Photoguns development for EIC and cooling

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P3 workshop

November 10-12, 2021

Electron-Ion Collider
EIC Electron sources requirements

Design based on existing RHIC, RHIC is well maintained, operating at its peak

• Hadron storage ring 40-275 GeV (existing)
  • RHIC Yellow(Blue) Ring
  • Many bunches, 1160 @ 1A beam current
  • Bright beam emittance
  • Strong hadron cooling (new)

• Electron storage ring (2.5–18 GeV, new)
  • Many bunches,
  • Large beam current (2.5 A) 10 MW S.R. power
  • s.c. RF cavities

• Electron rapid cycling synchrotron (new)
  • High charge polarized pre-injector
  • Spin transparent due to high periodicity

E$_{cm}$ = 20 GeV -141 GeV
High luminosity goal: L = $10^{34}$ cm$^{-2}$s$^{-1}$

100 mA, 1 nC high brightness electron source, lifetime > 1 week

7nC, 56 nA high polarization electron source, lifetime > 2 weeks
Electron gun development at RHIC/EIC

<table>
<thead>
<tr>
<th>Year</th>
<th>113 MHz SRF gun</th>
<th>400 kV HVDC gun</th>
<th>350 kV HVDC gun</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY 16</td>
<td>Commissioning</td>
<td>Operation</td>
<td>Commissioning</td>
</tr>
<tr>
<td>FY 17</td>
<td>Operation</td>
<td>R&amp;D</td>
<td></td>
</tr>
<tr>
<td>FY 18</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>FY 19</td>
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<td>FY 20</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>FY 21</td>
<td></td>
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113 MHz SRF gun: K2CsSb
400 kV HVDC gun: K2CsSb
350 kV HVDC gun: GaAs@780nm
SRF 113 MHz gun for CeC

**SRF Quarter wave resonator advantages: (DC like+RF)**
- 4K operation: Simple cryogenic system; Low cost
- High gradient: Small emittance; High bunch charge
- Long bunch: Reduce the space charge; Generate high bunch charge
- Constant field: Small energy spread
- Good vacuum: Long lifetime

<table>
<thead>
<tr>
<th>Design Goal</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge per electron bunch</td>
<td>0.1 - 10.7 nC</td>
</tr>
<tr>
<td>Peak current</td>
<td>50 -100A</td>
</tr>
<tr>
<td>Bunch duration, psec</td>
<td>12</td>
</tr>
<tr>
<td>Normalized beam emittance</td>
<td>3 - 5 mm mrad</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>78.17 kHz</td>
</tr>
<tr>
<td>CW beam</td>
<td>150 μA</td>
</tr>
</tbody>
</table>

![Diagram of SRF 113 MHz gun](image-url)
K$_2$CsSb Cathode lifetime in the gun for 1 month

- QE decay may be caused by multipacting at RF ramp up and field emission.
- Gun can be operating 78 µA routinely, (maximum 120 µA).
- The R&D will be focused on generating mA, up to 10s mA in next year.
What cause the QE drop in SRF gun?

- Base pressure at the cathode surface is about $2.3 \times 10^{-11}$ torr with the H$_2$O partial pressure under $10^{-13}$ torr.
- The cathode lifetime in our SRF gun is dominated most likely by the transient multipacting during the ramp up of the RF power to the gun to the operational voltage. E.g initial QE ~5% before insertion. <2% in the gun.
- Dark current may contribute to QE decay.
Cavity Performance over years

Typical Gun voltage vs radiation

2016 - 4 cathodes

2017

2016-2020 total 21 cathodes into the gun.
2020-2021 has gun contamination. But recovered by He conditioning.
## LEReC electron source

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>LEReC 2020-21 operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gun Voltage</td>
<td>kV</td>
<td>375</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>nC</td>
<td>36x0.06</td>
</tr>
<tr>
<td>Macro Bunch Charge</td>
<td>nC</td>
<td>2.2</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>MHz</td>
<td>9.3</td>
</tr>
<tr>
<td>Average current</td>
<td>mA</td>
<td>20 (tested 30)</td>
</tr>
<tr>
<td>Laser pulse duration</td>
<td>ns</td>
<td>0.02-0.04</td>
</tr>
<tr>
<td>Radius at the cathode</td>
<td>mm</td>
<td>2</td>
</tr>
<tr>
<td>Cathode peak current</td>
<td>A</td>
<td>2.5-3</td>
</tr>
<tr>
<td>Laser power, QE 5%</td>
<td>W</td>
<td>0.5-5</td>
</tr>
<tr>
<td>Cathode initial QE</td>
<td>%</td>
<td>8-9</td>
</tr>
</tbody>
</table>

- DC gun was built by Cornell University (2016)
- Gun reached 456kV at BNL (Dec. 2016)
- Stable for many hours at 450kV
- K₂CSb Cathode growth and transport system are commissioned (Dec. 2017)
- First operation with CW e-current up to 10 mA (2017)
Cathode storage and transfer

• Base pressure mid-11 torr
• Stores 12 pucks in **Ferris wheel**.
• Travels 1.3 mile in truck from Bldg 531 to RHIC IR2.
• Dark Lifetime >> year. After 6 months, no QE drop.
LEReC cathode lifetime

**QE from 7% to 1% in 12 days**

**QE from 9.5% to 8% in 3 days**

- Typical operation average current is 15-18 mA.
- Typical cathode exchange is once per 2 weeks.
- A step decay in QE was seen day to day between beam runs, compared to a gradual decay during beam operation in a day.
Centered cathode vs off centered cathode

Centered 1cm cathode
Many trips

Off centered 0.6 cm cathode
No trips
K₂CsSb Cathode QE lifetime significantly dropped once laser power on the cathode went above 5W (QE<1%). More studies of the QE drop at high laser power are planned. Likely cool the cathode or use more robust cathode is needed for future EIC.

- Cathode material R&D: Large crystal, surface protection.
- The next year R&D will focus on generating 93 mA beam.
SBU polarized gun R&D

<table>
<thead>
<tr>
<th></th>
<th>EIC</th>
<th>Achieved in stable operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch charge [nC]</td>
<td>7</td>
<td>7.5</td>
</tr>
<tr>
<td>Peak current [A]</td>
<td>3.8</td>
<td>4.8 (No SCL)</td>
</tr>
<tr>
<td>Frequency [Hz] (Bunch train #)</td>
<td>1(8)</td>
<td>1 (8000)</td>
</tr>
<tr>
<td>Voltage [kV]</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Average Current</td>
<td>56 nA</td>
<td>40 uA</td>
</tr>
<tr>
<td>Polarization [%]</td>
<td>&gt; 85%</td>
<td>Bulk (~35%)*</td>
</tr>
</tbody>
</table>

** Measure GaAs polarization at retarding field Mott polarimetry. Our gun beam line doesn’t have Mott polarimeter.

We choose inverted HVDC gun, incorporate following new features:
- Actively cool the cathode using Fluorinert.
- Large cathode with large cathode plug mass and good thermal conductivity.
- Developed low storage energy HV cable.
- X,Y,Z movable, electrically insulated biasable anode.
HVDC gun design

- **Ball diameter**: 20 cm
- **Chamber diameter**: 80 cm
- **Gap distance (lg)**: 5.7 cm
- **Voltage**: 350 kV
- **Cathode size (lc)**: 1.3 cm
- **Electrodes angle (α)**: 22 degs
- **Cathode gradients**: 4.0 MV/m
- **Maximum gradient**: <10 MV/m
- **Anode diameter (la)**: 2.2 cm
- **Peak current**: 4.8 A
- **Bunch charge**: 7 nC
- **N_emittance**: 3.6 mm-mrad
- **Pumping speed**: 35000 L/s
- **Anode bias**: 3000 V

**Graphical Information**
- **DC gap**
- **Triple-point shed**
HV electrodes treatment and installation

Corn cob polish at JLab → HPR at BNL SRF → Installation at SBU

Final assembled → Alignment
Beam-line vacuum in experiment

<table>
<thead>
<tr>
<th>ULVAC gauge</th>
<th>Beam dump</th>
</tr>
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<tbody>
<tr>
<td>Baseline</td>
<td>3-4 e-12</td>
</tr>
<tr>
<td>3 uA</td>
<td>3e-10</td>
</tr>
<tr>
<td>72 uA</td>
<td>1e-9</td>
</tr>
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<th>ULVAC gauge</th>
<th>Beam Line</th>
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<tbody>
<tr>
<td>Baseline</td>
<td>3-4 e-12</td>
</tr>
<tr>
<td>3 uA</td>
<td>5e-12</td>
</tr>
<tr>
<td>72 uA</td>
<td>1.5-3 e-11</td>
</tr>
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Gun Vacuum
3BG gauge

<table>
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<tr>
<th>3BG gauge</th>
<th>Gun</th>
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</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>5-8 e-12</td>
</tr>
<tr>
<td>3uA</td>
<td>Low (c.c)</td>
</tr>
<tr>
<td>72 uA</td>
<td>2e-11,Low (c.c)</td>
</tr>
</tbody>
</table>
Active cooling of HVDC gun

Aiming to absorb the laser power up to 10 W. We are collaborating with Dielectric Sci. developed the active cooling HV feedthrough.

Customer designed HV plug with cooling channel

Tested up to 410 kV with flow

Test in SF6

Routing operation >300 kV with FC72

• Tested in the gun. Operate @300-350 kV for more than 500 hrs. No failure.
• Maintain every 2-4 months.

It was designed for high current operation. Not necessary for EIC polarized source. But benefit to high current polarized/umpolarized gun.
Power supply and HV cable

- 400 kV Power supply is SF6 free set up.
- Resistors for gun conditioning and no resistor for beam operation.
- Custom designed Semiconductor jacket to reduce the stored energy in the cable itself.
Gun conditioned at Dec. 2020 (Total take 23 hrs, Cooling is on):
- Achieved gun design value 350 kV without field emission (without activated GaAs)
- Achieved gun design value 323 kV without field emission (with activated GaAs)
Bunch charge and GaAs Lifetime using 780 nm laser

- Using 7.5 nC bunch charge polarized beam, 400 pulses/s;
- We didn’t observe any QE drop in 16 hrs.
- QE~1%

- Using 7.5 nC bunch charge polarized beam, 5000 pulses/s;
  - With anode bias (orange), we didn’t observe QE drop.
  - Without anode bias (green), 1/e lifetime is 102 hrs.
  - Dominated by the outgassing from FC.

SCL start from 12 C
EIC requirements 7 nC

Beam image before the dump

Testing 9000 pulses on going, limited by laser
Summary

• CeC SRF gun (up to 120 uA) and LEReC HVDC gun (up to 30 mA) are in operation, generating beam for cooling experiment. Both guns show ~weeks operation lifetime.

• Cathode QE degradations mechanisms in high current operation are being studied. More high current experiment are is planned for next year.

• We developed an inverted large cathode HVDC polarized gun. It is operated at 300 kV and ~10 nC bunch charge stably.

• This R&D gun has cathode cooling, low storage energy cable and x,y,z moveable electric insulated anode.

• We have tested up to 64 uA average current of polarized beam. No observable QE decay with anode voltage on.
Thanks for your attention!

Questions

Acknowledge:

and Jlab, Cornell and StonyBrook University colleagues!
Back up
Summary of 2018-2019 cathode production

- 28 cathodes total in 2018
- 38 cathodes total in 2019

<table>
<thead>
<tr>
<th></th>
<th>Run 2018</th>
<th>Run 2019 (to May)</th>
</tr>
</thead>
<tbody>
<tr>
<td># of cathodes</td>
<td>28</td>
<td>38</td>
</tr>
<tr>
<td>RMS Deposition QE (%)</td>
<td>5.41</td>
<td>6.28</td>
</tr>
<tr>
<td>SDEV of QE (%)</td>
<td>0.97</td>
<td>0.85</td>
</tr>
</tbody>
</table>

- 10 cathodes
- 0.87% increase
- 0.12 decrease
High intensity electron sources

- Quarter-wave SRF photo-electron gun
- 4 K operating temperature
- Bi-alkali antimonide cathodes with QE up to 11 %
- CW operation at 80 kHz with little QE drop for months
- Bunch charge up to 10.7 nC charge per bunch
- Record low normalized emittance of 0.32 mm mrad at 0.5 nC
- High current operation limited by FPC
Beam Emittances from the gun

<table>
<thead>
<tr>
<th>Charge (pC)</th>
<th>Normalized RMS emittance (mm-mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>200</td>
<td>0</td>
</tr>
<tr>
<td>400</td>
<td>0</td>
</tr>
<tr>
<td>600</td>
<td>0</td>
</tr>
<tr>
<td>800</td>
<td>0</td>
</tr>
<tr>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>1200</td>
<td>0</td>
</tr>
</tbody>
</table>

- $\varepsilon_y$ @ YAG1 with LEBT1
- $\varepsilon_y$ @ YAG1 with LEBT1 by Kentaro
- $\varepsilon_y$ @ YAG2 with LEBT3
- $\varepsilon_y$ @ YAG2 with LEBT3 by Kentaro
- $\varepsilon_{min}$ @ YAG1 with Gun Sol by Kentaro
- $\varepsilon_{min}$ @ YAG1 with LEBT1
- $\varepsilon_{min}$ @ YAG2 with LEBT3

600 ps laser pulse
Cathode performance in the gun w. multip.

- Multipacting is the main reason that degrades the high QE cathode.
  1. Mask the cathode edge
  2. Cover all the view-ports on the gun to make sure no ambient light could leak into the gun.
  3. Move the main coupler to strong coupling position and off set the center frequency to break the multipacting resonance.
  4. Use pulse mode to boost gun voltage to desired range.
Cavity Turn On Attempt with Strong MP

- Lengthen period between attempts from ~ 20 min to ~ 40 min => 5th attempt = successful turn on.
- Cathode QE not impacted by turn on attempts as MP related vacuum activity is kept minimal.
- Four repeated attempts to turn on result in getting stuck at 22 kV MP barrier.
- Attempts last only 20ms, controlled by LLRF MP trap code.
- Prevents significant energy deposition => vacuum activity which would kill cathode QE.

1 kV turn on (2.3 kV MP level just above) to allow PLL to lock on to cavity resonance.
Beam Current During Experiment

![Graph showing beam current over time]

The graph illustrates the change in beam current over time. The beam current reaches 120 μA at a certain point during the experiment.