GaAs-based Spin-polarized photocathode research at Cornell

Matthew Andorf

The Bright Beams Lab

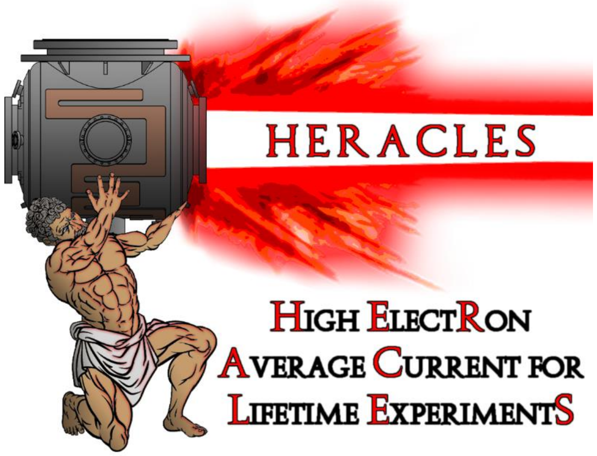
Acknowledgements to:

NP-DOE DE-SC0023517

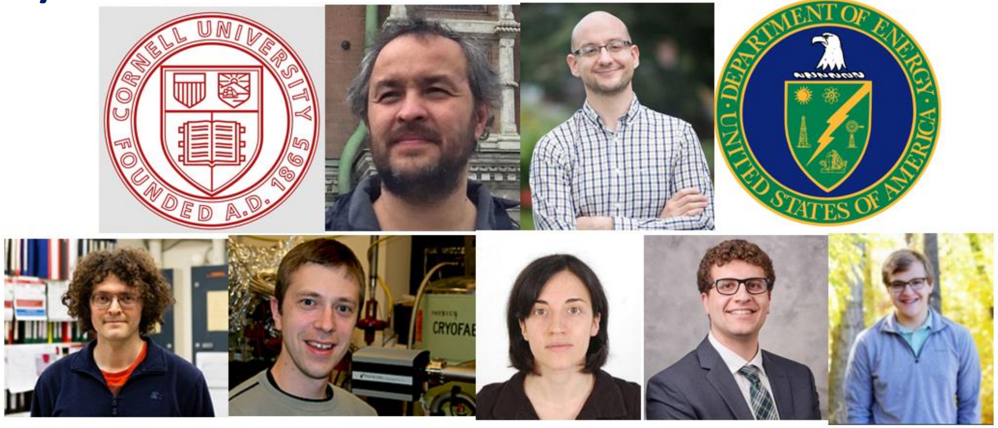
HEP-DOE DE-SC0021002

NFS PHY-1549132 CBB

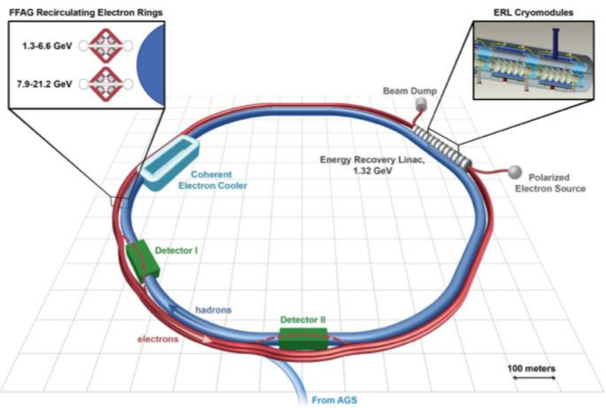
- Ivan Bazarov
- Jared Maxson
- Adam Bartnik
- Alice Galdi (now @U. of Salerno)
- **Sam Levenson (graduate student)**
- **Mark Reamon (undergrad)**

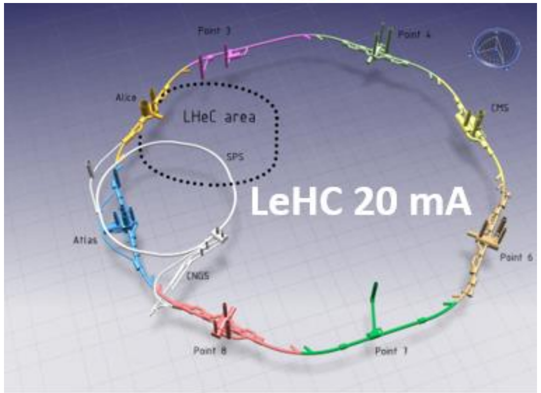


The Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center



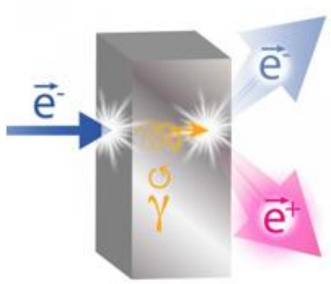
High current and spin polarization



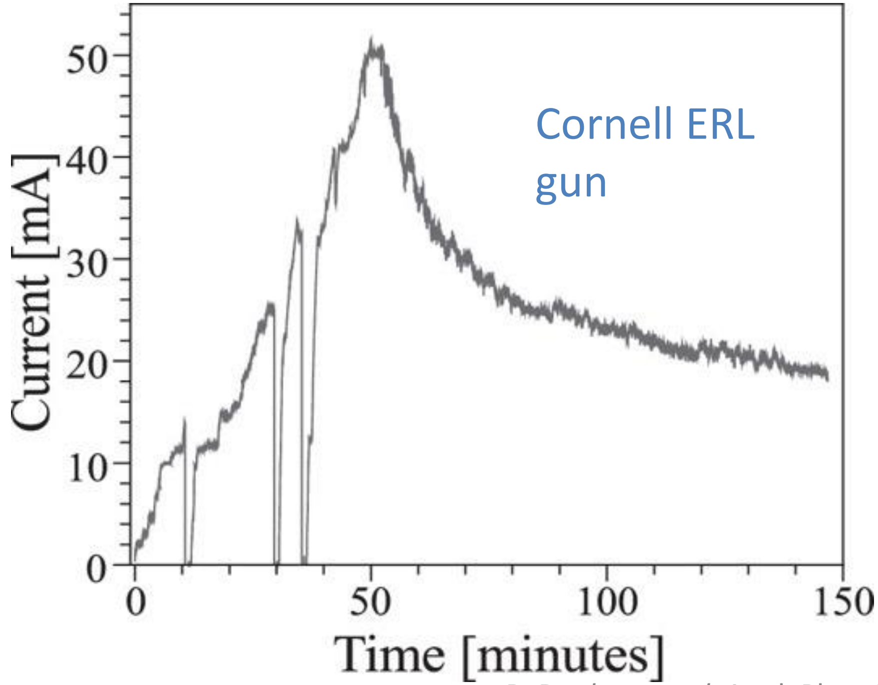


Several mA

PEPPo



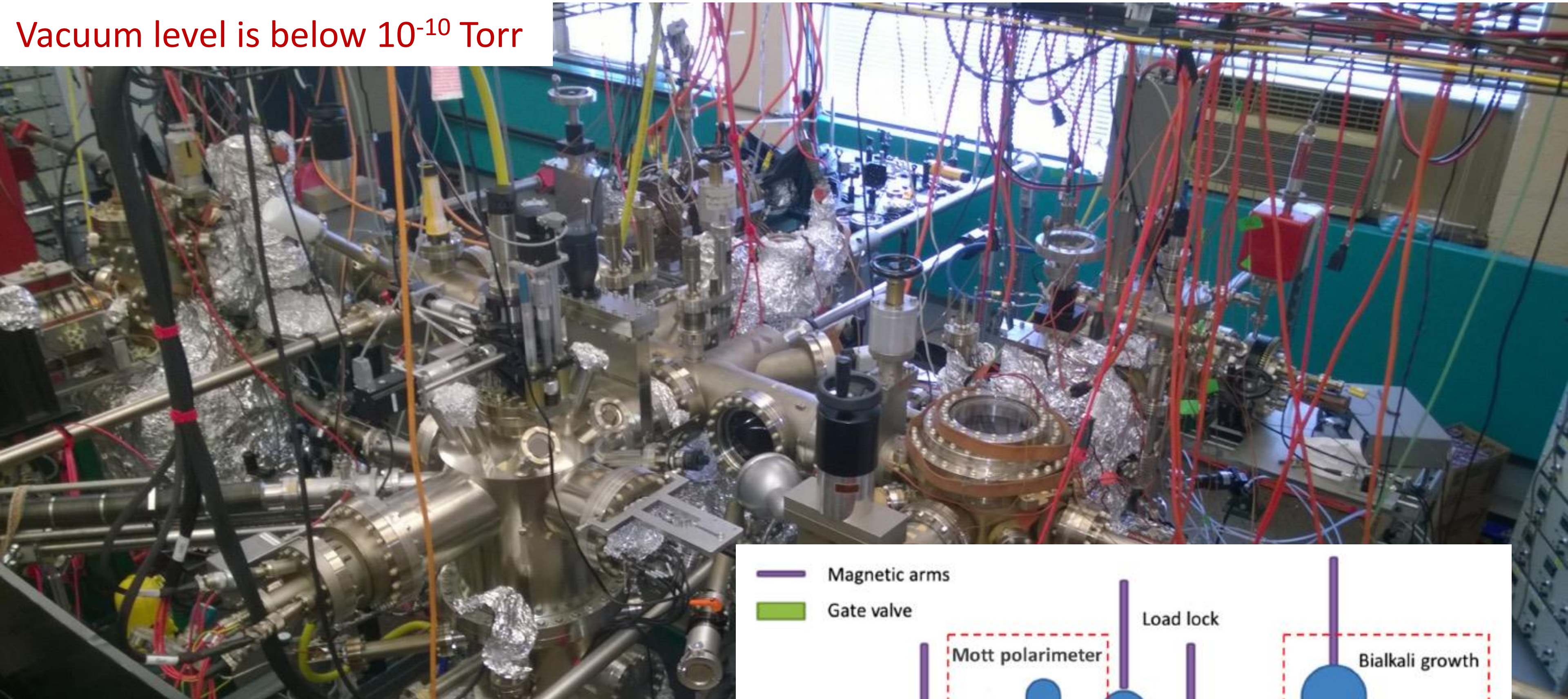
- One of the remaining challenges for photocathodes is a robust, spin-polarized electron source
- GaAs is by far the most studied spin-polarized electron source
- **Charge lifetime**: The amount of current extracted before the QE degrades by 1/e
  - 1000 C is state of the art→6 hours at 50 ma!

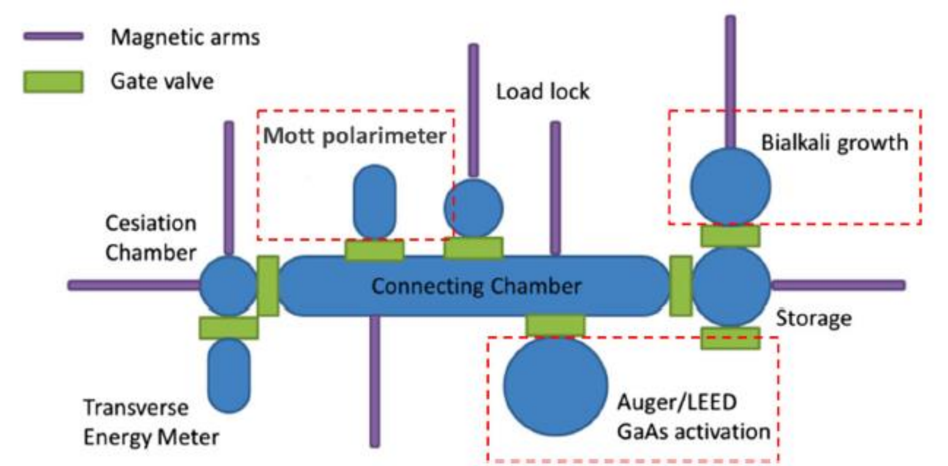


B. Dunham et al, Appl. Phys. Lett. **102**, 034105 (2013)

Cornell Photocathode Lab

Vacuum level is below 10^{-10} Torr

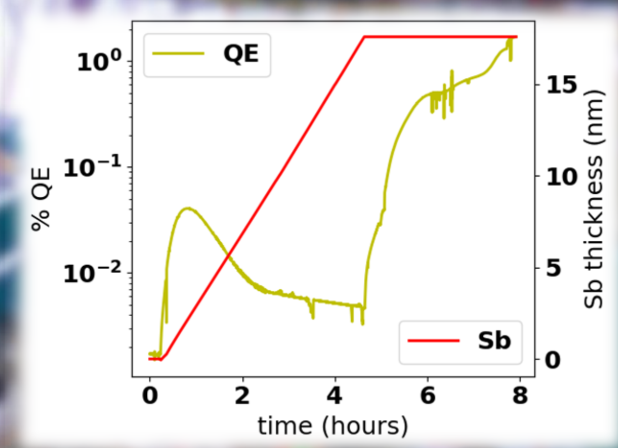


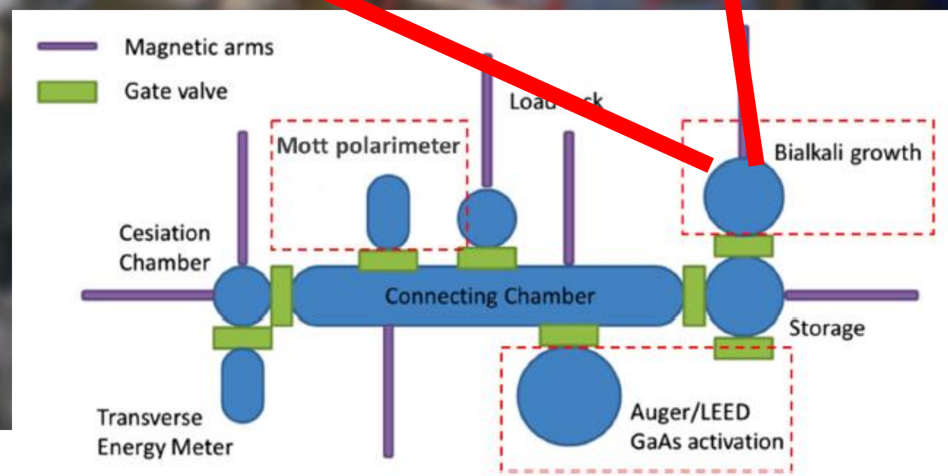


Cornell Photocathode Lab

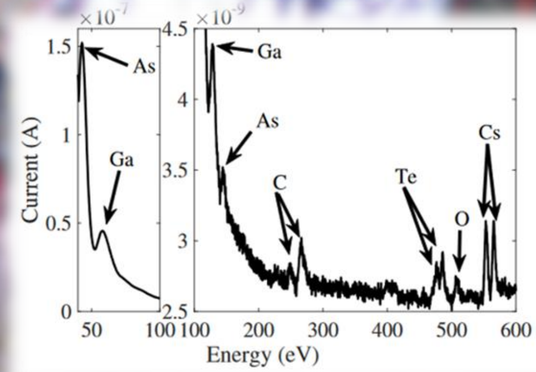
Bialkali growth chamber

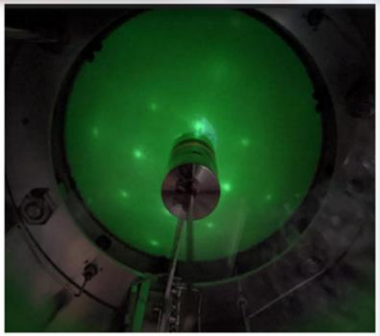
- Cs,Sb,Te sources+O_2 leak valve, thermally regulated with pneumatic valve control
- Quartz microbalance (QMB) for deposition monitoring
- Substrate heater





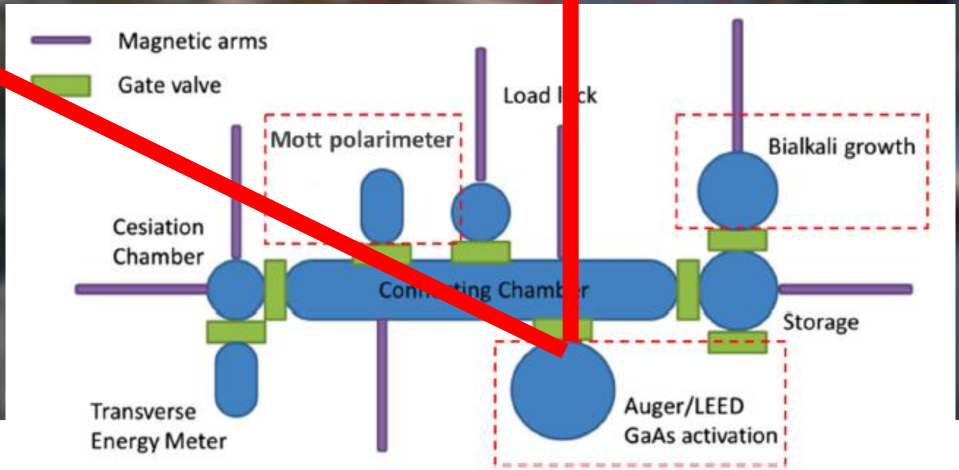
Cornell Photocathode Lab



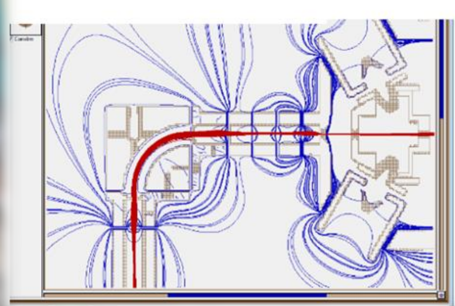


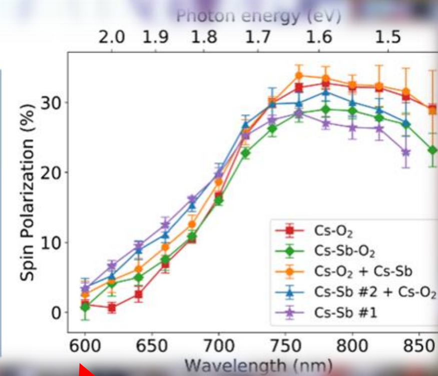
AUGER Chamber

- Auger Electron Spectroscopy-To characterize surface chemistry
- Low Energy Electron Diffraction-Chararacterize surface crystallinity
- Cs, O_2 leak valve.
- Insulated, bias-able cathode holder



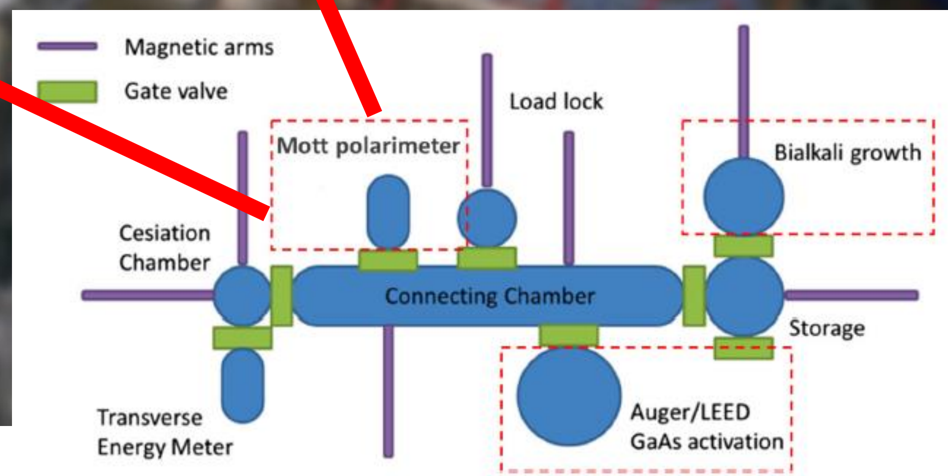
Cornell Photocathode Lab





Mott polarimeter

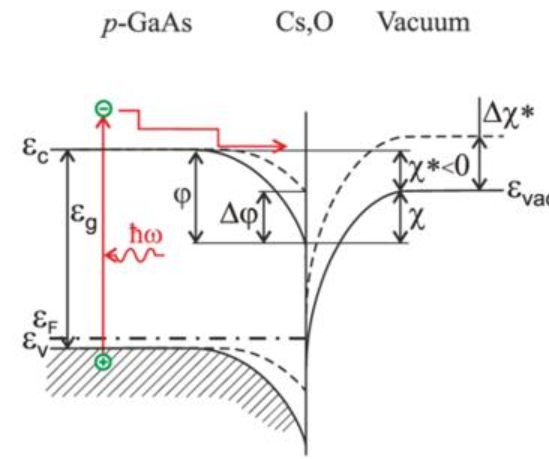
- 20 keV target bias + Einzel lens beamline
- Tungsten scattering target
- Measure spin-polarization

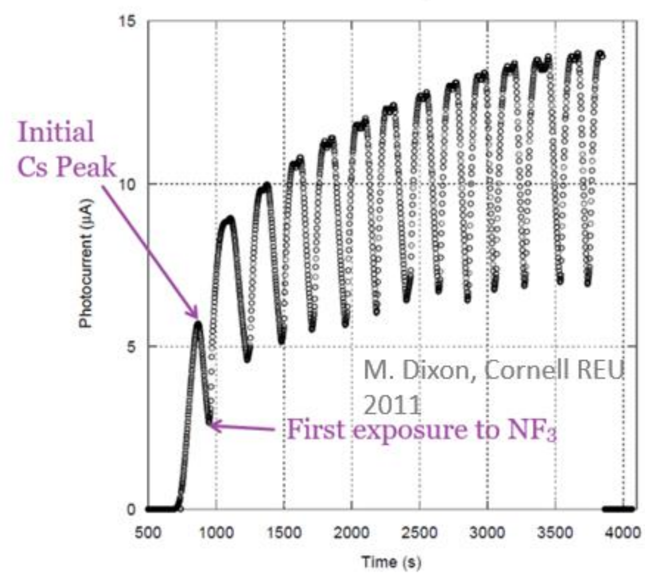


Negative Electron Affinity activation of GaAs

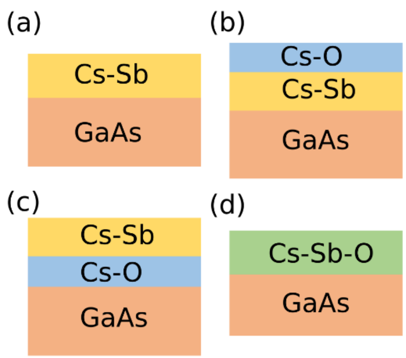
- For high QE, GaAs is "activated" to Negative Electron Affinity (NEA)
  - NEA means the bulk conduction band minimum is larger than the vacuum level
- NEA is typically achieved by depositing a monolayer of Cs-Oxidant onto the GaAs surface can be done by:
  - **Co-deposition**: Cs is deposited until QE peaks, at which point an oxidant is leaked while Cs source remains on
  - **Yo-yo method**: the cathode is over cesiated at which point the cesium source turns off. It is then exposed to an oxidant until the QE peaks, the oxidant is then turned off and cesium source back on. The cycle is repeated numerous times.
- Either O_2 and NF_3 can be used for an oxidant
- Problem: A monolayer is a fragile thing!
  - Chemical poisoning: Interaction with residual gas
  - Ion back bombardment: residual gas is ionized and accelerated towards the cathode

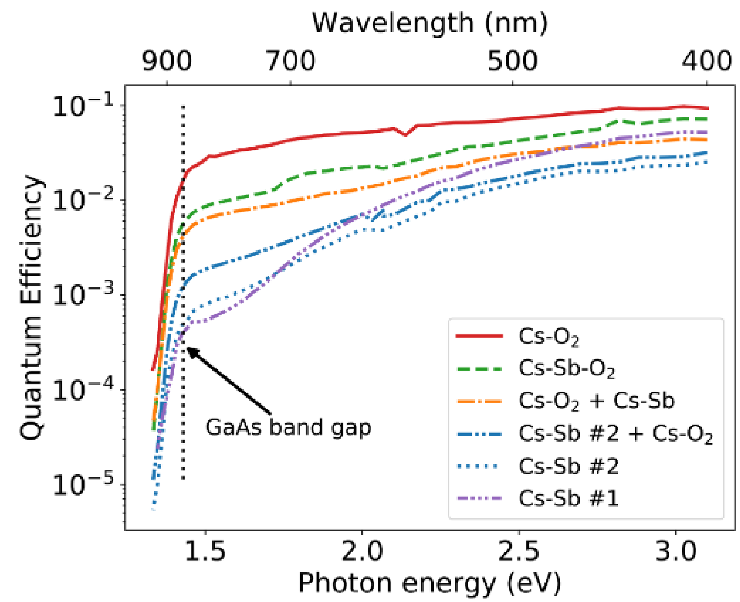
V. Khoroshilov at al. (2020). Journal of Physics: Conference Series. **1482**. 012013 DOI: 10.1088/1742-6596/1482/1/012013.



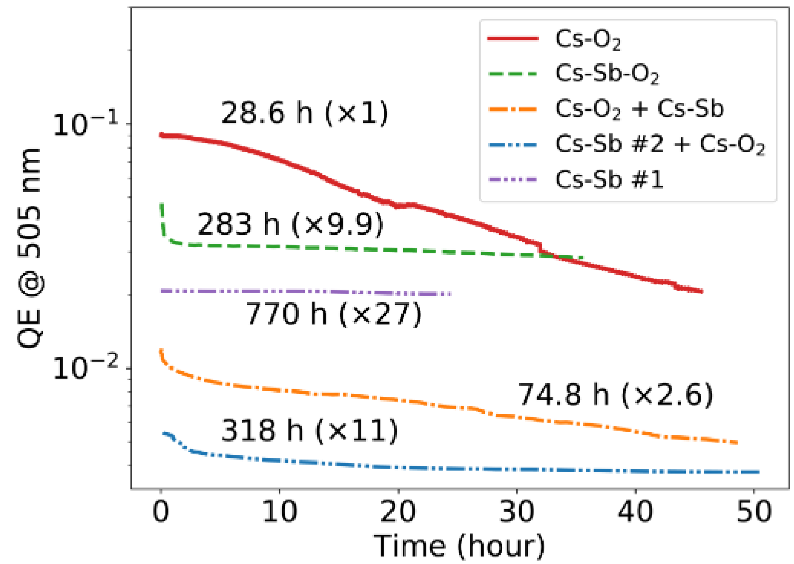


Sb-based recipes





- Various activation recipes were compared to Cs-O_2
  - Overall, Cs-O_2 produced the highest QE while Cs-Sb had the worse
  - Including O_2 in the activation improved QE of Sb containing recipes
- The QE was monitored over time to determine robustness
  - All Sb activations outperformed pure Cs-O_2 and pure Cs-Sb had the longest lifetime.
- **Co-deposition of Cs-Sb-O finds a happy middle ground**
  - 10x Improved lifetime over Cs-O activation.
  - 10x improved QE over Cs-Sb activation at bandgap

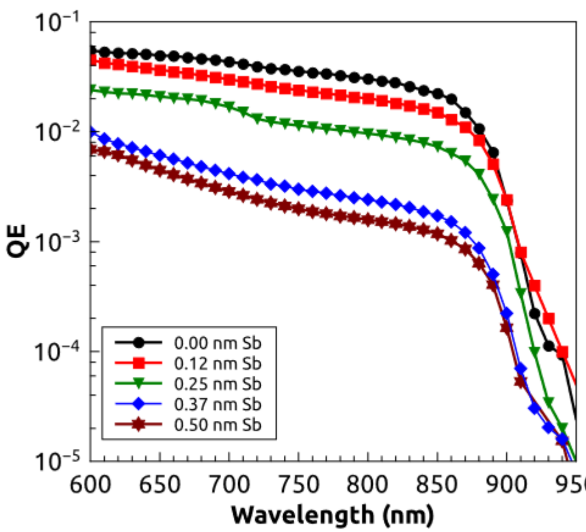


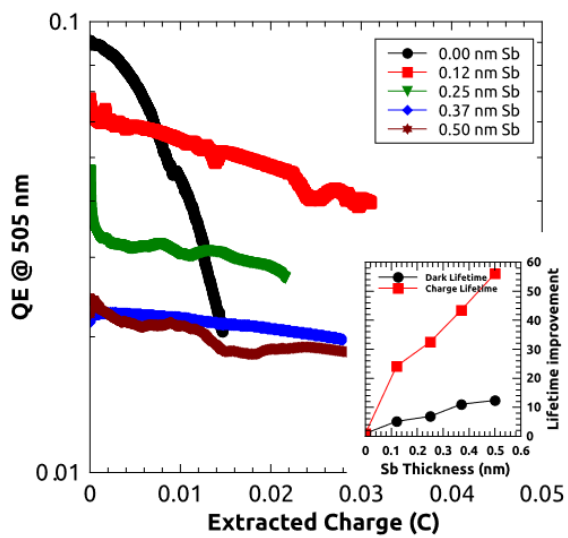
Sb-based activations-trade offs

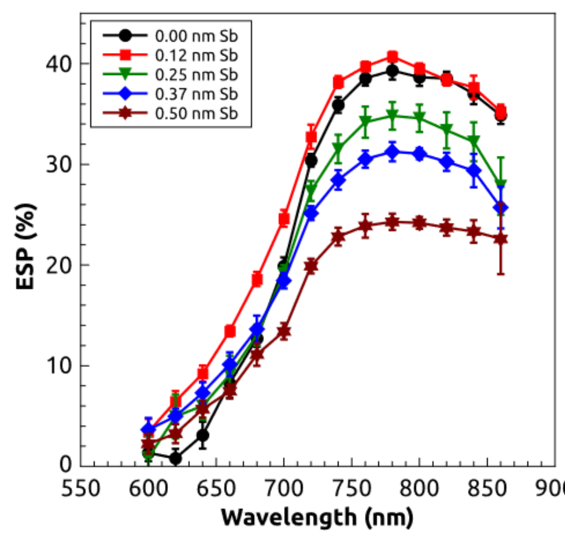
Cs-O-Sb co-deposition recipe was further refined through scanning the Sb layer thickness:

- QE and electron spin-polarization decrease with Sb layer thickness
- **0.12 nm layer results in only a small QE decrease while preserving max spin-polarization!**

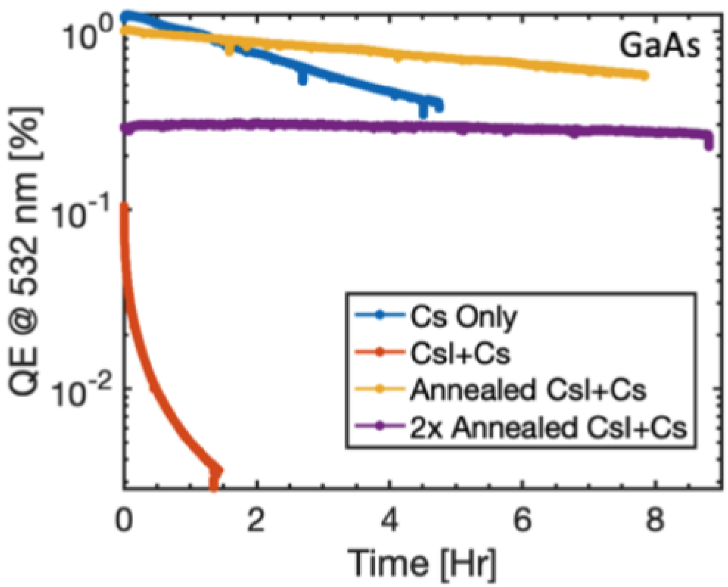
Cultrera et al, "Long lifetime polarized electron beam production from negative electron affinity GaAs activated with Sb-Cs-O: Trade-offs between efficiency,
spin polarization, and lifetime (2020)"





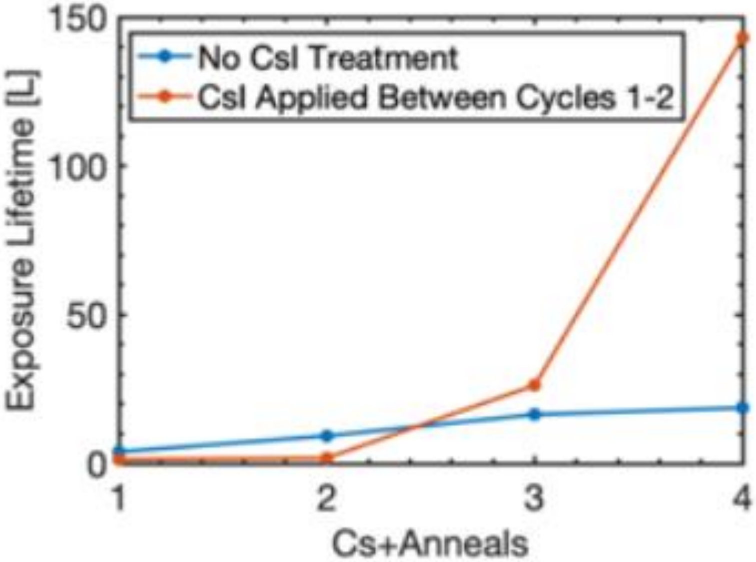


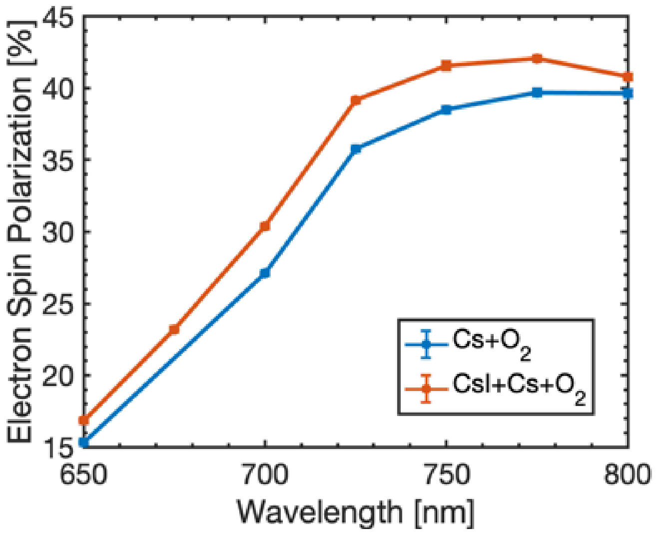
CsI surface treatment of GaAs



Use of CsI increases dark lifetime of GaAs!

- 30 second 1% HCl chemical etch+6 hour anneal at 600 C
- ~1 nm of CsI deposited on GaAs surface. Activated with Cs. Poor lifetime and QE.
- Sample annealed and re-cesiated. Lifetime improvement with comparable QE Cs only GaAs activation
- Additional anneal further improves lifetime at expense of QE
- Lifetime improvement not simply the result of additional annealing cycles





S.J. Levenson et al. IPAC’24. MOPR82

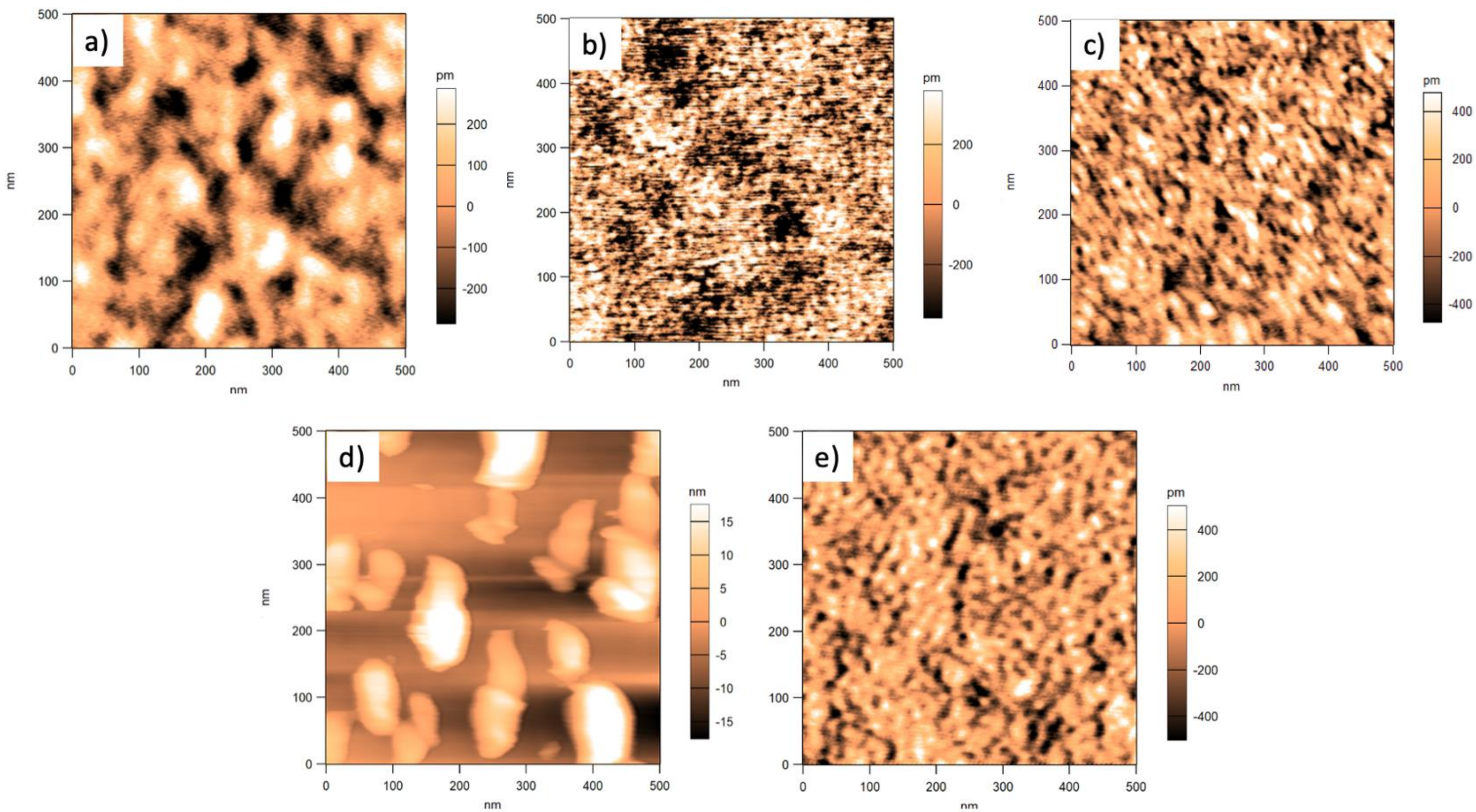
CsI surface treatment of GaAs

AFM performed at each step of surface treatment process

As received

After HCl etching

600 C anneal 6 hours

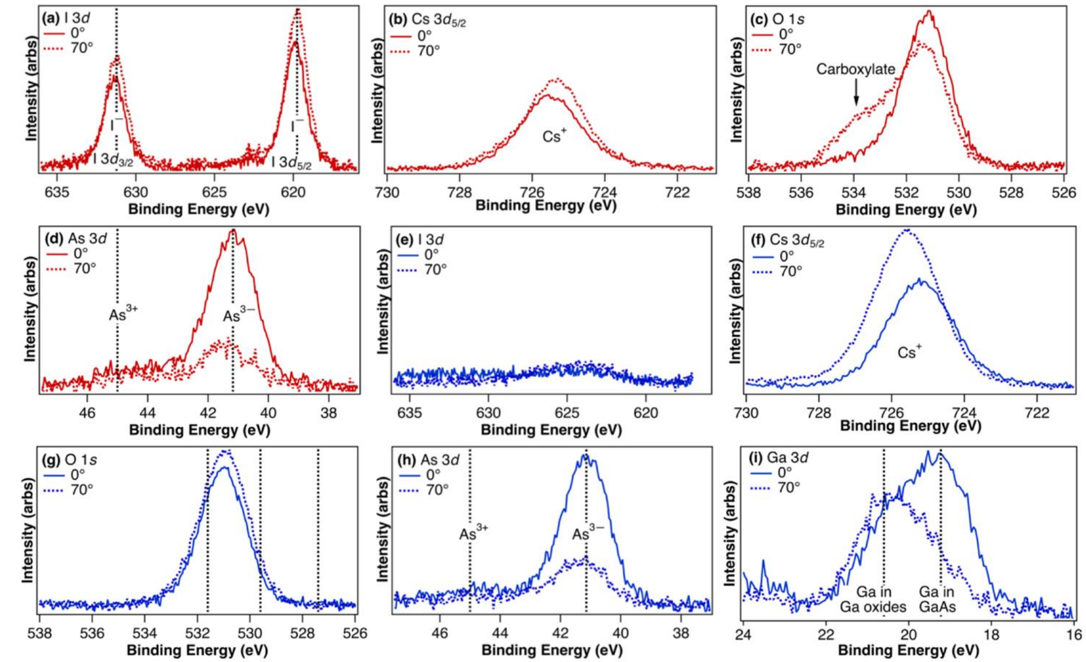


After CsI deposition

After 2nd 600 C, 6 hour anneal

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

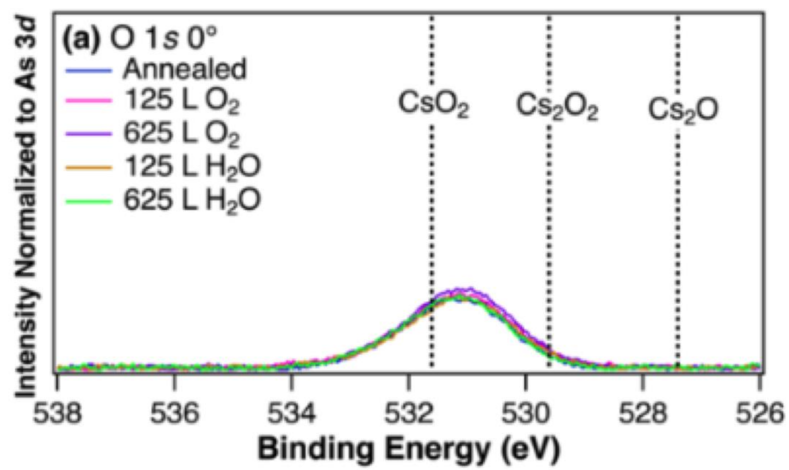
CsI surface treatment of GaAs



XPS analysis in collaboration with Q. Zhu and M. Hines, Cornell Chemistry Department

XPS analysis performed on pre- and post-annealed GaAs samples

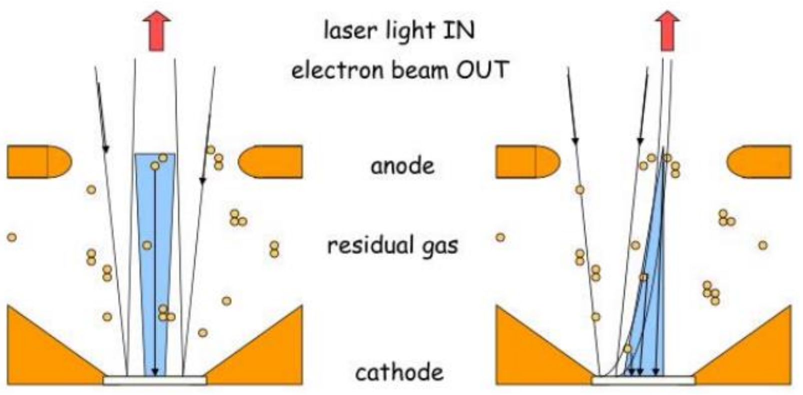
- Pre-annealed sample confirms presence of CsI
- No Iodine detected on post-annealed sample!
- Strong suppression Cs_20

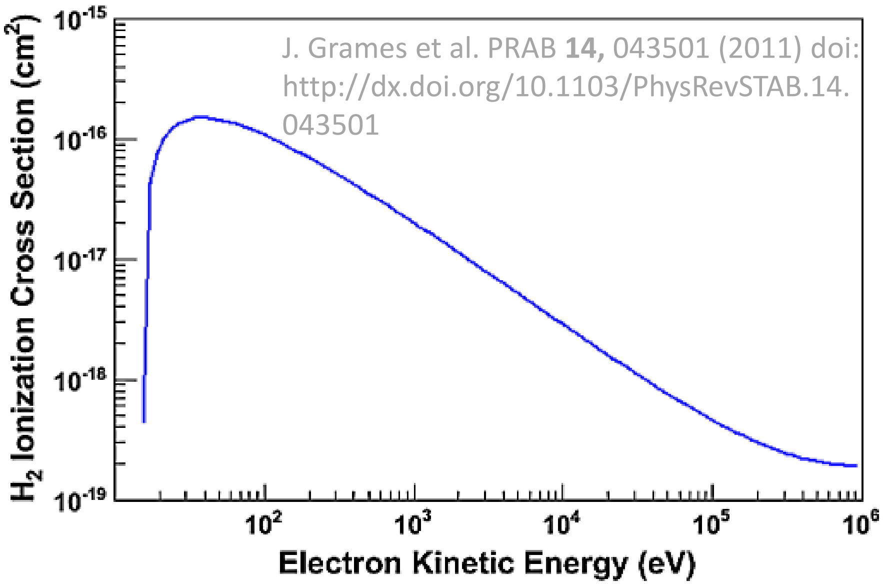


Ion back bombardment

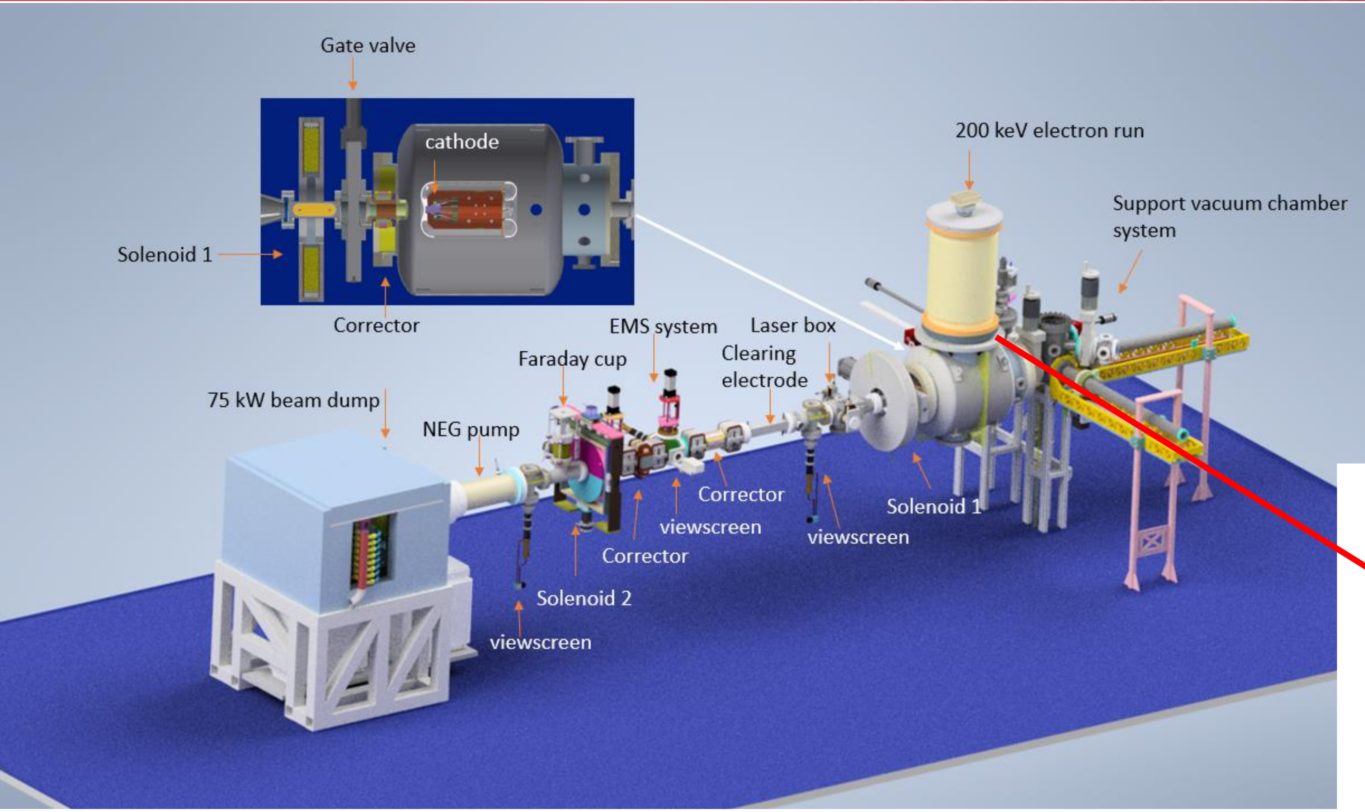
- An electron beam can ionize residual gas which will be positively charged
- Ions will be accelerated towards the cathode and cause damage
- So far, results have been in growth chamber
  - Low current (1-100 nA)
  - Low voltage (-18 V)
  - Main source of degradation comes from vacuum poisoning
- In a high voltage DC gun, induced damage from ion back bombardment is more severe
  - Lower energy ions can sputter off activation layer
  - High energy ions damage GaAs crystal structure
- **Operation at high voltage and current is critical to testing efficacy of alternative activation layers!**

Image courtesy J. Grames



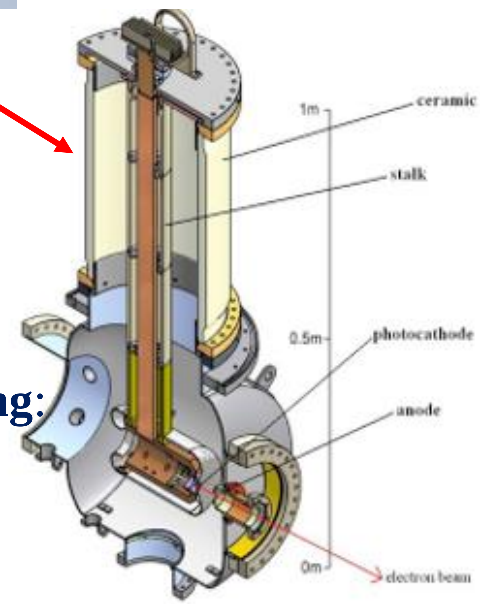


The HERACLES Beamline



HERACLES

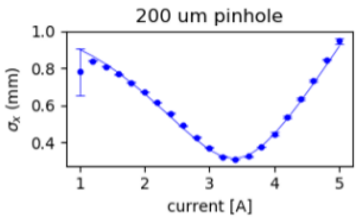
HIGH ELECTRON AVERAGE CURRENT FOR LIFETIME EXPERIMENTS

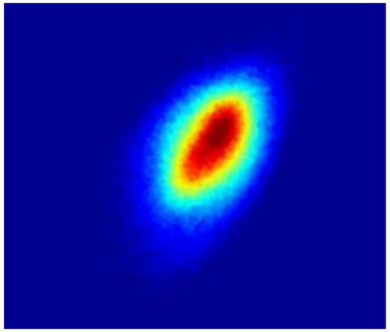


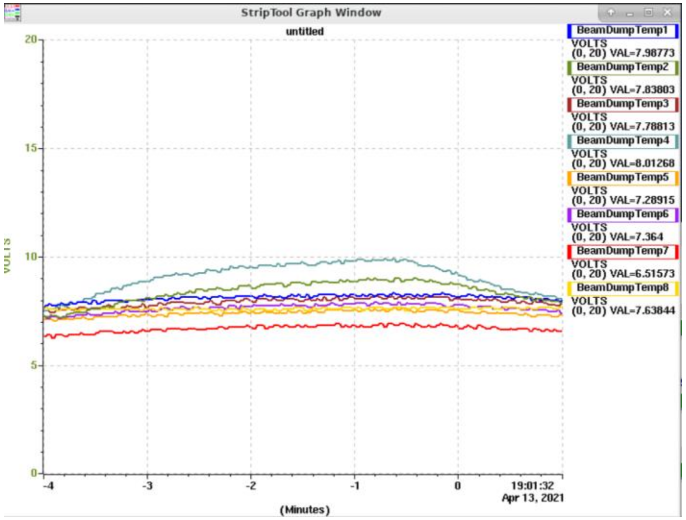
A beamline dedicated to the study of high current beam running:
- Former CU-ERL gun 200kV @ 10 mA
- Ion clearing electrodes
- 75 kW beam dump
- EPICS based control system

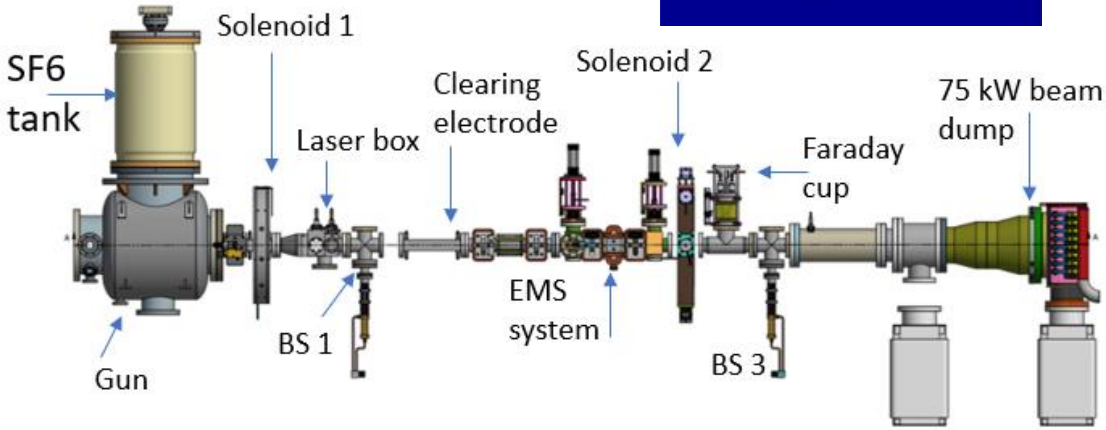
Beamline and Diagnostics

Solenoid scan characterizes cathode MTE





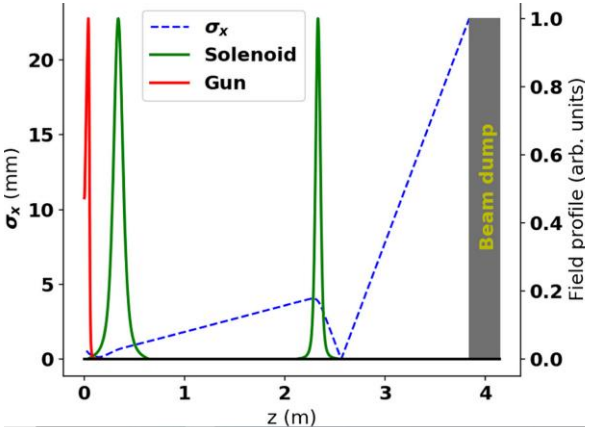




Thermal couples register beam induced temperature rise at the dump

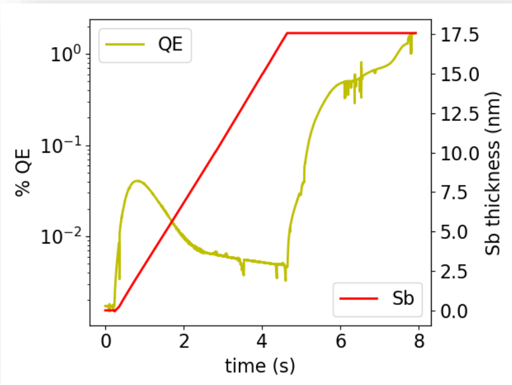
Beamline

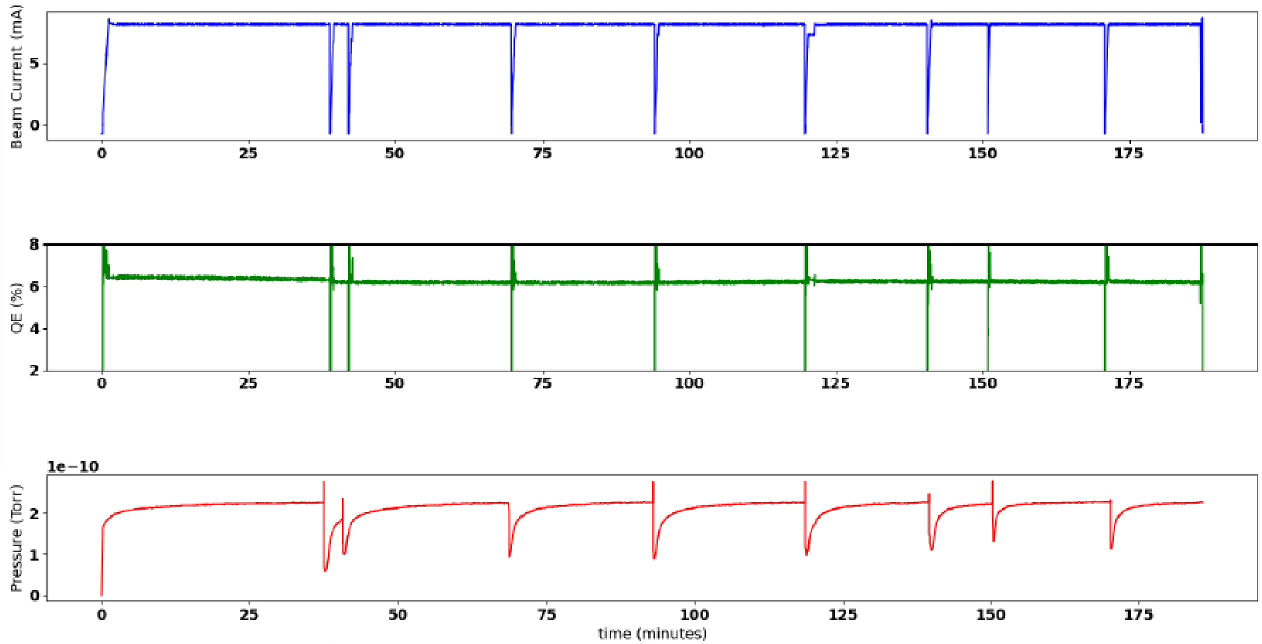
- 2 Solenoids, 3 corrector pairs (hor/vert)
- 2 clearing electrodes
- 3 screens, 1 quad detector
- 1 Faraday cup
- EMS system (not implemented)



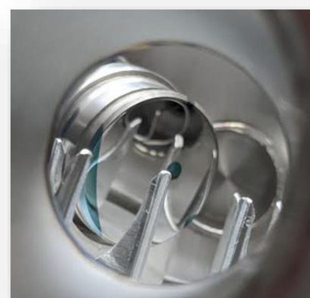
GPT simulation of fields/beam envelope

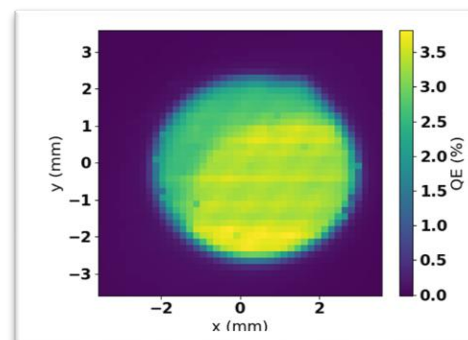
HERACLES high current performance





- Cs_3Sb cathode on stainless steel puck
- 10 mA max current, limited by radiation trips
- 8 mA constant current for 3 + hours with no significant change in cathode QE



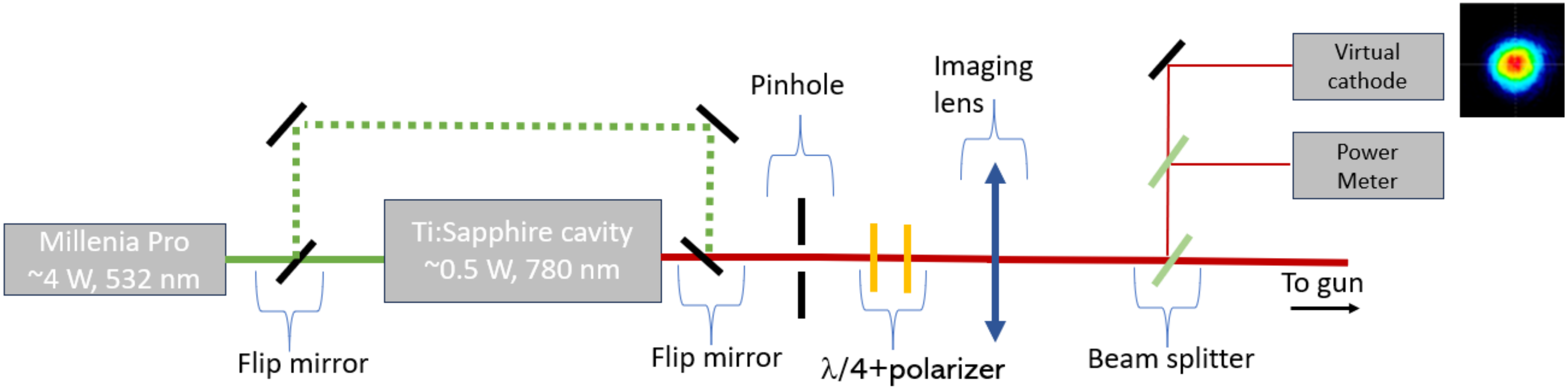


M. Andorf et al. NIMA: **1052** 168240 (**2023**) https://doi.org/10.1016/j.nima.2023.168240

HERACLES DRIVE LASER

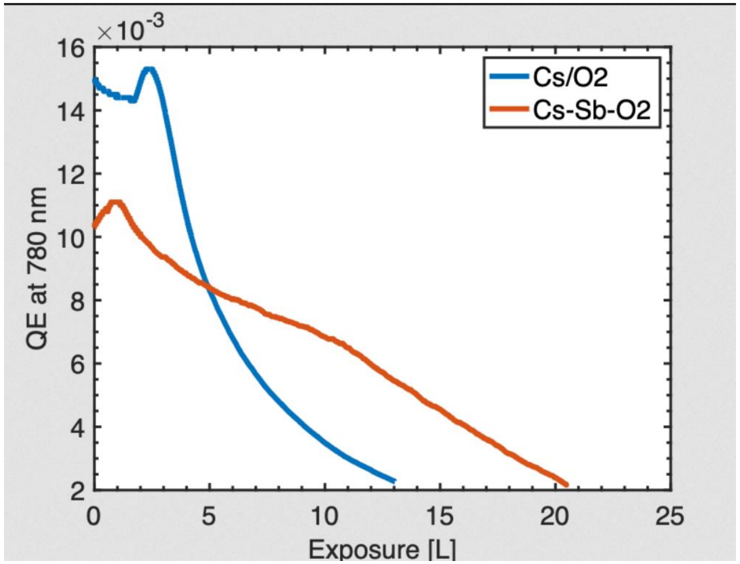
Drive Laser for high current GaAs operation

- Ti:Sapphire oscillator: lasing at GaAs bandgap energy
- Ti:Sapphire excited with external 532 nm diode laser
- Easily switch between IR and green operation

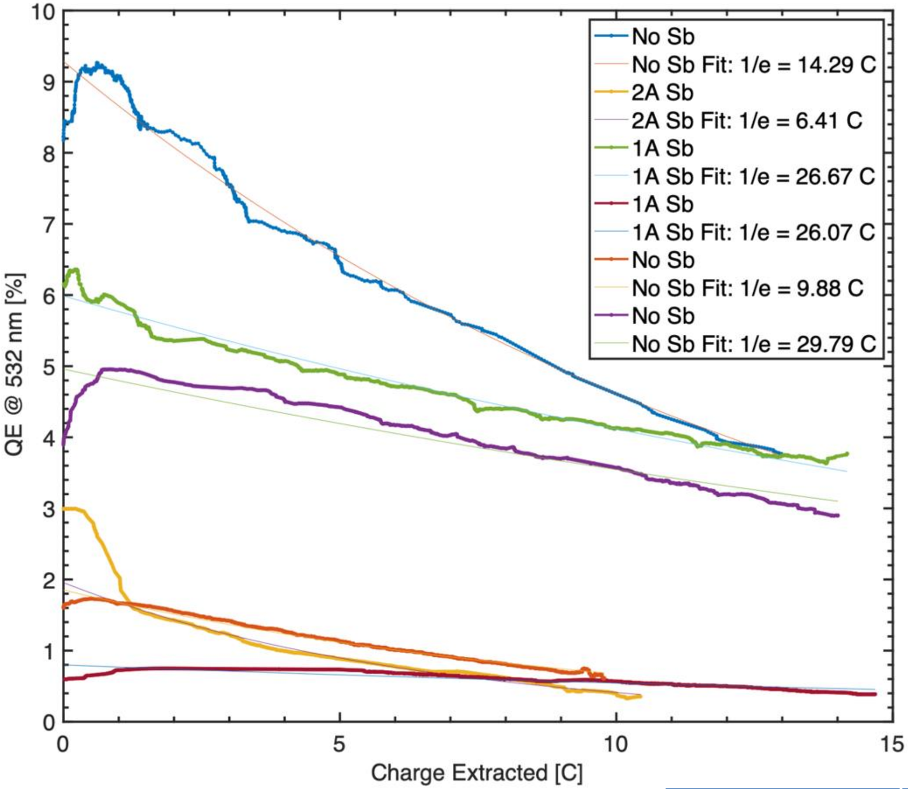


HERACLES growth chamber

- Upgraded HERACLES to have an MBE growth chamber
- 3 Effusion cells (Cs, Sb, Te)+oxygen leak valve
- Reproduced Sb-based activation lifetime improvements in growth chamber
- Ready for high current runs!



Initial high current runs



On going campaign to determine optimal Sb thickness for operational lifetime improvement

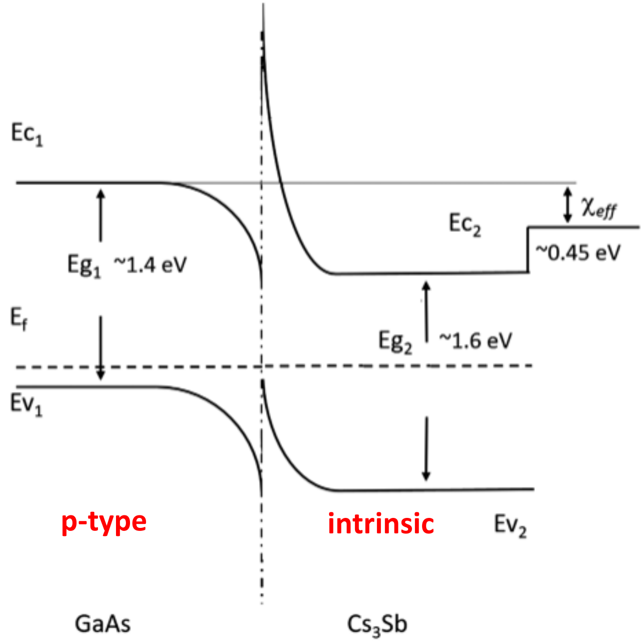
- Average beam current of 1 mA operated at 532 nm
- 10-15 C of charge extracted per run
- More runs to come!

Sb Thickness (Angstrom)	0	0	0	1	1	2
Lifetime (C)	14.3	9.88	29.7	26.7	26.1	6.4

Thank you for your attention!

BACK UP SLIDES

GaAs with alternative activation layers



- NEA GaAs can be generated by forming a heterojunction at the surface with another semiconductor (activation layer) subject to two criteria:
  1. In the activation layer, the gap from the fermi level to vacuum should be **smaller** than GaAs's bandgap (~1.4 eV).
  2. So that photoemission does not occur from activation layer, its bandgap should be **larger** than GaAs's.
     - This criteria can be violated if the activation layer is sufficiently thin
- The above suggest using p-doped GaAs with an intrinsic semiconductor with a small electron affinity for the activation layer
- Cs_3Sb and Cs_2Te can form the NEA heterojunction
  - Known to be less sensitive to chemical poisoning
  - As a photoemitters they are robust at high currents
  - **This indicates Cs-Sb Cs-Te may be a very robust activation layers!**