High Current Polarized Electron Source

Considerations for building a reliable photogun that provides mA beam current at 80% polarization

JLab NP interest:

- Parity Violation Experiments
- Photoguns for EIC
- Polarized Positrons

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C. Hernandez-Garcia, M. Poelker, M.Stutzman, R. Suleiman, K. Surles-Law,
Graduate students: M. BastaniNejad, M. Mamun

Source Parameter Comparison

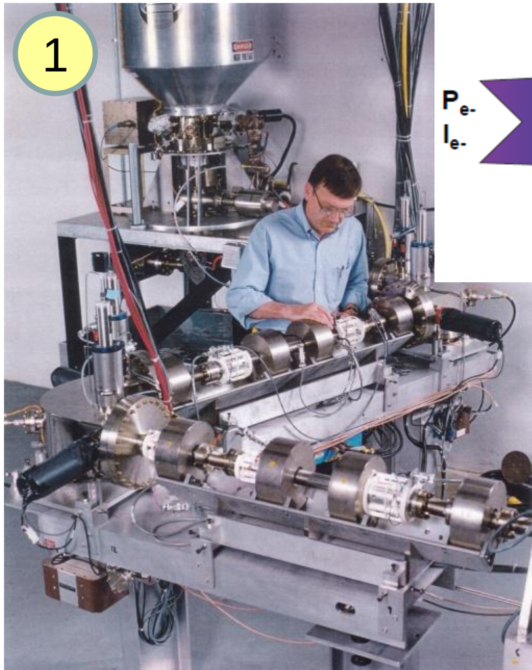
Parameter	CEBAF	JLab/FEL	Nuclear Physics at Jlab FEL	Cornell ERL	LHeC	eRHIC	CLIC	ILC
Polarization	Yes	No	Yes	No	Yes	Yes	Yes	Yes
Number electrons/microbunch	2.5×10^{6}	8.3×10^{8}	8.3×10^{6}	4.8×10^{8}	1×10^{9}	2.2×10^{10}	6×10^{9}	3×10^{10}
Number of microbunches	CW	CW	CW	CW	CW	CW	312	3000
Width of microbunch	50 ps	35 ps	35 ps	2 ps	~ 100 ps	~ 100 ps	~ 100 ps	~ 1 ns
Time between microbunches	2 ns	13 ns	1.3 ns	0.77 ns	25 ns	71.4 ns	0.5002 ns	337 ns
Microbunch rep rate	499 MHz	75 MHz	750 MHz	1300MHz	40MHz	14MHz	1999 MHz	3 MHz
Width of macropulse	-	-	-	-	-	-	156 ns	1 ms
Macropulse repetition rate	-	-	-	-	-	-	50 Hz	5 Hz
Charge per micropulse	0.4 pC	133 pC	1.3 pC	77 pC	160 pC	3.6 nC	0.96 nC	4.8 nC
Charge per macropulse	-	-	-	-	-	-	300 nC	14420 nC
Average current from gun	200 uA	10 mA	1 mA	100 mA	6.5 mA	50 mA	15 uA	72 uA
Average current in macropulse	-	-	-	-	-	-	1.9 A	0.0144 A
Duty Factor	2.5×10^{-2}	2.6×10^{-3}	2.6×10^{-2}	2.6×10^{-3}	4×10^{-3}	1.4×10^{-3}	0.2	3×10^{-3}
Peak current of micropulse	8 mA	3.8 A	38 mA	38.5 A	1.6 A	35.7 A	9.6 A	4.8 A
Current density*	4 A/cm^2	19 A/cm^2	5 A/cm^2	500 A/cm^2	8 A/cm^2	182 A/cm^2	12 A/cm^2	6 A/cm^2
Laser Spot Size*	0.05 cm	0.5 cm	0.1 cm	0.3 cm	0.5 cm	0.5 cm	1 cm	1 cm

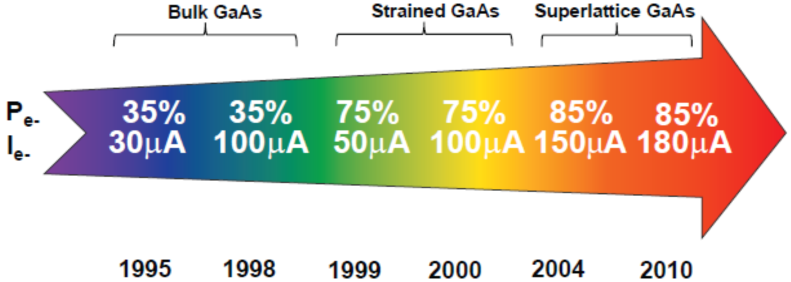
* Loose estimates

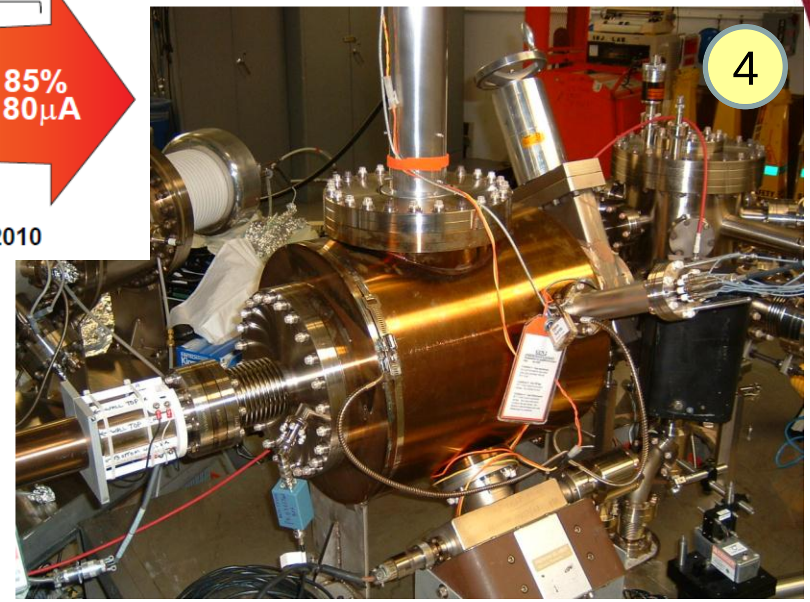
Existing (CEBAF, JLab/FEL, Nuclear Physics at Jlab FEL) — Proposed (Cornell ERL, LHeC, eRHIC, CLIC, ILC)

Challenges depend on specific accelerator requirements

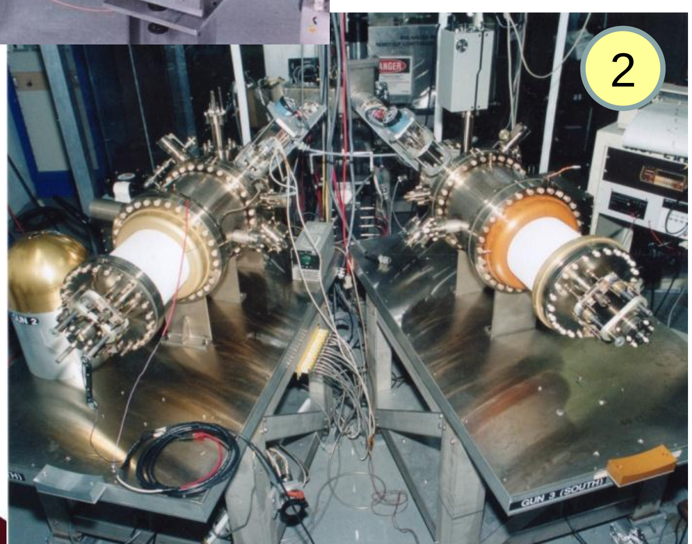
Always Tweaking the Design

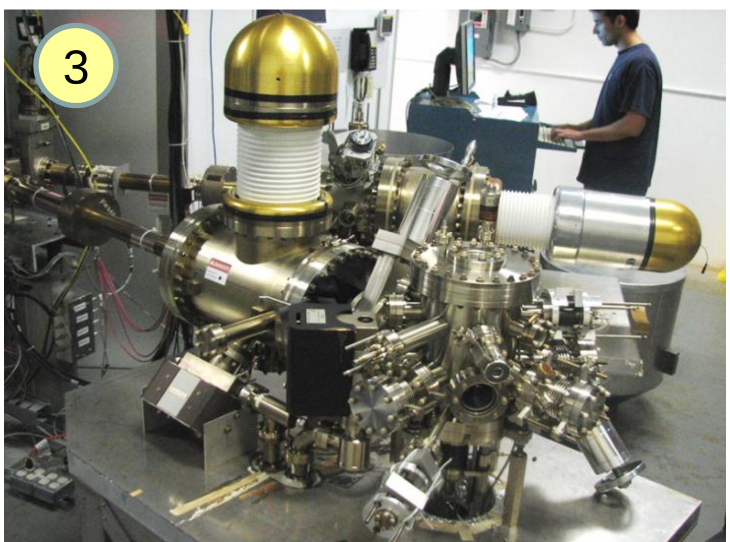






Endless (?) quest for perfection





Key Features of a Polarized Photogun

- Vacuum
  - Static Vacuum
  - Dynamic Vacuum
- High Voltage
  - Eliminating field emission
- Drive Laser
  - Reliable, phase locked to machine
  - Adequate Power, Wavelength Tunable?
- Photocathode
  - High Polarization,QE
  - Long Lifetime

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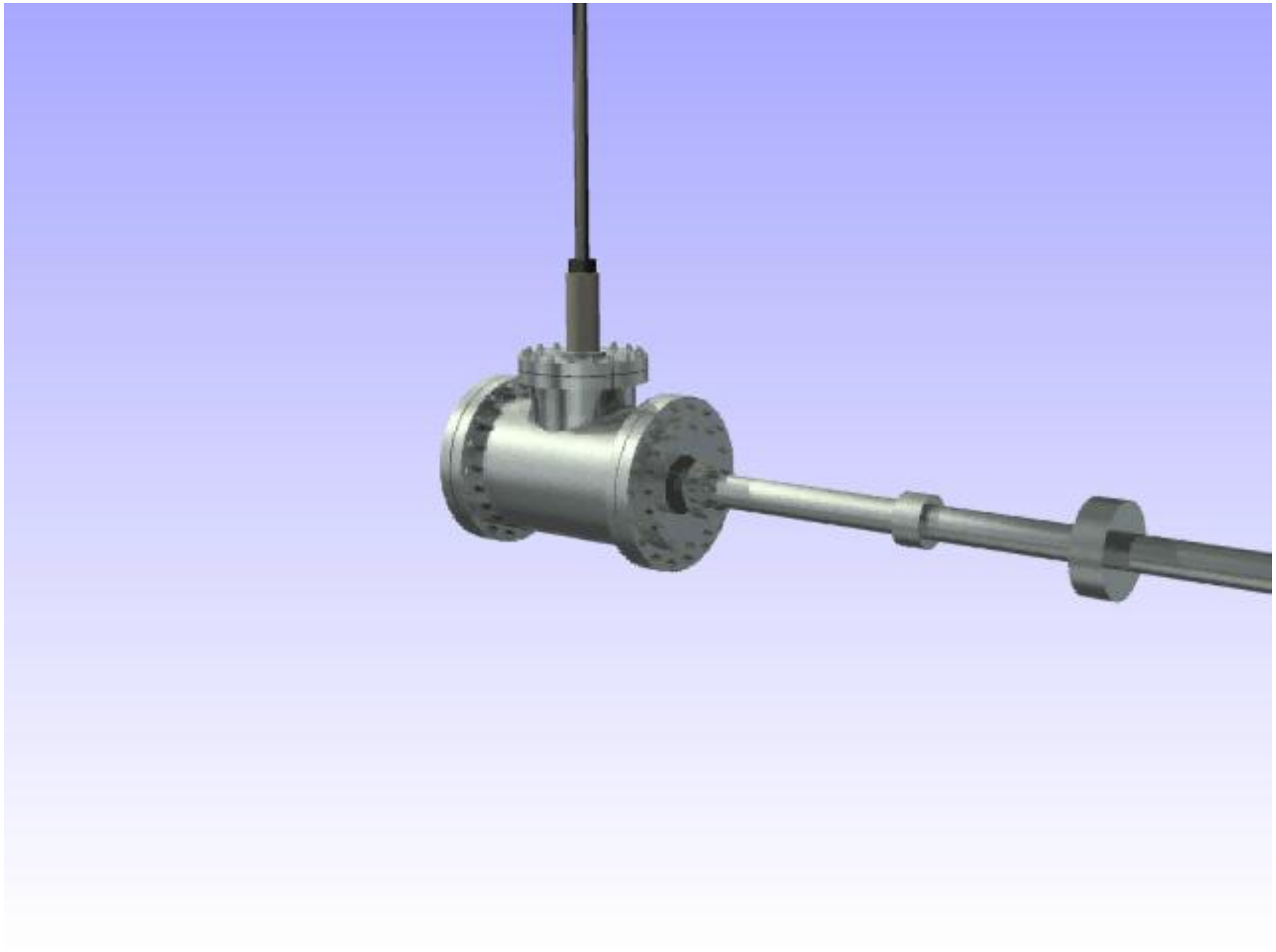
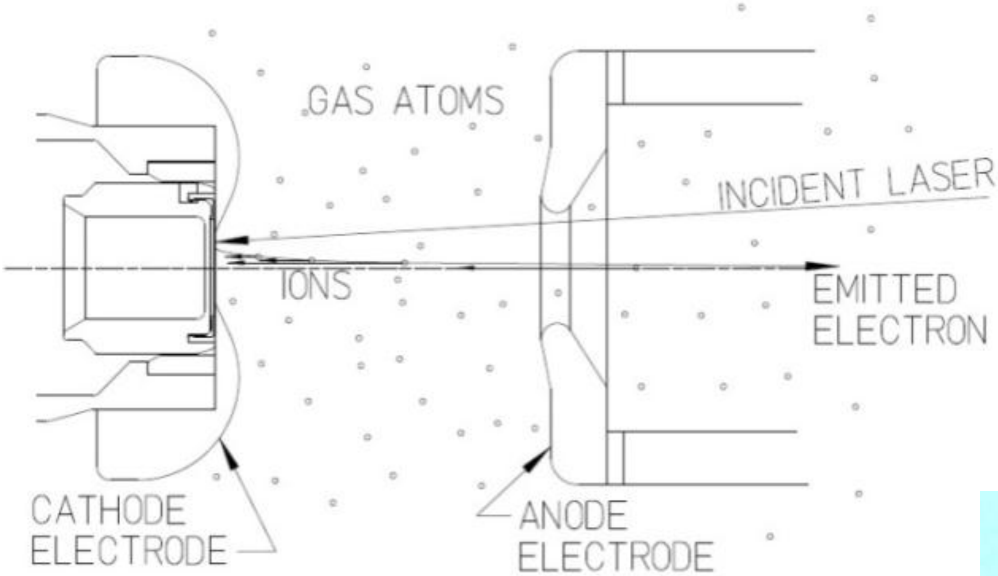
Ion Bombardment

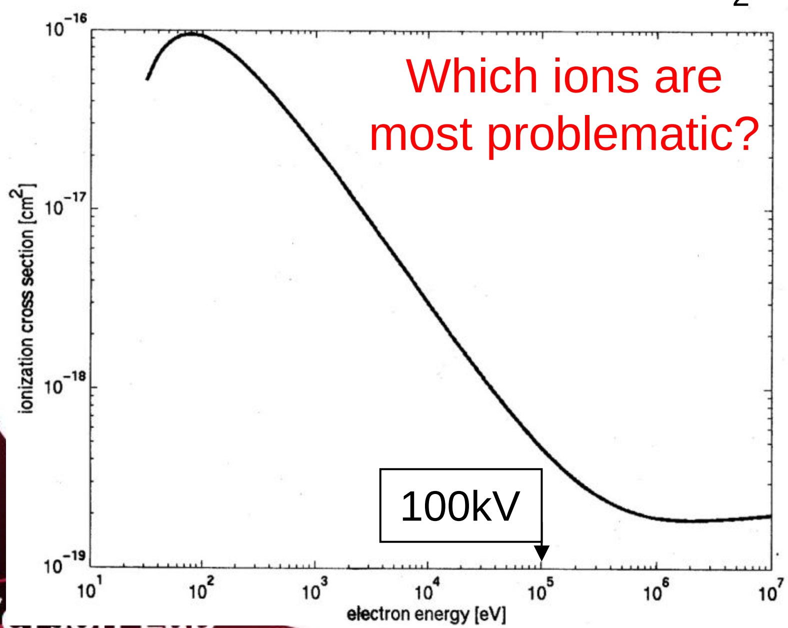


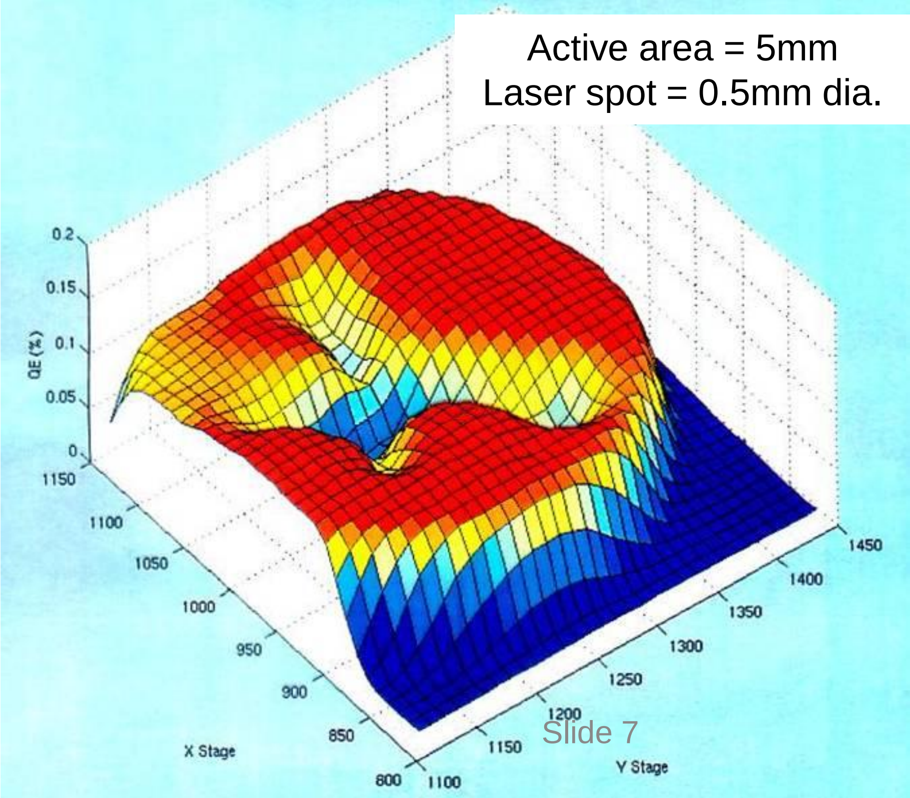
Imperfect Vacuum = Finite Lifetime



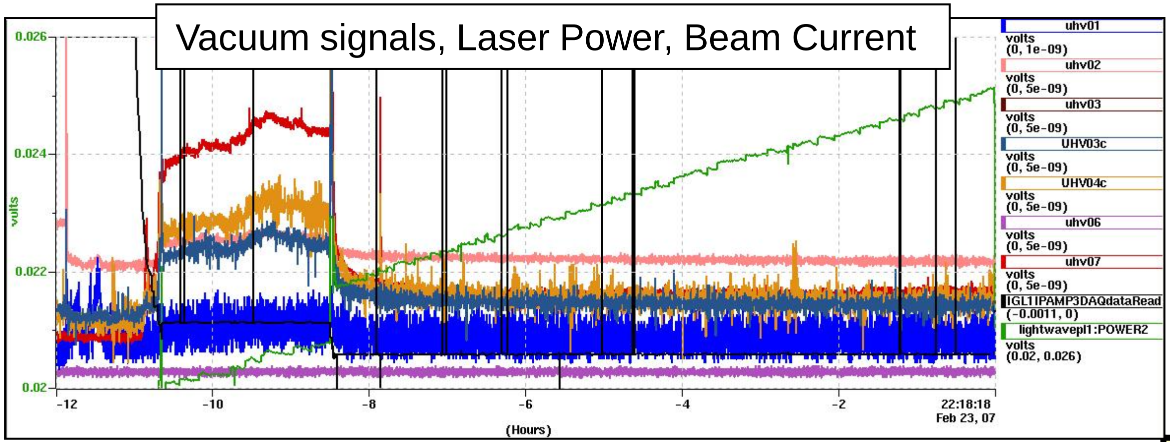
- Ion bombardment – characteristic “trench” from laser spot to electrostatic center of photocathode
- QE can be restored but takes about 8 hours

Ionization cross section for H_2

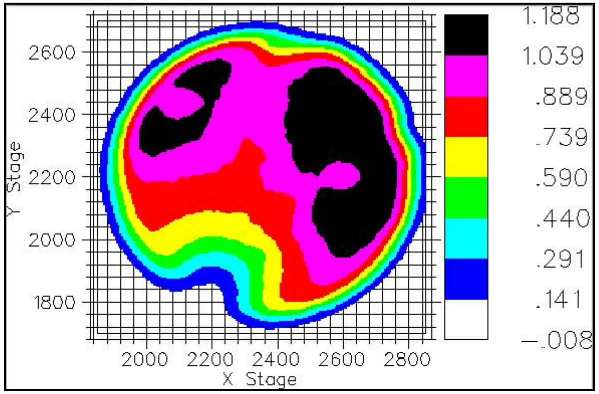


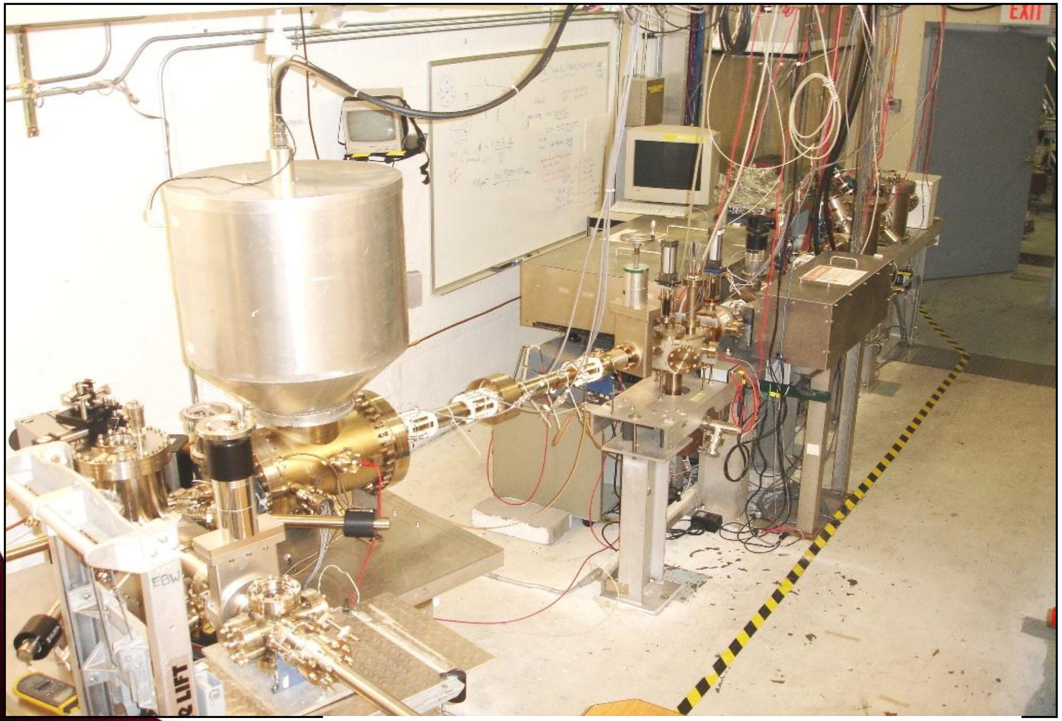


1mA at High Polarization*



High Initial QE





Joe Grames, et al., PAC07, THPMS064

Parameter	Value
Laser Rep Rate	499 MHz
Laser Pulselength	30 ps
Wavelength	780 nm
Laser Spot Size	0.45 mm
Current	1 mA
Duration	8.25 hr
Charge	30.3 C
Lifetime	210 C

How Long Can We Run at 1mA?

- 1mA operation, 3.6 C/hr, 86 C/day.
- Photocathode with 1% initial QE, 2 W at 780nm and gun with 210 C charge lifetime (i.e., what we had during Joe's test)
- Initial laser power = 160mW to produce 1mA
- ***Should*** be able to operate at 1mA for ***6 days*** before running out of laser power. Time to move to fresh photocathode spot (10 minutes), swap photocathode (1 hour), heat/reactivate photocathode (8 hours)
- Imagine a 10 W laser and 1000 C charge lifetime, we should be able to operate at 1mA for ***48 days*** before "doing something"!

How Long Can We Run at 6.5 mA?

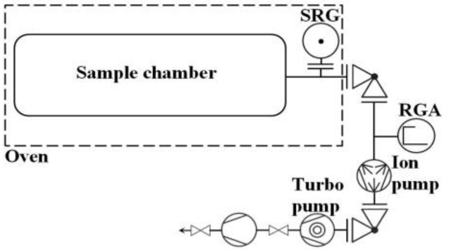
- 6.5 mA operation, 23 C/hr, 560 C/day.
- Photocathode with 1% initial QE, 2W at 780nm and gun with 80 C charge lifetime (i.e., what we had during a 4mA test)
- Need initial laser power ~ 1 W to produce 6.5mA
- ***Should*** be able to operate at 6.5mA for ***2 hours*** before running out of laser power.
- Imagine a 10W laser and 1000 C charge lifetime. This provides ***4 days*** of operation.
- **Message: high current polarized beam applications need photoguns with kC charge lifetime**

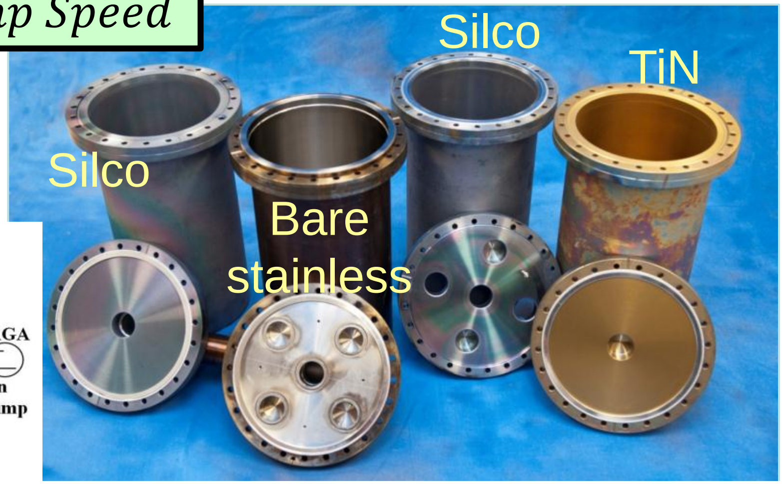
Static Vacuum

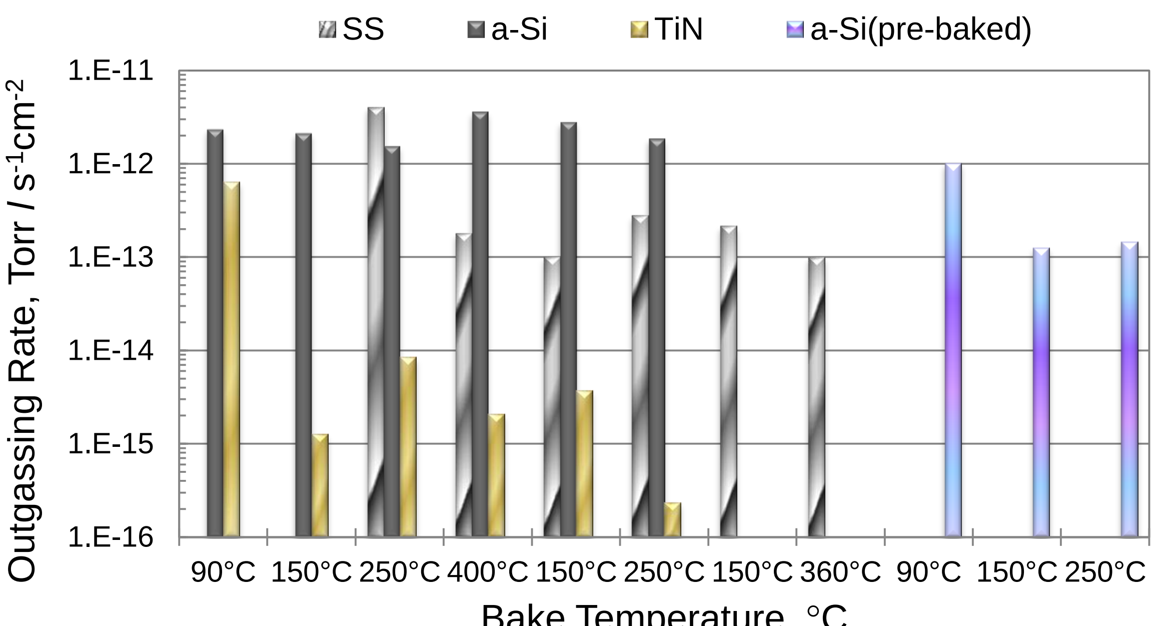
- NEGs and Ion Pump: mid -12 Torr common
- XHV the goal (P < 7.5 e-13Torr)
- Gauges that work at -13 Torr
- Cryopump to replace Ion Pump? to replace NEG pumps?
- Reducing Outgassing Rate
  - 400 C bakes
  - Diffusion barrier coatings
- Improving beamline vacuum

Reducing Outgassing

$$Pressure = \frac{Gas\ Load}{Pump\ Speed}$$

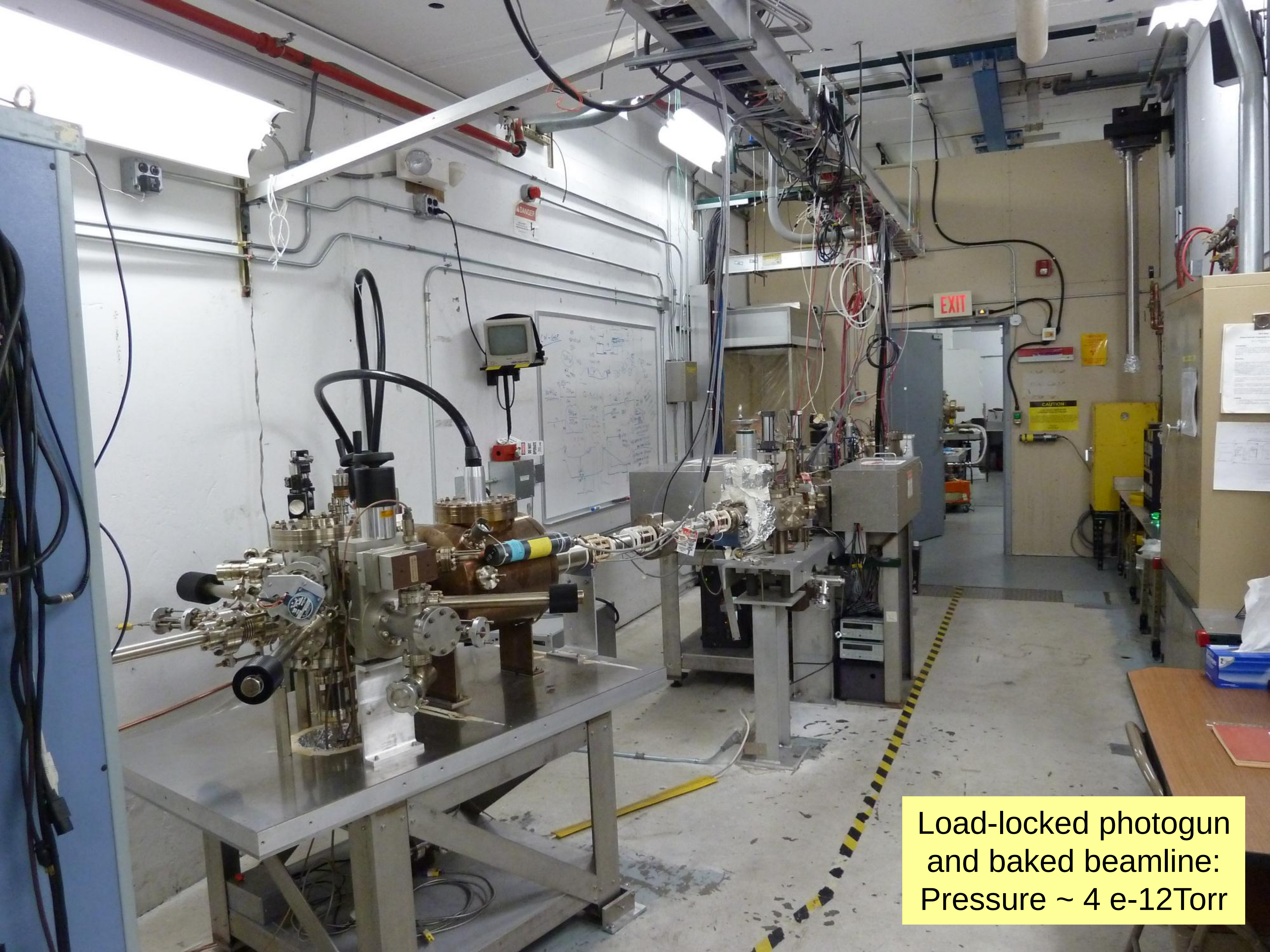






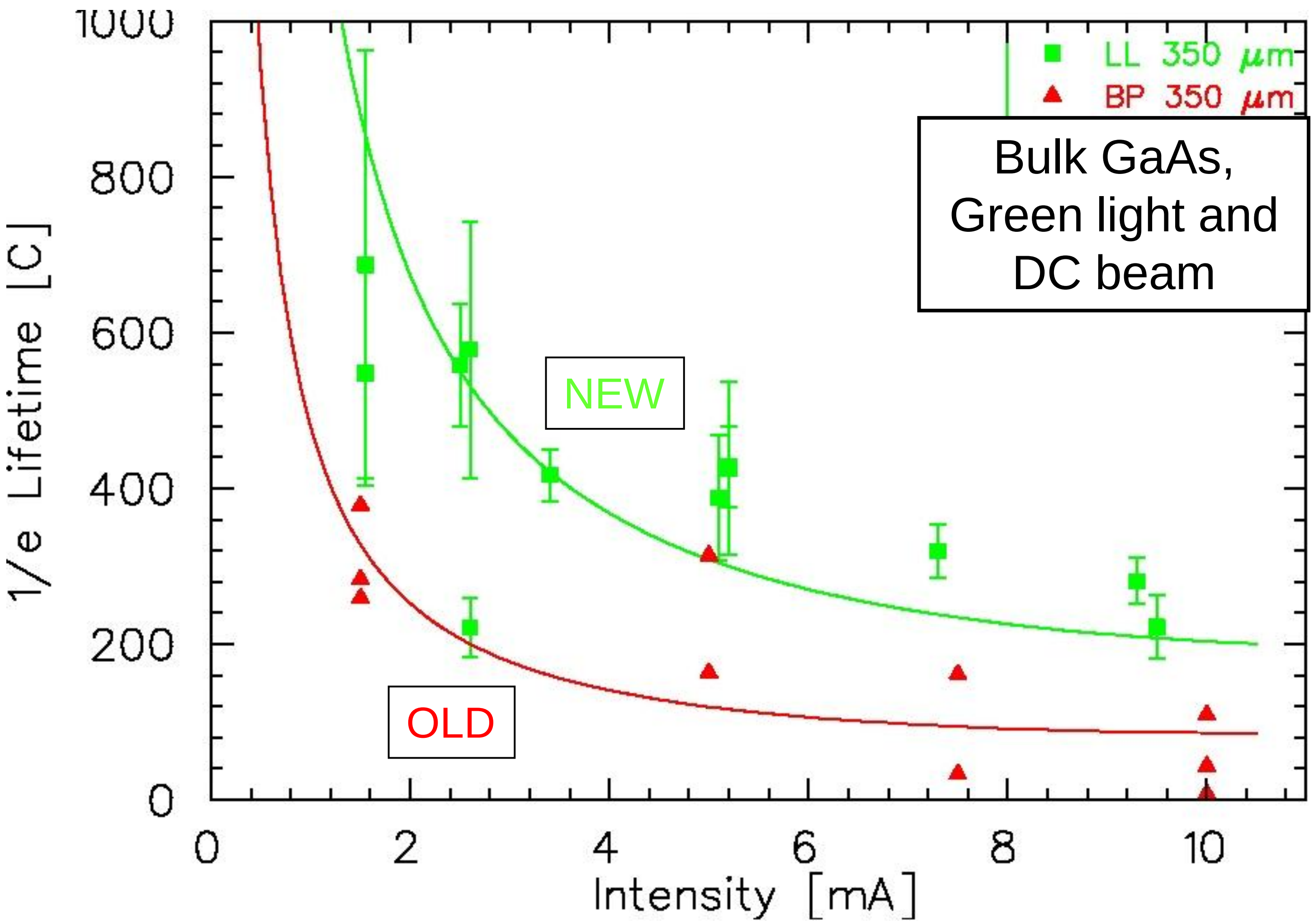
Bent belt beam gauge

Measured Pressure greater than Predicted Pressure



Load-locked photogun
and baked beamline:
Pressure ~ 4 e-12Torr

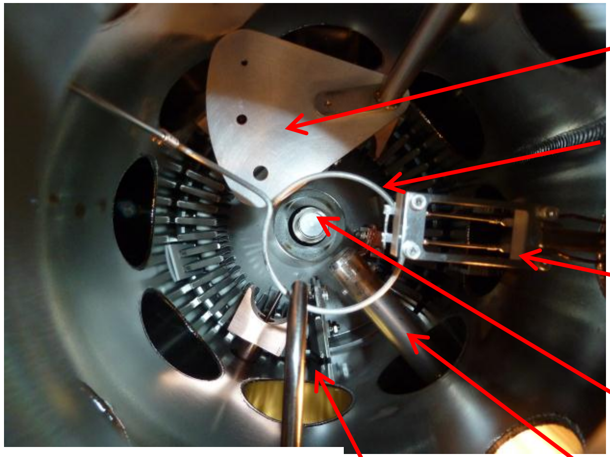
Compare NEW and OLD load locked guns

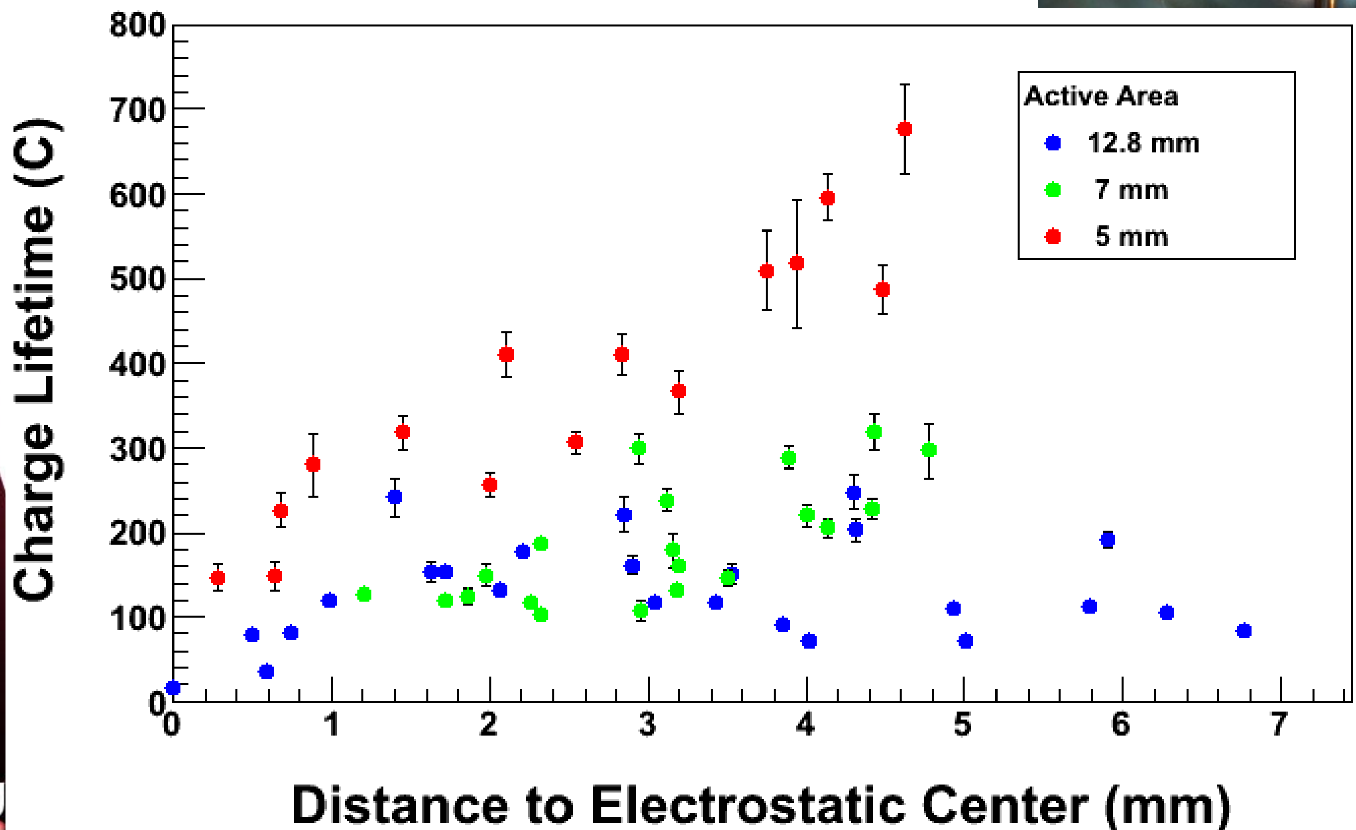


Photogun Lifetime - the best vacuum gauge

Lifetime vs. Laser Position and Active Area

Lesson: extremely important to manage ALL of the extracted beam
Beam from outside 5 mm active area hits beam-pipe walls, degrades vacuum, reduces lifetime



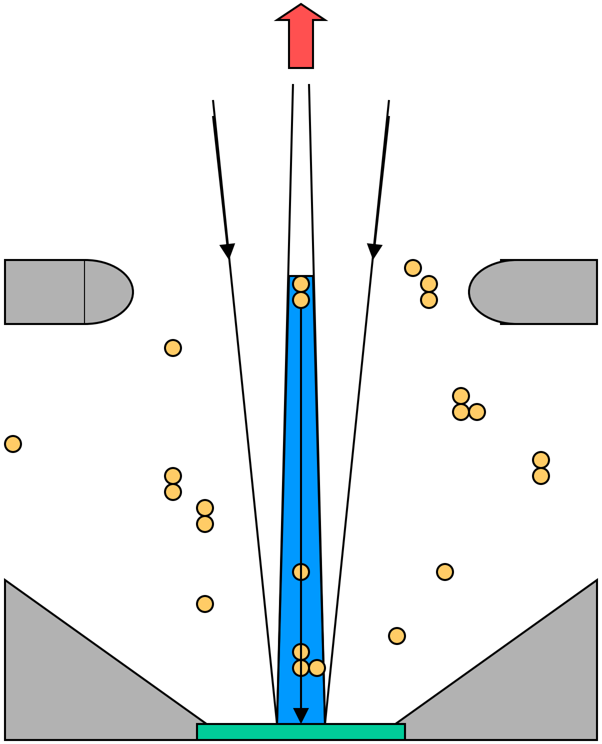


2mA DC current, green light and 0.35 mm dia. laser spot

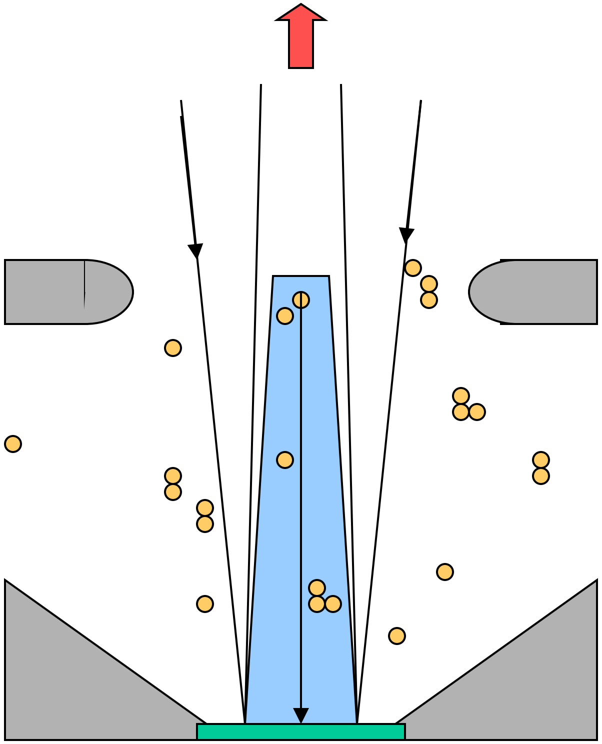
Improve Lifetime with Large Laser Spot?

(Best Solution – Improve Vacuum, but not easy)

Bigger laser spot, same # electrons, same # ions



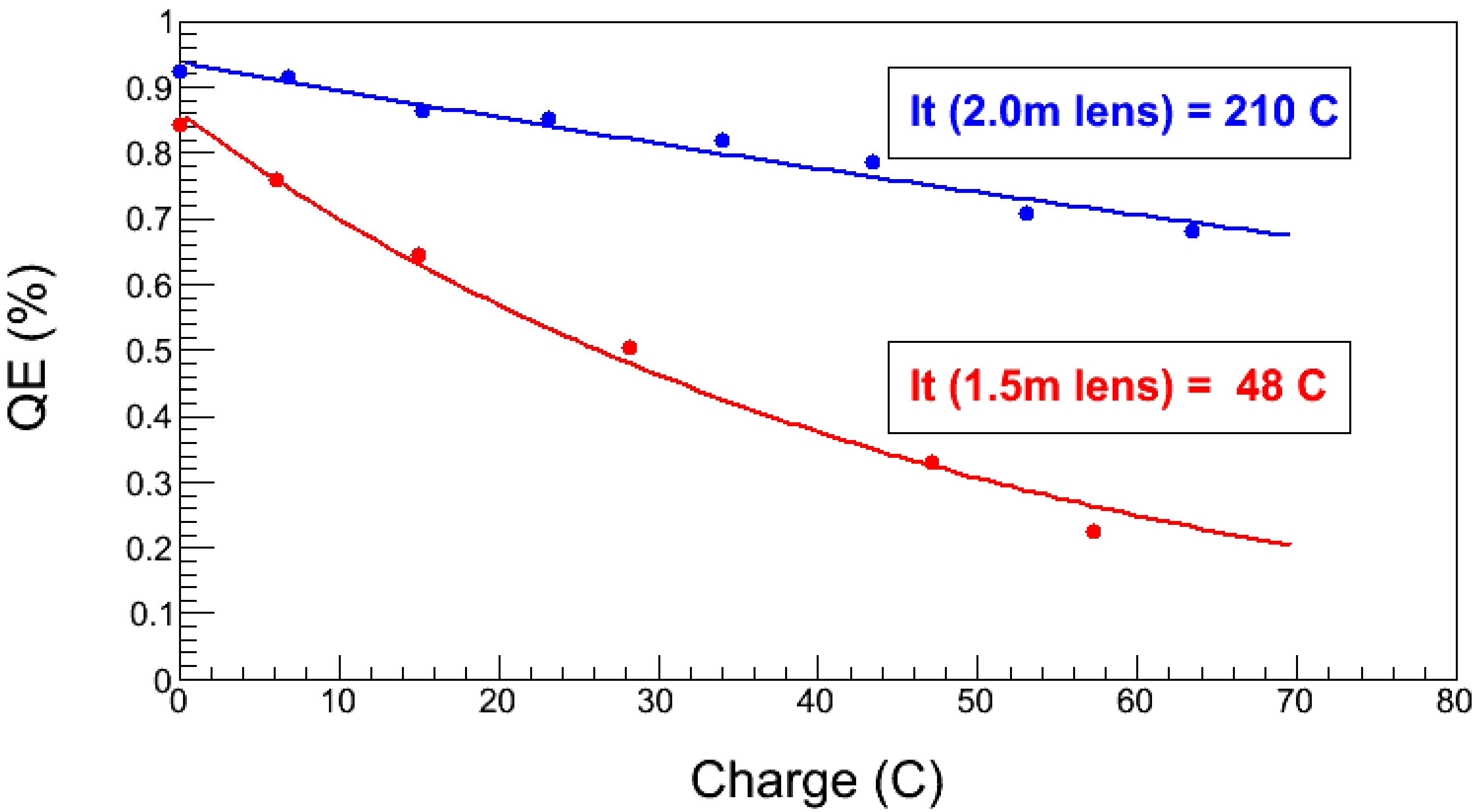
Ionized residual gas strikes photocathode



Ion damage distributed over larger area

Enhanced lifetime for Qweak

Increase size of laser beam from ~ 0.35 mm to ~ 0.7 mm dia.

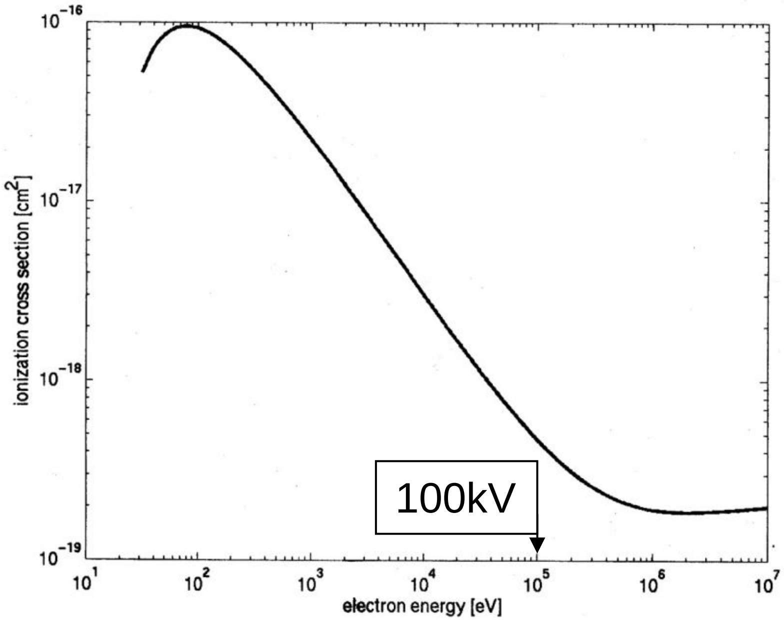


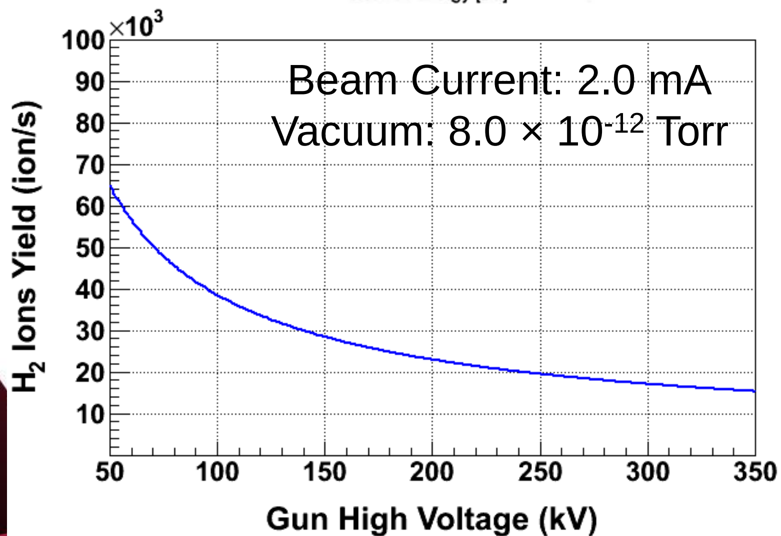
Can we use ~ cm size laser beams? Not in today's CEBAF photogun.
How far can we extrapolate? Need a better cathode/anode optic

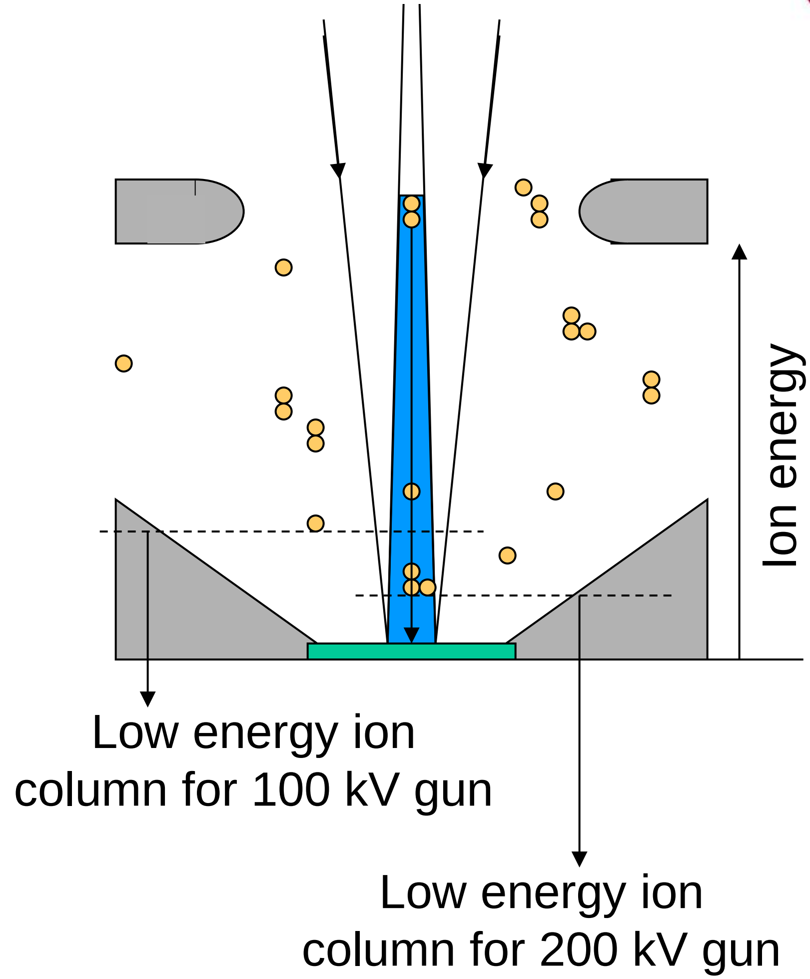
"Charge and fluence lifetime measurements of a DC high voltage GaAs photogun at high average current.," J. Grames, R. Suleiman, et al., Phys. Rev. ST Accel. Beams 14, 043501 (2011)

Improve Lifetime at Higher Bias Voltage ?

Ionization cross section for H_2



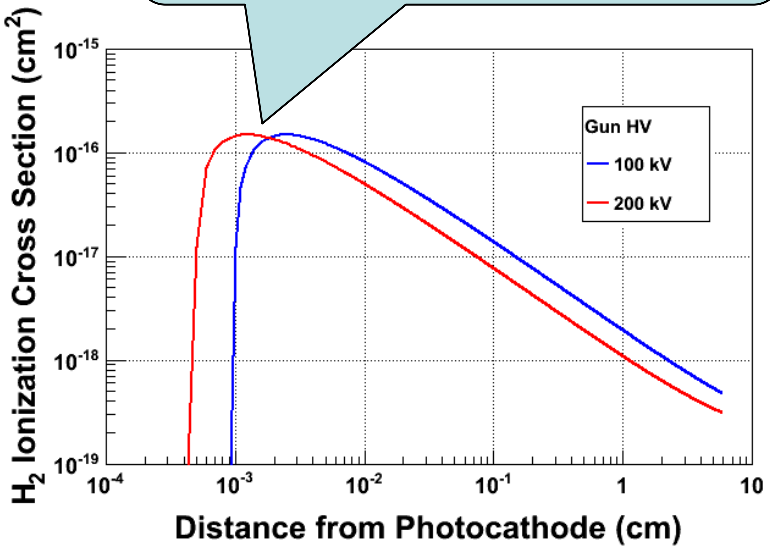


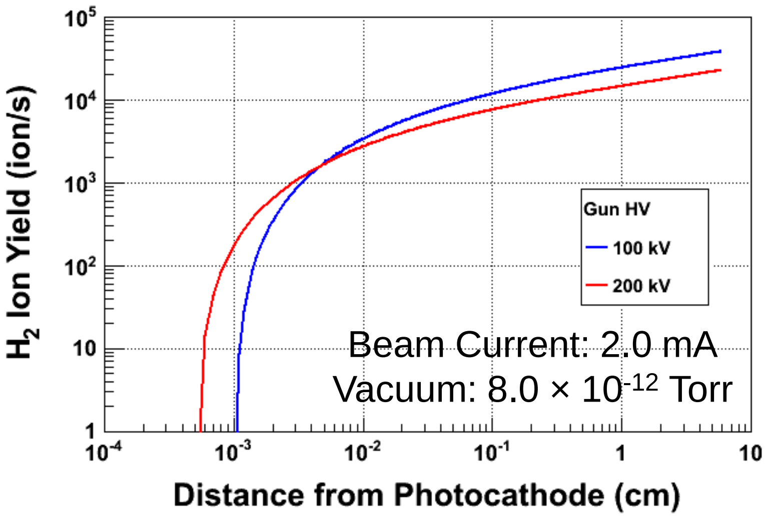


At 200 kV, only 60% of ions are created compared to 100 kV, longer lifetime?

Improve Lifetime at Higher Bias Voltage ?

Most ions created close to GaAs surface





But which ions are most problematic?

Awaits experimental verification (can't have field emission)

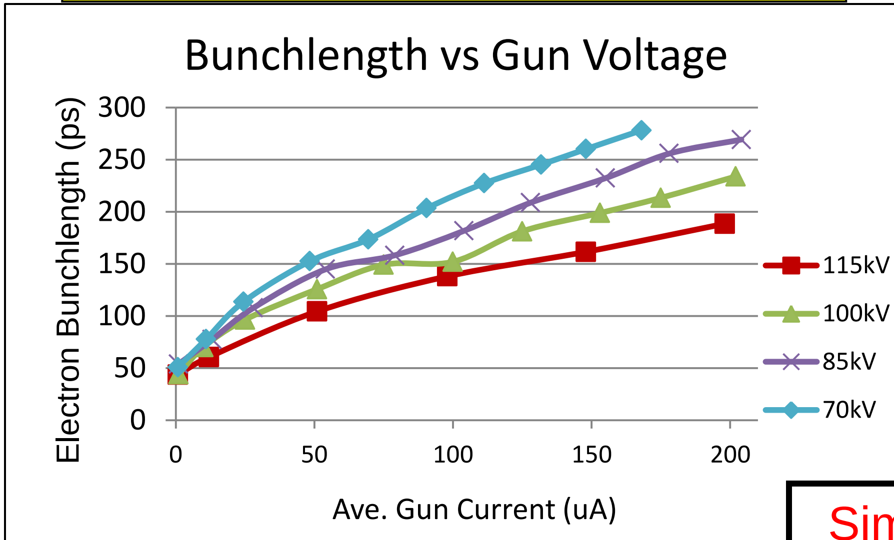
Benefits of Higher Gun Voltage

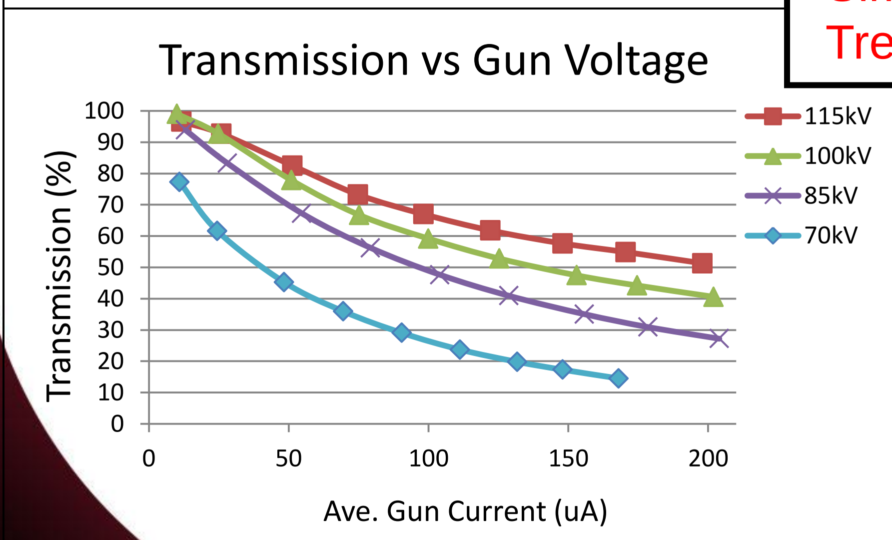
I. Reduce space-charge-induced emittance growth, maintain small transverse beam profile and short bunch-length. In other words, make a “stiff” beam right from the gun
II. Reduce problems associated with Surface Charge Limit (*i.e.*, QE reduction at high laser power)
III. Prolong Charge Lifetime (?)
IV. Compact, less-complicated and less-expensive injector, compatible with JLab FEL

Biggest Obstacle: Field Emission and HV Breakdown… which lead to bad vacuum and photocathode death

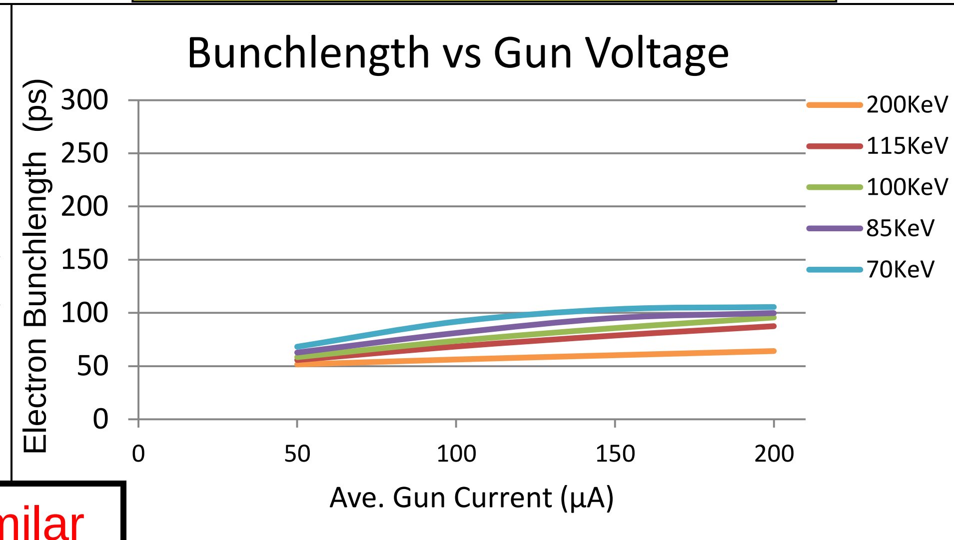
Benchmarking PARMELA Simulation Results Against Beam-Based Measurements at CEBAF/Jefferson Lab – work of Ashwini Jayaprakash, JLab

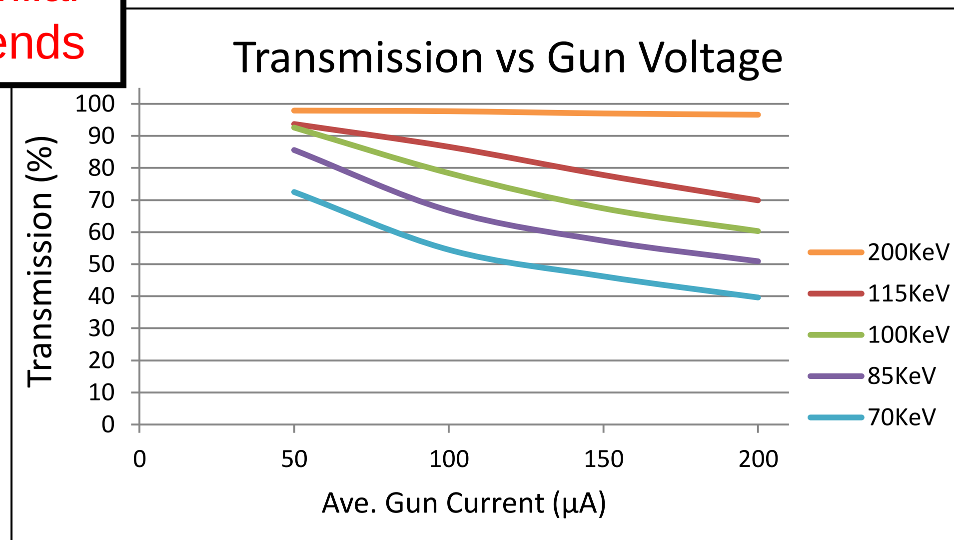
Measurements at CEBAF/JLab





PARMELA Simulation Results

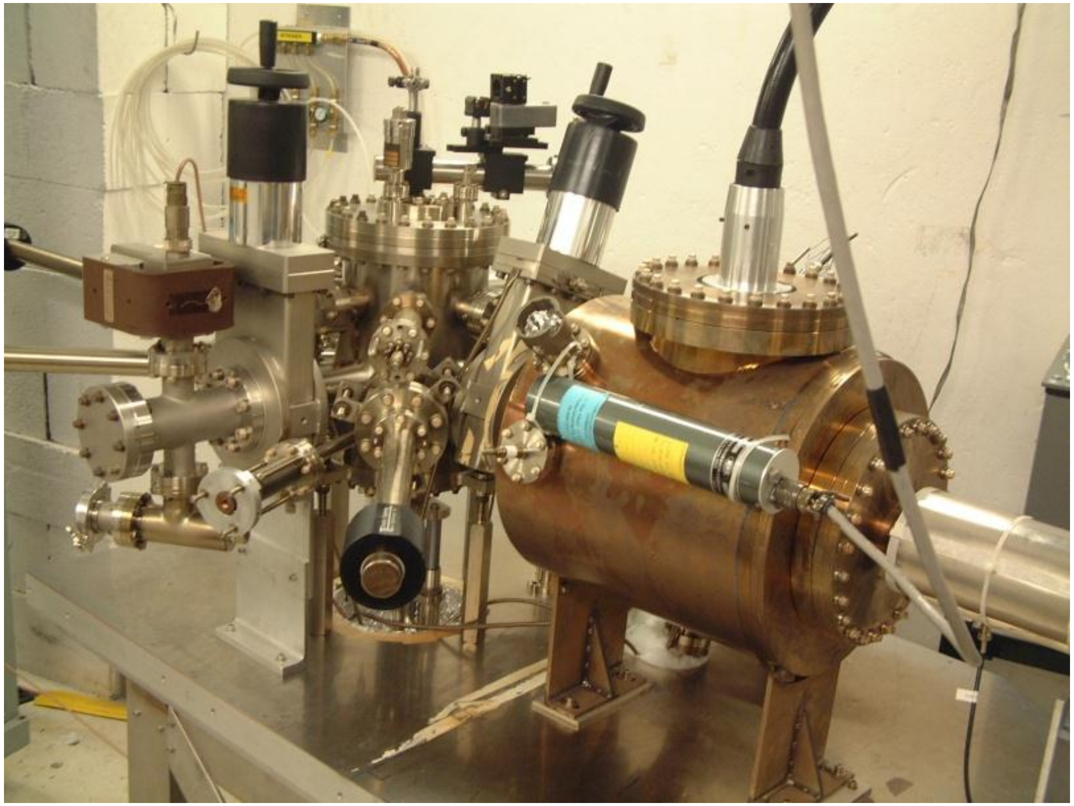


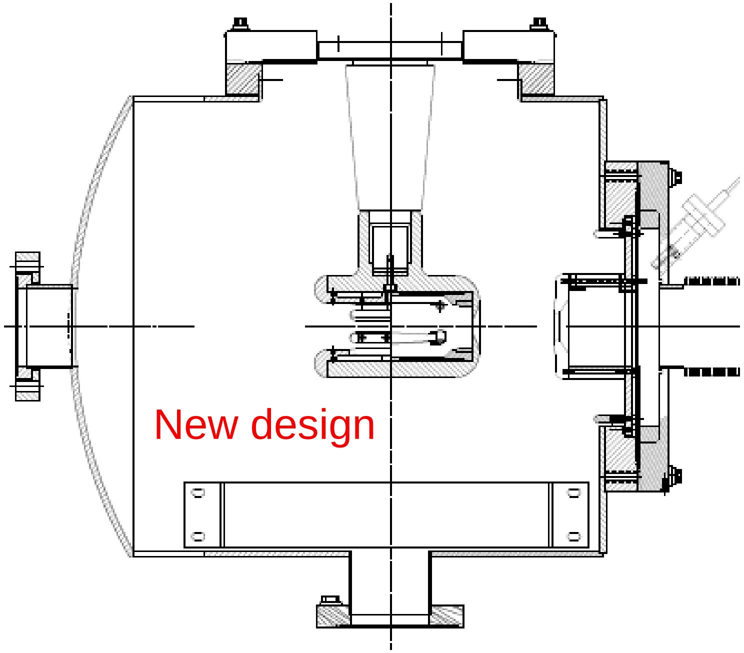


Similar Trends

Message: Beam quality, including transmission, improves at higher gun voltage

The CEBAF - ILC 200kV Inverted Gun

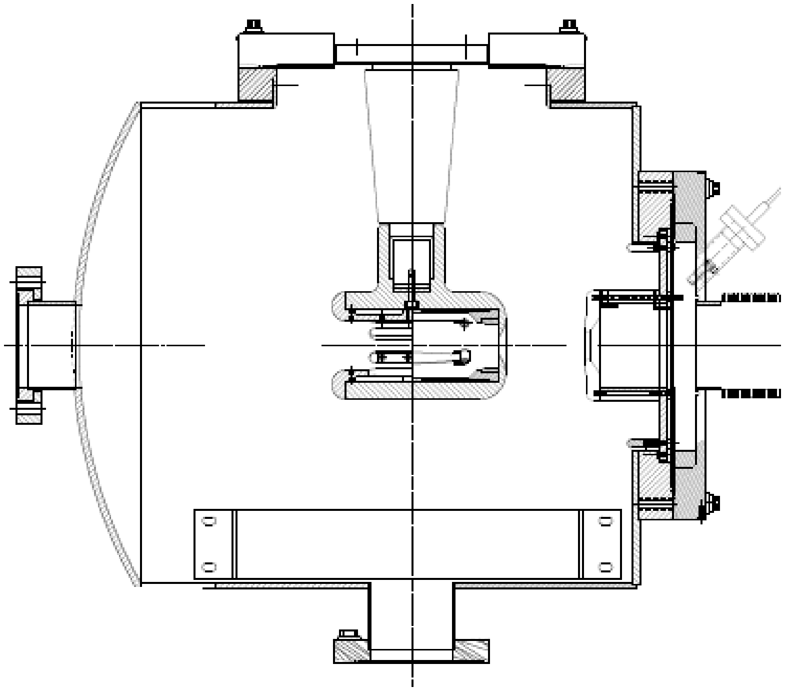




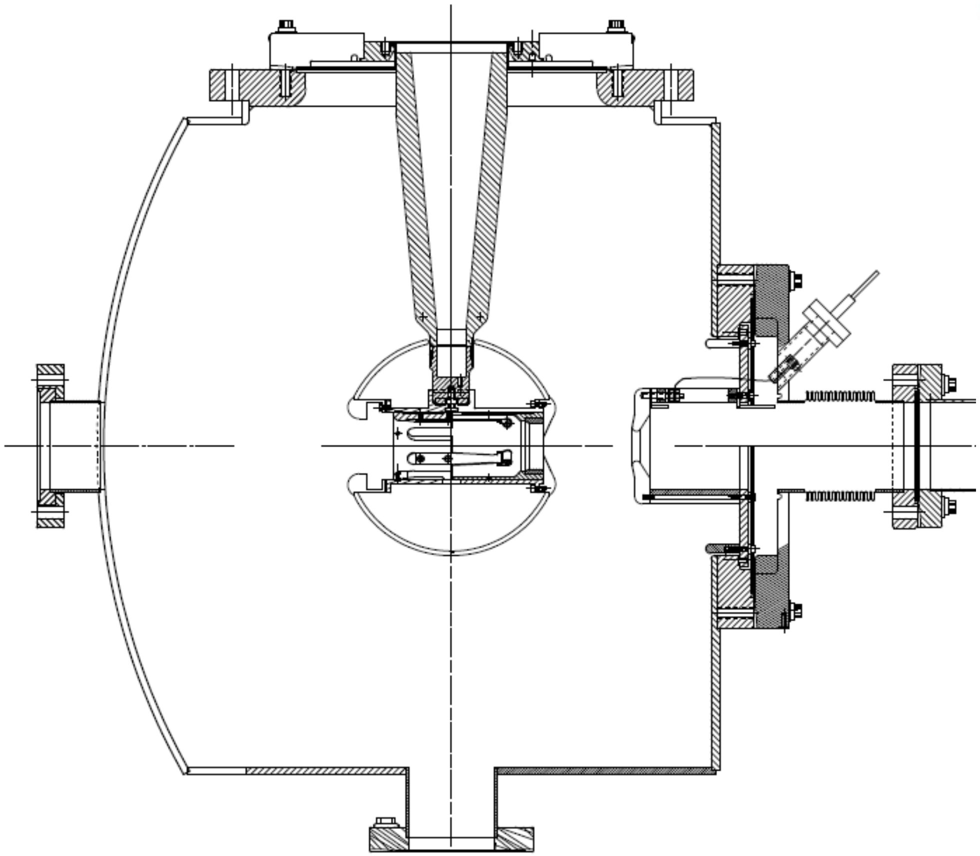
Higher voltage = better beam quality.

The inverted design might be the best way to reach voltages > 350kV

350kV Inverted Gun

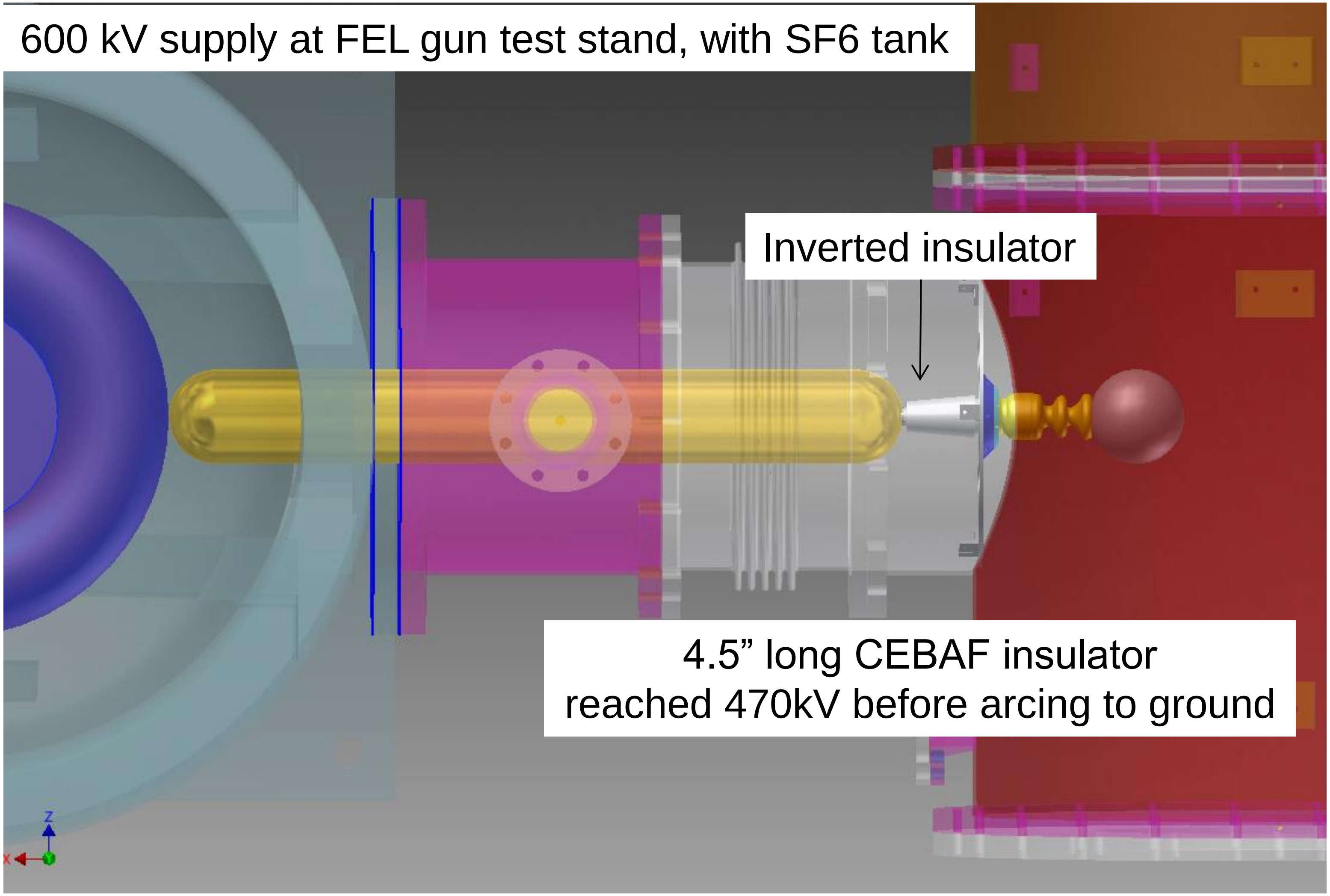


200kV Inverted Gun



- Longer insulator
- Spherical electrode
- Thin NEG sheet to move ground plane further away

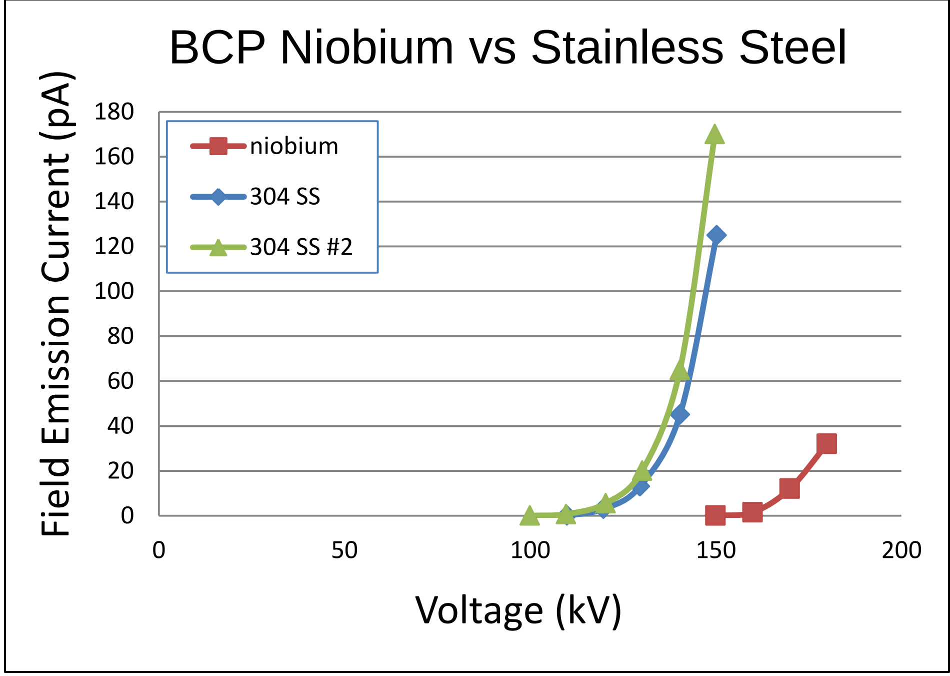
HV Issues: inside and outside the gun



Learn to apply high voltage without breakdown, dielectric plug inside insulator,
Then address the field emission problems inside the gun

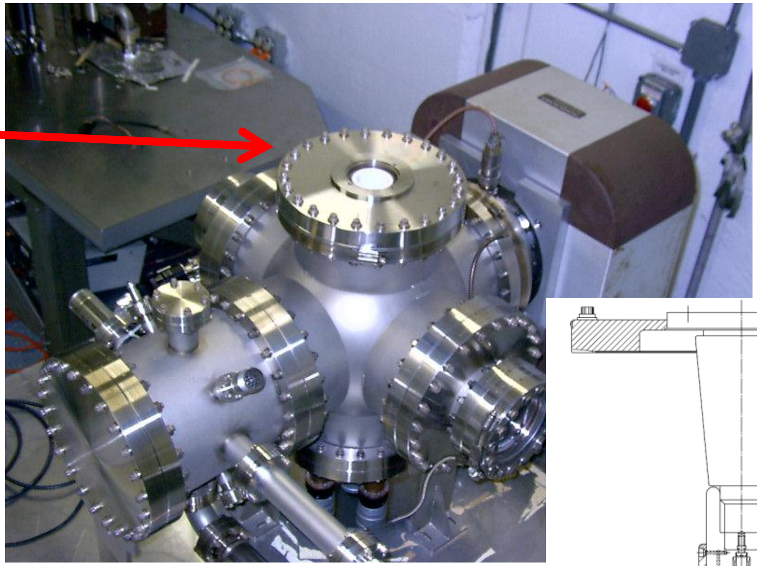
Niobium

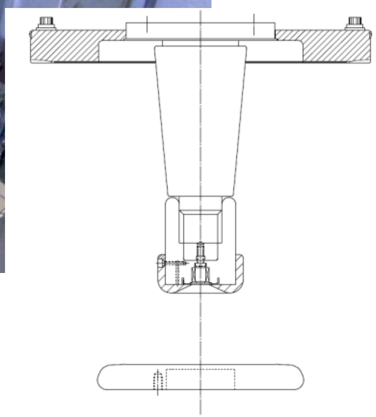
- Capable of operation at higher voltage and gradient?
- Buffer chemical polish (BCP) much easier than diamond-paste-polish



Conventional geometry: cathode electrode mounted on metal support structure

Replace conventional ceramic insulator with "Inverted" insulator: no SF6 and no HV breakdown outside chamber

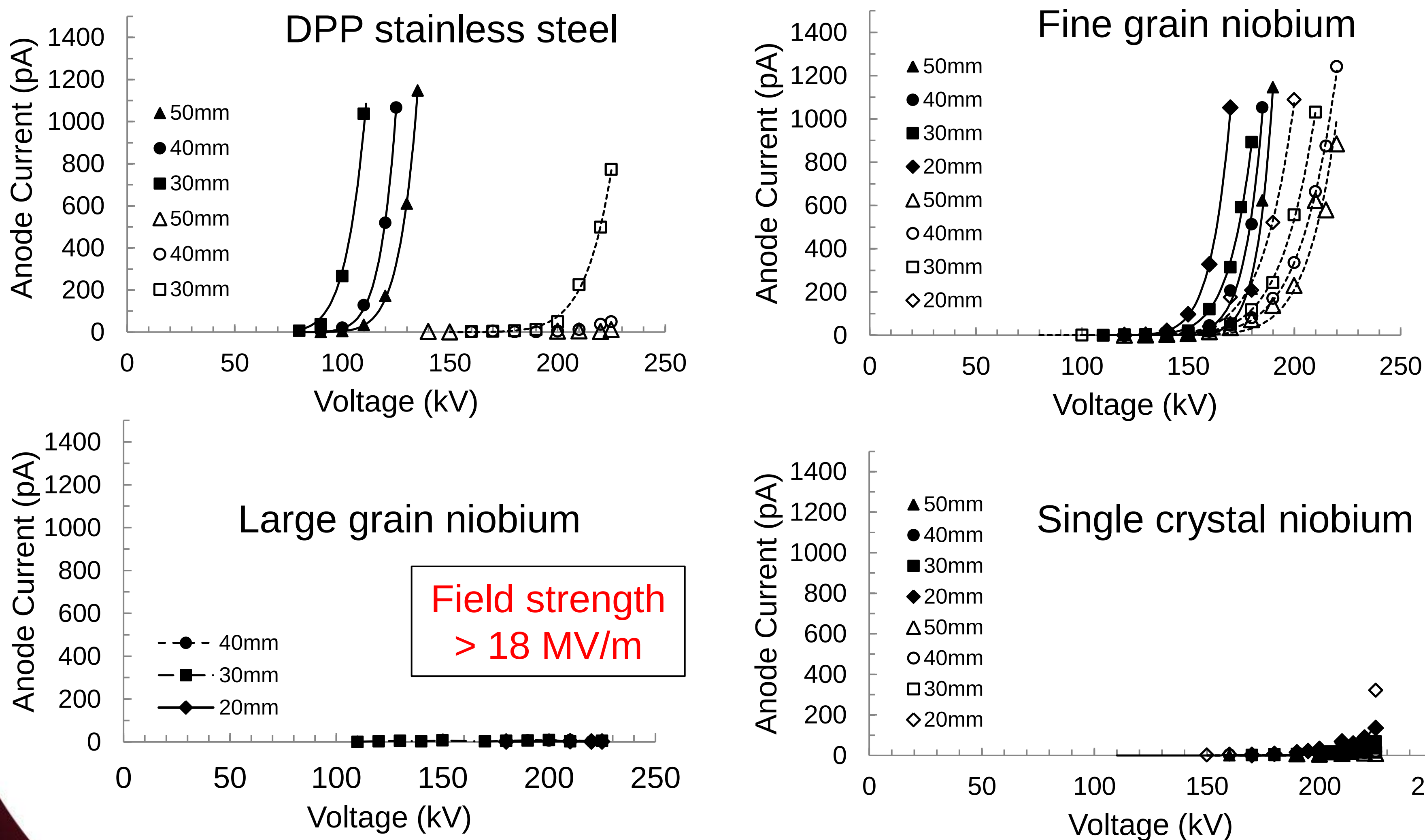




Work of Ken Surles-Law

Field Emission from Niobium

Work of M. BastaniNejad
Phys. Rev. ST Accel. Beams, 15, 083502 (2012)



Conventional High Voltage processing: solid data points
After Krypton Processing: open data points

R&D for high current polarized beam

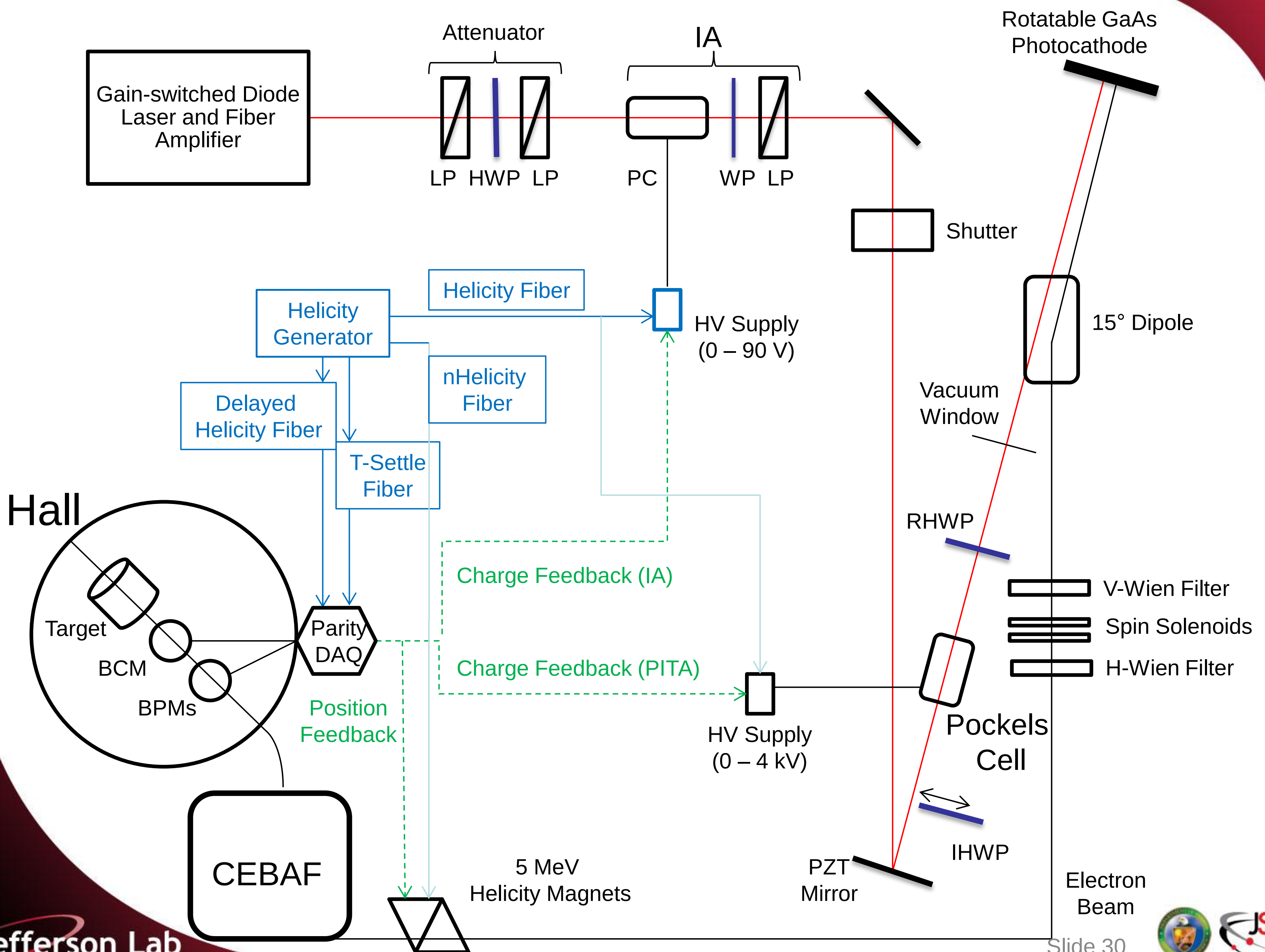
- Require kC charge lifetime at mA current
  - Improve the vacuum
  - Big laser spot to "get around" ion bombardment
  - Cathode/anode design for 100% transport
- Operation at gun voltage ~ 350kV
  - Field emission
- Surface charge limit? Probably Yes
- High laser power … need photocathode cooling
- Photocathode R&D: look for higher QE (~10%), something more rugged than superlattice GaAs
- Very reasonable to expect success at Jlab/FEL at 1mA and ~ 80% polarization

Backup Slides

Parity Violation Experiments at CEBAF

Experiment	Energy (GeV)	I (μA)	Target	A_{pv} (ppb)	Maximum Charge Asym (ppb)	Maximum Position Diff (nm)	Maximum Angle Diff (nrad)	Maximum Size Diff (δσ/σ)
HAPPEx-II (Achieved)	3.0	55	^{1}H (20 cm)	1400	400	1	0.2	Was not specified
HAPPEx-III (Achieved)	3.484	100	^{1}H (25 cm)	16900	200±100	3±3	0.5±0.1	10^{-3}
PREx	1.063	70	^{208}Pb (0.5 mm)	500	100±10	2±1	0.3±0.1	10^{-4}
QWeak	1.162	180	^{1}H (35 cm)	234	100±10	2±1	30±3	10^{-4}
Møller	11.0	75	^{1}H (150 cm)	35.6	10±10	0.5±0.5	0.05±0.05	10^{-4}

PV experiments motivate polarized e-source R&D

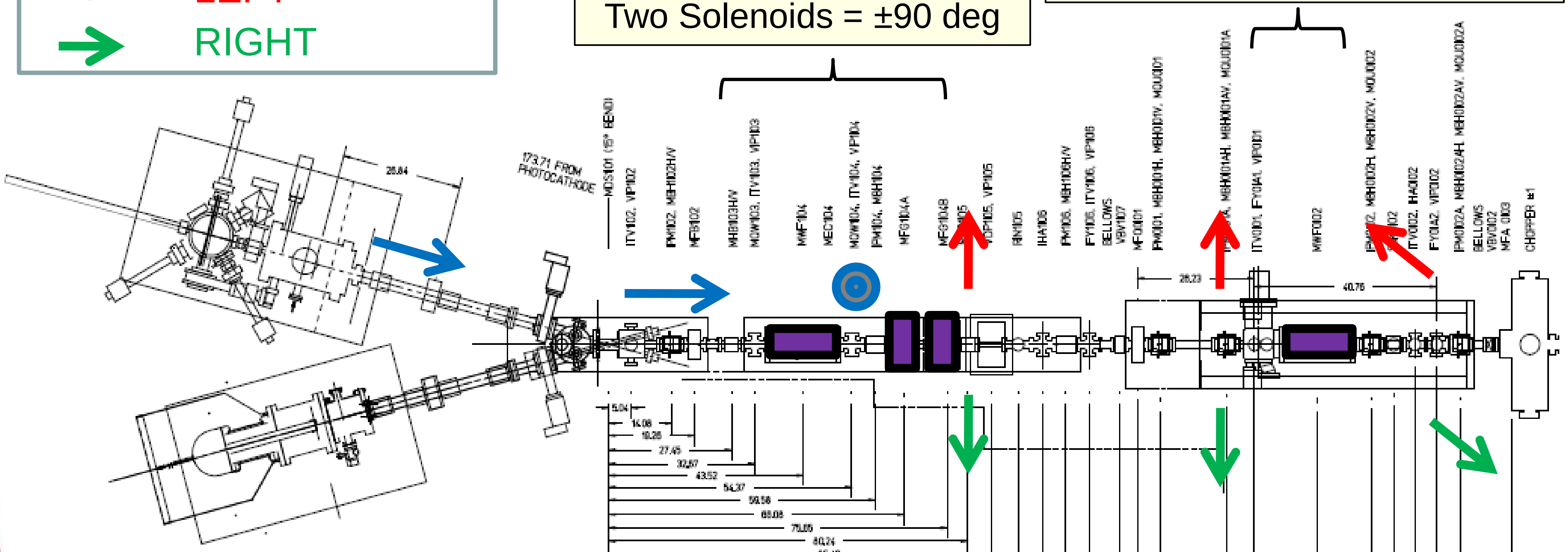

Gain-switched Diode Laser and Fiber Amplifier
Attenuator
LP
HWP
LP
IA
PC
WP
LP
Rotatable GaAs Photocathode
Shutter
Helicity Fiber
Helicity Generator
HV Supply (0 – 90 V)
15° Dipole
nHelicity Fiber
Delayed Helicity Fiber
Vacuum Window
T-Settle Fiber
Hall
RHWP
Charge Feedback (IA)
V-Wien Filter
Spin Solenoids
Target
Parity DAQ
H-Wien Filter
BCM
Charge Feedback (PITA)
BPMs
Position Feedback
HV Supply (0 – 4 kV)
Pockels Cell
IHWP
CEBAF
5 MeV Helicity Magnets
PZT Mirror
Electron Beam

Electron Spin Reversal for PV

From Gun
LEFT
RIGHT

"Spin Reversal"
Vertical Wien = 90 deg
Two Solenoids = ±90 deg

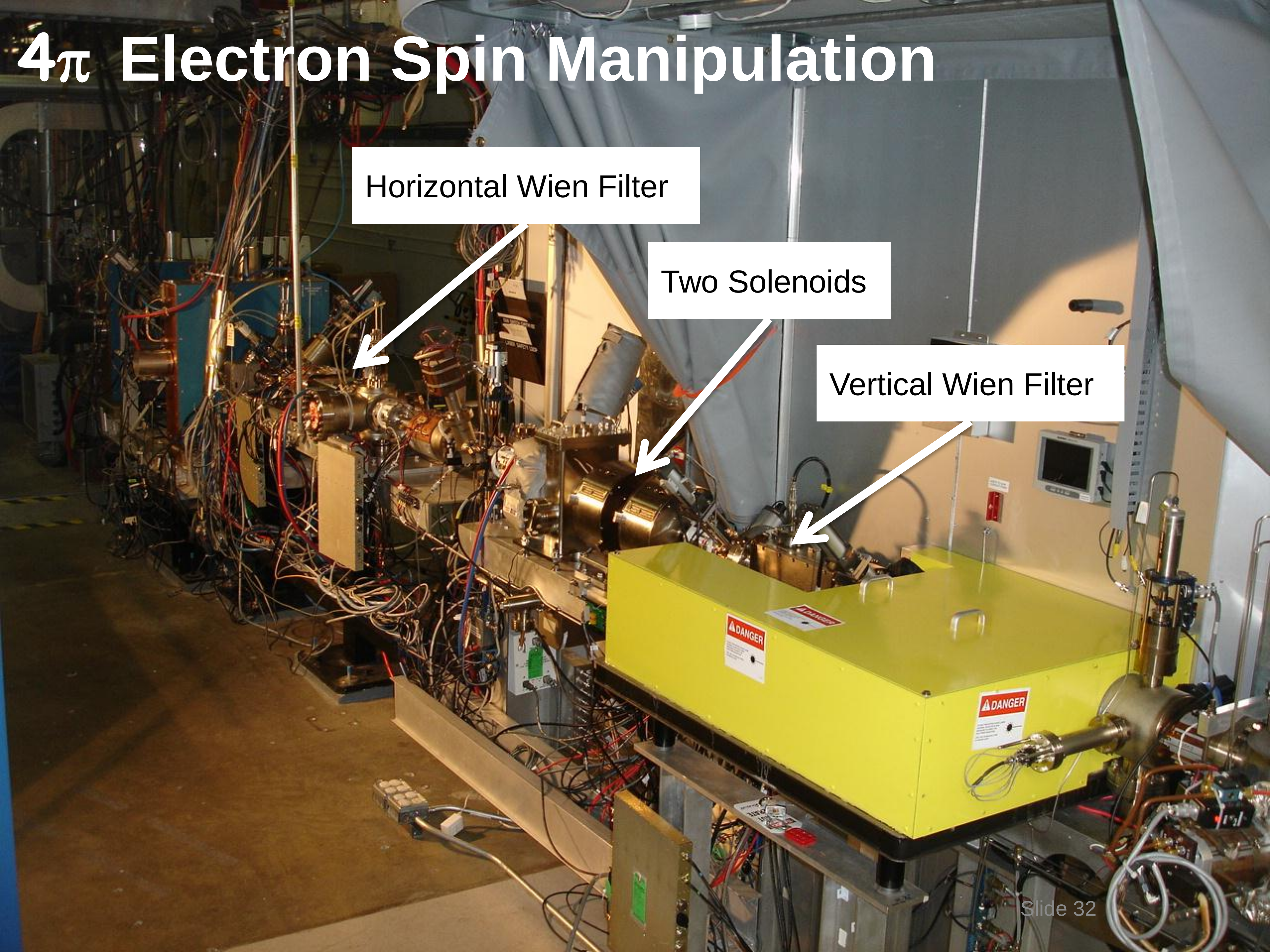
"Longitudinal Polarization"
Horizontal Wien = {-90…+90}



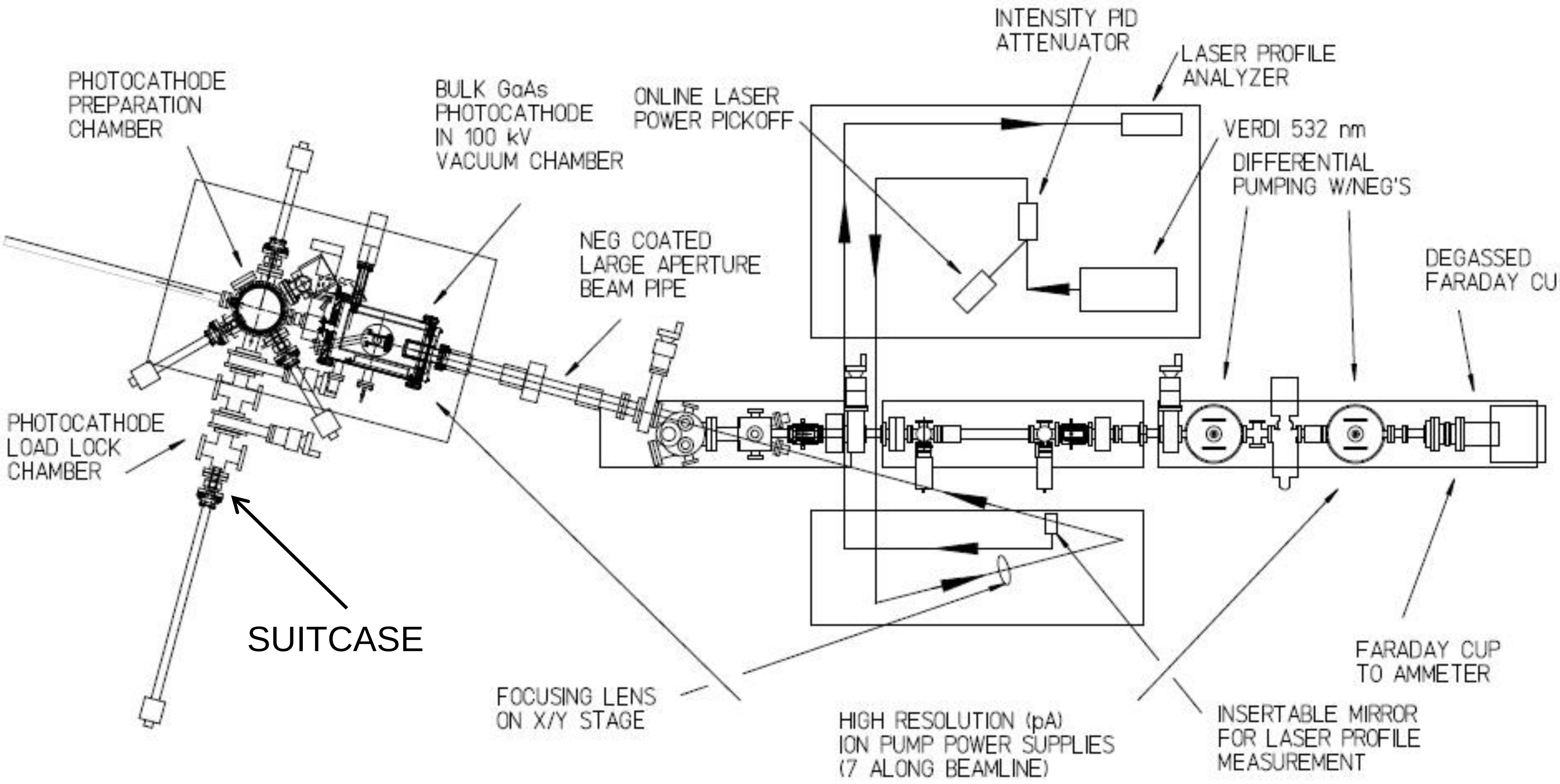
Two-Wien Spin Flipper:

Used to orient spin direction at target and to cancel some helicity-correlated beam systematic errors

4π Electron Spin Manipulation



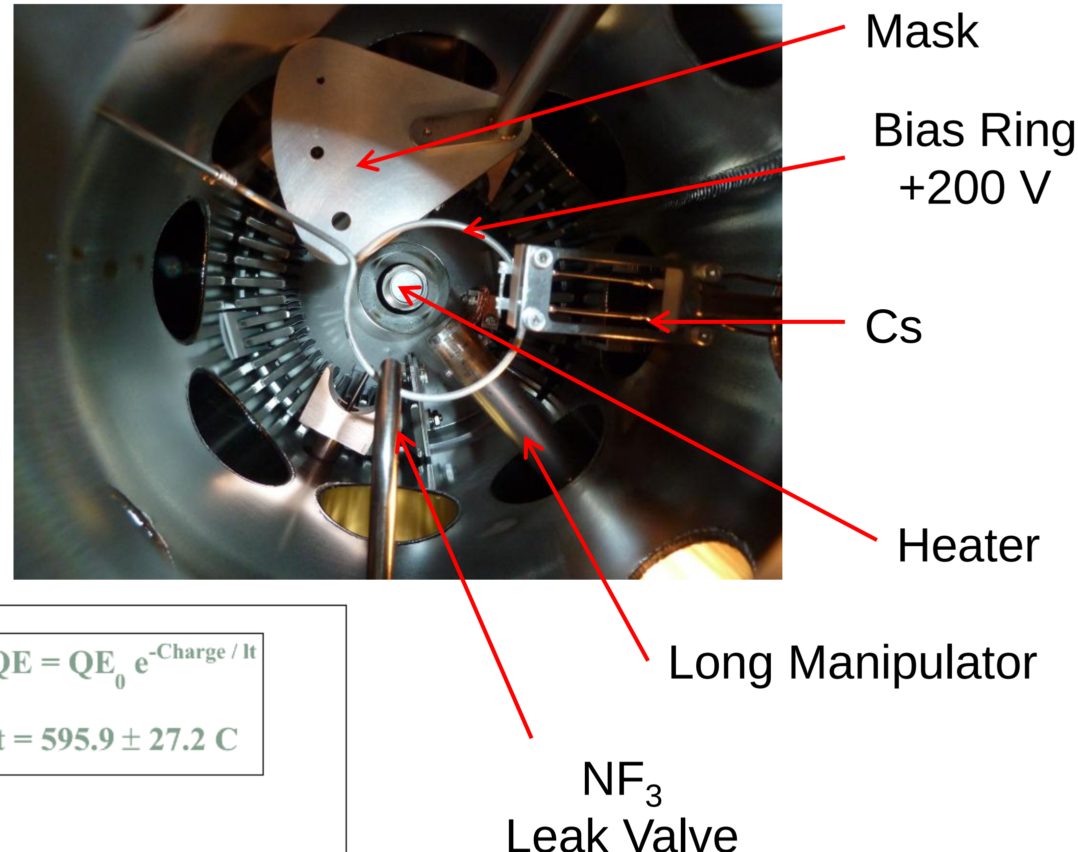
Injector Test Cave

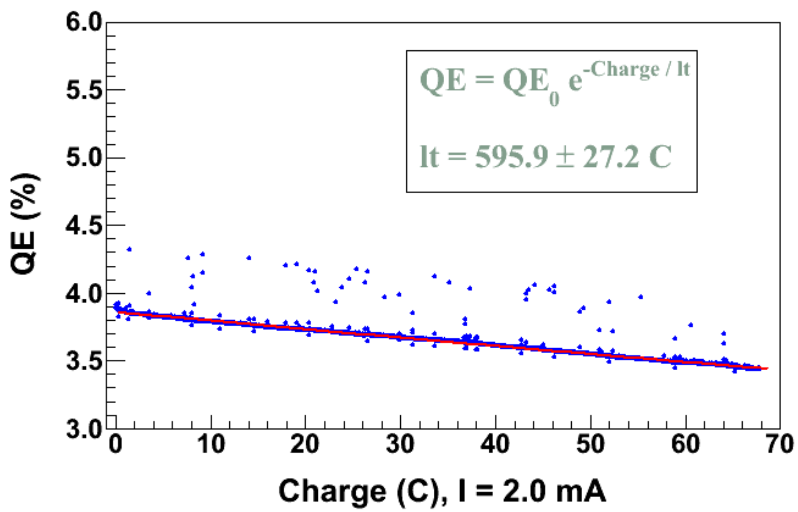


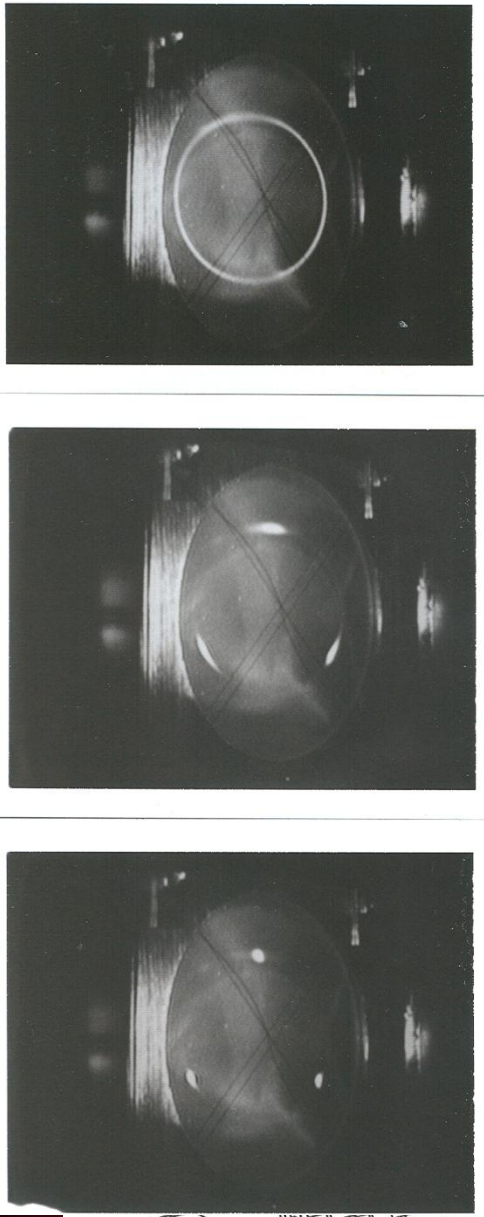
Measure Lifetime vs. Laser Position and Active Area

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

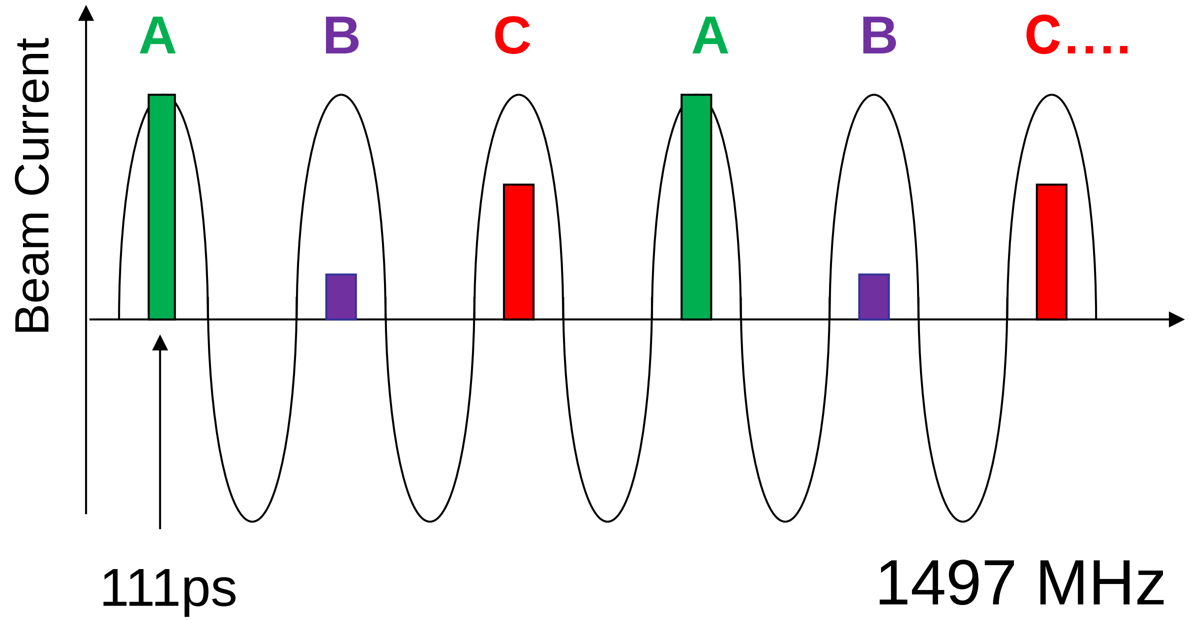
II. Measure Lifetime from different spots on Bulk GaAs with 532 nm green laser



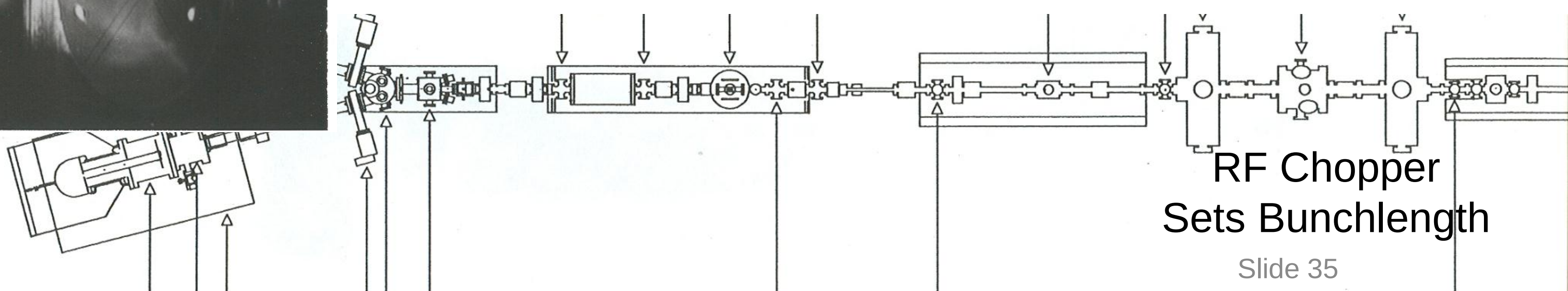




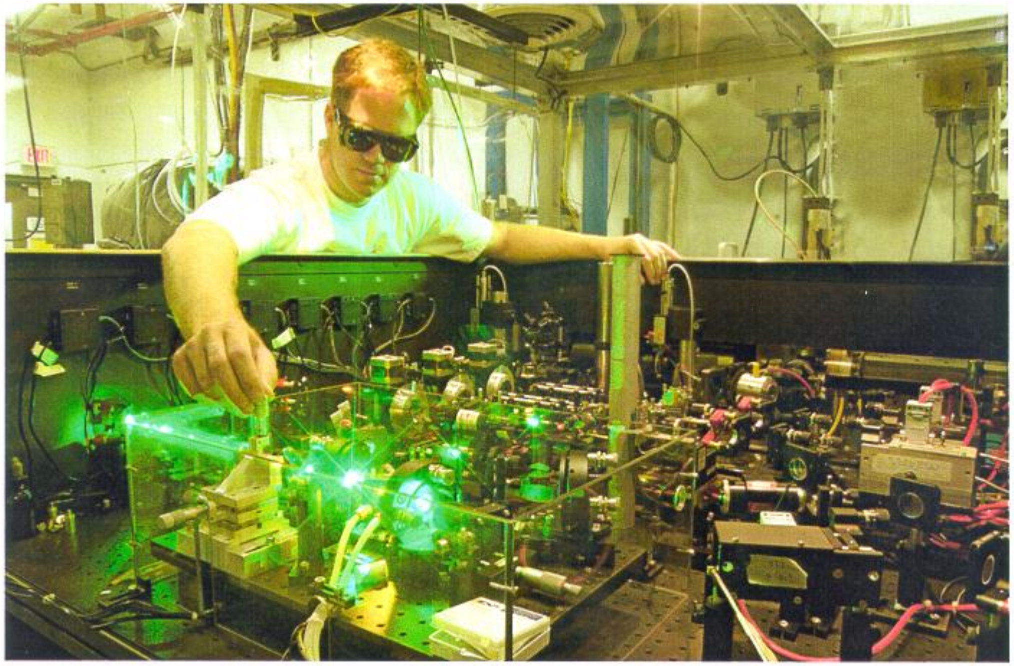
Synchronous Photoinjection



Extracting DC beam, very wasteful, most of the beam dumped at chopper. Need ~ 2mA from gun to provide 100uA to one hall. Gun lifetime not good enough…..yet.

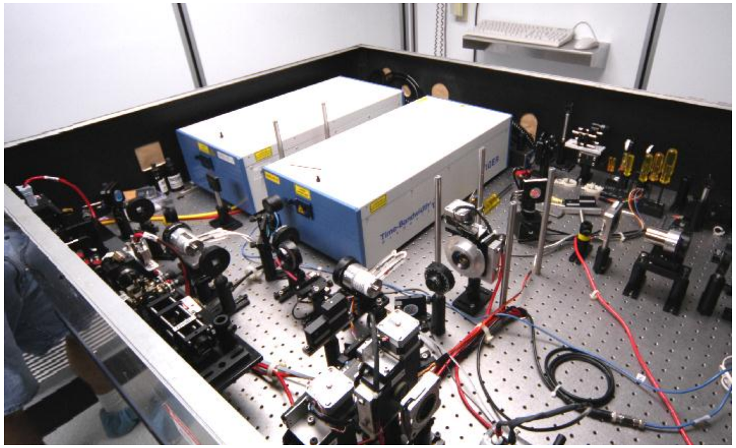


Ti-Sapphire Lasers at CEBAF



- Needed more laser power for high current experiments
- Diode lasers out, ti-sapphire laser in
- Re-align Ti-Sapphire lasers each week

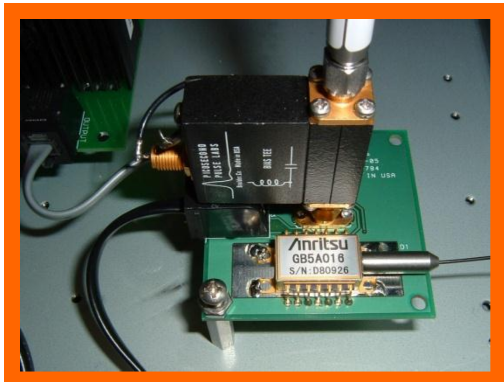
Homemade harmonic modelocked Ti-Sapphire laser. Seeded with light from gain switched diode. No active cavity length feedback. It was a bit noisy….

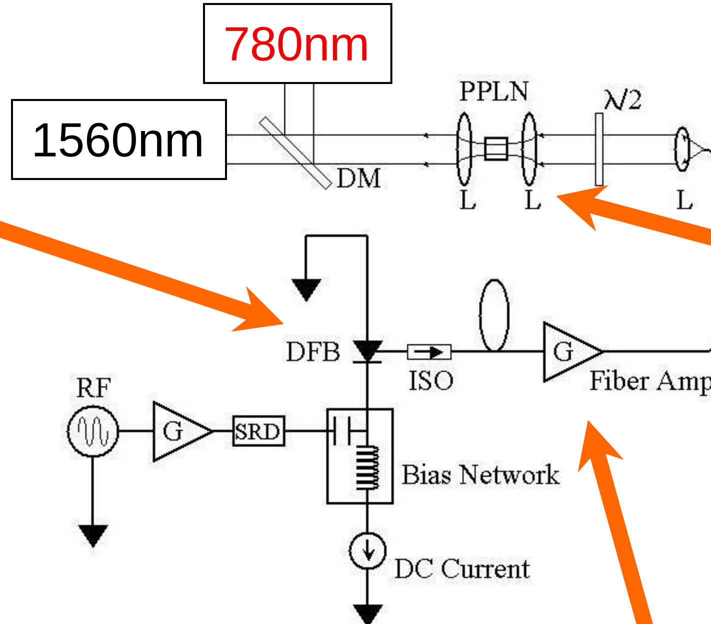


Commercial laser with 499MHz rep rate from Time Bandwidth Products

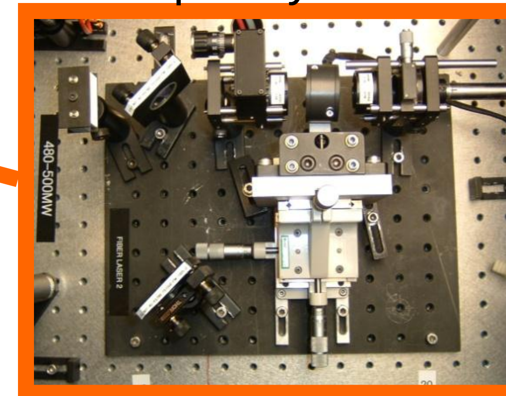
Fiber-Based Drive Laser

Gain-switched seed





Frequency-doubler



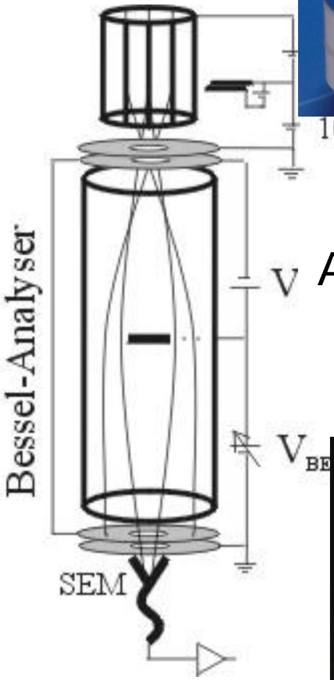
ErYb-doped fiber amplifier

Deep UHV/XHV gauges

- Extractor gauge
  - available for decades
  - x-ray limit reduced through geometry
  - x-ray limit quote: 7.5×10^{-13} Torr

- Axtran gauge
  - Bessel box energy discrimination
  - electron multiplier to assist in low current measurements
  - Purchased, not yet installed
  - Measurement limit quote: <7.5e-13 Torr

- Watanabe BBB (Bent Belt Beam) gauge
  - Newly designed (JVSTA **28** (2010) p. 486)
  - Operates with Leybold IE540 controller
  - 230° degree deflector (similar to Helmer)
  - BeCu housing to reduce $I_{heating}$
  - Manufacturer's lower limit: 4×10^{-14} Torr



Axtran

Cryopumped gun project

- Investigate adding bakable cryopump into system
  - Leybold Coolvac 2000 BL, special order
  - Cryosorber panel can be chilled with LN_2 during bakeout
  - Isolation valve for regeneration
  - Chamber: currently in heat treatment
- Can we measure improvement in vacuum due to cryopump?

➢ Characterize UHV/XHV gauges

Ionization gauge current contributions

$$I_{measured} = I_{real} + I_{x-ray} + I_{heating} + I_{ESD} + \left(I_{inv.x-ray} + I_{ESDneut.}\right)$$

I_{real} : pressure dependent gas phase ions – species sensitive

$I_{x\text{-}ray}$: x-ray induced electron desorption from collector

- reduce by geometry

I_{ESD} : ions arriving at collector from electron stimulated desorption (ESD) of molecules on the grid

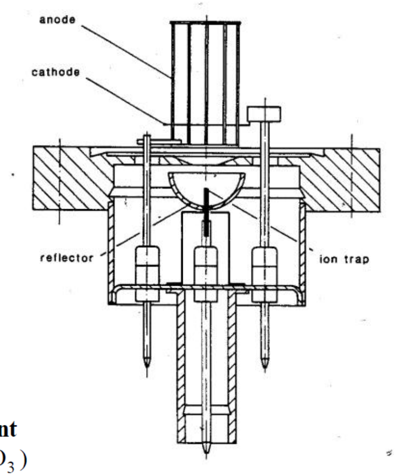
- reduce by degassing grid

$I_{heating}$: pressure rise due to filament heating – species sensitive

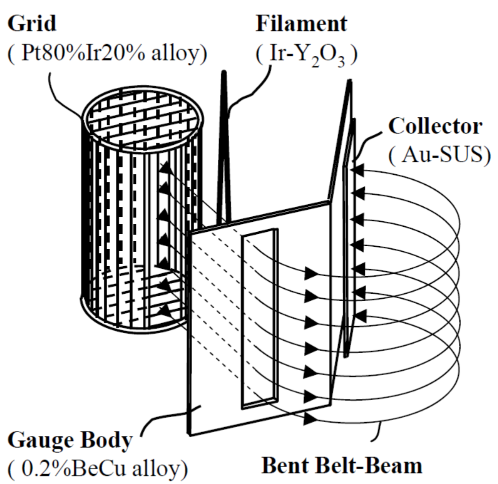
- reduce by material selection, geometry, long duration

Electron stimulated desorption

$$I_{measured} = I_{real} + I_{x-ray} + I_{heating} + I_{ESD} + \ldots$$

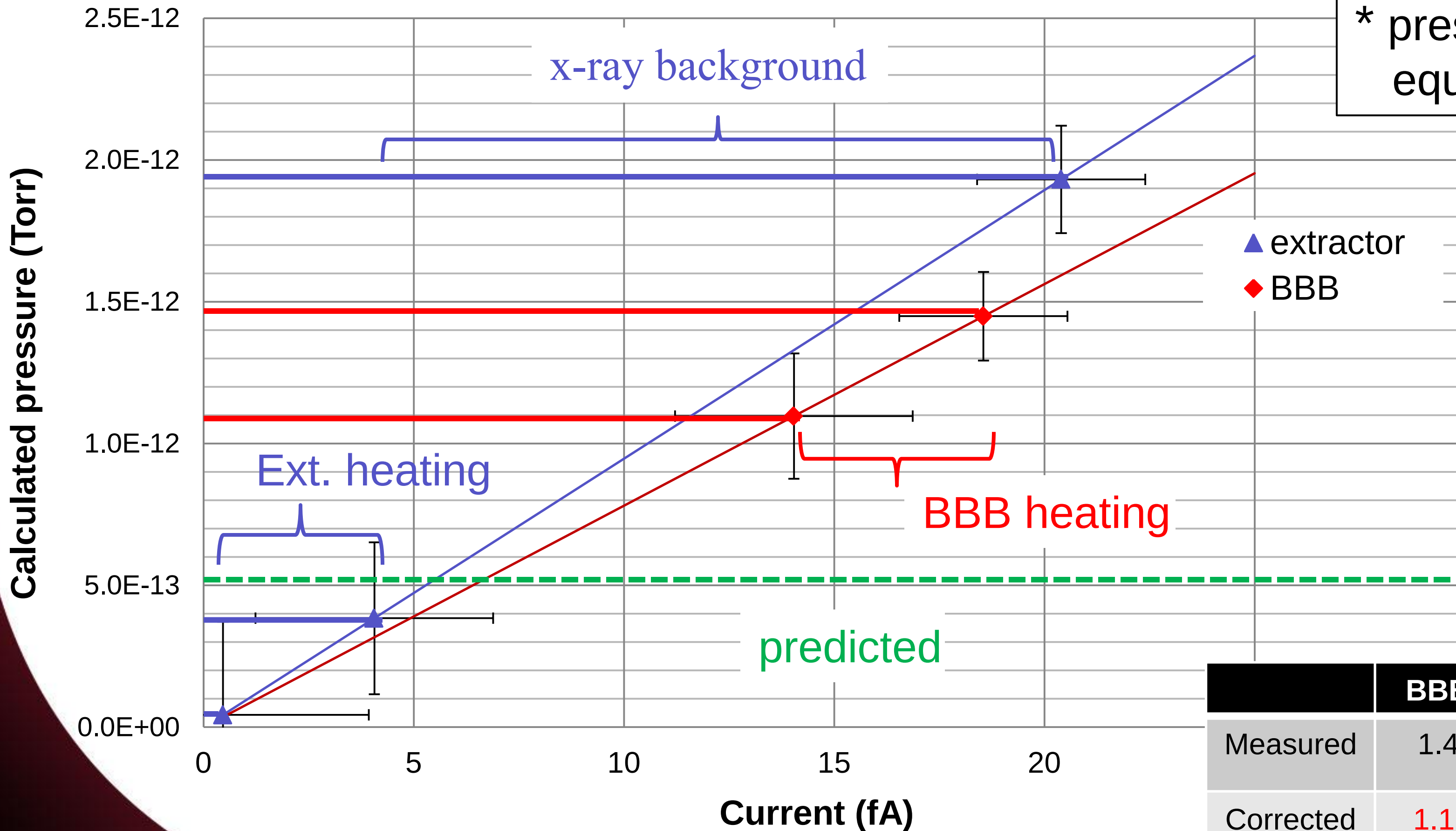


- Electrons can liberate elements adsorbed on the grid
- If grid - filament potential equal to electron energy, ESD difficult to separate
- Methods to reduce ESD
  - high energy electron bombardment (degas mode)
  - operate grid at elevated temperature
  - grid material optimization (BBB)
  - stabilize for months
  - Axtran: energy analysis since electron energy ≠ grid-filament potential



So what is our pressure?

$$I_{measured} = I_{real} + I_{x-ray} + I_{heating} + I_{ESD} + \ldots$$

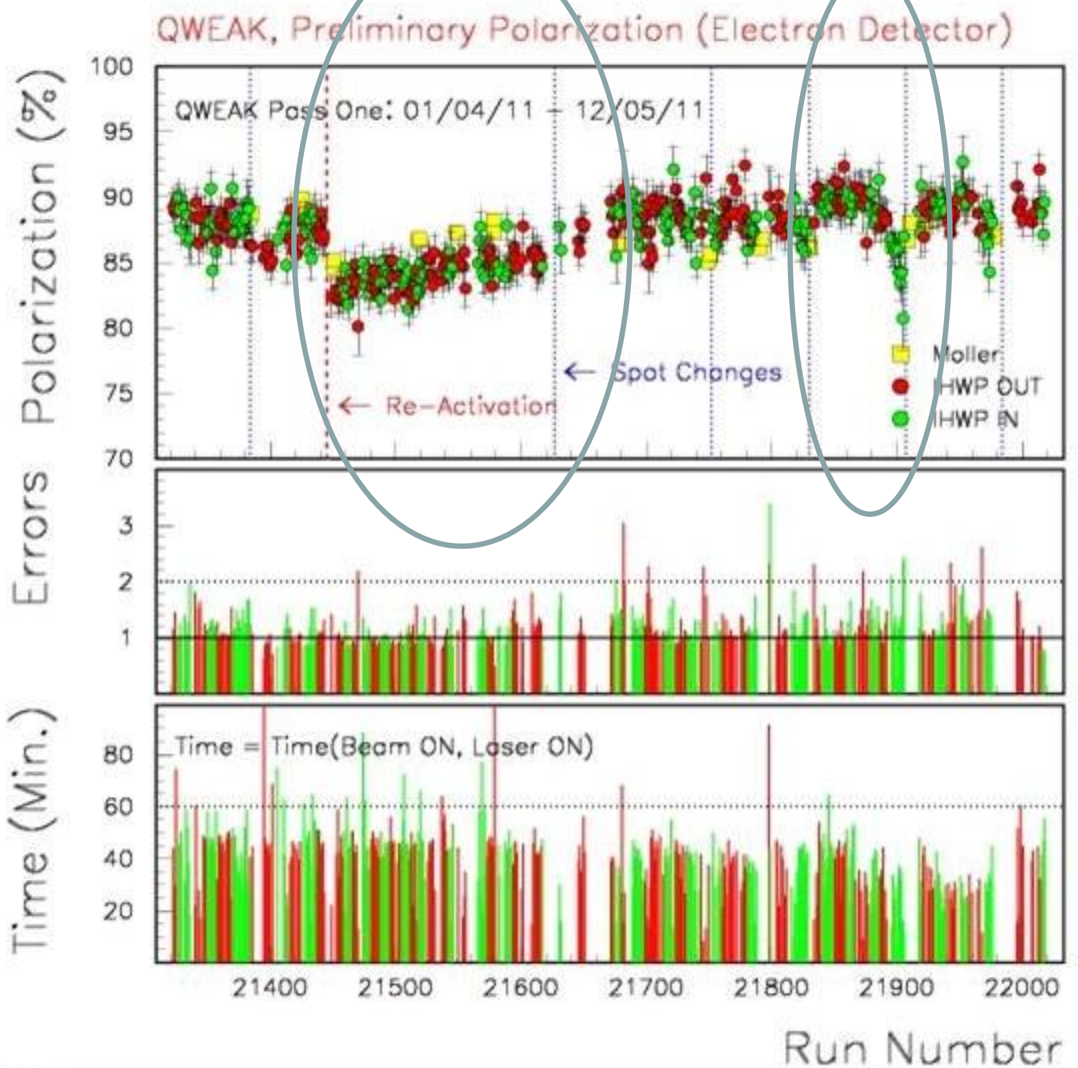


* pressures nitrogen equivalent, S_{vendor}

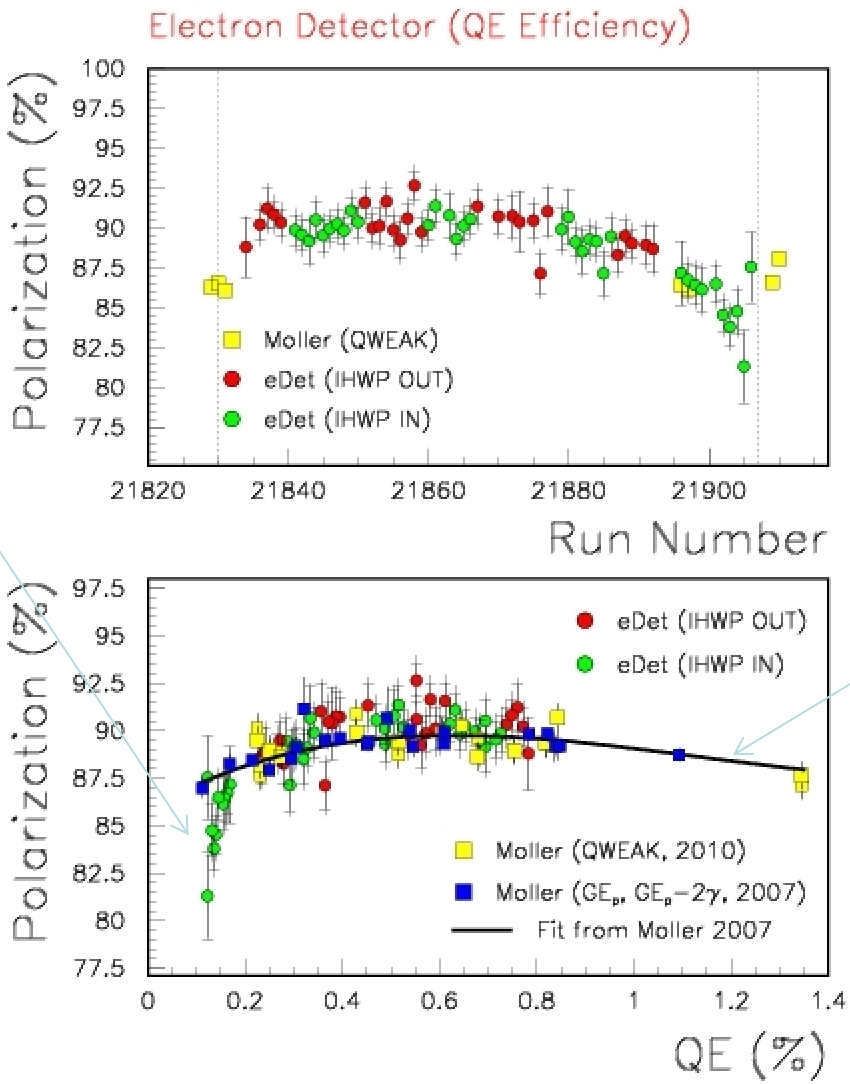
	BBB (Torr)	Extractor
Measured	1.4×10^{-12}	1.9×10^{-12}
Corrected	1.1×10^{-12}	5×10^{-14}
Predicted	6×10^{-13}	

Why does heating/reacitivating the wafer cause polarization to decrease so significantly?

Why did QE drop so significantly before the spot move?

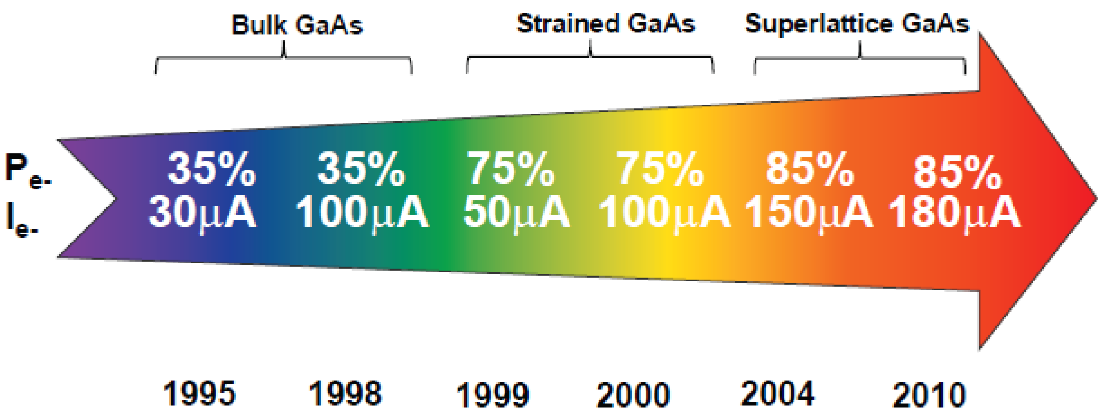


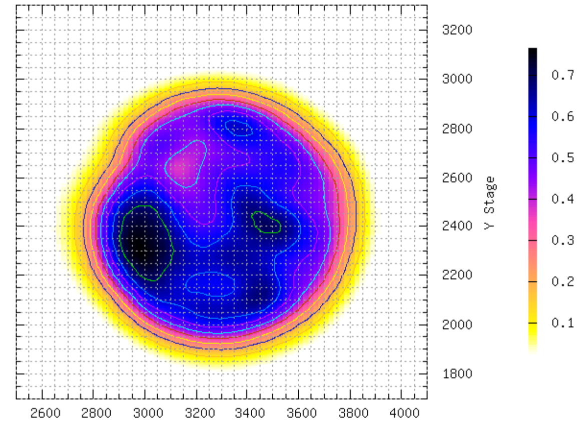
At low QE, we use ~ 500mW laser power to make required beam. Were we heating the wafer and shifting the bandgap?



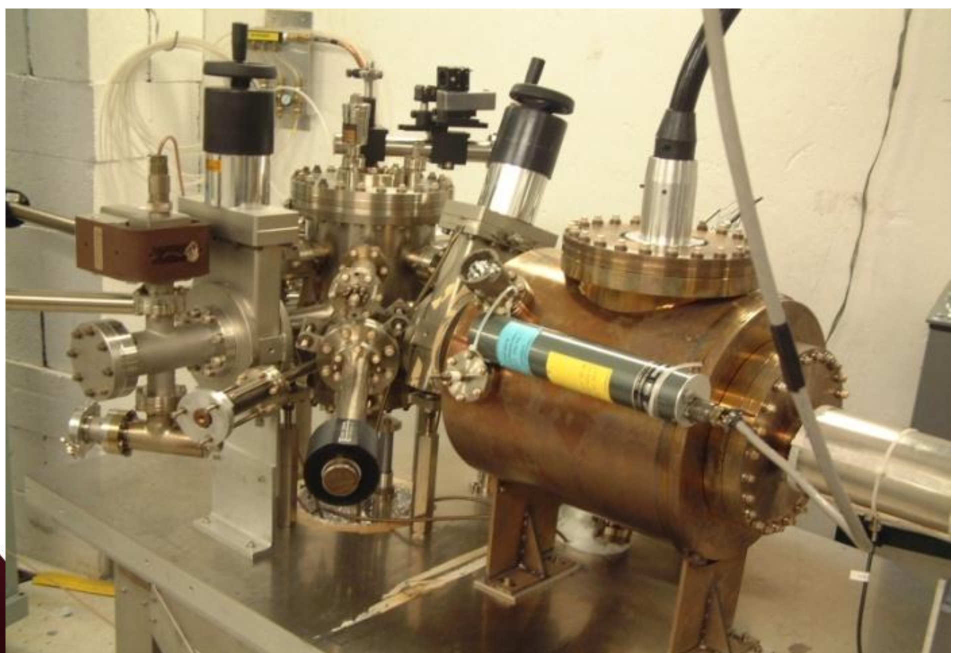
Here at high QE, perhaps polarization is lower because of depolarization in the BBR

Jlab - ILC High Current Polarized Electron Source





R. Suleiman et al., PAC'11, New York (NJ, USA), March 28 – April 1, 2011



Parameter	Value
Laser Rep Rate	1500 MHz
Laser Pulselength	50 ps
Laser Wavelength	780 nm
Laser Spot Size	350 μm FWHM
High-Pol Photocathode	SSL GaAs/GaAsP
Gun Voltage	200 kV DC
CW Beam Current	**4 mA**
Run Duration	**1.4 hr**
Extracted Charge	20 C
1/e Charge Lifetime	85 C
Bunch charge	2.7 pC
Peak current	53 mA
Current density	55 A/cm^2

Space Charge Limit

Old Slide

Child's Law

$$j_0 = \left(2.33\times10^{-6}\right)V_0^{3/2}/d^2$$

V (kV)	j_0 (A/cm^2)
100	7
140	14
200	23
350	53

People expect to operate beyond these current densities

Assume 3cm cathode/anode gap

More Realistic Space Charge Limit

Child's Law (1D): $j_1 = \left(2.33\times10^{-6}\right)V^{3/2}/d^2$

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

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

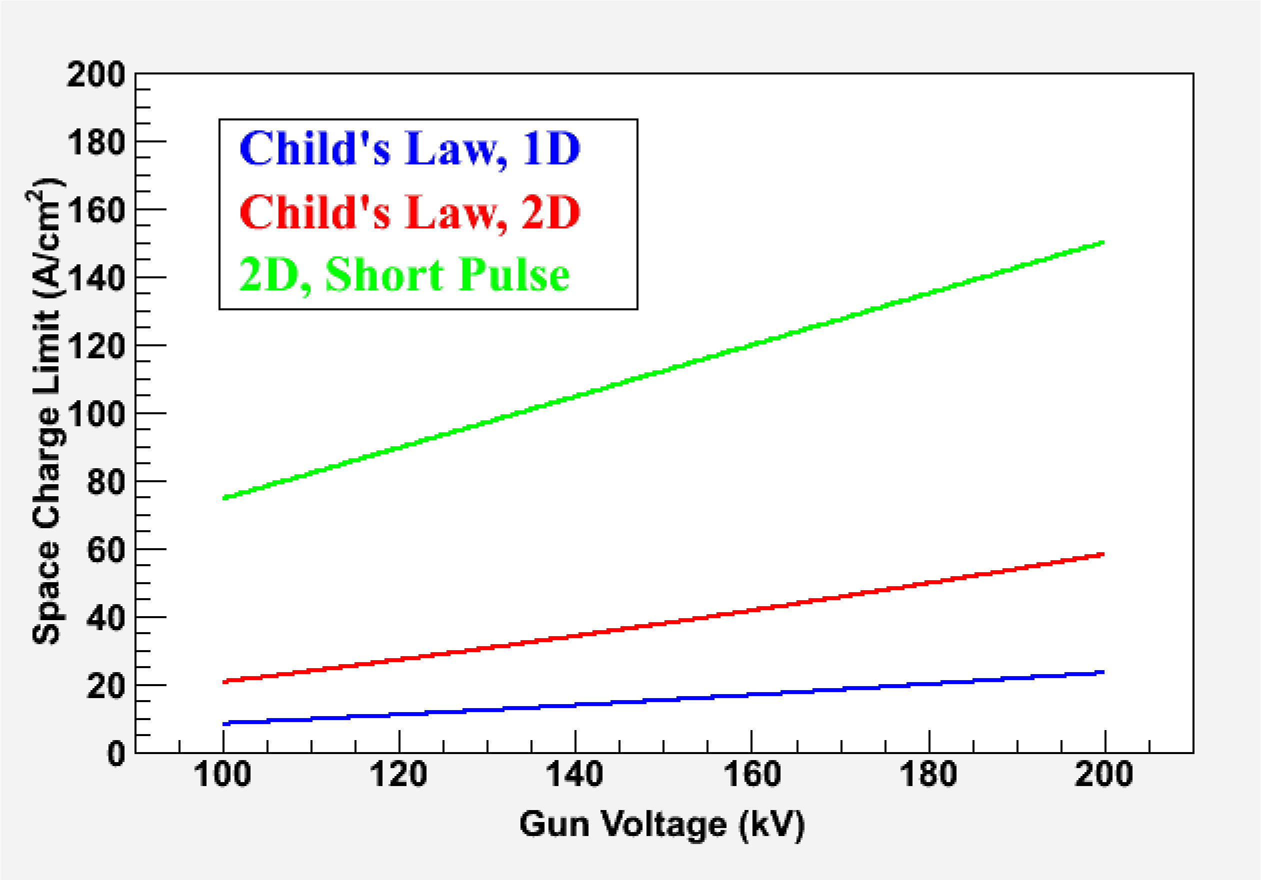
$$X_{CL} = \frac{t_b}{\tau}$$

V	Gun voltage
d	Cathode/anode gap (3 cm)
r	Laser spot size (1 cm = *2r*)
t_b	microbunch length (100 ps)
τ	Gap transit time (0.48 ns @ 100 kV)

Machines like ILC - with long microbunch - won't reap "short pulse" benefit

Space Charge Limit – Not an Issue

1D SCL does not apply (i.e. we don't have infinite charge plane)
Real world conditions, with finite beam size 2D and short pulses, push Child's Law Current Limit higher…..



Surface Charge Limit

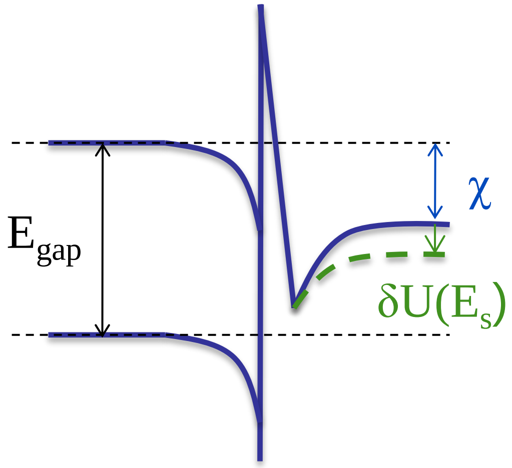
- NEA of GaAs depends on Gun HV. QE increases with external Electric Field at GaAs surface, E_s,

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

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

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

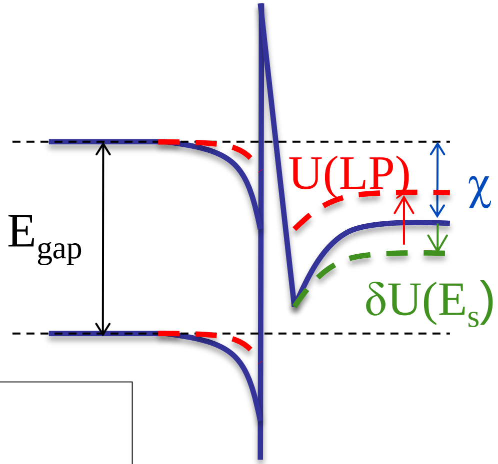
Where ε_s (= 13.1) is GaAs relative permittivity.



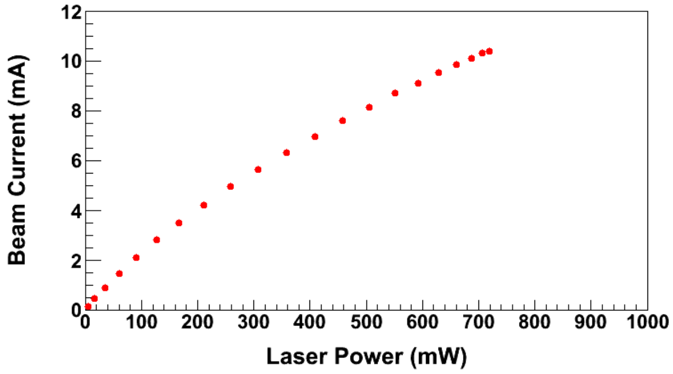
Gun HV (kV)	E_s (MV/m)	$\delta U(E_s)$ (meV)
100	2.0	50
140	2.8	59
200	4.0	70

- 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),

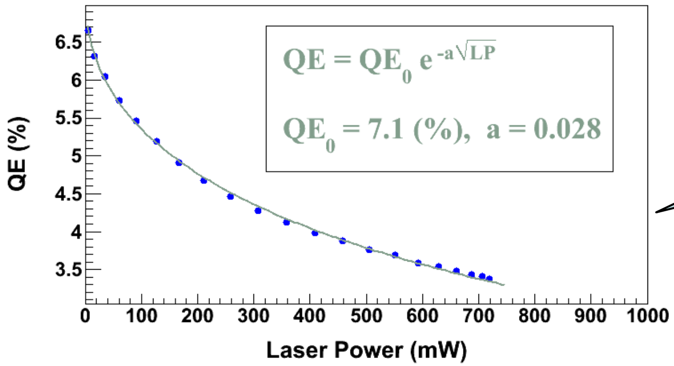
$$QE = QE_0\left(1 - \frac{U(LP)}{\chi + \delta U(E_s)}\right)$$



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



- For heavily Zn doped GaAs surface, $U(LP) \rightarrow 0$
- Higher Gun HV suppresses photovoltage



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

Emittance and Brightness

- Normalized Emittance from GaAs:

$$\varepsilon_{n,x,y} = \sqrt{\frac{q}{4\pi\varepsilon_0 E_s} \frac{k_B T_{eff}}{m_e c^2}}$$

q Bunch Charge (= 0.4 pC, 200 µA and 499 MHz)

E_s Electric Field at GaAs surface

T_{eff} Effective Temperature of GaAs (= 300 – 400 K, 780 nm)

$k_B T_{eff}$ Thermal Energy (= 34 meV)

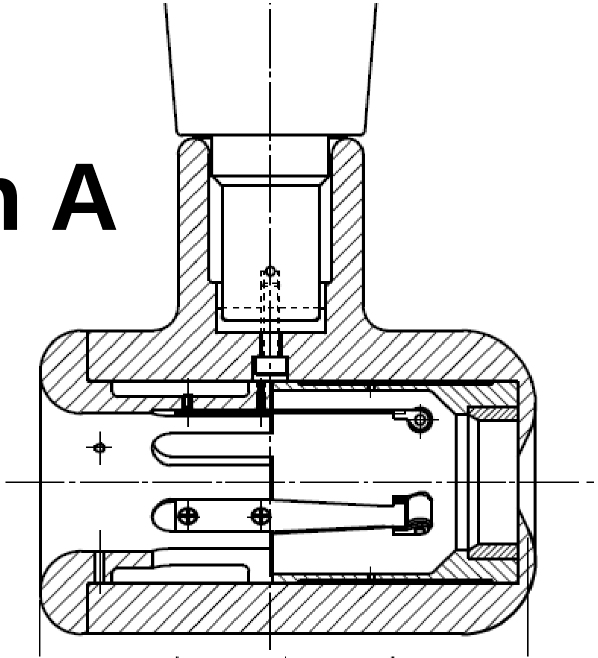
Gun HV (kV)	E_s (MV/m)	ε_n (µm)
100	2.0	0.011
140	2.8	0.009
200	4.0	0.008

- Normalized Brightness:

$$B_n \propto \frac{1}{\varepsilon^2} \propto E_s$$

Brightness is proportional to Gun HV

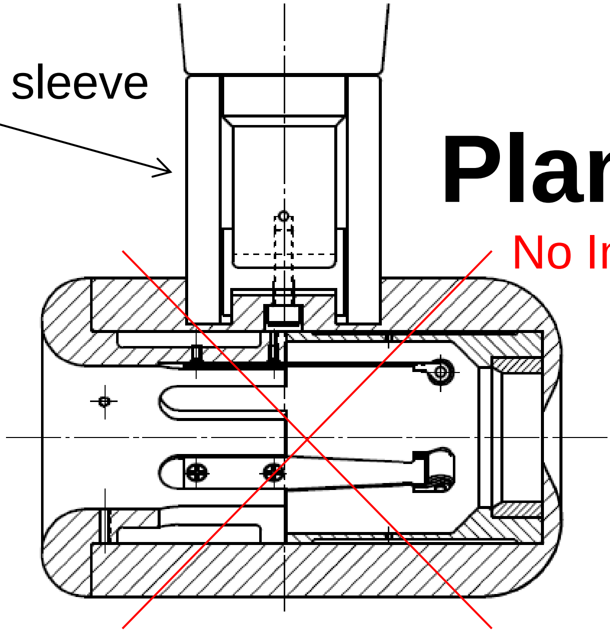
Plan A



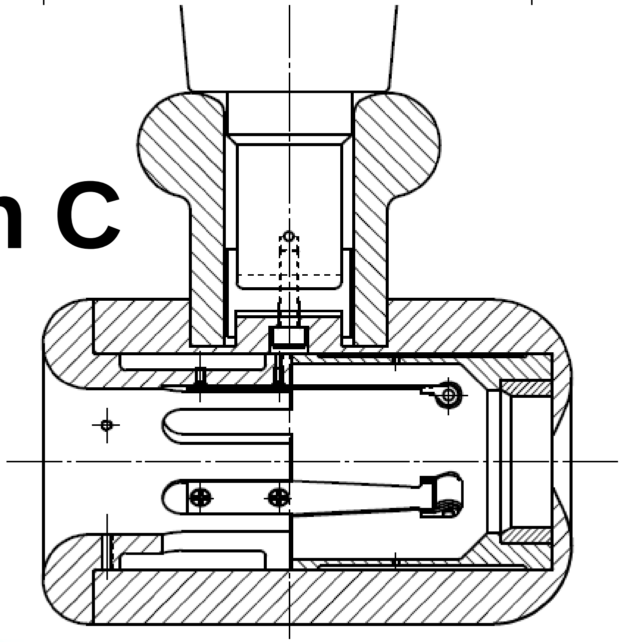
Insulator sleeve

Plan B

No Improvement



Plan C



In hand, but untested

Plan D