Magnetized Beam

LDRD

Abdullah Mamun
On behalf of JLab Injector Group

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Outline

• Magnetized Bunched-Beam Electron Cooling
• LDRD Magnetized Electron Source
  I. $K_xCs_ySb$ Photocathode and HV Chambers
  II. Gun Solenoid
  III. Beamline
• Generation of Magnetized Electron Beam
• Measuring Electron Beam Magnetization
  – Slit and View-screens
  – $TE_{011}$ Cavity: new non-invasive method
• Measuring Transverse Emittance of Non-magnetized Beam
• Measuring Charge Lifetime from High Current Beams
• Outlook
• Summary
Magnetized Bunched-Beam Electron Cooling

- Ion beam cooling in presence of magnetic field is much more efficient than cooling in a drift (no magnetic field):
  - Electron beam helical motion in strong magnetic field increases electron-ion interaction time, thereby significantly improving cooling efficiency
  - Electron-ion collisions that occur over many cyclotron oscillations and at distances larger than cyclotron radius are insensitive to electrons transverse velocity

- Long cooling solenoid provides desired cooling effect:
  - Counteracting emittance degradation induced by intra-beam scattering
  - Maintaining ion beam emittance during collisions and extending luminosity lifetime
  - Suppressing electron-ion recombination

but putting the electron beam into the cooling solenoid represents a challenge
Electron beam suffers an azimuthal kick at entrance of cooling solenoid. But this kick can be cancelled by an earlier kick at exit of photogun. That is the purpose of cathode solenoid.

Electrons born in strong uniform $B_z$

$$\langle L \rangle = \frac{eB_za_o^2}{4}$$

$a_0 = R_{laser} = 3.14 \text{ mm}$

$B_z = 0.5 \text{ kG}$

Upon exit of Cathode Solenoid

$$\langle L \rangle = \gamma m_e \langle r^2 \rangle \phi$$

$$\varepsilon_d = \frac{eB_z a_o^2}{8m_ec} = 36 \mu\text{m}$$

Upon entering Cooling Solenoid

$$\langle L \rangle = \frac{eB_{cool}r_e^2}{4}$$

$r_e = 0.7 \text{ mm}$

$B_{cool} = 1 \text{ T}$

$$\frac{B_{cool}}{B_z} = \frac{a_0^2}{r_e^2}$$
JLEIC Magnetized Source Requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch length</td>
<td>60 ps (2 cm)</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>43.3 MHz</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>3.2 nC</td>
</tr>
<tr>
<td>Peak current</td>
<td>53.9 A</td>
</tr>
<tr>
<td>Average current</td>
<td>140 mA</td>
</tr>
<tr>
<td>Transverse normalized emittance</td>
<td>&lt;19 microns</td>
</tr>
<tr>
<td>Cathode spot radius – Flat-top ($a_0$)</td>
<td>3.14 mm</td>
</tr>
<tr>
<td>Solenoid field at cathode ($B_z$)</td>
<td>0.5 kG</td>
</tr>
</tbody>
</table>

Cornell University demonstrated 65 mA and 2 nC, but not at same time, and non-magnetized

Fermilab Magnetized Photoinjector Laboratory:
- Pulsed NCRF gun with Cs$_2$Te photocathode and UV laser ($\lambda=263$ nm)
- Bunch charge: 0.5 nC and bunch length: 3 ps
- 0.5% duty factor (average current: 7.5 $\mu$A)
  - Bunch frequency: 3 MHz
  - Macropulse duration: 1 ms
  - Number of bunches per macropulse: 3000
  - Macropulse frequency: 5 Hz
Magnetized Source for e-cooler at 32 mA

- A high charge (420 pC) magnetized source is funded by the Jefferson Lab LDRD program that should operate up to 32 mA average current. This project concludes in 2018.

Magnetized beam parameters:
- $a_0 = 0.1-1$ mm, $B_z = 0-1.5$ kG
- Bunch charge: up to 2 nC
- Frequency: 1-15 Hz, 100-500 MHz
- Bunch length: 50 ps
- Average beam currents up to 32 mA
- Gun high voltage: 200 – 350 kV
Magnetized Beam LDRD

• Three-year project (FY16 – FY18):
  – Generate magnetized electron beam from dc high voltage photogun and measure its properties
  – Explore impact of cathode solenoid on photogun operation
  – Simulations and measurements will provide insights on ways to optimize JLEIC electron cooler and help design appropriate source
  – JLab will have direct experience magnetizing electron beams at high current
LDRD Magnetized Electron Source

- Bialkali Antimonide Photocathode Preparation Chamber, Gun, Solenoid and Beamline are all operational
Photocathode Preparation Chamber

- $K_xCs_ySb$ grown with a mask – limit photocathode active area (3 and 5 mm dia.) to reduce beam halo, minimize vacuum excursions and high voltage arcing, prolong photogun operating lifetime
- Active area can be offset from electrostatic center
- 3 and 5 mm dia. active area available; entire photocathode can be activated too
- Consistently growing photocathodes with 5-7% QE
Photocathode Preparation

• Co-deposition of alkalis (K and Cs) on Sb layer using an effusion alkali source to grow bialkali photocathode.
• Deposition chamber was initially baked at 200 °C for >180 h.
• Vacuum with NEG pumps and an ion pump, Vacuum ~10 nA (~10^{-10} Pa)
• Sb (99.9999%) , K (99.95%), and Cs (99.9+%).
• Working distance: 2 cm, -280 V bias, low power (4 mW) laser (532 nm) and wavelength tunable light source.
• Substrate temperatures: 120 °C (for Sb), dropping from 120 °C to 80 °C (for alkalis).
• Sb heater current supply from 25 A for 10-20 minutes.
• Temperature kept stable at effusion source and adjusted to control alkali evaporation rate: hot air inlet tube (381-462 °C), dispensing tube (232 - 294 °C), and reservoir tube (153 -281 °C).
• Chamber pressure: during bialkali deposition, > 1x10^{-6}Pa and post-deposition to ~10^{-7}-10^{-8}Pa quickly.
• H_{2}O partial pressure < 2x10^{-9} Pa.
Gun HV Chamber

- Upgraded HV Chamber with new doped-alumina inverted insulator and newly designed screening electrode (triple point junction shield) to lower gradient from 12 MV/m to 10 MV/m at 350 kV.
- Photogun operates at 300 kV with gun solenoid at 400 A.

- Two weeks ago we got a setback from ceramic breakdown.
- Under process of replacing with a new ceramic, afterward baking and conditioning the gun for making it operational again.
Use slit and viewscreens to measure mechanical angular momentum:

\[
\langle L \rangle = 2p_z \frac{\sigma_1 \sigma_2 \sin \phi}{D} = eB_z a_o^2
\]

- \( B_z \): solenoid field at photocathode
- \( a_o \): laser rms size
- \( \phi \): rotation (sheering) angle
Gun Solenoid

- Using spare CEBAF Dogleg magnet power supply (500 A, 80 V)
- Learned that gun solenoid can influence field emission
- First trials with gun at high voltage and solenoid ON resulted in new field emission and vacuum activity
- Procedure to energize solenoid without exciting new field emitters

<table>
<thead>
<tr>
<th>Size</th>
<th>11.811&quot; ID, 27.559&quot; OD, 6.242&quot; Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>L=500 m, A=0.53 cm² 16 layers by 20 turns</td>
</tr>
<tr>
<td>Coil Weight</td>
<td>254 kg (560 lbs)</td>
</tr>
<tr>
<td>Resistance</td>
<td>0.198 Ω</td>
</tr>
<tr>
<td>Field at Photocathode</td>
<td>1.5 kG</td>
</tr>
<tr>
<td>Voltage</td>
<td>79 V</td>
</tr>
<tr>
<td>Current</td>
<td>400 A</td>
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</tbody>
</table>

Magnetic field at 400 A
Slit and Viewscreen Measurement

0 G at photocathode

Beamlette observed on downstream viewer

1511 G at photocathode
Gun HV=300 kV, Laser spot size = 0.1 mm rms, Illumination position: 5 mm off centric on photocathode

Gun solenoid magnetizes beam but also focuses beam

Rotation angle influenced by Larmor oscillation in gun solenoid

Three curves correspond to measurements at three beamline viewers

Sign convention followed

JLEIC design requirement=500G

σ (V1)  σ (V2)  σ (V3)
Beam Size and Rotation Angle

Gun HV=300 kV, Laser spot size = 0.3 mm rms, Illumination position: center on photocathode

Beam size (rms), mm

B_z @cathode, Gauss

JLEIC design requirement=500G

Beam on V3 is too large

Rotation angle, degree

B_z @cathode, Gauss

JLEIC design requirement=500G

σ (V1)
σ (V2)
σ (V3)

Slit1-V3
Slit2-V3

B_z at cathode: 831 G

B_z at cathode: 1322 G
With/out Focusing with Beamline Lenses

Gun HV=300 kV, Laser spot size = 0.3 mm rms, Illumination position: center on photocathode

Focusing field used at 2nd lens (MFGGT03) ~ 2400 G-cm (2.206 Amps) and at 3rd lens (MFHGT05) ~ 700 G-cm (0.736 A)
On Center vs Off Center Illumination

Graph 1: Beam size (rms), mm vs. $B_z$@cathode, Gauss
- $\sigma$ (V2), 0.3 mm, on center
- $\sigma$ (V2), 0.1 mm, 5mm off center

JLEIC design requirement=500G

Graph 2: Rotation angle, degree vs. $B_z$@cathode, Gauss
- Slit2-V3, 0.3 mm, on center
- Slit2-V3, 0.1 mm, 5mm off center

JLEIC design requirement=500G

Gun HV=300 kV
Modeling Magnetized Beam

ASTRA simulation of beam size

300 kV 0.3 mm, laser at center position of photocathode
Simulation vs Experimental

Encouraging progress in modeling our apparatus and beam magnetization

Gun HV=300 kV, Laser spot size = 0.1 mm rms, position: 5 mm off center on photocathode

Graph showing beam size (rms) vs. $B_z$ at the cathode, with points indicating ASTRA Simulation and Viewer 1 Measured Size. The JLEIC design requirement is 500 G.
Simulation vs Experimental

In progress of optimizing our simulation

Gun HV=300 kV, Laser spot size = 0.3 mm rms, position: on center on photocathode

Beam size (rms), mm

JLEIC design requirement=500G
**TE$_{011}$ Cavity: Non-invasive Technique**

- New non-invasive technique to measure electron beam magnetization
- Filed inventor disclosure entitled “Non-invasive RF Cavity to Measure Beam Magnetization”
- Mechanical design and vacuum pressure analysis are completed
- Copper blocks are on-site and fabrication is in process

**E-field:**
- only in azimuthal direction

**H-field:**
- only in longitudinal and radial direction

Copper cavity in progress

Waveguide-coax out-coupler
Non-magnetized Beam Emittance

Measured beam emittance, typical thermal angle value of 0.6 mm mrad/mm(rms), consistent with published data

Beam current used ~100 nA

Electrostatic field asymmetry in gun chamber significantly influences emittance growth

Beam current used ~100 nA
Space Charge and Emittance Growth

- Increasing space charge effect causes in increased beam emittance as beam current increases.
- Beam current used for other measurements ~ 100 nA.

- Increasing beam emittance realized at lower gun HV due to increasing space charge effect.
- Operating gun HV at 200-300 kV.

**Normalized Emittance vs Beam Current**
(Gun HV = 200kV, Laser rms = 0.2 mm)

**Normalized Emittance vs Gun HV**
(Lens 1, RF laser, Laser rms = 0.31 mm)
High Current Magnetized Beam

- Delivered 4.5 mA DC magnetized beam for ~7 h.
- Investigated charge lifetime from twenty two 1 h long runs of 3 - 4.5 mA beams at 200-300 kV gun HV, and 0-400 A gun solenoid current conditions. No apparent Lifetime dependency on gun HV, magnetization effect, or run sequence.
- Only 3 times QE dropped due to arcing and happened only with non-magnetized beam. Strong focusing due to gun solenoid might have helped keeping ions stay away from e-beam.
- For same laser spot size (0.38 mm rms) and gun HV, observed better lifetime at lower beam current, or Increased lifetime at lesser laser power
- Investigating the efficacy and necessity of installed dc ion-clearing electrodes to stop ions in beamline from reaching gun and causing HV arcs.
- To improve lifetime we will investigate metal substrate (Mo) and use different K$_2$CsSb photocathode recipes with increasing Sb layer thickness.
Outlook

• Continue to characterize magnetized beam and cross check measurements with simulation
• Measure and simulate space charge effect on magnetized beam
• To study space charge effect with nano-coulombs bunch charge (1-2 nC), we will get a new laser 1-15 Hz, 50 ps.
• Build and install $TE_{011}$ cavity to measure beam magnetization in collaboration with JLab SRF Institute and Brock Roberts (Electrodynamics LLC)
• Demonstrate 32 mA magnetized beam. Need to install a new power supply (225 kV, 32 mA)
• We will study charge lifetime for different photocathode recipes and substrates

**Next:**

- Funded Phase-II SBIR with Xelera, to develop rf-pulsed dc high voltage thermionic gun to be installed at Gun Test Stand (GTS) in FY19 – will use LDRD beamline
- I will be submitting an early career proposal for FY2020 on magnetized injector (if regularized)
Summary

- K_xCs_ySb Photocathode Preparation Chamber, Gun, Solenoid and Beamline are all operational; photogun operates reliably at 300 kV
- Installed wire scanner and measured emittance
- Have successfully magnetized electron beam and measured rotation angle
- Demonstrated 4.5 mA magnetized beam and measured lifetime
- Installed RF pulsed laser, completed installation of Gain switched diode laser (1064 nm, 50 ps Gaussian pulses, doubling efficiency > 30%, 1.8W output, 1497/4=374.25 MHz)
- Then switch to 32 mA 225 kV HV power supply....

Thanks to the people involved in this team work:


ODU Graduate Students
JLEIC High Energy Electron Cooler

High Energy Electron Cooler

ion beam  magnetization flip  magnetization flip  ion beam

B < 0  B > 0  B > 0  B < 0

beam dump  linac  injector

fast extraction kicker  septum  circulating bunches  septum  fast injection kicker

e-re-chirper  vertical bend  extracted  injected  vertical bend  e-re-chirper

Circulator Cooler Ring

12 GeV CEBAF

100 meters
Charge Lifetime of High Current Beam

- No apparent Lifetime dependency on gun HV, magnetization effect, or run sequence
- Only 3 times QE dropped due to arcing and happened only with non-magnetized beam
- Strong focusing due to gun solenoid might have helped keeping ions stay away from e-beam

Graphs showing charge lifetime versus gun HV, solenoid current, and run sequence for different beam currents and gun HV settings.
Charge Lifetime of High Current Beam

- Same laser spot size (0.38 mm rms) and gun HV
  - Better lifetime at lower beam current, or
  - Increased lifetime at lesser laser power
  - Good beam alignment is important

- With HV off: No QE drop from 22 h illumination at 0.8 W (required for 4.5 mA runs), not even at 2 W for 2 h.

- Laser spot size↑ and QE↑, good beam alignment = Photocathode Lifetime↑
<table>
<thead>
<tr>
<th>Distance, m:</th>
<th>S1-V2</th>
<th>S1-V3</th>
<th>S2-V3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Old</strong></td>
<td>0.5</td>
<td>2.2965</td>
<td>1.7965</td>
</tr>
<tr>
<td><strong>New</strong></td>
<td>0.5</td>
<td>2.25666</td>
<td>1.75666</td>
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</table>