Testing Polarized and unpolarized photocathodes with high average current at the enhanced HERACLES facility at Cornell University

Matthew Andorf

Ivan Bazarov (PI)

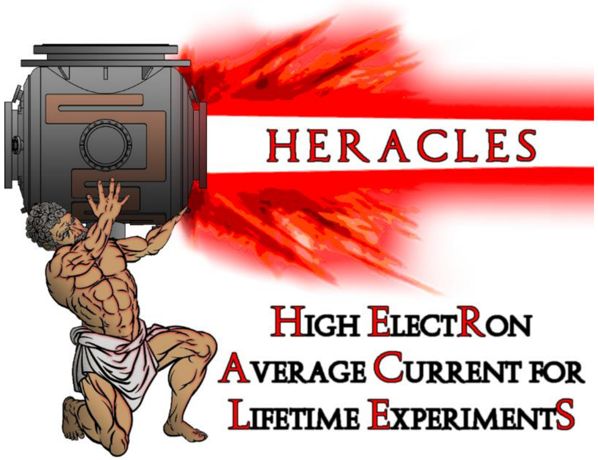
Outline

- Motivation
- Cornell Photocathode Laboratory, HERACLES
- HERACLES upgrade progress
  - Shielding
- GaAs photocathode research
  - CsI surface preparation for GaAs
  - GaAs PEA study
- Rb_3Sb update

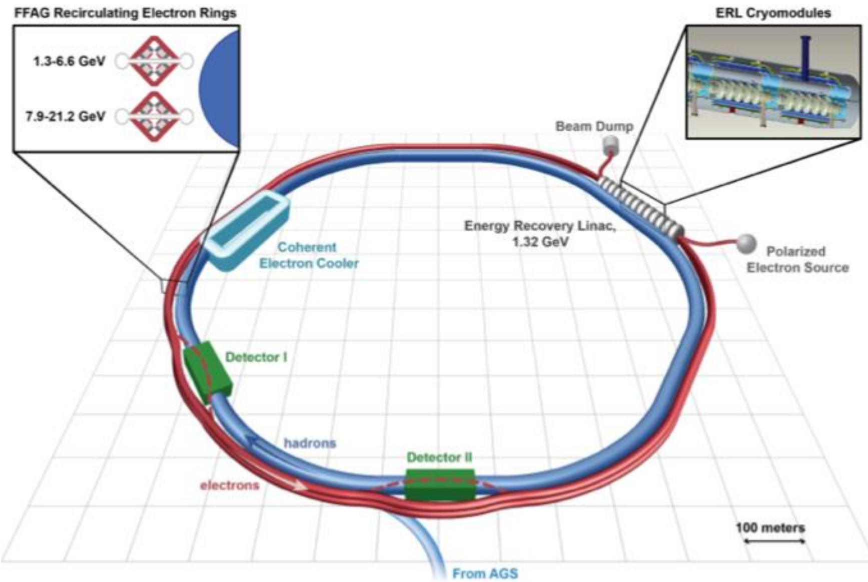
Bright Beams Laboratoy

Acknowledgements to:
***NP-DOE* DE-SC0025663**

- Ivan Bazarov
- Jared Maxson
- Adam Bartnik
- Elena Echevarria-**postdoc**
- **Sam Levenson, Ben Dickensheets (graduate students)**
- **Mark Reamon, Abbigail Flint (undergrad)**

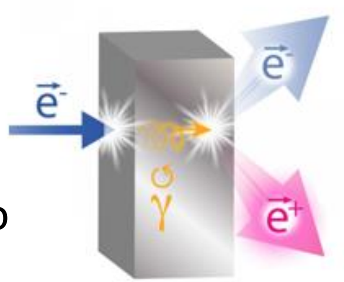


High current and spin polarization

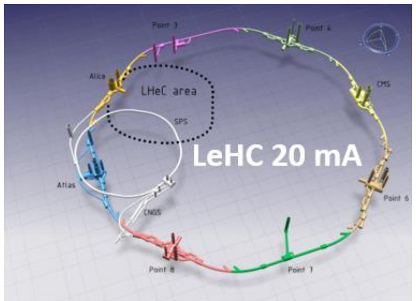


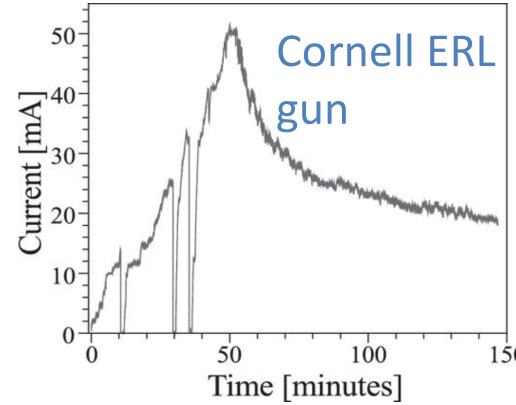
- Many future facilities want spin-polarized electrons at high average currents
- Only candidate cathode for the job: GaAs!
  - >90% ESP, percent level QE@780 nm
- **Charge lifetime**: The amount of current extracted before the QE degrades by 1/e
  - 1000 C is state of the art→6 hours at 50 ma!

Several mA



PEPPo



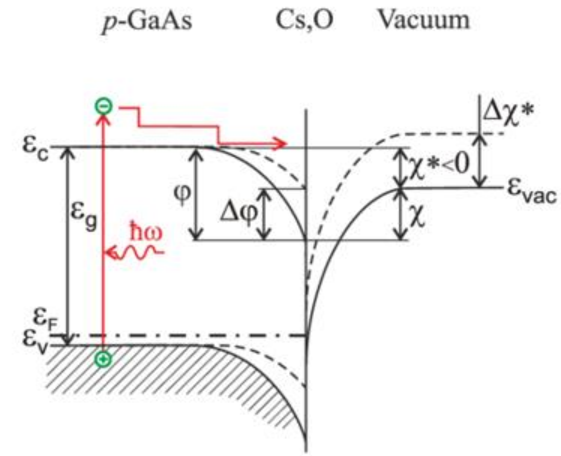


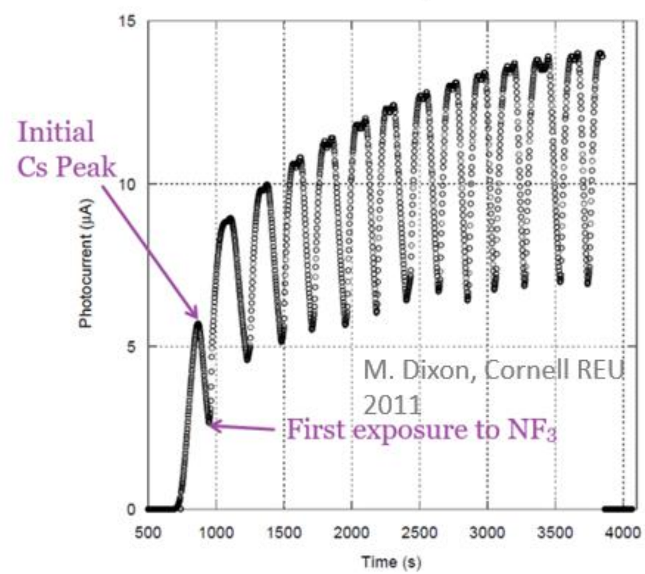
B. Dunham et al, Appl. Phys. Lett. **102**, 034105 (2013)

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

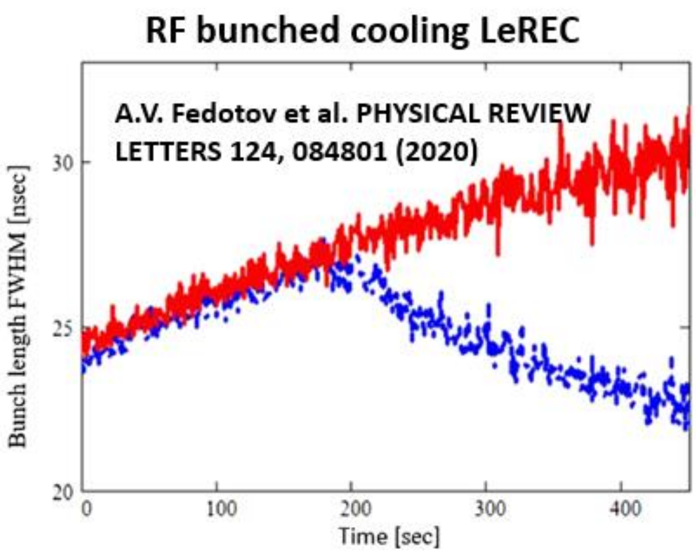
V. Khoroshilov at al. (2020). Journal of Physics: Conference Series. **1482**. 012013 DOI: 10.1088/1742-6596/1482/1/012013.





High current unpolarized beams

State-of-the-Art



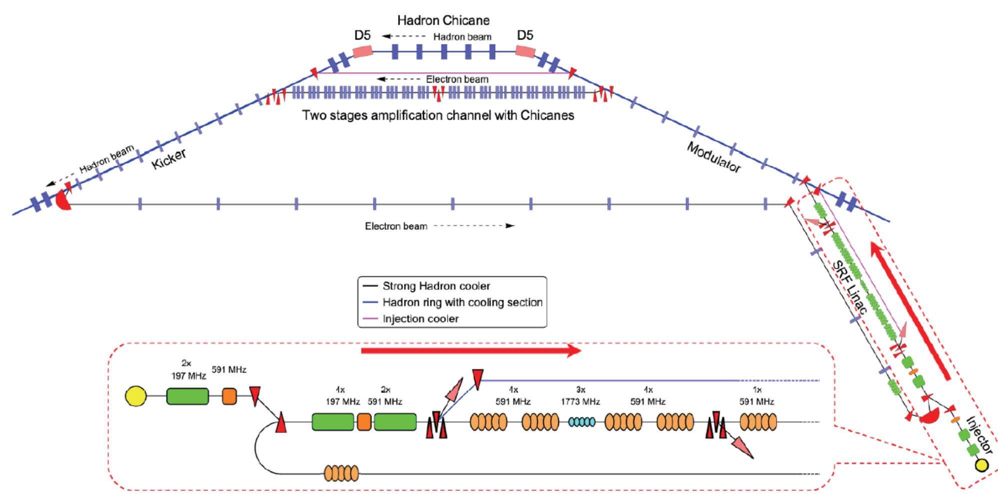
Alaki-antimonide photocathodes:

- High efficiency (~10%), visible light operation
- 100 hour lifetime @ 30 mA (M. Gaowei doi:10.18429/JACoW-ERL2019-WECOXBS02)

Beyond State-of-the-Art

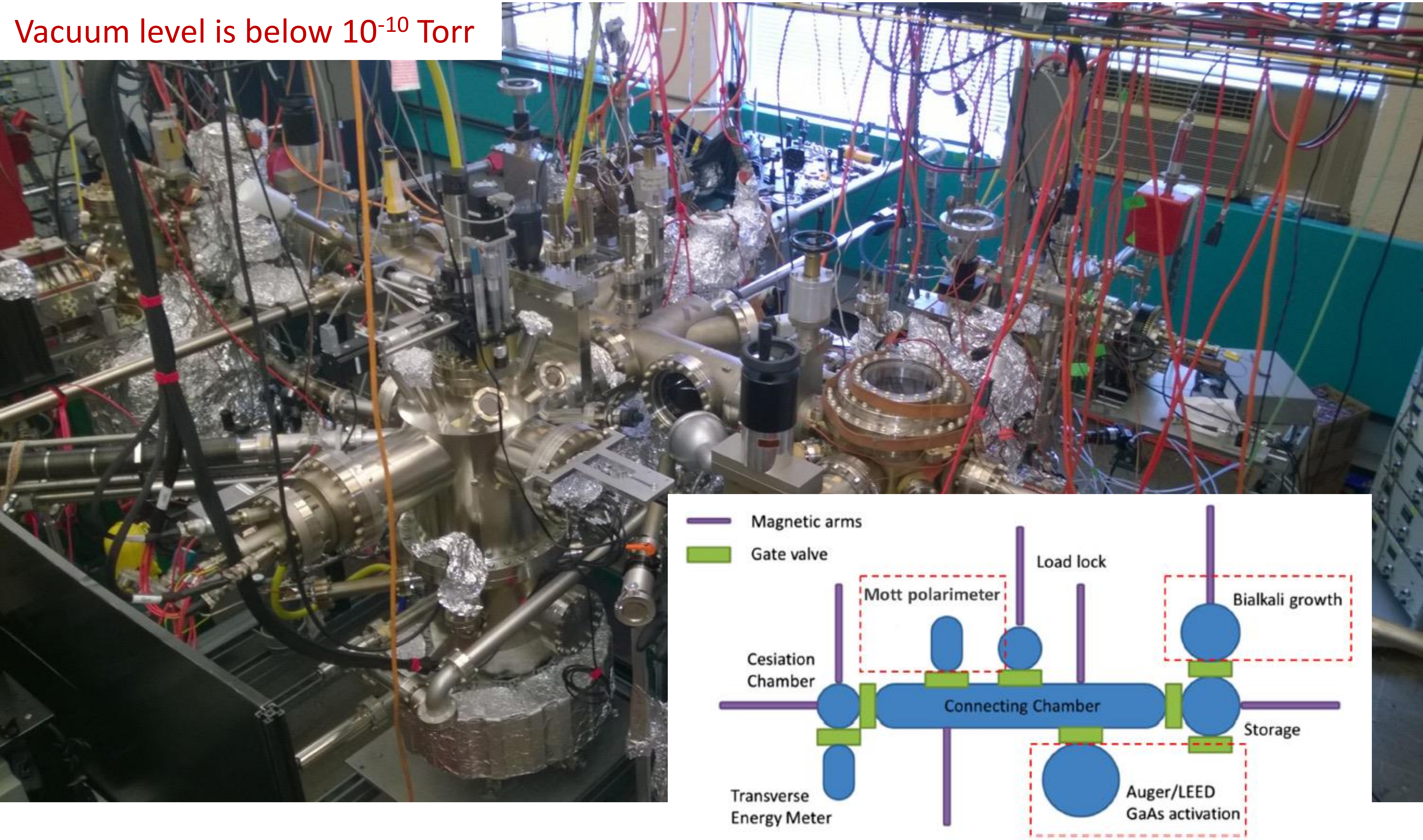
Case	100 GeV	275 GeV
ebeam Energy (MeV)	55	150
ebeam Norm. Emit. (mm·mrad)	2.8	2.8
Rep. rate (MHz)	98.5	98.5
ebeam Bunch Charge (nC)	1	1
ebeam Peak Current (A)	8.5	17
ebeam Bunch Length (mm)	14	7
ebeam Slice σ_δ	10^{-4}	10^{-4}
Hor./Vert. Elec. β in M (m)	86.6 / 14.1	64/ 11
Hor./Vert. Elec. β in K(m)	49.7 / 10	16 / 2
Modulator Length (m)	55	55
Kicker Length (m)	55	55
H/V/L Diffusion Time (hr)	2.0/4.0/2.5	2.0/5.0/2.9
H/V/L Cooling Time (hr)	1.3/2.5/1.7	0.9/2.4/1.3

→ 100 mA!



Cornell Photocathode Lab

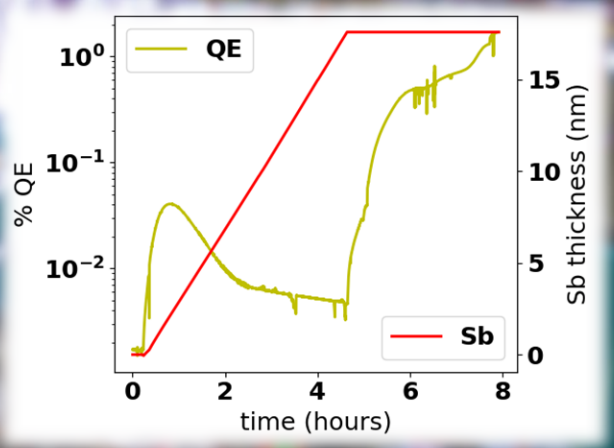
Vacuum level is below 10^{-10} Torr

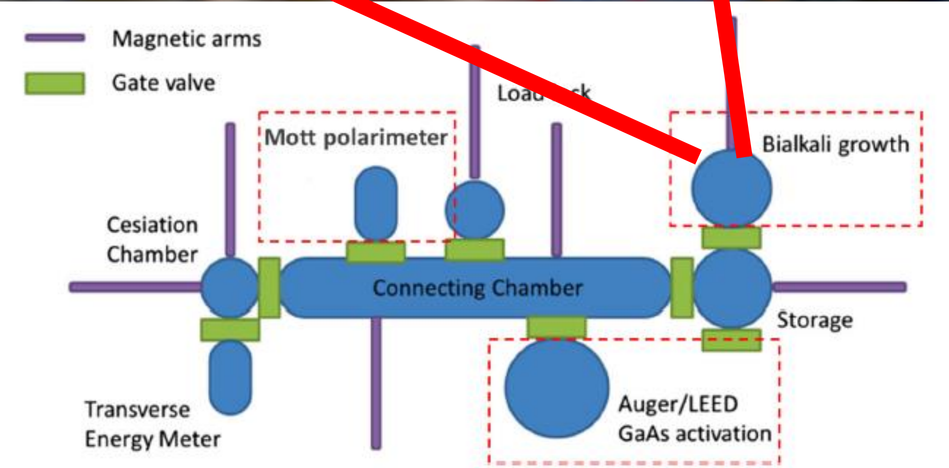


Cornell Photocathode Lab

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

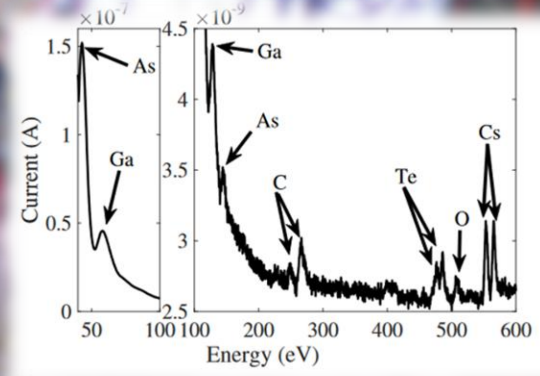


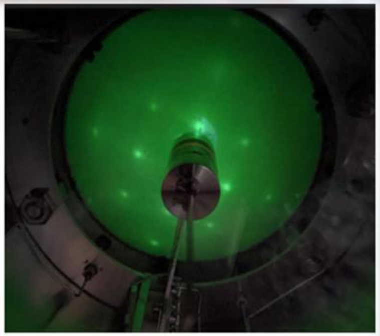


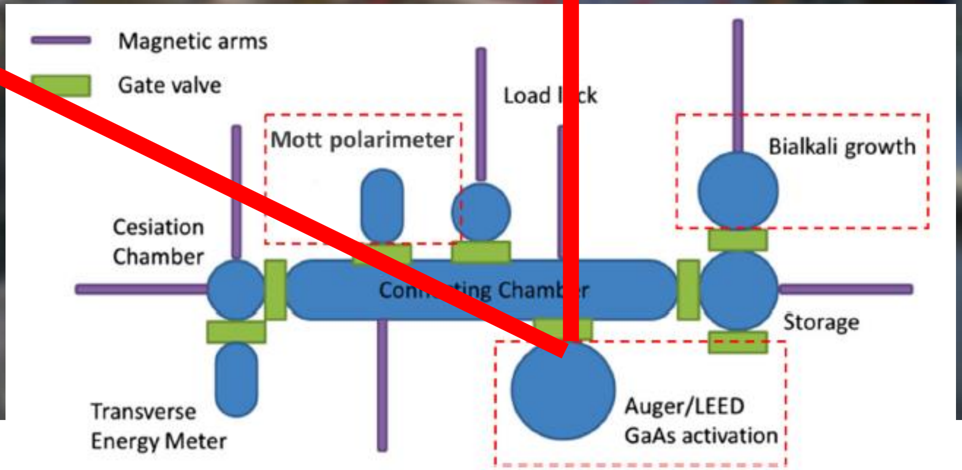
Cornell Photocathode Lab

AUGER Chamber

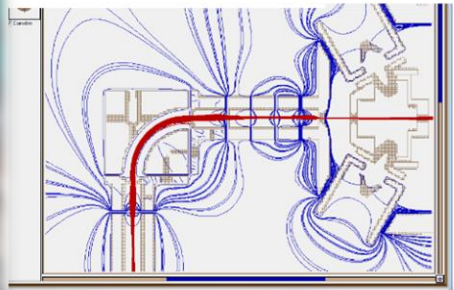
- Auger Electron Spectroscopy-To characterize surface chemistry
- Low Energy Electron Diffraction-Chararacterize surface crystallinity
- Cs, O_2 leak valve.
- Insulated, bias-able cathode holder

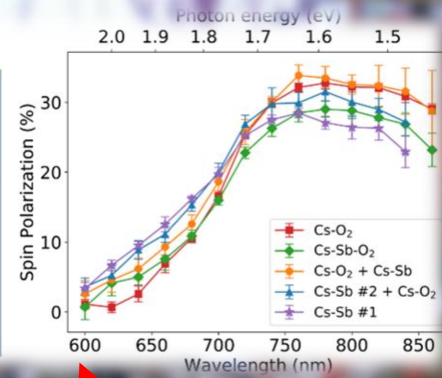






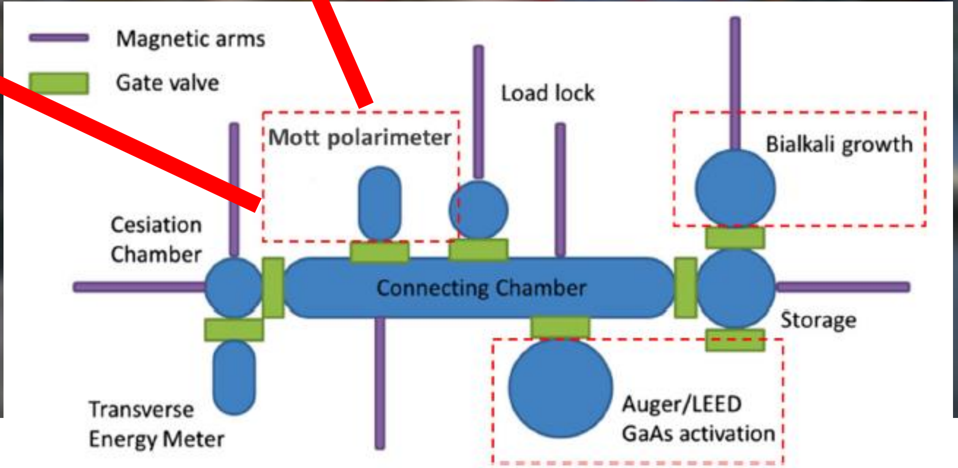
Cornell Photocathode Lab





Mott polarimeter

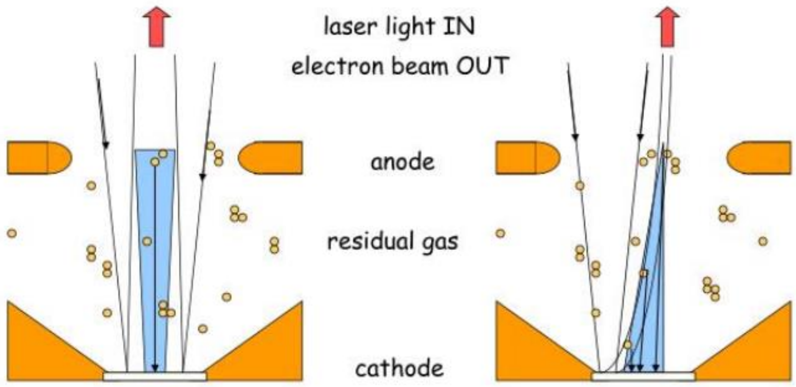
- 20 keV target bias + Einzel lens beamline
- Tungsten scattering target
- Measure spin-polarization

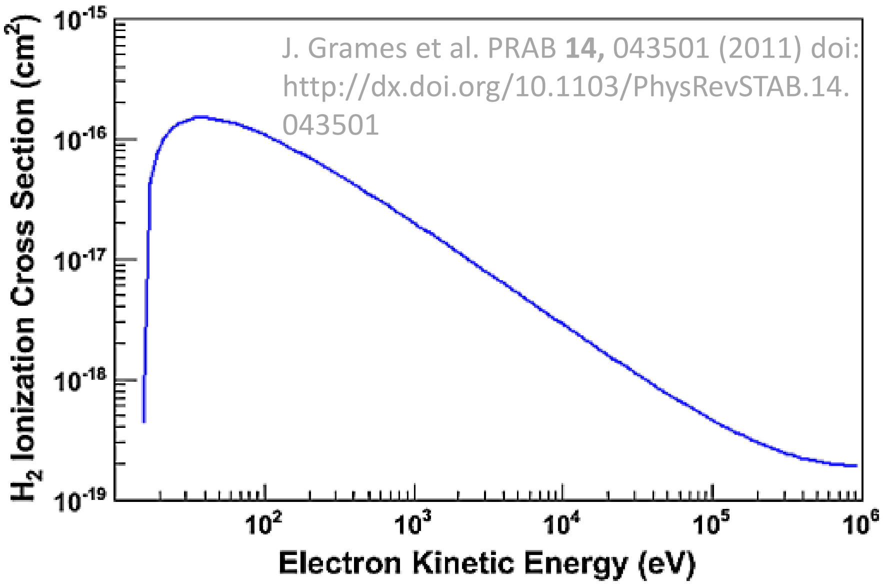


Ion back bombardment

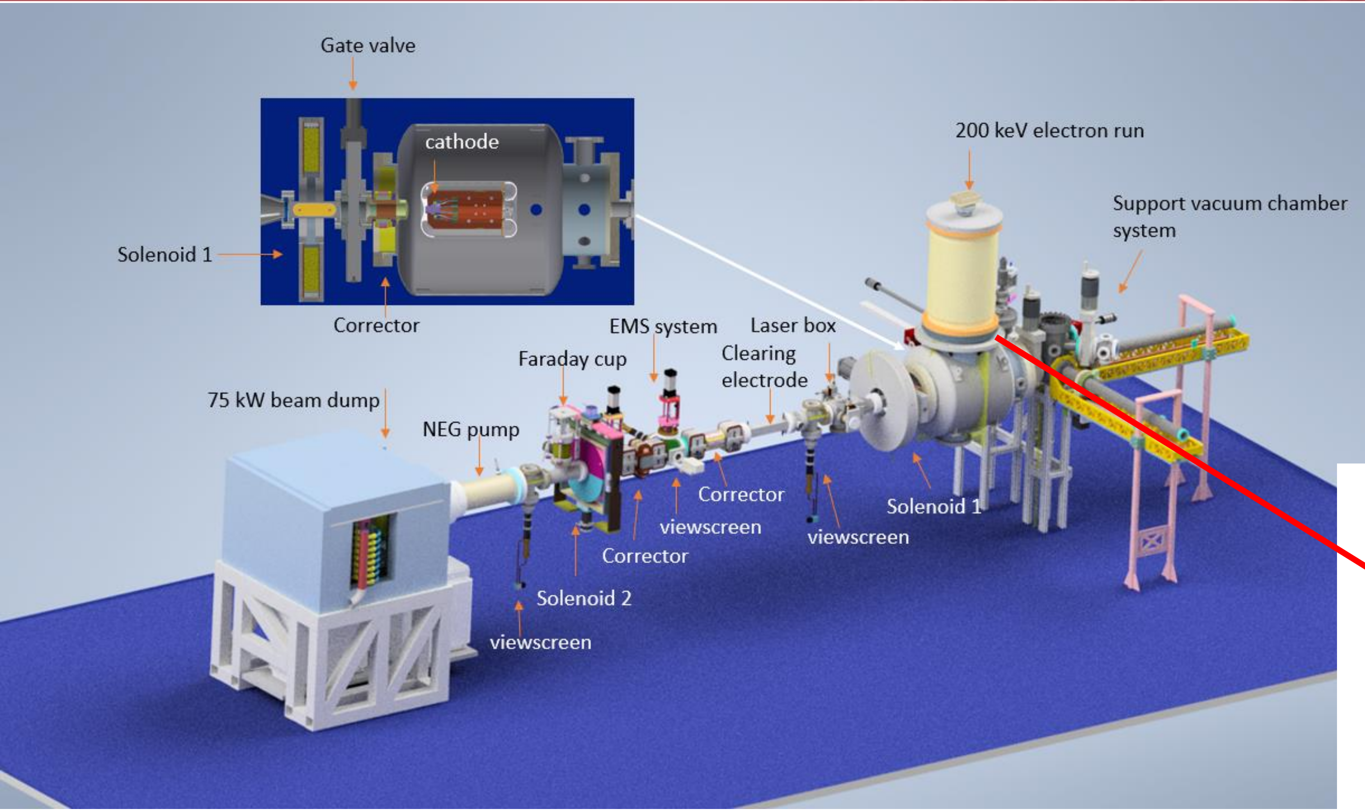
- An electron beam can ionize residual gas which will be positively charged
- Ions will be accelerated towards the cathode and cause damage
- So far, results have been in growth chamber
  - Low current (~ nA)
  - Low voltage (-10's V)
  - Main source of degradation comes from vacuum poisoning
- In a 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

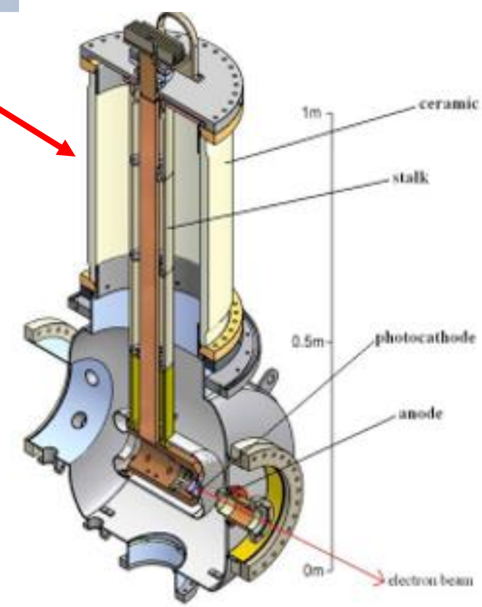




The HERACLES Beamline



HERACLES
HIGH ELECTRON AVERAGE CURRENT FOR LIFETIME EXPERIMENTS

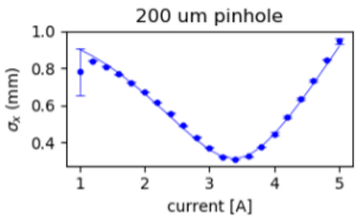


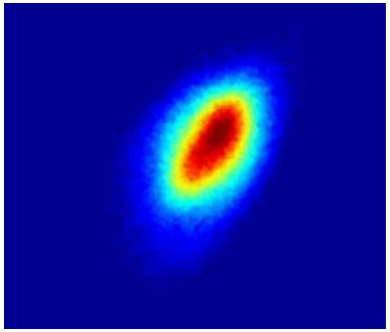
A beamline dedicated to the study of high current beam running:

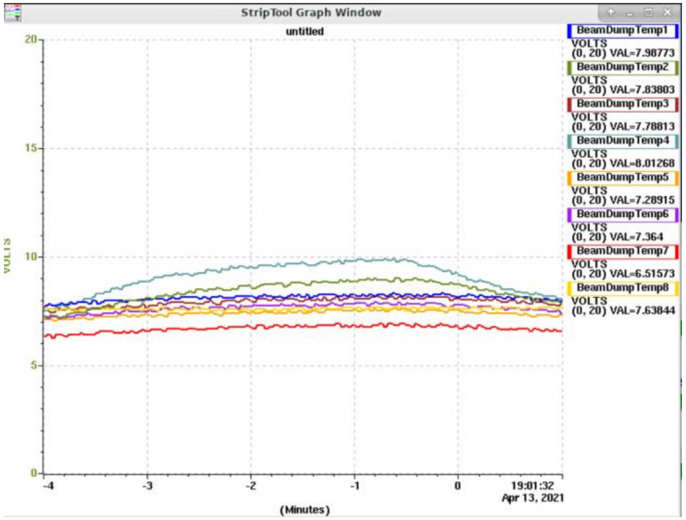
- Former CU-ERL gun 200kV @ 10 mA
- Ion clearing electrodes
- 75 kW beam dump
- EPICS based control system

Beamline and Diagnostics

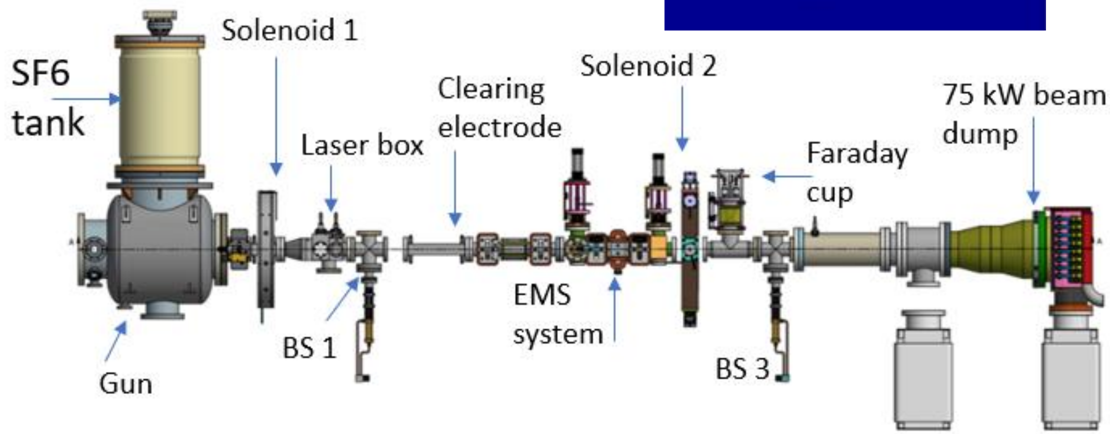
Solenoid scan characterizes cathode MTE





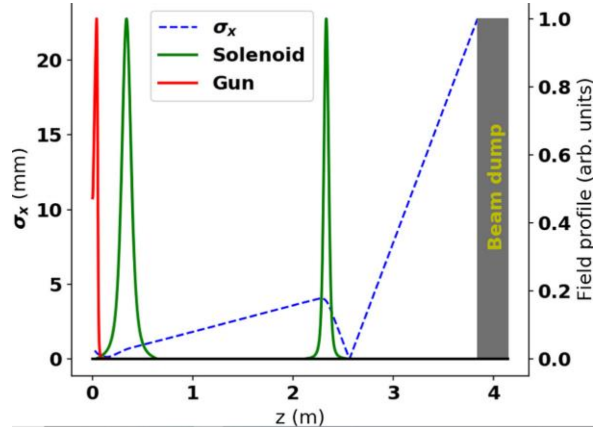


Thermal couples register beam induced temperature rise at the dump



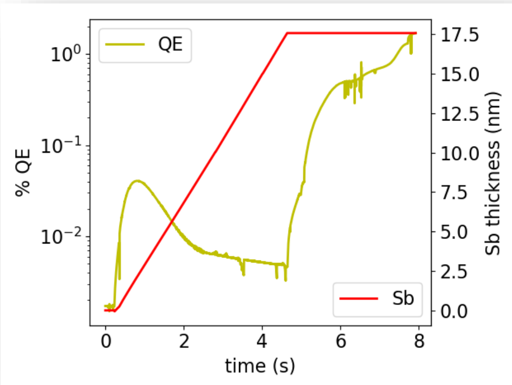
Beamline

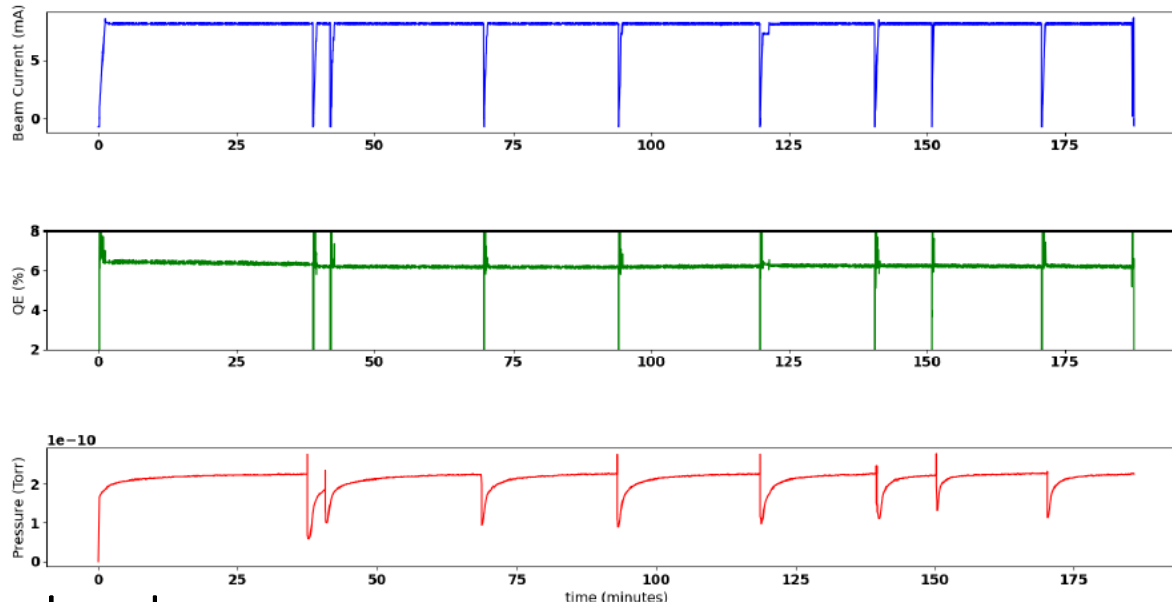
- 2 Solenoids, 3 corrector pairs (hor/vert)
- 2 clearing electrodes
- 3 screens, 1 quad detector
- 1 Faraday cup
- EMS system (not implemented)



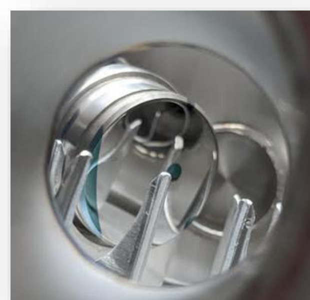
GPT simulation of fields/beam envelope

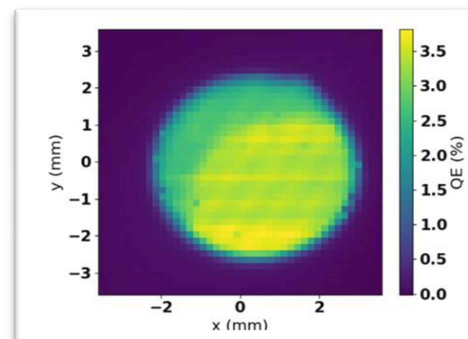
HERACLES high current performance





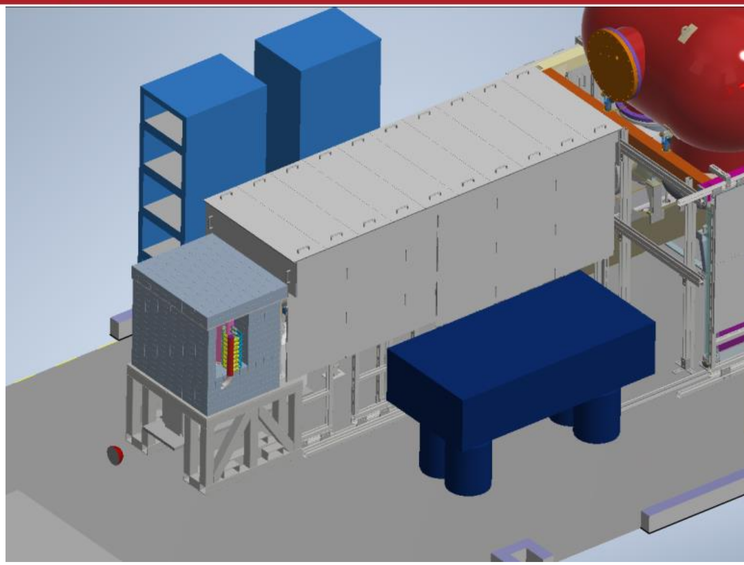
- Cs_3Sb cathode on stainless steel puck
- 10 mA max current, limited by radiation trips
- 8 mA constant current for 3 + hours with no significant change in cathode QE
- **Major goal: Operate HERACLES above 50 mA**

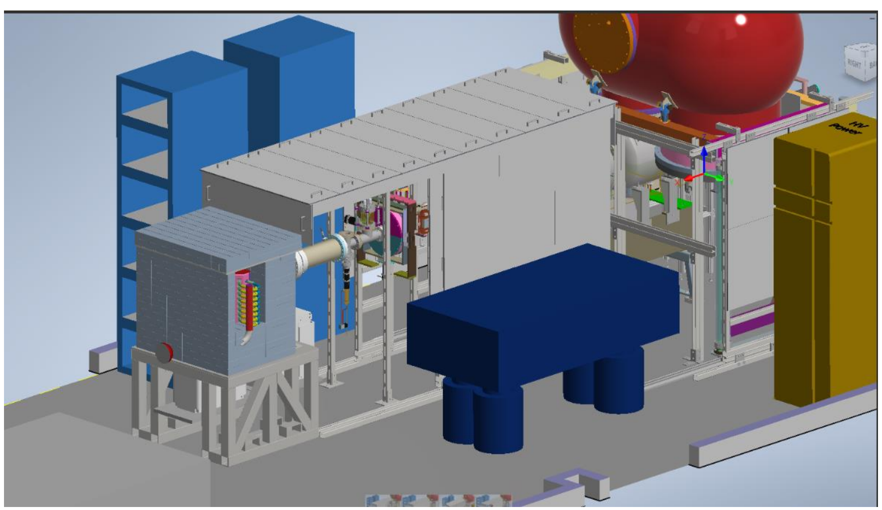




M. Andorf et al. NIMA: **1052** 168240 (**2023**) https://doi.org/10.1016/j.nima.2023.168240

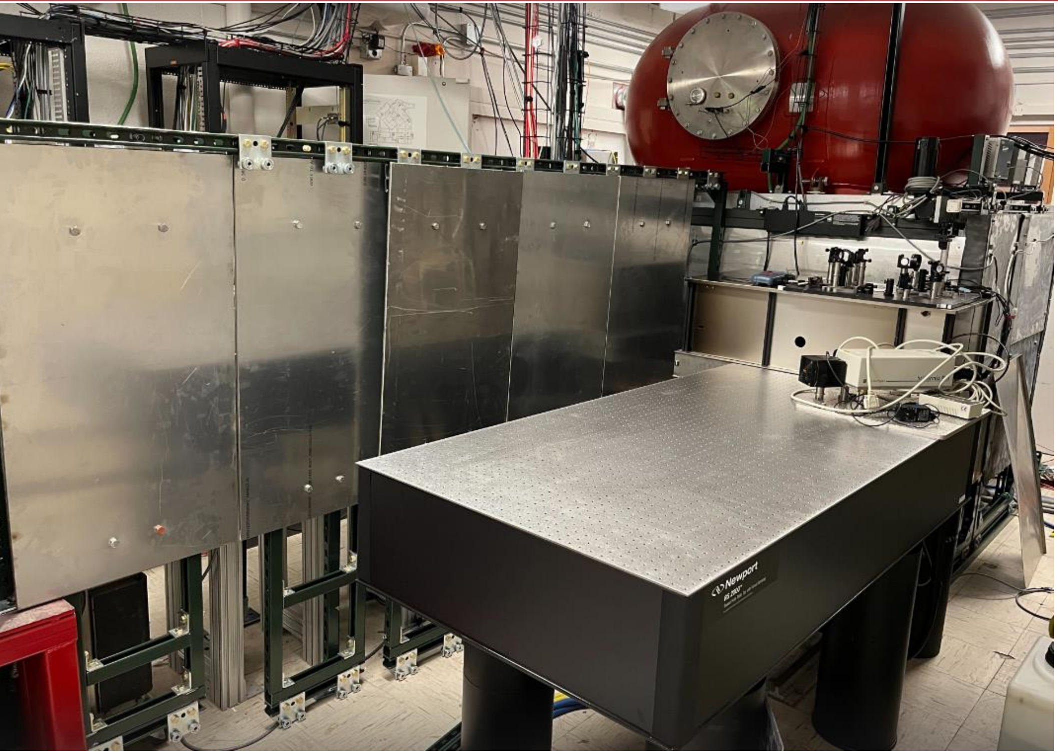
HERACLES shielding upgrade





- Project goal: enable 50 mA or beyond average beam current in HERACLES
  - Shielding upgraded needed for radiation containment
- Study performed to determine lead parameters
  - @ 200 keV primary radiation source is x-rays.
  - ¼” lead panels sandwiched between 1/8” and 3/16” aluminum panels
  - Design allows easier access to beamline AND better coverage

Construction is underway!



Status:

- Framing assembled and installed
- Sliding side panels installed
- Top panels next
- **Construction to be completed before the end of 2025 and commissioning to follow shortly!**

HERACLES laser system

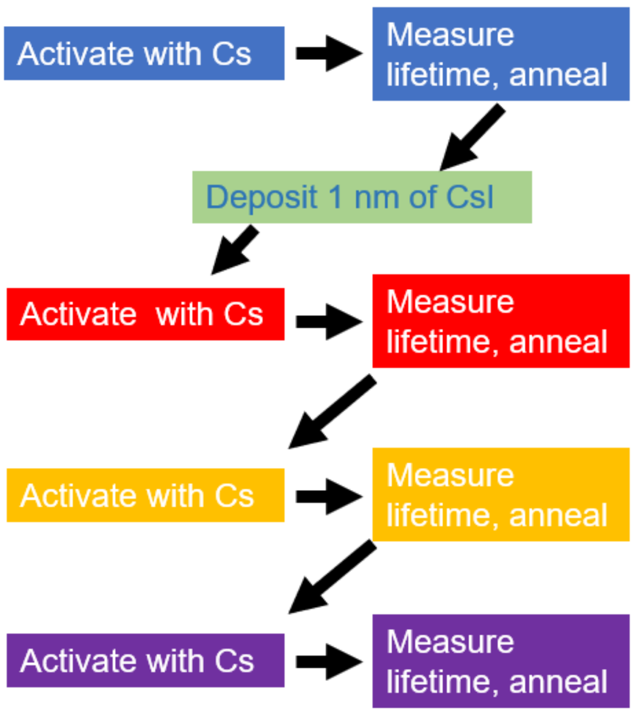
High current operation laser

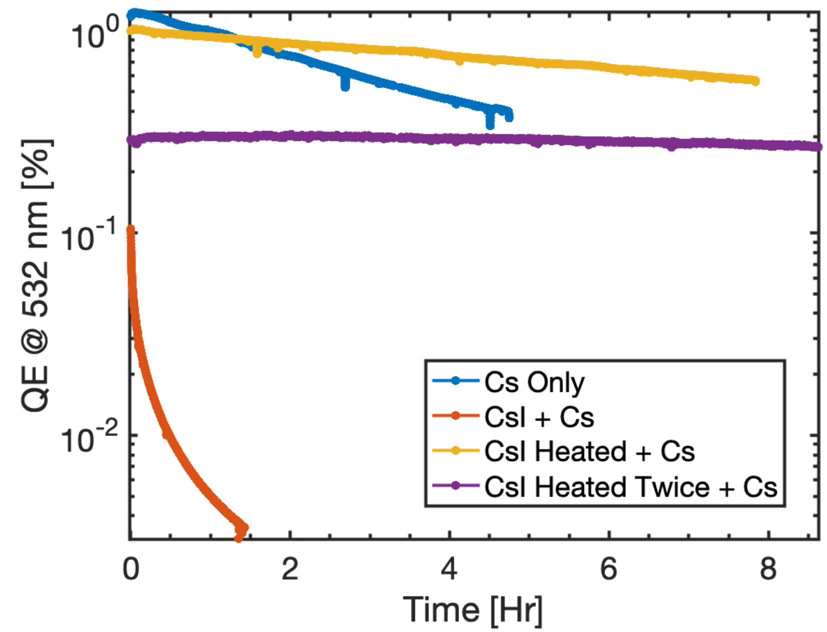
- Second harmonic generation of 1030 nm seed pulse (515 nm light @ photocathode)
- Flexible repetition rate (10.2 MHz→ 1.3 GHz) and pulse energy (14 → 300 nJ)
- Assuming 5% QE laser can produce:
  - Up to 6.2 nC bunch charge
  - 375 mA beam current (i.e. laser power will not be the limiting factor for high current operation!)

Tunable laser source

- Optical parametric amplifier
  - Shared with MEDUSA beamline
  - 650-2300 nm
- High bunch charge:
  - 4-8 uJ→ > 100 nC for GaAs (i.e. pulse energy not a limiting factor for high charge operation!)

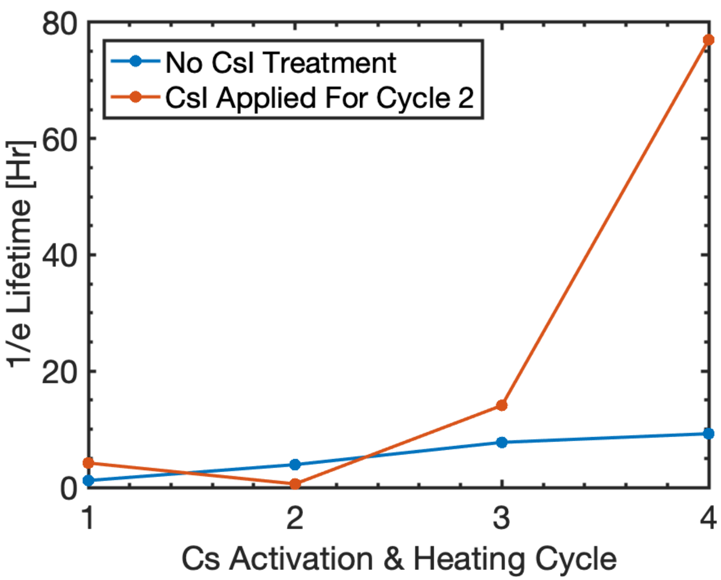
CsI surface treatment of GaAs

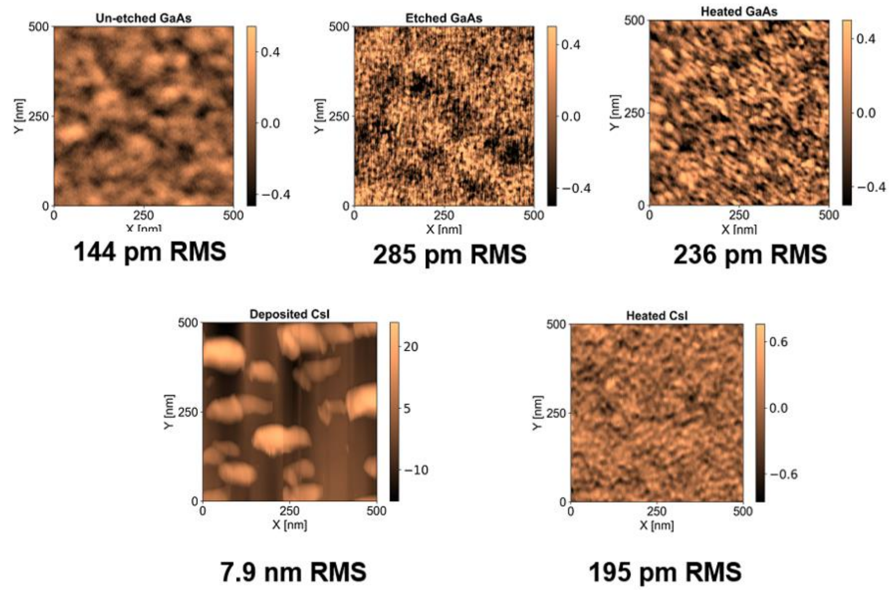




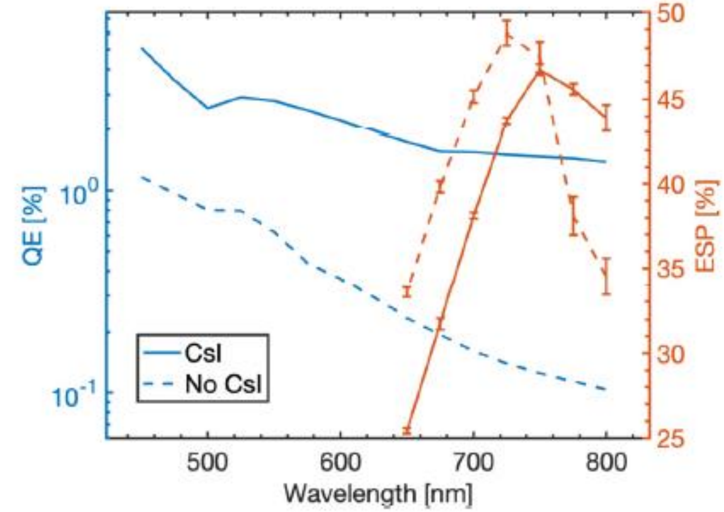
- Cesium Iodide has been used as the photoemitter material in Ring Imaging CHerenkov (RICH) detectors
- We were investigating the possibility of using it for NEA activation (similar to Sb approach)
  - Had been used in conjunction with laser activation to improve metal cathode QE (Chemical Physics Letters 621 (2015) 155–159)
- **cycle of deposition and heating resulted 20x better lifetime!**

CsI surface treatment of GaAs



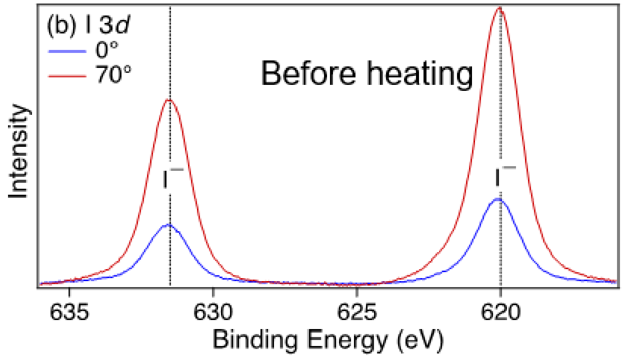


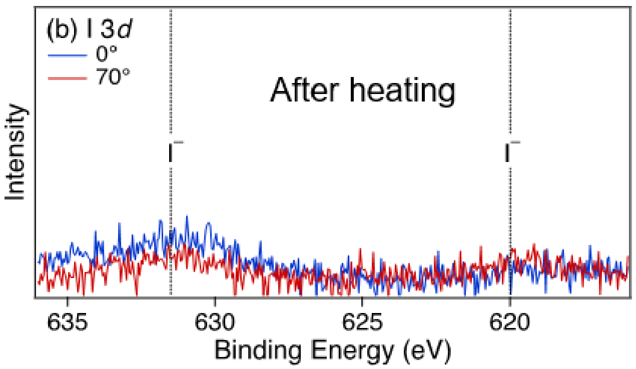
- Improvement in lifetime NOT the result of longer heating time
- ESP is not degraded with improved lifetime

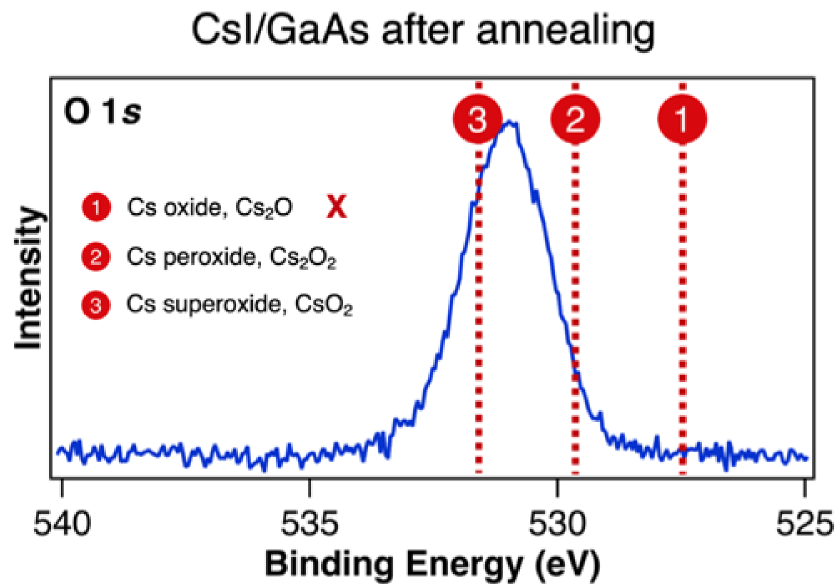


Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

CsI Surface treatment of GaAs







Q. Zhu, M. Hines.

- XPS analysis shows clear presence of Iodine before heating but none after!
- Post heated surface shows suppression of Cs-oxide while Cs per/super-oxide is present

GUNS TEST PLANNED FOR THIS PROJECT!

A cesium-iodide surface treatment for enhancement of negative electron affinity photocathode chemical robustness

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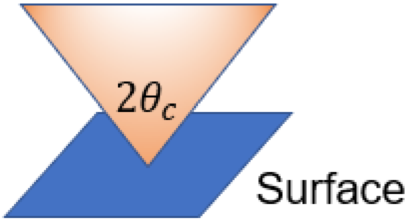
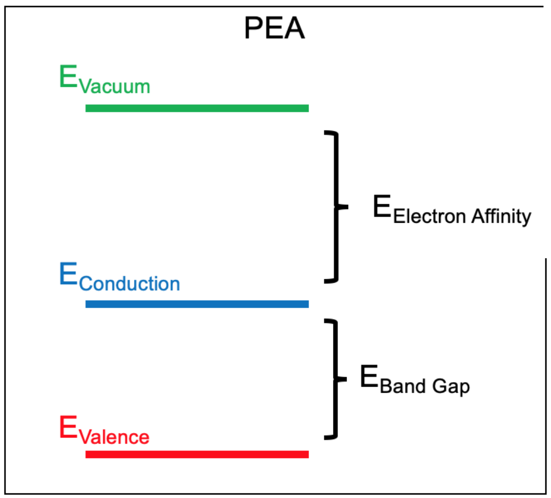
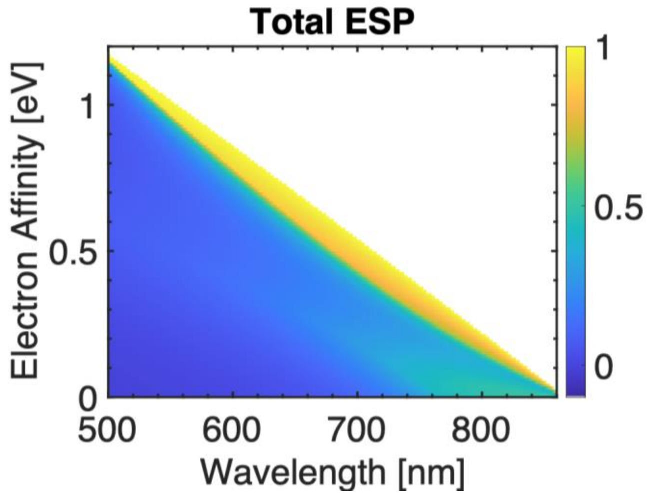
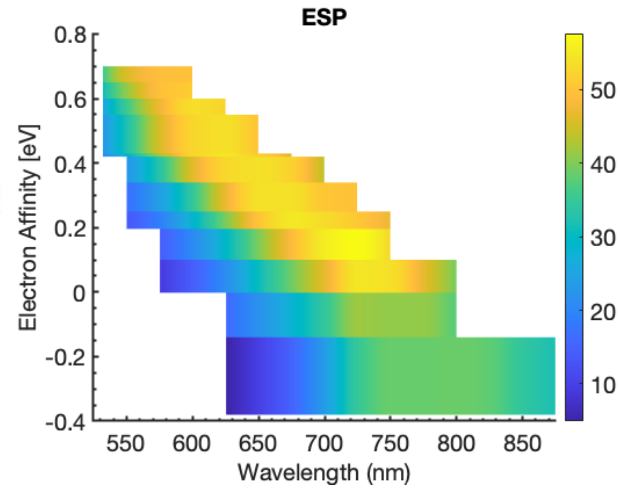
S. J. Levenson,[1,a)] M. B. Andorf,[1] M. A. Reamon,[1] I. V. Bazarov,[1] A. Galdi,[2] Q. Zhu,[3] M. A. Hines,[3] J. Encomendero,[4] V. V. Protasenko,[4] D. Jena,[4,5,6] H. G. Xing,[4,5,6] and J. M. Maxson[1]

GaAs in PEA









- Ordinarily GaAs operated in NEA
  - Bulk GaAs theoretical 50% ESP limit
- During beam operation GaAs PC evolves from NEA to PEA
  - Decrease in QE
  - Increase in polarization
- Effect of PEA characterized experimentally and modelled analytically

Characterization of electron spin polarization from positive electron affinity GaAs photocathodes

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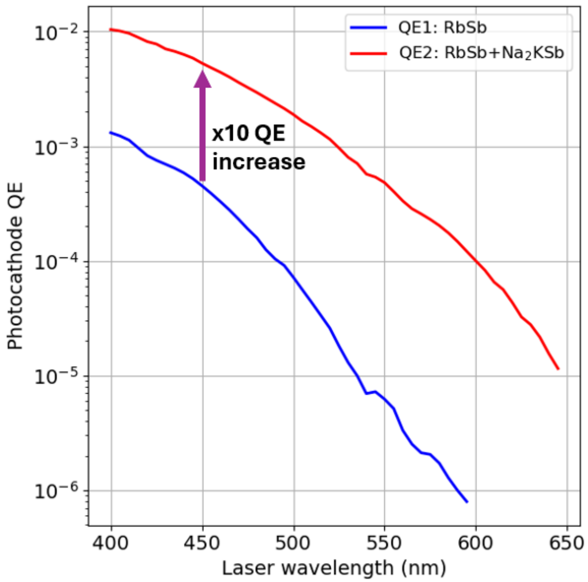
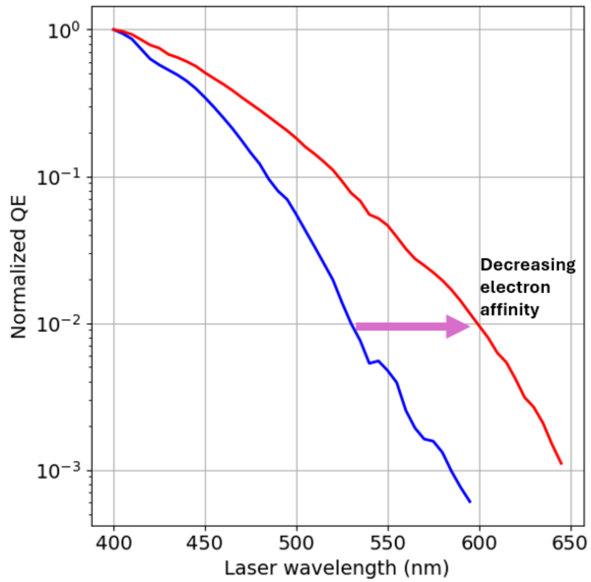
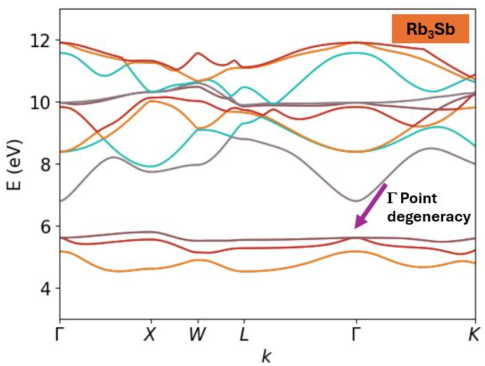
S. J. Levenson,[1,a)] M. B. Andorf,[1] M. A. Reamon,[1] B. Vareskic,[2] A. Galdi,[3] O. Chubenko,[4] J. Callahan,[4] J. M. Maxson,[1] and I. V. Bazarov[1]

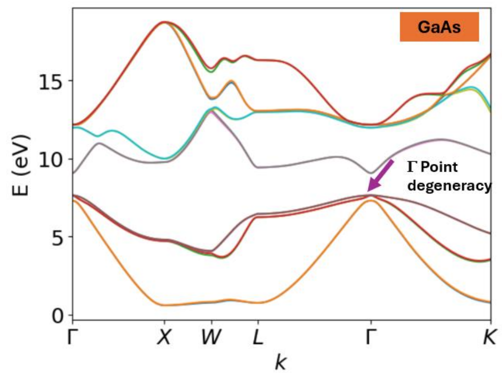
Rb_3Sb as spin-polarized source

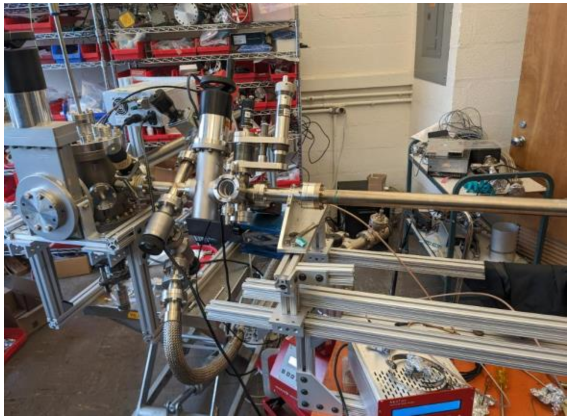




- Work supported by NCE of DOE-NP No. DE-SC0021002 (ended summer 2025)
- Applied 0.1 nm of Na_2KSb on top of Rb_3Sb observed:
    - x10 increase in QE
    - Spectral response indicates shift to lower EA
- Actively working towards spin polarization measurement!







Budget and Deliverables

	FY2025	FY2026	Total
a) Funds allocated	250 k*	180 k	410
b) Actual cost to date	98** k	0	214 k

As of 8/31/25*
**does not included shielding purchase

	1st quarter	2nd quarter	3rd quarter	4th quarter	5th quarter	6th quarter	7th quarter	8th quarter
Dark and Charge lifetime studies of CsI-GaAs activated with CsO and Cs-Sb-O							■	■
Design and install upgraded shielding in HERACLES and ensure safe operation	■	■	■	■	■			
Recommission pulsed laser system for HERACLES					■	■		
Commission HERACLES up to or beyond 50 mA						■	■	■

Thank you for your attention!

Milestones

Task 1: *Perform lifetime studies of CsI surfaced treated GaAs to assess CsI's ability to improve photocathode lifetime at high average current in HERACLES.*

In previous work we have already demonstrated that CsI surface treated GaAs is more robust against chemical poisoning. In this work we propose to perform charge lifetime tests of surface treated GaAs in HERACLES with both Cs-O and Cs-Sb-O NEA activation.

Milestone 1.1: Measure the charge lifetime of CsI-GaAs activated with Cs-O and compare it to the charge lifetime of bare Cs-O activated GaAs in HERACLES. An average beam current of 1 mA or greater will be used during the charge lifetime tests.

Milestone 1.2: Perform the first ever Cs-Sb-O activation of CsI-GaAs and compare its dark lifetime to bare Cs-O and CsI treated Cs-O activated GaAs in the HERACLES growth chamber.

Milestone 1.3: Measure the charge lifetime of CsI-GaAs activated with Cs-Sb-O and compare it to the charge lifetimes obtained in **Milestone 1.1**.

Task 2: *Upgrade HERACLES infrastructure to enable safe operation of beam currents of up to 50 mA and beyond.*

During commissioning of HERACLES we observed that insufficient shielding prohibited practical operations beyond 10 mA average beam current. Thus, we propose upgrading our shielding to enable higher current operation. If needed, we will make additional improvements to the shielding as we ramp to higher currents.

Milestone 2.1: Design and install lead shielding to enable safe operation of beam current up to and beyond 50 mA.

Milestone 2.2 Staged high current testing of safe beam operation using continuous wave (and pulsed laser, as it becomes available) from 1 mA to above 50 mA. At each stage,

radiation surveys will be performed, and the efficacy of the shielding assessed to assure personnel safety during high current operation.

Task 3: *Install and recommission an existing laser system to enable pulsed beam production in HERACI*

To ensure the beam dynamics in HERACLES are as close as possible to what is found in photoinjectors relevant to current and future NP colliders, we propose to upgrade our laser system to enable pulsed beam operation. We will utilize an existing laser system that will be recommissioned at the HERACLES facility.

Milestone 3.1: Generate 1030 nm laser light from the 1.3 GHz Pritel oscillator and amplify oscillator output to 40 nJ per pulse, 50 W total average power.

Milestone 3.2: Perform second harmonic generation and pulse stacking to produce 8 nJ green pulses with order 10 ps length for an average laser power of 10 W.

Task 4: *Recommission HERACLES with pulsed beam operation. Our goal is to establish stable 50 mA operation.*

Using a Cs_3Sb photocathode we will recommission the upgraded HERACLES facility. We will first establish 10 mA pulsed beam operation before pressing on to 50 mA or higher. While **task 2** is focused on personnel safety, here we focus on machine performance.

Milestone 4.1: Establish stable operation with 10 mA average current of pulsed electron beam for the first time ever in HERACLES.

Milestone 4.2: Establish stable operation with 50 mA average current.

Milestone 4.3: We view this final milestone as a stretch goal: set a new record for average current produced by a high brightness DC gun. Cornell currently holds the record[7] for high average current of 65 mA, which was established using the same DC gun used in HERACLES.