Characterization of CERN Scandia doped hollow electron gun (CHG-16-sc) at Fermilab electron-lens test stand

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Outline

- Introduction
  - Cathode
  - E-gun design development

- Installation of Scandia-doped cathode e-gun (CHG-16-sc) at FNAL

- Tests of Scandia-doped cathode e-gun (CHG-16-sc) at FNAL

- Next steps

- Conclusions
Introduction

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

- Electron beam generated by hollow cathode
- Thermionic cathode $\rightarrow$ electron emission $T$ - activated

**ANODE**  **CATHODE**

- Porous tungsten matrix impregnated with oxides

\[ E=E_F \text{ Fermi level} \]
\[ T=0K \]
HEL cathode

Target: minimize cathode dimensions fulfilling the HEL requirements

<table>
<thead>
<tr>
<th>HEL parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field of the main solenoid $B_{MS}$</td>
<td>5 T</td>
</tr>
<tr>
<td>Magnetic field in the e-gun $B_{GS}$</td>
<td>0.25 T</td>
</tr>
<tr>
<td>Inner radius of hollow electron beam</td>
<td>0.9 mm</td>
</tr>
<tr>
<td>Outer radius of hollow electron beam</td>
<td>1.8 mm</td>
</tr>
<tr>
<td>Cathode - Anode voltage difference $V$</td>
<td>10 kV</td>
</tr>
<tr>
<td>Current at cathode $I$</td>
<td>5 A</td>
</tr>
</tbody>
</table>

Dimensions

A small cathode allows decreasing the field in main solenoid

$$\frac{R_{\text{beam,cathode}}}{R_{\text{beam,MS}}} = \sqrt{\frac{B_{MS}}{B_{GS}}}$$

Performance

Small cathode means high current density → material play a key role

- Barium aluminate dispenser $\bar{O}_o = 25$ mm $J < 2$ A/cm$^2$
- Scandia doped dispenser $\bar{O}_o = 8$ mm $J > 20$ A/cm$^2$

HEL cathode parameters

$\bar{O}_o = 16.10$ mm $\bar{O}_i = 8.05$ mm $J = 3.3$ A/cm$^2$
Scandia-doped cathode

Scandia-doped W cathode

\[ \varnothing_o = 16.10 \text{ mm} \quad \varnothing_i = 8.05 \text{ mm} \]

\[ J = 3.3 \text{ A/cm}^2 \]

BVERI (Beijing Vacuum Electronics Research Institute)
BJUT (Beijing University of Technology)

Required current density = 13.6 A/cm²

\[ \varnothing_e = 8 \text{ mm} \]

Operating temperature 905 °C
About 50 ° higher than knee

Courtesy of BJUT
First e-gun manufactured at CERN (EN-MME workshop)

- E-gun design: FNAL → few modifications added (different standards)
- HeatWave Labs (US) dispenser cathode - $\varnothing_o = 25 \text{ mm}$ $\varnothing_i = 12.5 \text{ mm}$
- $P = 6.14 \mu \text{perv} \rightarrow 5.5 \text{ A @ 10kV}$
Scandia-doped cathode in FNAL e-gun design

February 2018

Manufacturing and first tests

October 2018

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To test HEL size cathode

Second e-gun: design modifications minimized to allow to fit in the HEL nominal dimension cathode

- FNAL e-gun design with scaled electrode dimensions
- BJUT & BVERI Scandia-doped cathode

\[ \Phi_o = 16.10 \, \text{mm} \quad \Phi_i = 8.05 \, \text{mm} \]
E-gun installation at FNAL

- **June 5, 2018** → Scandia-doped cathode installed in CHG1b electron gun body at FNAL electron-lens test stand (Coiffet, Gobbi, Stancari and Crawford)

  - CHG1 disassembling – insert HEL cathode with scaled electrodes – electrical connections – e-gun installation in the test stand – pump down

- New e-gun assembly → **CHG-16-sc** (CERN hollow gun, 16 mm diameter, Scandia-doped cathode)
Scandia-doped cathodes first test objectives:

• Small cathode can deliver 5 A needed for HEL?

• Scaled electrode distance and dimensions match perveance of CHG1 e-gun?
Tests at FNAL – first cathode heating

Possible factors:

- aging of one ion-getter pump → improved after high-voltage conditioning
- one faulty HV ion-pump controller → replaced
- outgassing of e-gun

Example of first heating procedure

Filament resistance (estimate of temperature)

Ion pump vacuum monitor

Filament current

Courtesy of G. Stancari
Tests at FNAL – first cathode heating

Possible factor:

- Outgassing of the e-gun

Improved electrical connections

Cu wire

Cu connector

Ni wire

Tool to minimize cathode contamination during e-gun assembly
Tests at FNAL – first cathode heating

Second and third heating ramps were faster and smoother

Ion pump vacuum monitor
Filament resistance (estimate of temperature)
Filament current
HV PS current

Courtesy of G. Stancari
At high voltage, cathode still temperature limited → Further conditioning is under way to extend space-charge-limited emission up to 10 kV
Next steps?

- Complete the tests on CHG-16-sc
  - Emission uniformity
  - Profile measurements
  - Long term reproducibility

- E-gun design optimization

Courtesy of G. Stancari – CHG1B 25 mm cathode
Conclusions

- Scandia doped cathode (BVERI & BJUT) for HL-LHC HEL was successfully tested at FNAL.

- The first results, 5.2 A at 10 kV, prove that the cathode fulfills the HEL requirements!

- Next tests to measure the profile and to assess the long-term performance of the cathode foreseen for the next months at FNAL.
Thank you for your attention
Perveance

Child-Langmuir law:

\[ I = PV^{3/2} \]

\[ I = JA \quad P = \text{const} \cdot \frac{A}{d^2} \]

- \( A \) cathode area
- \( d \) cathode-anode distance
Impregnated tungsten dispenser cathode

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

Produce a Tungsten matrix containing Barium compound.

- Barium Calcium aluminate $\text{BaO : CaO : Al}_2\text{O}_3$
- Porous tungsten $\rho < 0.8\rho_{\text{theor}}$

During operation free Barium is ‘dispensed’.

$$6 \text{BaO} + W \rightarrow 3 \text{Ba} + \text{Ba}_3\text{WO}_6$$

The released Barium diffuses to the surface and forms a low work function monolayer.
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Courtesy of Diego Perini