Operation of Jefferson Lab Polarized Electron Sources at High Currents

Challenges and Lessons-learned

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EIC14, March 17-21, 2014

Source Parameter Comparison

Parameter	CEBAF	JLab/FEL	EIC eRHIC	EIC MEIC	Cornell ERL	LHeC	CLIC	ILC
Polarization	Yes	No	Yes	Yes	No	Yes	Yes	Yes
Photocathode	GaAs / GaAsP	Bulk GaAs			K_2CsSb			
Width of microbunch (ps)	50	35	100	50	2	100	100	1000
Time between microbunches (ns)	2	13	106	1.34	0.77	25	0.5002	337
Microbunch rep rate (MHz)	499	75	9.4	748.5	1300	40	1999	3
Width of macropulse	-	-	-	2.3 μs	-	-	156 ns	1 ms
Macropulse repetition rate (Hz)	-	-	-	20	-	-	50	5
Charge per microbunch (pC)	0.4	133	5300	173.5	77	640	960	4800
Peak current of microbunch (A)	0.008	3.8	53	3.5	38.5	6.4	9.6	4.8
Laser Spot Size (cm, diameter)	0.1	0.5	0.6	0.3	0.3	0.5	1	1
Peak current density (A/cm^2)	1	19	188	50	500	32	12	6
Average current from gun (mA)	0.2	10	50	0.006	100	25	0.015	0.072

Proposed

* Unpolarized: Bulk GaAs (Cs,F), K_2CsSb, Na_2KSb, …
Polarized: GaAs/GaAsP (Cs,F).

Outline

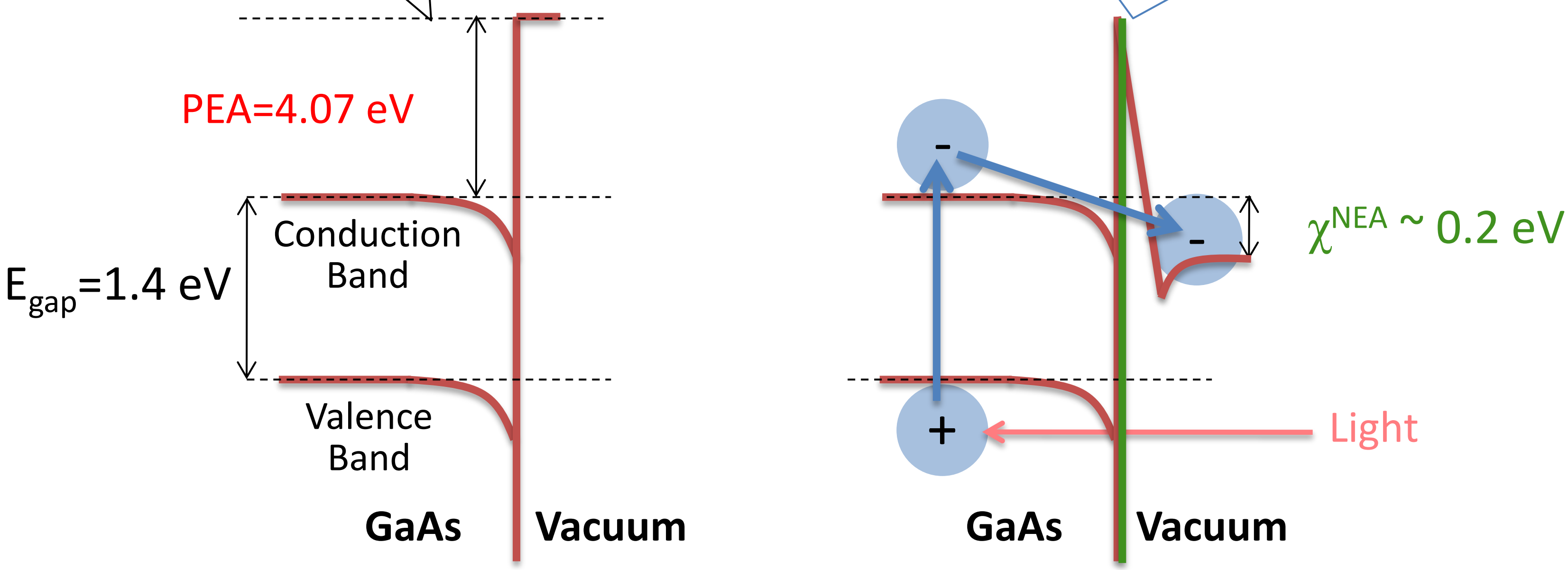
- Key Features of Polarized Electron Source:
  - Photocathode
  - Drive Laser: Reliable, Phase Locked to Accelerator, Adequate Power
  - Load-Lock Gun:
    - Vacuum and Ion Bombardment
    - High Voltage and Eliminating Field Emission
- High Current Runs at Injector Test Facility
- How to Prolong Charge Lifetime?
- R&D for High Current Polarized Electron Source

Photoemission from GaAs

Bare GaAs surface
- Large Work Function
- Positive Electron Affinity (PEA)

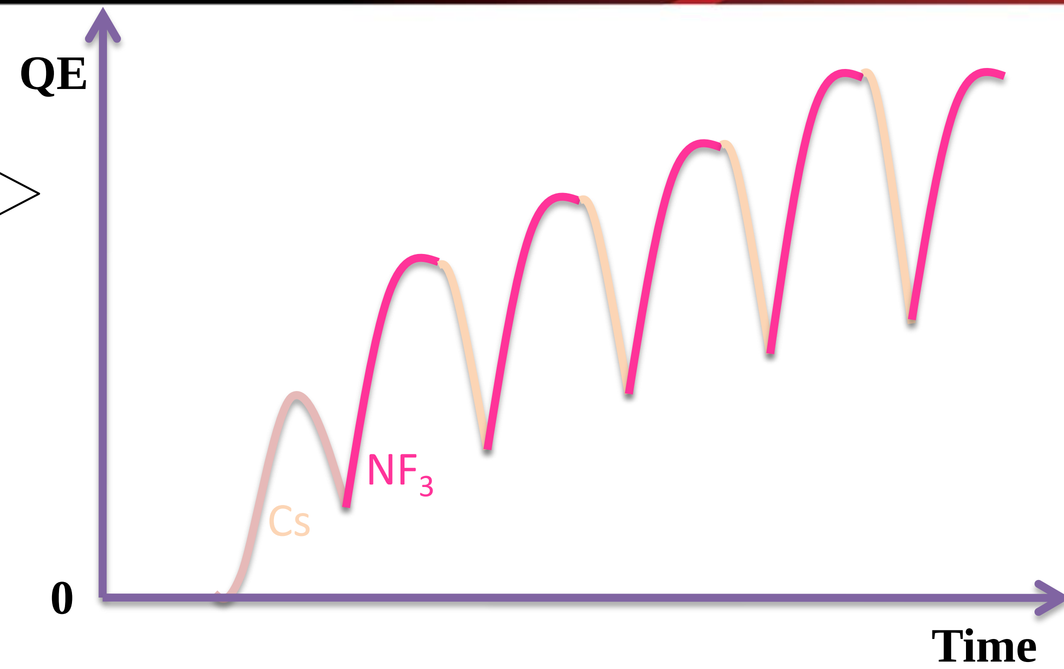
NEA Surface Activation

Dipole layers of Cesium + NF_3
- Reduces Work Function
- Negative Electron Affinity (NEA)



NEA Activation of GaAs

"**Activate**" GaAs photocathode by applying about one mono-layer of Cesium and NF_3 to very clean surface



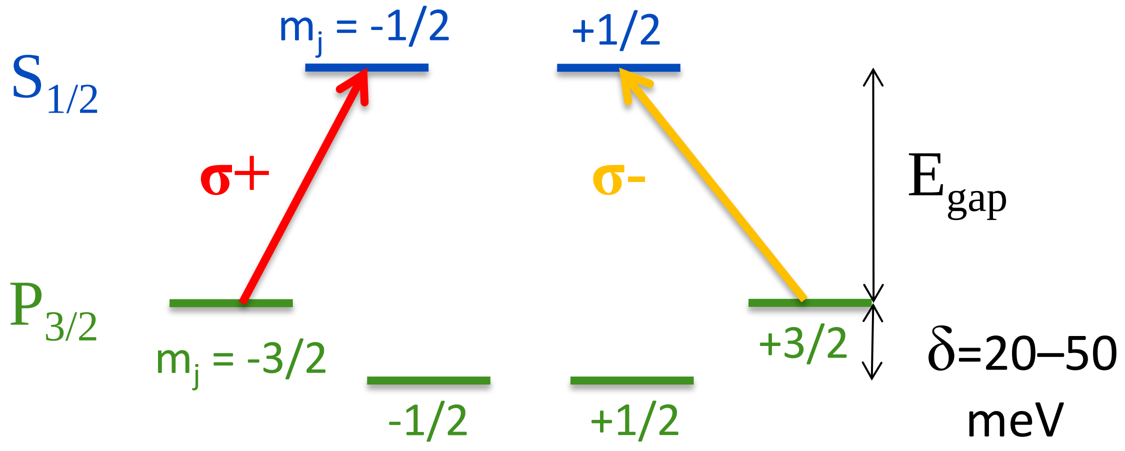
$$QE(\hbar\omega) = (1 - R)d\alpha(\hbar\omega)B(\chi)$$

R	GaAs Light Reflection Coefficient (~ 0.3)
d	GaAs layer thickness (~ 0.1 μm)
$\alpha(\hbar\omega)$	Photo-absorption Coefficient (~ $5\text{x}10^3$ cm^{-1})
$B(\chi)$	Surface Tunneling Probability(~ 0.2)

High P: Breaking GaAs Degeneracy

- Split degeneracy of $P_{3/2}$: Introduce strain on GaAs crystal by growing it on substrate (GaAsP) with different lattice constant

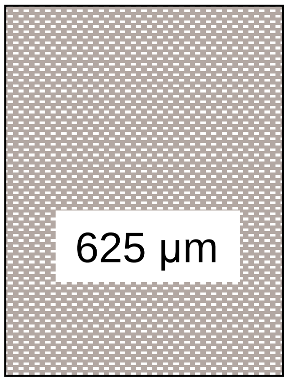
- High polarization by circularly polarized laser excitation from $P_{3/2}$ to $S_{1/2}$: $E_{gap} < E_{\gamma} < E_{gap}+\delta$



- Higher QE: Alternating layers of GaAs and GaAsP – **Superlattice GaAs**

GaAs Photocathode Evolution

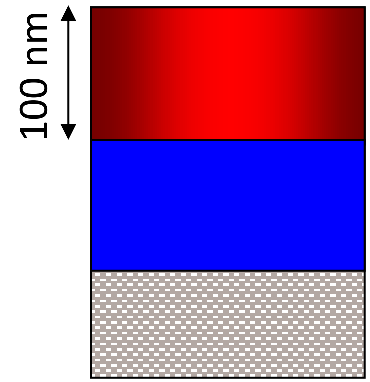
Bulk GaAs



QE ~ 20%, 120 μA/mW
Unpolarized @ 532 nm

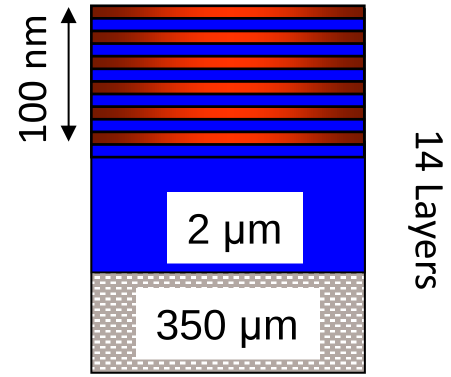
QE ~ 5%, 30 μA/mW
Pol ~ 35% @ 780 nm

Strained GaAs:
GaAs on GaAsP



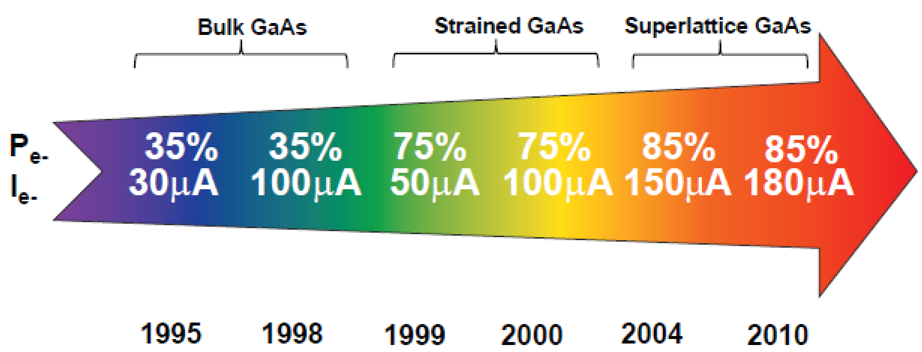
QE ~ 0.2%, 1 μA/mW
Pol ~ 75% @ 850 nm

Superlattice GaAs:
Layers of GaAs on GaAsP



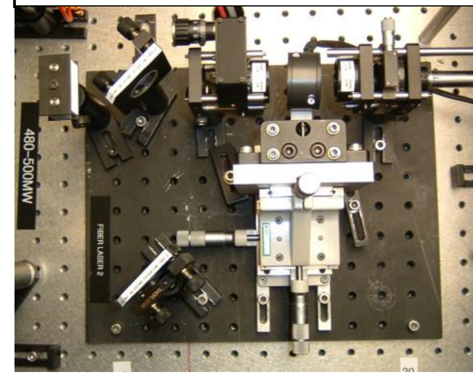
No strain relaxation
QE ~ 1%, 6 μA/mW
Pol ~ 85% @ 780 nm (1.59 eV)

Timeline of Polarized Source at CEBAF

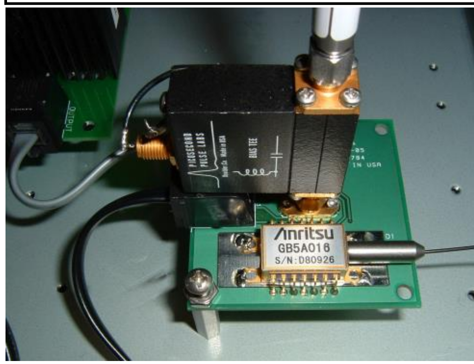


Fiber-based Drive Laser

PPLN Frequency-Doubling Crystal
1560 nm to 780 nm
30% Efficiency (2 W)

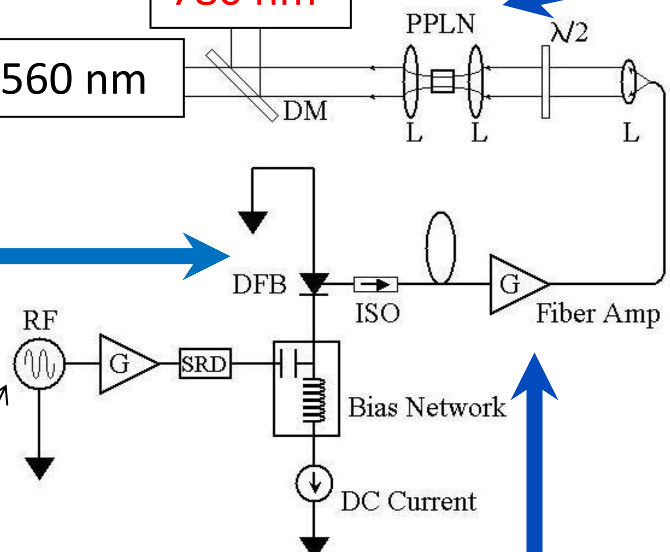


RF Locked Low-Power (1 mW)
1560 nm Fiber Diode

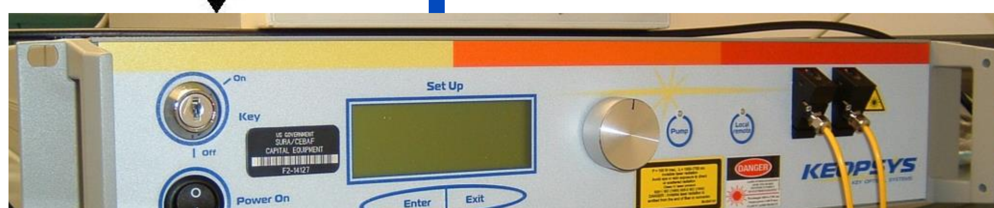


780 nm

1560 nm

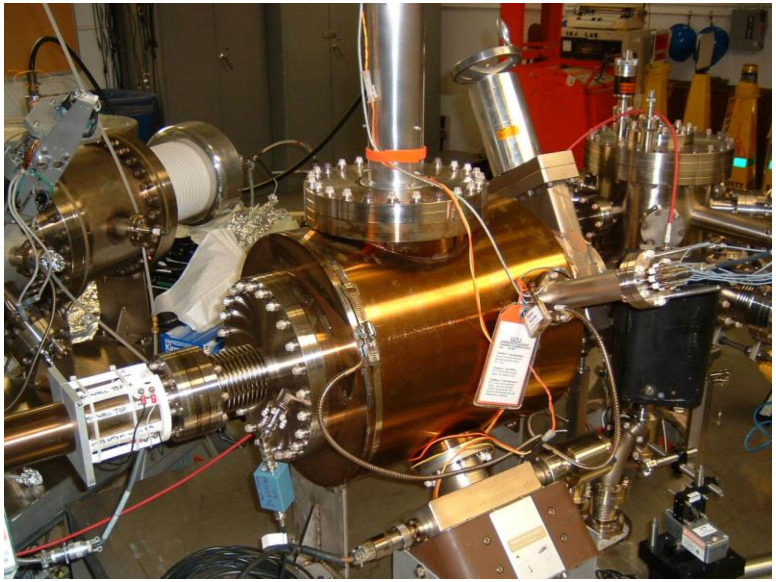


499 MHz



High Power (6 W) 1560 nm Fiber Amplifier

Inverted Guns at JLab

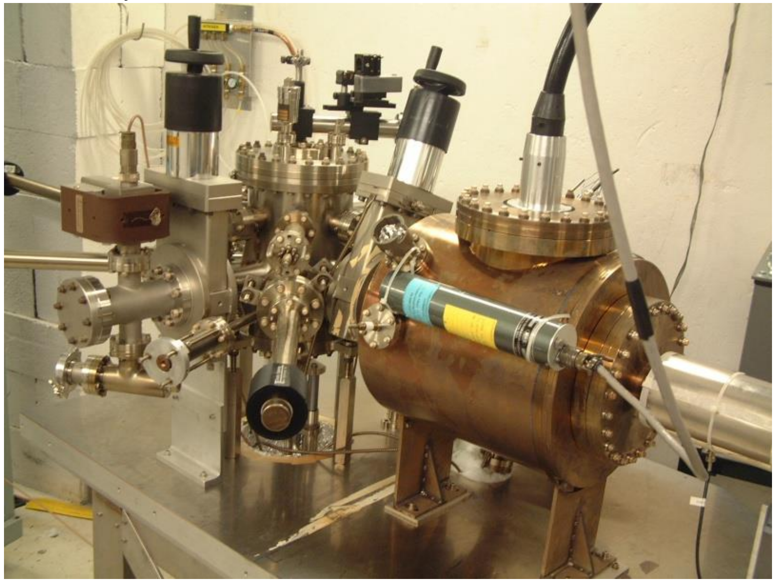


Inverted Gun #2 at Injector Test Facility

- HV Conditioned to 225 kV, with large grain Niobium (Nb) Electrode
- Operating at 200 kV
- Used for photocathodes lifetime studies at high currents

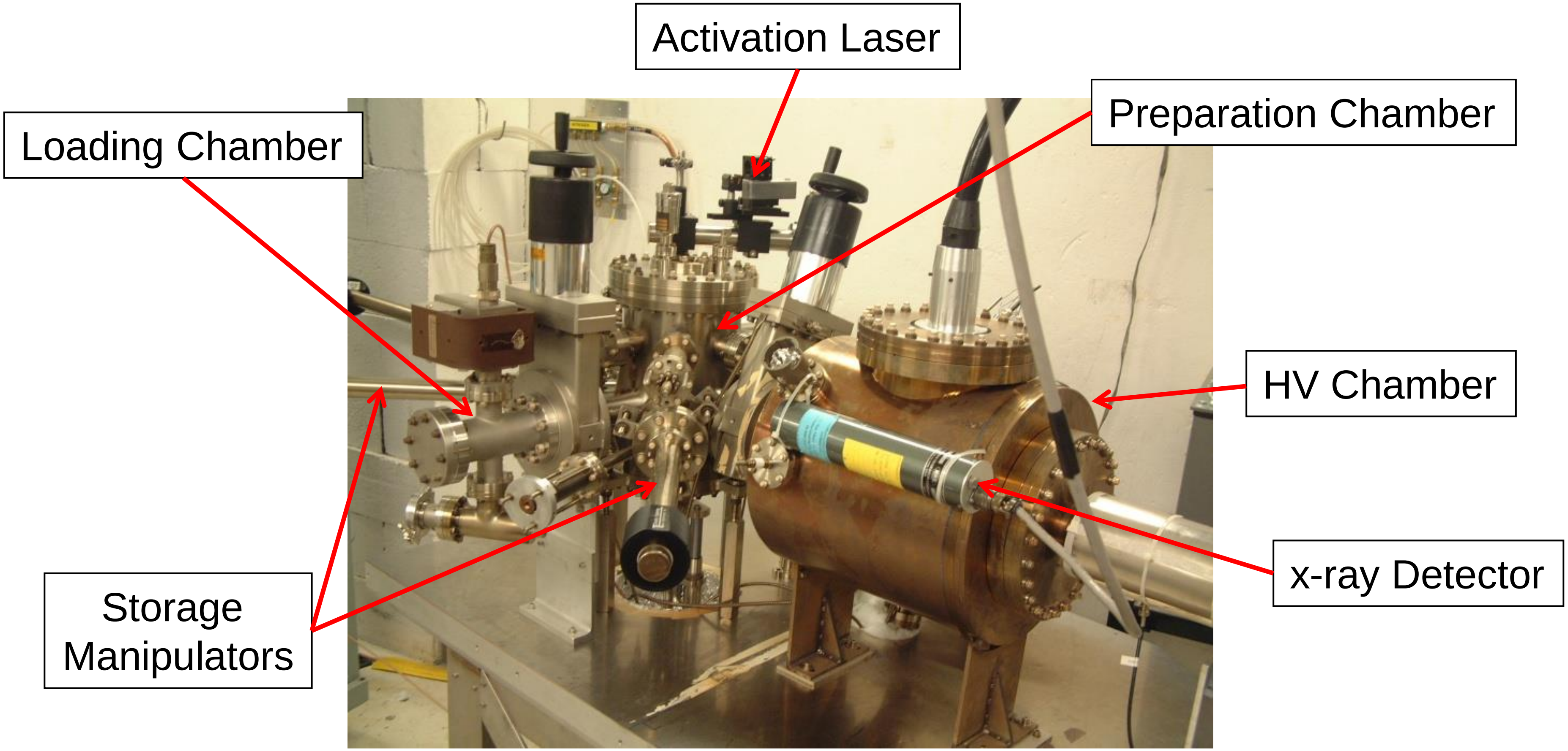
Inverted Gun #1 at CEBAF

- HV Conditioned to 150 kV with Stainless Steel Electrode
- Operating at 130 kV. Charge lifetime ~ 200 C at 180 μA with transmission of 95%
- Delivered 1800 C of polarized beam to QWeak



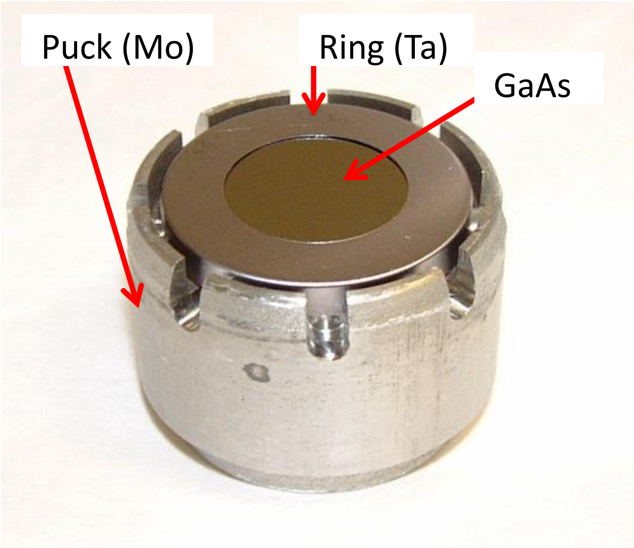
Load-lock Photogun

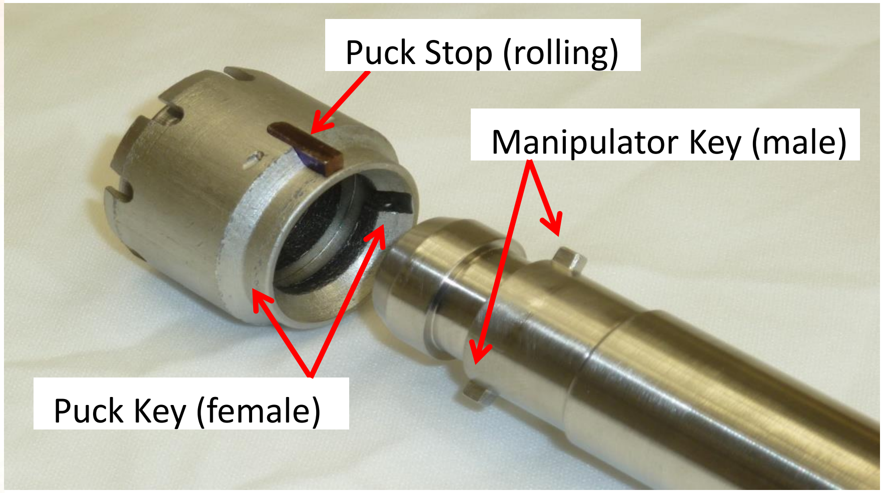
- Best vacuum inside HV Chamber, which is never vented except to change electrodes
- Photocathode Heat and Activation takes place inside Preparation Chamber
- Use “Suitcase” to replace photocathodes through a Loading Chamber



Key Features:

- 5 pucks can be stored in Storage Manipulators
- 8 hours to heat and activate photocathode
- Mask to limit active area
- Suitcase for installing new photocathodes (one day to replace all pucks)





Vacuum

I. Static Vacuum:

I. Primary source of gas in Polarized Gun is hydrogen outgassing

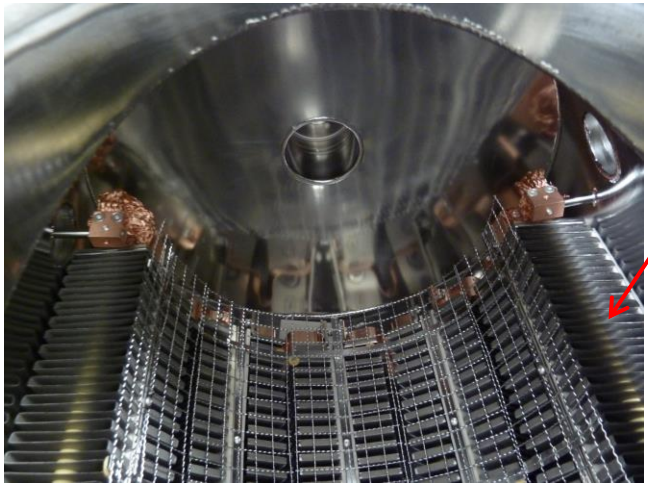
II. Reduce outgassing:
- Reduce thick flange area
- HV Chamber 400°C bake for 10 days
- Diffusion barrier coatings (TiN)

III. Improve Pumping:
- Non-Evaporable Getters (NEGs) (Zr-V-Fe)
- Ion Pumps
- Cryo-pump (planned)

IV. Improve beamline vacuum

✓ Outgassing rate: 1.0×10^{-13} Torr·L/s·cm^2

✓ Extractor Gauge: 2.0×10^{-12} Torr (raw value), our lowest value



NEGs

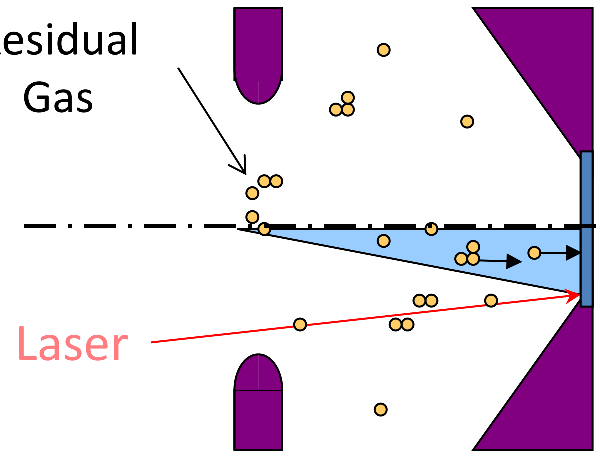
II. Dynamic Vacuum:

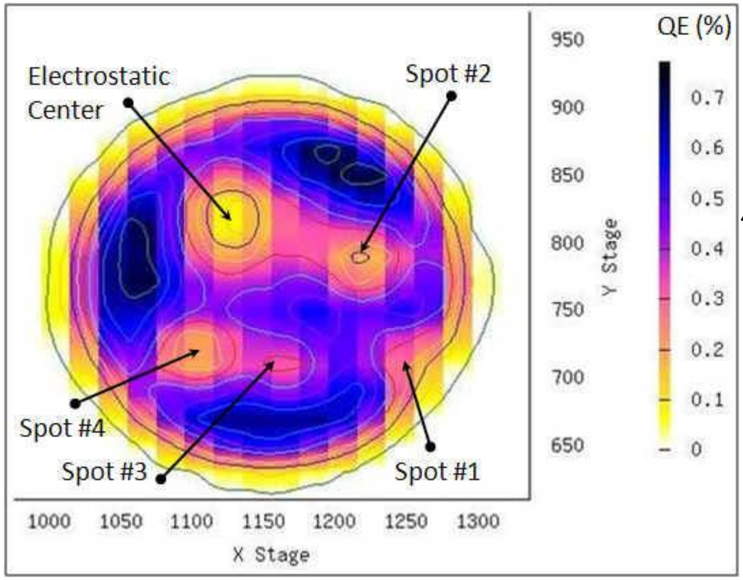
I. Eliminate field emission

II. No beam loss

Imperfect Vacuum = Finite Lifetime

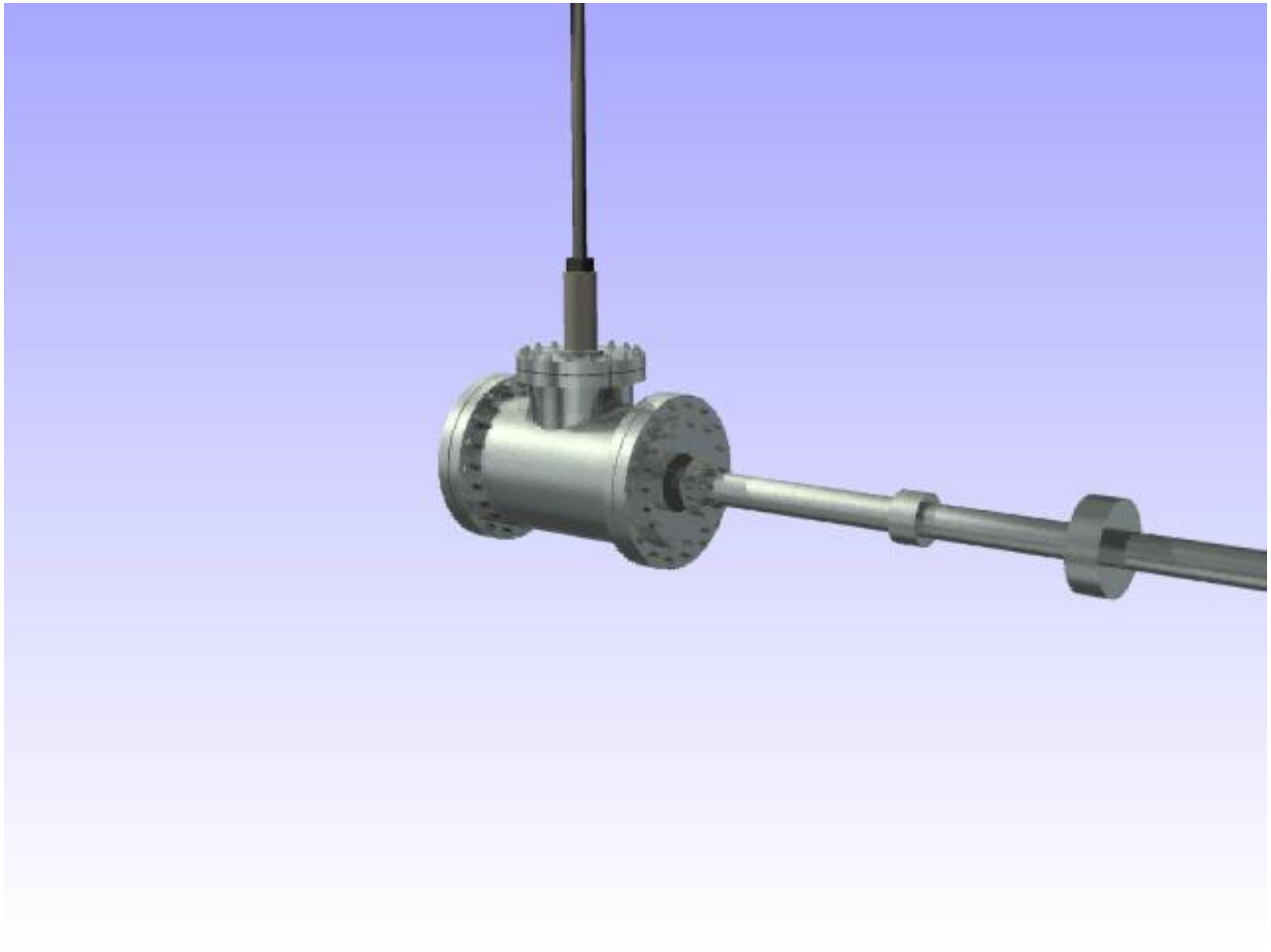
- Ion bombardment – with characteristic QE "trench" from laser spot to electrostatic center of photocathode – **damages NEA** of GaAs
- High energy ions are focused to electrostatic center: create QE "hole" (We don't run beam from electrostatic center)
- QE can be restored, but takes about 8 hours to heat and reactivate





- Photocathode "QE scan"
  - Active area = 5 mm
  - Laser size = 0.35 mm
- Can run beam from 6 locations (spots) before heating and reactivating

Ion Bombardment

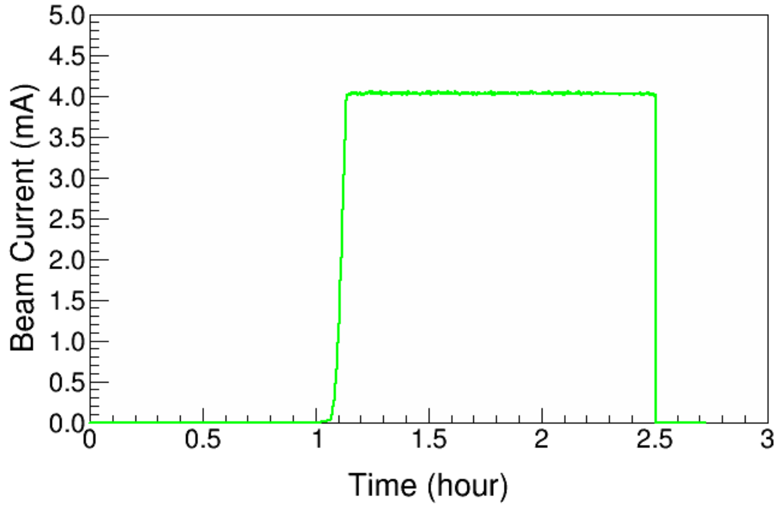


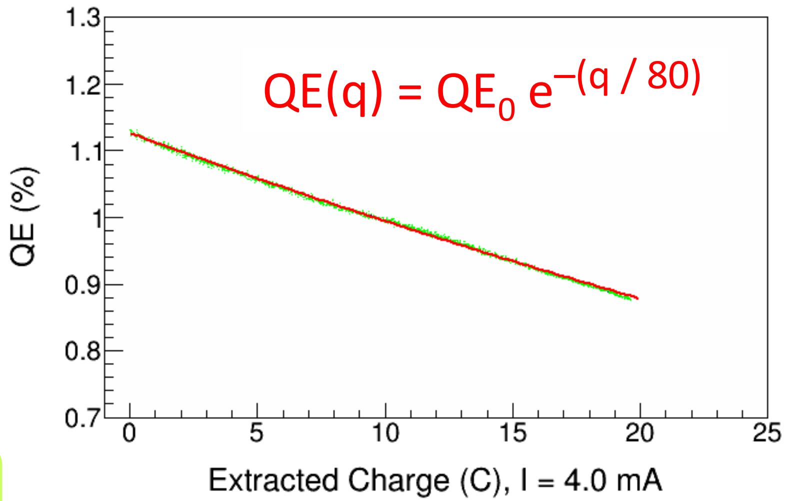
High Polarization Runs

Parameter	Value	Value
Laser Rep Rate	499 MHz	1500 MHz
Laser Pulse Length	30 ps	50 ps
Laser Wavelength	780 nm	780 nm
Laser Spot Size	**0.45 mm**	**0.35 mm**
Photocathode	GaAs/GaAsP	GaAs/GaAsP
Gun Voltage	100 kV	200 kV
Beam Current	**1 mA**	**4 mA**
Run Duration	8.25 hr	1.4 hr
Extracted Charge	30.3 C	20 C
Charge Lifetime	**210 C**	**80 C**
Fluence Lifetime	**132 kC/cm^2**	**83 kC/cm^2**
Bunch Charge	2.0 pC	2.7 pC
Peak Current	67 mA	53 mA
Peak Current Density	42 A/cm^2	55 A/cm^2

J. Grames *et al.*, PAC07, THPMS064

R. Suleiman *et al.*, PAC11, WEODS3





How Long Can We Run at 4 mA?

- Photocathode with 1% initial QE, 10 W laser at 780 nm and gun with 80 C charge lifetime. 4.0 mA operation, 14 C/hr, 346 C/day

- Need initial laser power of about 1 W to produce 4 mA

- Should be able to operate at 4 mA for 13 hours before running out of laser power

- Spot Move (it takes 1 hr). With 6 spots, this provides <u>3 days</u> of operation (since laser spot size is much smaller than active area) before heat and reactivate

Message: High current polarized electron sources need photoguns with kC lifetime

How to Prolong Charge Lifetime?

I. Larger Laser Size (also reduces space-charge emittance growth and suppresses surface charge limit)

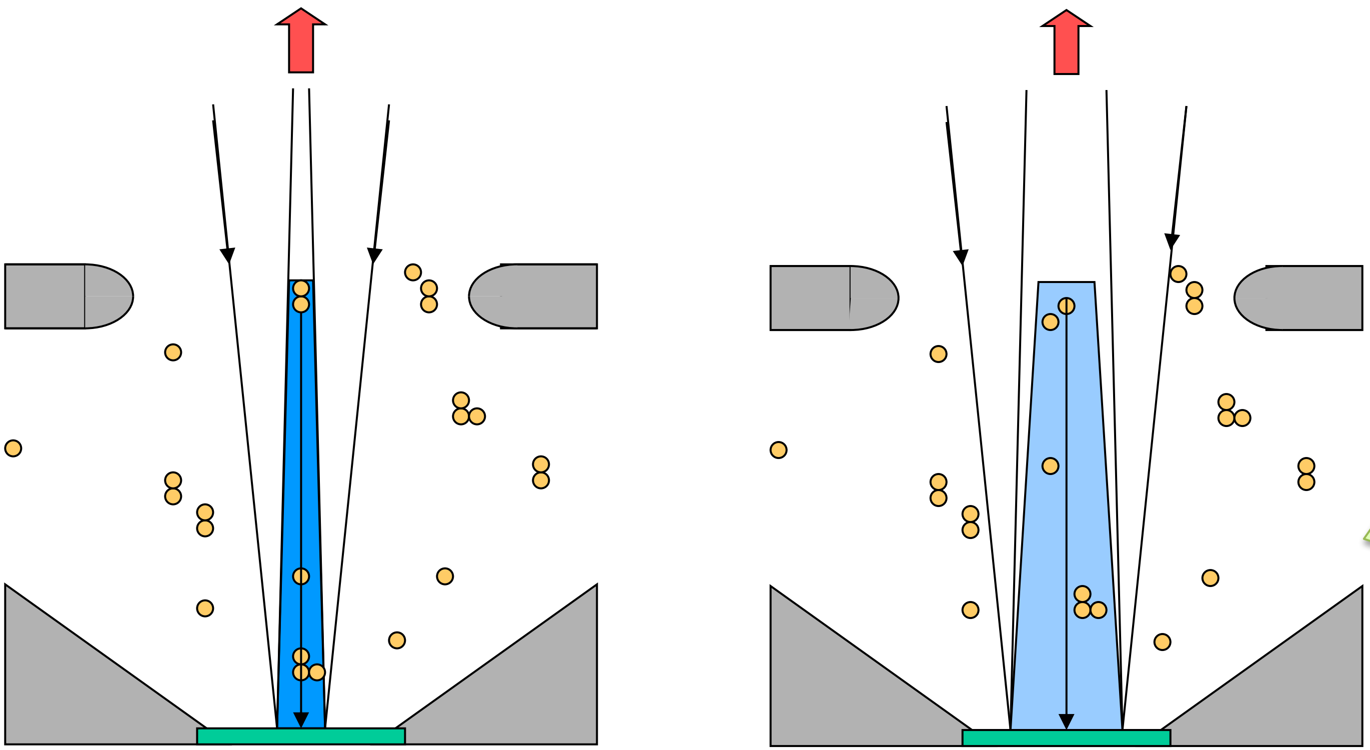
II. Laser Position on Photocathode and Active Area

III. Higher Gun Voltage:
   I. Less ions are created
   II. Reduce space-charge emittance growth, maintain small transverse beam profile and short bunch-length; clean beam transport
   III. Increase QE by lowering potential barrier (Schottky Effect)
   IV. Compact, less-complicated injector

Biggest Obstacle: Field emission and HV breakdown… which lead to bad vacuum and photocathode death

"Charge and fluence lifetime measurements of a DC high voltage GaAs photogun at high average current.," J. Grames, R. Suleiman, et al., Phys. Rev. ST Accel. Beams 14, 043501 (2011)

Improve Lifetime with Larger Laser Size



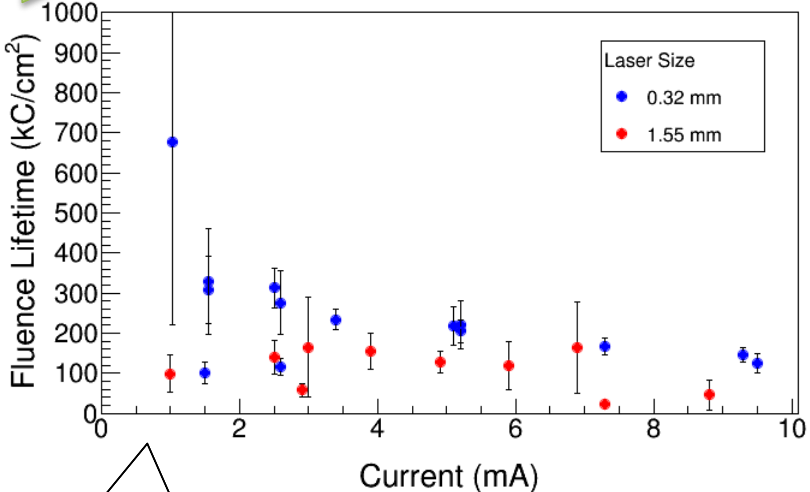
Larger laser size (same # electrons, same # ions)

Ionized gas strikes photocathode

Ion damage distributed over larger area

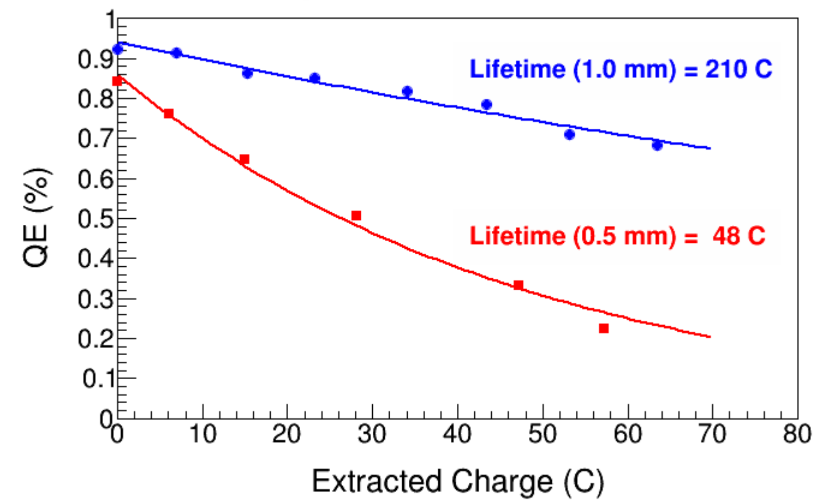
Fluence Lifetime

Fluence Lifetime: Charge Lifetime per Emission Area



Bulk GaAs, 532 nm, 5 mm Active Area

Enhanced Charge Lifetime for QWeak: Increase laser size from 0.5 mm to 1.0 mm (diameter)



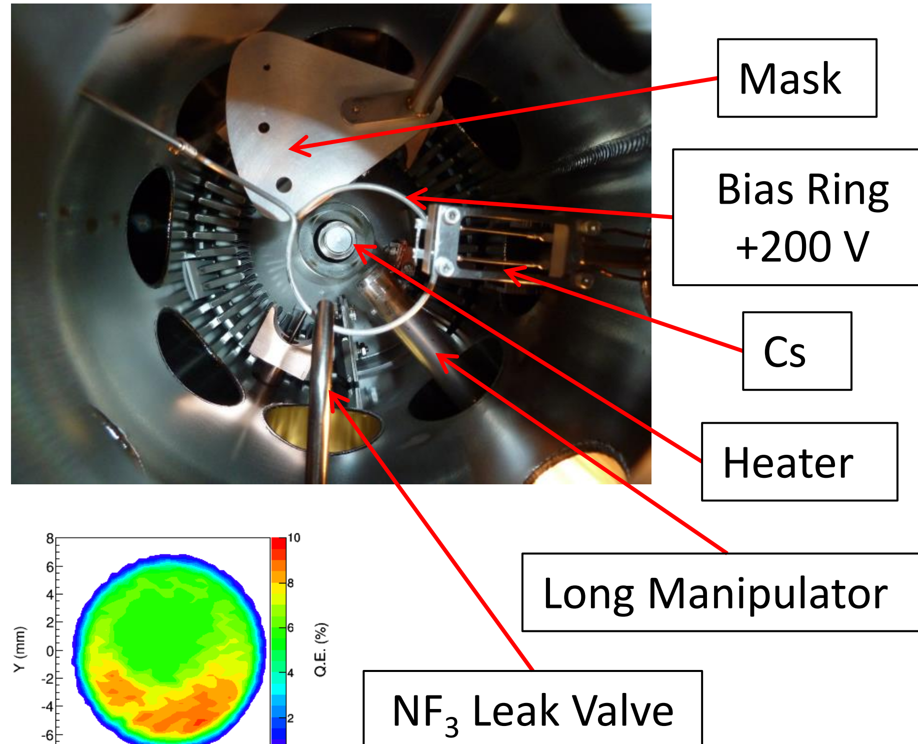
Can we use cm size laser beams?

- Not in today's CEBAF photogun
- Need a better cathode/anode beam transport optics

Lifetime vs. Laser Position and Active Area

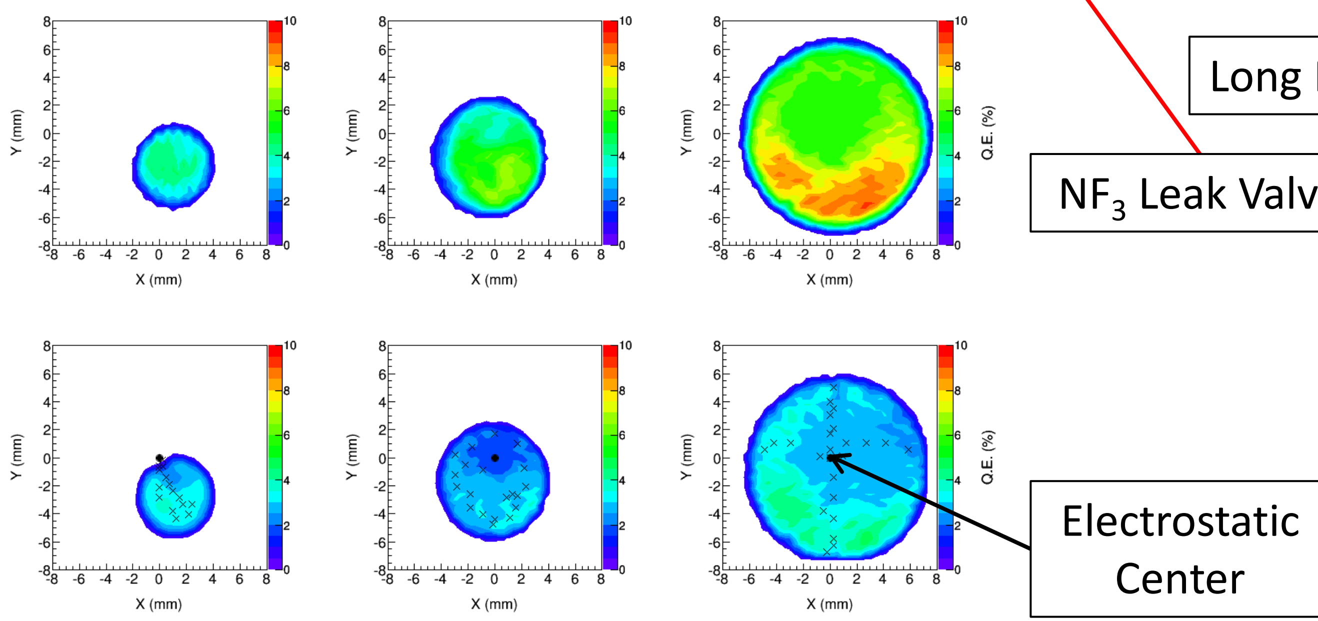
I. Activate with different Masks: 5 mm, 7 mm, and No Mask (12.8 mm)

II. Measure Lifetime from different spots on Bulk GaAs with 532 nm green laser



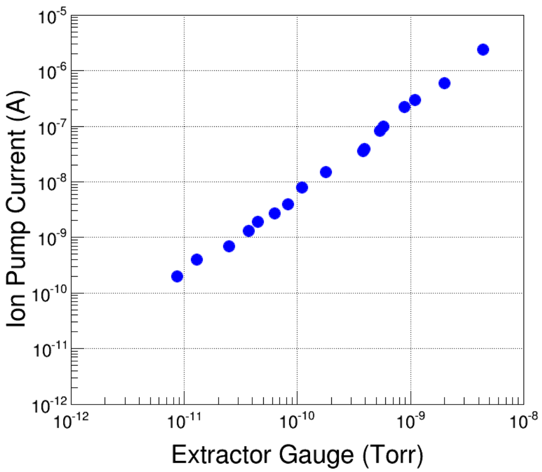
After Activation

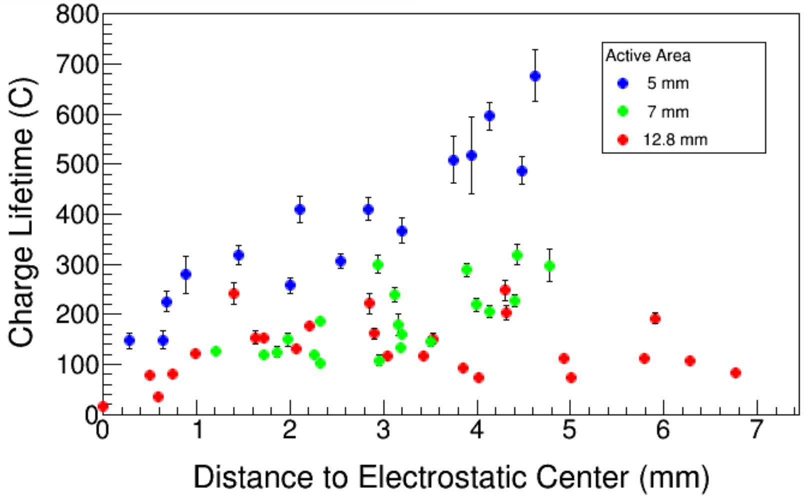
After Lifetime Runs



	I=0 (HV = 0, 100 kV)	I = 2 mA (Bulk GaAs, 532 nm, 0.35 mm Laser Size) (HV = 100 kV)		
		5 mm Active Area	7 mm Active Area	12.8 mm Active Area
Anode Current (pA)	0.0 ± 0.3	0.0 ± 0.3	0.0 ± 0.3	-100 – -1000
X-ray Detector (E-2 mR/h)	0.6 ± 0.3	1.5 ± 0.5	1.8 ± 0.5	3 – 7
Gun Vacuum (pA)	0	0	0	0 – 30
Y-Chamber Vacuum (nA)	3.0	3.0	3.0	4 – 20

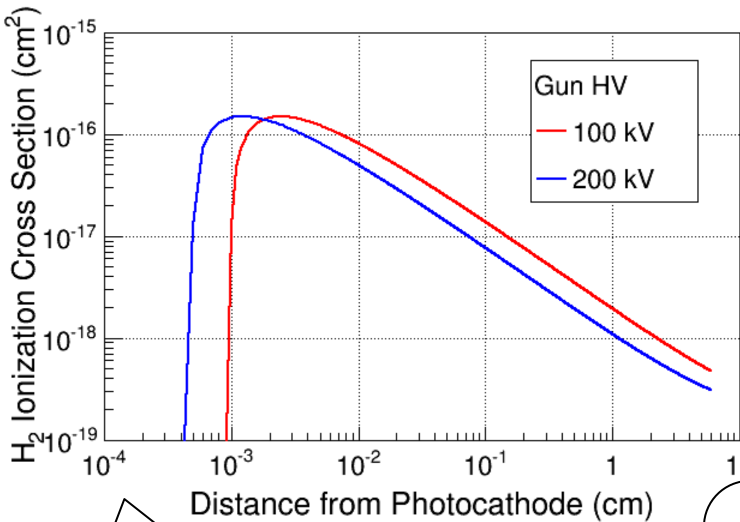
Range of values at start of lifetime measurements. Anode current is proportional to laser power.





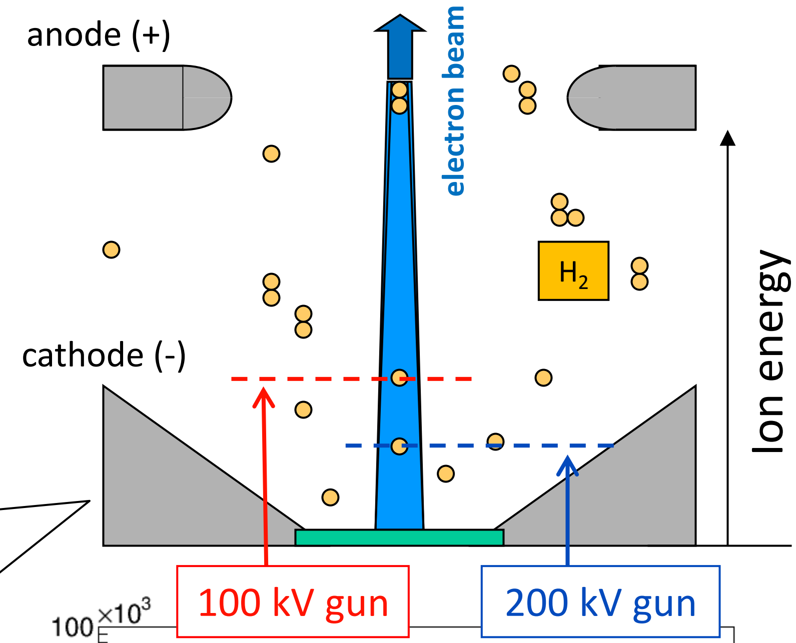
- Extremely important to manage ALL of extracted beam
- Beam from outside 5 mm active area hits beam-pipe walls, degrades vacuum, reduces lifetime
- Stay away from Electrostatic Center and limit Active Area

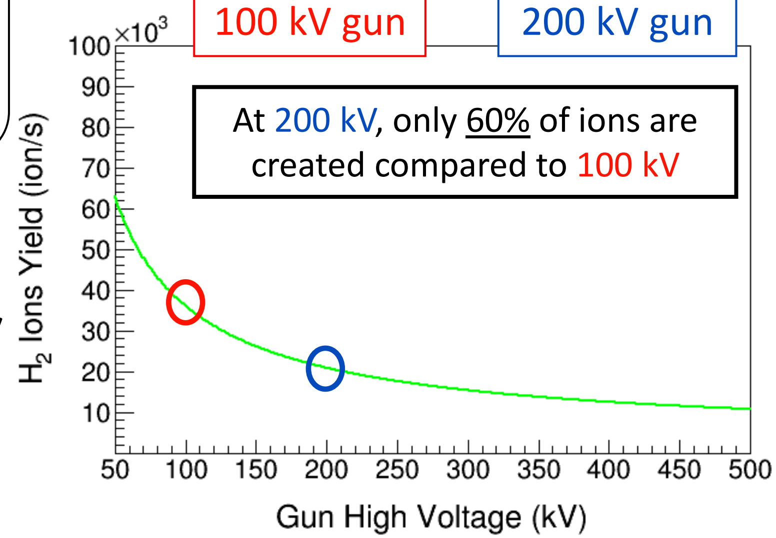
Will Higher HV Improve Lifetime?



Most ions created close to GaAs surface

At lower HV, cross section is larger over longer distance

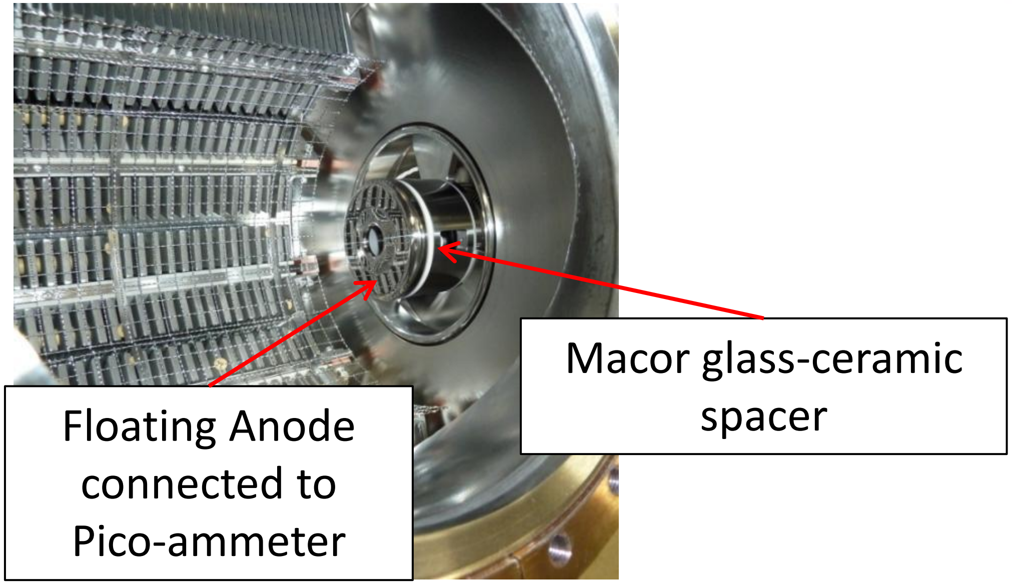


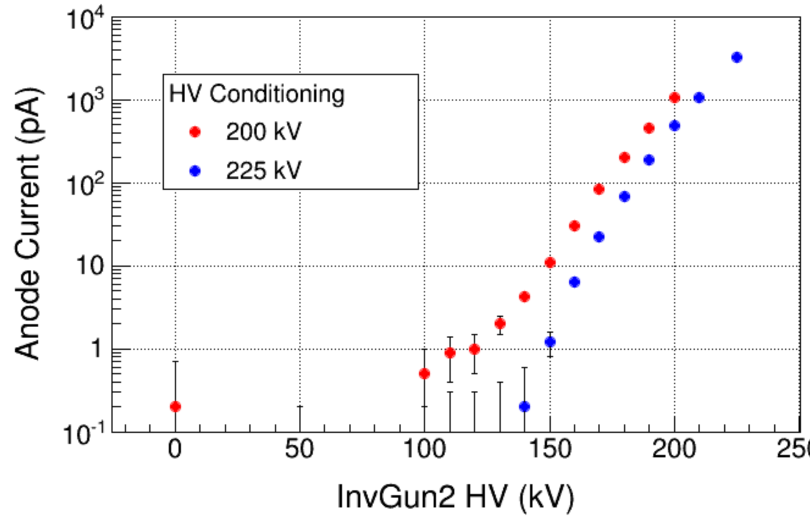


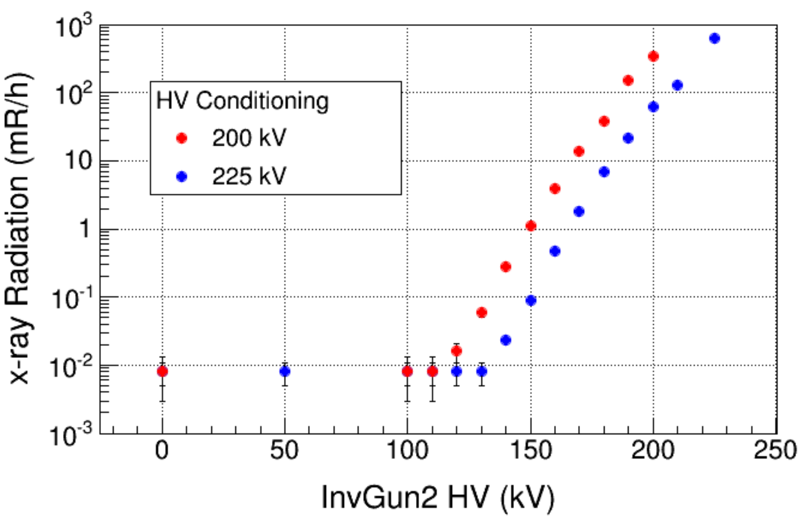
Awaits experimental verification

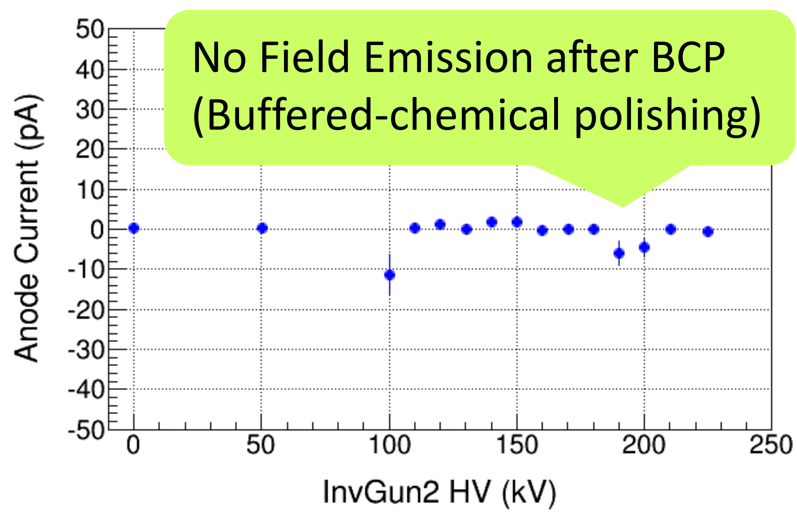
Beam Current:
2.0 mA
Vacuum:
8.0×10^{-12} Torr

Field Emission

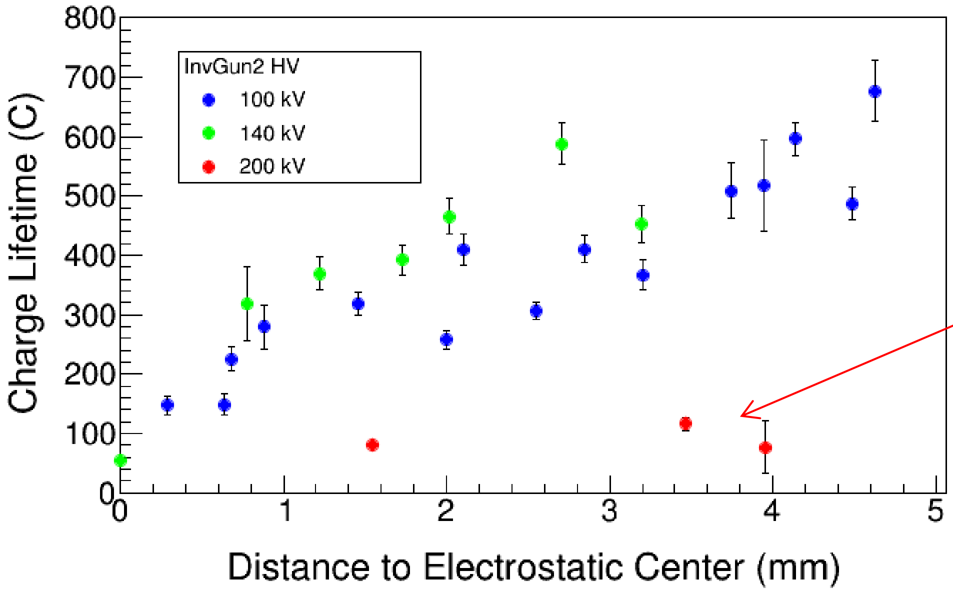








Poor Lifetime with Field Emission

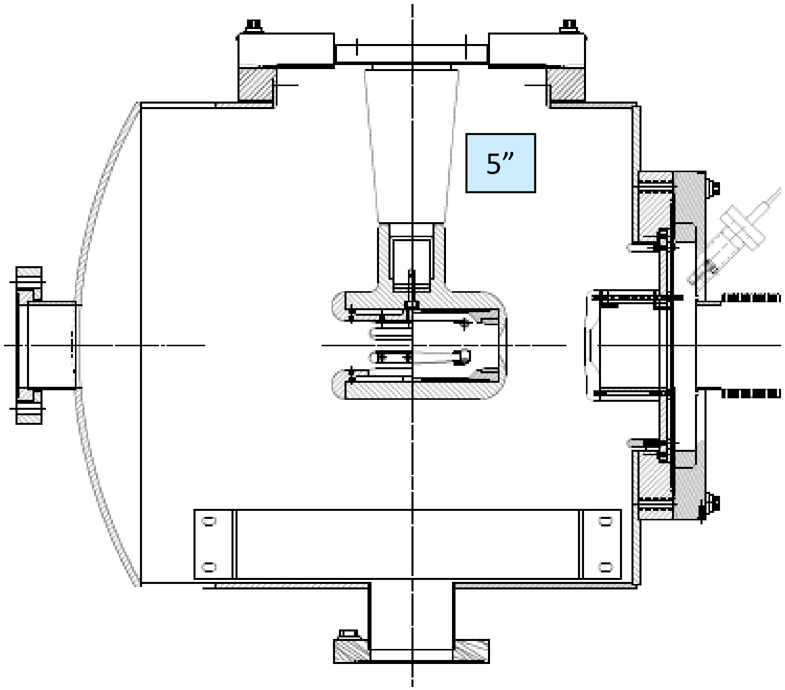


Poor lifetime at 200 kV due to field emission

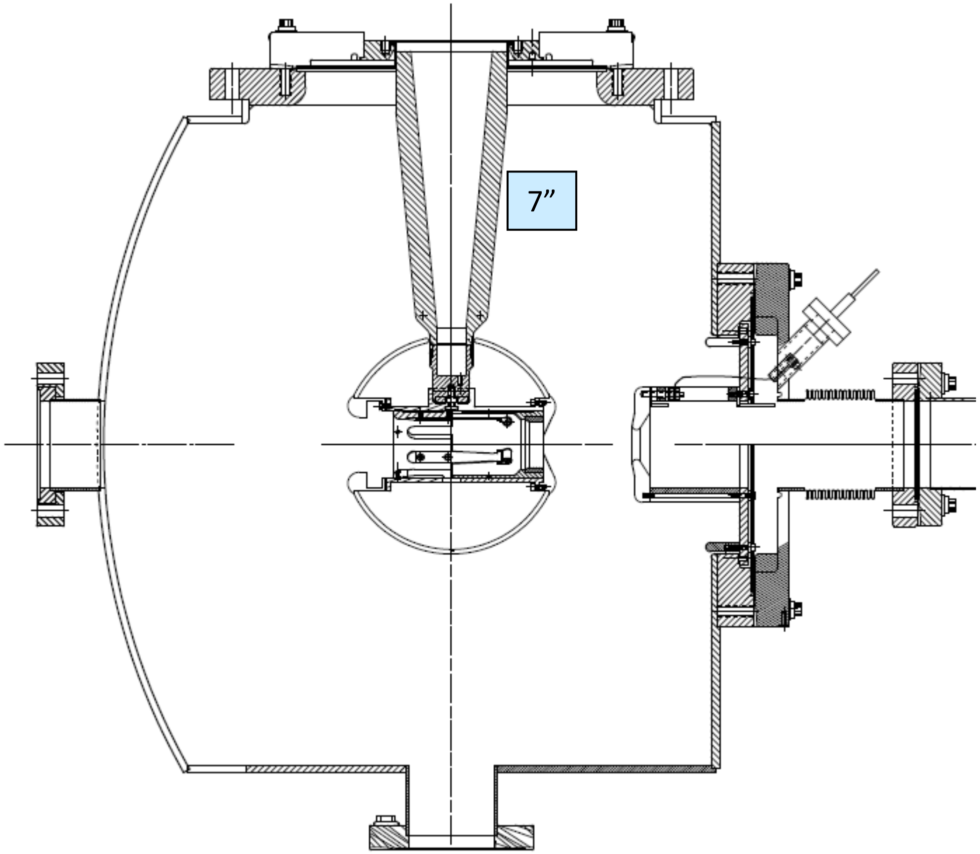
And vacuum bursts often killed QE completely

	I = 2 mA, Bulk GaAs (5 mm Active Area, 0.35 mm Laser Size)		
Gun HV	100 kV	140 kV	200 kV
Anode Current (pA)	0.0 ± 0.3	-8 ± 1	-520 ± 20
X-ray Detector (E-2 mR/h)	1.5 ± 0.5	105 ± 5	5700 ± 300
Gun Vacuum (pA)	0	0	400
Y-Chamber Vacuum (nA)	3.0	3.0 – 3.2	3 – 4

500 kV Inverted Gun



200 kV Inverted Gun



- Longer insulator
- Spherical electrode

See C. Hernandez-Garcia Talk

Summary and Outlook

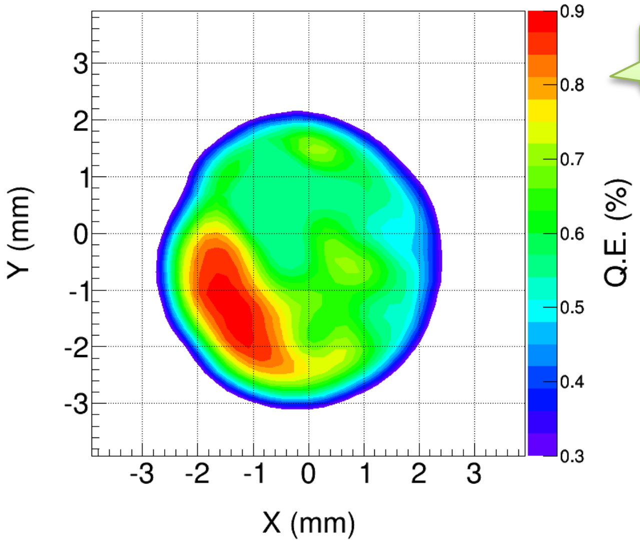
- Polarized sources require kC charge lifetime:
  - Improve vacuum
  - large laser spot size to accommodate ion bombardment
  - Cathode/anode design for 100% beam transport

- Operation at higher gun voltage (500 kV) is beneficial
- With high laser power … need photocathode cooling

- Polarized photocathode R&D Goals:
  - Higher QE (>1%): thicker superlattice absorber region and more efficient photon absorption
  - Longer Lifetime: reduce structural and surface decomposition, more robust in poor vacuum
  - Higher Polarization: higher-gradient-doping to reduce surface charge limit and depolarization
    - ➢ Possible candidate: GaAsSb/AlGaAsP Superlattice (SVTA – DOE SBIR)

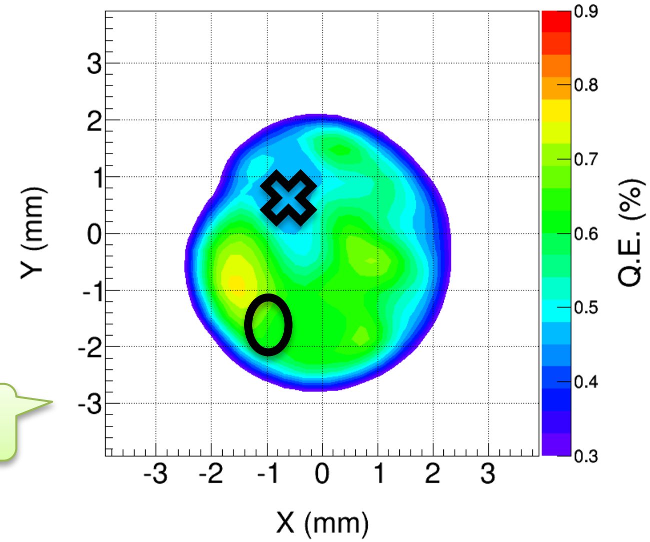
BACKUP SLIDES

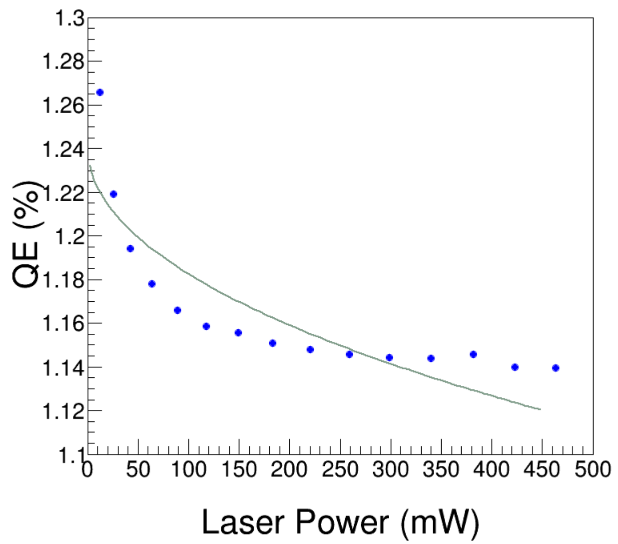
QE Scans – 4 mA SSL



Before Run

After Run





QE at 200 kV is higher than Scans (done at 372 V) because of Schottky Effect

Electric Field Enhancement of QE

- NEA of GaAs depends on Gun HV. QE increases with external Electric Field at GaAs surface, E_s,

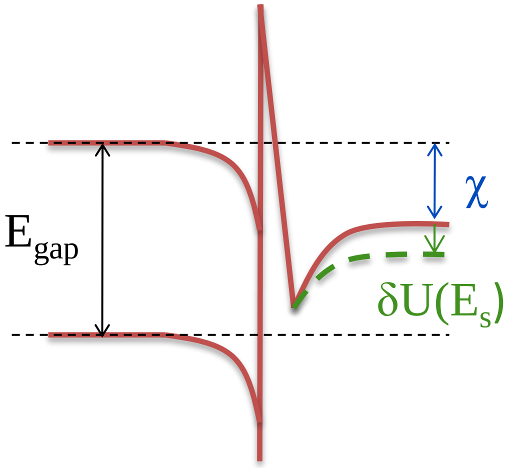
$$QE = QE_0\left(1+\frac{\delta U(E_s)}{\chi}\right)$$

Where χ (~200 meV) is the zero-field NEA value (Physics Letters A **282**, 309) and potential barrier lowering due to Electric Field (Schottky Effect) is

$$\delta U(E_s) = \sqrt{\frac{e^3 E_s(\varepsilon_s - 1)}{4\pi\varepsilon_0(\varepsilon_s + 1)}}$$

Where ε_s (= 13.1) is GaAs relative permittivity.

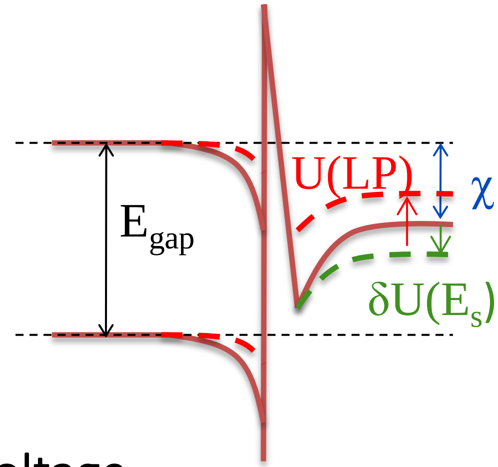
Gun HV (kV)	E_s (MV/m)	$\delta U(E_s)$ (meV)
100	2.0	50
200	4.0	70



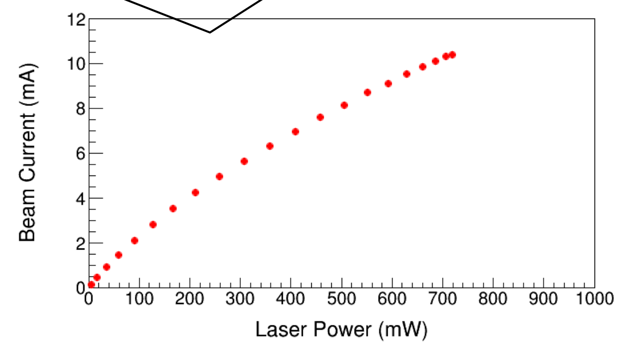
Surface Charge Limit

- Surface Charge Limit, also known as Surface Photovoltage Effect, reduces NEA of GaAs: Photoelectrons trapped near GaAs surface produce opposing field that reduces NEA resulting in QE reduction at high laser power (LP),

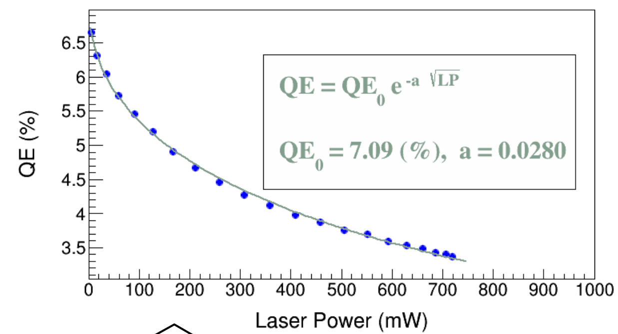
$$QE = QE_0\left(1 - \frac{U(LP)}{\chi + \delta U(E_s)}\right)$$



Bulk GaAs, 532 nm, 100 kV



Where U(LP) is up-shifting of potential barrier due to photovoltage.



$$U(LP) \propto \sqrt{LP}$$

- For heavily Zn doped GaAs surface, $U(LP) \rightarrow 0$ (doping introduces high internal electric field to facilitate charge transport, increase diffusion length, and reduce chance of depolarization in active layer)

- Higher Gun HV suppresses photovoltage

Space Charge Limit

- Maximum current density that can be transported across cathode-anode gap is (for an infinite charge plane):

Child's Law (1D) $$j_1 = \left(2.33\times10^{-6}\right)V^{3/2}/d^2 \quad [\text{A/cm}^2]$$

- For electron emission from a finite circular spot on the cathode:

Child's Law (2D) (PRL **87**, 278301) $$j_2 \sim j_1\left(1+\frac{1}{4}\frac{d}{r}\right)$$

- For CEBAF electron beam (499 MHz):

Short Bunch (PRL **98**, 164802) $$j_{SCL} = j_2\left(2\frac{1-\sqrt{1-3X_{CL}^2/4}}{X_{CL}^3}\right),$$

$$X_{CL} = \frac{t_b}{\tau_{CL}}, \tau_{CL} = \frac{3}{2}\tau_{Single-electron}$$

V	**Gun HV**
d	Cathode-anode Gap (6.3 cm)
r	Laser Spot Size (2r = 0.1 cm)
t_b	Bunchlength (50 ps)
τ_{CL}	Gap Transit Time (0.713 ns at 200 kV)