High current sources for spin polarized and unpolarized electron beams

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Outline

- Motivation
- Cornell Photoinjector Laboratory and HERACLES
- High current lifetime studies:
    - Robust NEA activation coatings for GaAs
    - Alkali Antimonide Visible vs UV illumination
    - GaN photocathodes

HERACLES Team

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In collaboration with
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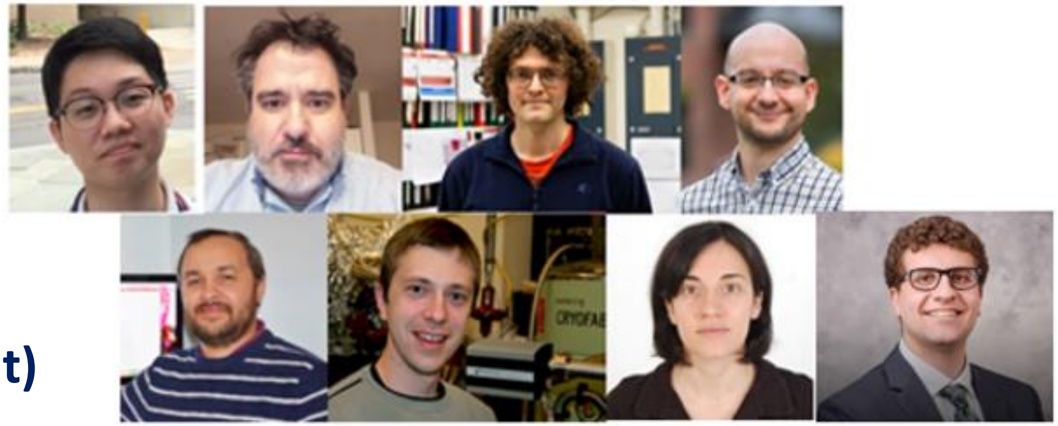
- Luca Cultrera (now @ BNL)
- Jared Maxson
- Ivan Bazarov
- Adam Bartnik
- Alice Galdi (now @U. of Salerno)
- **Sam Levenson (graduate student)**

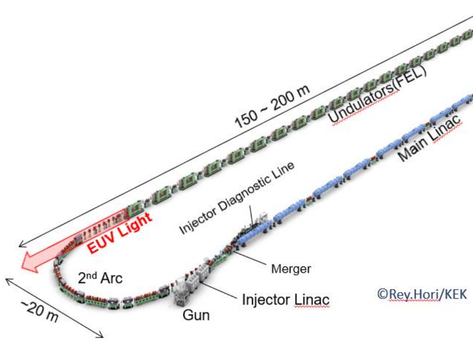


Photocathodes for High Current

Photocathodes for High Current applications

For high brightness, photocathodes are ideal. They provide low transverse and longitudinal energy spreads

- Low emittance beams enable the FEL-lasing process
- SHC requires, a high charge bright beam with low energy spread



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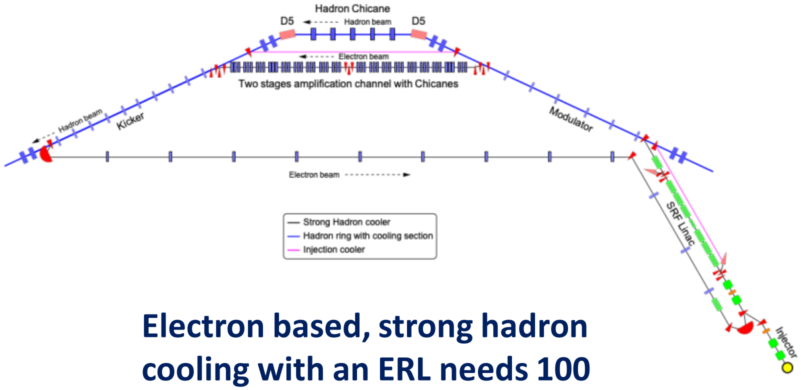
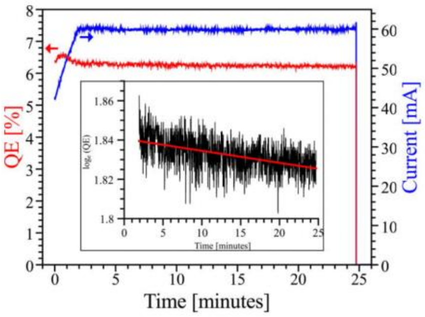
ERL-FEL based UV lithography~ 10 mA average current

For high current operation, we require a relatively high Quantum Efficiency (QE)

- For visible light photons, a 1% QE cathode yields ~4 mA per 1 W of laser power
- Metal cathodes provide QE's several orders of magnitude too small. Must use semiconductor-based cathodes!



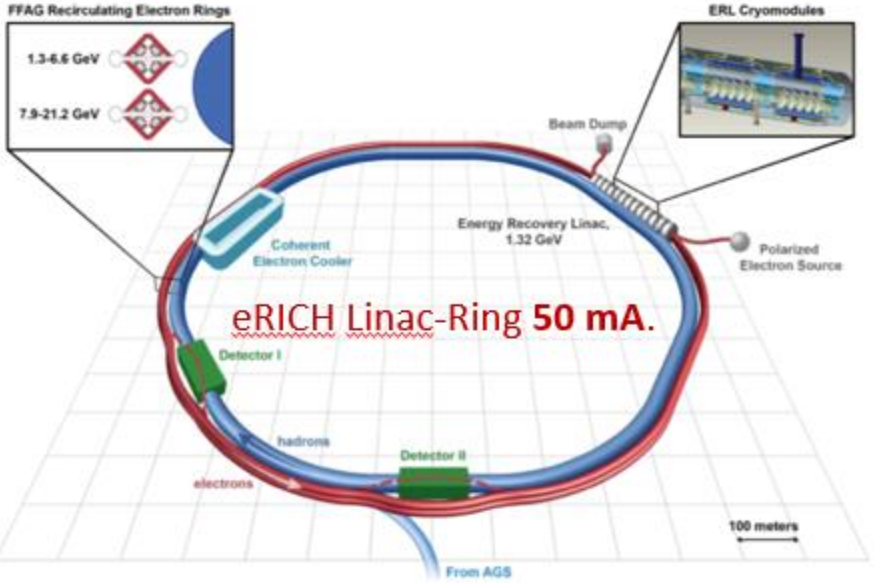
Electron based, strong hadron cooling with an ERL needs 100 mA!



Cornell has a long history of high current photocathode development. Current record holder for highest average current from a photoinjector, 65 ma!

Alkali-antimonides are great for these applications

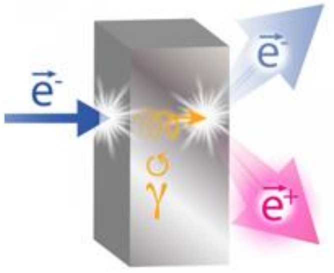
High current and spin polarization

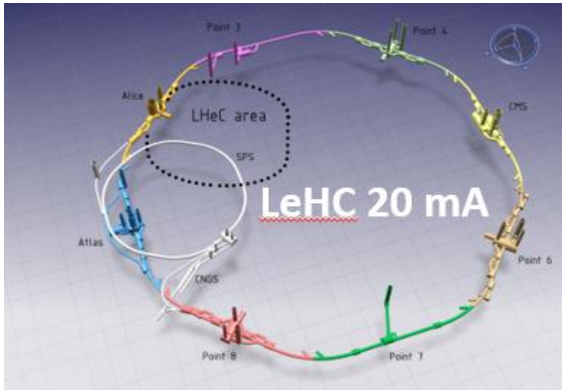


eRICH Linac-Ring **50 mA.**

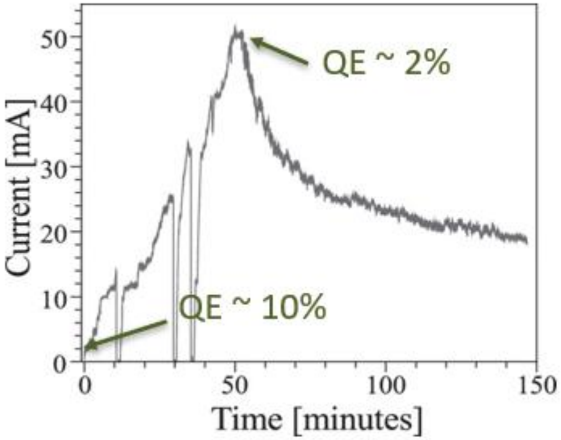
- Many future facilities want spin-polarized electrons at high average currents
- Only candidate cathode for the job: GaAs!
- **Charge lifetime**: The amount of current extracted before the QE degrades by 1/e
    - 1000 C is state of the art→6 hours at 50 ma!

Several mA





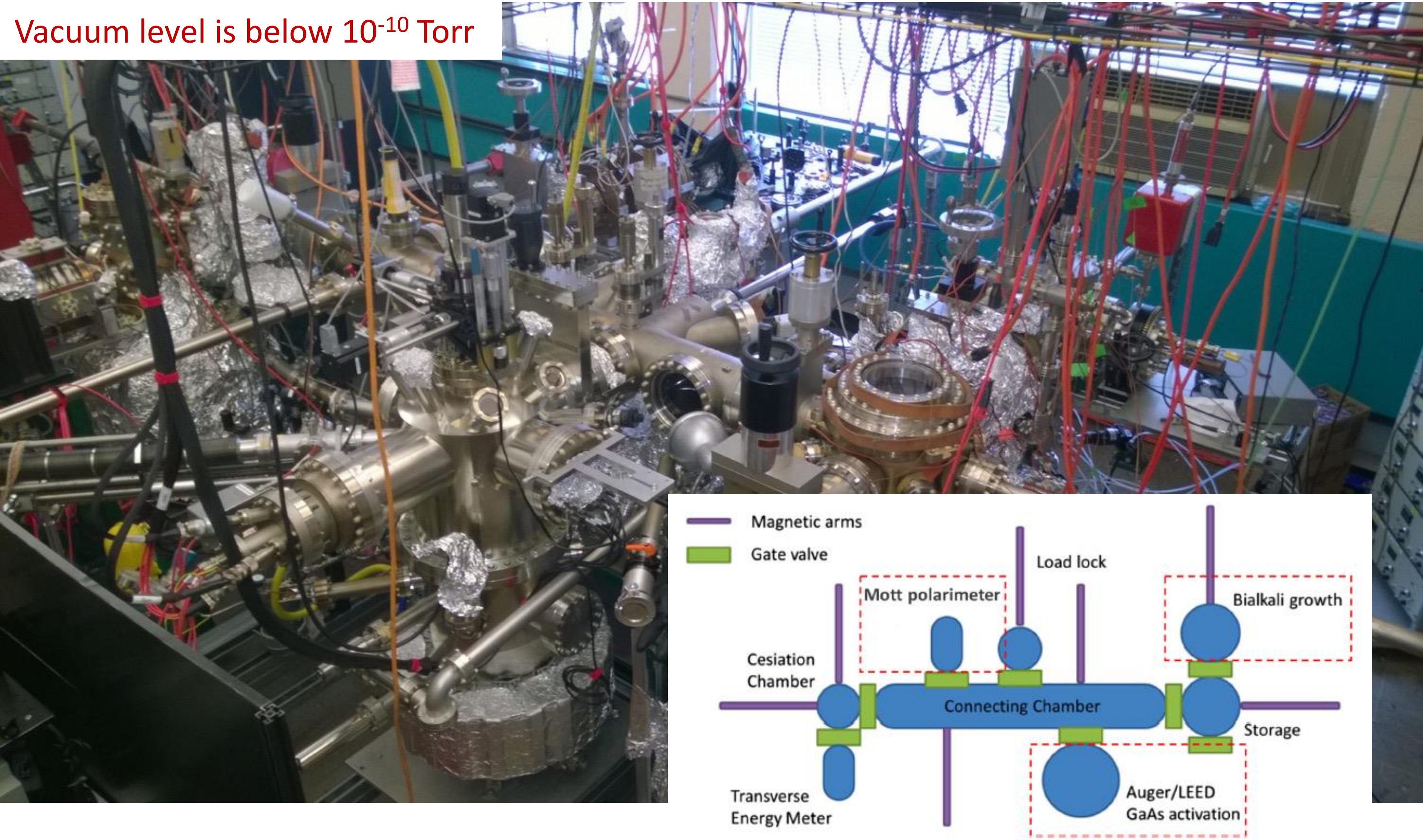
LeHC 20 mA



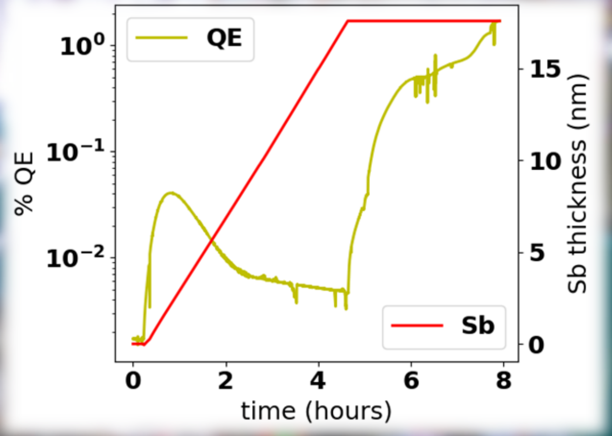
B. Dunham et al, Appl. Phys. Lett. **102**, 034105 (2013)

Cornell Photocathode Lab

Vacuum level is below 10^{-10} Torr

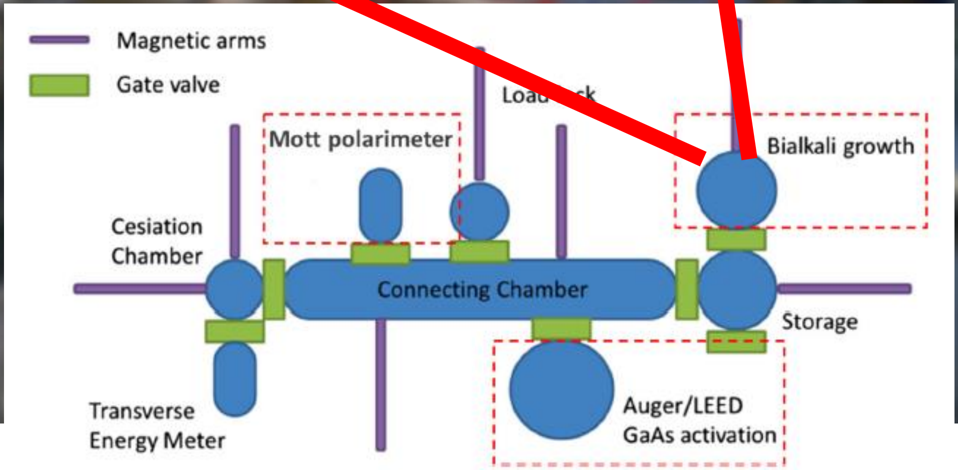


Cornell Photocathode Lab



Bialkali growth chamber

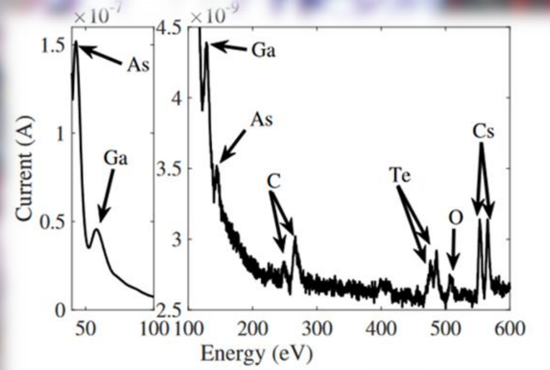
- Cs,Sb,Te,Rb sources+O_2 leak valve, thermally regulated with pneumatic valve control
- Quartz microbalance (QMB) for deposition monitoring
- Substrate heater

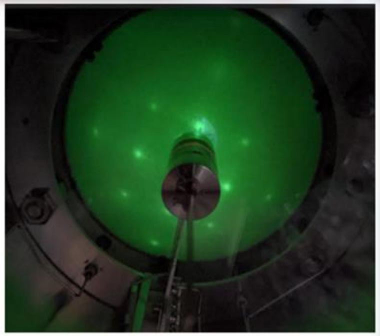


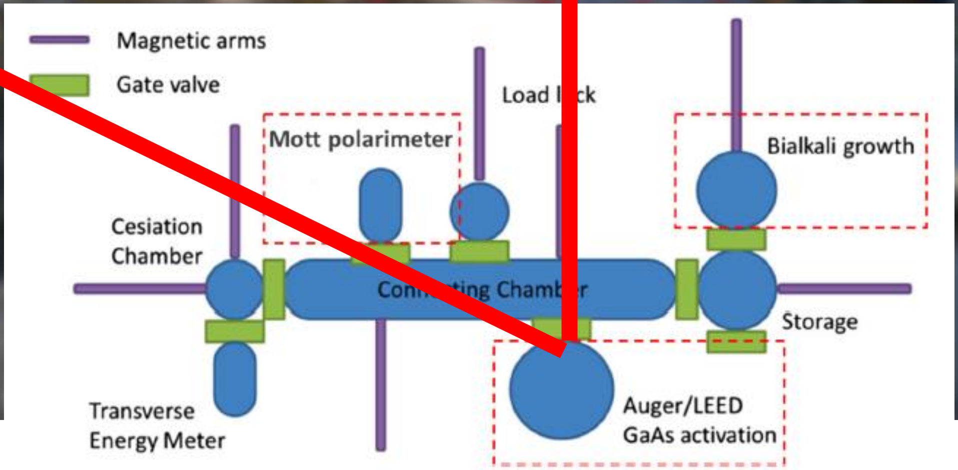
Cornell Photocathode Lab

AUGER Chamber

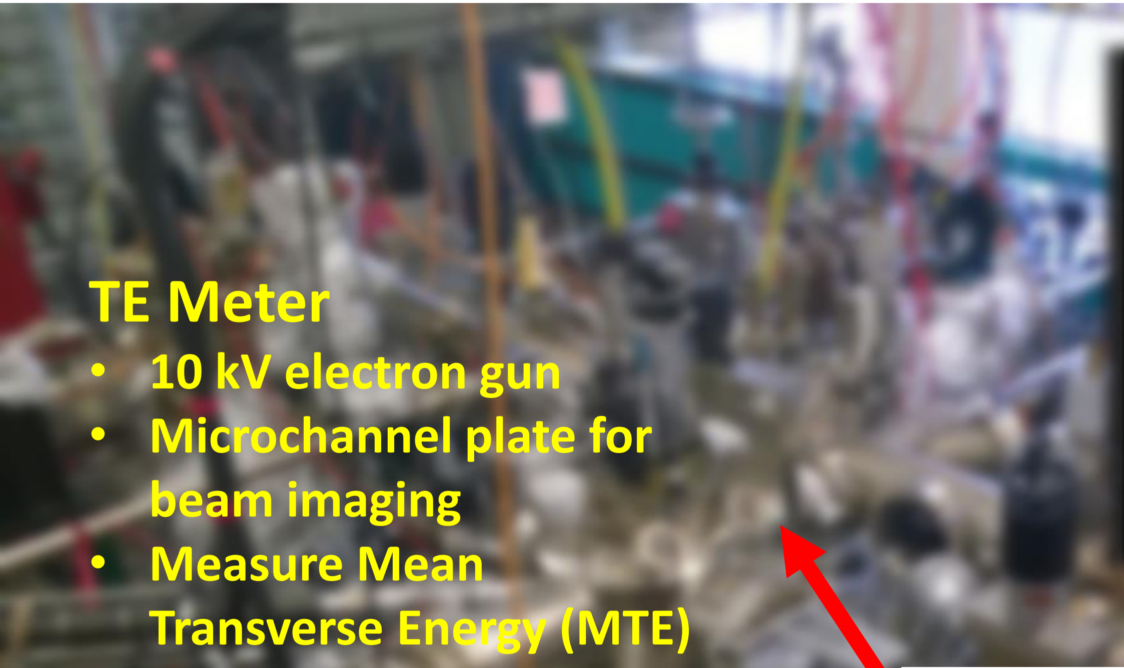
- Auger Electron Spectroscopy-To characterize surface chemistry
- Low Energy Electron Diffraction-Chararacterize surface crystallinity
- Cs, O_2 leak valve.
- Insulated, bias-able cathode holder





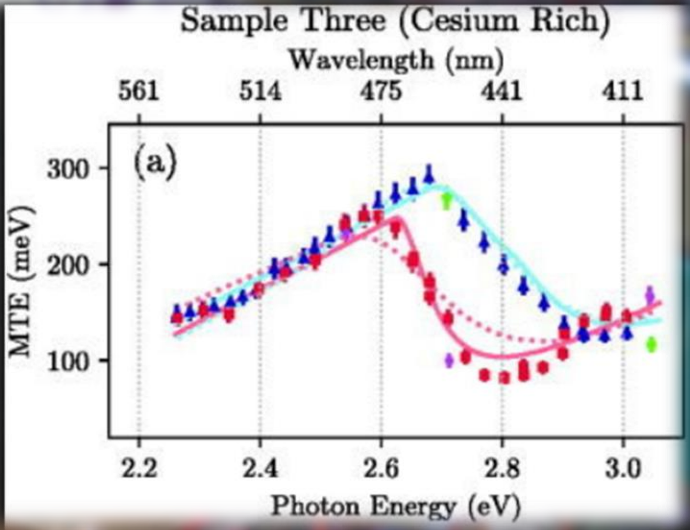


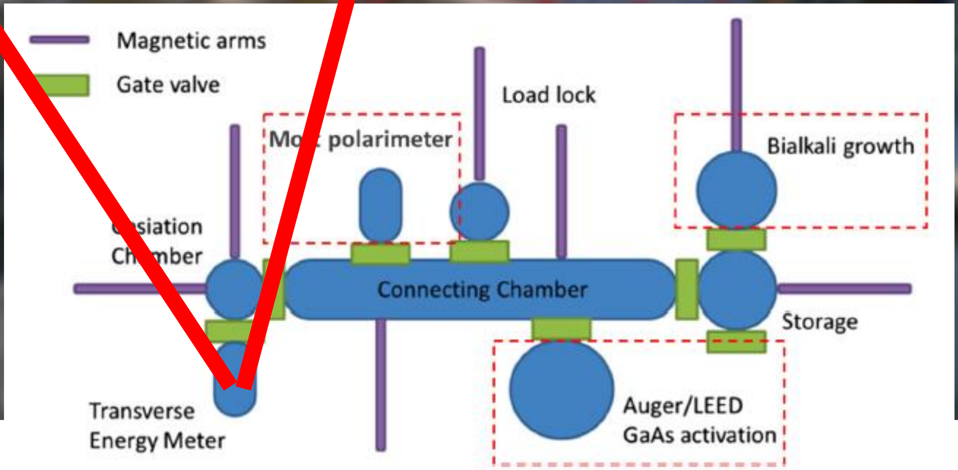
Cornell Photocathode Lab



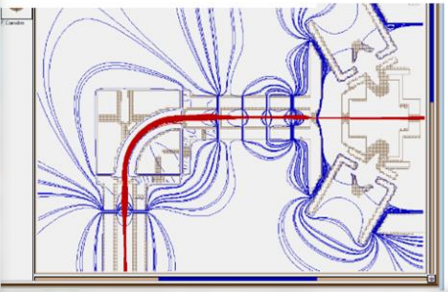
TE Meter

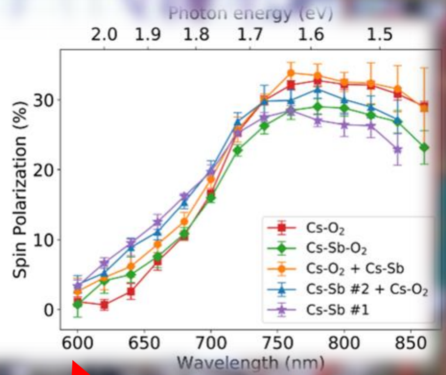
- 10 kV electron gun
- Microchannel plate for beam imaging
- Measure Mean Transverse Energy (MTE)





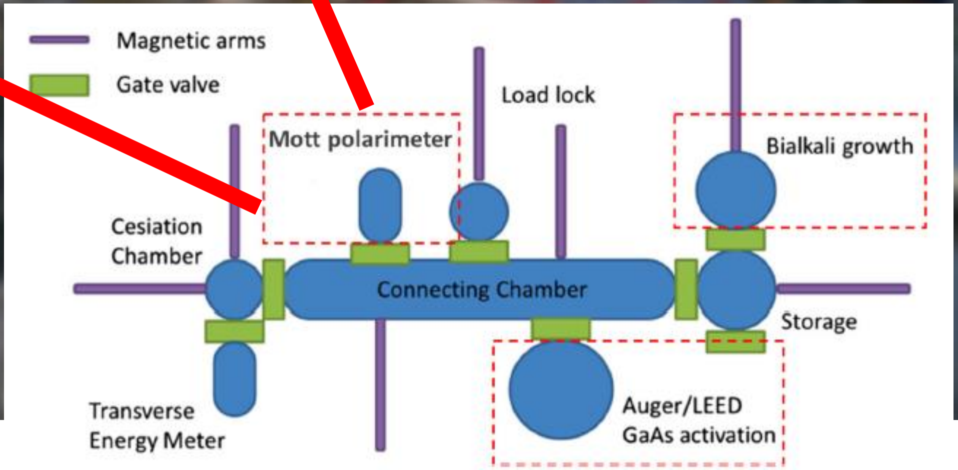
Cornell Photocathode Lab



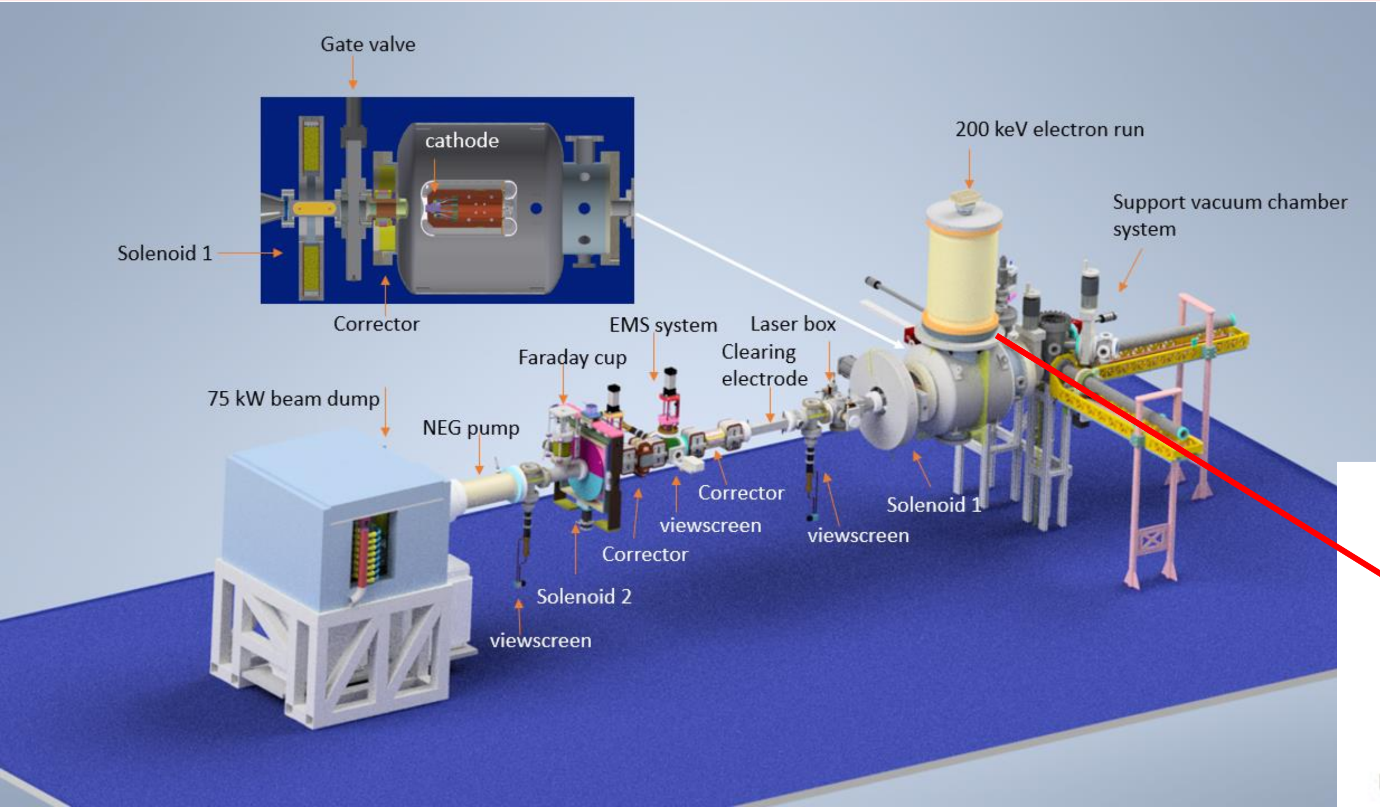


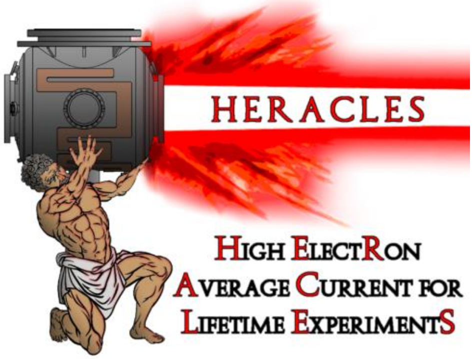
Mott polarimeter

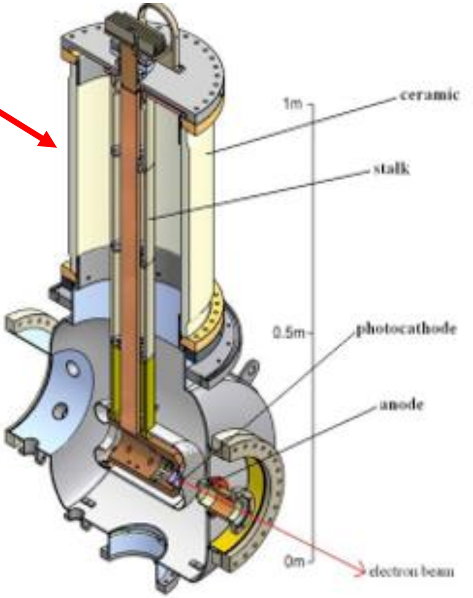
- 20 keV gun + einzel lens beamline
- Tungsten scattering target
- Measure spin-polarization



The HERACLES Beamline





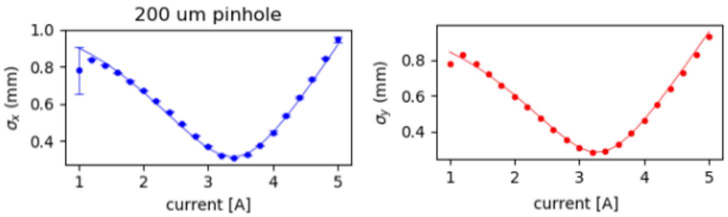


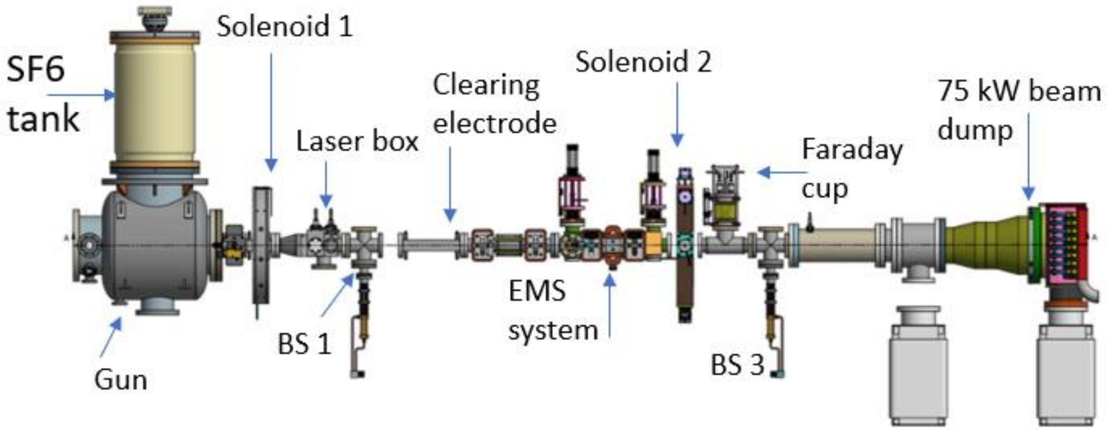
A beamline dedicated to the study of high current beam running:

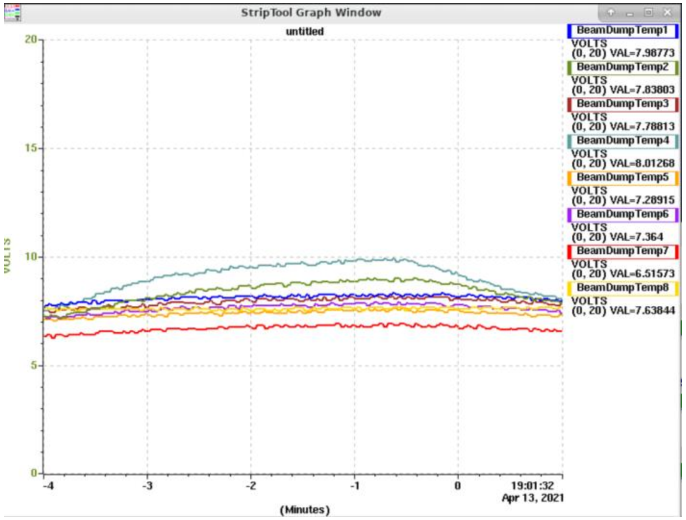
- Former CU-ERL gun 200kV @ 10 mA
- Ion clearing electrodes
- 75 kW beam dump
- EPICS based control system
- Attached storage system: QE mapping, Cs-O activation

Beamline and Diagnostics

Solenoid scan characterizes cathode MTE



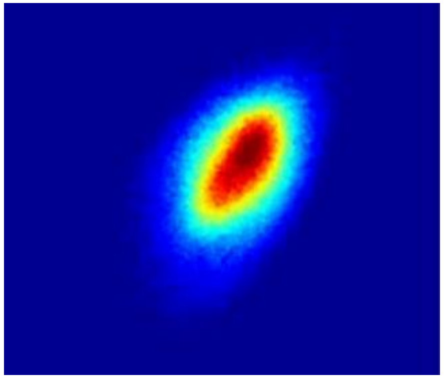




Thermal couples register beam induced temperature rise at the dump

Beamline

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



3 Beam screens ensure clean beam transport from cathode to dump

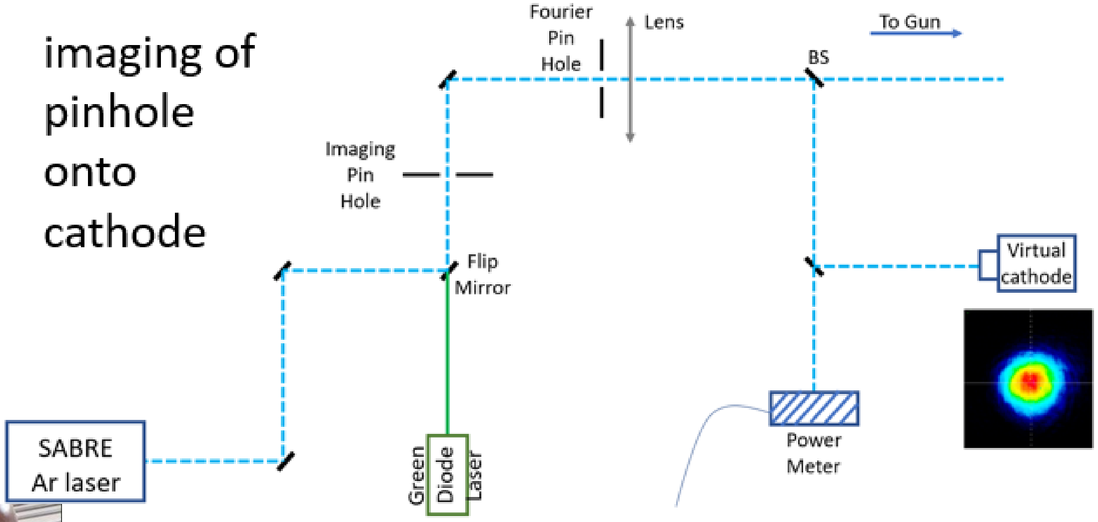
Laser setup

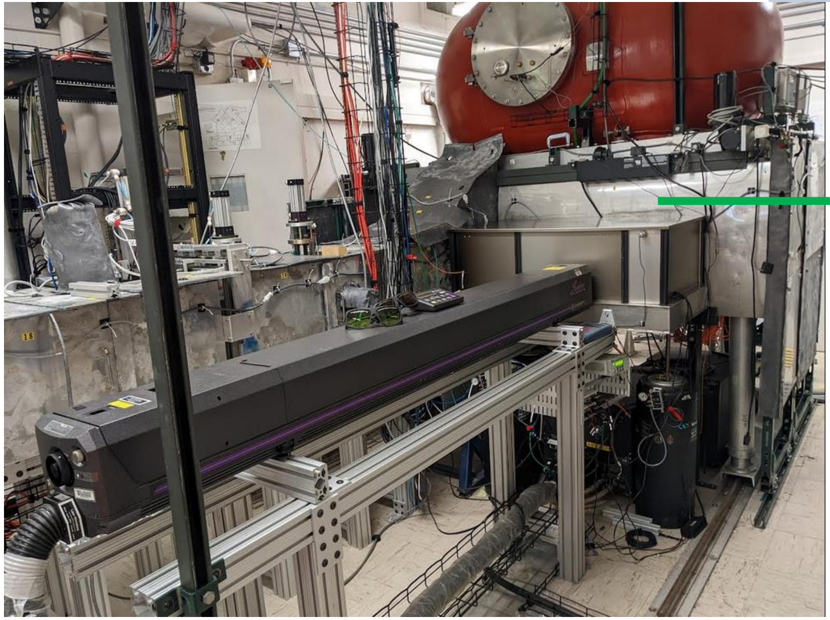
The Ar ion laser has been refurbished and now can operated with tunable wavelength in the visible and UV.

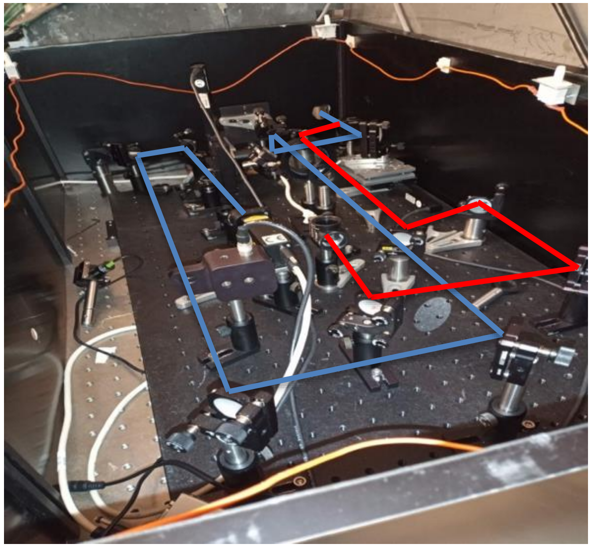
5 W in the visible (ML)

2 W in the UV (ML)

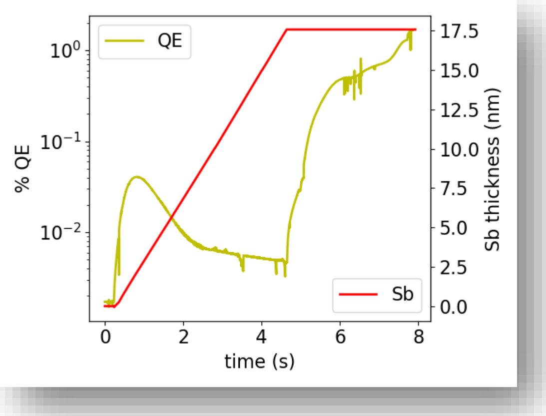
imaging of pinhole onto cathode

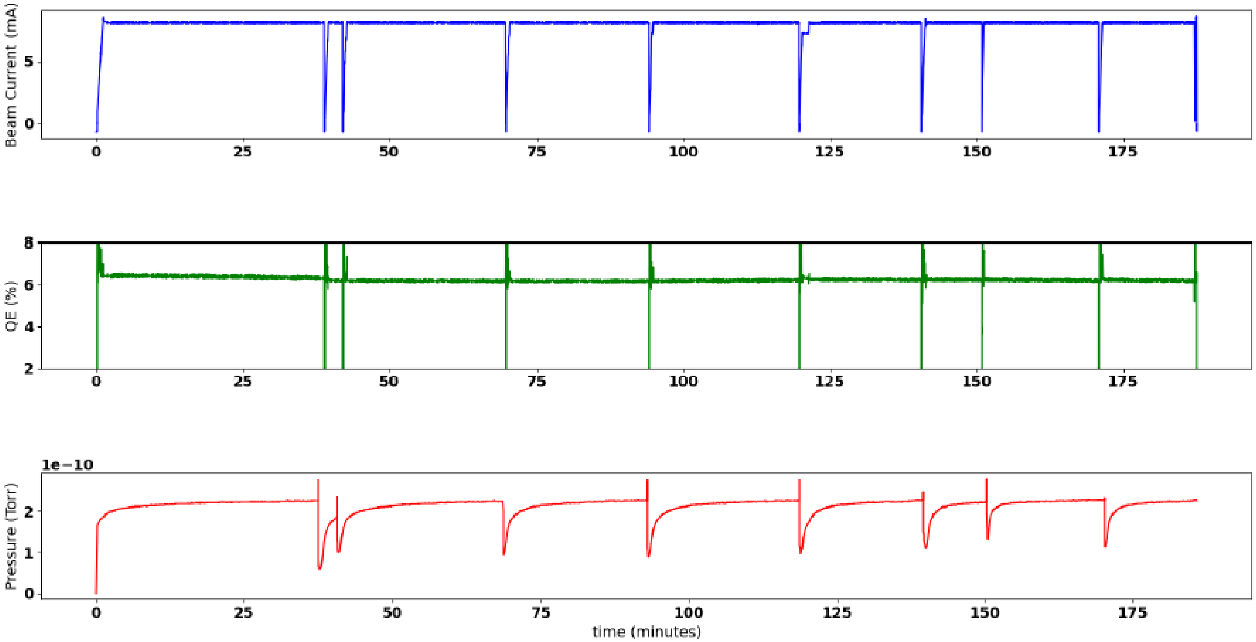




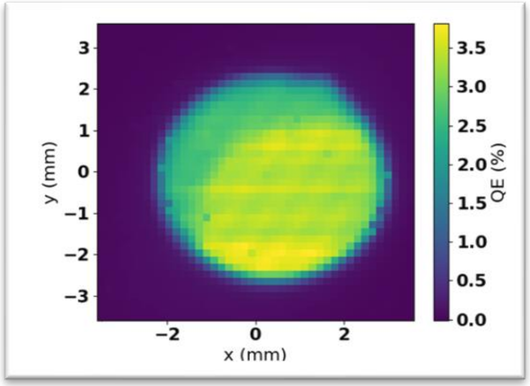


HERACLES high current demonstration

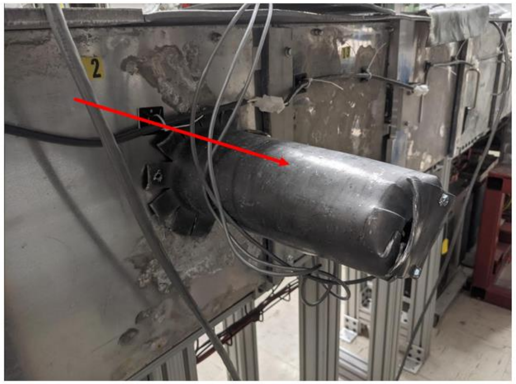




- Cs_3Sb cathode on stainless steel puck
- 10 mA max current, limited by radiation trips
- 8 mA constant current for 3 + hours with no significant change in cathode QE
- **Ready for cathode lifetime studies!**

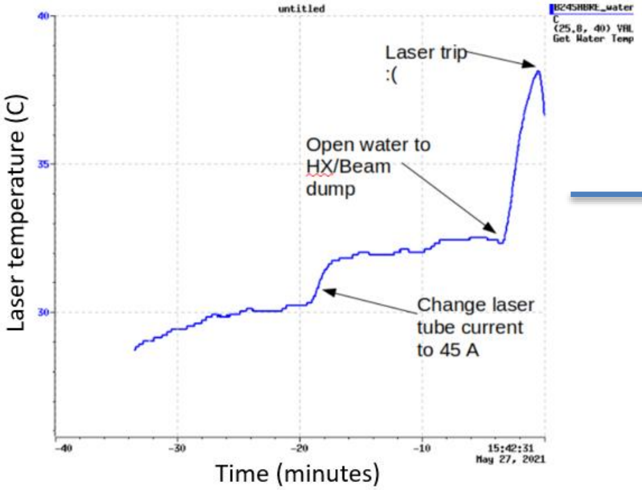


Cooling and Shielding Improvements



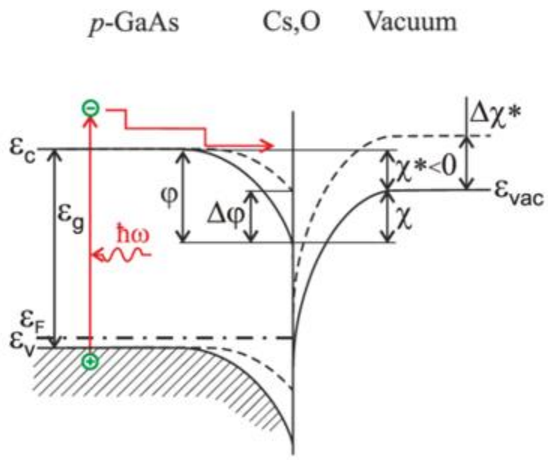
- Study performed to find and cover radiation hot spots
- Sets beam current to 10 mA

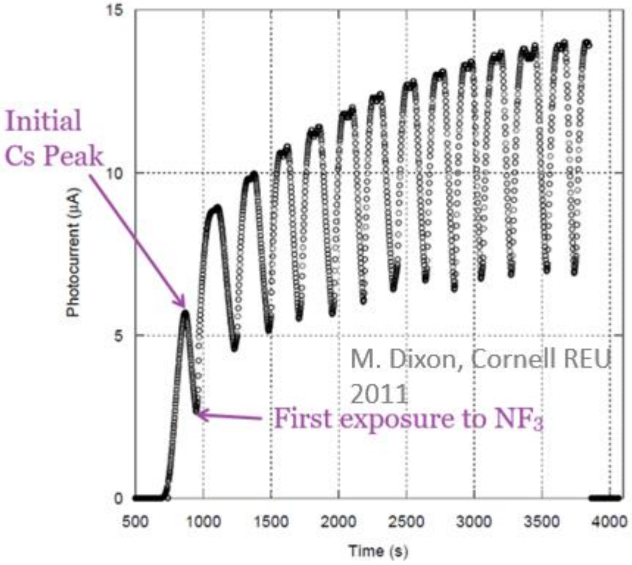
- Facility water flow not adequate to cool laser, beam dump and HV supply
- All systems moved to closed loop heat exchanger.
- **Eliminated high temperature laser trips!**



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





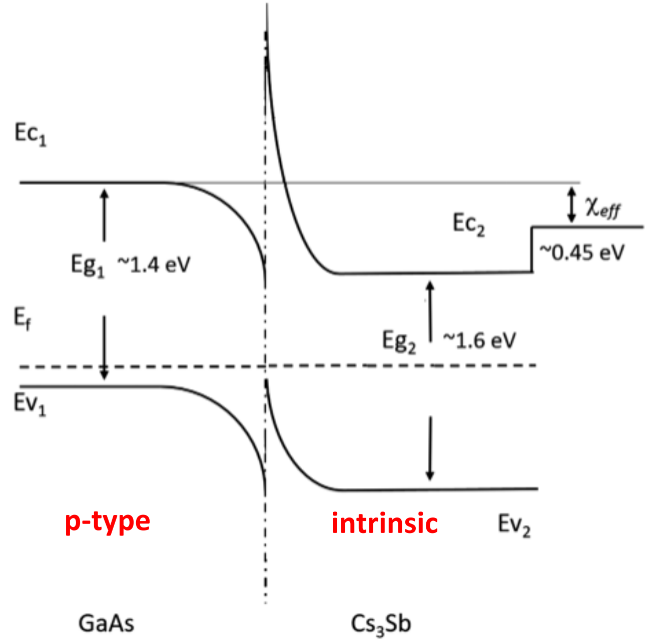
Initial Cs Peak

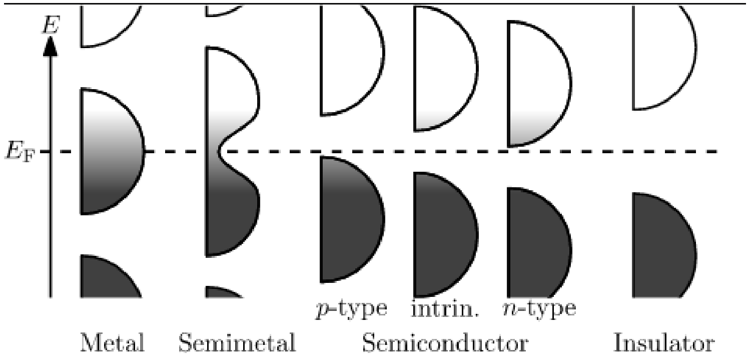
First exposure to NF_3

M. Dixon, Cornell REU 2011

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_3Sb/Cs_2Te may be a very robust activation layers!**

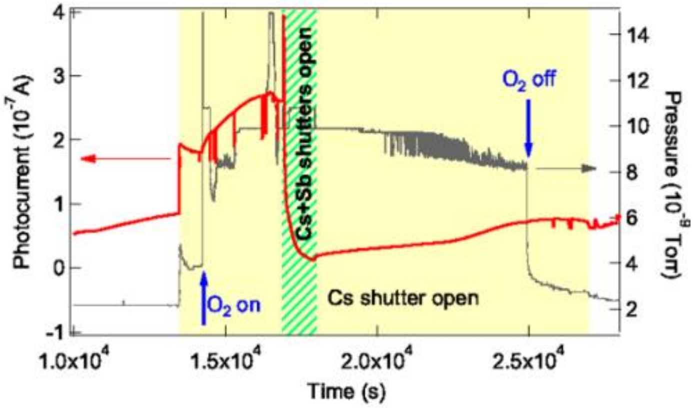


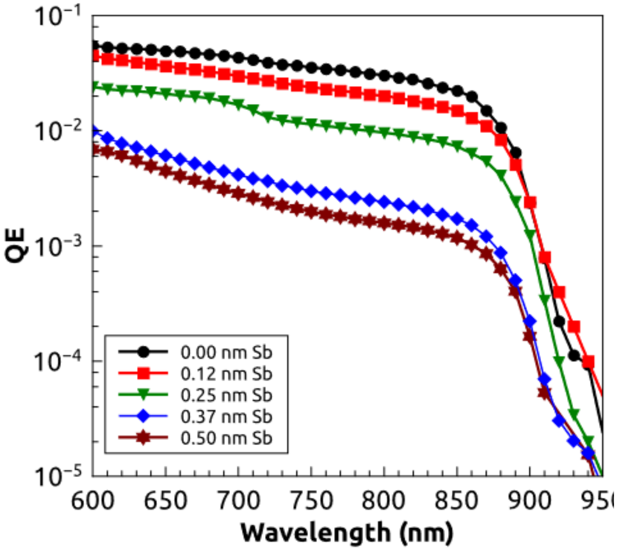


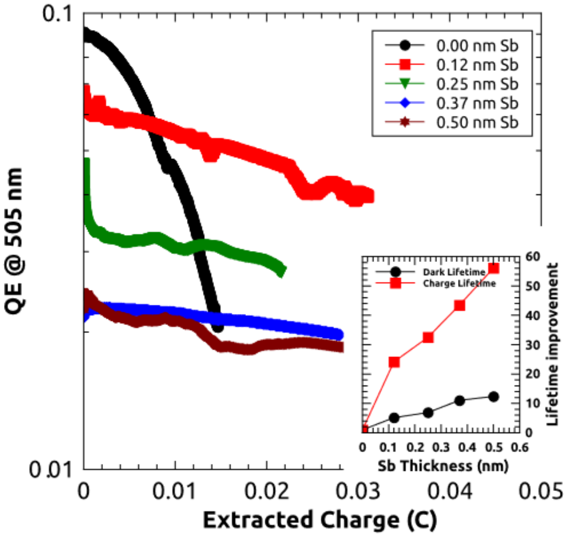
GaAs with Cs-Sb-O NEA activation layer

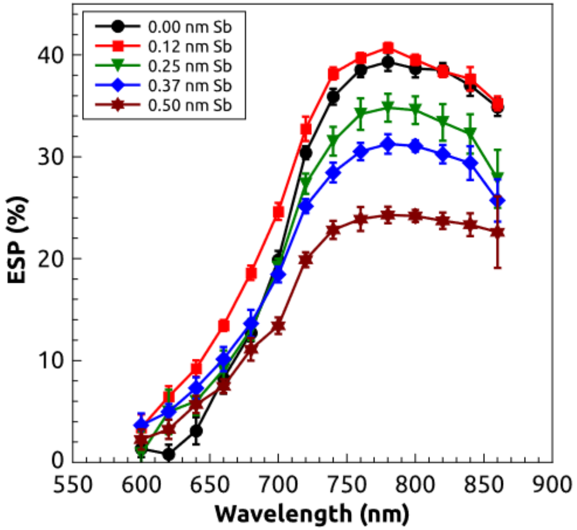
Cs-O-Sb co-deposition recipe optimized through scanning the Sb layer thickness:

- 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!**





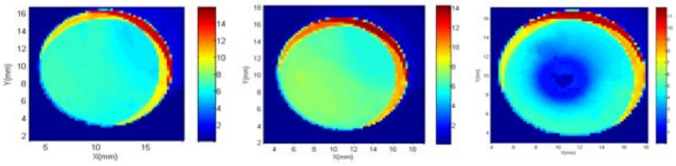




Cultrera et al, "Long lifetime polarized electron beam production from negative electron affinity GaAs activated with Sb-Cs-O: Trade-offs between efficiency, spin polarization, and lifetime (2020)"

QE alone is not sufficient

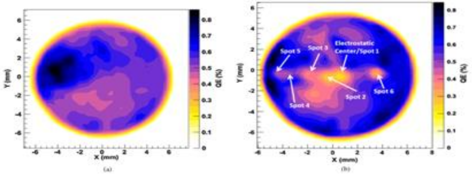
- NEA is achieved and can be maintained only in **extreme vacuum**
  - XHV require massive pumping to reach **10^{-12} Torr**;
- **Ions backstreaming** is still limiting operating lifetime
  - Clearing electrodes and or biased anode;
  - Higher gun voltages;

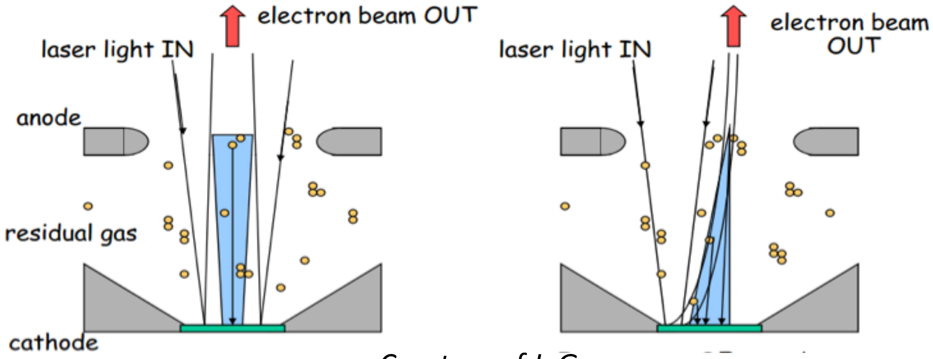


Fresh cathode

~10 mA
2 hours
No RF trips

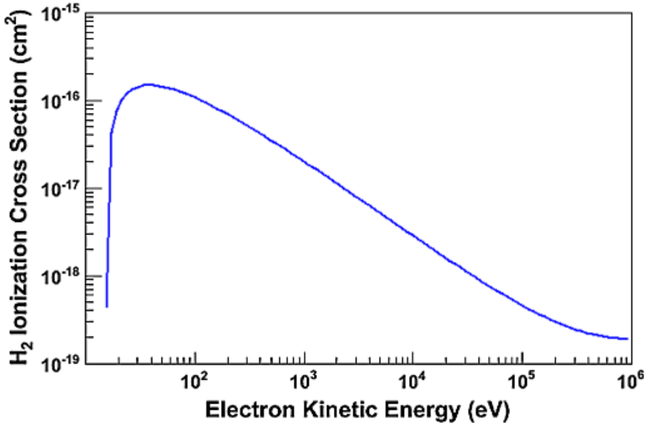
~20 mA
2 hours
many RF trips





Courtesy of J. Grames

GaAs and alkali antimonides both suffer from ion backstreaming



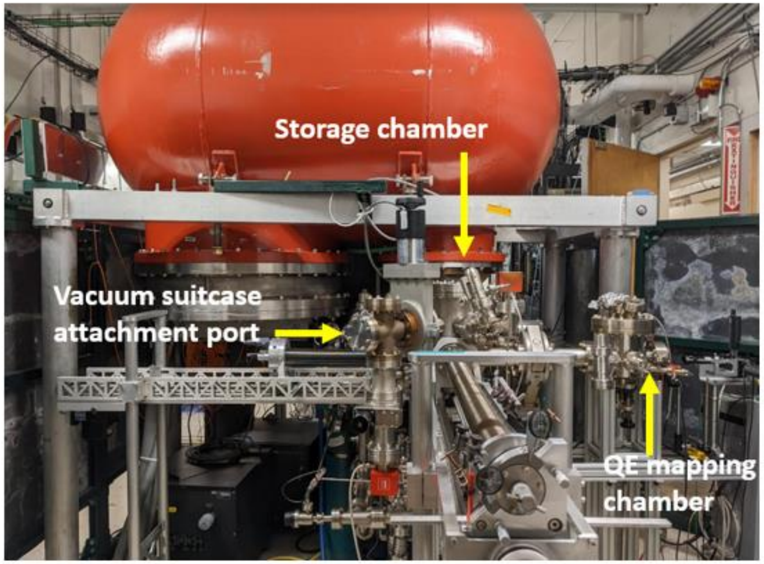
A single HV breakdown event inside the gun Can get the vacuum high enough to instantly "kill" the cathode

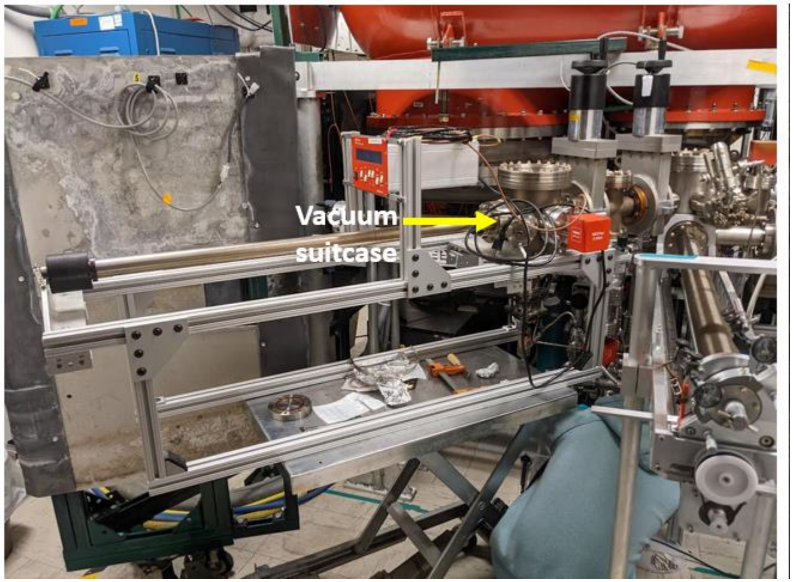
Cs-Sb-O activated GaAs cathode in HERACLES

Goal
- Compare the charge lifetimes of Cs-Sb-O vs Cs-O activated GaAs.

Sample Preparation:
- Cs-O:GaAs
  - activated with co-deposition in a chamber attached to the rear of HERACLES.
  - Lifetime measurements performed within hours of activation
- Cs-O-Sb:GaAs
  - Activated in Mother chamber and transported via a vacuum suitcase to HERACLES
  - ~24 hours between activation and lifetime measurement

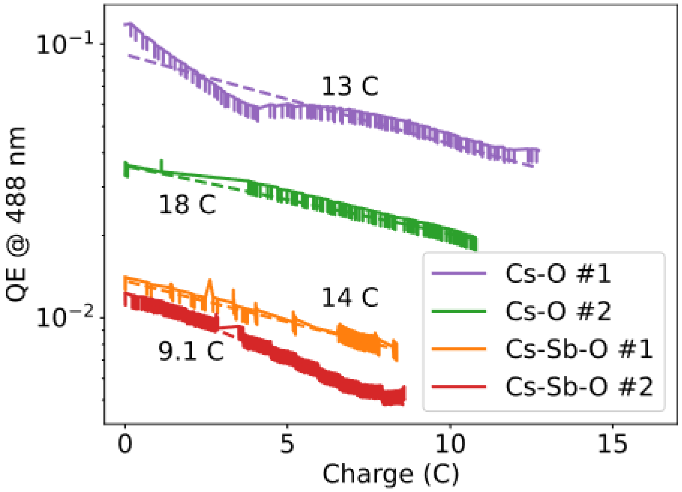
Run Conditions
  - 1 mA beam current held constant for 2-3 hours
  - 488 nm drive laser. QE map at 532 and 780 nm
  - Typical vacuum pressure in the low e-10’s during run

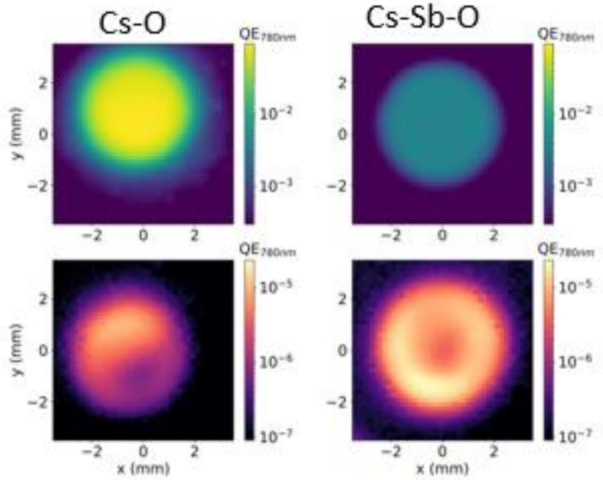


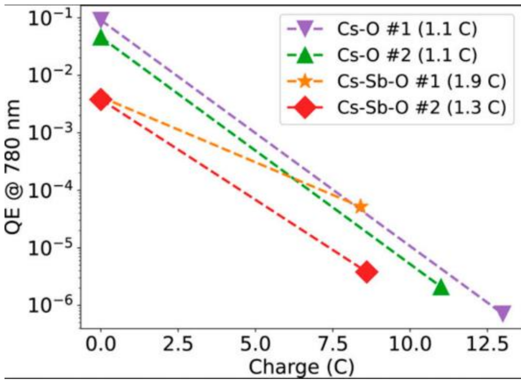


Cs-Sb-O activated GaAs cathode in HERACLES (results)

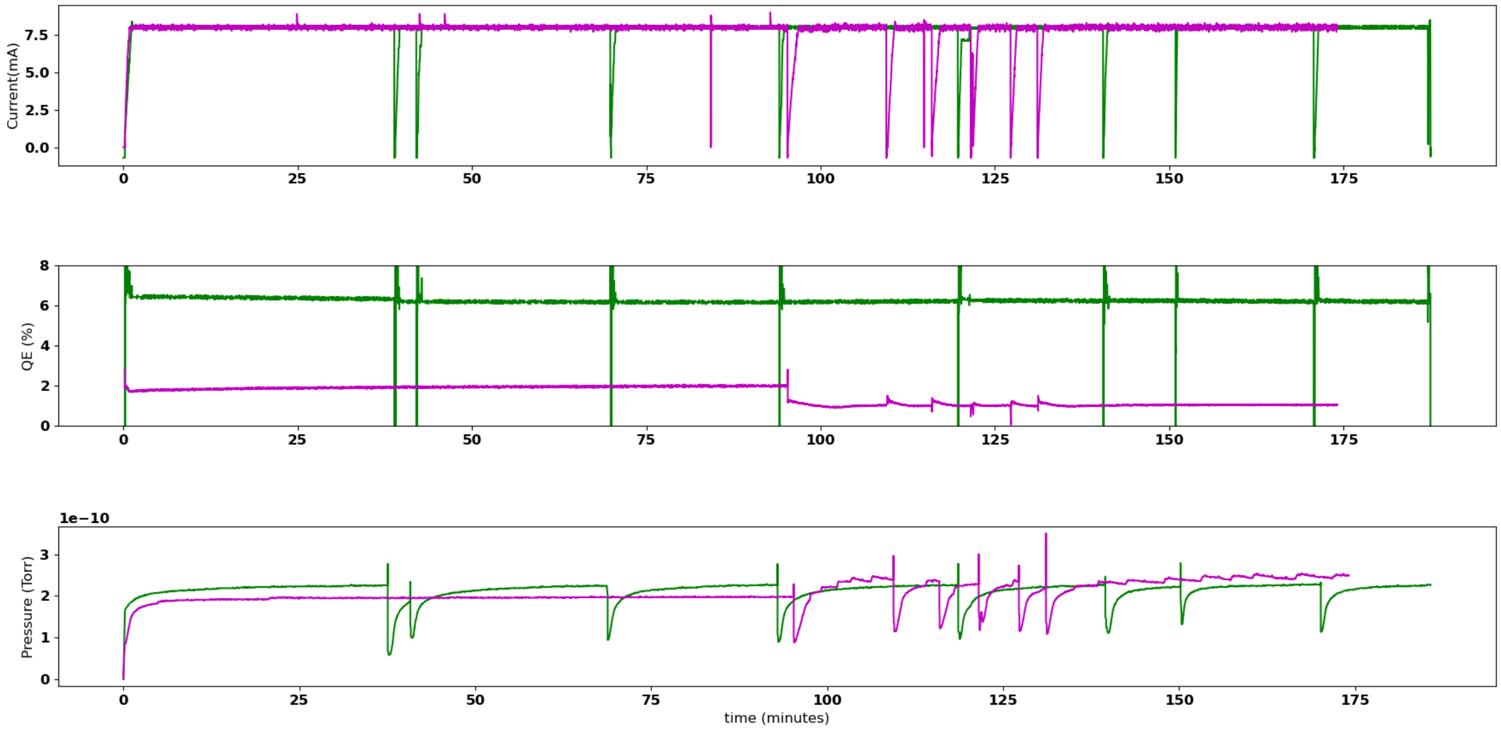
- We did not see an improvement in the charge lifetime at 488 nm
- Pre/post run comparisons of QE indicate lifetime at 780 nm may have improved.
  - Relative QE change smaller for Cs-Sb-O samples
- Cs-Sb-O had lower QE's
  - We observed roughly a factor of 3 reduction in the QE between activation in the Mother chamber and beginning the run.
  - Required laser power a factor of 4-10 higher
- **The story is not over!**
  - **New growth chamber on HERACLES to support Cs-Sb-O activation**
  - **780 nm drive laser**

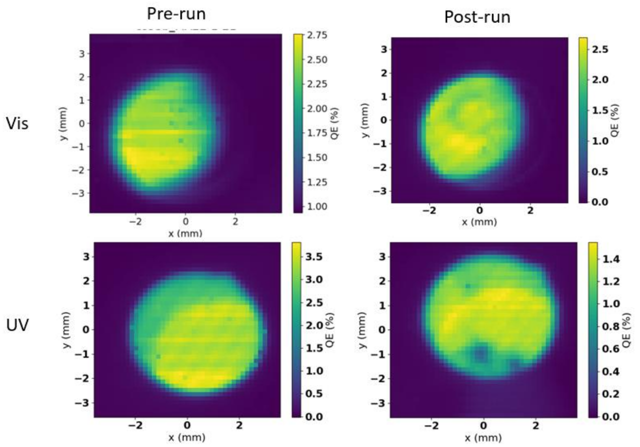






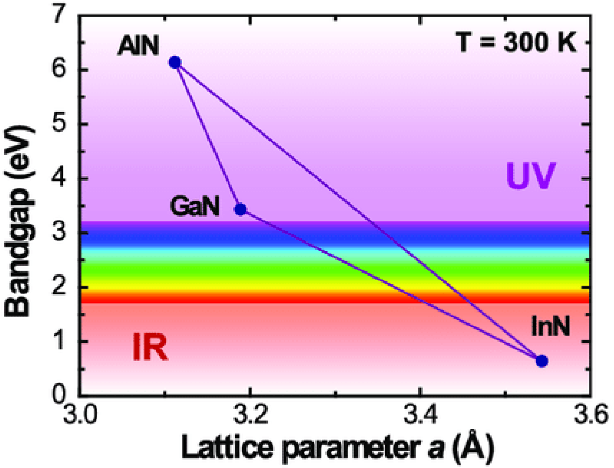
Vis/UV alkali operation

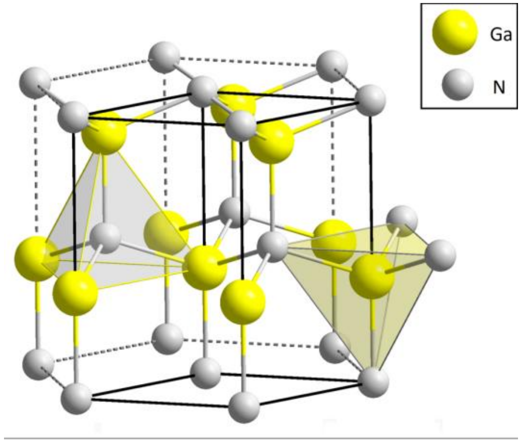




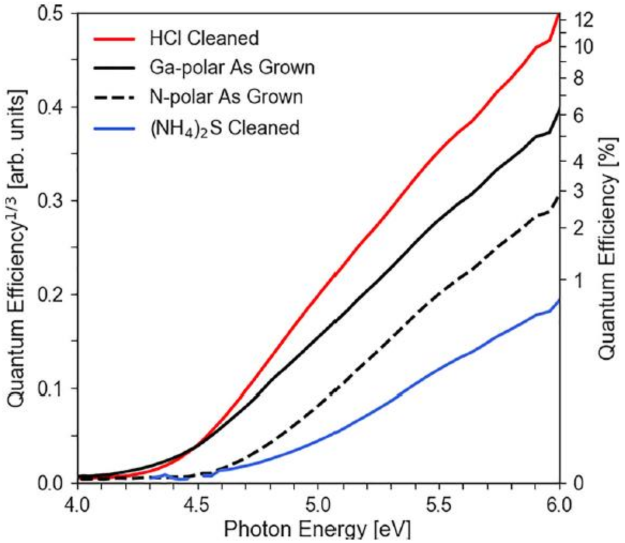
- 8 mA average beam current
- Visible light, single line 488 nm. UV multiline 351/361 nm
- Similar run conditions:
    - Laser size
    - Gun pressure
- No lifetime improvement at UV

GaN photocathodes





Wurzite (hexagonal) GaN



- **For photoemission near the bandgap (3.5 eV) GaN requires NEA**
- **Typically, NEA is achieved with Cs making it sensitive to vacuum poisoning**
- **Recently NEA activation of AlGaN was achieved and found to be qausi-airstable producing comparable QE to cesiated GaN**
- **Excellent thermal stability and thermal conductivity: great high current candidate!**

Polarization engineered N-polar Cs-free GaN photocathodes

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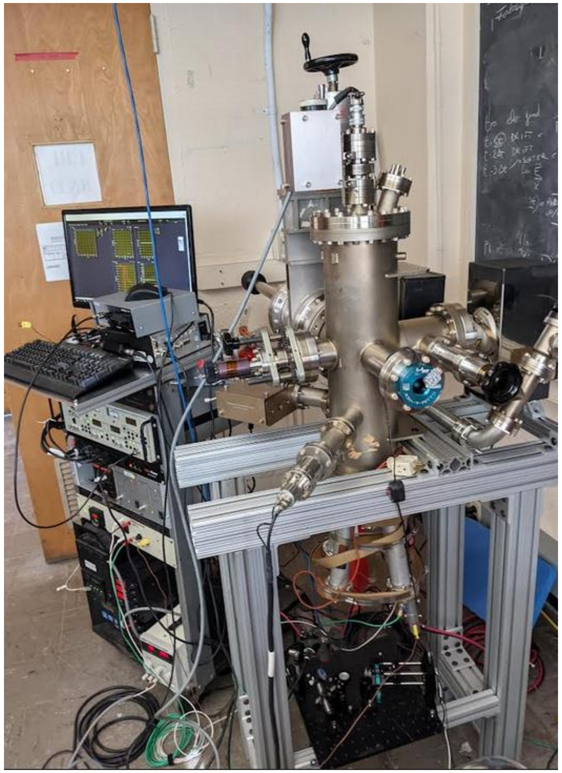
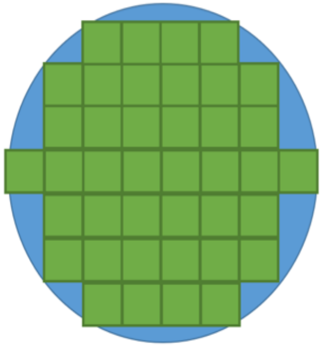
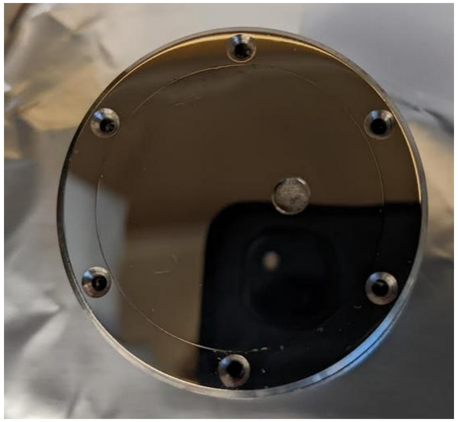
GaN studies status

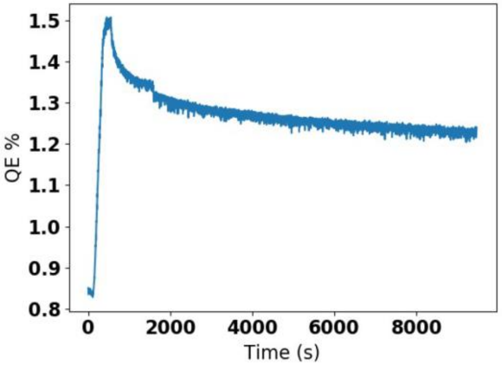


Dedicated GaN activation chamber complete!

- NEA activation with Cs
- CsI (Alkali Halide) source

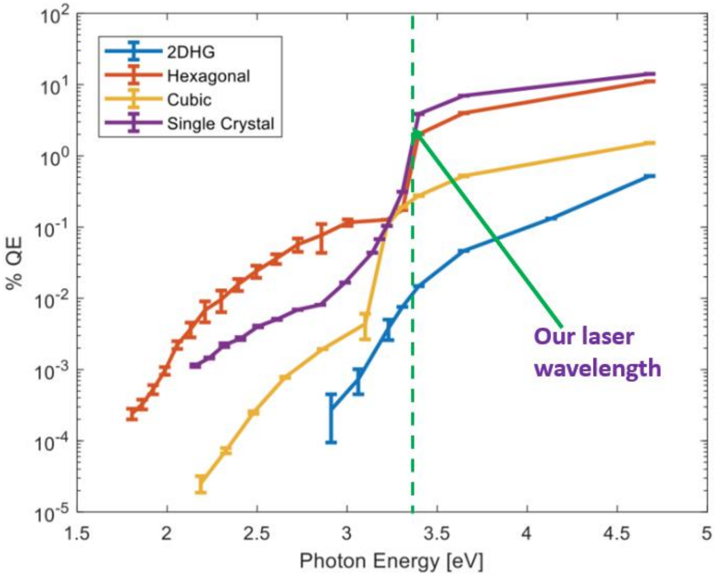


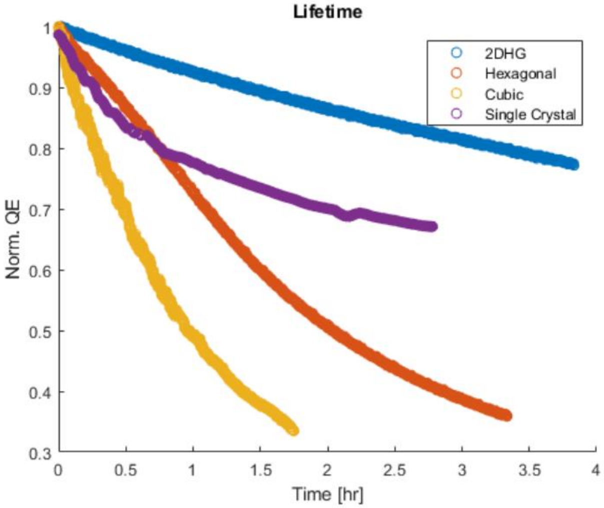




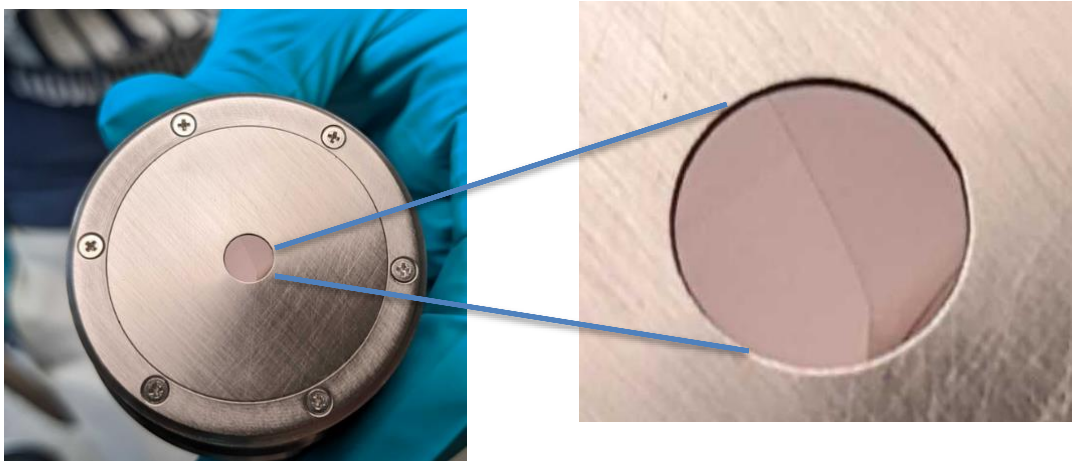
- New sample holder tested in DC gun at 200 keV. No measurable field emission!
- Compatible with III-nitride samples as well as GaAs samples

GaN Studies (cont.)





- **First ever demonstration of high current** (~ mA). Goal is to measure the charge lifetime.
- Single crystal sample looks to be the best candidate
  - Highest QE
  - longest (vacuum poisoning dominated) lifetime
- **A 1% QE corresponds to 2.9 mA/W** (beam current per laser power). **High current is very achievable!**
- **Sample cracked. Expecting a new sample soon.**



Budget and Deliverables

	FY20	FY21	Total
a) Funds allocated	184 k	184 k	368 k
b) Actual cost to date	115 k	218 k	333 k

Funds

2022 timeline

Calendar year 2022	1st quarter	2nd quarter	3rd quarter	4th quarter
Task 1 (Vis/UV Alkali antimonide)	🟥	⬛	⬛	🟩
Task 2 GaAs studies	⬛	⬛	🟩	🟩
Task 3 GaN Chamber Fab.	🟩	🟩	🟩	🟩
Task 4 GaN lifetime	🟥	🟥	🟥	⬛

🟥 preparation

⬛ Lifetime in HERACLES

🟩 Task completed

Thank you for your attention!

BACKUP SLIDES

Tasks and milestones

TASK 1:Operate the photogun and beamline with alkali antimonide photocathodes at the highest possible beam current and study the effect of the laser heating as limiting effect on the cathode lifetime.

- **Milestone 1.1**:Operate alkali antimonide photocathodes with visible laser light in the beamline with ion clearing electrodes and measure the photocathode lifetime as function of the average current level and laser power.
- **Milestone 1.2**:Operate alkali antimonide photocathodes with UV laser light in the beamline with ion clearing electrodes and measure the photocathode lifetime as function of the average current level and laser power. Compare results with the ones obtained with visible laser light.

TASK 2:Test of GaAs-based photocathodes for spin polarized electron beam activated with Cs_2Te and Cs_3Sb at the highest possible beam current and studies of the effect of ion back bombardment on the operational lifetime.

- **Milestone 2.1**:Cs2Te and Cs3Sb activated GaAs-based photocathode will be prepared with our optimized procedures in the photocathode laboratory and moved using a vacuum suitcase to the photogun load lock. QE characterization will be performed during every step of the move to verify the cathodes will survive the move.
- **Milestone 2.2**: the Cs2Te and Cs3Sb activated GaAs-based photocathodes will be loaded into the photogun and we will measure the operational lifetime as function of the average current. Comparison will be made with GaAs photocathodes activated to NEA using the Cs-O “yo-yo” method and operated at identical conditions.

Tasks and milestones

TASK 3:Design and build the hardware: a new cathode holder and a dedicated activation chamber-required to operate III-nitride photocathodes in the photogun.

- **Milestone 3.1**:design,build and gun test a new photocathode gun sample holder, compatible with the high fields of the DC photogun and can support the operation of III-nitrides and more in general small size samples(6x6 mm2).
- **Milestone 3.2**:we will repurpose existing hardware to build and commission a vacuum chamber dedicated to the alkali halides activation of III-Nitride which can interface with our existing vacuum suitcase.

TASK 4:III-nitride materials in their stable wurtzite structure (based on GaN and InGaN) will be tested and characterized as photo-emitters in the photocathode lab and in the photogun.

- **Milestone 4.1**: Design and procure candidate III-nitride layered structures based on their wurtzite phase that can be used as photocathode in the near UV or VIS range of the spectrum.
- **Milestone 4.2**:Perform extensive test on III-nitride layered structure at low field and average current in the photocathode lab and in the photogun at high field and high average current comparing the performance achieved with different methods for the NEA activation (Cs, alkali halides, N-polar Cs free activation)