Milliampere beam studies using high polarization photocathodes at the CEBAF Photoinjector

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Outline

- **PEPPo** – an application requiring **milliampere** polarized electron beams

- Ion bombardment, the dominant **lifetime limiting mechanism** of polarized photocathodes

- To operate at mA current without interruption, requires **kC charge lifetime**

- R&D to **extend the charge lifetime** of polarized electron sources
Polarized Electrons for Polarized Positrons

\[ e^- \rightarrow \gamma \rightarrow e^+ (\mp e^-) \]

**electron beam polarization**

\[ 85.2 \pm 0.6 \pm 0.7 \% \]

**Positron polarization, \( P_p \)**

**Transfer efficiency, \( \xi_p \)** (\%)

PEPPo demonstrated efficient transfer of polarization from electrons to positrons by bremsstrahlung + pair creation at low energy (<10 MeV).

In the range of 10-100 MeV conversion efficiency \( 10^{-4} \) to \( 10^{-3} \) suggests useful polarized positron current benefits from milliamperes of polarized electrons.

Polarization Studies at mA Beam Current

First measurement of beam polarization at JLab from superlattice (GaAs/GaAsP photocathode at milli-Ampere current

CEBAF 5 MeV Mott polarimeter: on-going effort to ascribe **sub-percent accuracy** (collaborators D. Moser, X. Roca-Maza, Charles Sinclair, M.J. McHugh, and Tim Gay)

![CEBAF 5 MeV Mott Polarimeter](image)

![Graph showing polarization vs. beam current](image)
CEBAF Load Lock Photogun (-130kV)

CEBAF Polarized Inverted Load Lock Gun (Spring 2017)

1 mA  86 C/day
5 mA  432 C/day
10 mA 860 C/day
50 mA 4320 C/day
Gun2 Photocathode (Fall 2016 – Spring 2017)

- Strained Superlattice GaAs/GaAsP #5756-4
- Good Polarization 85-87% (measured at Mott)
- Good QE > 1% after activation => 6 mA/Watt/% @ 780 nm
- Lifetime about 200°C ($\sigma_{4D} \sim 1\text{mm}$) with intensity < 200μA
Ion Bombardment
Improving Lifetime with Larger Laser Size


GaAs @ 532nm
Indeed, we enhanced the Charge Lifetime for QWeak by a factor of four when doubling the laser spot size from 0.5 mm to 1.0 mm (diameter)

But milliampere applications require kiloCoulomb charge lifetime to provide uninterrupted operation of reasonable duration.
Lifetime Studies at mA Beam Current

Polarized positrons for CEBAF, and on-going discussions with BNL related to high current eRHIC EIC, prompted experiments at CEBAF to characterize lifetime vs. laser spot size using high-polarization photocathodes.

Make beam here
(-130kV, 0-1.5mA, 0-3pC)

Monitor vacuum and radiation levels along beam line

Vary the laser beam size
(f=499 MHz, $\sigma_t \sim 50$ ps)

Deliver it here
(Faraday cup)
Variation of Laser Spot Size

- Photocathode diameter 5 mm (defined by a mask during activation)
- Varied laser diameter $\sigma_{4D} \sim 1$-5 mm (area 3-20 mm$^2$)
- Laser profile defined at photocathode plane
Lifetime Studies at mA Beam Current

Required laser power, slope proportional to QE decay

1 mA

Increasing laser size reduces QE decay proportionally

Adjust beam to decrease level
First Results: GaAs/GaAsP at mA Current

- CEBAF charge lifetime improves with spot size, as expected, but eventually beam size becomes “too large”
- Laser diameters greater than ~4 mm (4 sigma) will require properly designed cathode/anode electrodes, to ensure 100% transmission, to maintain excellent vacuum, to minimize ion bombardment

1 mA for 7 days is 600 C

1mA(2007)

CEBAF(2011)
Sensitivity of x-ray detectors for beam loss

X-ray monitors demonstrate high sensitivity and localization for beam intentionally lost. Sensitivity as good as 60 pA (typ. 1-5 nA)

While increased vacuum levels are a good indicator of decreased photocathode lifetime, in this study we observe little indication of beam loss.
The best charge lifetime is achieved when x-ray levels are smallest.
Vacuum vs. Lifetime

- Correlation of vacuum with charge lifetime most evident near the Gun
- Vacuum levels generally not as sensitive as x-ray levels
Managing Laser Power to Improve Charge Lifetime

✓ A large fraction of laser light (33%) is reflected from GaAs leading to the possibility of “stray” electrons, a bad thing...
✓ The remaining light is mainly absorbed in GaAs substrate, leading to heating, also a bad thing...

(6mA/%/W)

I = 1 mA

QE < 1%

=> P > ~100’s mW
Benefits of Distributed Bragg Reflector (DBR)

- Standard strained superlattice: absorption in the GaAs/GaAsP superlattice < 5%
  - Most light passes into the substrate leading to unwanted heating
- DBR photocathode: absorption in the GaAs/GaAsP superlattice > 20%
  - Less light required to make required beam, less light means less heat

- The highest reported QE of any high polarization photocathode
- Excellent candidate for mA operations, will test at CEBAF this shutdown

## Source Parameter Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CEBAF</th>
<th>SLC</th>
<th>JLab/FEL</th>
<th>Cornell ERL</th>
<th>LHeC</th>
<th>eRHIC</th>
<th>CLIC</th>
<th>ILC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polarization</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Number electrons/microbunch</strong></td>
<td>$2.5 \times 10^6$</td>
<td>$1 \times 10^{11}$</td>
<td>$8.3 \times 10^8$</td>
<td>$4.8 \times 10^8$</td>
<td>$1 \times 10^9$</td>
<td>$2.2 \times 10^{10}$</td>
<td>$6 \times 10^9$</td>
<td>$3 \times 10^{10}$</td>
</tr>
<tr>
<td><strong>Number of microbunches</strong></td>
<td>CW</td>
<td>2</td>
<td>CW</td>
<td>CW</td>
<td>CW</td>
<td>CW</td>
<td>CW</td>
<td>312</td>
</tr>
<tr>
<td><strong>Width of microbunch</strong></td>
<td>50 ps</td>
<td>2 ns</td>
<td>35 ps</td>
<td>2 ps</td>
<td>100 ps</td>
<td>~ 100 ps</td>
<td>~ 100 ps</td>
<td>~ 1 ns</td>
</tr>
<tr>
<td><strong>Time between microbunches</strong></td>
<td>2 ns</td>
<td>61.6 ns</td>
<td>13 ns</td>
<td>0.77 ns</td>
<td>25 ns</td>
<td>71.4 ns</td>
<td>0.5002 ns</td>
<td>337 ns</td>
</tr>
<tr>
<td><strong>Microbunch rep rate</strong></td>
<td>499 MHz</td>
<td>16 MHz</td>
<td>75 MHz</td>
<td>1300 MHz</td>
<td>40 MHz</td>
<td>14 MHz</td>
<td>1999 MHz</td>
<td>3 MHz</td>
</tr>
<tr>
<td><strong>Width of macropulse</strong></td>
<td>-</td>
<td>64 ns</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>156 ns</td>
<td>1 ms</td>
</tr>
<tr>
<td><strong>Macropulse repetition rate</strong></td>
<td>-</td>
<td>120 Hz</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>50 Hz</td>
<td>5 Hz</td>
</tr>
<tr>
<td><strong>Charge per micropulse</strong></td>
<td>0.4 pC</td>
<td>16 nC</td>
<td>133 pC</td>
<td>77 pC</td>
<td>500 pC</td>
<td>3.6 nC</td>
<td>0.96 nC</td>
<td>4.8 nC</td>
</tr>
<tr>
<td><strong>Charge per macropulse</strong></td>
<td>-</td>
<td>32 nC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>300 nC</td>
<td>14420 nC</td>
</tr>
<tr>
<td><strong>Average current from gun</strong></td>
<td>200 uA</td>
<td>2 uA</td>
<td>10 mA</td>
<td>100 mA</td>
<td>20 mA</td>
<td>50 mA</td>
<td>15 uA</td>
<td>72 uA</td>
</tr>
<tr>
<td><strong>Average current in macropulse</strong></td>
<td>-</td>
<td>0.064 A</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.9 A</td>
<td>0.0144 A</td>
</tr>
<tr>
<td><strong>Duty Factor</strong></td>
<td>$2.5 \times 10^{-2}$</td>
<td>$2.8 \times 10^{-7}$</td>
<td>$2.6 \times 10^{-3}$</td>
<td>$2.6 \times 10^{-3}$</td>
<td>$4 \times 10^{-3}$</td>
<td>$1.4 \times 10^{-3}$</td>
<td>0.2</td>
<td>$3 \times 10^{-3}$</td>
</tr>
<tr>
<td><strong>Peak current of micropulse</strong></td>
<td>8 mA</td>
<td>8 A</td>
<td>3.8 A</td>
<td>38.5 A</td>
<td>5 A</td>
<td>35.7 A</td>
<td>9.6 A</td>
<td>4.8 A</td>
</tr>
<tr>
<td><strong>Current density</strong></td>
<td>$4 \text{ A/cm}^2$</td>
<td>$10 \text{ A/cm}^2$</td>
<td>$19 \text{ A/cm}^2$</td>
<td>$500 \text{ A/cm}^2$</td>
<td>$100 \text{ A/cm}^2$</td>
<td>$182 \text{ A/cm}^2$</td>
<td>$12 \text{ A/cm}^2$</td>
<td>$6 \text{ A/cm}^2$</td>
</tr>
<tr>
<td><strong>Laser Spot Size</strong></td>
<td>0.05 cm</td>
<td>1 cm</td>
<td>0.5 cm</td>
<td>0.3 cm</td>
<td>0.5 cm</td>
<td>0.5 cm</td>
<td>0.5 cm</td>
<td>1 cm</td>
</tr>
</tbody>
</table>

* Loose estimates

Demonstrated

Proposed
Inverted-Insulator Photoguns

with optimized triple point shields and mildly conductive insulators

CEBAF 200 kV Gun

350 kV gun for GTS and UITF

Both designs, maximum field strength < 10 MV/m
3 photoguns with barrel polished electrodes

CEBAF 200 kV
Installed June 2018
Commissioning now.

GTS 350 kV
In operation since Nov. 2016 with CsK$_2$Sb photocathode:
500 uA magnetized beam
4.5 mA non-magnetized

UITF 350 kV
Polarized Gun
Under assembly
metric of success: High Voltage without Field Emission

Reached 360 kV in 70 hours

Vacuum and radiation levels indistinguishable from bkgd at 350 kV
Summary

- Extending the charge lifetime of today’s spin polarized GaAs photoguns from tens to **thousands of Coulombs is a requirement** for extended uninterrupted operation at milliampere beam current.

- These new results demonstrate **highest charge lifetime from high polarization GaAs/GaAsP photocathodes** by increasing laser spot sizes using at mA current but...

- **Managing ALL of the beam remains essential.** These results suggest CEBAF gun requires larger electrodes for sustainable milliampere operation.

- **New DBR photocathode is an excellent candidate for high current (mA) polarized electron beam initiatives.** Lifetime tests at CEBAF are planned.

- Managing application of high voltage to the cathode and **eliminating field emission are essential** for achieving long charge lifetime.

- Importantly, **realistic dynamic lifetime models** are critically needed to to separate and understand the dependencies of operational gun conditions.
High Polarization High Current Sources at Jefferson Lab

- GaAs/GaAsP strain-layer superlattices reliably yield QE>1% to provide ~6 mA/W/% polarization >85% (at 780 m).

- 10 mA operations (~1000 C/day) requires extending present-day charge lifetime (~100 C) to the kilo-Coulomb charge lifetime regime.

- Recent work at Jefferson Lab demonstrated higher charge lifetime of >500C at current 1-2 milliAmps by increasing the laser spot size, limited by correlated beam loss at the ~ppm level.

- Managing ALL of the beam remains essential; a sufficiently large area photocathode requires corresponding larger electrode.

- A new Diffracted Bragg Reflection photocathode is an excellent candidate providing ~30 mA/W/%, but lifetime tests are required.

- Managing the application of high voltage necessary for high bunch charge application w/o breakdown and eliminating field emission are both essential for operating GaAs photocathodes.

- A DC photogun to produce magnetized beam (~460pC) has been reliably operated at 300 kV. Work is on-going to build a high voltage >300 kV polarized gun counterpart.