Polarized Electron Source for eRHIC

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Electron Ion Collider – eRHIC

EIC Collaboration meeting 2017
• Polarized electron source development at BNL
• 400 MeV pre-injector design
• Recent high current/high charge polarized electron gun R&D project
• Potential polarized electron gun R&D collaboration topics
eRHIC baseline pre-injector specifications

- Low repetition rate, high charge
  - 1 Hz for 10 nC with accumulate in storage ring; Or bunch train for smaller charge.
- Short bunch length
  - 3~6 ps (< 2 mm) for 2.856 GHz Linac
  - High peak current >2 kA
### eRHIC RR eSource requirements

<table>
<thead>
<tr>
<th></th>
<th>Nominal</th>
<th>SLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch charge [nC]</td>
<td>10</td>
<td>9-16 (20% loss)</td>
</tr>
<tr>
<td>Bunch length [ps]</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>1</td>
<td>120</td>
</tr>
<tr>
<td>Energy [MeV]</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>Polarization [%]</td>
<td>80%-85%</td>
<td>45%-80%</td>
</tr>
</tbody>
</table>

SLC injector meets our requirements. Can we make it better?
- Less beam loss
- Simplify maintain
• Recent results from SVT/JLab using DBR super lattice GaAsP photocathode.
• QE is greater than 5%.
• Achieved 86% polarization at the peak.
Gun choices for eRHIC injector

- First load-locked gun used at an accelerator
- High bunch charge, low avg. current, very long operating lifetime
- Four days to re-activate photocathode, because load lock at HV...

- Inverted shape has less outgassing surface and eliminated field emission to ceramic
- High average current, long operating lifetime.
- Easy to replace GaAs cathode.
- $10^{-12}$ torr scale vacuum
## Comparison of guns

<table>
<thead>
<tr>
<th></th>
<th>SLC</th>
<th>Inverted gun (JLab)</th>
<th>Inverted gun in fabrication (BNL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage [kV]</td>
<td>120</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>Gradient [MV/m]</td>
<td>1.8</td>
<td>3.4</td>
<td>4.2</td>
</tr>
<tr>
<td>Cathode size [cm²]</td>
<td>3</td>
<td>1.13</td>
<td>4.98</td>
</tr>
<tr>
<td>Pulse length [nC]</td>
<td>2</td>
<td>0.01</td>
<td>1.5</td>
</tr>
<tr>
<td>Bunch charge [nC]</td>
<td>16 (9~12)</td>
<td>0.003</td>
<td>10</td>
</tr>
<tr>
<td>Average current [µA]</td>
<td>5</td>
<td>4000</td>
<td>NA (to be measured)</td>
</tr>
<tr>
<td>Charge lifetime[C]</td>
<td>&lt;1 (20% loss)</td>
<td>80 (0.1% loss)</td>
<td>NA (to be measured)</td>
</tr>
<tr>
<td>In-situ Cs evap.</td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Bias Anode</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>
### BNL large cathode inverted gun

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Inverted gun (LR)</th>
<th>Inverted gun (RR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball diameter</td>
<td>20 cm</td>
<td>20 cm</td>
</tr>
<tr>
<td>Chamber diameter</td>
<td>80 cm</td>
<td>50 cm</td>
</tr>
<tr>
<td>Gap distance (lg)</td>
<td>5.7 cm</td>
<td>5.7 cm</td>
</tr>
<tr>
<td>Voltage</td>
<td>350 kV</td>
<td>350 kV</td>
</tr>
<tr>
<td>Cathode size (lc)</td>
<td>1.26 cm</td>
<td>1.50 cm</td>
</tr>
<tr>
<td>Electrodes angle (α)</td>
<td>22 degs</td>
<td>28 degs</td>
</tr>
<tr>
<td>Cathode gradients</td>
<td>3.8 MV/m</td>
<td>4.0 MV/m</td>
</tr>
<tr>
<td>Maximum gradient</td>
<td>9.9 MV/m</td>
<td>10 MV/m</td>
</tr>
<tr>
<td>Anode diameter (la)</td>
<td>1.8 cm</td>
<td>2.2 cm</td>
</tr>
<tr>
<td>Pumping speed</td>
<td>35000 L/s</td>
<td>35000 L/s</td>
</tr>
<tr>
<td>Space charge limit</td>
<td>Up to 45 A</td>
<td>Up to 45 A</td>
</tr>
<tr>
<td>Anode bias</td>
<td>3000 V</td>
<td>3000 V</td>
</tr>
</tbody>
</table>
Gun and cathode preparation

Cathode preparation system

The RR gun will be similar to the R&D gun, except
- More optimized chamber
- Pumps setup
- Optimized Pierce shape (similar to SLC gun)
- Larger cathode
10 nC case

Beam Energy: 400 MeV

RMS bunch length 1.8 mm ~ 6 ps

Energy spread dp/p: 2e-2

N_ε x,y: 55mm-mrad
Beam trajectory
The polarized gun R&D goal:

- High average current (6~50 mA), high bunch charge (5.3 nC) large cathode inverted gun for L-R eRHIC source.
- High bunch charge for R-R eRHIC source.

Sub-R&D items:

- Achieve and measure XHV
- High power laser
- Eliminate ion back bombardment
- Surface charge limit measurement
- Lifetime as the function of charge
- Beam halo reduction studies
- Cathode cooling

BNL 1st inverted gun in fabrication
### E-gun beam test

E-gun beam test setup diagram with labeled components: TSP, FCT, BPM, NEG.

#### Now

<table>
<thead>
<tr>
<th></th>
<th>check</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gun vacuum [torr]</strong></td>
<td>$&lt;1 \times 10^{-11}$</td>
</tr>
<tr>
<td><strong>High voltage [kV]</strong></td>
<td>100</td>
</tr>
<tr>
<td><strong>Diagnostics</strong></td>
<td>FCT, YAG, BPM, FC</td>
</tr>
<tr>
<td><strong>Current [uA]</strong></td>
<td>3uA stable/haven’t try higher current</td>
</tr>
<tr>
<td><strong>Beamline vacuum [torr]</strong></td>
<td>$&lt;1.2 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

**In progress:**

- Beamline vacuum [torr]

---

**Now check:**

- Gun vacuum [torr] $<1 \times 10^{-11}$
- High voltage [kV] 100
- Diagnostics FCT, YAG, BPM, FC
- Current [uA] 3uA stable/haven’t try higher current
- Beamline vacuum [torr] $<1.2 \times 10^{-11}$
## Potential R&D collaboration topics

- Cathode lifetime modeling and experiments
- Large cathode gun experiments
- Extremely high vacuum studies
- High polarization cathode and spin related simulation
- Beam halo induced beam loss, Beam dynamics studies
Prolong the cathode lifetime

Larger Laser Size
i. Reduces space-charge emittance growth
ii. Suppresses surface charge limit
iii. Increase charge lifetime

Laser Position on Photocathode and Active Area
i. Avoid ion back bombardment range
ii. Reduce beam halo

Higher Gun Voltage: (Difficult to do in a short term)
i. Less ions are created
ii. Reduce space-charge emittance growth
iii. Increase QE by Schottky Effect

Better vacuum
i. Reduces the ions
ii. Reduces the molecules desorption

- Large cathode gun experiments
- Cathode lifetime modeling and experiments
- Beam loss, Beam dynamics studies
- Extremely high vacuum studies
Estimate charge lifetime

In DC gun, ion back bombardment is dominated the GaAs photocathode lifetime.

Ion generation by the e-beam:
\[
\frac{dN}{dt} = \frac{ni}{e} \int_0^d \sigma(E_{\text{field}})dz = I \times F
\]

Differential equation describe the surface bond damage:
\[
\frac{E(t)}{B} FIdt = -dE(t)
\]

In constant current case, QE decay:
\[
E_{\text{end}}(\tau) = B e^{-\frac{I}{B} F \tau}
\]

Charge lifetime:
\[
L_c = \frac{B}{F} \log\left( \frac{B}{E_{\text{end}}} \right)
\]
B is the bond density times the area

The charge lifetime is proportional to the cathode size and inverse proportional to the F.

F: The number of ions generated by 1C electrons
\[
F(n_i, \sigma(E)) = \frac{ni}{e} \int_0^d \sigma(\int_0^Z E_{\text{field}}(z)dz)dz dZ
\]
Charge lifetime is proportional to the area, inverse proportional to the pressure, increase by enhance the voltage.
If we have beam loss?

• Without RF booster cavities, the downstream ions will be blocked by the biased anode. The beam loss generated desorption gas will go back to dc gap and reduce the charge lifetime.

• With constant peak current, beam loss is proportional to average current.

\[ P = \frac{Q}{S} + P_0 = \frac{(kI + Q_0)}{S(P)} + P_0 \]

\[ CL \propto P^{-1} \propto Ions^{-1} \propto I^{-\frac{1}{2}} \]

\[ \propto I^{-1} \text{productlog}\left[\frac{I}{m}\right] \]

With constant average current, how is the charge lifetime changed by the bunch charge?

\[ S(P) = m \log(P) \]
The activated cathode spot is covered by a large number of low energy ions.

The center of the cathode area receives most of the ions with high energy, resulting in much higher power density.

The over focusing of high energy ions are always distributed on opposite direction of laser spots.
This year, JLab is carrying out a high current (mA level) polarized gun test. Large laser size shows that the charge lifetime is saturated, as expected. This is a good chance to study the ion back bombardment and beam loss by simulation and comparison with experiment. Use our large cathode gun to study the limitation of laser size and ion back bombardment modeling.
• large cathode size
  ➢ 2~3mm for the cathode’s offset.
  ➢ 7~9mm for the diameter of the cathode’s illuminated spot. 2~3 mm to the edge.
  ➢ Our total cathode size should be 24.5~27 cm in diameter

• Ring shape laser to eliminate high energy ions back to electron emission position.
• Very useful cathode cooling mechanism.

Courtesy Evgeni Tsentalovich, MIT Bates
Topic III: Extremely high vacuum studies

• If the vacuum could be one order better, the charge lifetime will be one order longer. Cost on the vacuum is very worthwhile.

• Could we get into $10^{-13}$ torr scale?
  ➢ Low outgassing material and post-treatment
  ➢ Outgassing procedure
  ➢ Better XHV pump
  ➢ Better XHV gauge

Material science, Vacuum engineering in universities and Labs
Topic IV and V

- Polarized electron spin dynamics simulation in cathode material. It will help to develop new polarized electron cathode material with robust, high performance and good quality.

- New spin materials study: Spin filter (EuS,Co2MnSi), Optically pumped alkali gas, Topographic Insulator.
Summary

• The RR scheme eRHIC pre-injector design are presented. No show stopper.

• We are developing large cathode inverted prototype DC gun as one of R&D project. Aiming at high current/high charge polarized electron source for cost saving eRHIC.

• The prototype gun has designed and under fabrication right now. The gun fabrication will be ready early next year.

• The potential broad collaboration topics are discussed. We welcome any collaboration on polarized electron source!
Thanks for your attention!
Welcome to have collaborations!
eSource Lab in CAD

• Necessary to build a polarized electron source onsite.

• Most of the floor space is dedicated for the ATF-II project. Recently it was determined the second experimental hall of the ATF-II project will not be constructed for at least the next 5 years. CAD management has agreed to lend this space to be used as the polarized source laboratory.

• The Electron Source R&D facility will be located in the same building as other important facilities that will support it’s efforts.
  ➢ Two class 100 particle free clean rooms
  ➢ Large In-vacuum bake out oven
  ➢ Deionized water source and large high pressure rinsing facilities.
  ➢ 2K system and Cryogenic refrigerator
  ➢ Technical work force
  ➢ Large overhead crane
eSource Lab layout
No risk on R-R source design:
Dr. Charles Sinclair: If the ring-ring eRHIC parameters are really 12.5 nC (4 bunches) and 1 Hz, then I think you will have no problem at all. Several laboratories have demonstrated performances well above this level.

- The eRHIC (RR) polarized electron source needs to generate high charge (12.5 or 50 nC) and high polarization electron beam.

- Both SLC PES gun and JLab inverted gun are being considered. 12.5 nC SL-GaAs DC gun has been achieved by SLC. No show stoppers.

- Series of experiments will be carried out for high charge (50 nC) beam generation.

- New eSource lab will be built onsite.

- Polarized electron source as one of eRHIC R&D project is starting right now.
Coil-plates RF deflector

RF deflector:
Resonant circuits which are tuned with a resonating inductor and a pair of tunable external capacitors in parallel with the deflection plates.
Eight guns beamline arrangement

- Eight guns need 19 deflectors.
- Each deflector bends the beam about 10 degree, then use dipole bending to beam 80 more degree.
- After beam combined, it will be rotated the spin and compression and boost the energy.
Alternative 8 Gun combiner scheme

- Use rotatable magnetic field combiner.
- Reduce the drift length, reduce the energy spread from space charge.
- Fast switch to other 8 guns if one gun fail.
- Simulation considered the rotation factor.
- Normalized transverse emittance:
  \[ \text{Emitt}_x = 45.1 \text{ mm-mrad} \]
  \[ \text{Emitt}_y = 45.6 \text{ mm-mrad} \]
- Bunch length 3mm
- Fine tune the combiner quads and dipole can make both same.