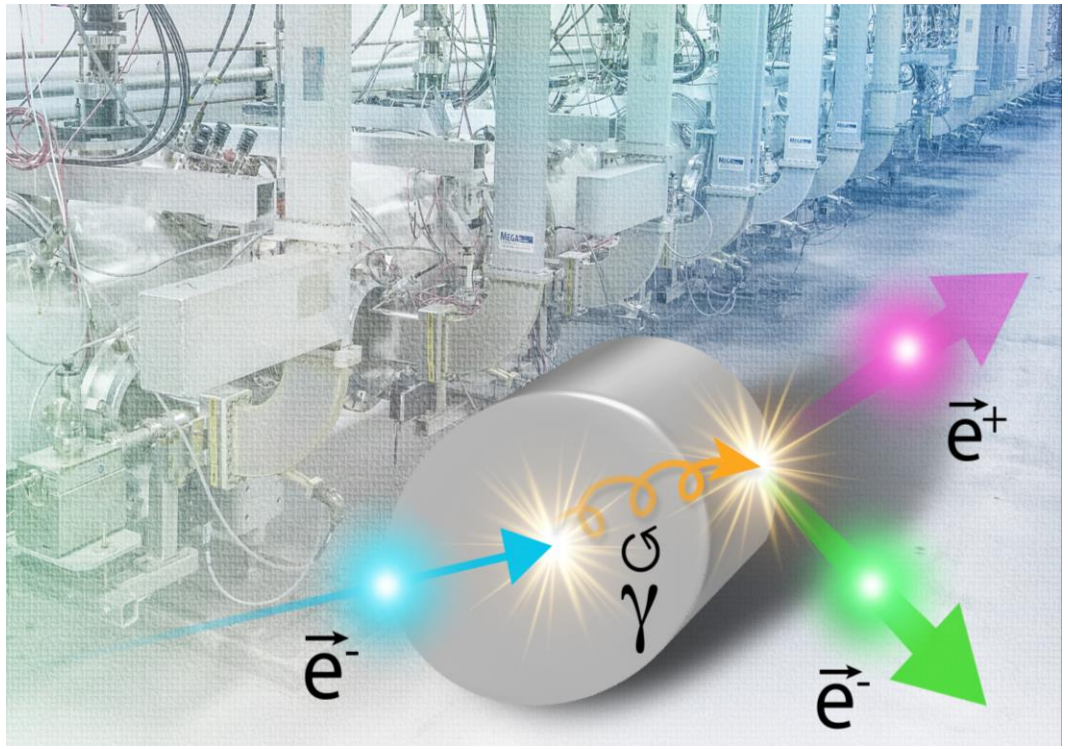
Extreme high vacuum for polarized electron sources

Marcy L. Stutzman, Ph.D.

Thomas Jefferson National Accelerator Facility



2023 CCM & IMEKO INTERNATIONAL CONFERENCE ON PRESSURE AND VACUUM METROLOGY

CCM-PV 2023

WASHINGTON DC • MAY 15-19, 2023

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

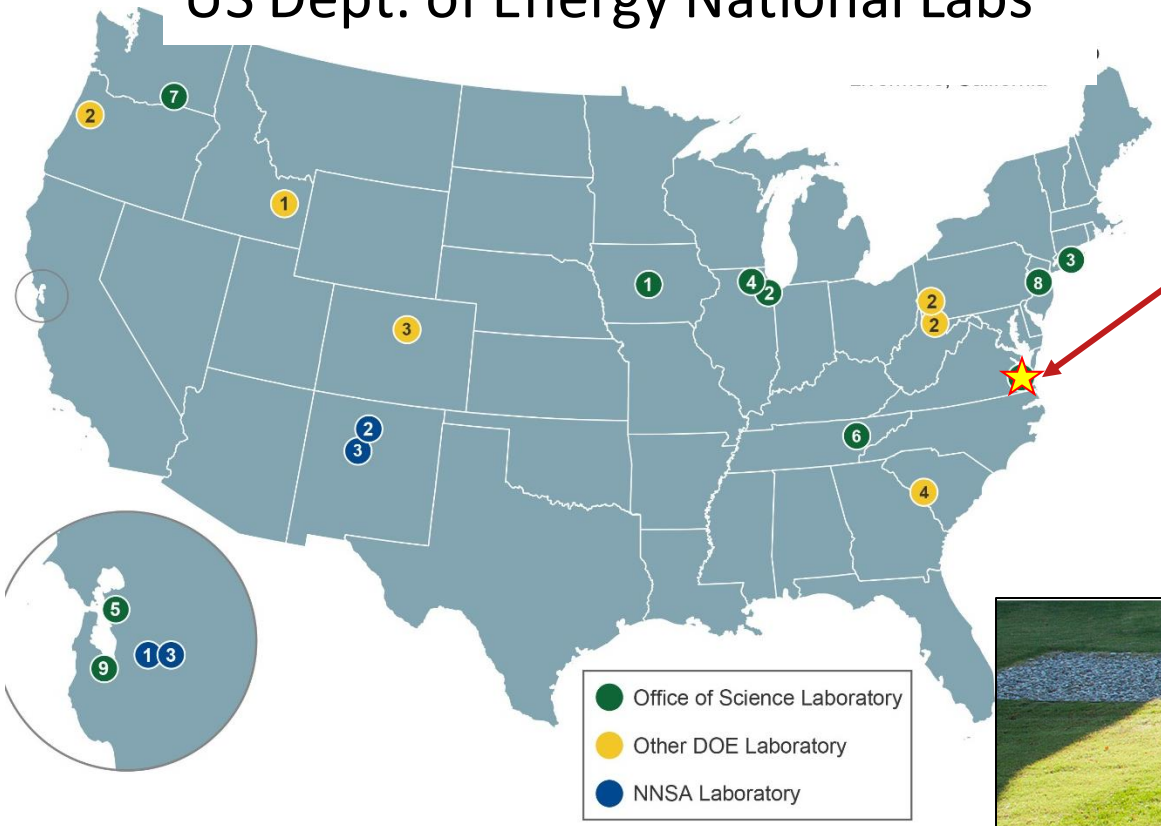
JSA

Outline

- Motivation for Polarized Electron Sources
  - Jefferson Lab Physics & Future facilities
  - Polarized Electrons
  - Polarized Source Lifetime
- JLab Vacuum research and characterization
  - Efforts to achieve XHV
  - Efforts to measure XHV
- Conclusions

Thomas Jefferson National Accelerator Facility

US Dept. of Energy National Labs



Newport News, VA

Thomas Jefferson National Accelerator Facility

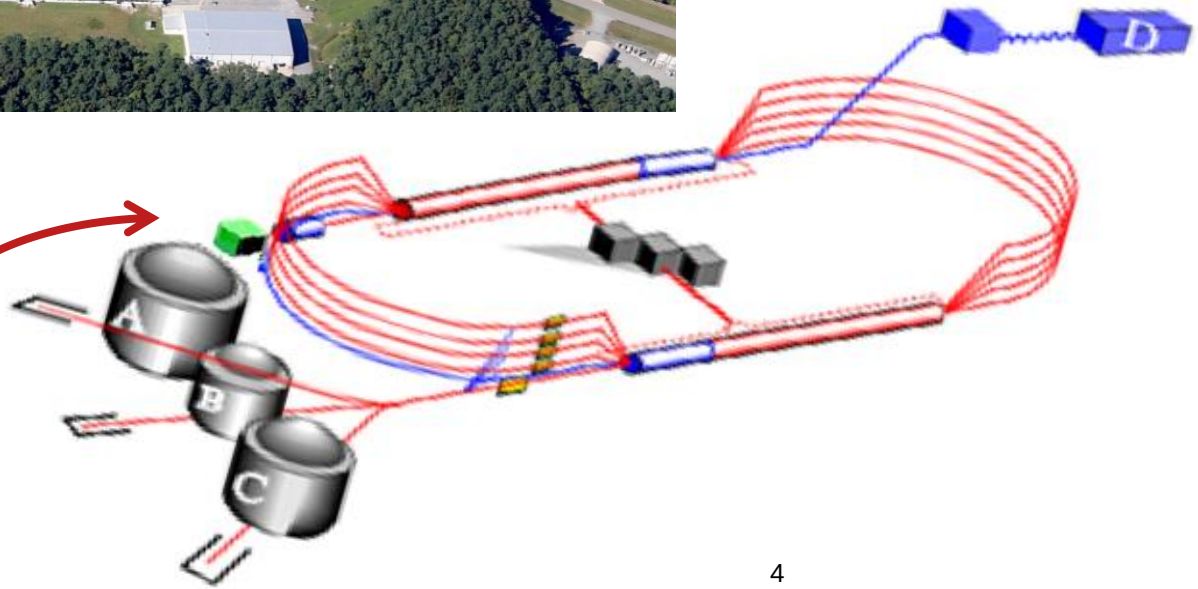
- Recirculating linear accelerator
  - Up to 5 passes through 2 LINACs
- Polarized Electron Beam

Hall D

Source

Halls A, B, C

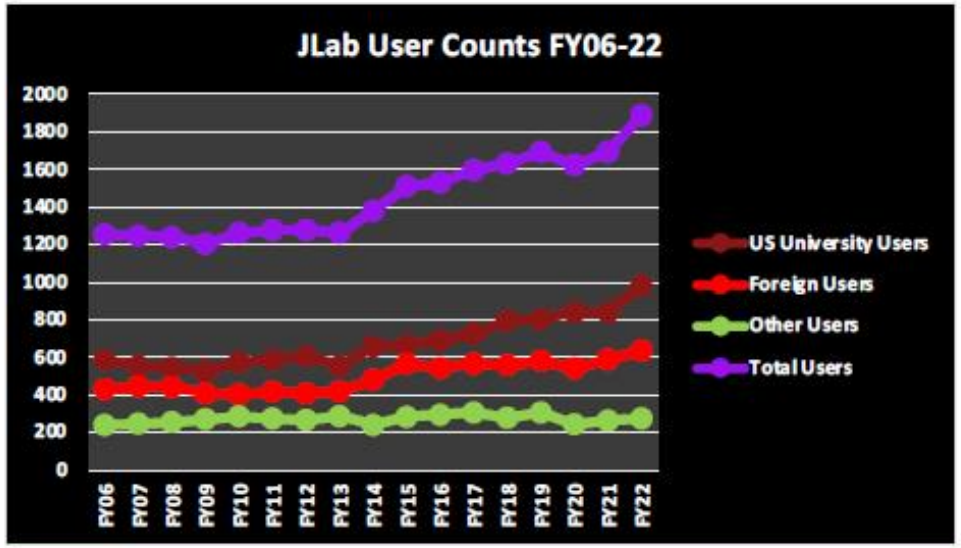
Polarized source

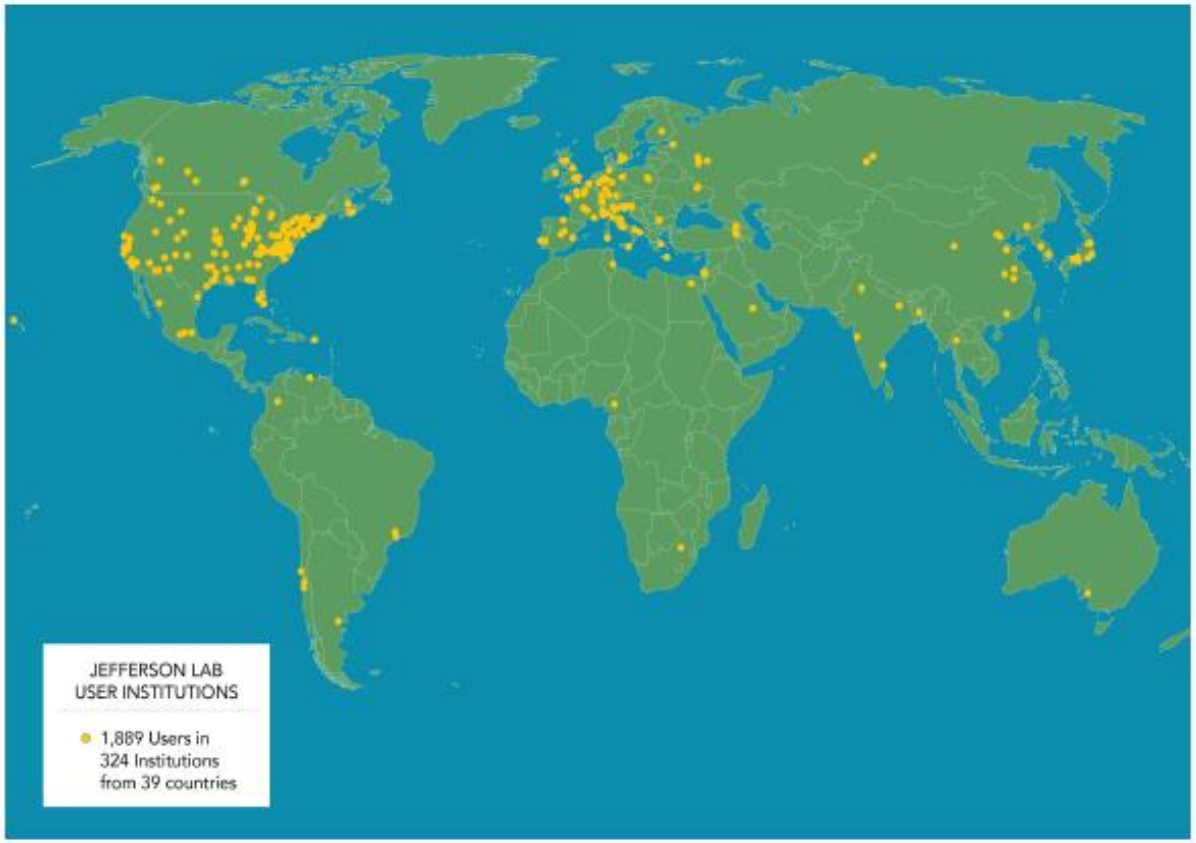


Extensive, engaged user community

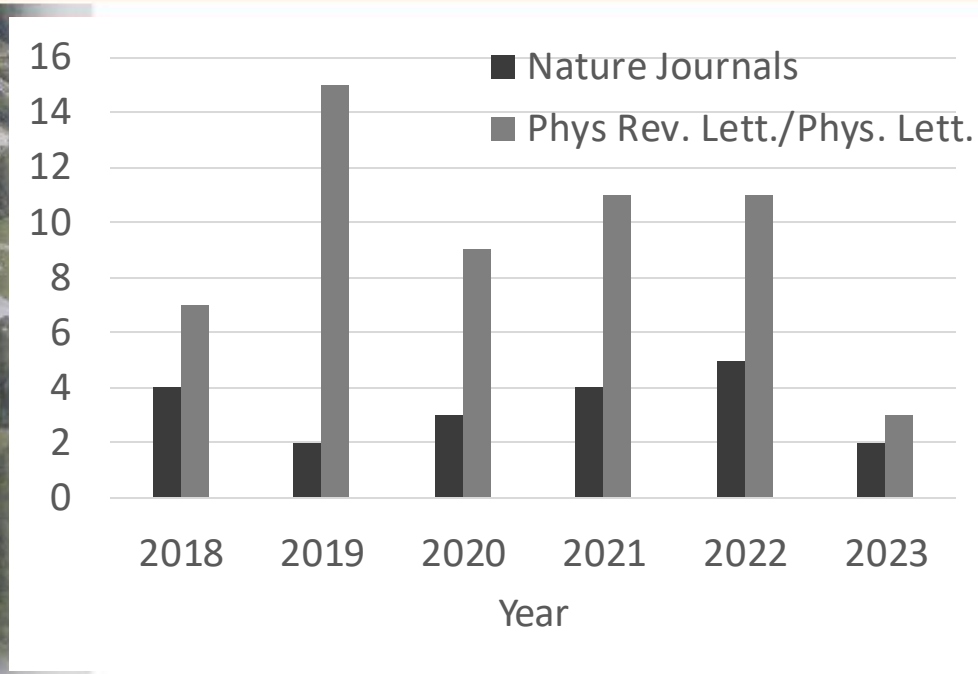
CEBAF: a world-unique user facility for Nuclear Physics

Delivers a vibrant research program
- operating more than 30 weeks per year
- supporting ~1,900 users annually





Jefferson Lab and CEBAF



- Probe the structure of matter

  Complex **non-pQCD** problem which demands different approaches and measurements to access multiple observables

- Discover evidence for physics beyond the standard model

Hadron Spectra

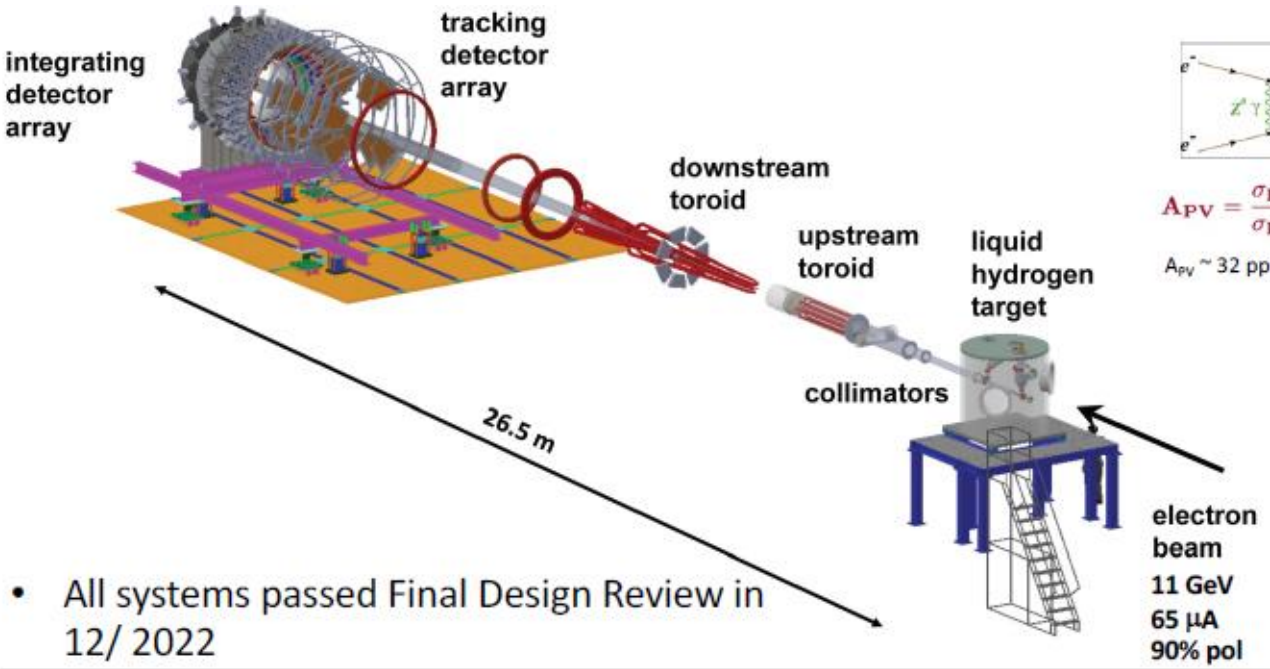
1D-3D Nucleon Structure

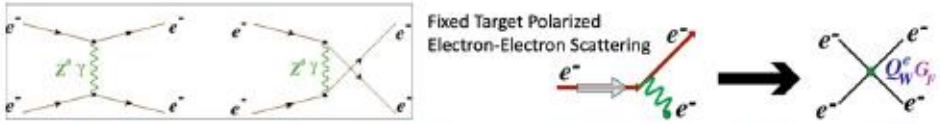
Hadrons & Cold Nuclear Matter

Test of SM & Fundamental Sym.

High profile experiments require highly polarized electrons

MOLLER- Measurement Of a Lepton-Lepton Electroweak Reaction



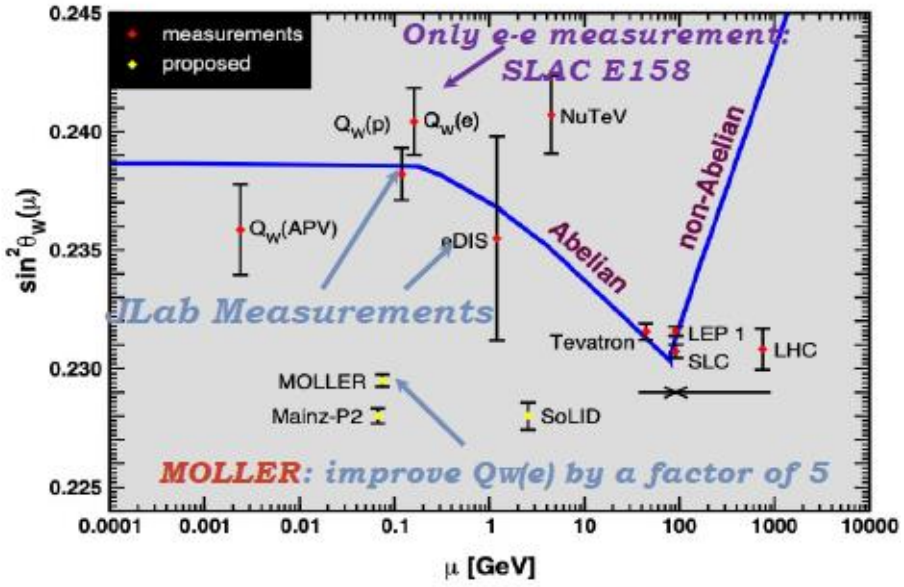


$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}Q_W^e \qquad Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075$$

A_{PV} ~ 32 ppb $\delta(A_{PV})$ ~0.8 ppb

Project: $50M

$\delta(Q^e_w)$ = ±2.1% (stat) ± 1.1% (syst.)



- All systems passed Final Design Review in 12/ 2022
- Nearly all of the needed funding has been appropriated
- Achieved CD-3A, Approve Long Lead Procurements, in March 2023
- On track for CD-2/3, Start of Construction, in late CY2023
- On track to be ready for installation by Q1FY25

Polarized Electron Sources

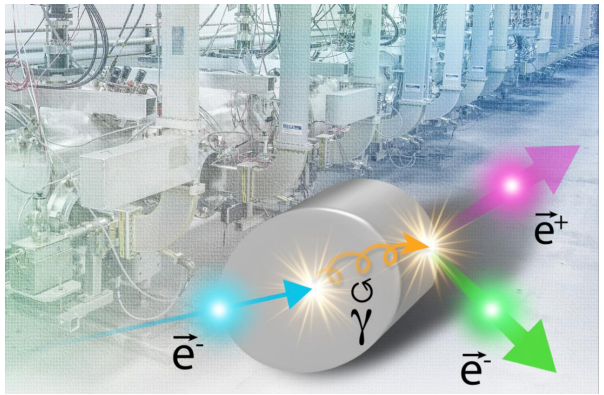
Polarized electron sources in 1996

- SLAC (Stanford)
- NIKHEF – Amsterdam
- Mainz
- Jefferson Lab (in development)
- MIT-Bates
- Nagoya
- HERA

- Operational polarized sources today
  - Jefferson Lab
  - MAMI-C at Mainz, Germany
  - Electron Ion Collider at Brookhaven National Lab (in development)
- Future polarized sources
  - Polarized Positrons at Jefferson Lab
  - Belle II SuperKEKB Polarization Upgrade
  - International Linear Collider
  - CERN LHeC polarized electron upgrade

EIC

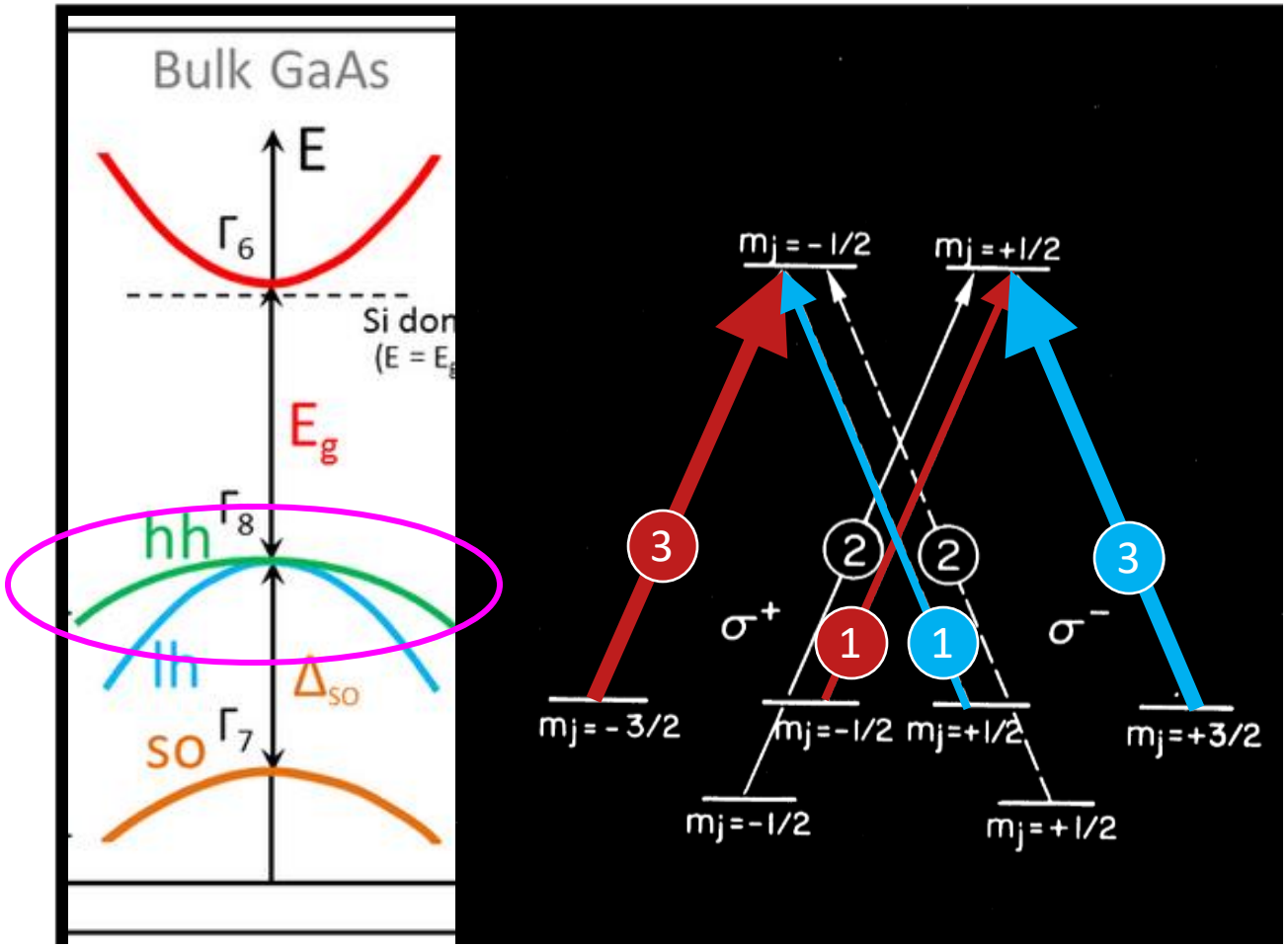
Non-accelerator applications
- Atomic physics
- Surface analysis: P-LEED, P-LEEM



JLab Polarized Positrons

Higher current polarized electron sources required for future projects

Polarized Electron Emission



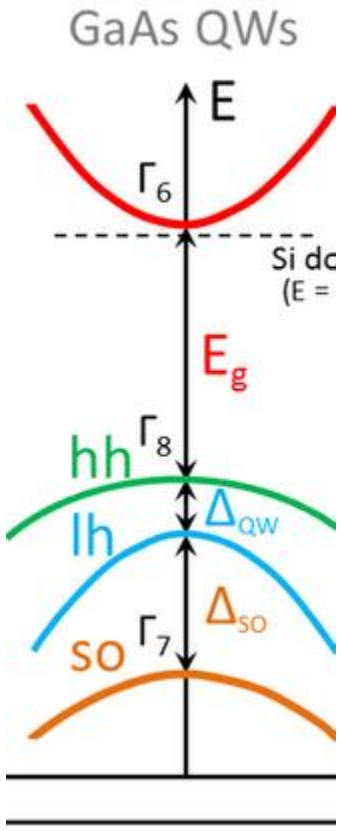
- Crystalline (bulk) GaAs
- Direct band gap semiconductor
- 780 nm laser light
- Circular laser polarization
  - Flip helicity of laser light ~1kHz to change beam polarization

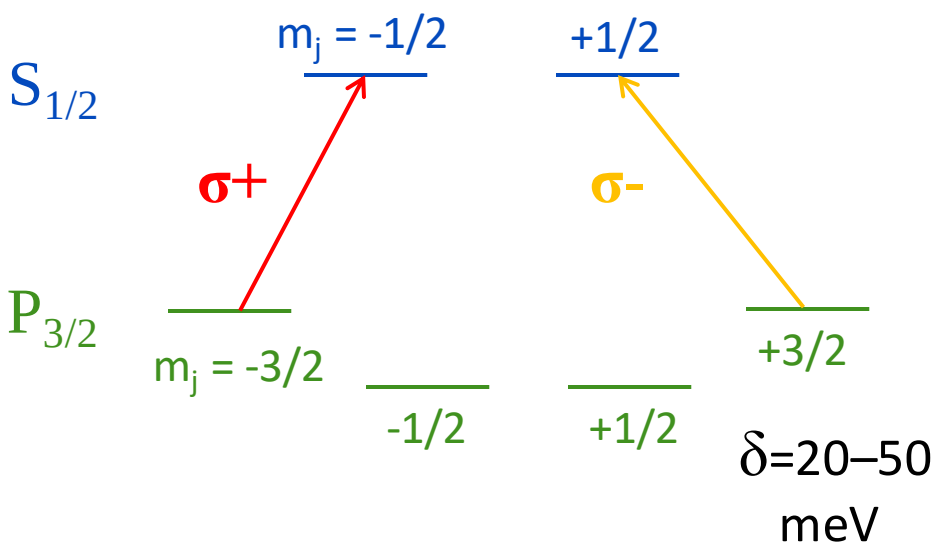
$$P = \frac{e\uparrow - e\downarrow}{e\uparrow + e\downarrow} = \frac{3-1}{3+1} = 50\%$$

Maximum theoretical polarization: 50%

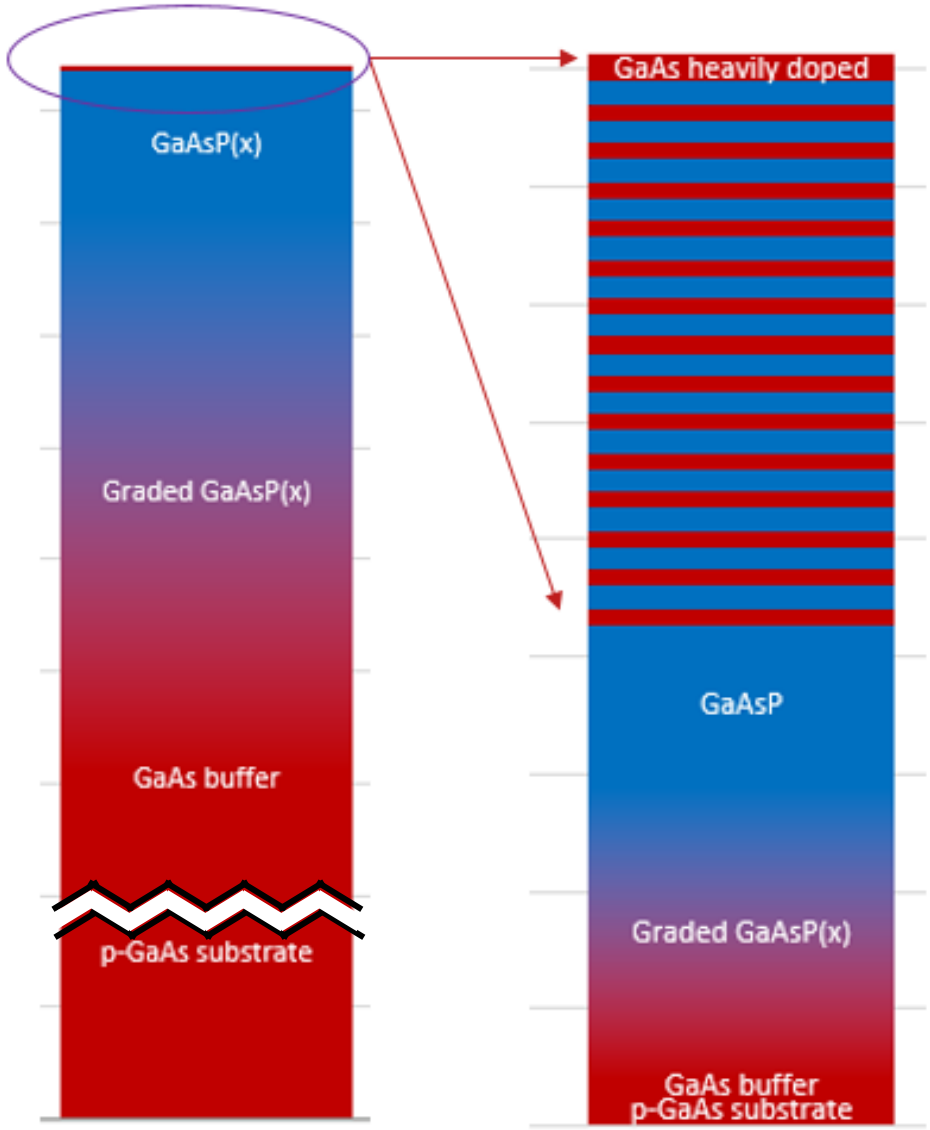
Strained Superlattice GaAs structures

- Grow strained GaAs structure
  - Split degeneracy between heavy hole and light hole bands





Max 100% theoretical polarization



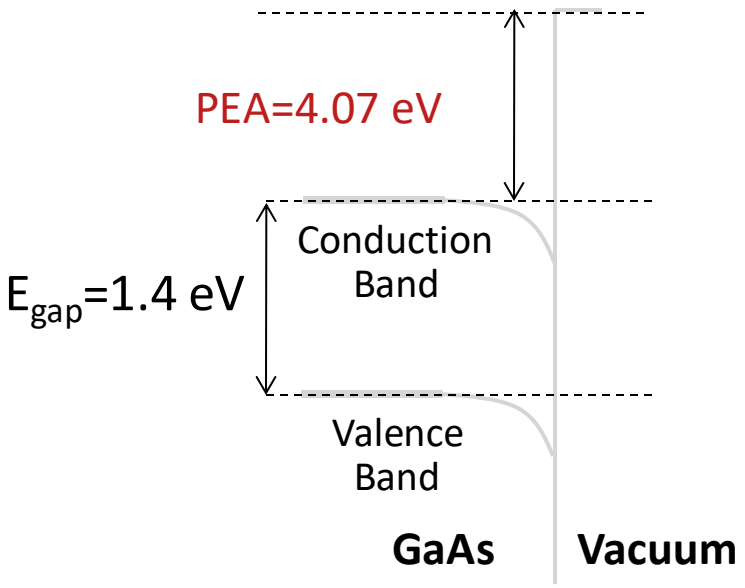
To scale

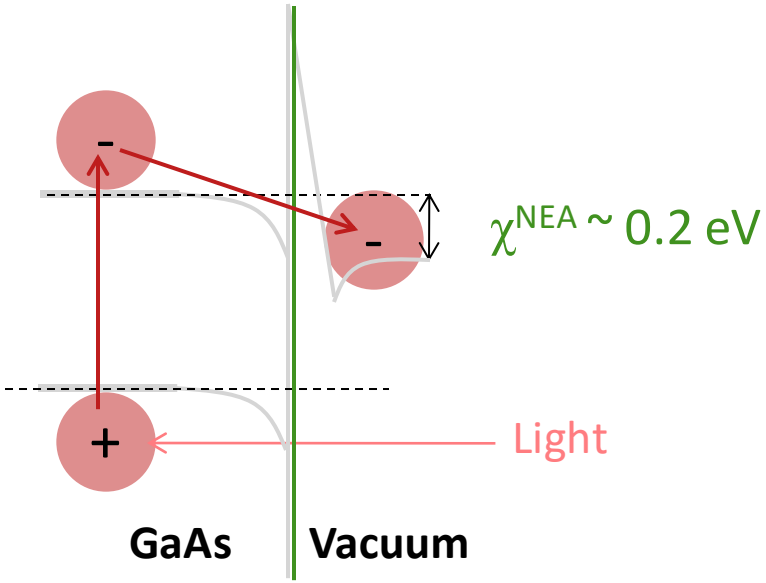
Superlattice scaled up

Strained Superlattice GaAs:GaAsP yield and polarization

GaAs
- Direct Bandgap Semiconductor
- Large Work Function
- Positive Electron Affinity (PEA)

Dipole layers of Cs + NF_3 or Oxygen
- Reduces Work Function
- Negative Electron Affinity (NEA)





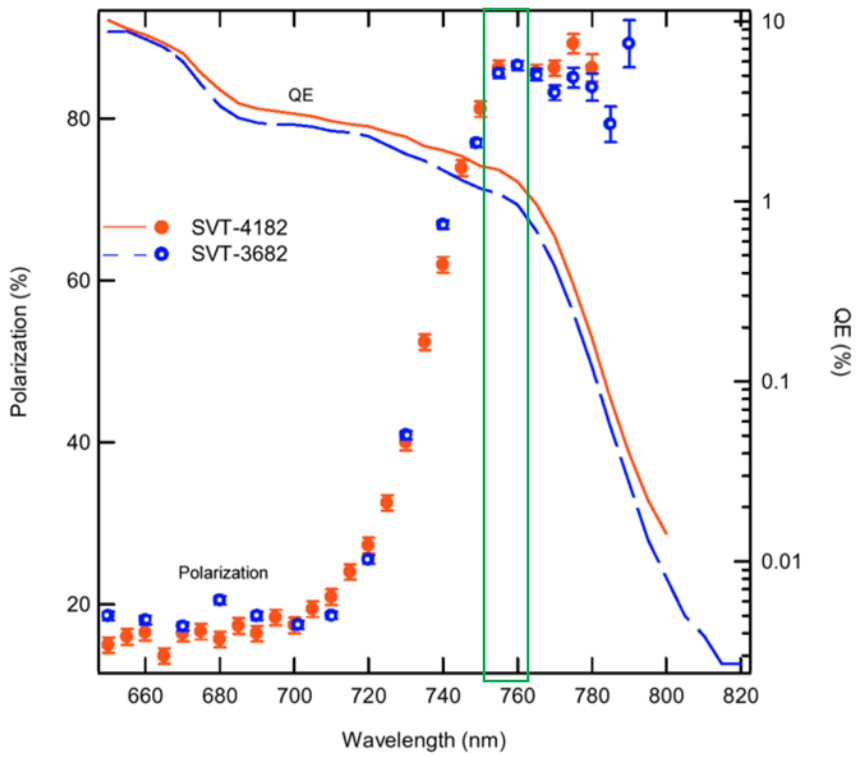
Photocathode Quantum Efficiency (QE)

$$QE = \frac{N_{electron}}{N_{photon}}$$

$$= \frac{124 \cdot I(\mu A)}{P(mW) \cdot \lambda(nm)}$$

GaAs Spin Polarized Electron Source, D.T. Pierce et al., Review of Scientific Instruments 51(4), 478 (1980).

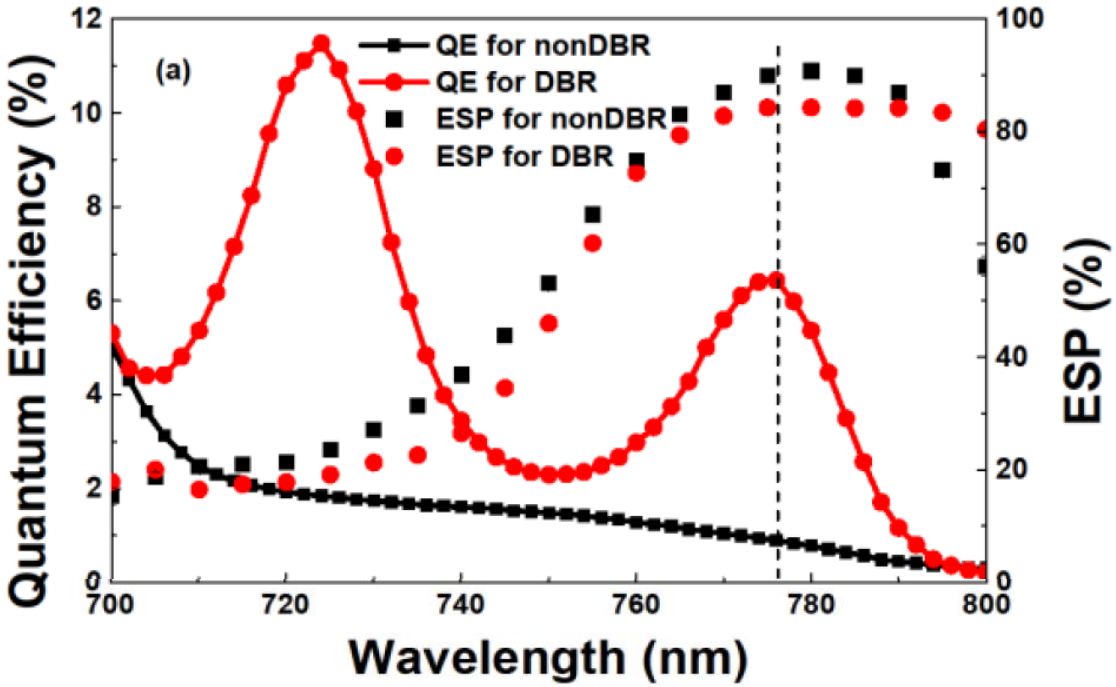
Strained Superlattice QE and Polarization



- Highest polarization at wavelength just over the band gap
- Higher QE with shorter wavelengths

J.L. McCarter, … M.L. Stutzman et al., NIMA **618** (2010) 30.

- Continuous improvement
  - Distributed Bragg Reflector->
  - Higher QE, maintain polarization



Wei Liu, …M.L. Stutzman et al., *Appl. Phys. Lett.* **109**, 252104 (2016)

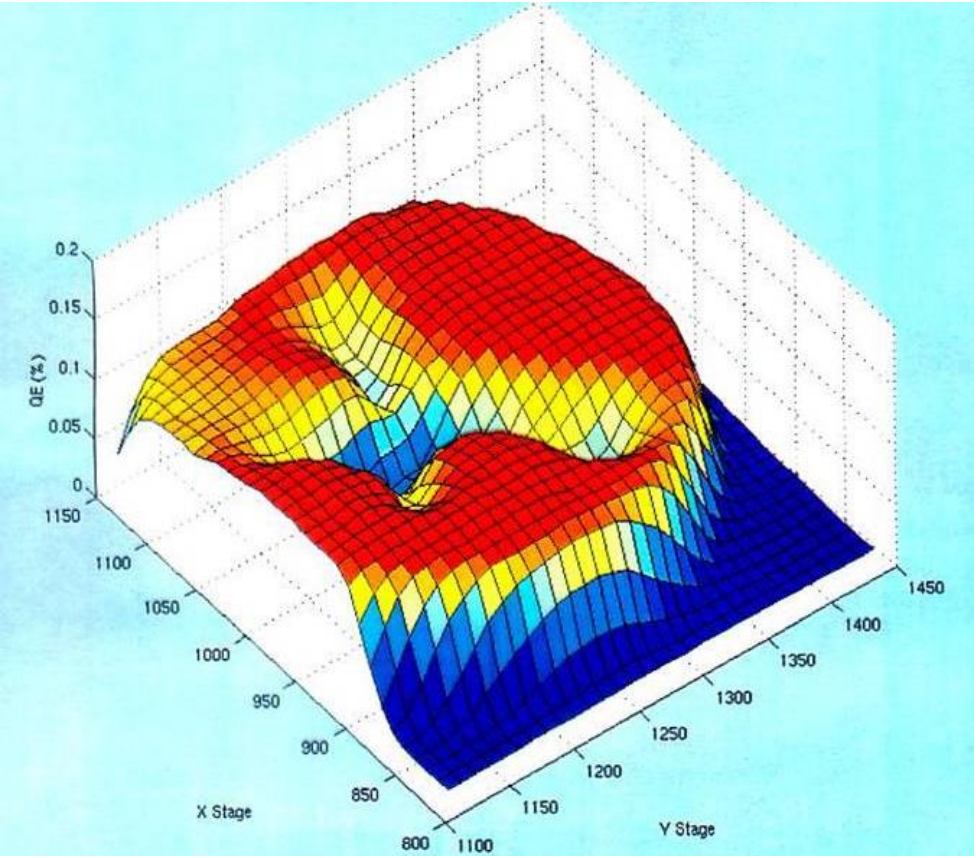
Photocathode lifetime limitations

★ Surface chemistry reaction with residual gas
- Excess oxygen, CO, CO_2 disrupt surface Cs-O or Cs-F balance

★ Ion acceleration into photocathode
- Residual gas in chamber ionized by electron beam
- Ions accelerated into photocathode

- Laser Heating
  - Surface chemistry disrupted at T>50C
  - Must limit laser power and/or cool cathode

- Surface charge limit
  - More laser power ≠ more photoemission

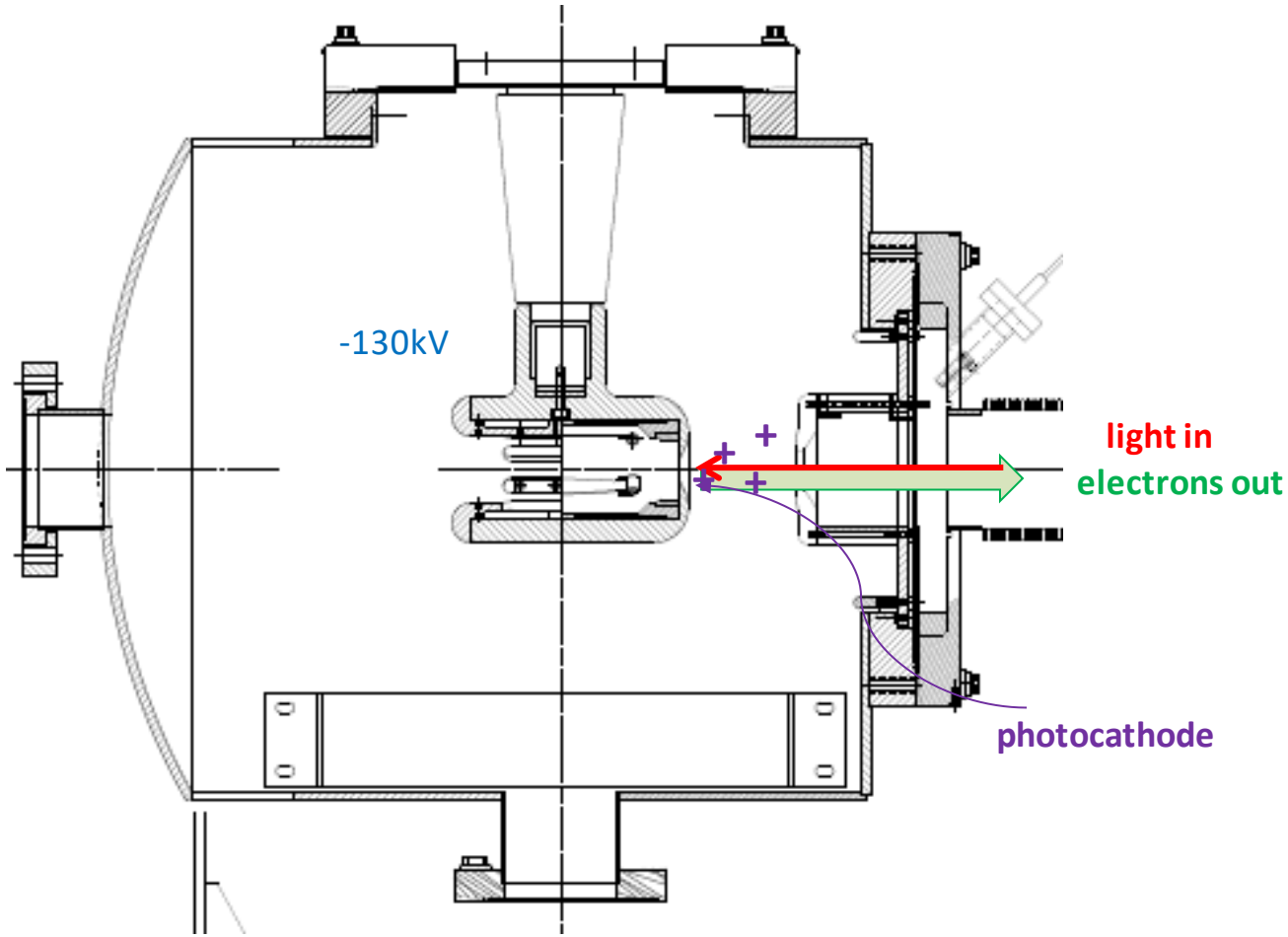


QE vs. position across photocathode after beam operation at several locations

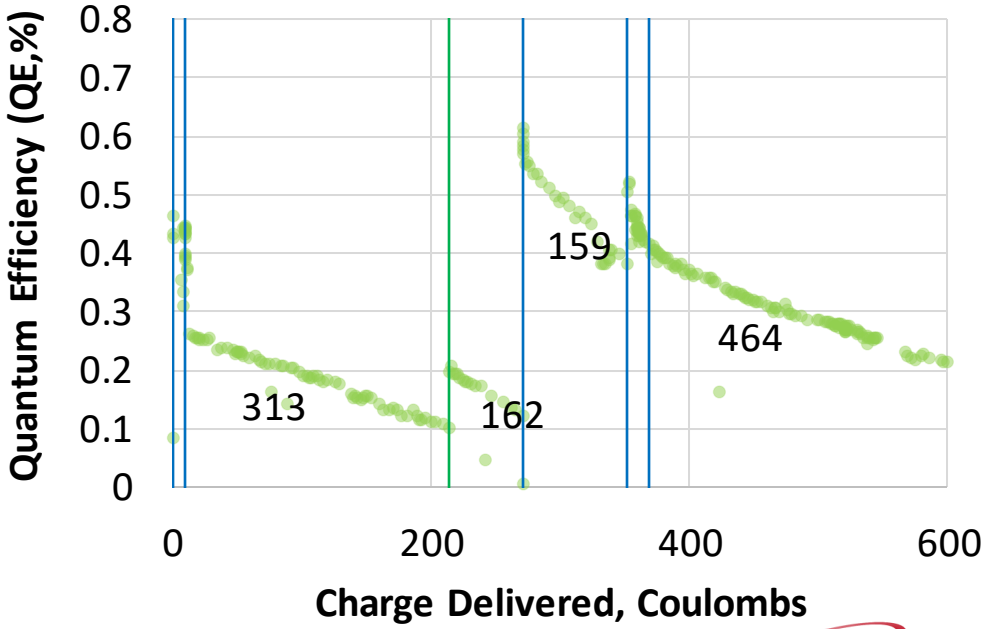
★ Will benefit from vacuum improvements

JLab Polarized Electron Source

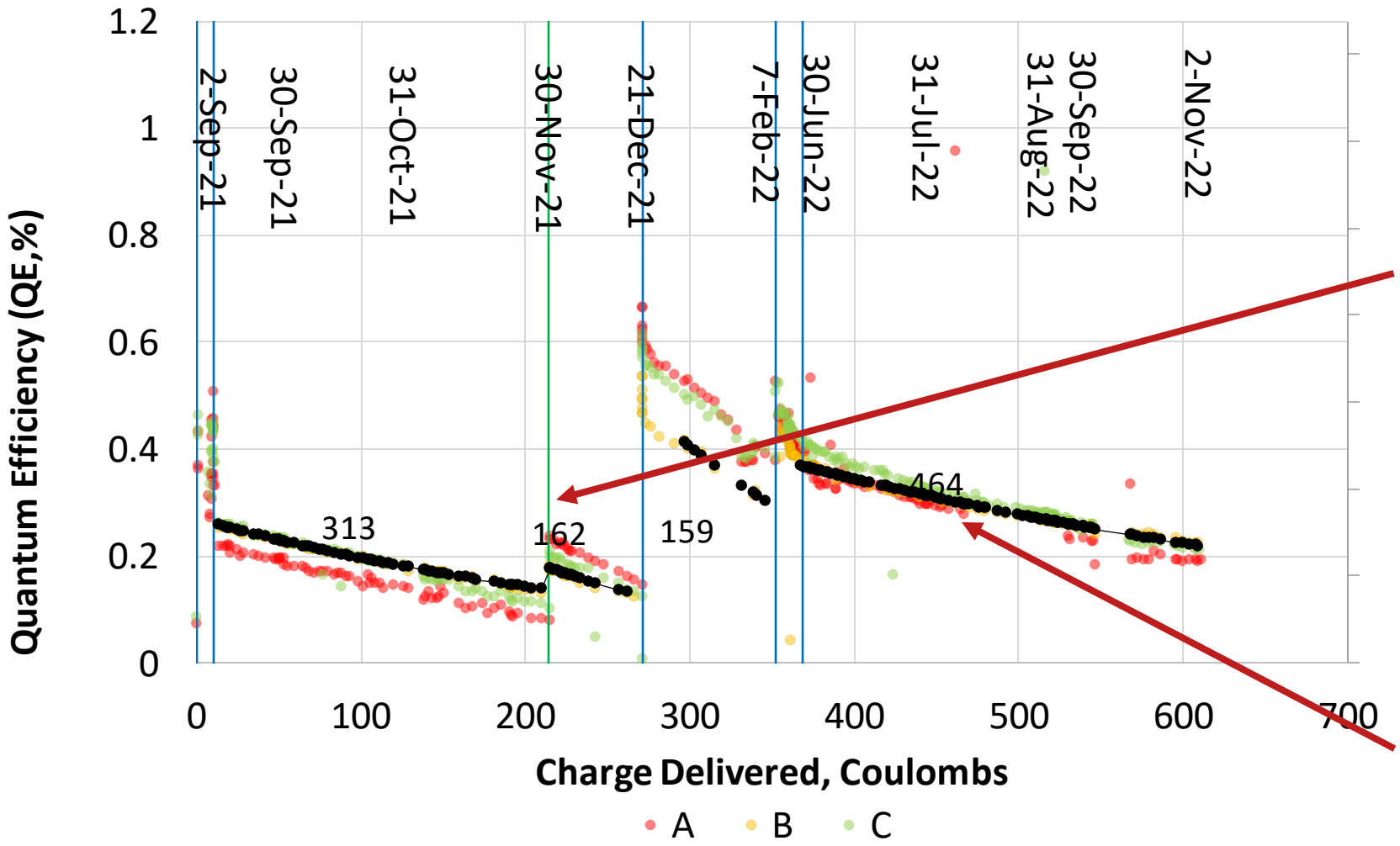
130 kV gun



- Gas in cathode-anode gap ionized by electron beam
- Ions accelerate into cathode and limit lifetime
- Damage evident through decreasing QE with beam delivery
  - Lifetime: Coulombs until $QE=1/e\cdot(QE)_o$

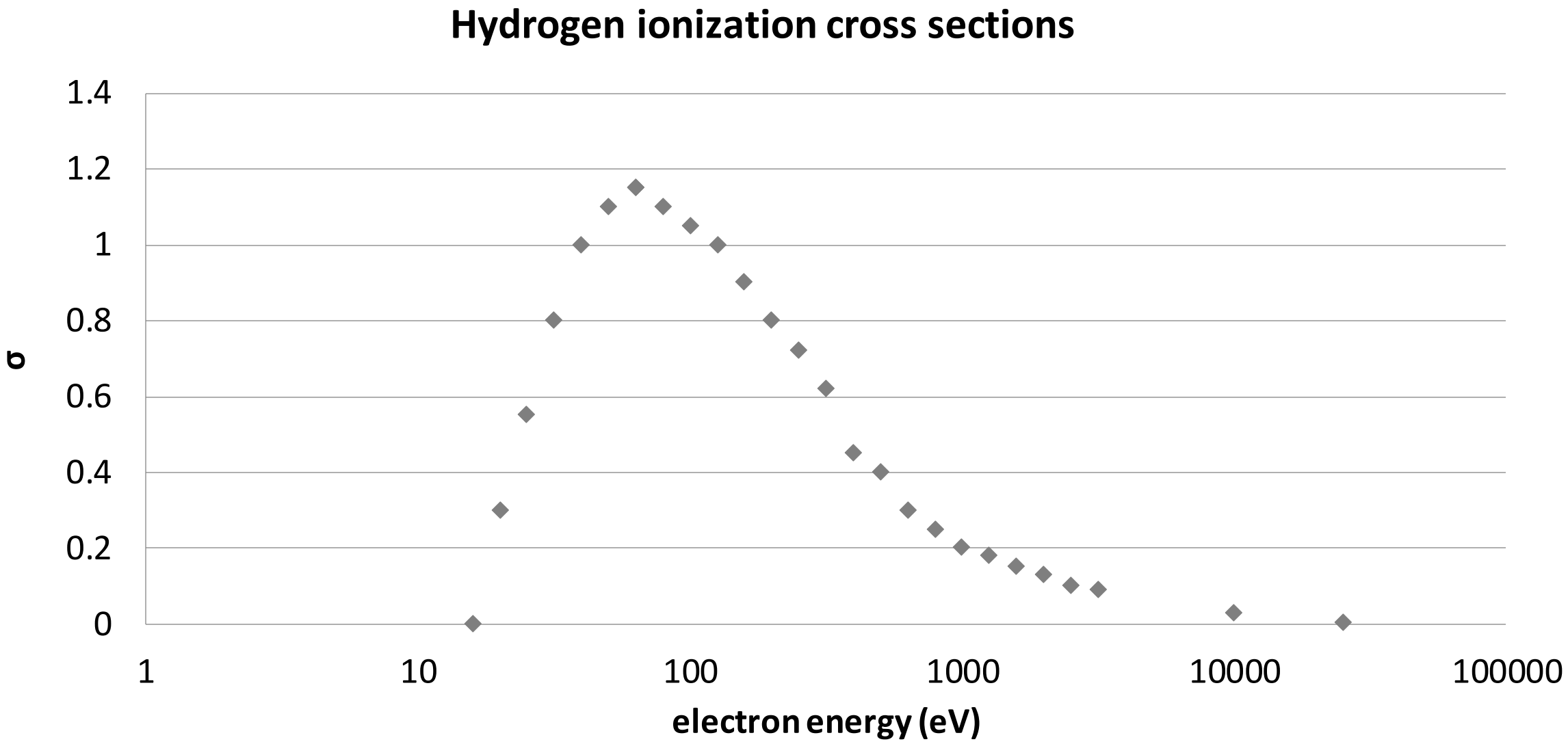


Effect of Vacuum on Photocathode Lifetime

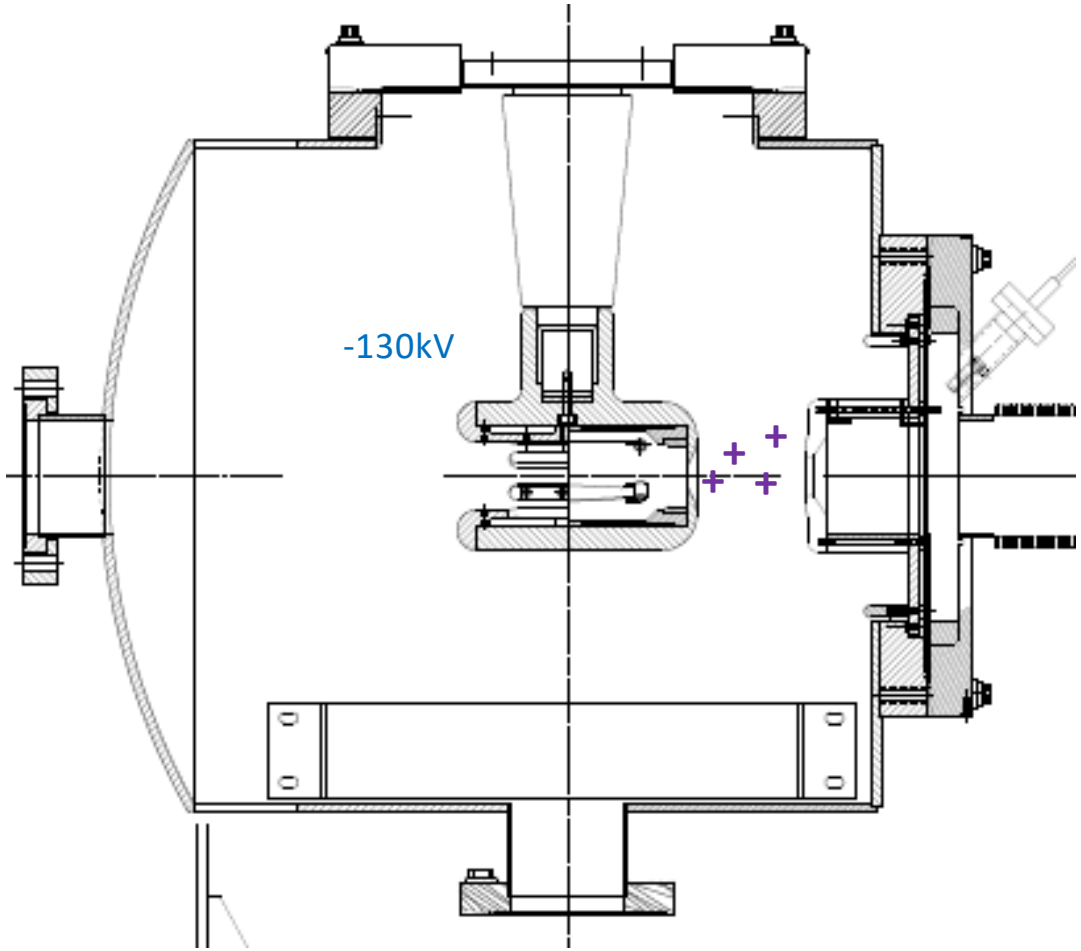


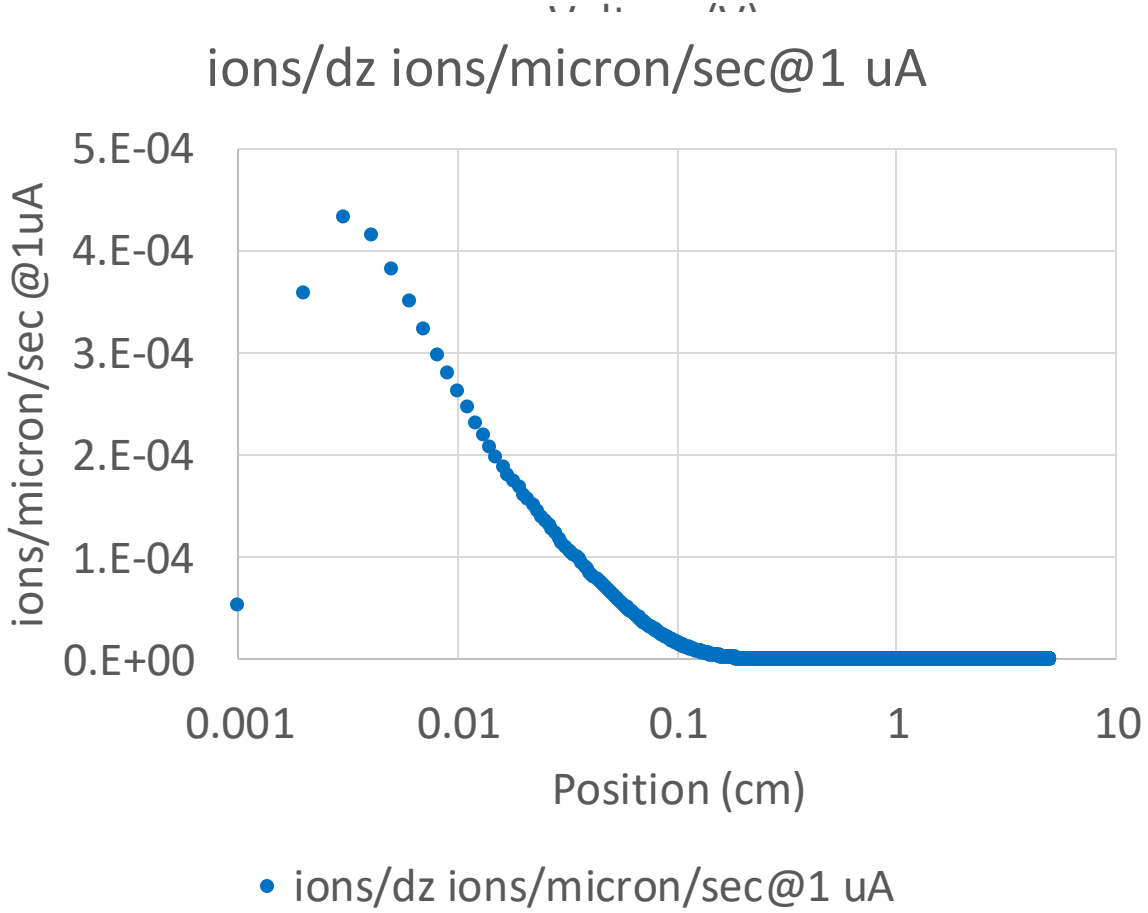
- Daily measurement of photocathode yield during beam operation
- Around Nov 2021, power supply for ion pump supplies malfunctioned
- Pressure increased (with no alarms)
- Lifetime fell by factor of 2
- Repair system, recover lifetime

Ion generation

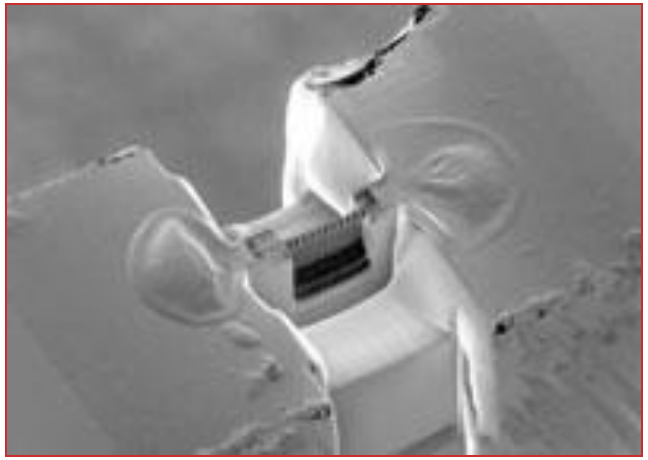


Ion generation in cathode anode gap



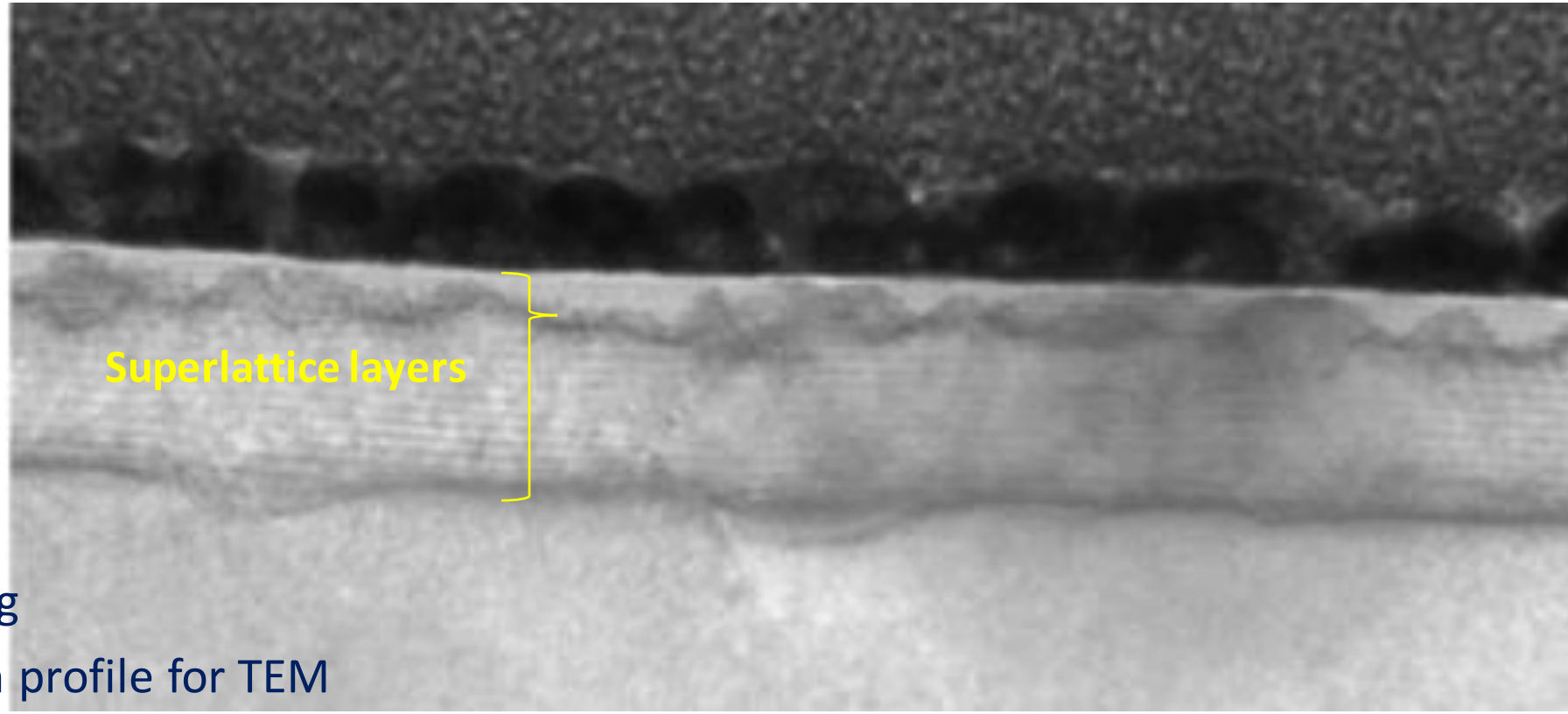


Photocathode damage analysis: Liftout FIB / TEM



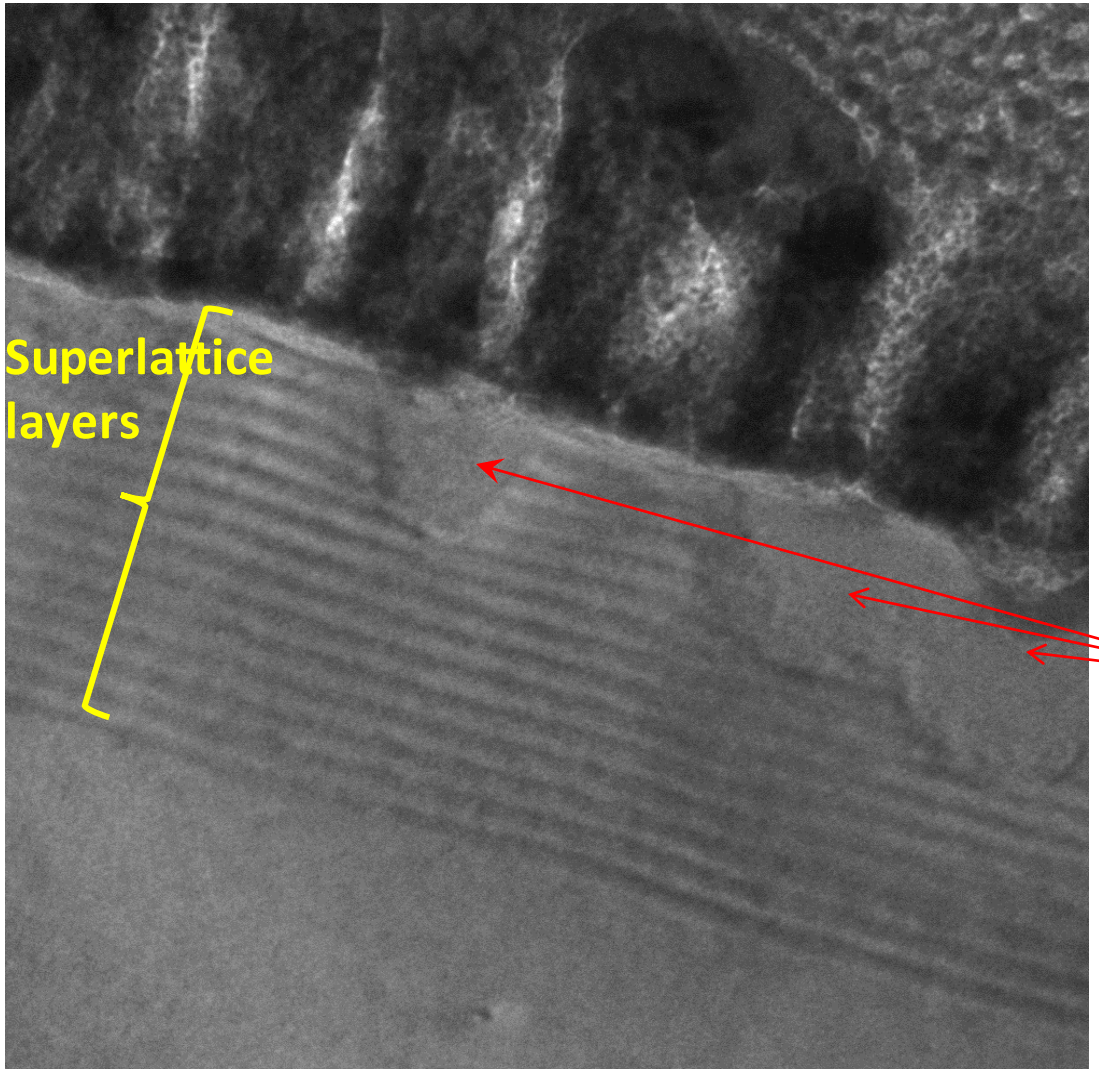
F.A.Steve et al., Surf. Interface Anal. **31**, 345, (2001).

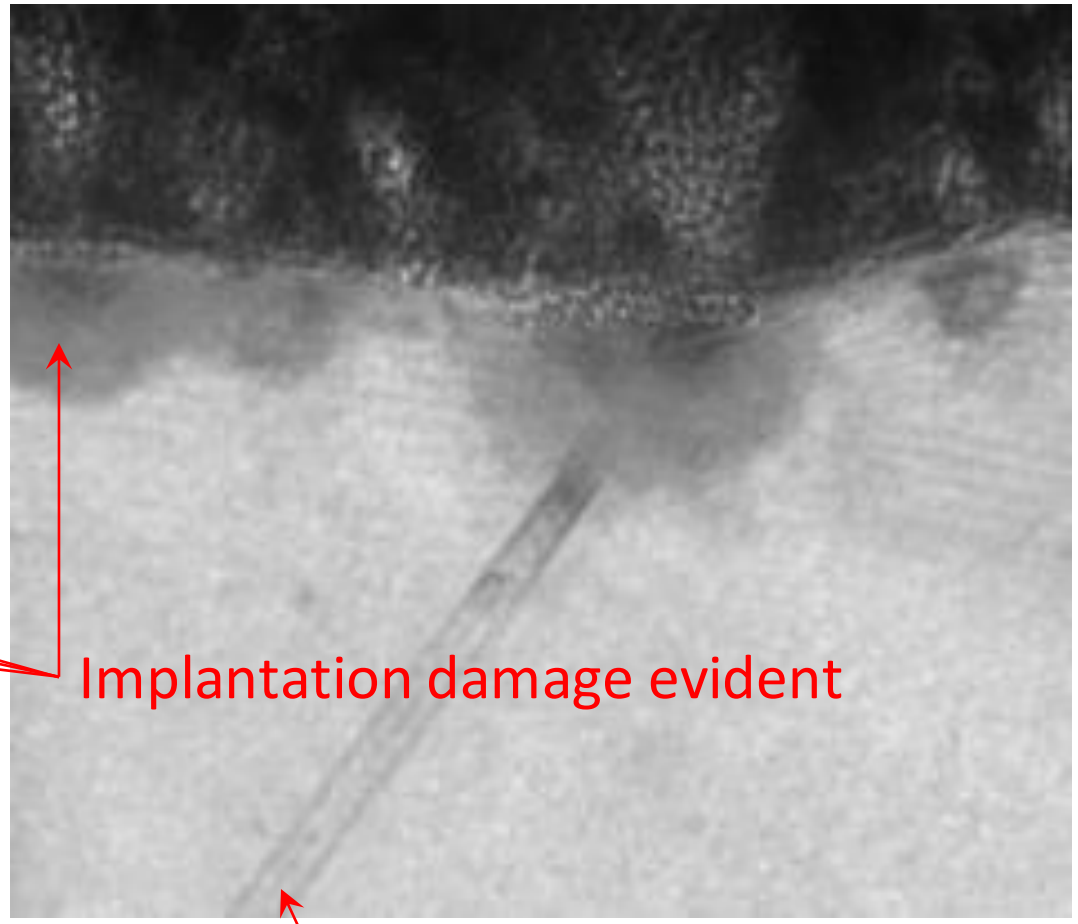
Unused sample



- Focused Ion Beam Milling
  - cross sectional depth profile for TEM
- Au/Pd evaporated, Pt sputtered to protect surface (misalignment = shadows)
- Uniform layers, no darkening

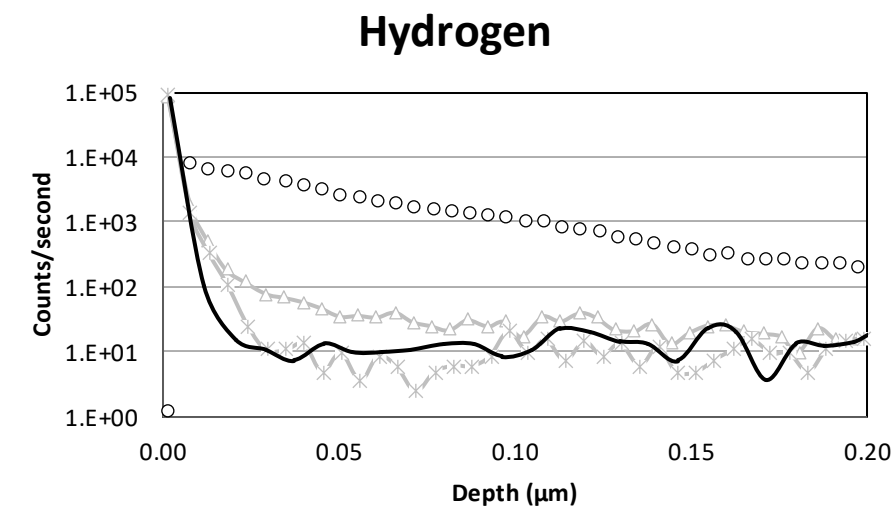
Photocathode damage imaging

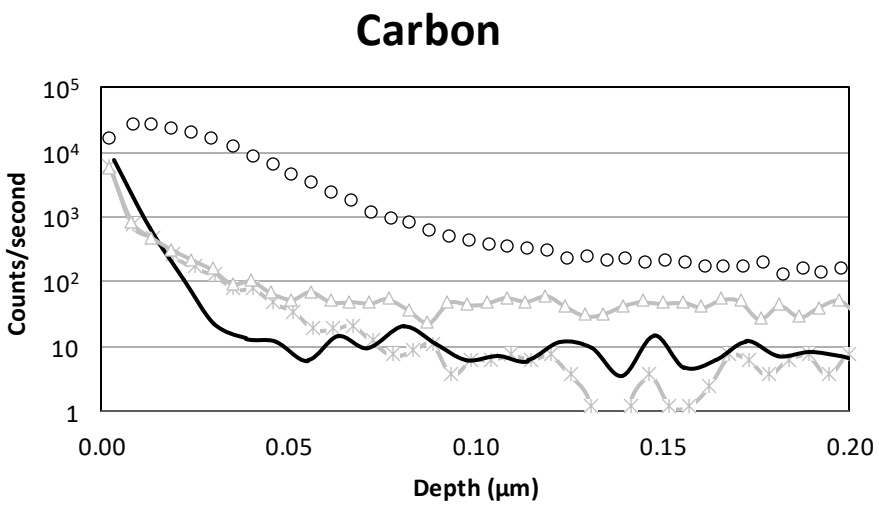


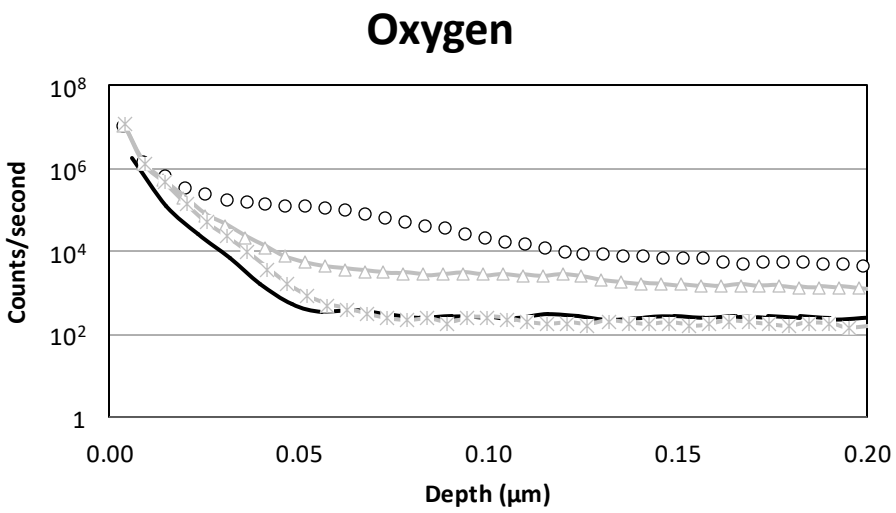


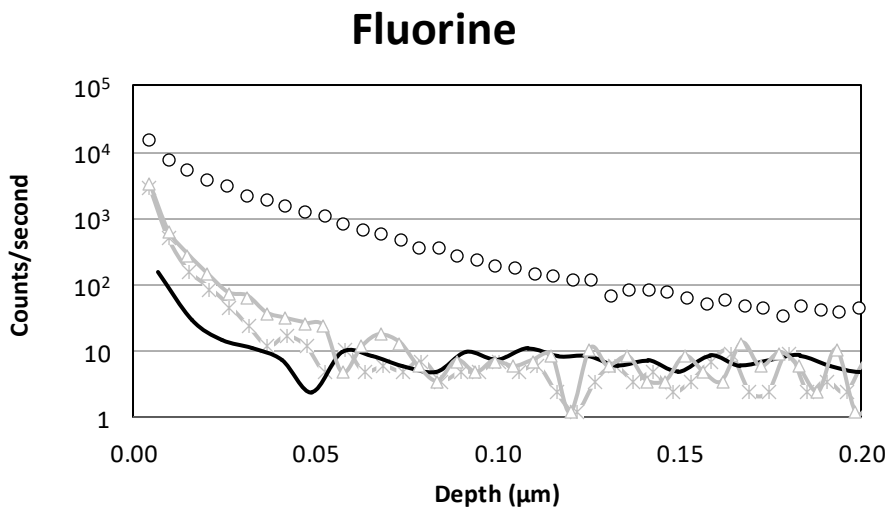
Crystal dislocations visible
Relaxation during heating?

Electrostatic center implantation: SIMS







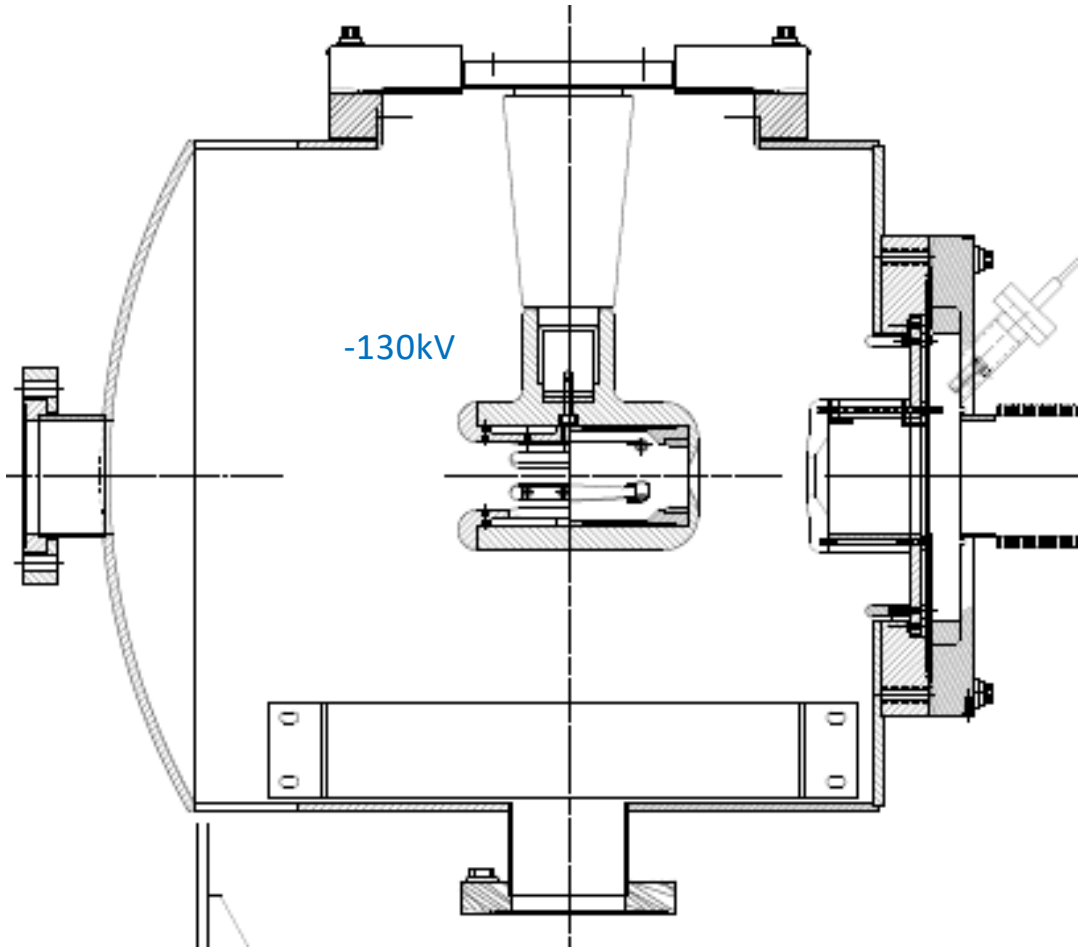


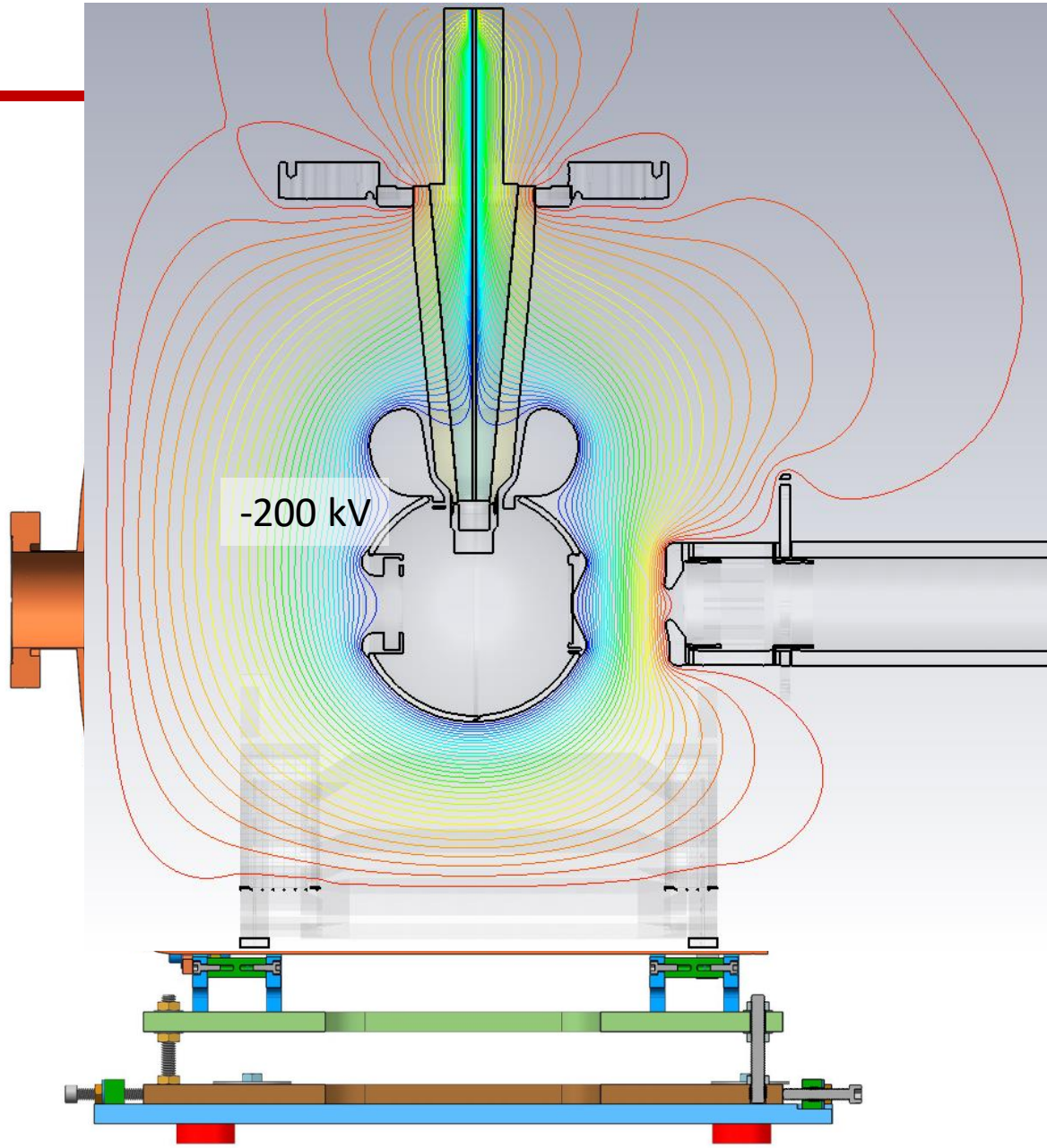
- Analysis shows expected UHV gas species + F
- Data from gun ~2004
  - NF_3 used in situ for activation

V. Shutthanandan, …, M.L. Stutzman, et al., Surface science analysis of GaAs photocathodes following sustained electron beam delivery, PRSTAB **15** 063501 (2012)

Jefferson Lab

Next generation JLab electron gun





Next Generation JLab High Voltage Chamber Design and Installation

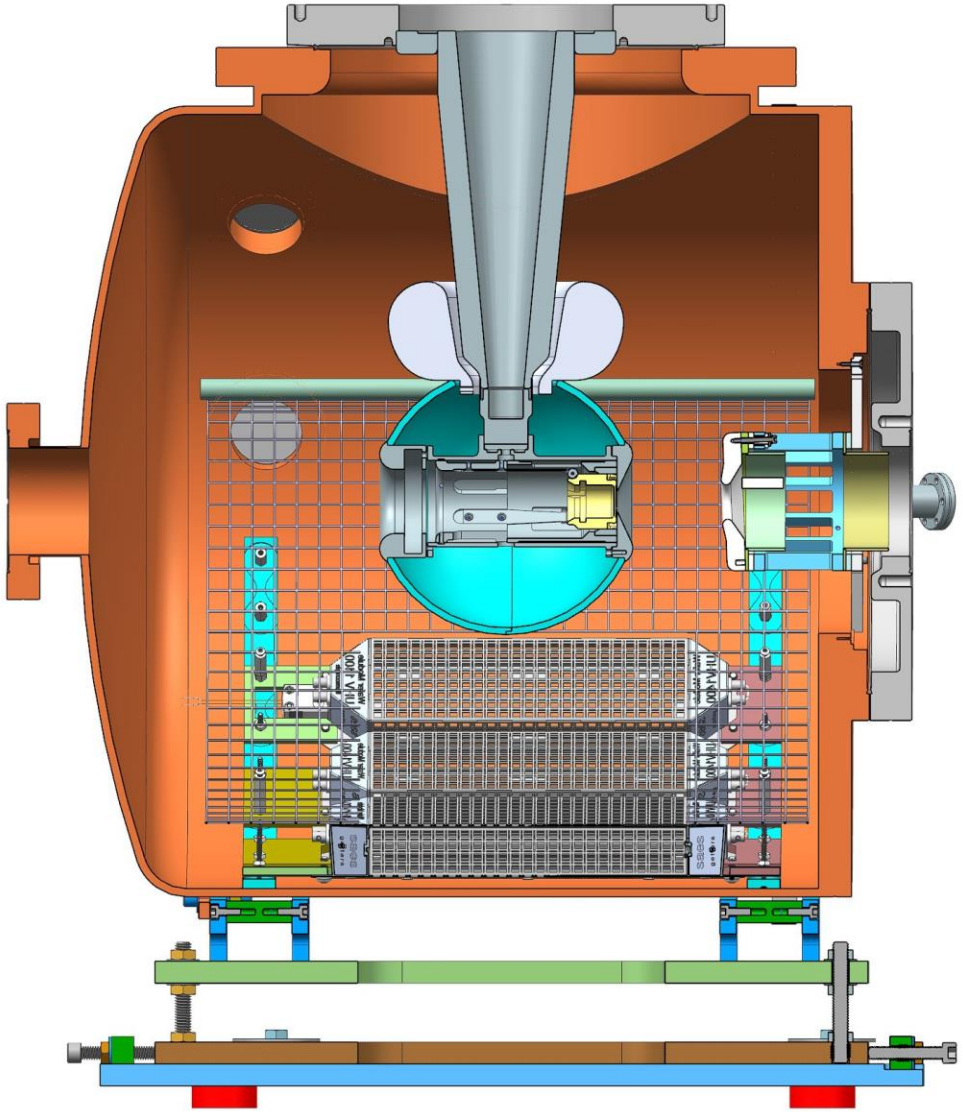
Vacuum system changes

- Improvement: ZAO NEG modules
- Larger diameter for high voltage
- Potential Issues
  - 304L instead of 316L stainless steel
  - Thick walls at top and front

Processing and Installation

- Heat treated at 400°C, heat treat electrode 950°C
- NEG coating
- In-situ bake, 48 hours at 250°C, activate NEGs fully

- Electrode optimization & cleanroom assembly
- Biased anode: repel beamline ions



C. Hernandez-Garcia et al., Phys. Rev. Accel. Beams **22**, 113401 (2019)

Outline

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  - Jefferson Lab Physics & Future facilities
  - Polarized Electrons
  - Polarized Source Lifetime
- JLab Vacuum research and characterization
  - Efforts to achieve XHV
  - Efforts to measure XHV
- Conclusions

Routes to Improved Vacuum: Heat treatment and coatings

Identical 304L chambers

- Bare steel
- TiN coating (9 µm): coating provides pump speed
- a-Si (SilcoGuard-1000®~900 nm): no better

Outgassing rates

- Accumulation with Spinning Rotor Gauge
- Multiple bakes
- $Q(T_{room})$ after each bake

"Effect of heat treatments and coatings on the outgassing rate of stainless steel chambers", J. Vac. Sci. Technol. A 32, 021604 (2014);

- Adopt heat treatments at 400°C
- Internal components without knife edges: 950°C 2 hours
- No benefit to base pressure with TiN, Silco

Next: Mild Steel outgassing and base pressure with gravitational wave observatory collaborations

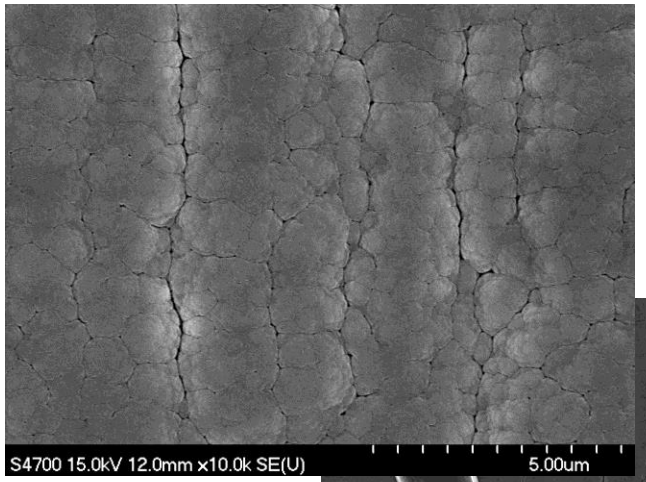
Wish list: Aluminum? What else?

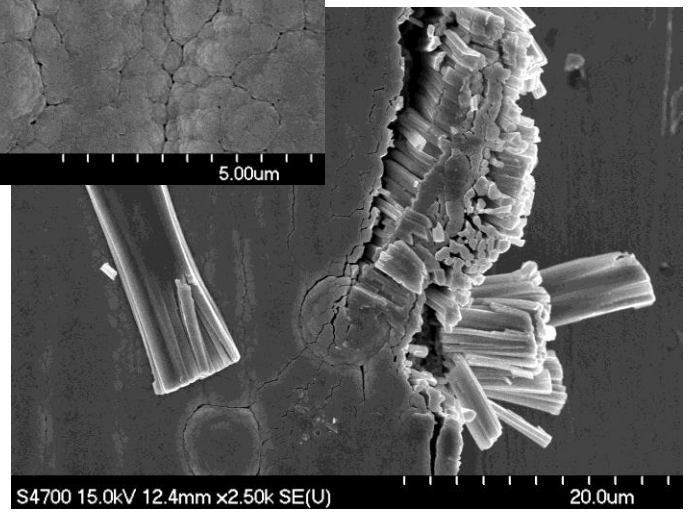
Jefferson Lab

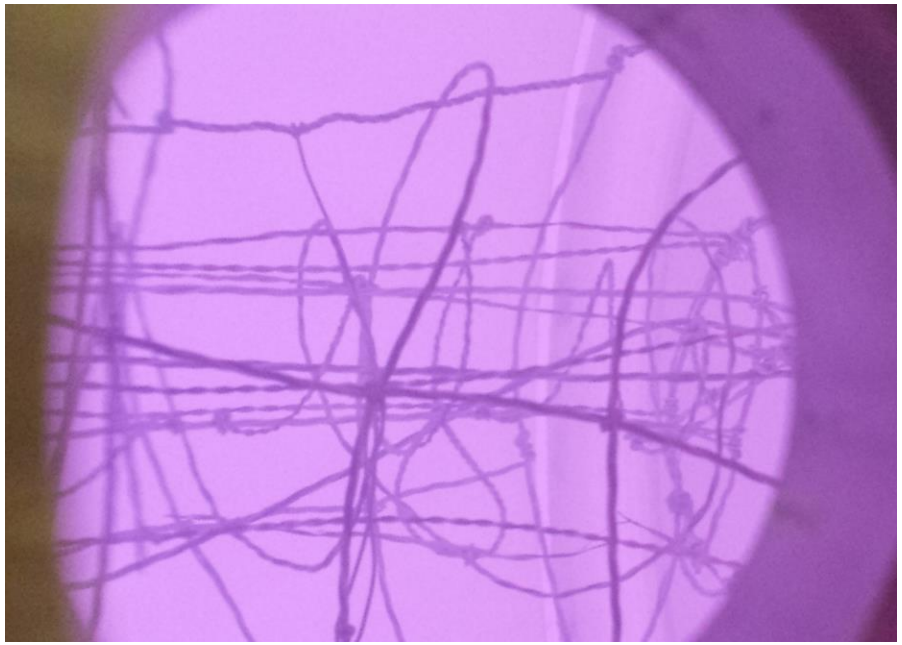
Routes to Improved Vacuum: NEG coating

JLab NEG coating gun tubes and chambers since ~2000

- DC sputtering, no magnetron, Ar or Kr gas
- Use “basket” of Ti, Zr and V wires twisted to reduce distance
- Dense columnar structure, flaking evident on test



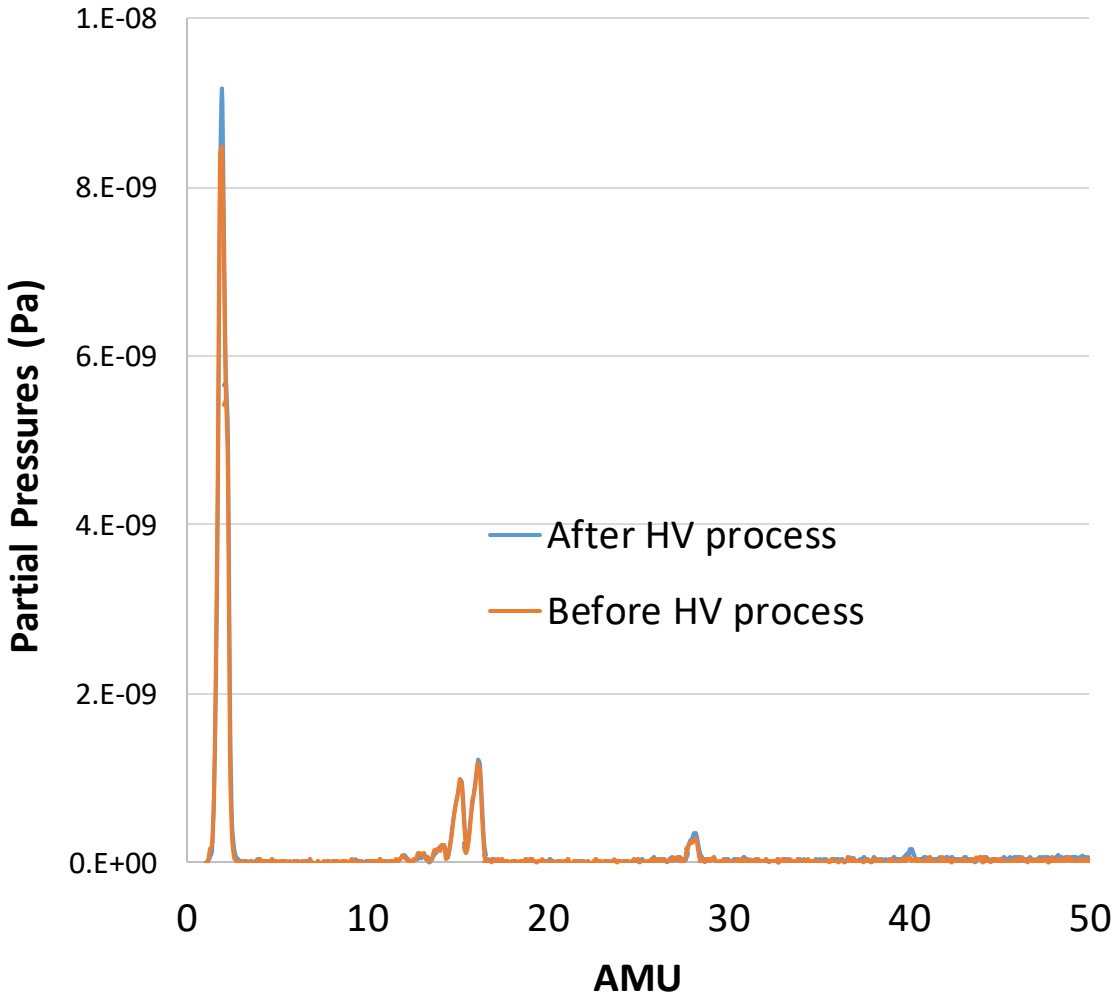


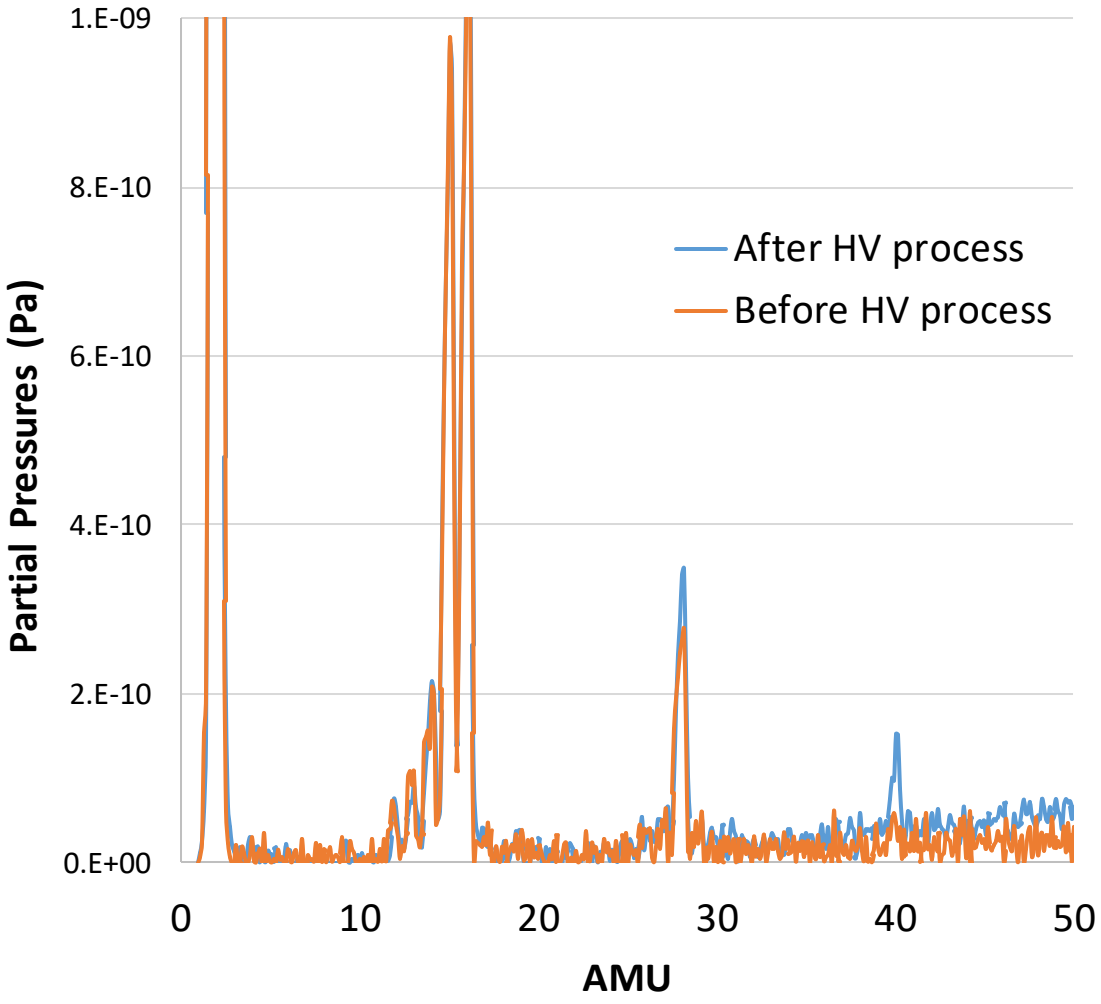


Potential drawbacks to NEG coating?

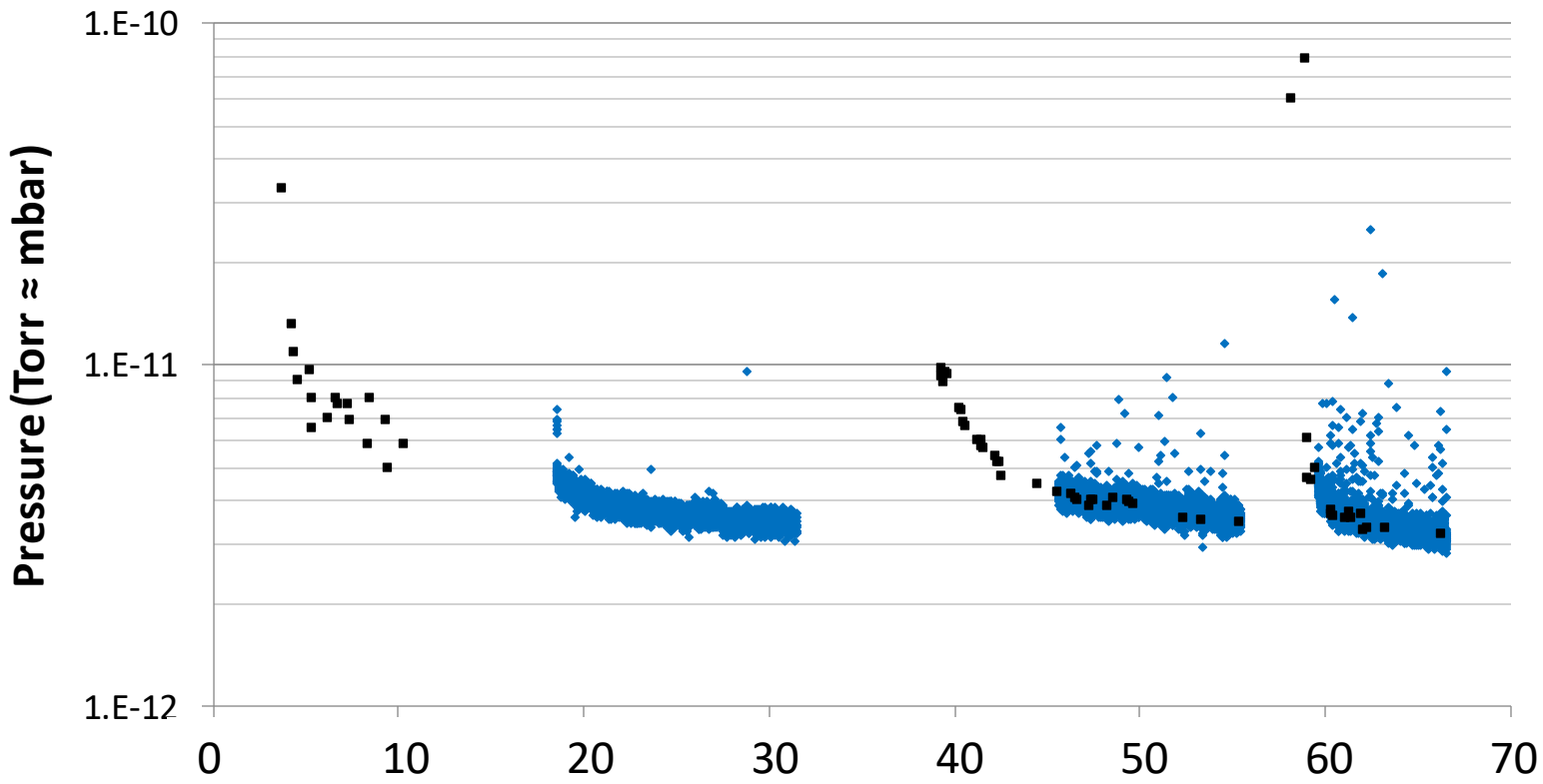
- 2 years at CEBAF with poor lifetime
- High voltage electrode removed
- Hazy spot – evidence of field emission
- Correlated with flaky NEG coating?

Does NEG Coating leads to Argon desorption during HV processing?





Pressure in NEG coated chamber: coating + 45 L/s ion pump



- Heat treat 400°C
- NEG coat
- install gauge, ion pump
- Bake
- Measure pressure

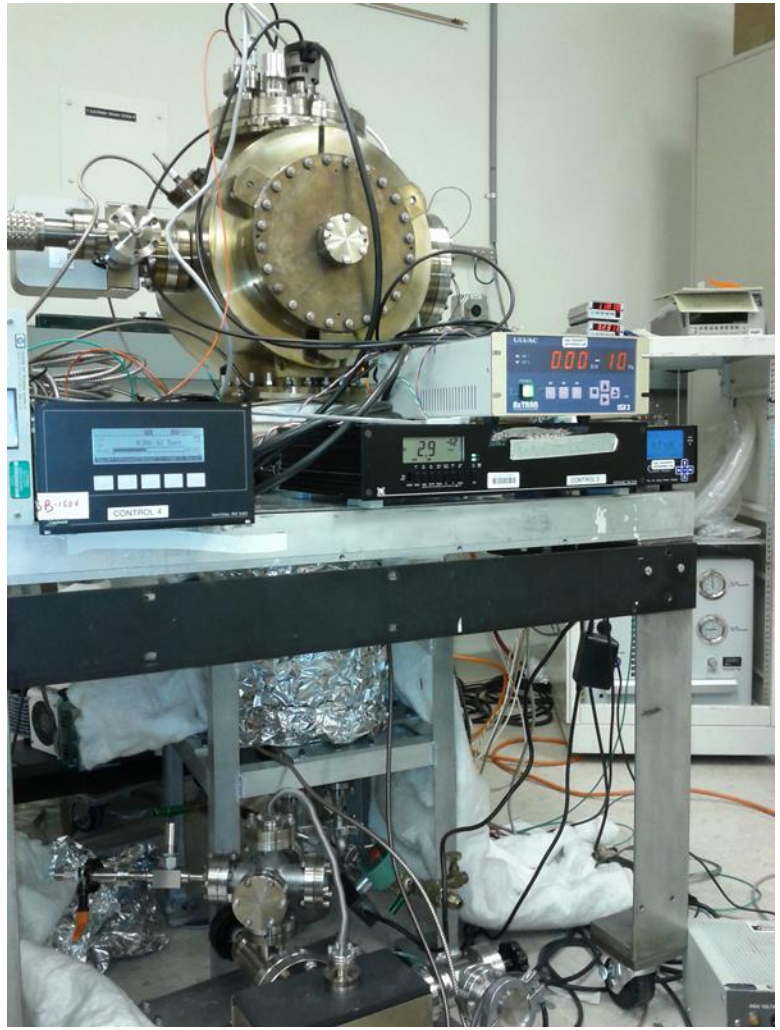
  - Approaching XHV with coating + Ion Pump

M.L. Stutzman et al., Journal of Vacuum Science & Technology A Vacuum Surfaces and Films **36** 2018.

Pressure measurement on system similar to electron gun

- 304L steel heat treated 400C ~10 days
  - Outgassing measured $1x10^{-13}$ $TorrLs^{-1}cm^{-2}$
    - =1.33x10-13 $mbarLs^{-1}cm^{-2}$
- NEG pumps
  - 4x WP950 + GP500 ≈ 2200 L/s
- XHV Gamma ion pump (45s)
- Volume= 40L and area = 8000 cm2

- Antipated pressure
  - 4×10^{-13} Torr = 5.3×10^{-11} Pa



Chamber with NEG/Ion pumps

Anticipated pressure

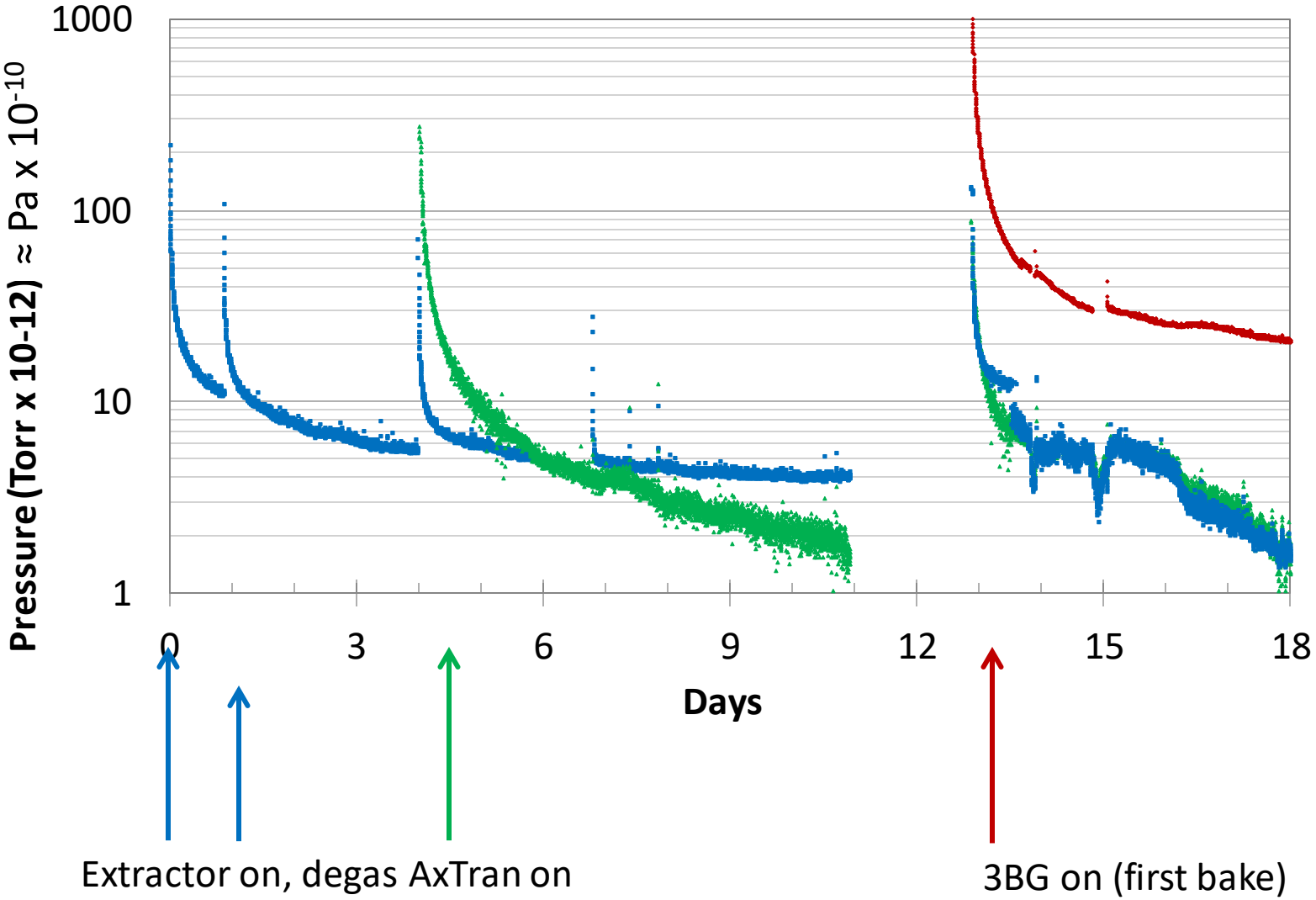
5×10^{-11} Pa

Lowest Measured Pressures (Pa)

Extractor	3×10^{-10}
Axtran	2×10^{-10}
3BG	8×10^{-10}

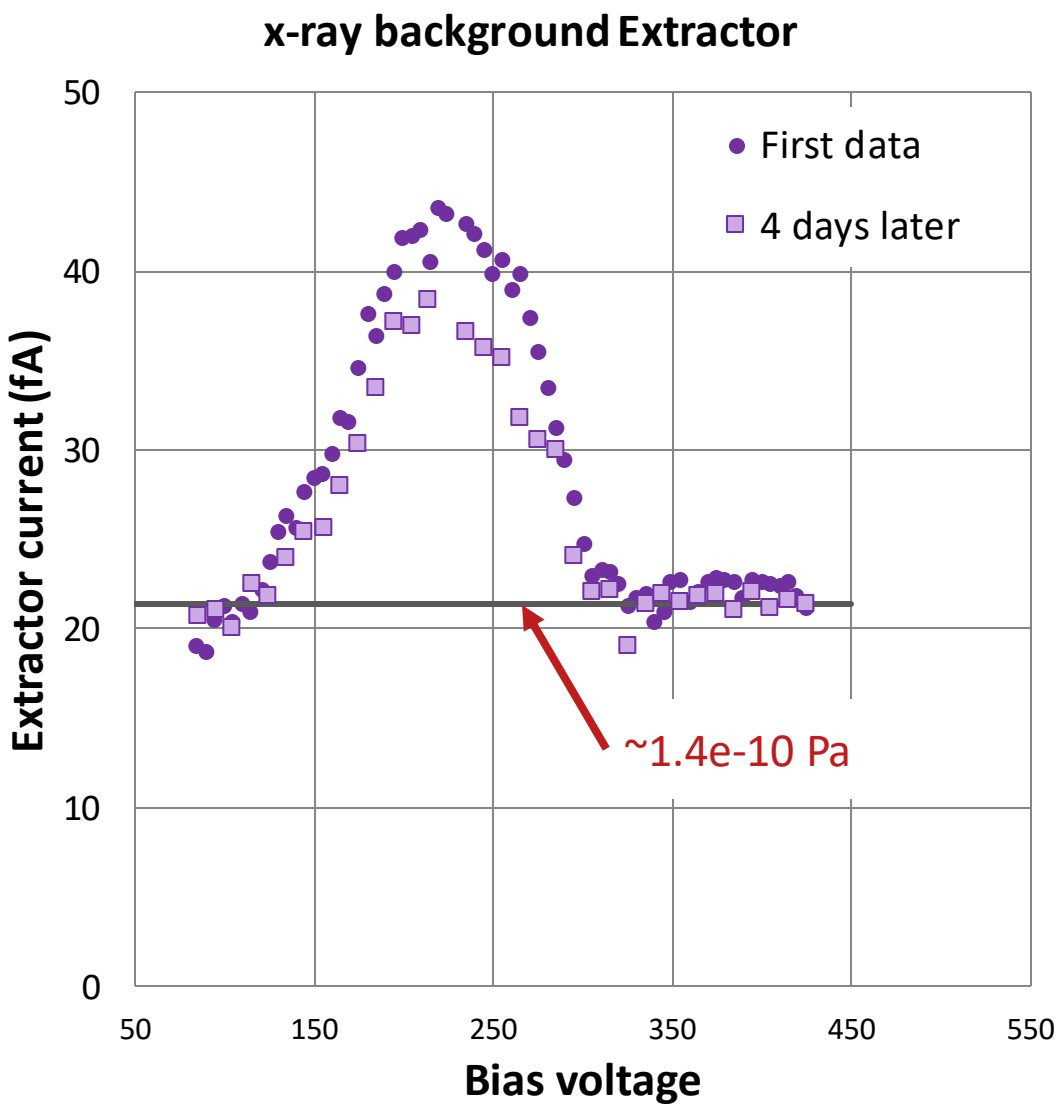
What Limits Pressure

- Outgassing
- Pumping
- Gauges



Jefferson Lab

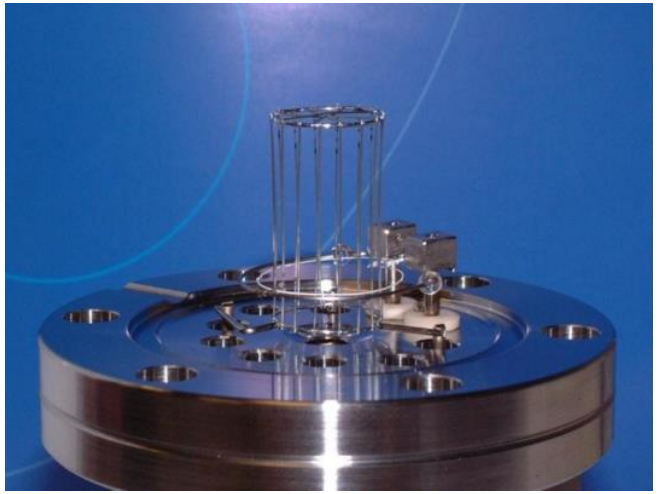
Approaching Gauge x-ray limit



X-ray limit measurements

- Add jumpers to each extractor gauge pin
- Electrometer for current measurement
- Control repeller with variable voltage supply
- Measure gauge current/pressure vs. reflector voltage

  - When V ≥ 325V, all signal from background
  - Background ~ 50% of signal

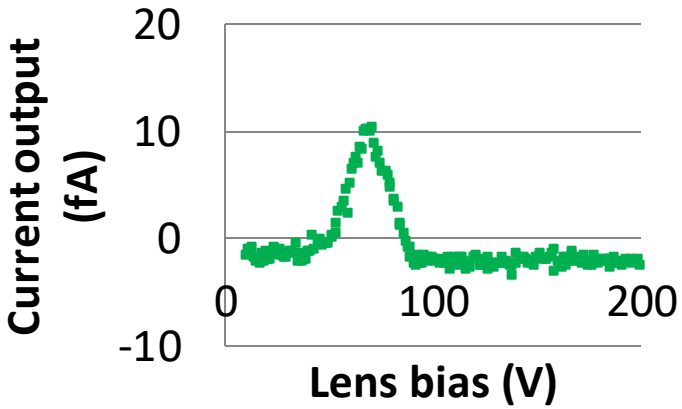


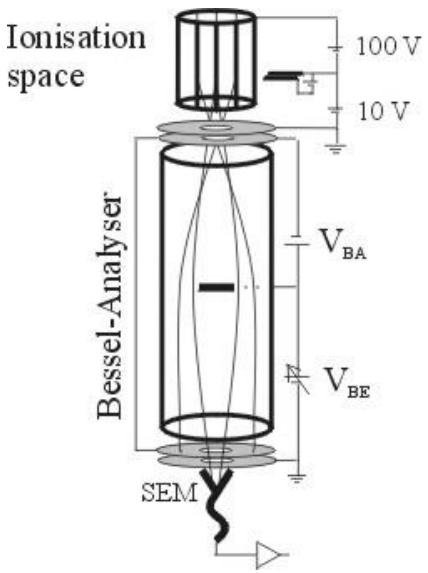
Next Generation XHV gauges: x-ray background eliminated

- AxTran gauge (Axial Transmission)
  - Bessel box energy discrimination
  - electron multiplier to assist in low current measurements

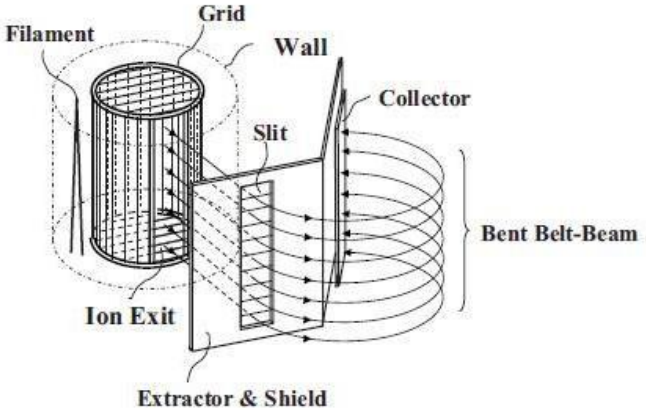
- Watanabe 3BG (Bent Belt Beam Gauge)
  - 230° deflector BeCu housing
  - JVSTA **28**, 486 (2010)

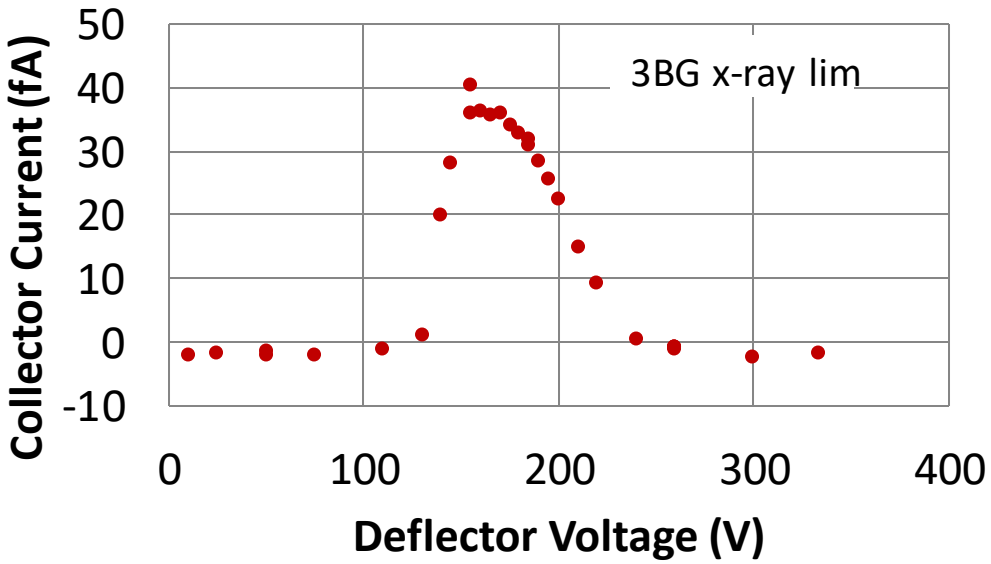
ULVac AxTran



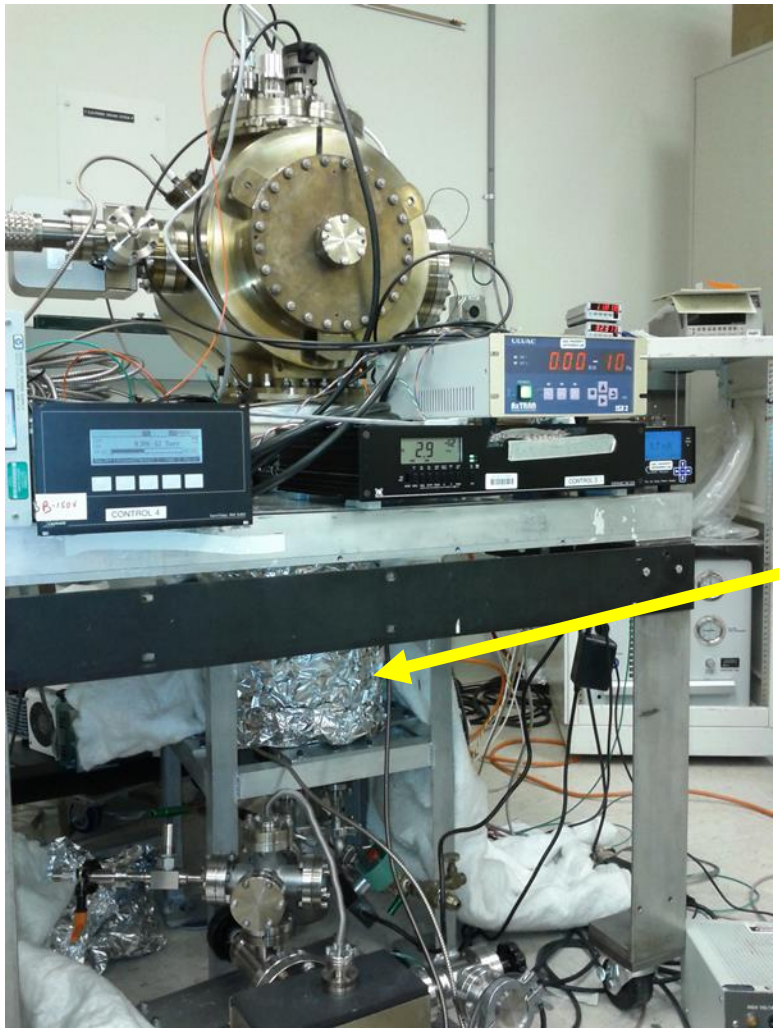


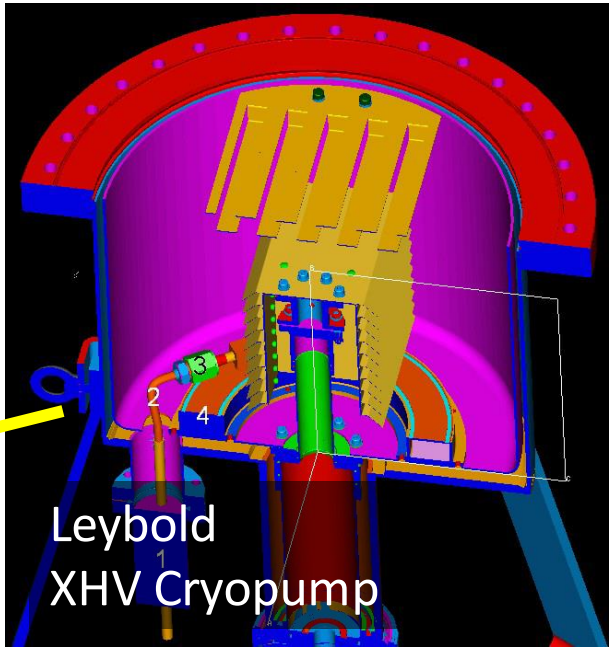
Watanabe 3BG





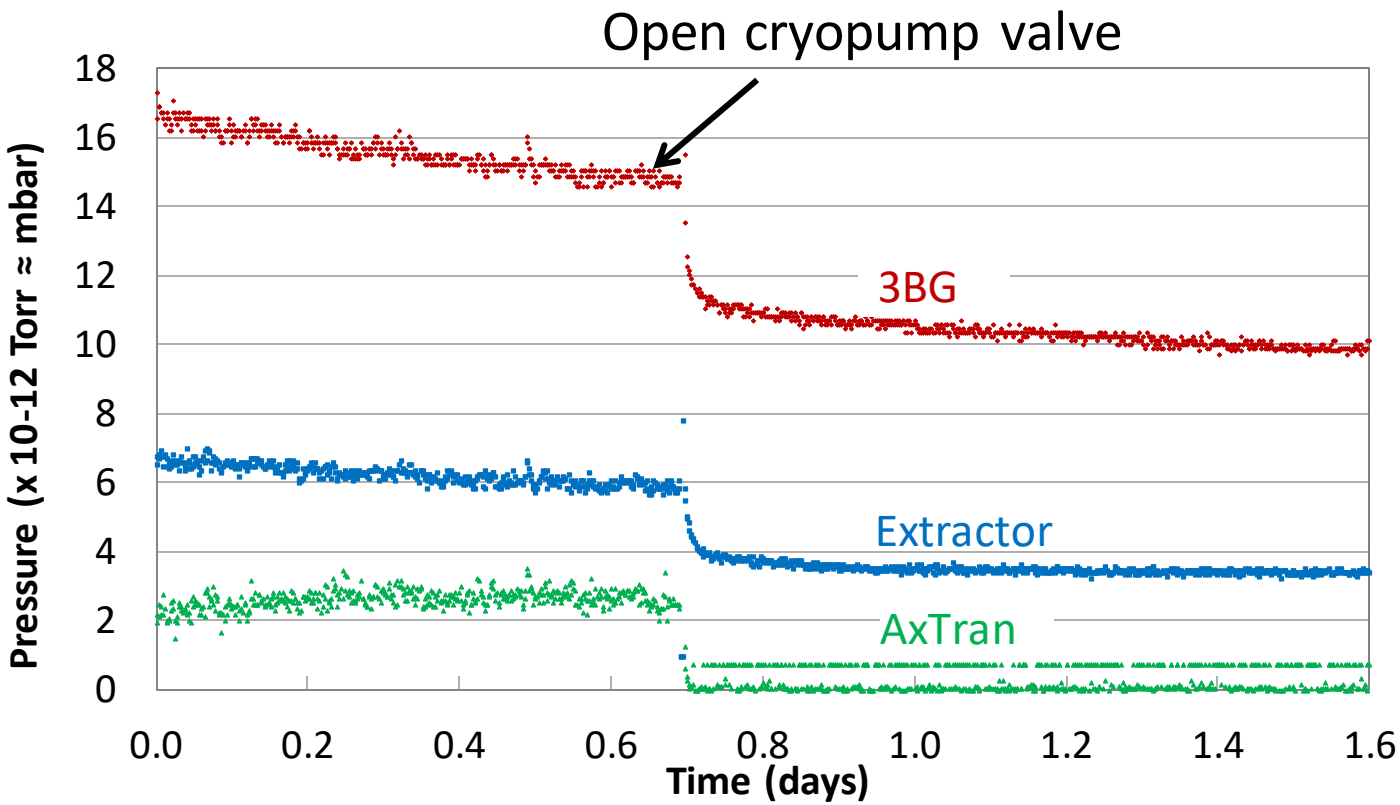
Explorations of pumping improvements: XHV cryopump

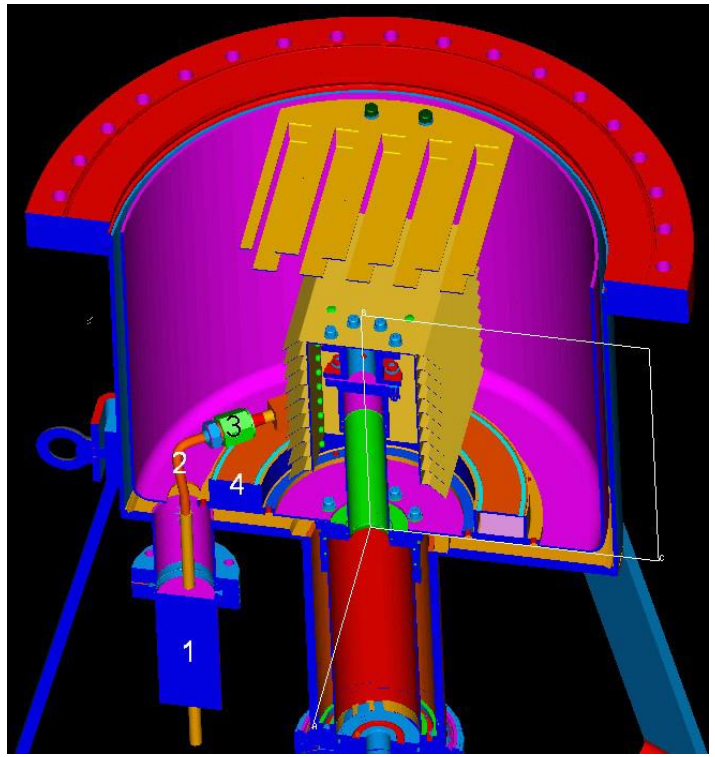




- 10” all metal gate valve
- Bellows (12” to 10” adapter)
- Cryopump
  - Overboard bake ion pump
  - Compressor
  - ColdHead
  - LN_2 chill line/ chill line evacuation system

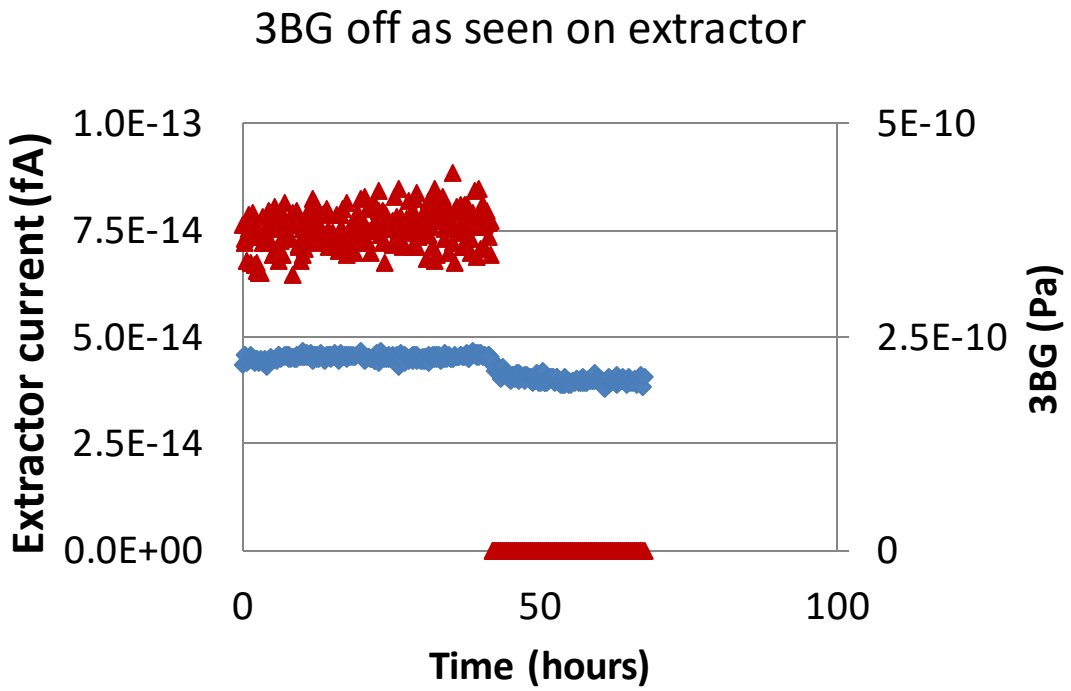
Recorded pressure opening valve to cryopump

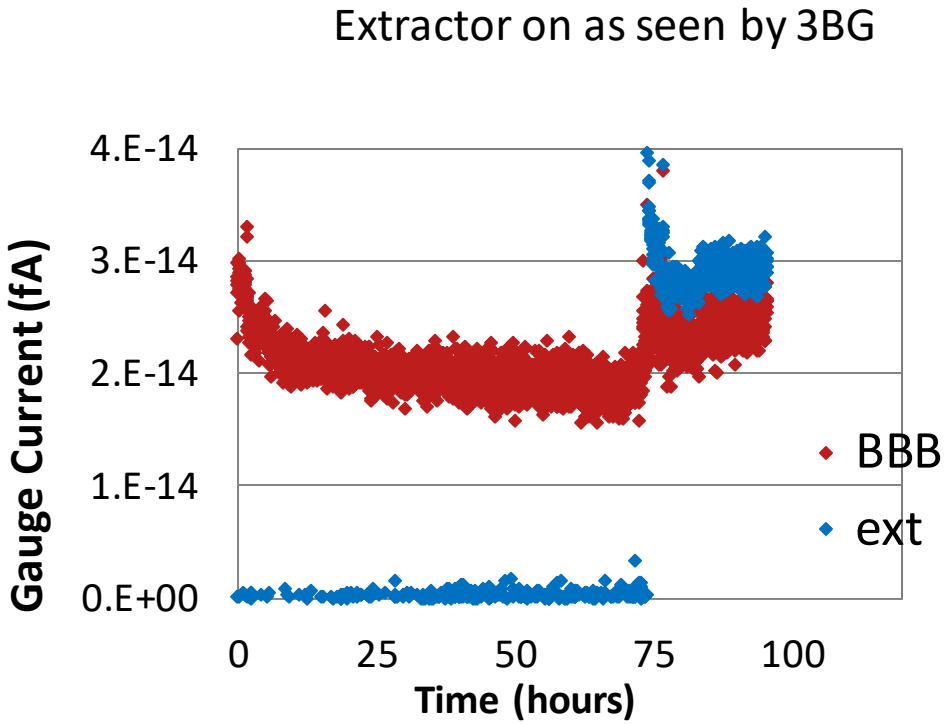




- All gauges sensitive to pressure change
- Cryopump reduces pressure
  - Cryopump infrastructure & vibration incompatible with electron gun

Additional Background characterized: gauge heating





Measure pressure rise turning on gauge using second gauge

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Conclusions

- Polarized electrons enable high-impact physics programs
- High-P Photocathodes require XHV
- Gauge effects significant for XHV

- Lifetime depends strongly on vacuum
  - Next generation -> longer lifetimes

- Measuring XHV accurately required for advances