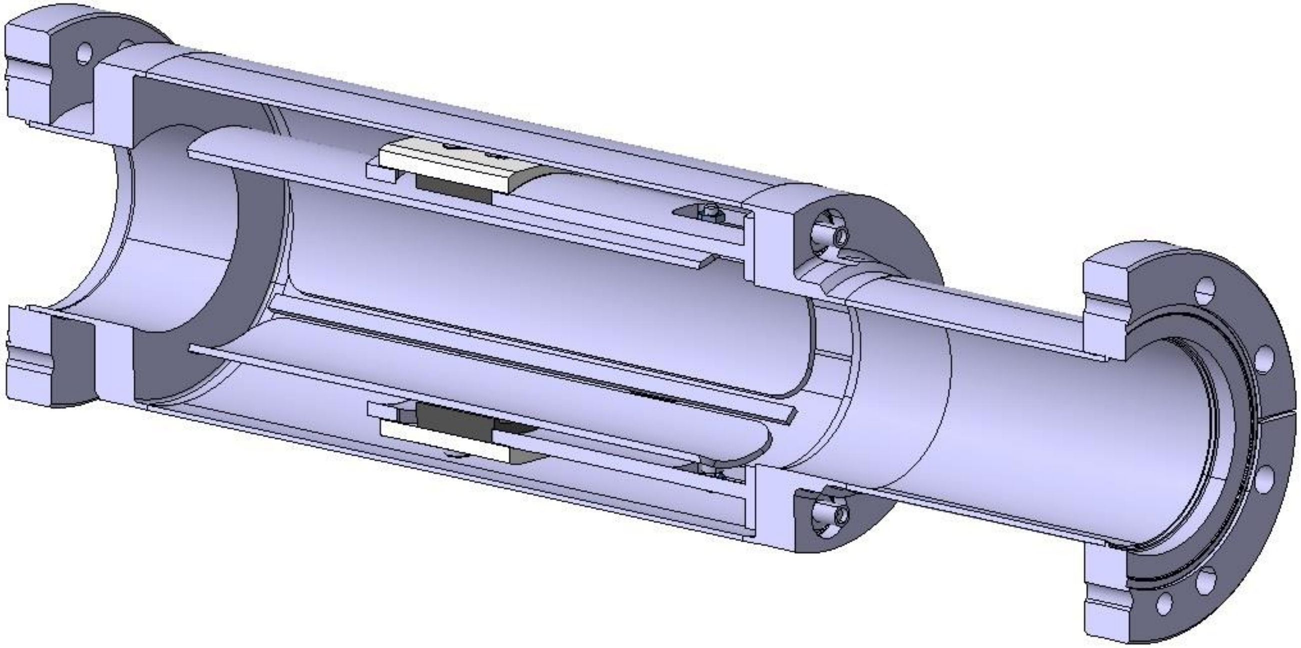
- 1 Dipole V e-gun
- 1 Dipole H e-gun
- 2 Dipole V main
- 2 Dipole H main
- 1 Dipole V at the exit (in series with the bending)

Tot: 6 circuits with current < 450 A, 6 circuits with current < 70 A

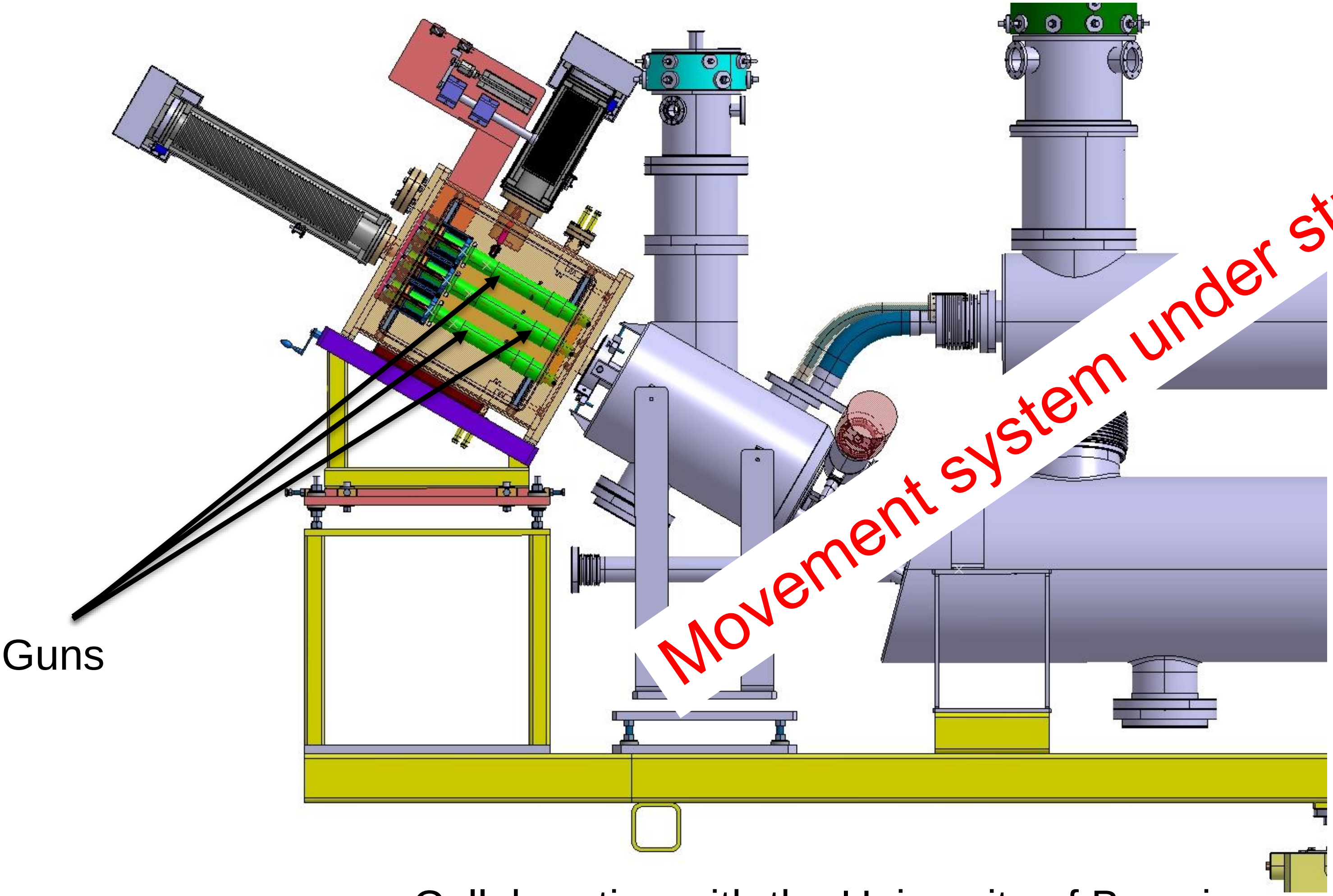


Collaboration with Lapland University of Applied Sciences – Kemi (Fin)

# Longitudinal section of the electron gun region



# Possibility of having multiple guns



Collaboration with the University of Brescia

# Changes since November 2017

**International Review on the e-lens concept readiness for integration into the HL-LHC baseline. October 2017.**

- ✓ Field of the main solenoid from 4T to 5T.
  Main solenoid bore from 200 mm to 180 mm.

- ✓ Pressure load on the He tank 20 bars.

- ✓ One single beam gas monitor in the centre of the system.

- ✓ Simplified construction.

- ✓ Some of the circuits can be in series (less power supplies and current leads).

# Next design steps

Preparation of detailed 3D model, documentation of the assembly sequence, production of a few specification 2D drawings to support the discussions with possible suppliers.

Need of further electron beam stability studies.

- ✓ Optimization of the number and strength of the correctors.
- ✓ Study and optimization of the electron trajectory. Possible small changes of the e-gun solenoid position.

# Cathode development programme

In collaboration with Fermilab and Beijing University of Technology

G. Stancari
Y.Yang, W. Liu, Z. Pan, J. Li, J. Wang, Y. Wang

Goal:

- Demonstrate the feasibility of cathodes and guns delivering the currents required by WP5 for HL-LHC guns (Tevatron x 5).
- Bring know how at CERN.

Programme phases:

Tests at FNAL under LARP: hollow e-beam characterization up to 5-6 A

- re-produce results obtained at FNAL with an LHC-type gun, push the current.
- Optimize the gun. Smaller size for HL-LHC HEL.
- final prototype.

We started early (June 2015) since the cathode size and performances are key parameters of the HEL design.

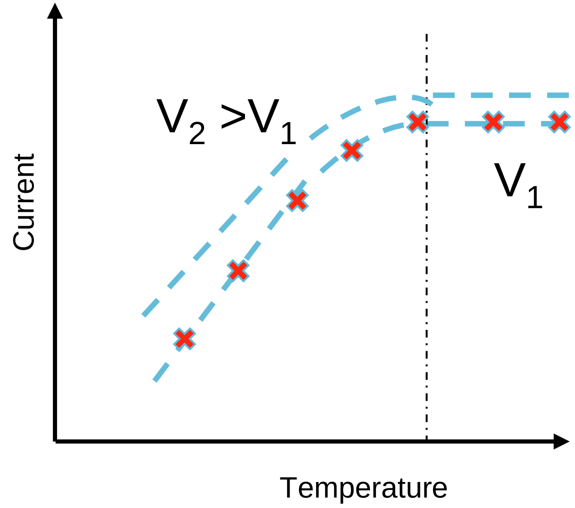
# Cathode development programme

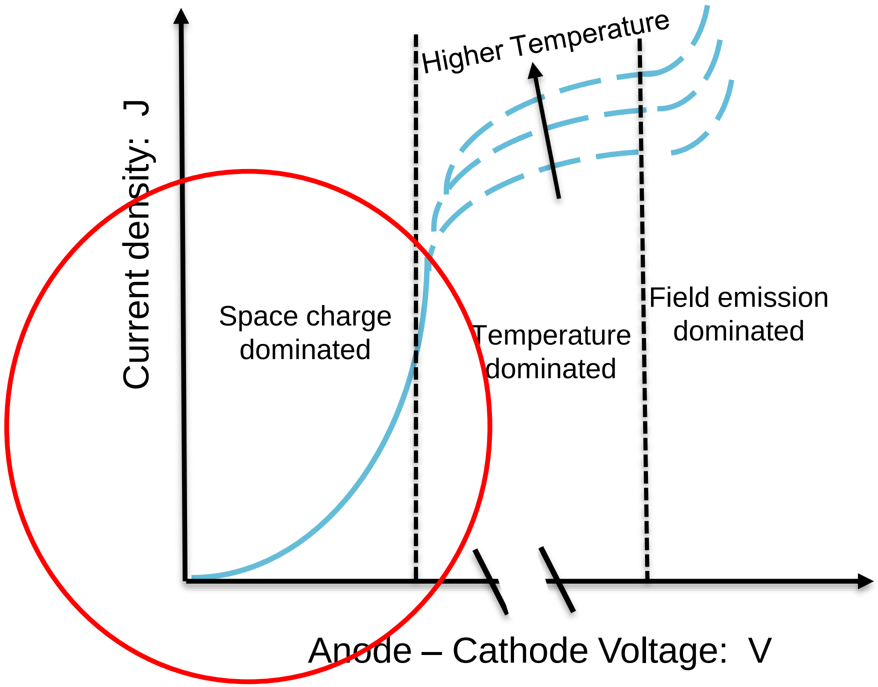
- ✓ Build a test gun with available ‘large’ size cathode. Annular impregnated barium calcium aluminate dispenser cathode. Tungsten matrix. Dimensions OD=25.4 mm, ID 12.5 mm. Current 5 A, $J=1.3\ A/cm^2$. T 1100 °C.
- ✓ Build and test a HEL size cathode. Use an intermediat r as possible to the first one. Annular nano-sized ser cathode, adapted from existing production .05 mm. Current 5 A, $J=3.28\ A/cm^2$. T
- ✓ Design an optim nsions.
- ✓ B -sized Scandia doped dispenser cathode with an mm, ID=4 mm. Current 5 A, J= $13.2\ A/cm^2$. T 8
- ✓ Buil e same cathode with OD=16.1 mm ID=8.05 mm.
- ✓ Build an optimized gun and test it with nano-sized Scandia doped dispenser cathodes:
  - Dimensions OD=16.1 mm, ID 8.05 mm. Current 5 A, $J=3.28\ A/cm^2$. T 950 °C
  - Dimensions OD=16.1 mm, ID 8.05 mm. Current 5 A, $J=3.28\ A/cm^2$. T 850 °C.

High currents and low temperatures are important to operate efficiently the HEL.

Decreasing cathode surface and working temperature

# Definition of perveance: P





Free parameters in design:

- Cathode Surface: A ($R_i$ , $R_o$)
- Cathode – Anode distance: d

$I = P V^{3/2}$ $I = J A$

$P = K A/d^2$

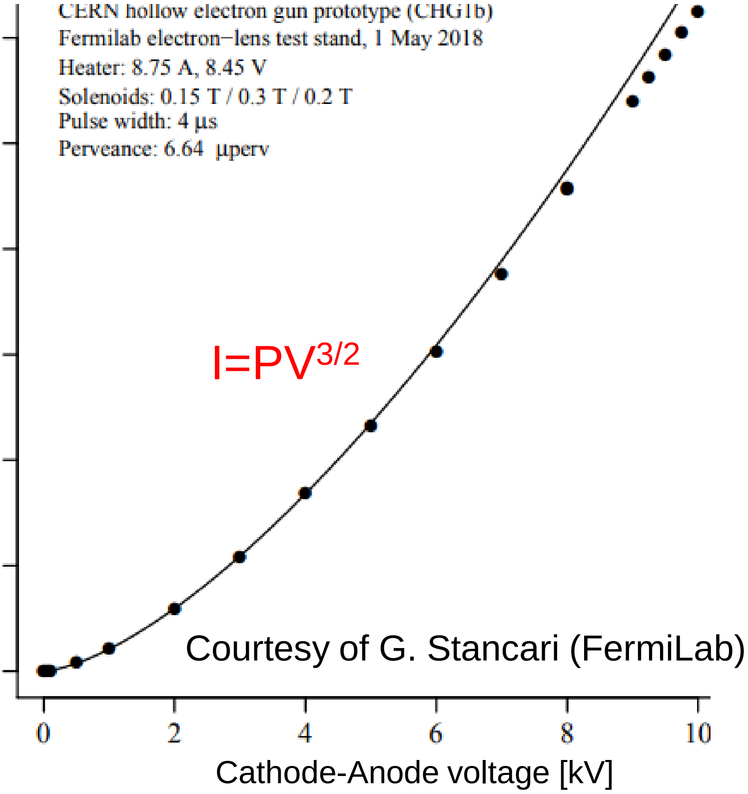
# Results of the CERN hollow electron gun prototype (CHG1)

Perveance 6.64 μperv

Tungsten dispenser cathode,
OD=25.0 mm, ID=12.5 mm , S= 3.68 cm$^2$

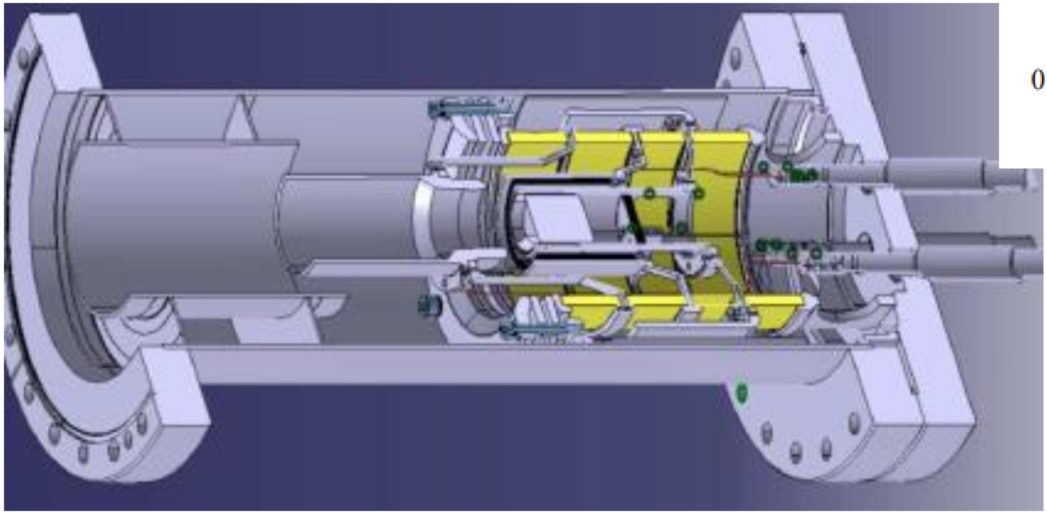
Cathode temperature ~ 1100 $^o$C
(8.9 A , 8.6 V).

Current 6.25 A at 10 kV. $J_{max}$=1.7 A/cm$^2$



$I=PV^{3/2}$

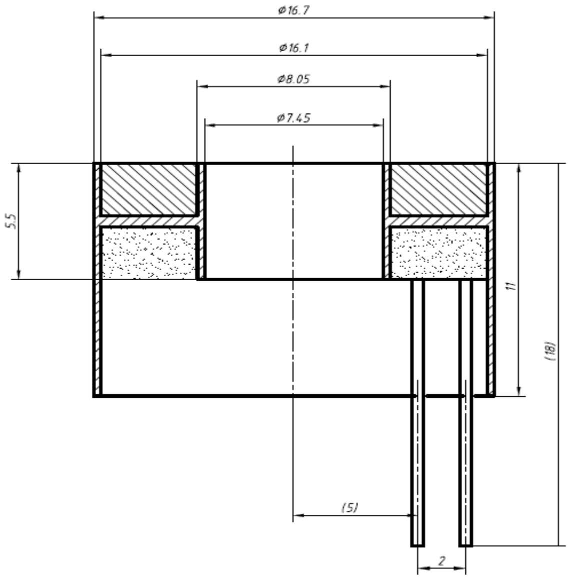
Courtesy of G. Stancari (FermiLab)



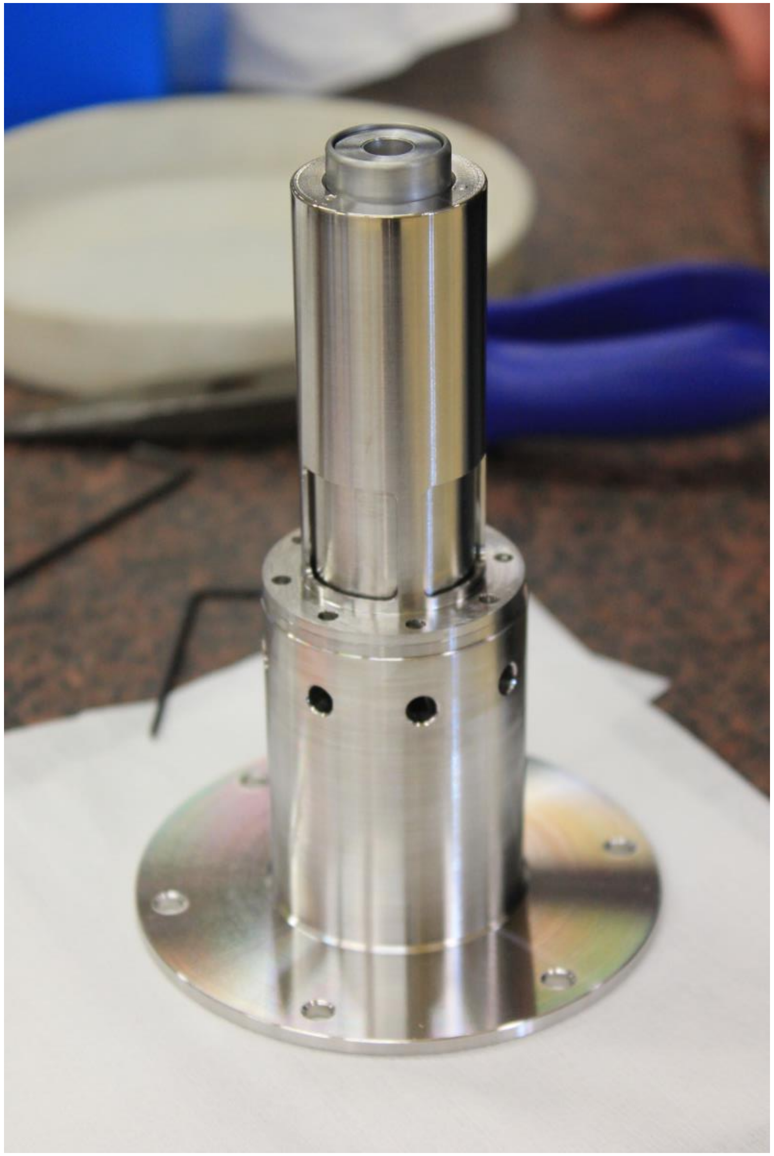
Total weight ~23 kg, outside diameter ~ 100 mm

Cathode No：001#  Type：Scandate

HEL good size
Outer diameter: 16.1mm
Internal diameter：8.05mm    $S = 1.5\,cm^2$;

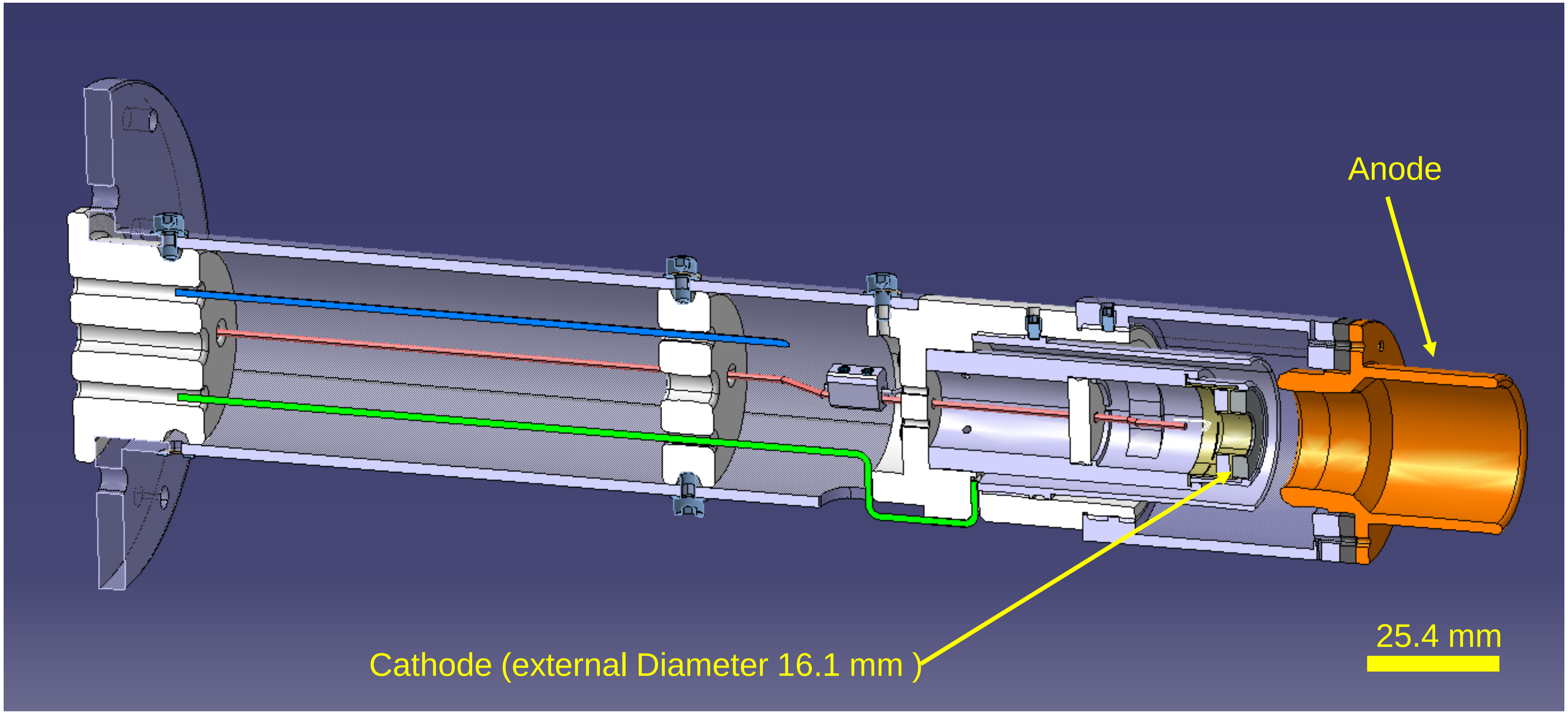


| T(℃b) | Saturation Current density<br>J a（$A/cm^2$） |
|---|---|
| **800** | 1.6 |
| **850** | >4.1 |
| **900** | >5.1 |
| **950** | >5.7 |
| **1000** | >5.1 |



Cathode adapted from a similar application.
E-gun adapted to house the smaller size cathode.
Parts at Fermilab. Tests are starting.

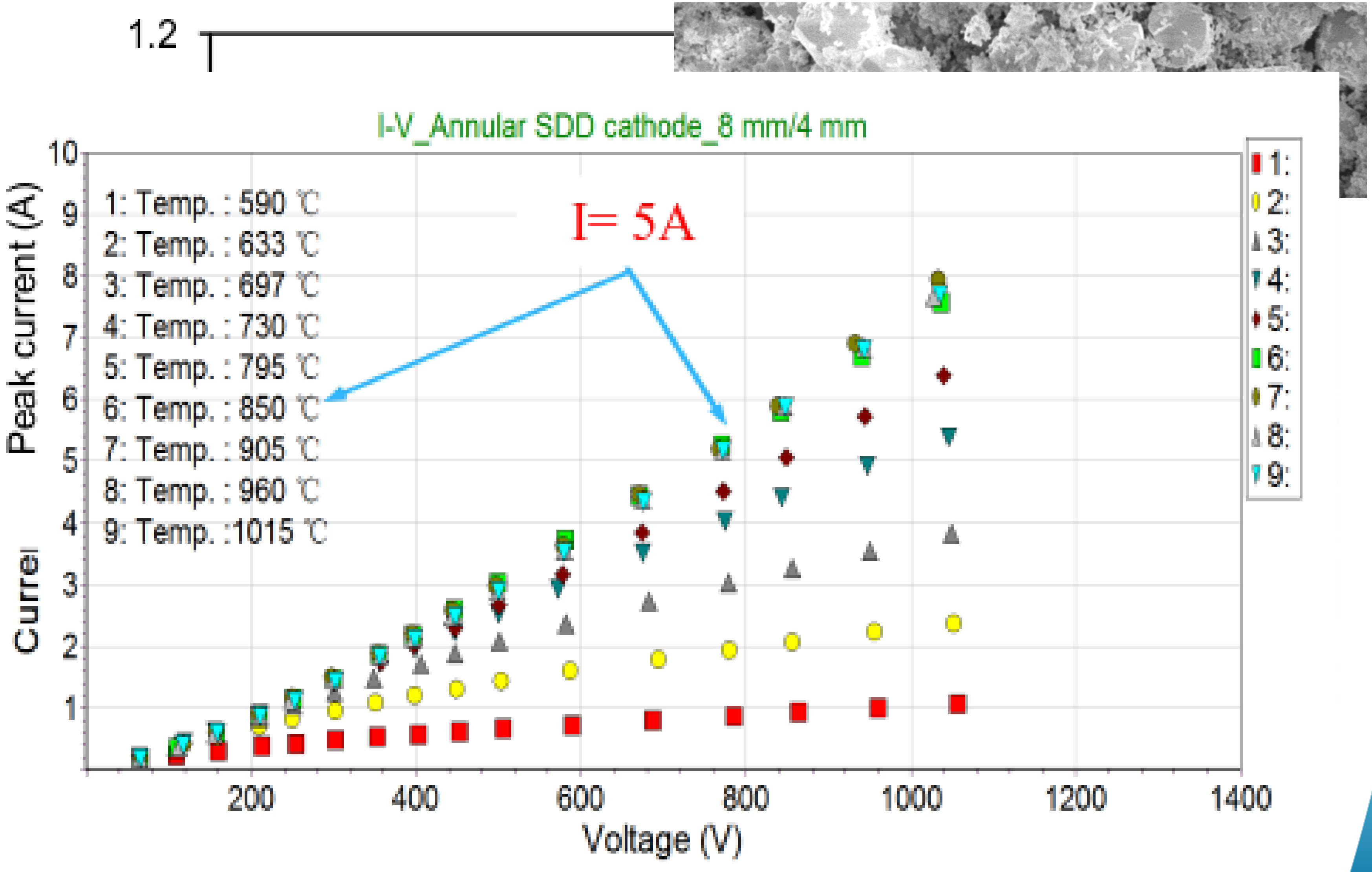
# Longitudinal section of the optimized electron gun



Total weight < 1 kg

# Optimized cathode for HEL.

## First test with small diameters (8 mm – 4 mm)



# Next steps

- Test the first real size Scandia doped cathode (16.1 mm external diameter) in Fermilab (from June 2018).
- Build the first real size gun and test it with Scandia doped cathodes. (from end 2018).

# Conclusions

- The design of the HEL is almost ready. In some weeks we will have a consolidated CAD model to discuss with possible suppliers.

- The development of optimized gun and cathodes is well advanced. First results are very positive. Now we have to build and test the final configuration. Results are expected during next year.

- It is possible to reduce the surface of the cathode and its working temperature.

- Many thanks to the colleagues of Fermilab and of the Beijing University of Technology.

HiLumi
HL-LHC PROJECT

# *Thank you for your attention*

CERN

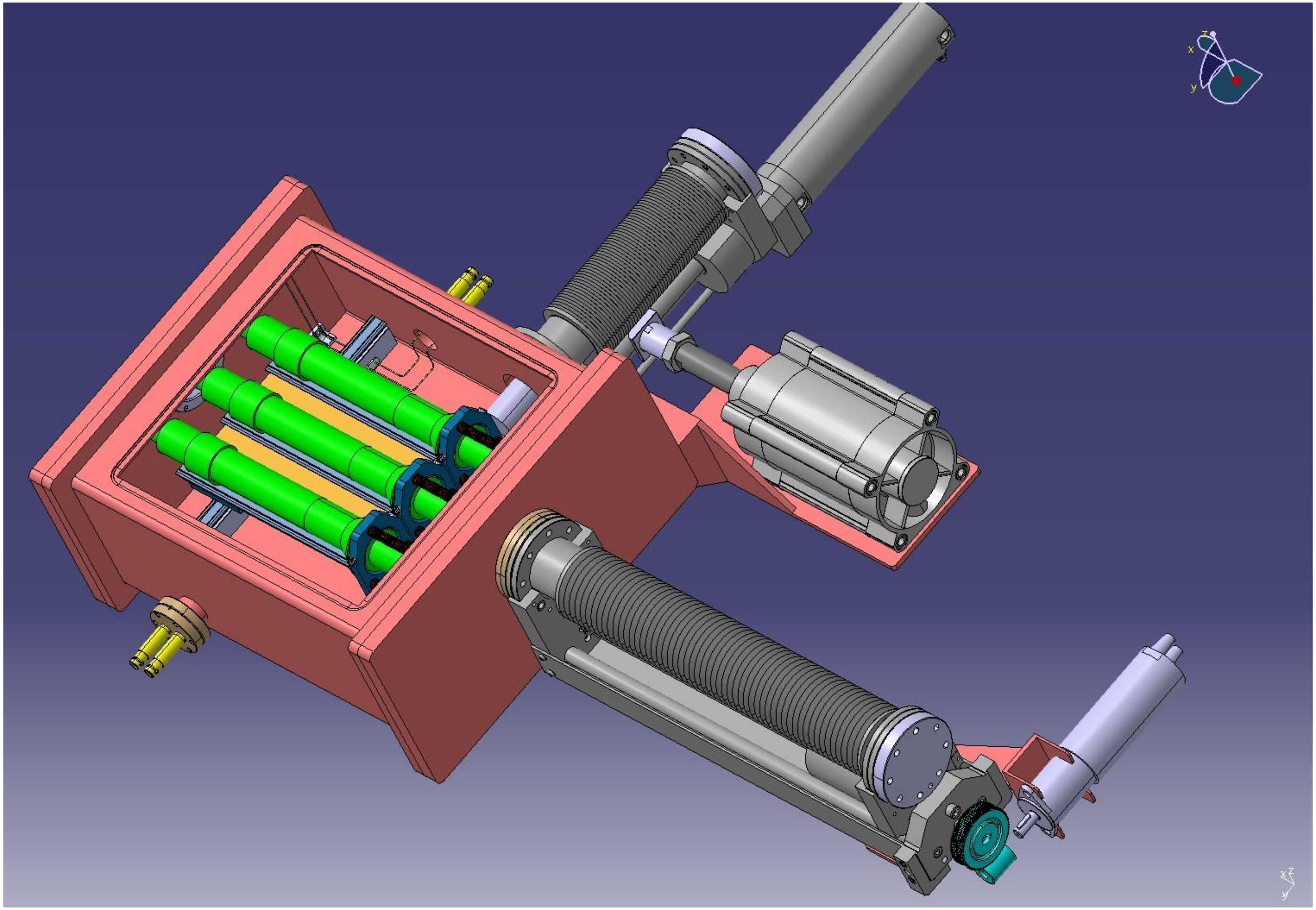
# Where?

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

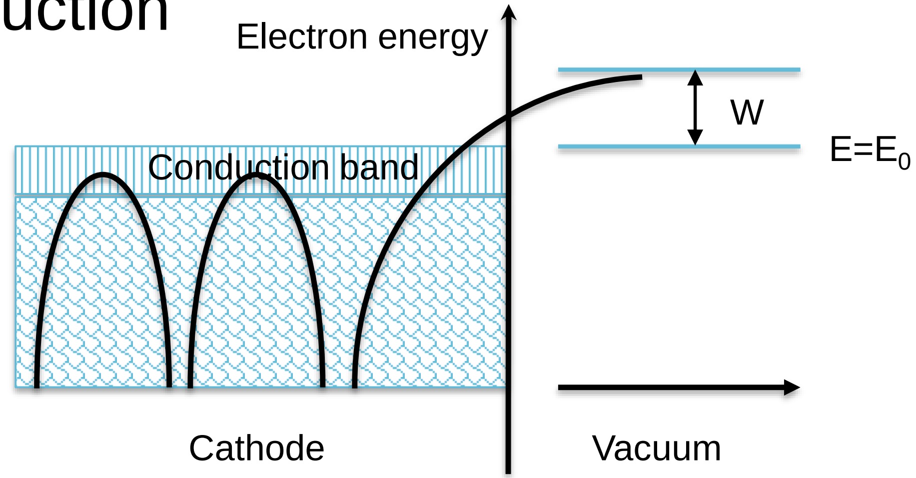
The beam to beam distance is 420 mm.
The longitudinal available space is limited.

→

Compact design


x
y
z

# Electron beam production



Electrons need to be moved from bound states to the vacuum level
External excitation:

- Light (photoemission)
- Thermal energy (thermionic emission)

The work function W is the minimum energy to overcome.

# Richardson-Dushman equation: $J = A_0 T^2 \exp(-W/kT)$

J current density [$mA/mm^2$]
$A_0$ is Richardson's constant. $A_0 = \sim 1202\ mA/mm^2K^2$
W is the work function of the cathode material (J or eV)
k is the Boltzmann constant (8.6173324E-5 eV $K^{-1}$)
T temperature of the cathode [K]

| | Melting point | W | |
|---|---|---|---|
| Tungsten | 3695 K | 4.3 eV | Highest melting point |
| Barium | 1000 K | 2.11 eV | Low work function |

| Material | | W (eV) |
|---|---|---|
| Molybdenum | | 4.15 |
| Nickel | 4.61 | |
| Tantalum | | 4.12 |
| Tungsten | | 4.54 |
| Barium | 2.11 | |
| Cesium | 1.81 | |
| Iriduim | 5.40 | |
| Platinum | 5.32 | |
| Rhenium | | 4.8 |
| Thorium | 3.38 | |
| Ba on W | 1.56 | |
| Cs on W | 1.36 | |
| Th on W | 2.63 | |
| Thoria | 2.54 | |
| BaO + SrO | | 0.95 |
| Cs-oxide | 0.75 | |
| TaC | 3.14 | |
| LaB6 | 2.70 | |

# Impregnated tungsten cathode dispenser

It is possible to combine the two favourable properties of these elements to obtain a cathode with low work function at high temperature.

Produce a Tungsten matrix containing Barium compound.

- Barium Calcium aluminate BaO : CaO : $Al_2O_3$
- Porous tungsten $\rho < 0.8\rho_{\text{theor}}$

During operation free Barium is ‘dispensed’.

$$6\ BaO + W \longrightarrow 3\ Ba + Ba_3WO_6$$

The released Barium diffuses to the surface and forms a low work function monolayer.