Next Generation Robust Polarization Photocathodes for EIC

Luca Cultrera

Outline

- Spin polarized photocathode requirements
  - – eRHIC and Linac Ring option;
- Non-Exaustive state-of-the-art of GaAs-based photocathodes;
- Photocathode R&D at Cornell University
- Cs_2Te activated GaAs;
- New venues for improving polarized sources;

Projects Goals

NEXT GENERATION ROBUST POLARIZATION PHOTOCATHODES OR EIC

Task 1: Cornell University group will experiment on the **optimal conditions to achieve the NEA** on III-V semiconductors using a **thin layer of Cs_2Te** based on the previous result from the Japanese group.

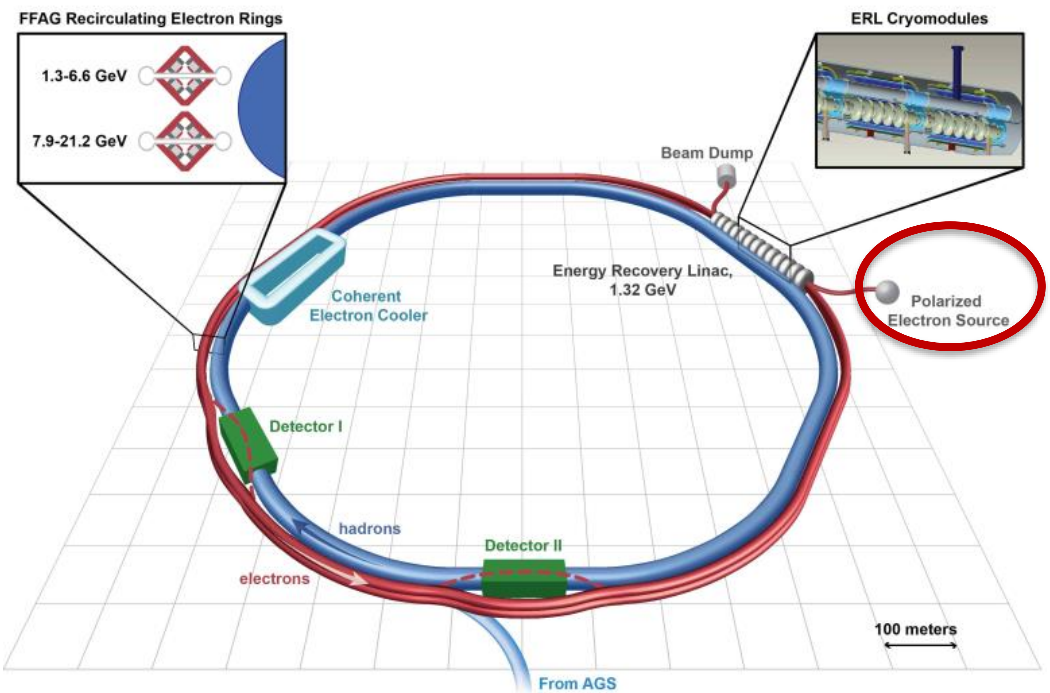
Task 2: Cornell University group will integrate in the UHV photocathode lab and **recommission the Mott polarimeter** so that the spin-polarization of photoelectrons generated from Cs_2Te-coated GaAs-based photocathodes can be measured.

Row	Proponent	Concept		Panel priority	Panel sub-priority
7	Panel	LR	High current polarized and unpolarized electron sources	High	B

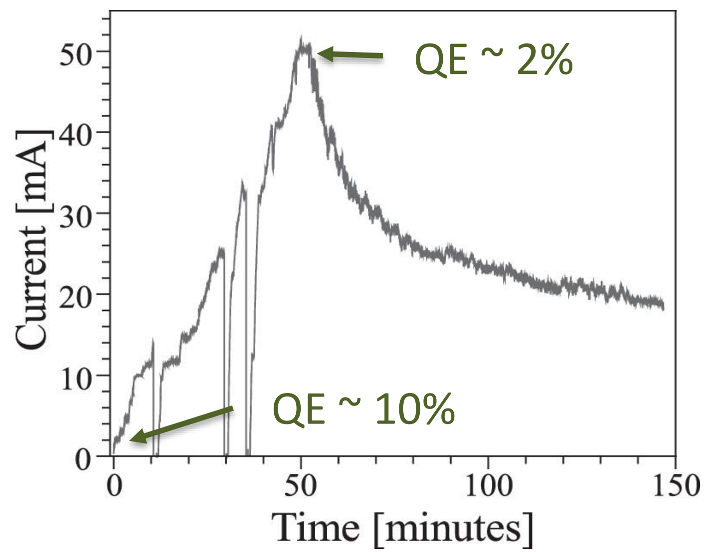
	FY10+F11	FY12+F13	FY14+F15	FY16+F17	Totals
a) Funds allocated				280,000	280,000
b) Actual costs to date				271,857	271,857

eRHIC and the linac ring option

- The linac-ring option needed polarized electron beam with average currents up to **50 mA**.



GaAs @ 532 nm (~5 Watts)
200 Coulomb
(off center active area)

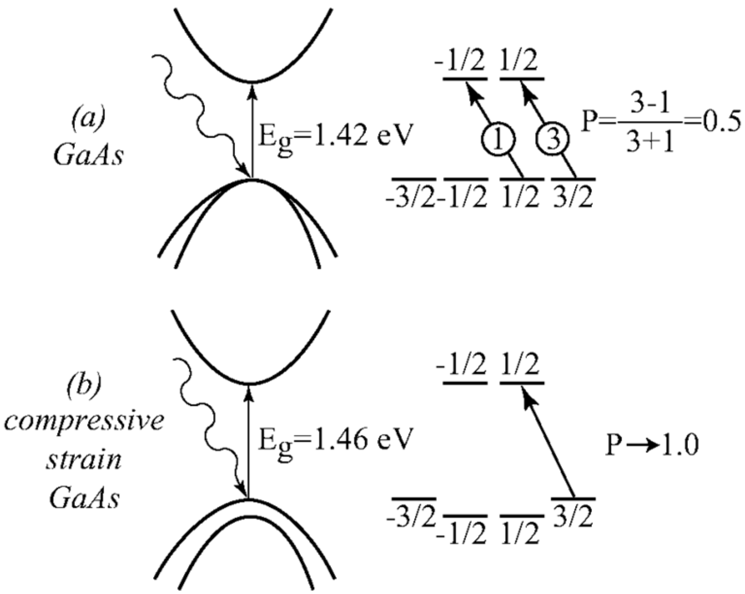


B. Dunham et al, Appl. Phys. Lett. **102**, 034105 (2013)

Electron sources was based on III-V semiconductors photocathodes materials that cannot sustain that average current for longer than few minutes.
Limited effort to address the actual **challenge of improving** the polarized photocathodes using ***new classes of materials and/or activation strategies***

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

Existing photocathodes



Existing Polarized Photocathodes

- High Pol. Satisfies most physics experiment
- But low QE only supporting ~ uA sustained beam delivery

Material / Structure	P (%)	QE (%)
Bulk GaAs	35	10
GaAsSb/AlGaAsP	75	0.3
GaAs/GaAsP	92	1.2
GaAs/GaAsP	92	1.6
InGaAs/AlGaAs	77	0.7
AlInGaAs/GaAs	91	0.5
AlInGaAs/AlGaAs (with DBR)	92	0.85
AlInGaAs/GaAsP (with DBR)	92	0.6

S. ZHANG, P3 Workshop 2016, Newport News, VA — Jefferson Lab

At 1.6% QE the required laser power "on the cathode" @800 nm to generate **50 mA** is about **5 Watts**

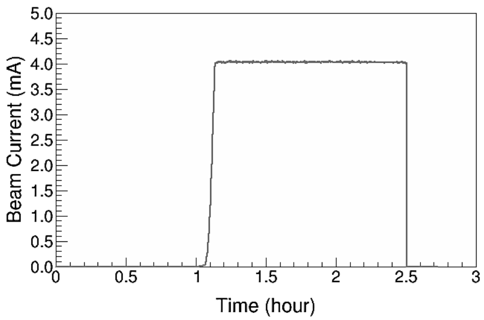
All these photocathodes requires Cs-O activation to achieve Negative Electron Affinity (NEA) and vacuum levels better than 10^{-11} Torr to survive a few days (without even running the beam)

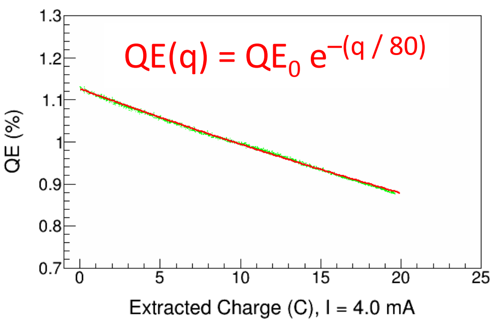
• Superlattices are the best choice

Parameter	Value	Value
Laser Rep Rate	499 MHz	1500 MHz
Laser Pulse Length	30 ps	50 ps
Laser Wavelength	780 nm	780 nm
Laser Spot Size	**0.45 mm**	**0.35 mm**
Photocathode	GaAs/GaAsP	GaAs/GaAsP
Gun Voltage	100 kV	200 kV
Beam Current	**1 mA**	**4 mA**
Run Duration	8.25 hr	1.4 hr
Extracted Charge	30.3 C	20 C
Charge Lifetime	**210 C**	**80 C**
Fluence Lifetime	**132 kC/cm²**	**83 kC/cm²**
Bunch Charge	2.0 pC	2.7 pC
Peak Current	67 mA	53 mA
Peak Current Density	42 A/cm²	55 A/cm²

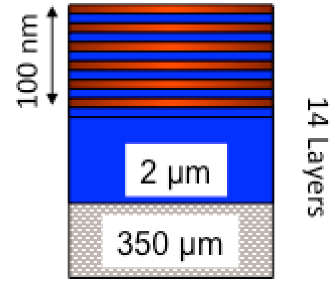
J. Grames *et al.*, PAC07, THPMS064

R. Suleiman *et al.*, PAC11, WEODS3





Superlattice GaAs:
Layers of GaAs on GaAsP



No strain relaxation
QE ~ 1%, 6 μA/mW
Pol ~ 85% @ 780 nm (1.59 eV)

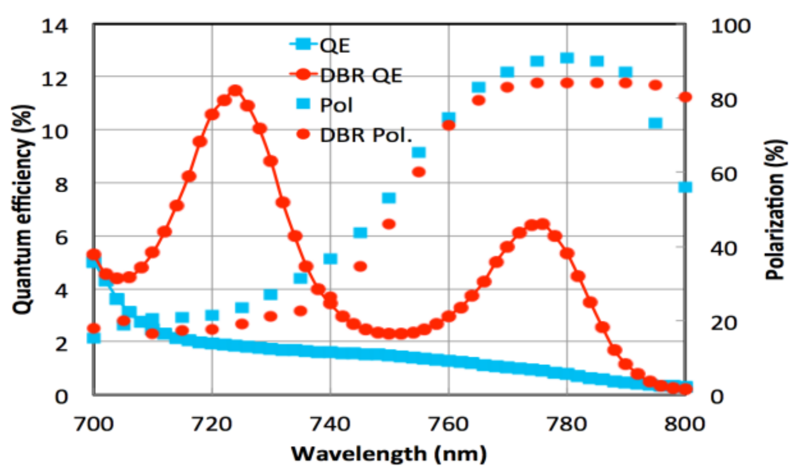
*Up to **4 mA** of polarized e-beam*
*Lifetime limited to **few hours***

Distributed Bragg Reflector

- *Total laser absorption in the SL layer is usually **<5%***
- *A DBR can be used to reflect the unused laser beam back to the SL*

Experimental Results

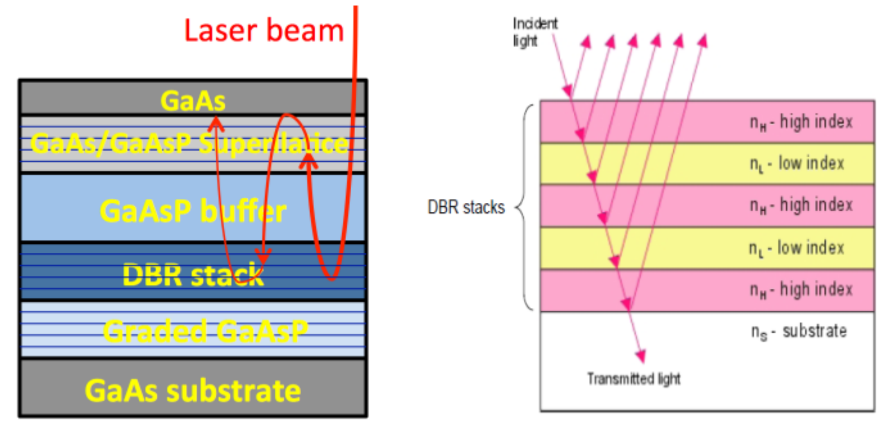
- non-DBR: QE ~ 0.89%, Pol ~ 92% @ 776 nm:
  - DBR: Pol. ~ 84%, QE ~ 6.4%, Enhancement: ~7.2



S. ZHANG, P3 Workshop 2016, Newport News, VA — Jefferson Lab

Benefits of DBR

- DBR photocathode : absorpt. in GaAs/GaAsP SL >20%
  Less light needed ⇨ less heat deposited
- F-P can be formed btw top layer & DBR

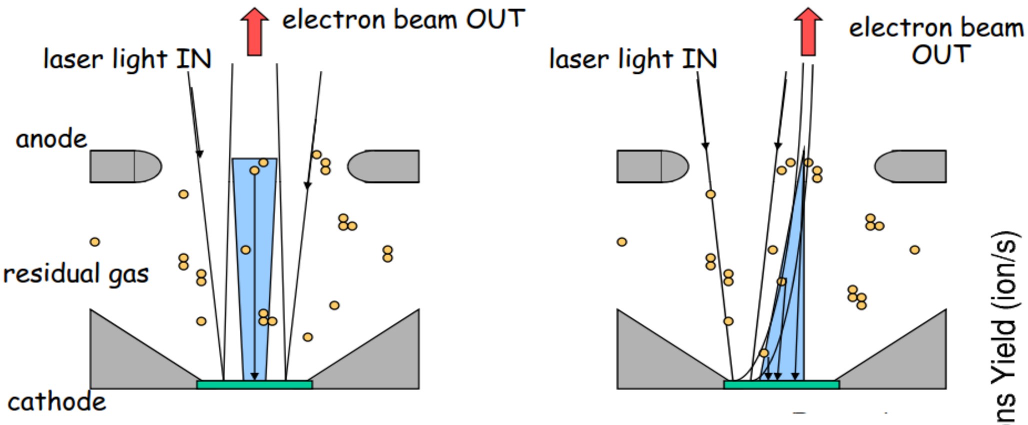


S. ZHANG, P3 Workshop 2016, Newport News, VA — Jefferson Lab

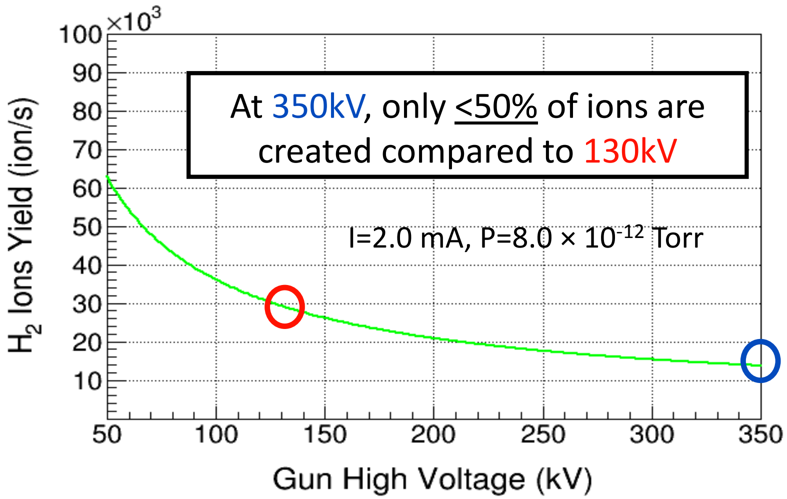
- ***QE is now a factor 6 larger***
- ***Potential for higher currents***
- *Less laser power, less heat to dissipate*
- *Quite complex structure*

But 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;

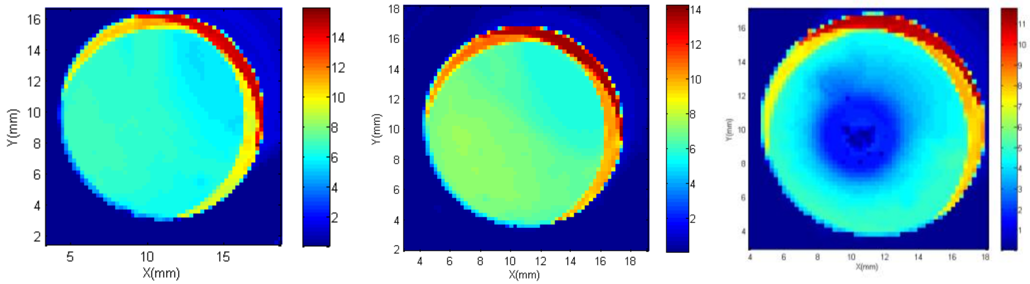


A single HV breakdown event inside the gun Can get the vacuum high enough to instantly "kill" the cathode



Courtesy of J. Grames

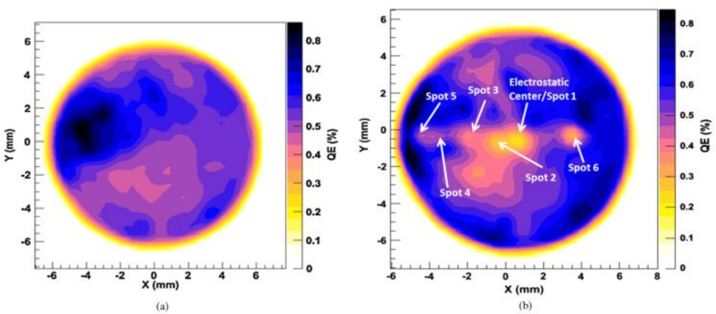
Alkali antimonides ion back bombardment

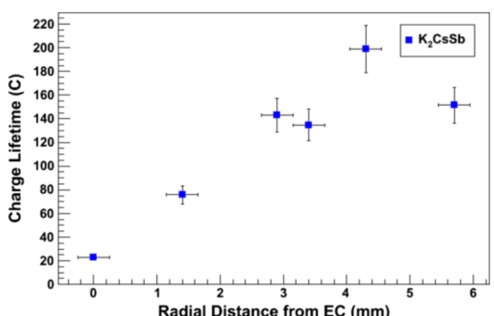


Fresh cathode

~10 mA
2 hours
No RF trips

~20 mA
2 hours
many RF trips



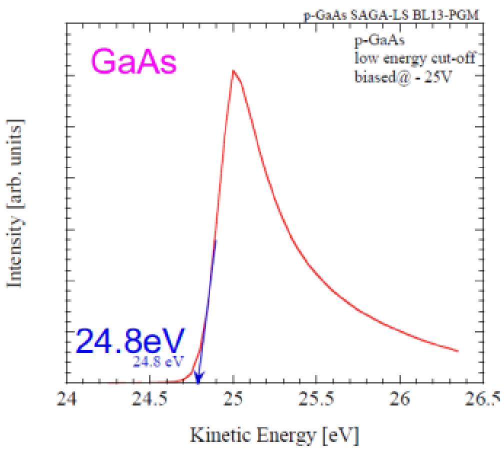


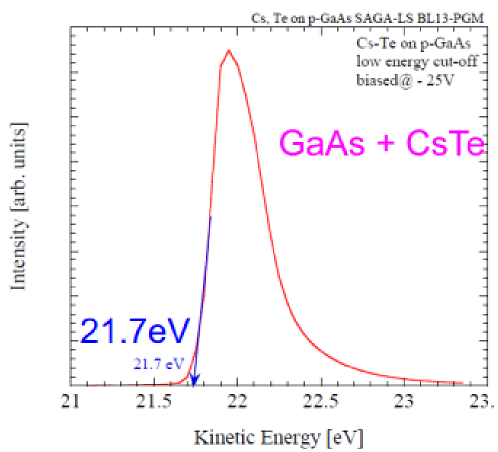
Stay away from the electrostatic center!

Alternatives to Cs-O for NEA

There are **alternative ways for generating the NEA** on GaAs that are less sensitive to vacuum conditions?

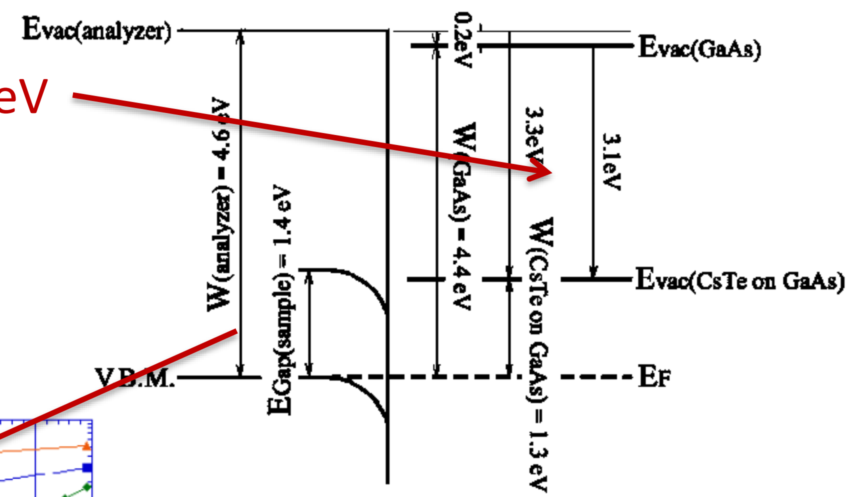
H. Sugiyama et al , *J. Phys. Conf. Series* **298** 012014 (2011)

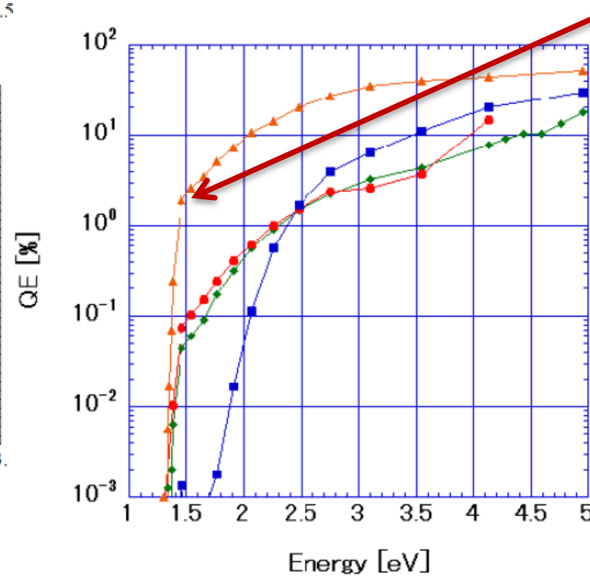


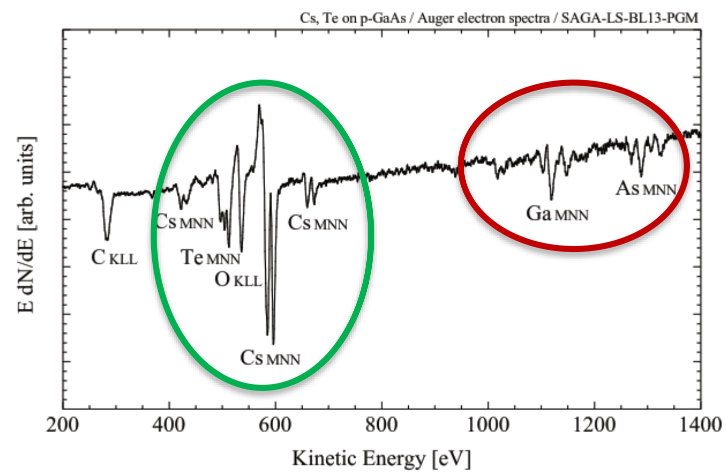


M. Kuriki, P3 workshop, LBNL, 2014

$\Delta\phi=(24.8-21.7)= 3.1\text{eV}$





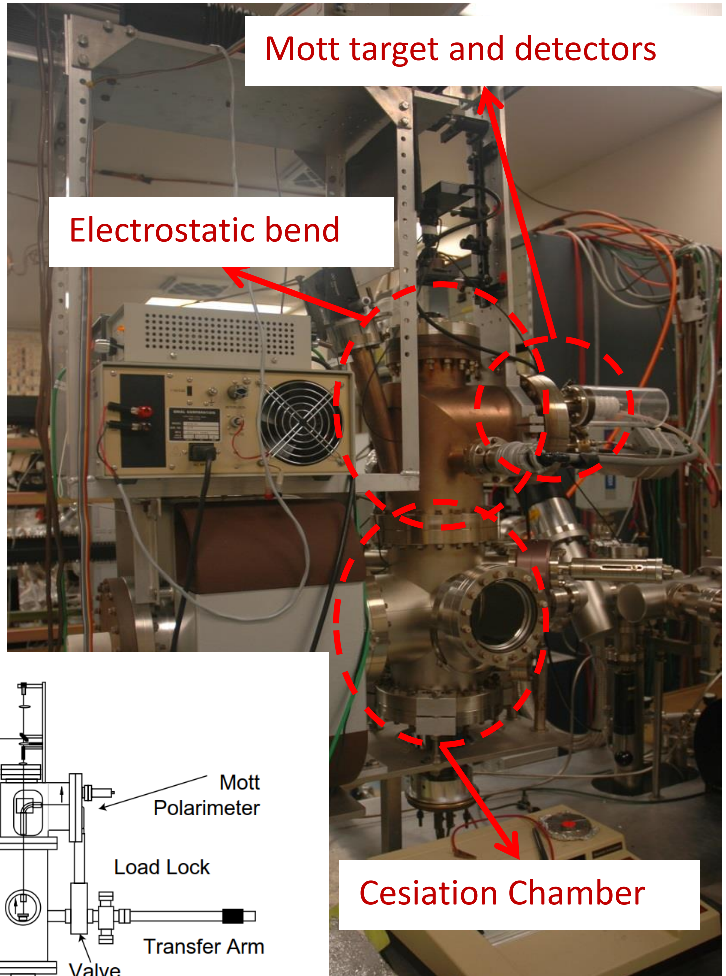


Cs_2Te over GaAs can yield NEA!!

- *Cs_2Te is used in many RF gun (FLASH, DESY, LBNL…)*
- *Promises:*
  - *Operating gun at **higher voltages**;*
  - ***Operation in RF** (and SRF) guns;*
  - ***Long term** cathodes storage;*
  - *Cathodes transport in **suitcases**;*

*Will the Cs_2Te layer **preserve the spin polarization** during the electron transport?*

Mott polarimeter @SLAC



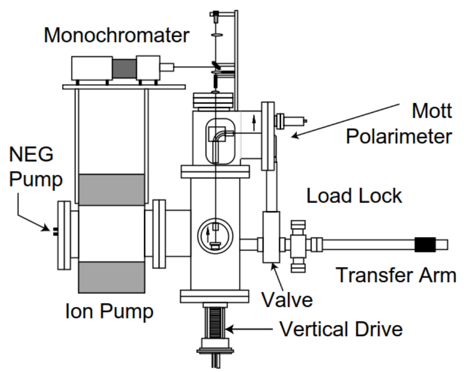
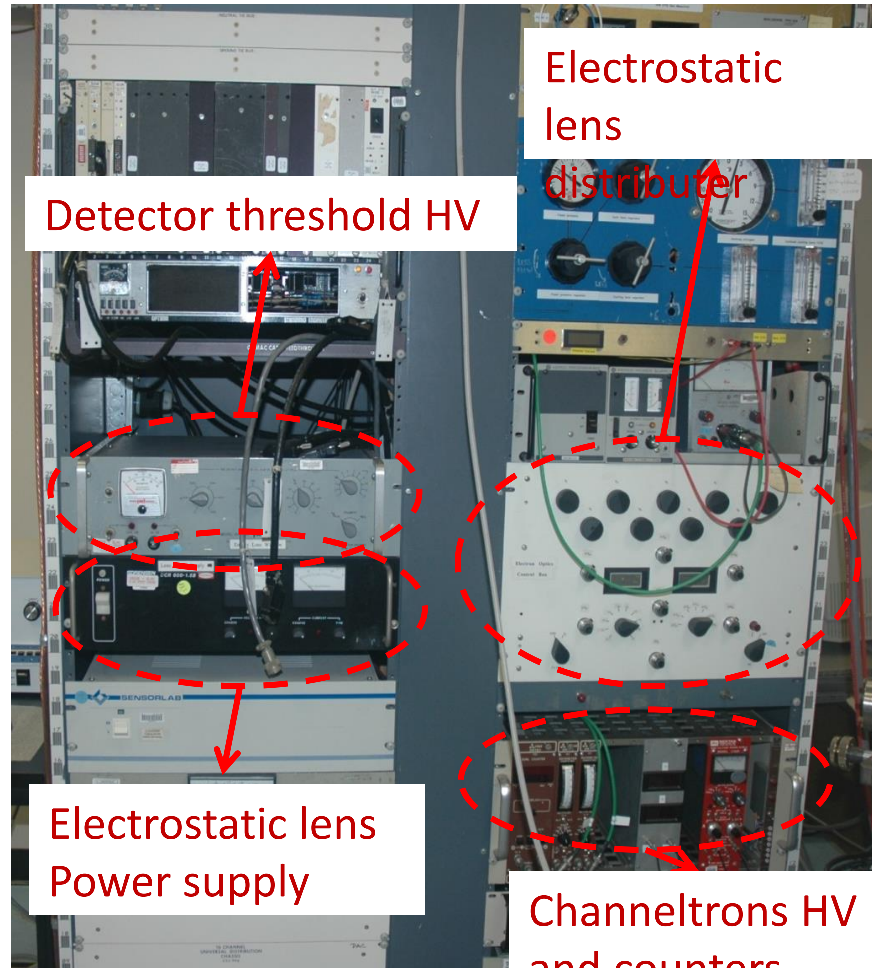


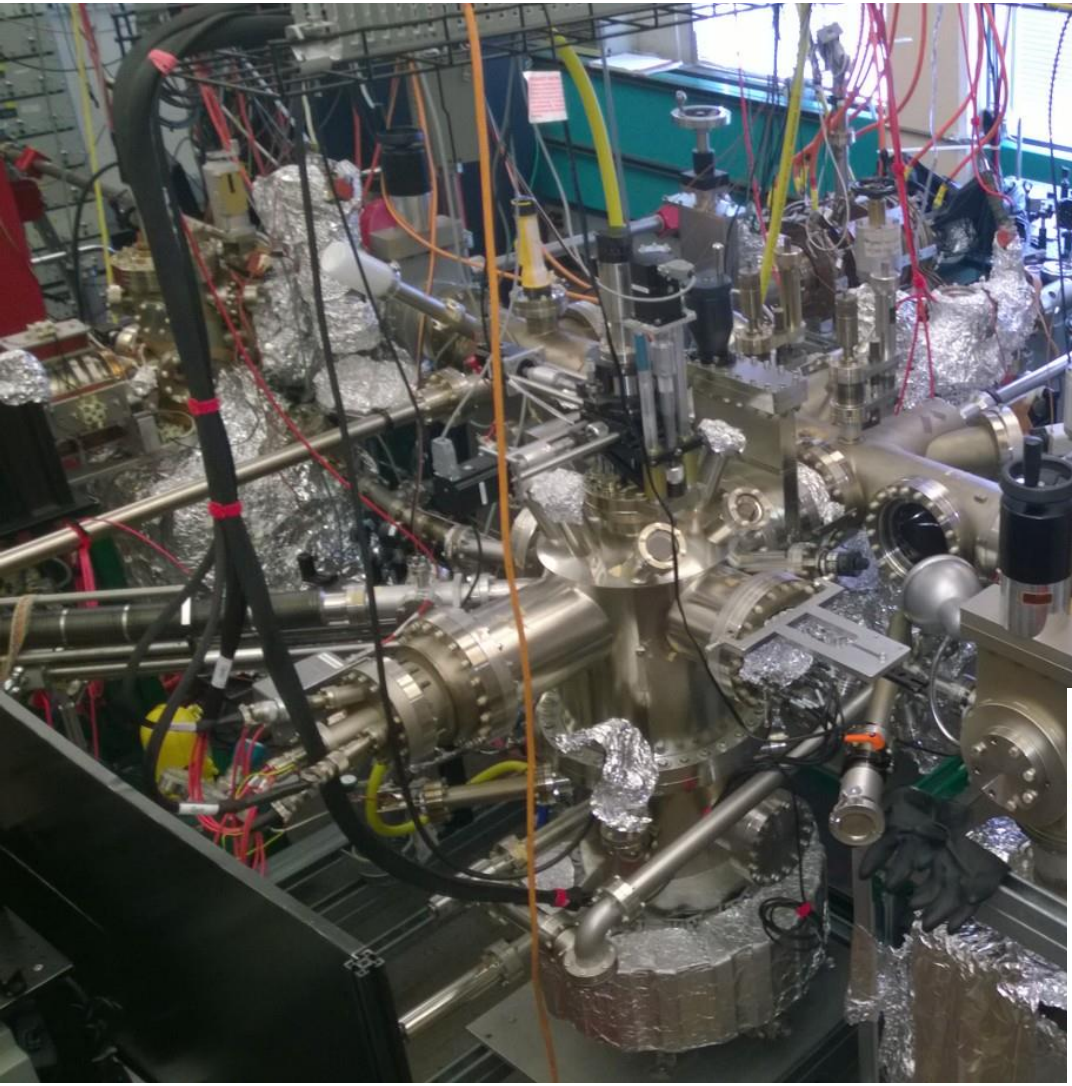
Fig. 2. Schematic diagram of the SLAC Cathode Test System showing the load lock.

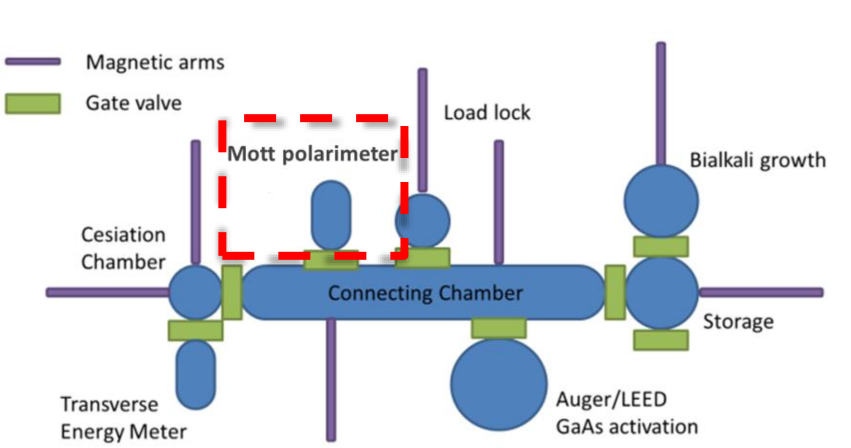


In 1993!!

SLAC => Jlab => Cornell University

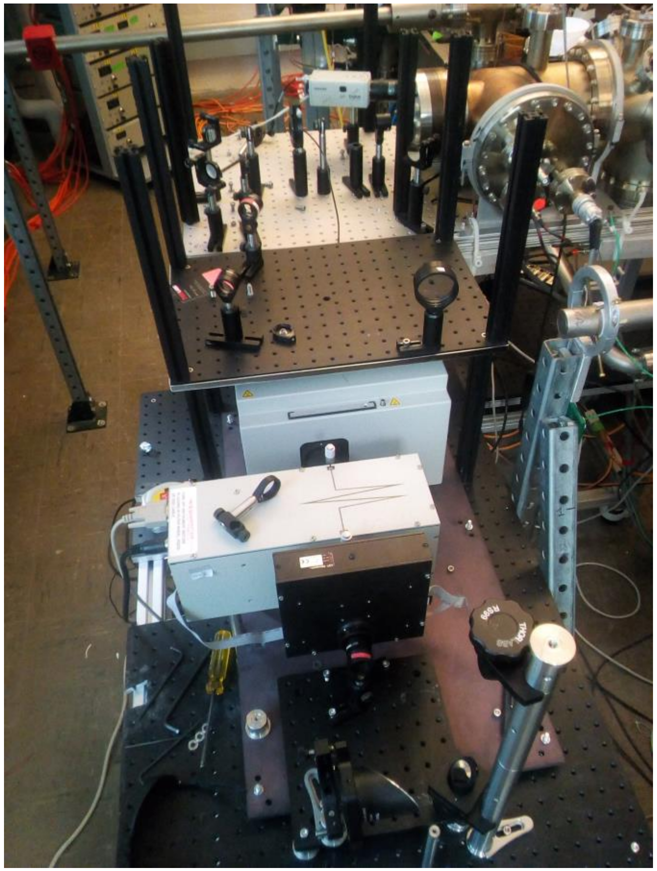
Photocathode Lab

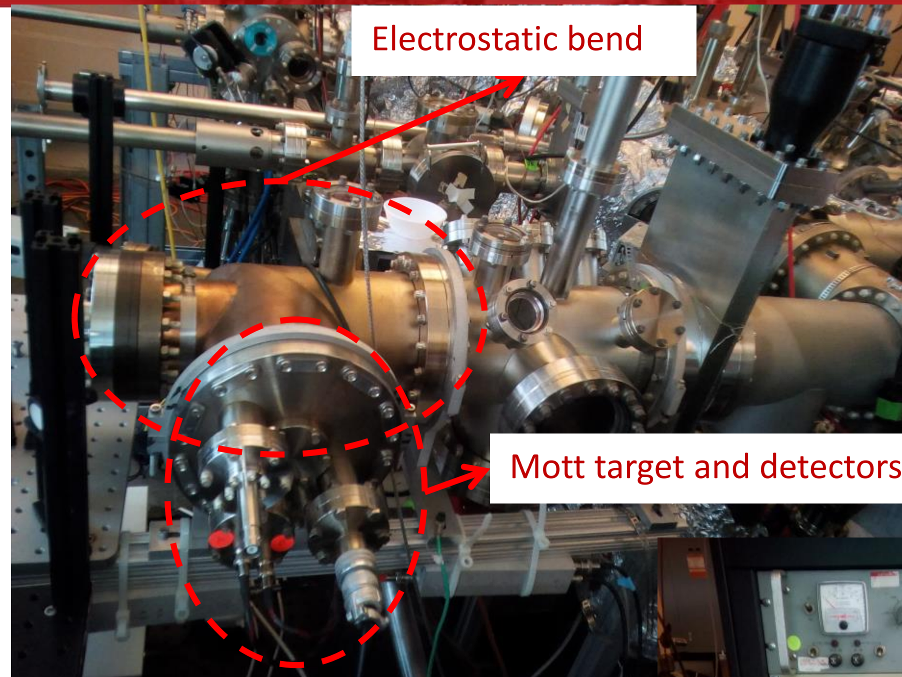




Mott polarimeter @ CU

Vacuum level is below 10^{-10} Torr



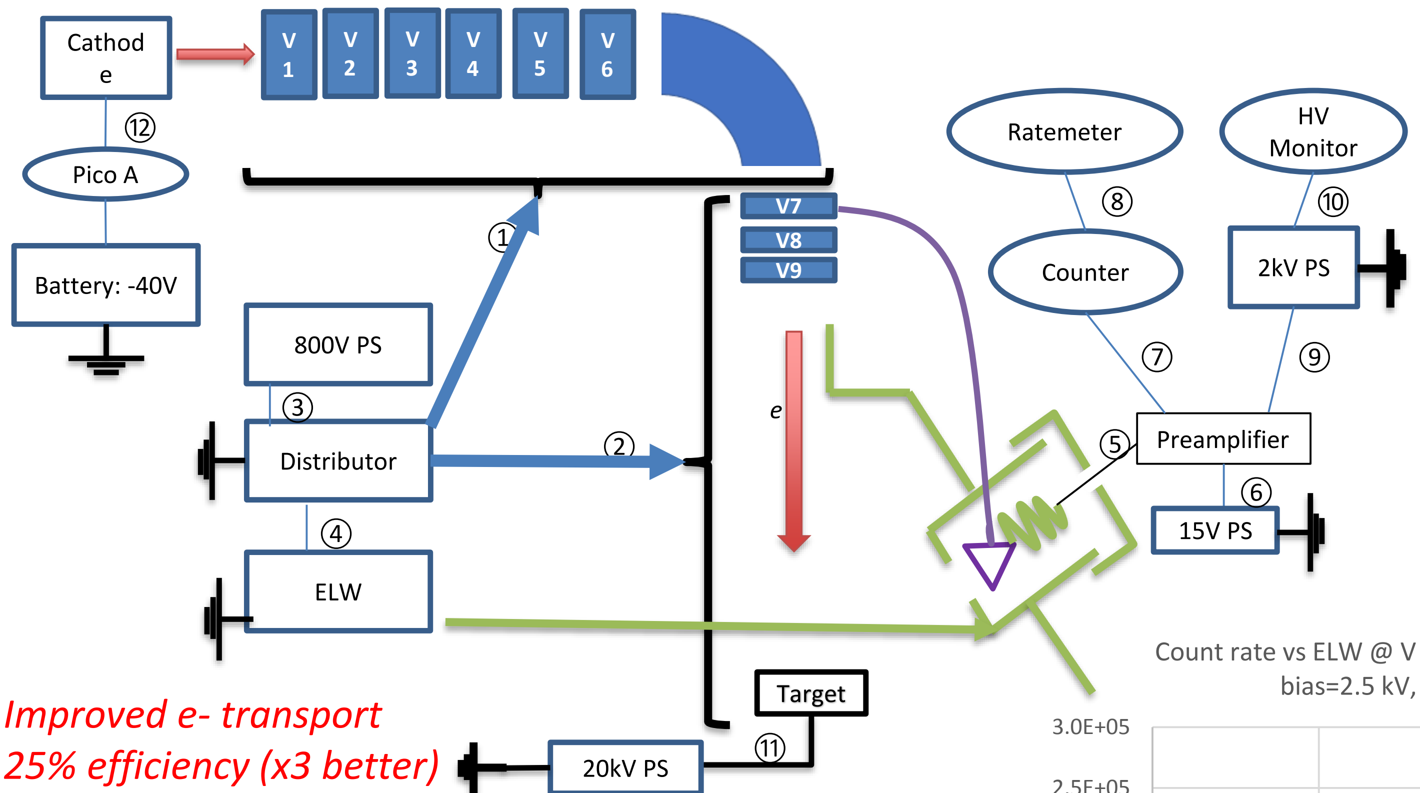


Bulk GaAs cathode

The retarding field Mott polarimeter has been refurbished upgraded and fully integrated into the photocathode lab UHV installation.

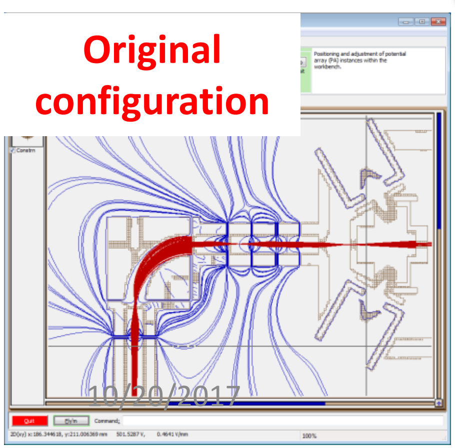
Thanks to M. Poelker and M. Stuzman for helping in debugging and setting up the polarimeter

Reverse engineering

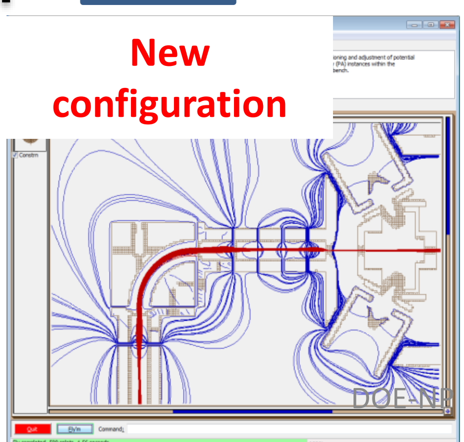


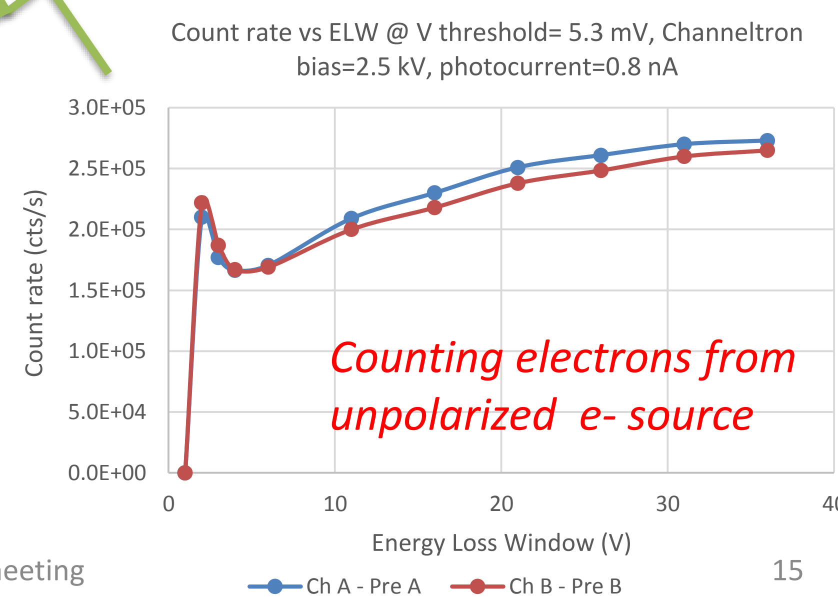
Improved e- transport
25% efficiency (x3 better)

Original configuration

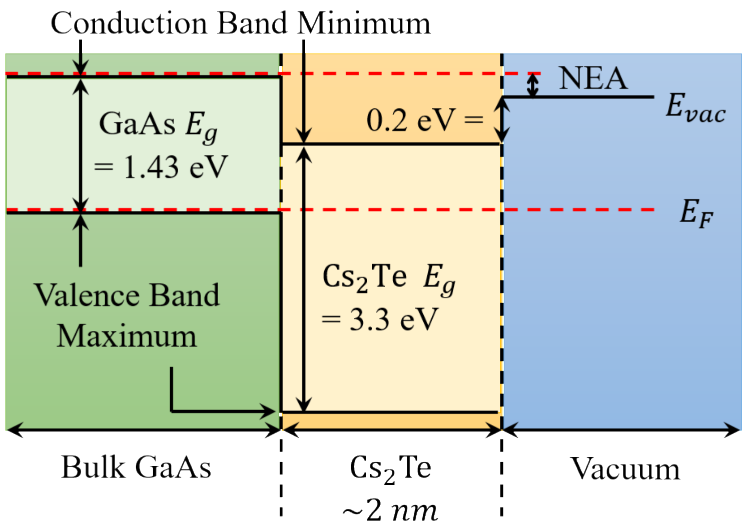


New configuration





Cs_2Te on GaAs

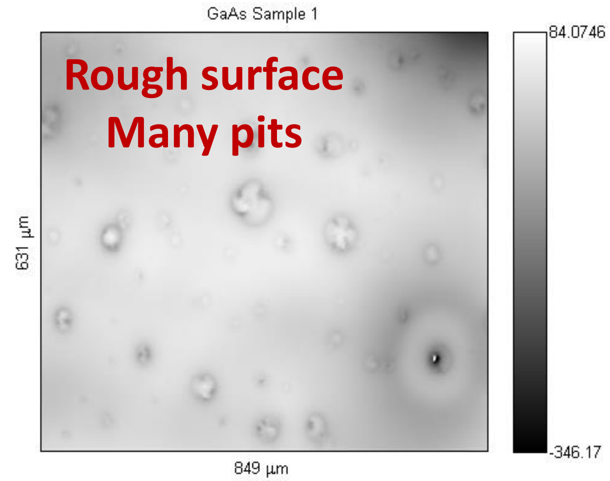


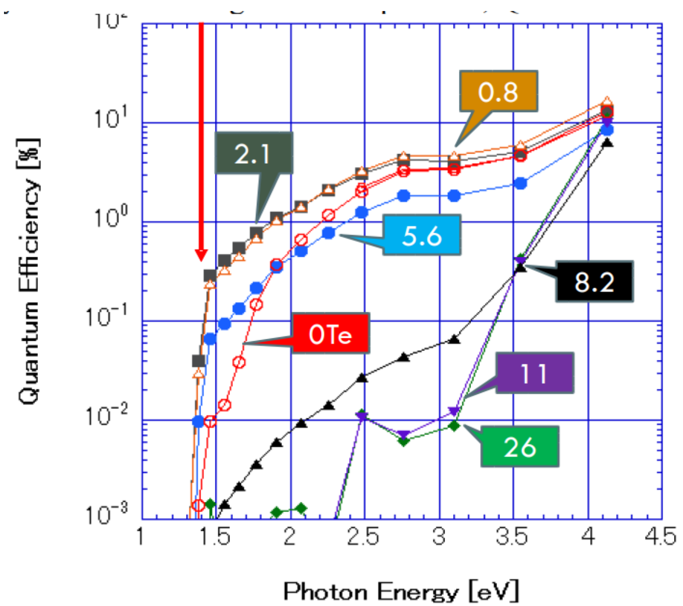
GaAs substrate samples p-type Zn doped 1e18 cm-3

Wet etch to remove oxide and passivate surface

-H_2SO_4:H_2O_2:H_2O (20:1:1) 2 min @ RT

-HCl:iPA (20:80) 3 min @ RT





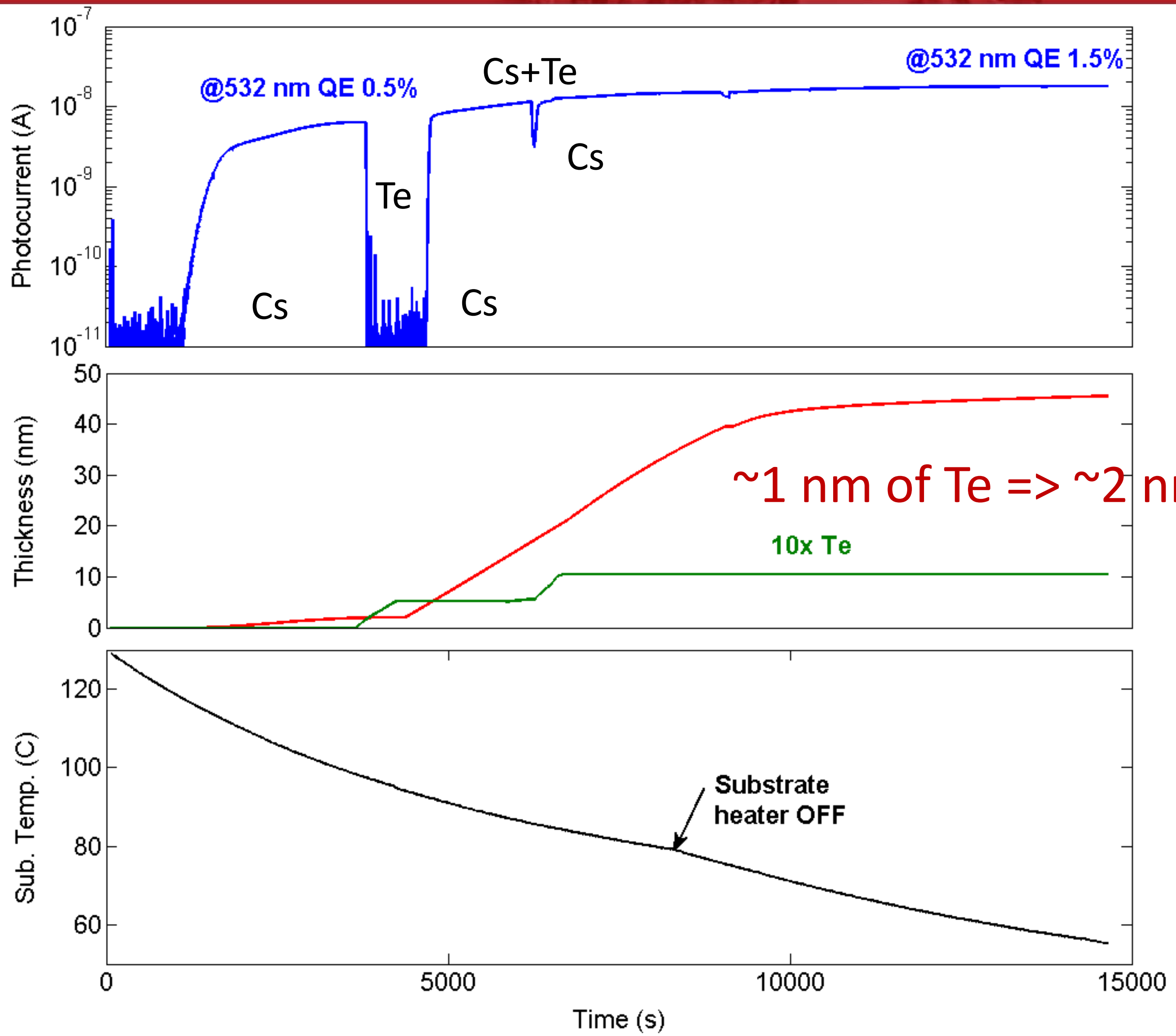
Heat cleaning at 400 C overnight

Room Temperature Cs activation yields ~3% QE @ 532nm

Surface is clean enough to perform NEA activation!!

We also used H_3PO_4 and HF to remove the oxides with HF giving the best results in terms of QE

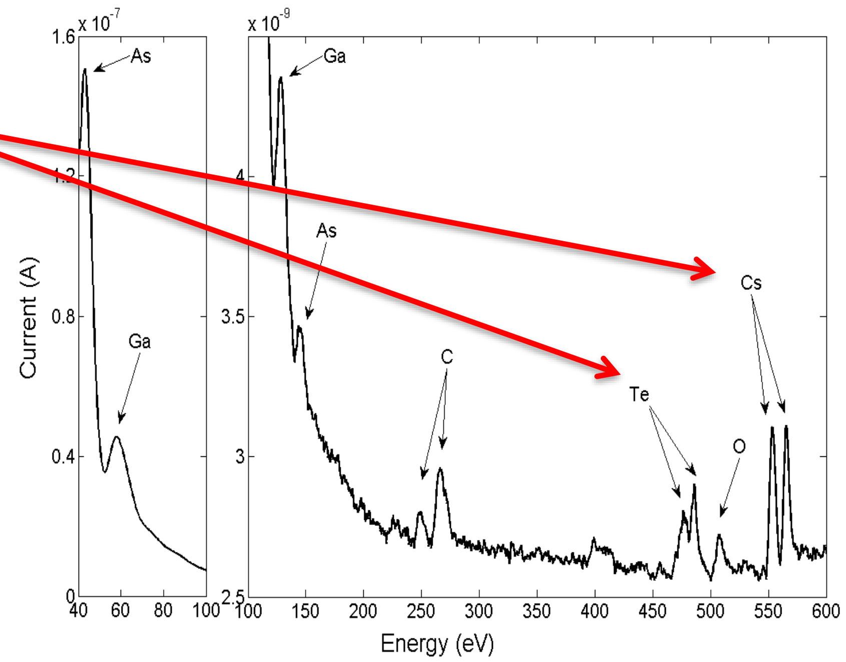
Growth Cs_2Te on GaAs

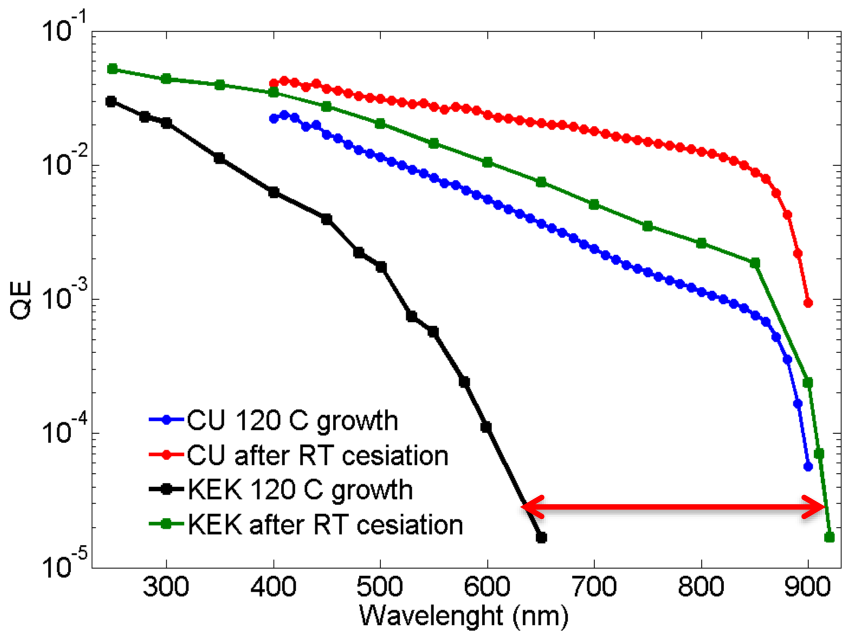


~1 nm of Te => ~2 nm Cs_2Te

Cs_2Te on GaAs

- **Auger spectroscopy confirms the presence of Cs and Te over the GaAs surface**
- Ga ans As peaks are still visible meaning that the CsTe layer is thinner than few nm
- C and O peaks likely coming from the e-gun





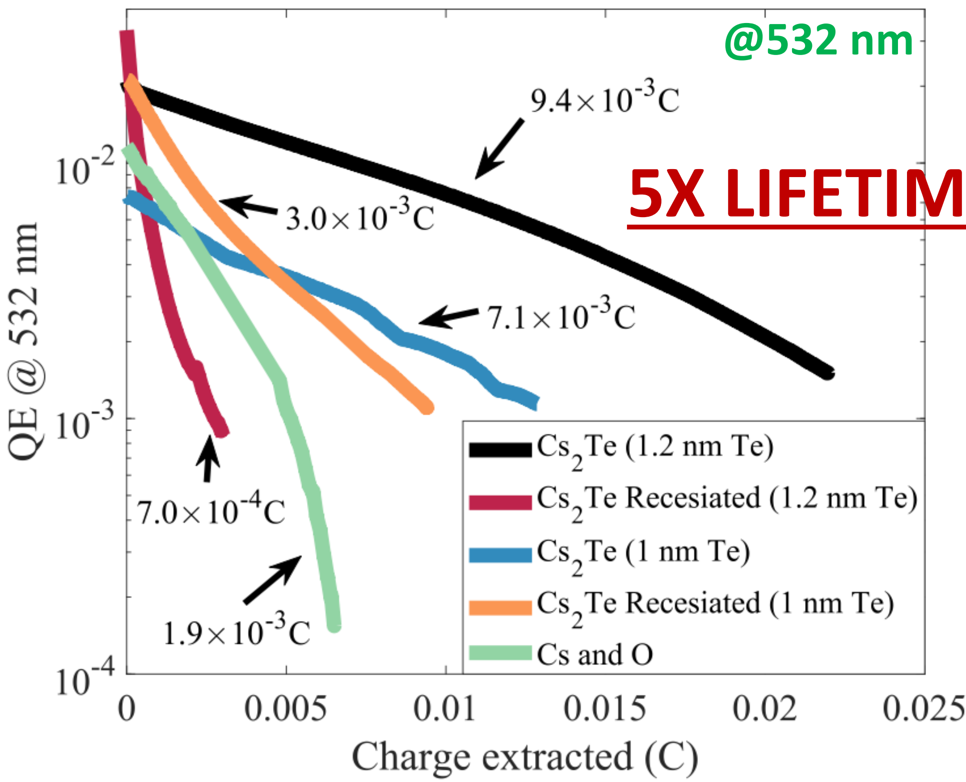
- We do **NOT** see an emission threshold shift

Partial coverage of the surface?

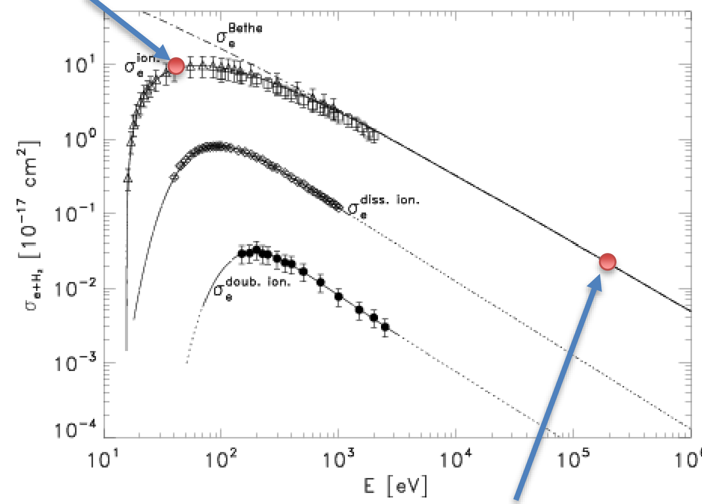
Lifetime measurements

- Lifetime measurements were performed using a small laser diode at 532 nm;
- The purpose was to extract electron current from photocathodes under similar conditions and look at the robustness od Cs_2Te with respect to the ion back bombardment;
- Due to the limited bias (-40 V) not more than few hundreds of nA can be extracted;
- There is no offset area;
- Results can be extended to any GaAs based photocathode (superlattices, DBR, etc);

Cs_2Te on GaAs



Beam energy in our setup is about 40 eV



Beam energy in PES gun

- About 3 order of magnitude larger probability to ionize hydrogen than in a real gun
- Due to low energy electron the ion back bombardment damage is likely to affect the very surface of our samples.

Why the re-cesiated samples have a lower lifetime than the as-grown samples?
Could it be because the Cs stays only at the surface?

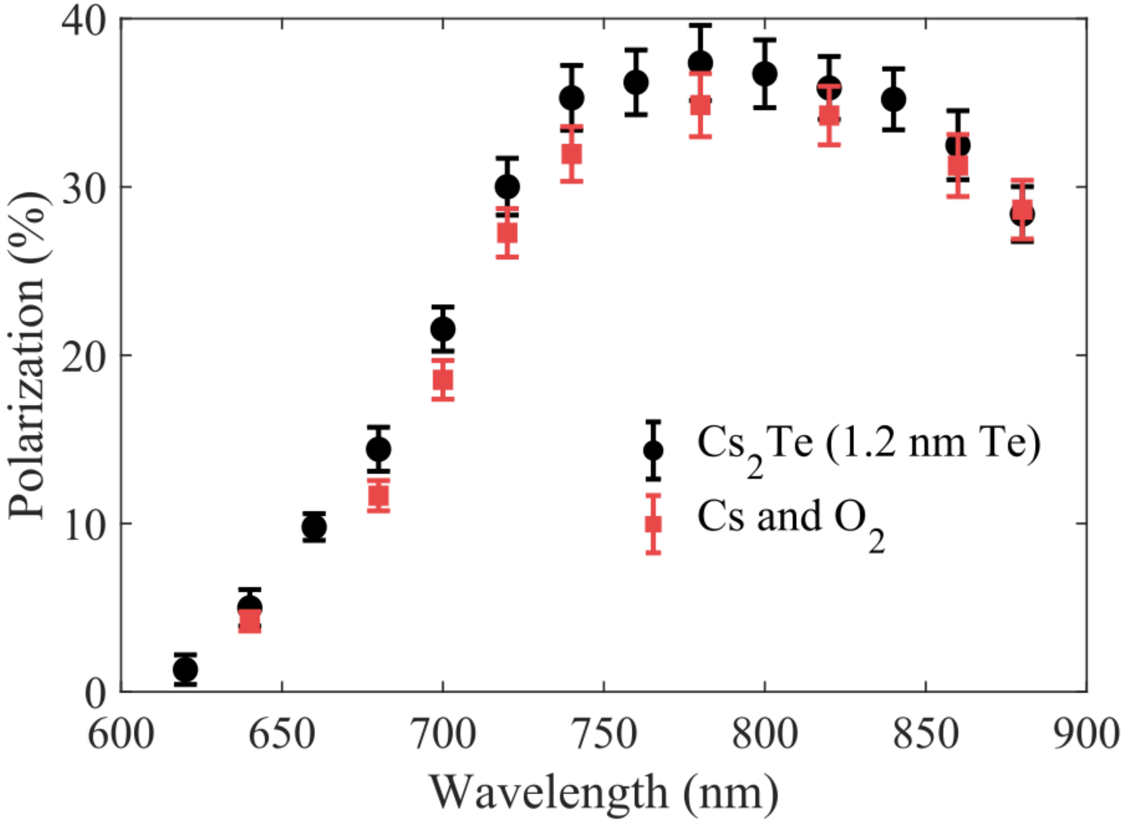
BNL folks have replicated and confirmed this results

Polarization measurements

- Polarization measurements were performed using a light from a lamp and monochromator;
- The purpose was to compare the spin polarization obtained from the same specimen activated with standard Cs-O method and new Cs_2Te;
- Due to the limited bias (-40 V) not more than few hundreds of nA can be extracted;
- Results can be extended to any GaAs based photocathode (superlattices, DBR, etc);

Electron beam polarization

The same GaAs wafer was activated first with Cs-O and later with Cs_2Te



Spin polarization is not affected by the Cs_2Te surface layer

APPLIED PHYSICS LETTERS 112, 154101 (2018)

Rugged spin-polarized electron sources based on negative electron affinity GaAs photocathode with robust Cs_2Te coating

Jai Kwan Bae, Luca Cultrera, Philip DiGiacomo, and Ivan Bazarov
Cornell Laboratory for Accelerator-Based Sciences and Education, Cornell University, Ithaca, New York 14853, USA

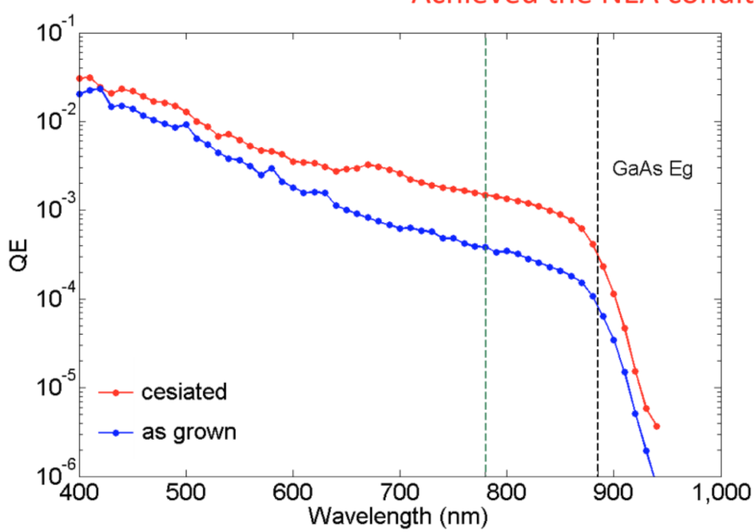
(Received 22 February 2018; accepted 24 March 2018; published online 9 April 2018)

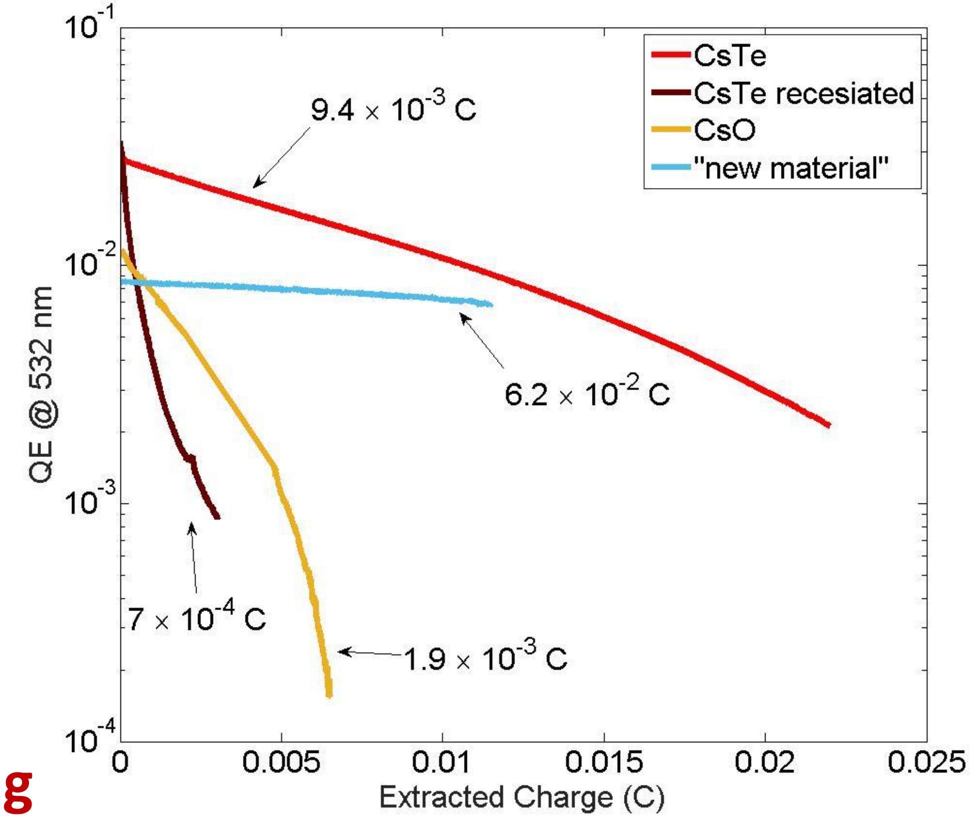
few weeks ago…

We attempted achieving NEA with a new material

(submitting a patent for the method)

Achieved the NEA condition!!



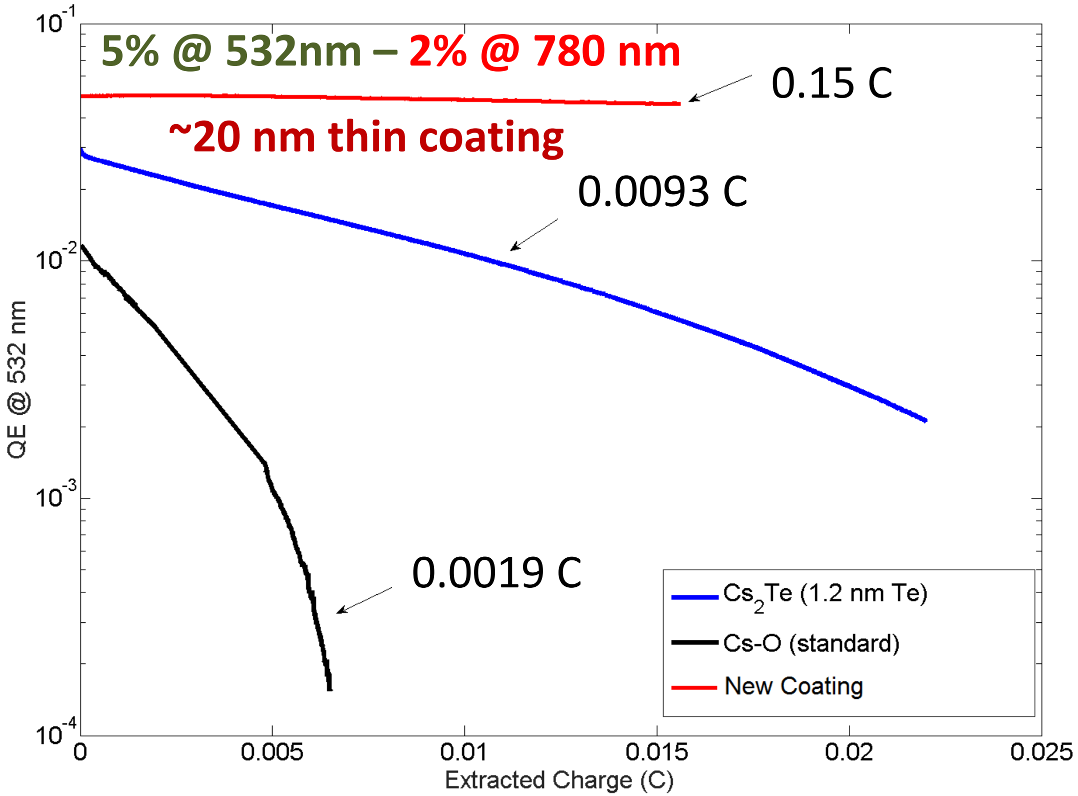


Initial QEs were not that exciting

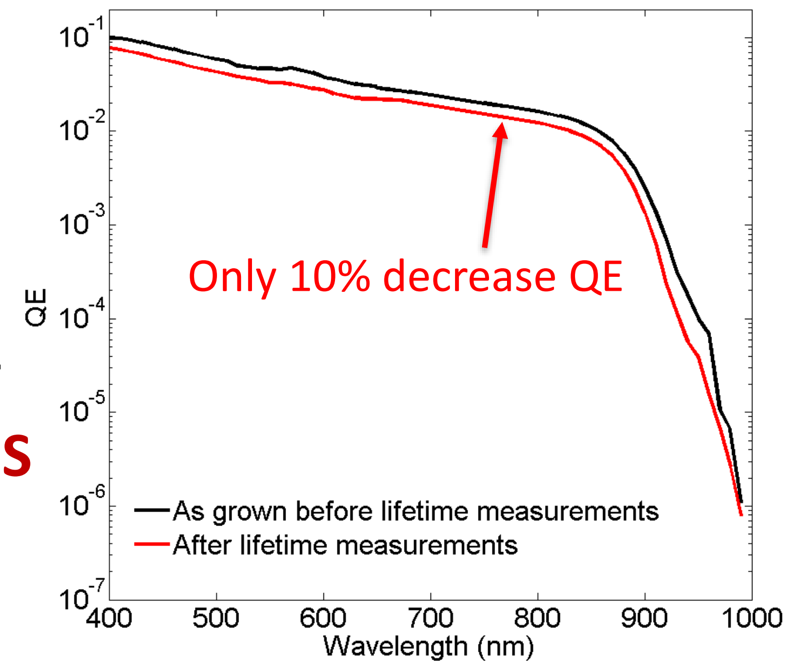
(we believed the wet etch with H_3PO_4 was not effective)

but anyway this new coating shows 30x lifetime w.r.t. Cs-O

two weeks ago…



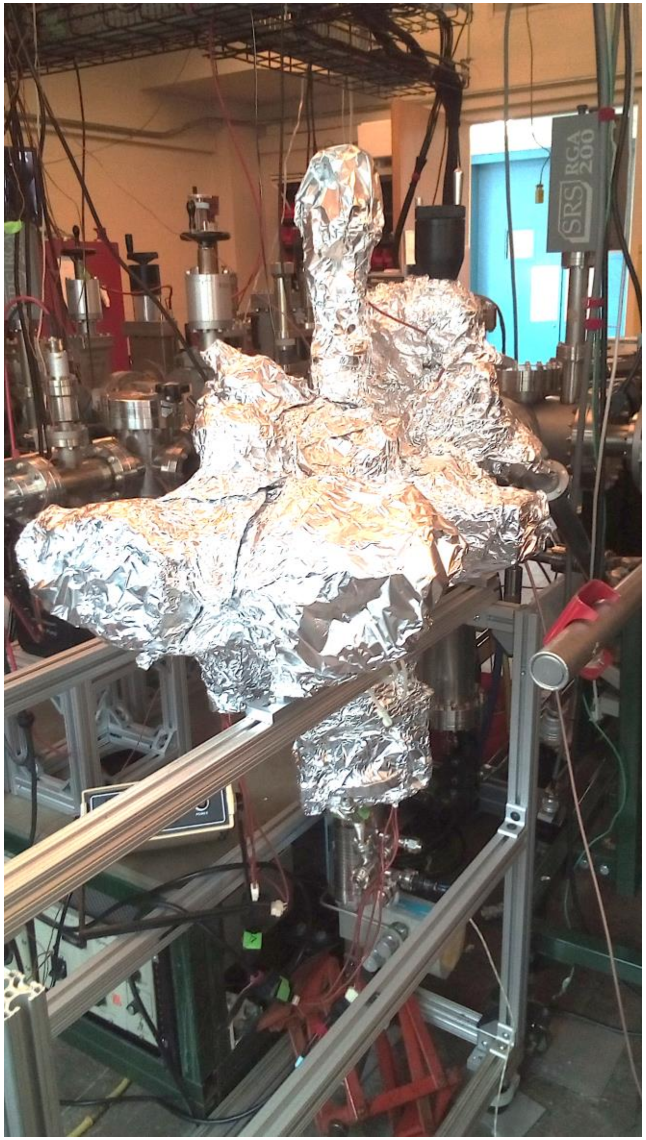
We used HF based wet etching and 600 C heat clean cycle to fully remove oxides from GaAs surface



LIFETIME UNDER SIMILAR CONDITION IS MEASURED TO BE ABOUT 80x LONGER

Polarization will be measured soon
(*but, as for Cs_2Te, we do not anticipate issues*)

Polarization in few days



The polarimeter is currently being baked

Upgraded with a cryogenic sample holder

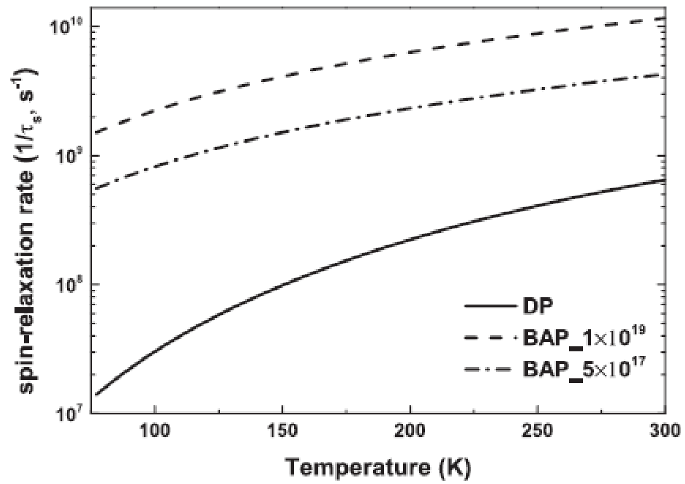


TABLE I. Figure of merit for polarized electron sources.

Cathode	Reference	P (%)	QE (%)	P^2QE (%)
$GaAs\text{-}GaAsP_{0.36}$	SLAC/SVT[15]	86	1.2	0.89
$GaAs\text{-}GaAsP_{0.38}$	Nagoya[20]	92	1.6	1.35
$Al_{0.19}In_{0.2}GaAs\text{-}Al_{0.4}GaAs$	St. Peterburg[18]	92	0.85	0.72
$GaAs\text{-}gaAsP_{0.35}$ (with DBR)	JLab/SVT	84	6.4	4.52

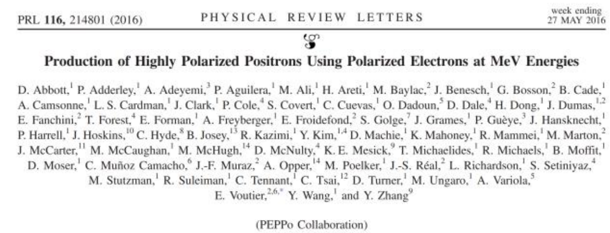
W. Liu et al., APPLIED PHYSICS LETTERS **109**, 252104 (2016)

Improve the beam spin polarization by mitigating the relaxation rates as function of temperature

During last EIC meeting…

- JLab has shown interest in our results:
  - Provided us with 3 superlattice samples;
  - Interest in test the coating in one of their guns;
  - Measure polarization and lifetime at high energies and high currents;

SL with P>80% @780nm


PRL 116, 214801 (2016) PHYSICAL REVIEW LETTERS week ending 27 MAY 2016

Production of Highly Polarized Positrons Using Polarized Electrons at MeV Energies

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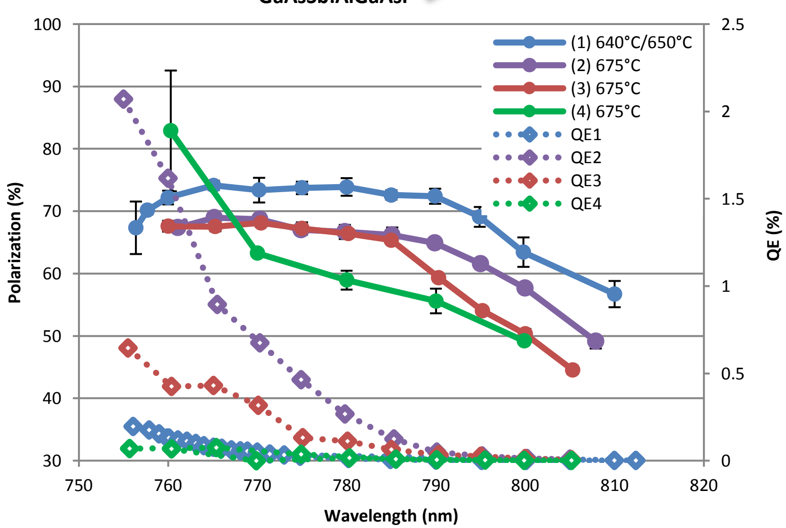
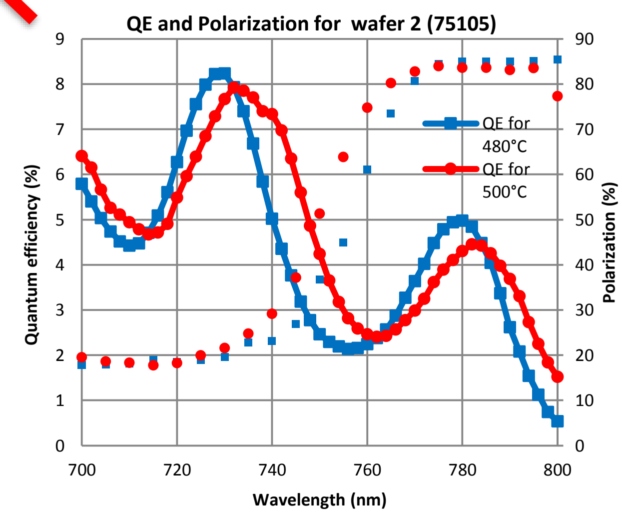
(PEPPo Collaboration)

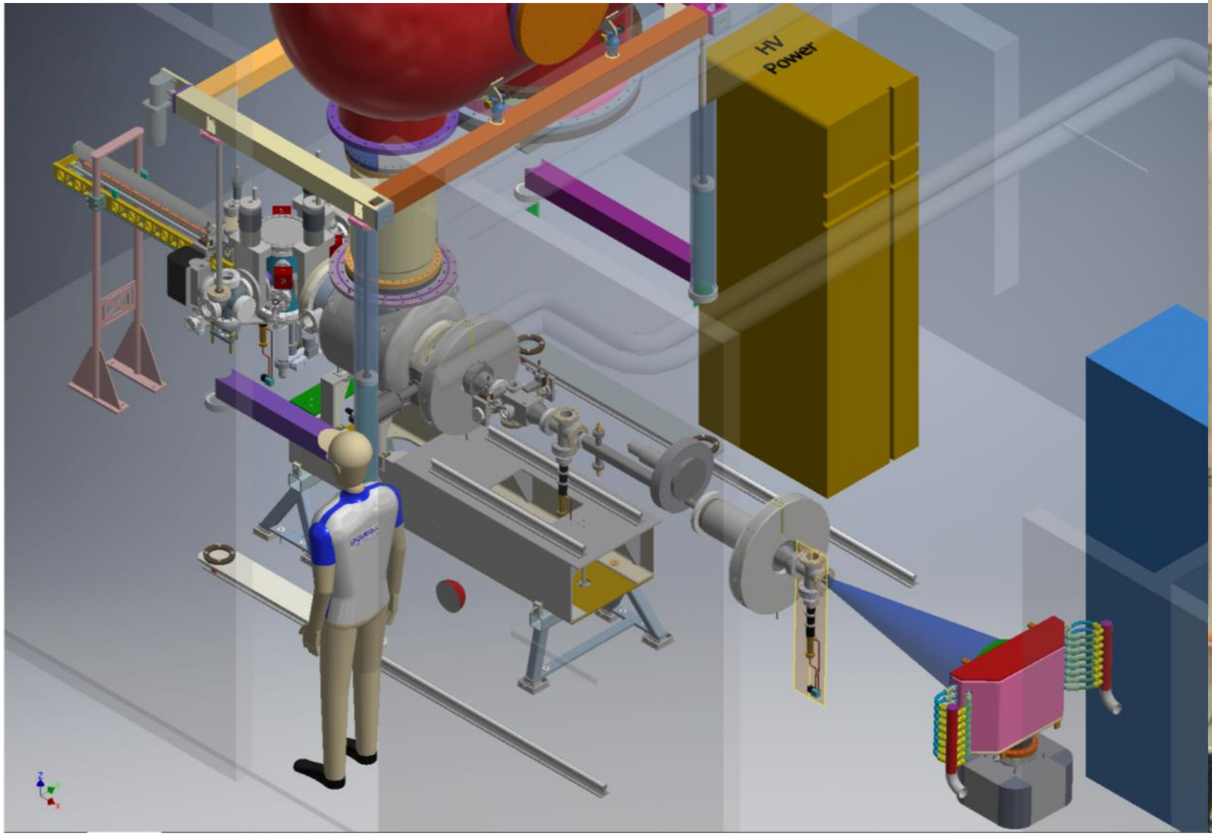
GaAsSb:AlGaAsP





In the near future

We plan to perform test in our 400 kV gun in 2019
Aiming at demonstrating high average current levels and measuring lifetime



DE-SC0019122

Conclusions

- Robust PES capable of high currents:
  - most relevant for LR-eRHIC;
  - Longer operational lifetime;
  - Other application (polarized positrons @CEBAF);
- PES still based on III-Vs semiconductor:
  - **Robust NEA activation can yield almost two orders of magnitude longer lifetime;**
  - **Polarization measurement in few days;**
  - **Lifetime measurement in the gun in few months;**

Thank you for the attention!!

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