Milliampere beam studies using high polarization photocathodes at the CEBAF Photoinjector

Joe Grames, Phil Adderley, B. Bullard, John Hansknecht, C. Hernandez-Garcia, G. Palacios, Matt Poelker, Daniel Moser, Marcy Stutzman, Shukui Zhang

LHeC, FCC-eh and PERLE Workshop
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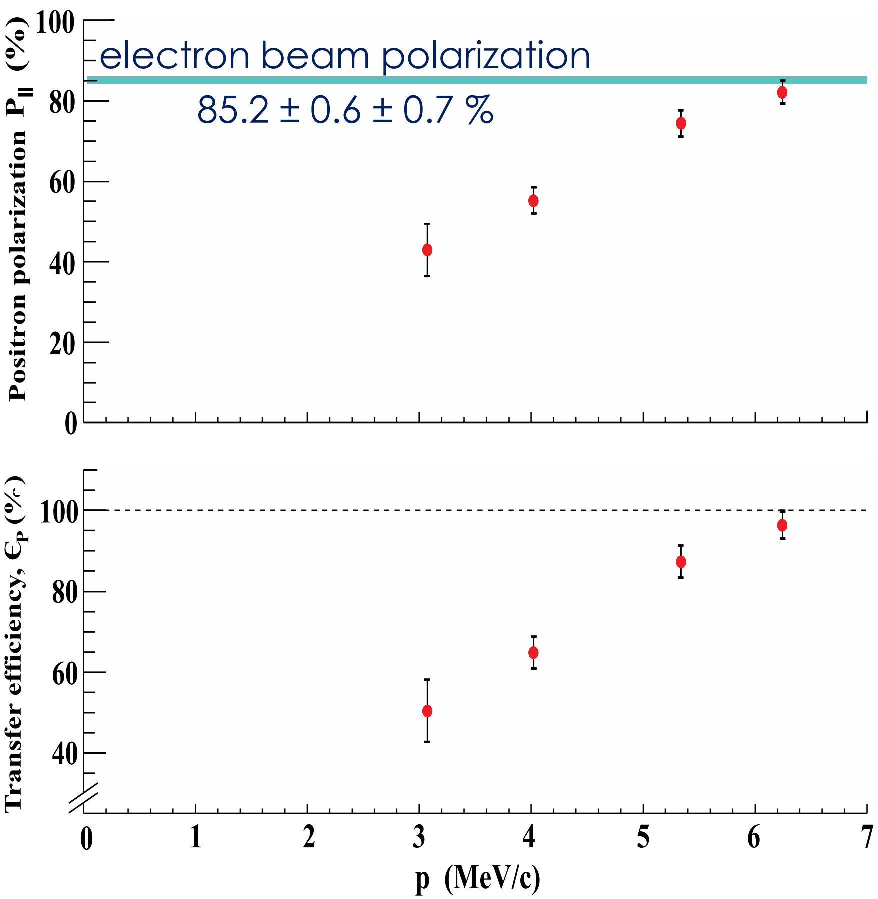
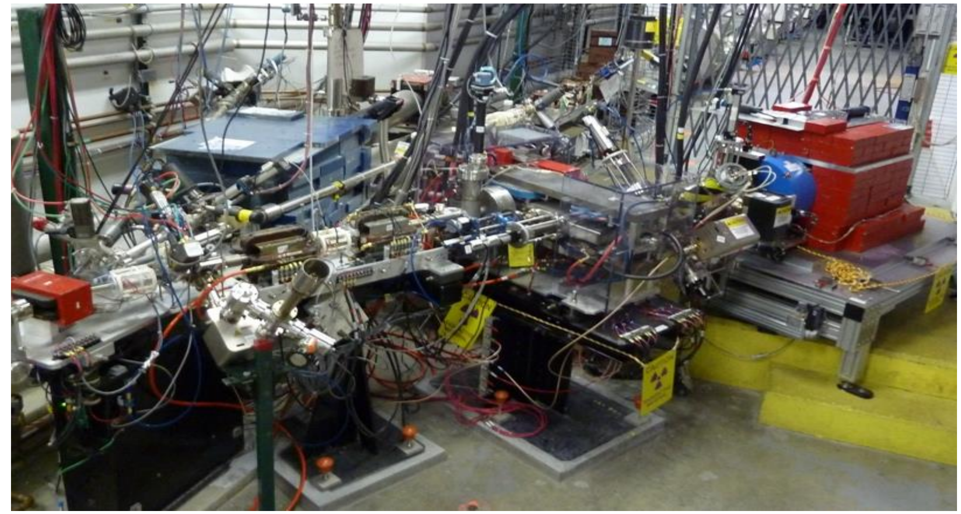
Outline

- 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

$$\vec{e}^{\,-} \rightarrow \vec{\gamma} \rightarrow \vec{e}^{\,+} \; (+\, \vec{e}^{\,-})$$





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**

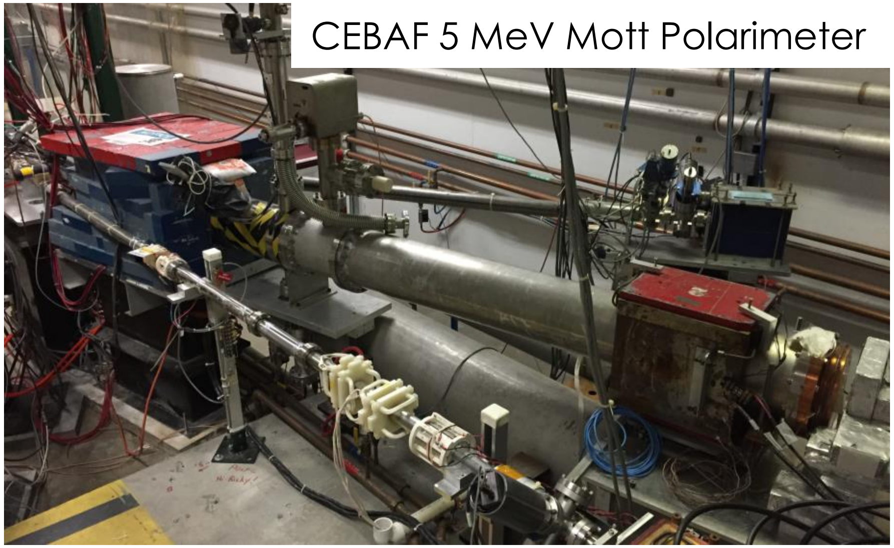
D. Abbott et al, "*Production of Highly Polarized Positrons Using Polarized Electrons at MeV Energies*", Phys. Rev. Lett, 116, 214801 (2016)

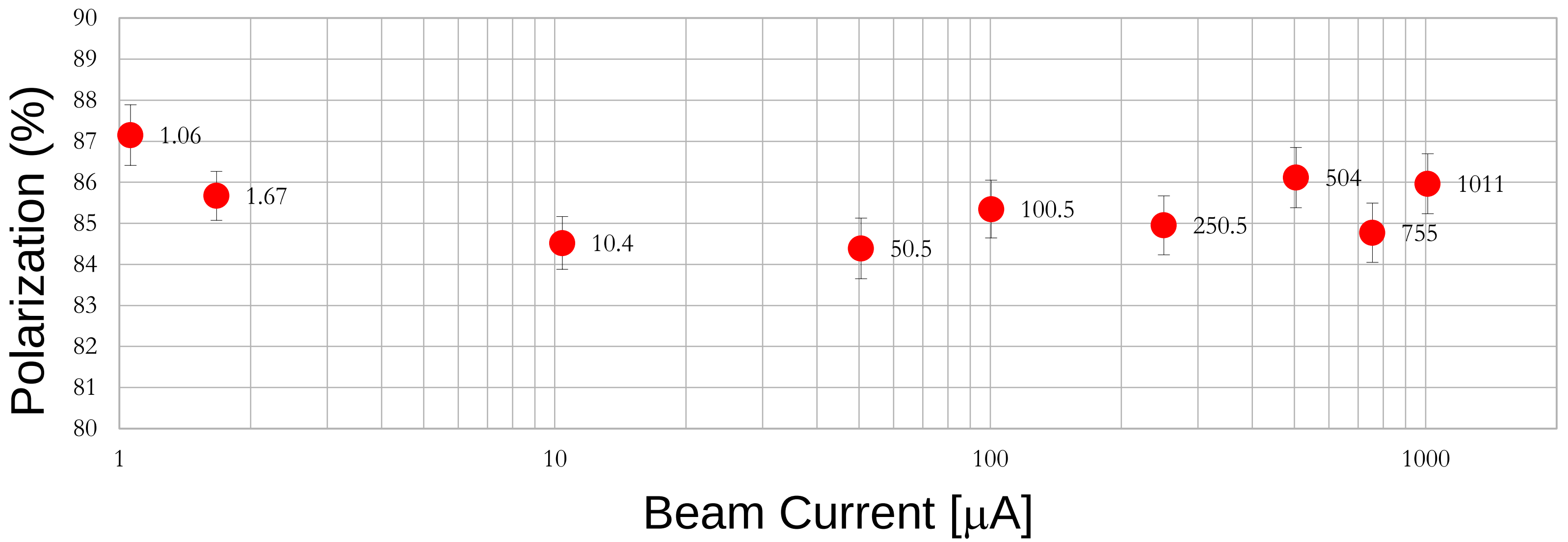
Polarization Studies at mA Beam Current

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)

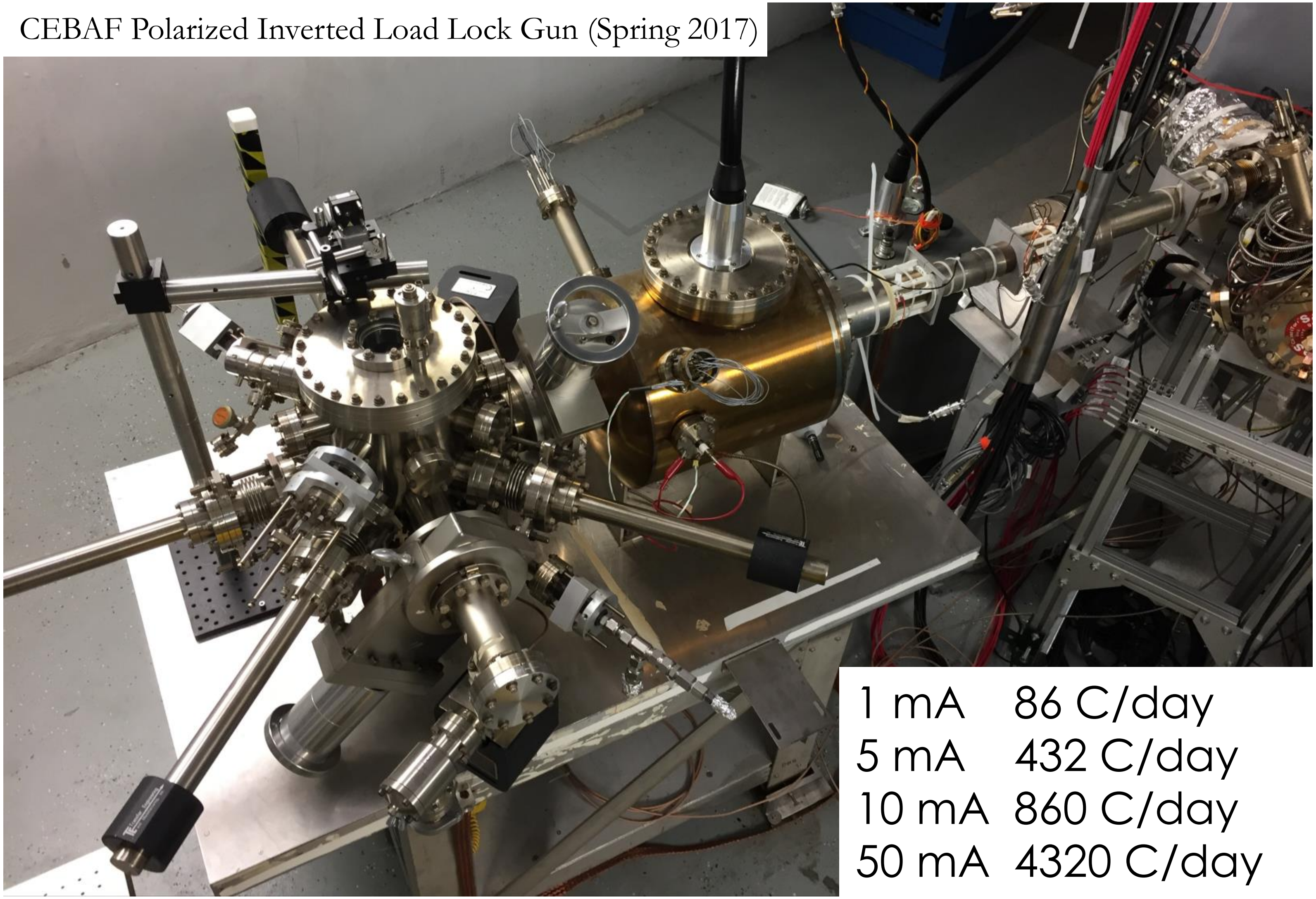
CEBAF 5 MeV Mott Polarimeter





CEBAF Load Lock Photogun (-130kV)

CEBAF Polarized Inverted Load Lock Gun (Spring 2017)

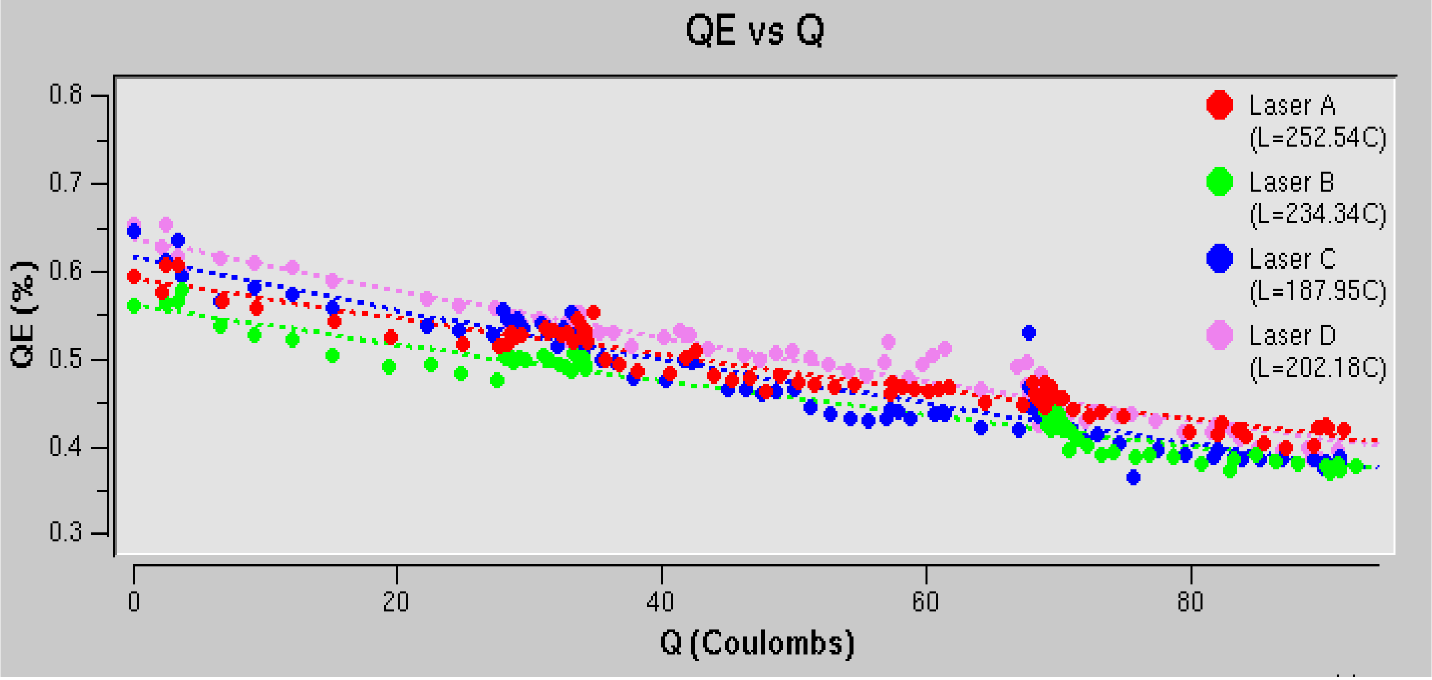


1 mA	86 C/day
5 mA	432 C/day
10 mA	860 C/day
50 mA	4320 C/day

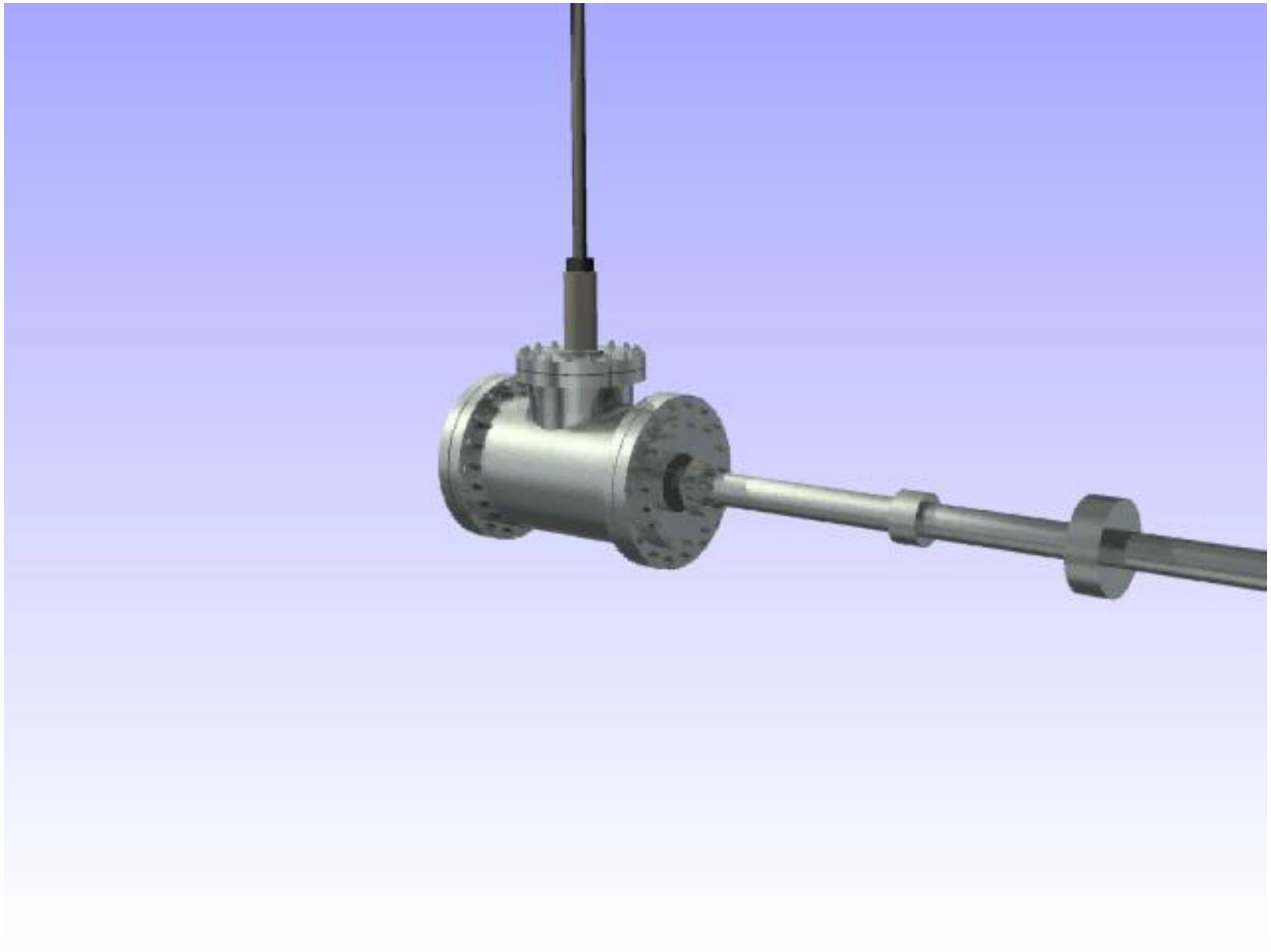
Recent CEBAF Polarized Source Performance

Gun2 Photocathode (Fall 2016 – Spring 2017)

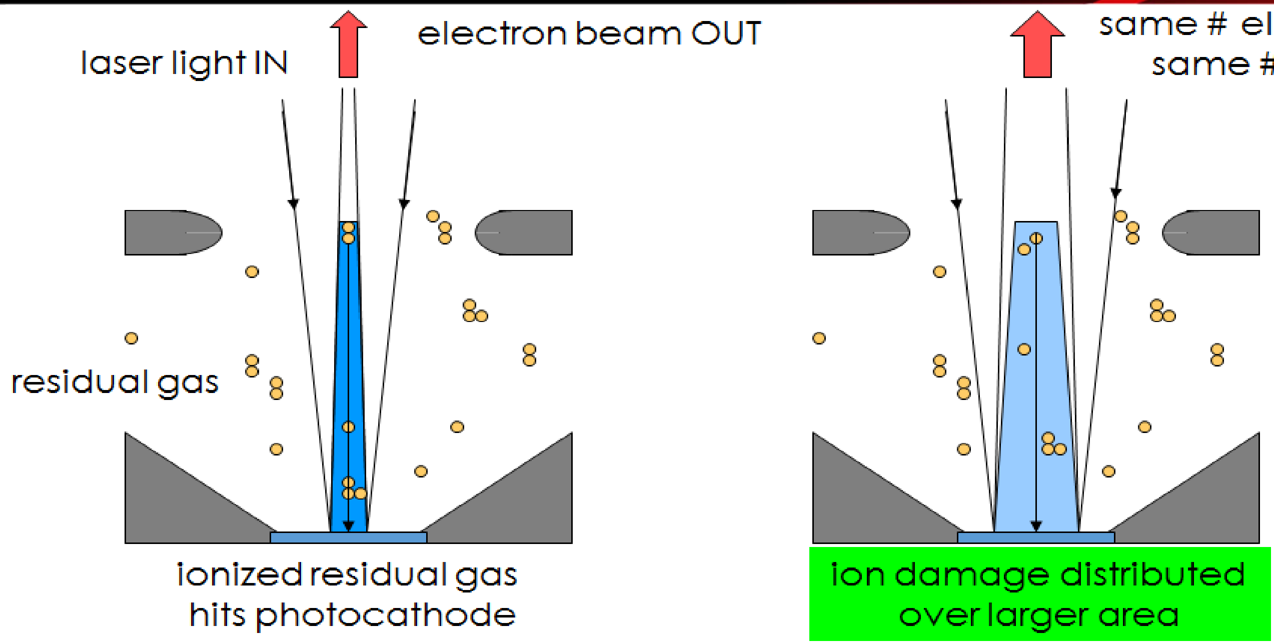
- Strained Superlattice GaAs/GaAsP #5756-4
- Good Polarization 85-87% (measured at Mott)
- Good QE > 1% after activation => 6 mA/Watt/% @ 780 nm
- Lifetime about 200C (σ_{4D} ~ 1mm) with intensity < 200μA



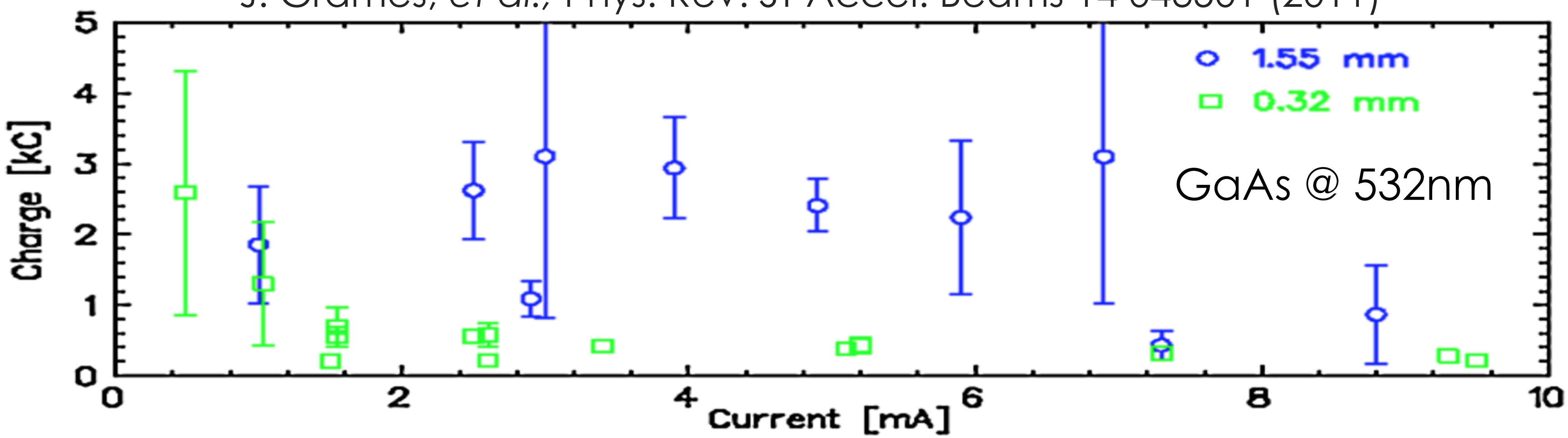
Ion Bombardment



Improving Lifetime with Larger Laser Size

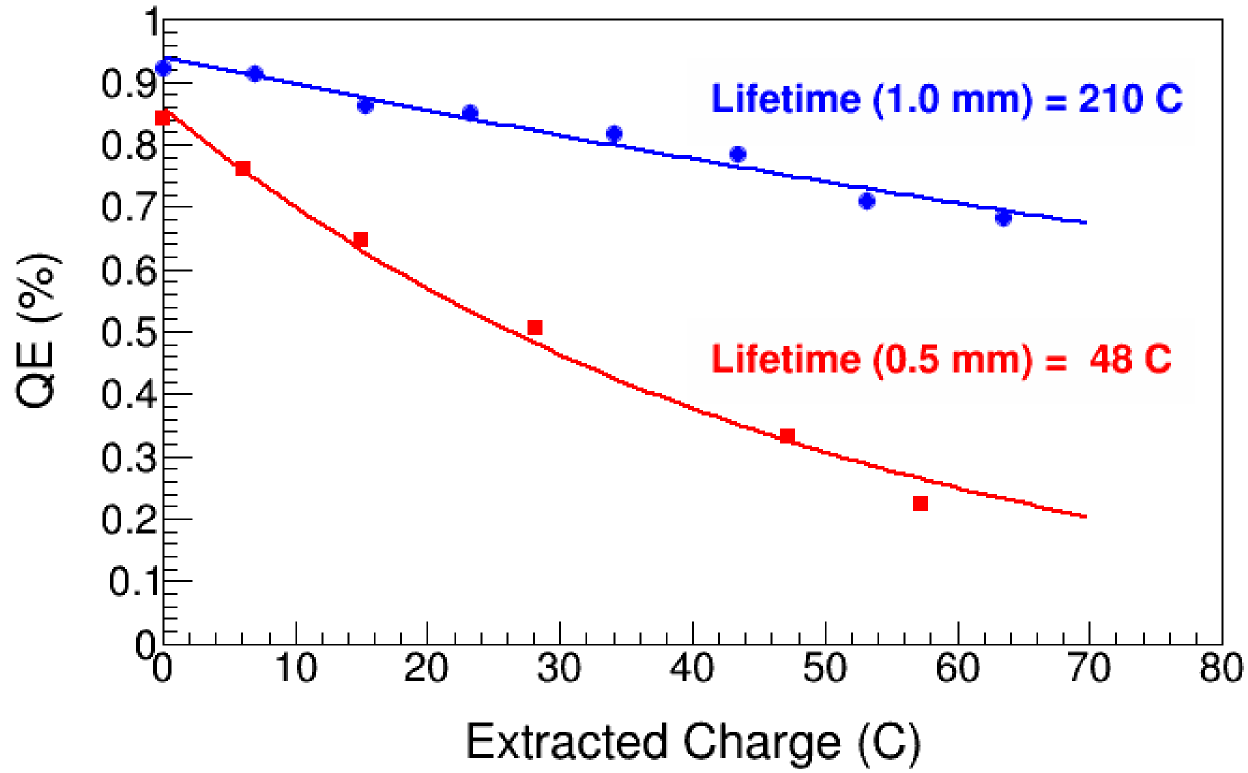


J. Grames, *et al.*, Phys. Rev. ST Accel. Beams 14 043501 (2011)



Improving charge lifetime with GaAs/GaAsP

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)

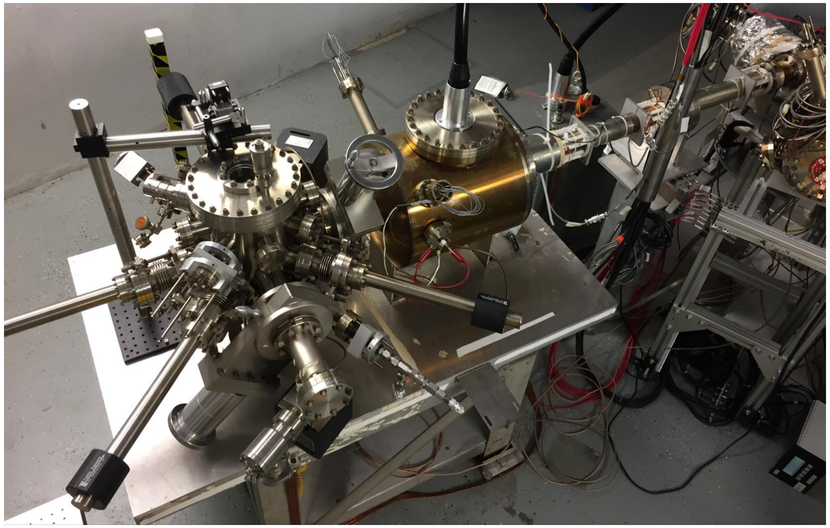


but milliampere applications require kiloCoulomb charge lifetime to provide uninterrupted operation of reasonable duration

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

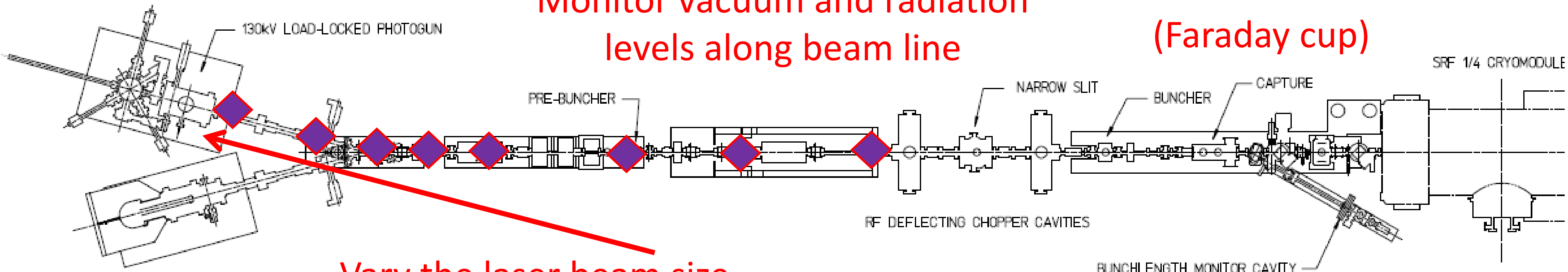
CEBAF 130kV polarized "inverted gun" with load lock



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

Monitor vacuum and radiation levels along beam line

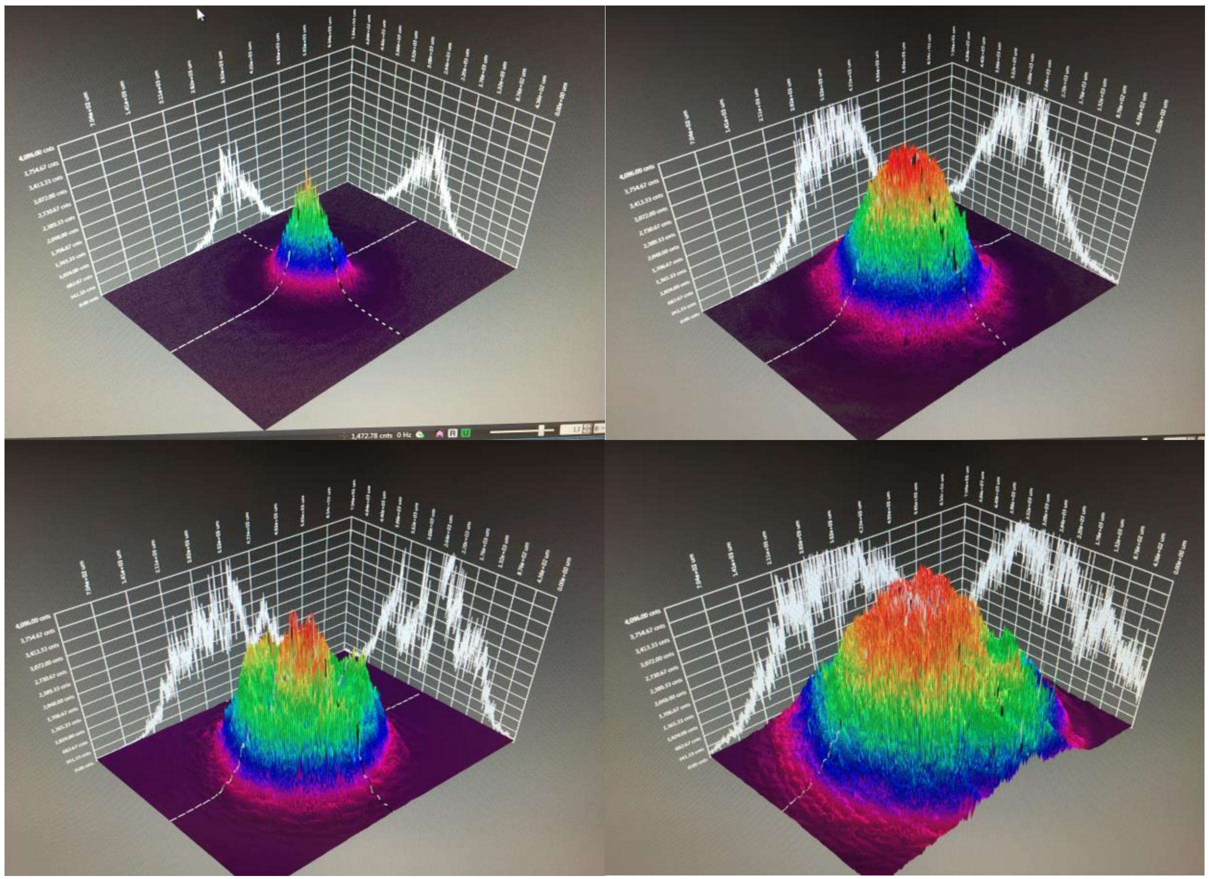
Deliver it here
(Faraday cup)



Vary the laser beam size
(f=499 MHz, σ_t ~ 50 ps)

Variation of Laser Spot Size

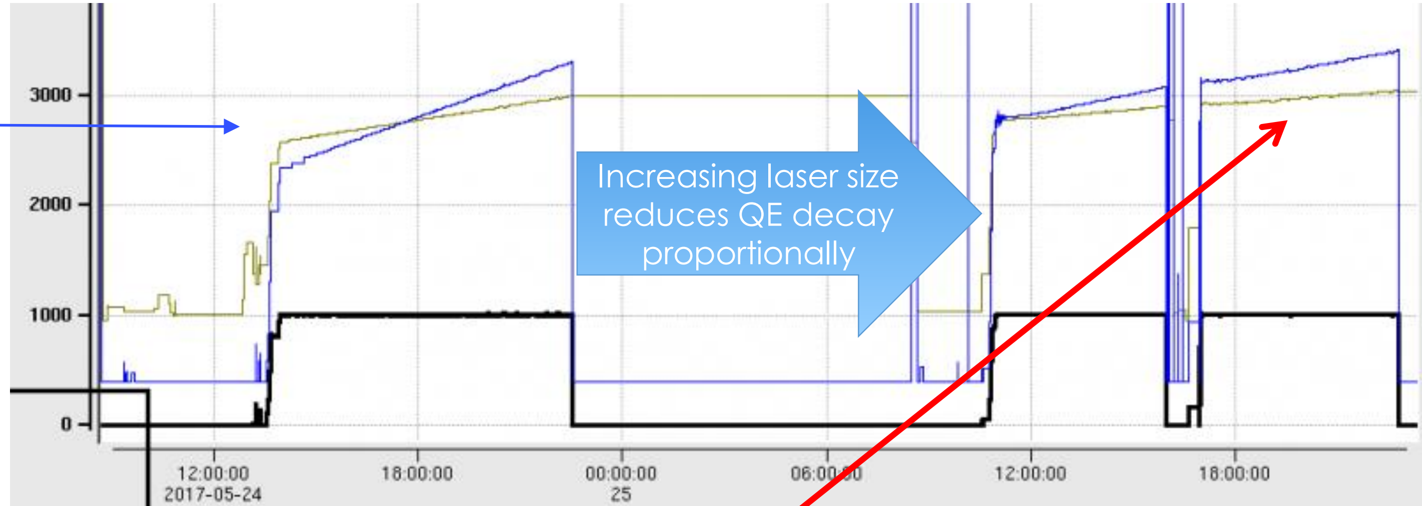
- ✓ Photocathode diameter 5 mm (defined by a mask during activation)
- ✓ Varied laser diameter σ_{4D} ~1-5 mm (area 3-20 mm^2)
- ✓ Laser profile defined at photocathode plane

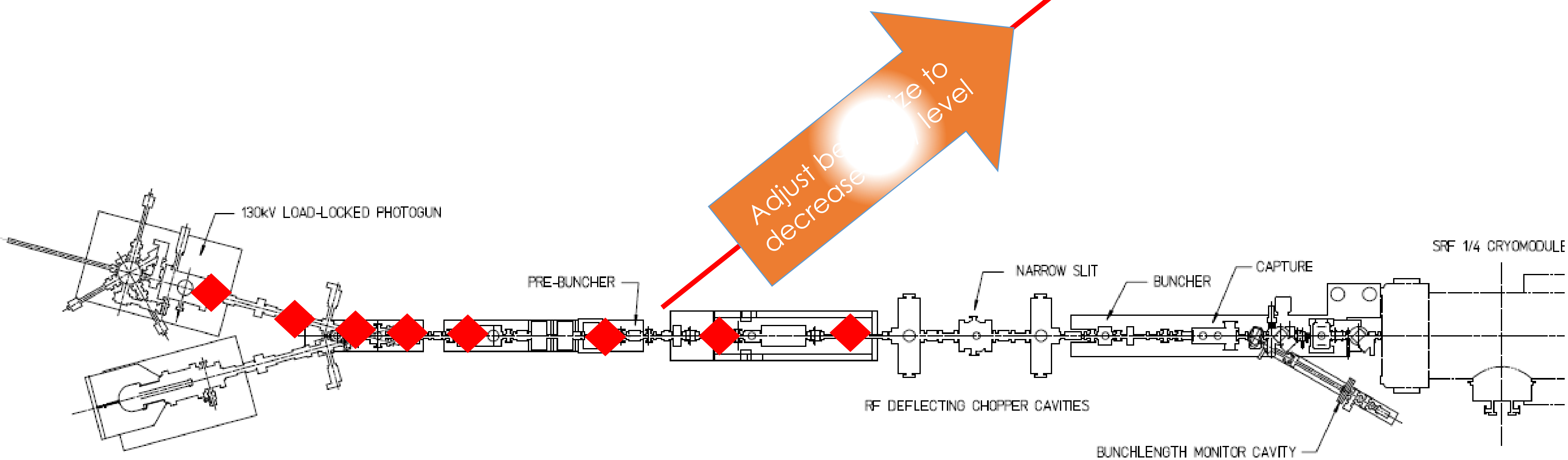


Lifetime Studies at mA Beam Current

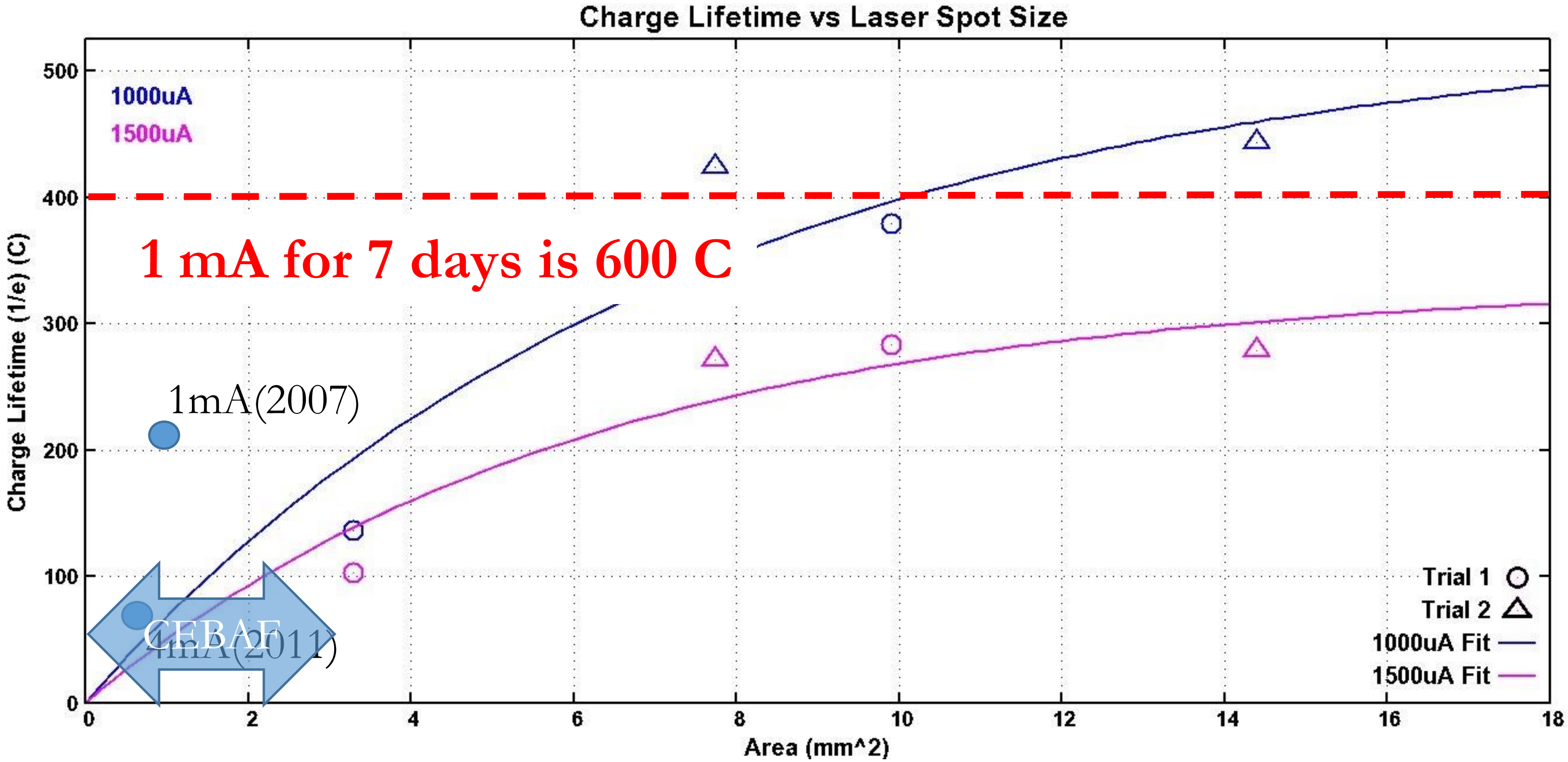
Required laser power, slope proportional to QE decay

1mA





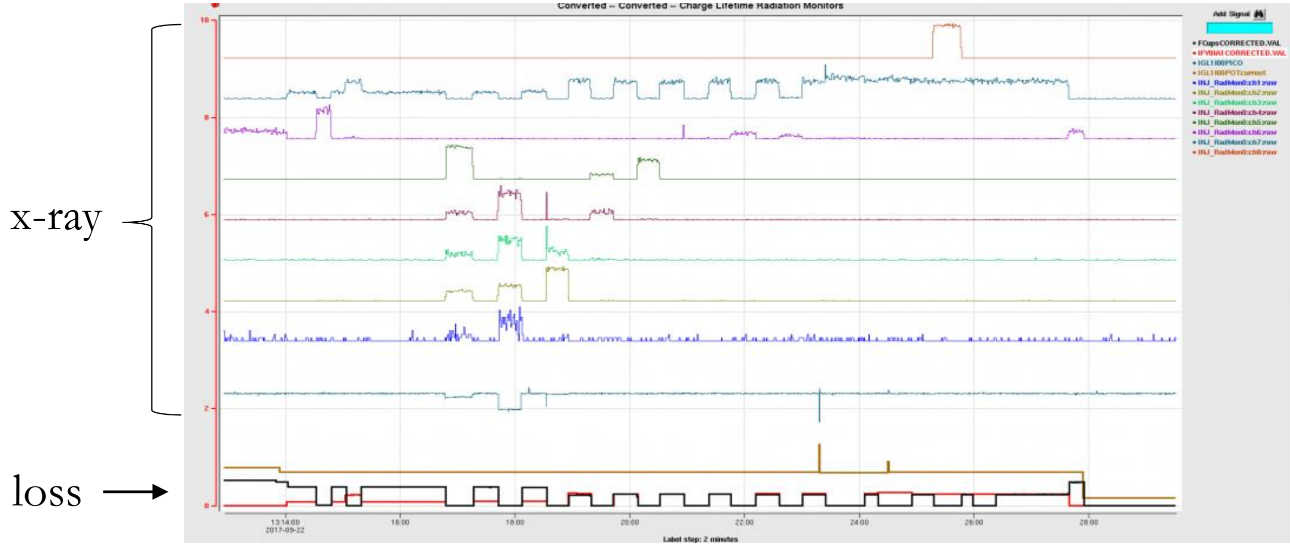
First Results: GaAs/GaAsP at mA Current



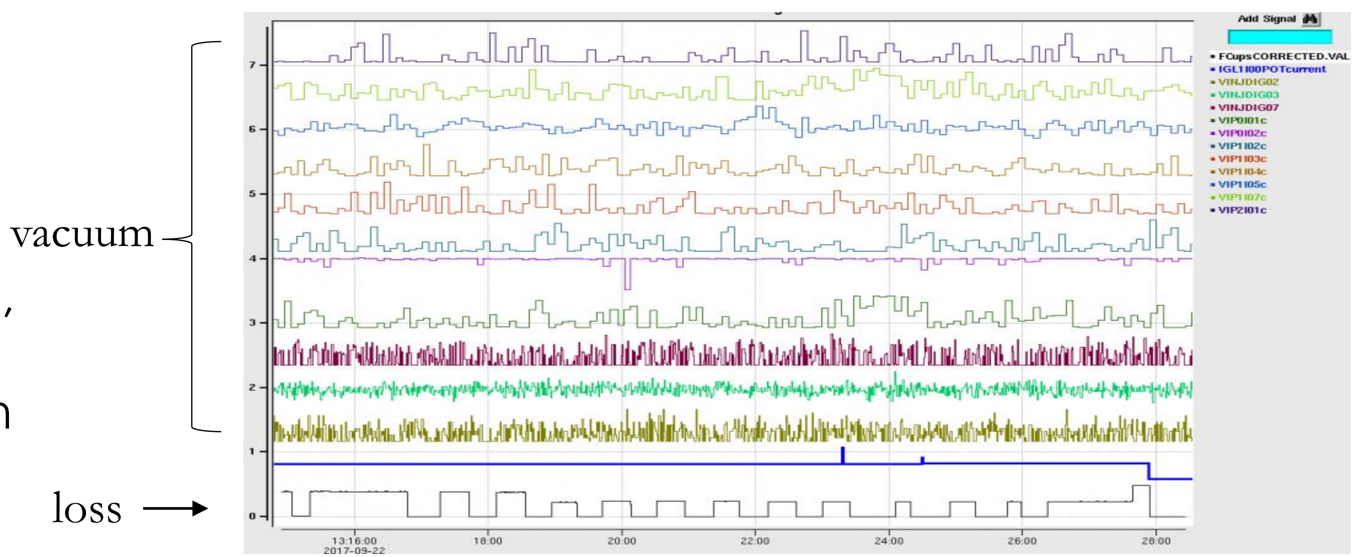
- CEBAF charge lifetime improves with spot size, as expected, but eventually beam size becomes "too large"
- Laser diameters greater than ~4 mm (4 sigma) will require properly designed cathode/anode electrodes, to ensure 100% transmission, to maintain excellent vacuum, to minimize ion bombardment

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)

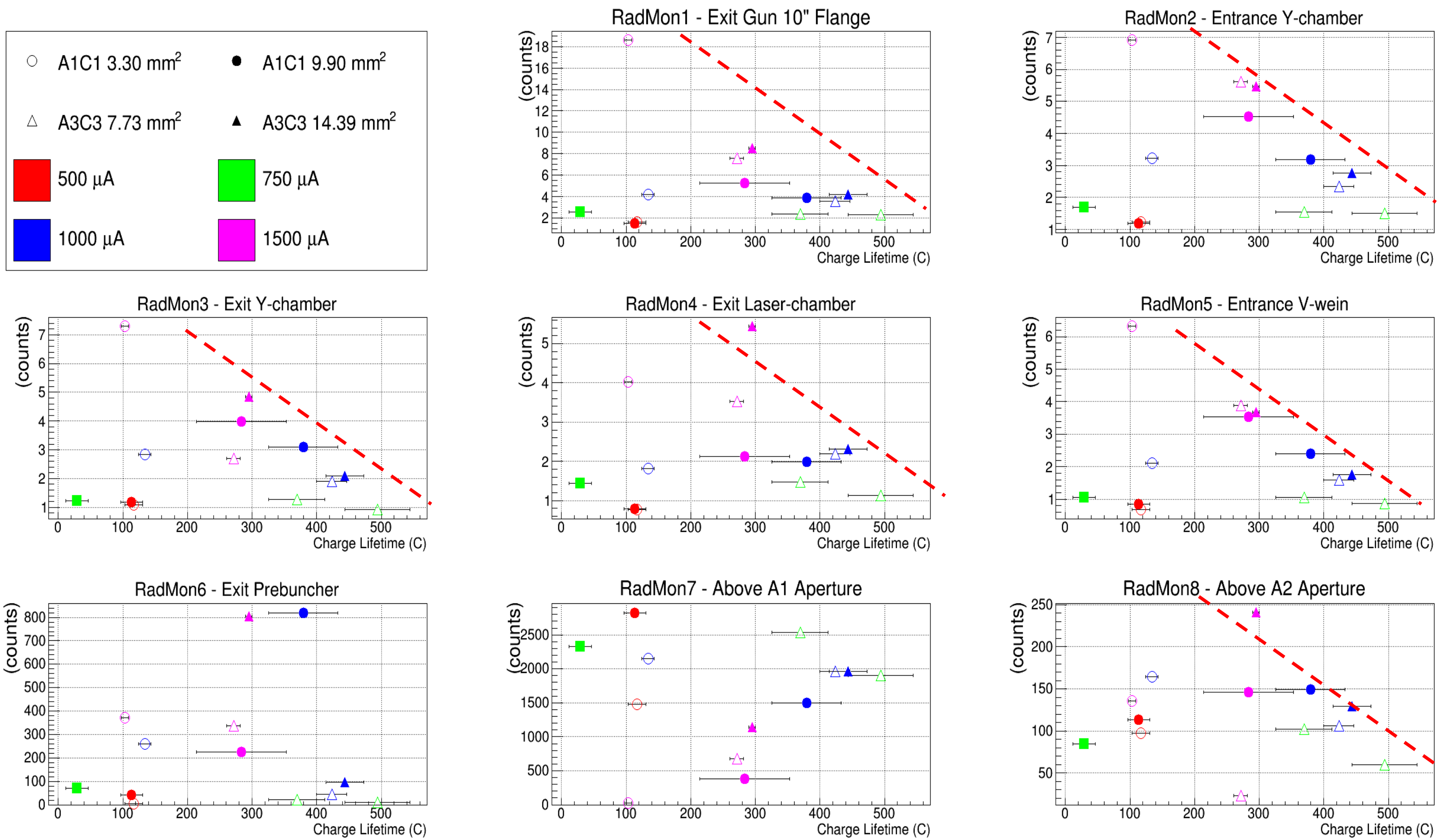


While increased vacuum levels are a good indicator of decreased photocathode lifetime, in this study we observe little indication of beam loss.



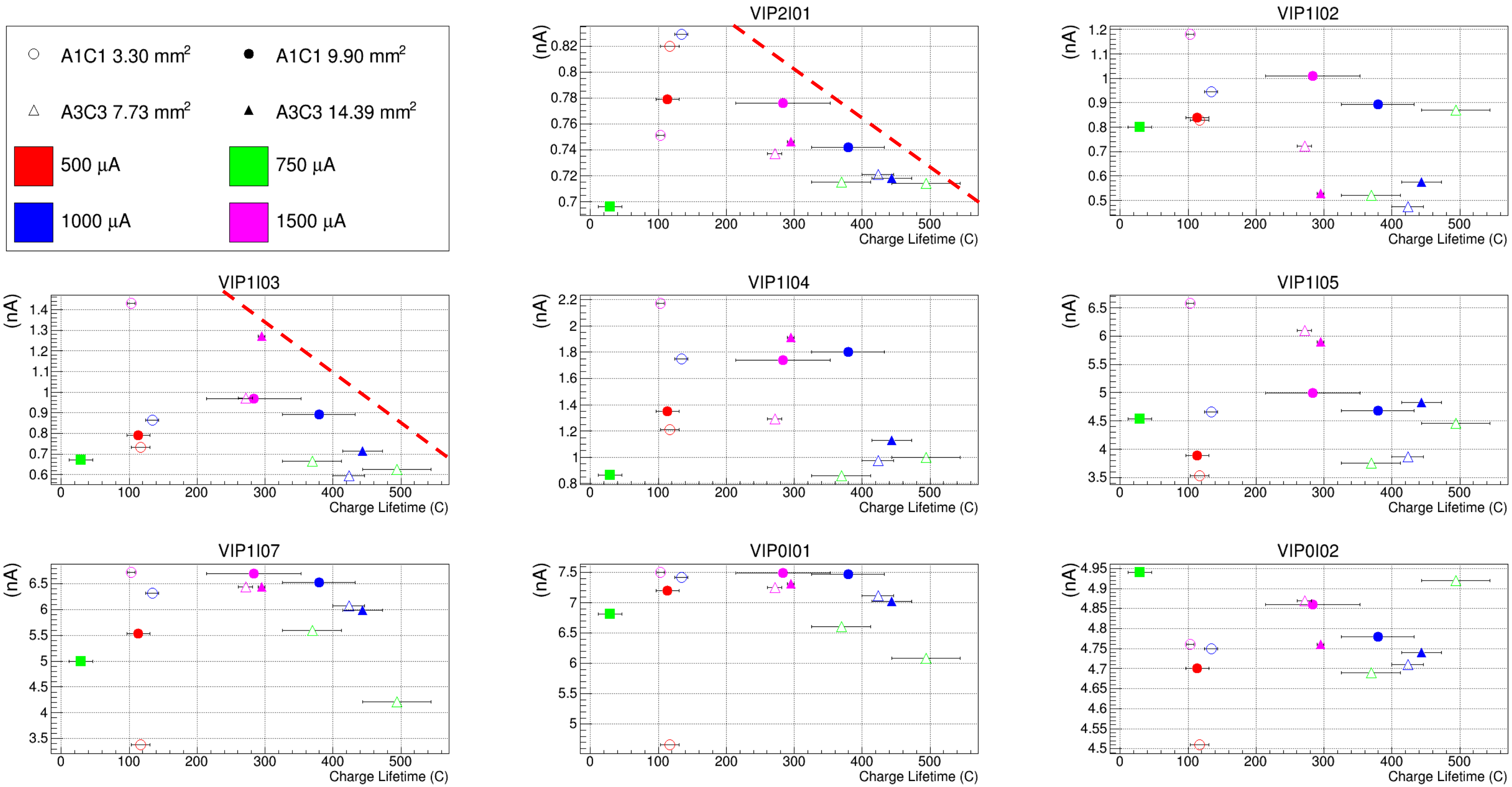
Radiation Level vs. Lifetime

✓ 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…

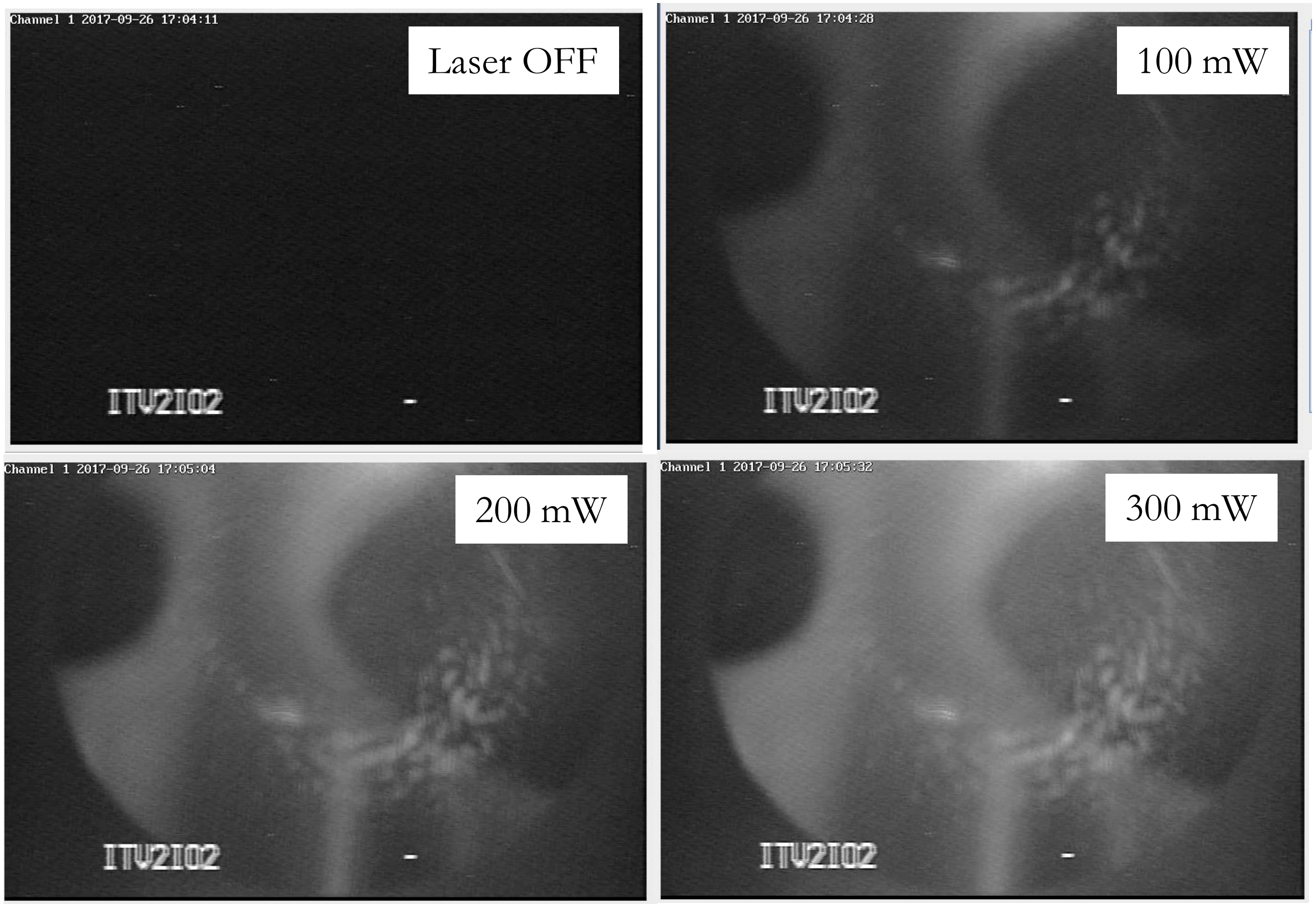
(6mA/%/W)

I = 1 mA

&

QE < 1%

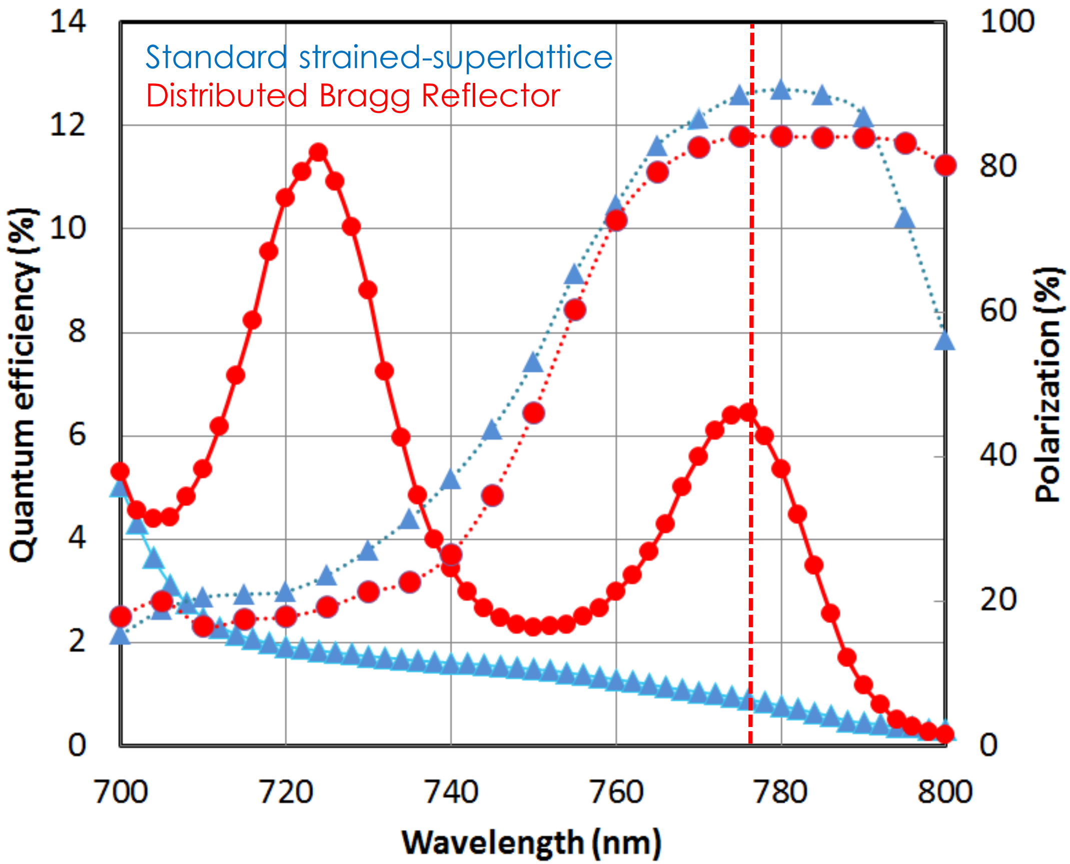
=> P > ~100's mW



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



W. Liu, S. Zhang, M. Stutzman, M. Poelker, Y. Chen, W. Lu, and A. Moy, Appl. Phys. Lett. **109**, 252104 (2016)

Source Parameter Comparison

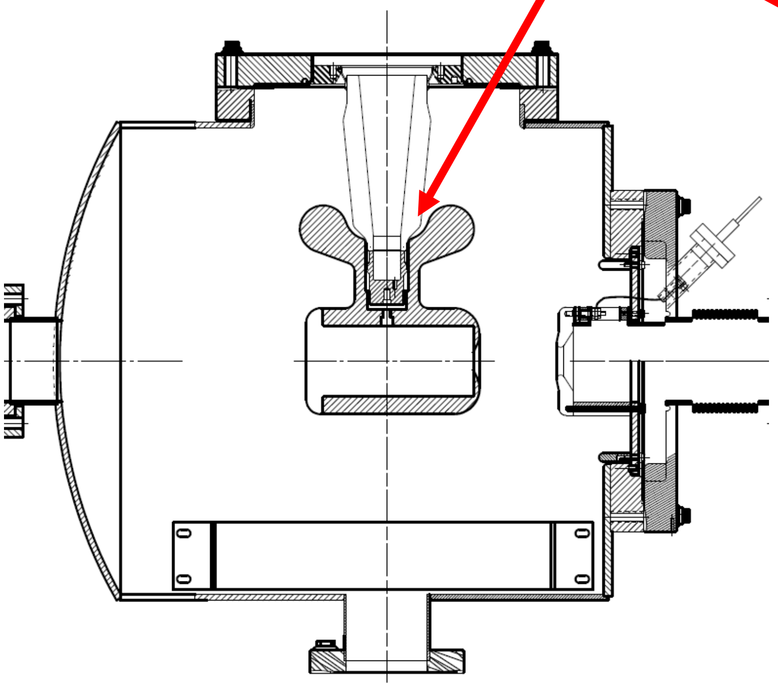
Parameter	CEBAF	SLC	JLab/FEL	Cornell ERL	LHeC	eRHIC	CLIC	ILC
Polarization	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Number electrons/microbunch	2.5×10^6	1×10^{11}	8.3×10^8	4.8×10^8	1×10^9	2.2×10^{10}	6×10^9	3×10^{10}
Number of microbunches	CW	2	CW	CW	CW	CW	312	3000
Width of microbunch	50 ps	2 ns	35 ps	2 ps	100 ps	~ 100 ps	~ 100 ps	~ 1 ns
Time between microbunches	2 ns	61.6 ns	13 ns	0.77 ns	25 ns	71.4 ns	0.5002 ns	337 ns
Microbunch rep rate	499 MHz	16 MHz	75 MHz	1300 MHz	40MHz	14MHz	1999 MHz	3 MHz
Width of macropulse	-	64 ns	-	-	-	-	156 ns	1 ms
Macropulse repetition rate	-	120 Hz	-	-	-	-	50 Hz	5 Hz
Charge per micropulse	0.4 pC	16 nC	133 pC	77 pC	500 pC	3.6 nC	0.96 nC	4.8 nC
Charge per macropulse	-	32 nC	-	-	-	-	300 nC	14420 nC
Average current from gun	200 uA	2 uA	10 mA	100 mA	20 mA	50 mA	15 uA	72 uA
Average current in macropulse	-	0.064 A	-	-	-	-	1.9 A	0.0144 A
Duty Factor	2.5×10^{-2}	2.8×10^{-7}	2.6×10^{-3}	2.6×10^{-3}	4×10^{-3}	1.4×10^{-3}	0.2	3×10^{-3}
Peak current of micropulse	8 mA	8 A	3.8 A	38.5 A	5 A	35.7 A	9.6 A	4.8 A
Current density*	4 A/cm^2	10 A/cm^2	19 A/cm^2	500 A/cm^2	100 A/cm^2	182 A/cm^2	12 A/cm^2	6 A/cm^2
Laser Spot Size*	0.05 cm	1 cm	0.5 cm	0.3 cm	0.5 cm	0.5 cm	1 cm	1 cm

* Loose estimates

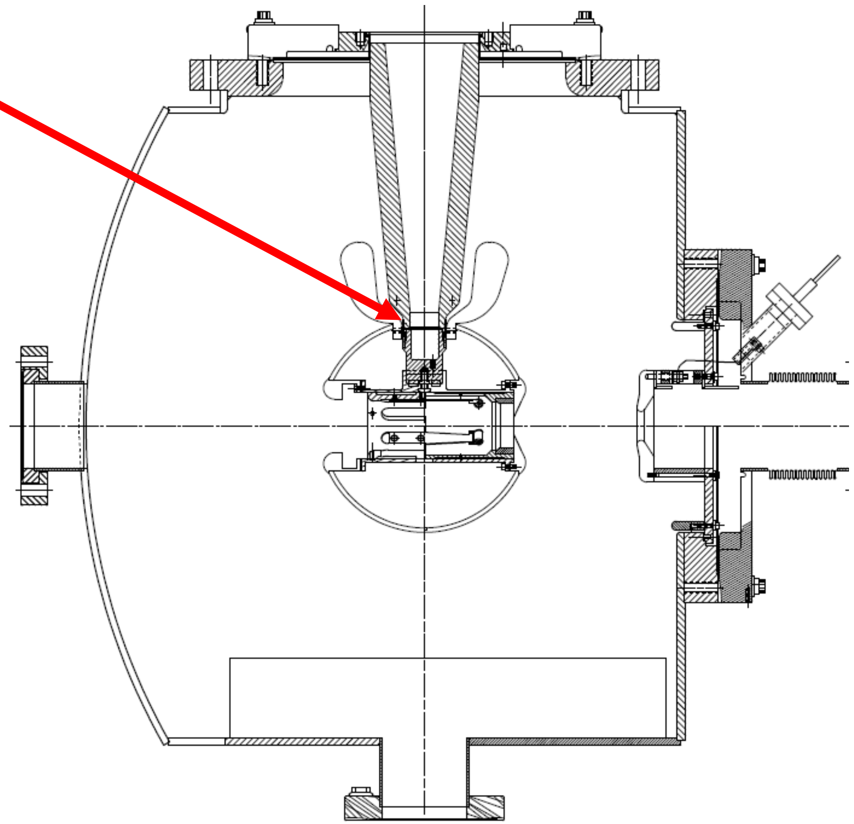
Demonstrated (CEBAF, SLC, JLab/FEL) — Proposed (Cornell ERL, LHeC, eRHIC, CLIC, ILC)

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

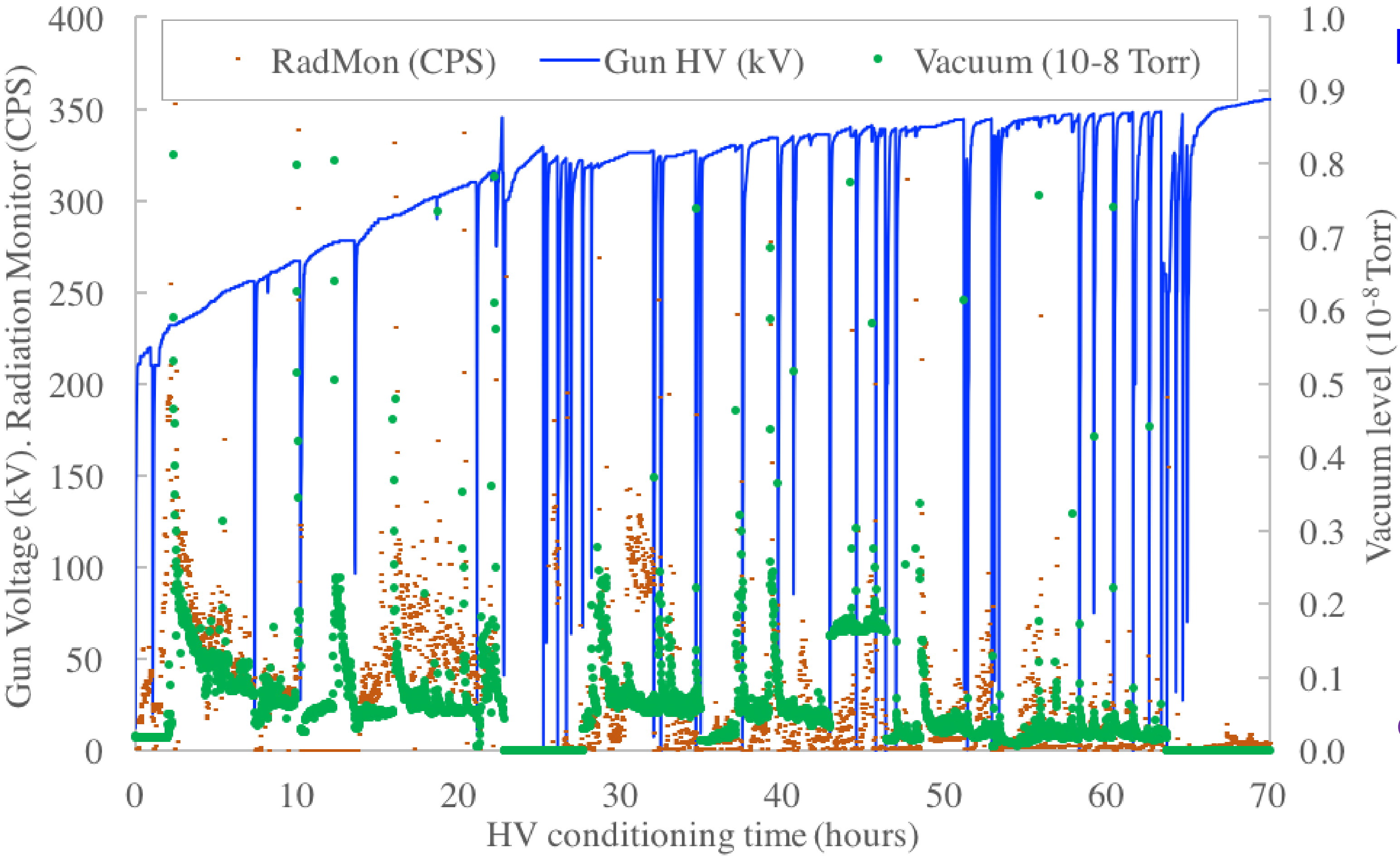
3 photoguns with barrel polished electrodes

<u>CEBAF 200 kV</u>
Installed June 2018
Commissioning now.

<u>GTS 350 kV</u>
In operation since Nov. 2016 with CsK_2Sb photocathode:
<u>500 uA magnetized beam</u>
<u>4.5 mA non-magnetized</u>

<u>UITF 350 kV</u>
Polarized Gun
Under assembly

metric of success: High Voltage without Field Emission



Reached 360 kV in 70 hours

10 MV/m at 350 kV

Vacuum and radiation levels indistinguishable from bkgd at 350kV

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 rquires 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.