Scientists - Matt Poelker, Marcy Stutzman, Riad Suleiman, Joe Grames
Senior Technicians - Phil Adderley, John Hansknecht
Junior Technicians - Josh Brittian, Jim Clark
PhD Students
  • Jonathan Dumas (Joseph Fourier University, France)
  • Ashwini Jayaprakash (Old Dominion University)
  • James McCarter (University of Virginia)
  • Ken Surles-Law (Hampton University, JLab staff)
  • Alicia Hofler (Old Dominion University, JLab staff)

Source Group “Hall of Famers” - Charlie Sinclair, Bruce Dunham, Larry Cardman, Scott Price, Peter Hartmann, Michael Steigerwald, Tony Day, Kim Ryan, Danny Machie, John Hogan, Bill Schneider, Reza Kazimi, Paul Rutt, Ganapati Rao Myneni

JLab Summer Science Series
July 7, 2008
A history 30+ years and growing...

Polarized electron beams have wide application in studies which range from materials science to nuclear and high energy physics:

⇒ the latter has driven the development of polarized e- sources

Semiconductor sources introduced in 1975 via optical pumping of GaAs
First e- source on an accelerator (P ~ 35%) : PEGGY, at SLAC (1978)
Strained GaAs reaches higher polarization (P~75%) in early 90’s (SLAC)
Strained Superlattice GaAs even higher (P~85%) last few years (SLAC)
Many accelerator facilities have had polarized e- GaAs sources:
  CEBAF, MAMI, Bonn, SLAC, MIT-BATES
1980 ~ 1 microAmp .... 2000 ~ 100 microAmp .... 2010 ~ milliAmp ??
Gallium Arsenide

3” wafer cleaved into square photocathodes (15.5 mm) for mounting on a “stalk” using In and Ta cup.
Photo-Emission from GaAs

Bare GaAs surface; Large work function. No electrons

Alkalai (Cs) reduces work function. Some electrons.

Cesium + Oxidant (O or NF3) “Negative Electron Affinity”. Many electrons

\[ QE = \frac{\# e^{-}'s}{\# \gamma's} \]

\[ E_a > 0 \quad E_a \approx 0 \quad E_a < 0 \]
Electron Spin & Polarization

0% Polarization

50% Polarization
Aligning the Spin States in GaAs

Optical pumping between \( P_{3/2} \) and \( S_{1/2} \)

\[
E_{\text{gap}} < E_\gamma < E_{\text{gap}+\Delta}
\]

\[
P_e = \frac{3-1}{3+1} = +/- 50\%
\]
The First GaAs Photoemission Gun

Photoemission of spin-polarized electrons from GaAs

Daniel T. Pierce* and Felix Meier
Laboratorium für Festkörperphysik, Eidgenössische Technische Hochschule, CH 8049, Zürich, Switzerland
(Received 10 February 1976)

\[
P = \frac{3-1}{3+1} = 50\%
\]
First High Voltage GaAs Photogun

Polarized e⁻ Gun for SLAC Parity Violation Experiment

Beam polarization, 35% to 45%
Beam current, I ~ 1 µA to 15 A peak

Electrons into the accelerator Dec., 1977
Collaboration announces parity violation June, 1978
Breaking the degeneracy ...

Split degeneracy of $P_{3/2}$

& optical pumping between $P_{3/2}$ and $S_{1/2}$

$P_e = +/- 100\%$, with $E_{\text{gap}} < E_\gamma < E_{\text{gap}+\delta}$
Strained layer GaAs

Bandwidth Semiconductor (formerly SPIRE)

- MOCVD-grown epitaxial spin-polarizer wafer
- Lattice mismatch
  \[ \Rightarrow \text{split degeneracy of } P_{3/2} \]

- \[ \text{GaAs}_{1-x}P_x \]
  - \[ x = 0.29 \]
  - \[ 0 < x < 0.29 \]
  - p-type GaAs substrate
Strained Layer - Superlattice GaAs

Be doping (cm\(^{-3}\))

- \(5.10^{19}\):
  - GaAs (5 nm)

- \(5.10^{17}\):
  - GaAsP (3 nm)
    - GaAs (4 nm) [14 pairs]

- \(5.10^{18}\):
  - GaAs\(_{0.64}\)P\(_{0.36}\) (2.5 \(\upmu\)m)
  - GaAs\(_{1-x}\)P\(_x\), 0<x<0.36 (2.5 \(\upmu\)m)

p-type GaAs substrate

SVT associates, per SLAC specs.
Photocathode Material

Bulk GaAs

- High QE ~ 20%
- Pol ~ 35%

Strained GaAs:
- GaAs on GaAsP
- 100 nm
- "conventional" material
- QE ~ 0.2%
- Pol ~ 75%
- @ 850 nm

Superlattice GaAs:
- Layers of GaAs on GaAsP
- 14 pairs
- No strain relaxation
- QE ~ 1.0%
- Pol ~ 85%
- @ 780 nm

FOM \propto IP^2
And, it really works!

Experiment Figure of Merit

\[
\frac{P_{\text{sup.}}^2 I}{P_{\text{str.}}^2 I} = 1.38
\]
CEBAF Overview

CEBAF Benefits:
- Recirculating LINACs
- Superconducting Cavities
- Three Halls = 3x the physics

A B C A B C

f=1.5 GHz
60 degrees
Radio Frequency Pulsed Lasers

RF Gain Switching

Diode seed laser

Diode amplifier


0.5 GHz

1 GHz

1.5 GHz

2 GHz
Continuous Electron Beam Accelerator Facility

Gain switched diode lasers
499 MHz, $\Delta \phi = 120^\circ$

Pockels cell

0.6 GeV linac
(20 cryomodules)
1497 MHz

67 MeV injector
(2 1/4 cryomodules)
1497 MHz

RF separators
499 MHz

Double sided septum

Gun
Synchronous Photoinjection

- **DC Laser**
  (wasted electrons)

- **Pulsed laser**
  (much better)

- **PreBuncher**
  (even better)

Chopper viewer for three beams:

- Beam to Hall B
- Beam to Hall A
- Beam to Hall C
Laser Room for Dust & Climate Control

Lasers are cool!!!
New Fiber-Based Drive Laser

- Gain-switching better than modelocking; no phase lock problems
- Very high power
- Telecom industry spurs growth, ensures availability
- Useful because of superlattice photocathode (requires 780nm)

New fiber technology-based laser system

- RF locked low-power 1560 nm fiber diode
- High power 1560 nm fiber amplifier
- Non-linear frequency doubling converter for 1560 nm to 780 nm
“100 keV” Photoinjector
JLab vent/bake polarized source...

- Cathode (GaAs)
- Ceramic Insulator
- Anode
- Laser
- Cs
- NF$_3$
- NEG coated beampipe
- Non evaporable getter pumps (NEG)
- 4,000 liter/s pump speed $\Rightarrow$ 5E-12 Torr

-100 kV
Who wants polarized electrons?

Plot for 3-26-0

QE dying !!!

Current / QE

Gun current / 100 uA

Gun charge / C

Quantum efficiency / 0.1%

Time / hours

0 2 4 6 8 10 12 14 16 18 20 22 24

0.0 1.5 3.0 4.5 6.0 7.5 9.0 10.5 12.0 13.5 15.0

0.0 0.3 0.6 0.9 1.2 1.5 1.8 2.1 2.4 2.7 3.0

Gun charge
Ion Back-Bombardment

High energy ions focused to electrostatic center

We don’t run beam from electrostatic center

laser light IN

electron beam OUT

anode

residual gas

cathode

Ions create QE trough to electrostatic center
Bad, bad ions...

Imperfect vacuum => QE degrades via ion backbombardment
Better Vacuum = Longer Lifetime
We understand Alice’s worry...

“The woods were dark and foreboding, and Alice sensed that sinister eyes were watching her every step. Worst of all, she knew that Nature abhorred a vacuum” – Gary Larson
## Vacuum Conditions at CEBAF

<table>
<thead>
<tr>
<th>Application</th>
<th>Pressure Range</th>
<th>Location</th>
<th>Vacuum Regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beamline to dumps</td>
<td>$10^{-5}$ Torr</td>
<td>Target to dump line</td>
<td>Medium</td>
</tr>
<tr>
<td>Insulating vacuum for cryogens</td>
<td>$10^{-4}$ Torr to $10^{-7}$ Torr</td>
<td>Cryomodules, transfer lines</td>
<td>Medium to high</td>
</tr>
<tr>
<td>Targets, Scattering Chambers</td>
<td>$10^{-6}$ to $10^{-7}$ Torr</td>
<td>Experimental Halls</td>
<td>High to very high</td>
</tr>
<tr>
<td>RF waveguide warm to cold windows</td>
<td>$10^{-7}$ to $10^{-9}$ Torr</td>
<td>Between warm and cold RF windows</td>
<td>High to very high</td>
</tr>
<tr>
<td>Warm beamline vacuum</td>
<td>$10^{-7}$ to $10^{-8}$ Torr or better</td>
<td>Arcs, Hall beamline, BSY, some injector</td>
<td>High to very high</td>
</tr>
<tr>
<td>Warm region girders</td>
<td>$10^{-9}$ Torr or better</td>
<td>Girders adjacent to cryomodules</td>
<td>Very high to ultrahigh</td>
</tr>
<tr>
<td>Differential pumps</td>
<td>Below $10^{-10}$ Torr</td>
<td>Ends of linacs, injector cryomodules and guns</td>
<td>Ultrahigh vacuum</td>
</tr>
<tr>
<td>Baked beamline</td>
<td>$10^{-10}$ to $10^{-11}$ Torr</td>
<td>Y chamber, Wien filter, Pcup</td>
<td>Ultra high vacuum</td>
</tr>
<tr>
<td>Polarized guns</td>
<td>$10^{-11}$ to $10^{-12}$ Torr</td>
<td>Inside Polarized guns</td>
<td>Ultra/Extreme high vacuum</td>
</tr>
<tr>
<td>SRF cavity vacuum</td>
<td>$&lt; 10^{-12}$ Torr</td>
<td>Inside SRF cavities with walls at 2K</td>
<td>Extreme high vacuum</td>
</tr>
</tbody>
</table>
Vacuum regimes

- Low, Medium Vacuum (>10^{-3} Torr)
  - Viscous flow
    - interactions between particles are significant
  - Mean free path less than 1 mm
- High, Very High Vacuum (10^{-3} to 10^{-9} Torr)
  - Transition region
- Ultra High Vacuum (10^{-9} - 10^{-12} Torr)
  - Molecular flow
    - interactions between particles are negligible
    - interactions primarily with chamber walls
  - Mean free path 100-10,000 km
- Extreme High (<10^{-12} Torr)
  - Molecular flow
  - Mean free path 100,000 km or greater

Air \sim 10^{16} / \text{Torr-cm}^3
Where does the gas come from?

- **Outgassing from the system**
  - Metal and non-metal (viton o-rings, ceramics) all outgas
  - Primarily water in unbaked systems
  - Primarily hydrogen from steel in baked systems

- **Leaks**
  - Real
    - Gaskets not sealed
    - Cracks in welds, bellows, ceramics, window joints
    - Superleaks that only open at very low temperatures
  - Virtual
    - Small volumes of gas trapped inside system (screw threads, etc.) that pump out slowly over time

- **Gas load caused by the beam**
  - Desorption of gases by elevated temperatures, electrons or photons striking surfaces, etc.

- **Engineered Loads** (targets, etc.) where gas is added

- **Permeation of gasses through materials**
  - Viton gaskets worse than metal seals
  - Hydrogen can permeate through stainless steel!
Ultra High Vacuum Pumps

- **Getter Pumps**
  - Chemically active surface
    - Titanium sublimed from hot filament
    - Non-Evaporative Getters
  - Molecules stick when they hit
    - Does not work well for inert gasses such as Argon, Helium or for methane

- **Ion Pumps**
  - Electric field to ionize gasses
  - Magnetic field to direct gasses into cathodes where they are trapped
    - Has some pumping capability for noble gasses

- **Baking used to get pressures below 10^{-10} Torr**
  - 250°C for 30 hours removes water vapor bonded to surface that otherwise limits pressure

- Avoid contamination by oils due to roughing pumps, fingerprints, machining residue.
Charge Lifetime Steadily Decreasing
NEG replacement Summer 2003 improves lifetime
GaAs Trending Higher Average Current

JLab FEL program with unpolarized beam
Cornell/JLab (construction)
ELIC (idea)
Qweak (2010)

First polarized beam from GaAs photogun
First low polarization, then high polarization at CEBAF

The Qweak Apparatus

Ave. Beam Current (mA)

Year

JLabFEL program with unpolarized beam
Cornell/JLab (construction)
ELIC (idea)
Qweak (2010)

First polarized beam from GaAs photogun
First low polarization, then high polarization at CEBAF
CEBAF Photoinjector

Long photocathode lifetime:
- Gun & Beamlines “NEG’s” ⇒ Good Vacuum
- No short focal length elements
- Photocathodes with anodized edge
- Synchronous photoinjection
- (Spare Gun)

What now … ???
Improvements to the High Voltage Chamber Vacuum

304 SS: Electropolished & Vacuum Fired (AVS: 3 hrs @ 900 C @ 3x10^{-6} T)

304SS without (blue) and with (red) electropolishing and vacuum firing

NEG coating (Ti/Zr/V)
100 hrs @ 70 C
200 L/sec
New Load Lock Gun in Test Stand Spring '06

Heat/activation chamber

Goal: 8 hours swap photocathode
Present: ~12 hours

Small bake Load region

NEG-coated HV chamber

Suitcase x4
CEBAF e-source: current & lifetime

**Bulk GaAs w/ 532nm DC light**

- Improve vacuum
  - Reduce surface area
  - 400°C bake
  - Ion pump = Gas Source?

- Limit “bad” electrons
  - Eliminate FE
  - Laser handling

- Increase QE
  - Longer heat clean
  - Better vacuum

**High-P Photocathode**

### 1 milliAmp demo from High-P Photocathode*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Rep Rate (CW)</td>
<td>499 MHz</td>
</tr>
<tr>
<td>Laser Pulse Length</td>
<td>30 psec</td>
</tr>
<tr>
<td>Wavelength</td>
<td>780 nm</td>
</tr>
<tr>
<td>Laser Spot Size (FWHM)</td>
<td>450 μm</td>
</tr>
<tr>
<td>Average Current</td>
<td>1 mA</td>
</tr>
<tr>
<td>Run Duration</td>
<td>8.25 hr</td>
</tr>
<tr>
<td>Extracted Charge</td>
<td>30.3 C</td>
</tr>
<tr>
<td>Charge Lifetime</td>
<td>210 C</td>
</tr>
<tr>
<td>Areal Charge Lifetime</td>
<td>160 kC/cm²</td>
</tr>
</tbody>
</table>

* Note: did not measure polarization

---

**High Initial QE [%]**

- **Vacuum signals**
- **Laser Power**
- **Beam Current**

---

* Jefferson Lab*
NEW CEBAF Load Locked Gun

No more gun bakeouts! Photocathode replaced in 8 hours versus 4 days.

- Multiple samples,
- No more photocathode edge anodizing,
- Smaller surface area and no more venting means:
  - Better gun vacuum,
  - Longer photocathode lifetime
Build Higher Voltage Inverted Gun

Present Ceramic
- Exposed to field emission
- Large area
- Expensive (~$50k)

New Ceramic
- Limited FE
- Compact
- ~$5k

Medical x-ray technology
Eliminate Field Emission

Implement the SRF-cavity technique “high pressure rinsing”

Recent work of Maria Chevtsova, Ken Surles-Law with shaped electrodes

FE from Handpolished 304 SS Cathode Electrode with ~6 mm gap

Ken is collaborating with SRF Institute to build single crystal Niobium electrodes.