Northern Illinois University

Towards Low-MTE Photocathodes in Accelerators

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Introduction

High-quality electron beams =

- bright beams $B_{4D} \propto \frac{N_{bunch}}{\epsilon_x \epsilon_y} \propto \frac{(E_z)^k}{MTE}$

High charge density regime:

$N_{bunch} \propto \sigma_x \sigma_y (E_z)^k, \quad 1 \le k \le 2$

$\epsilon_{x,y} = \sigma_{x,y}\sqrt{MTE/m_e c^2}$

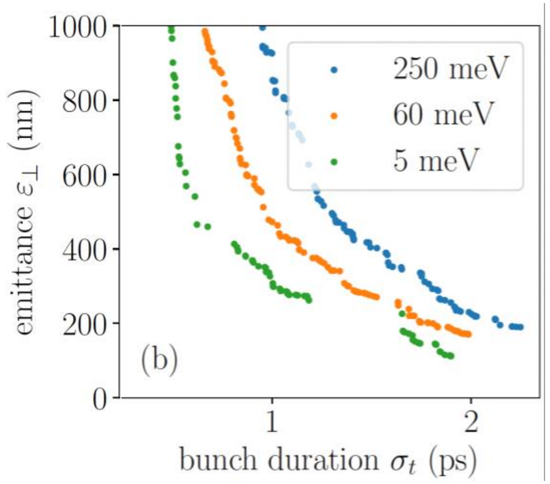
Bazarov *et al.*, Phys. Rev. Lett. **102**, 104801 (2009).

High-quality photocathodes =

- low mean transverse energy, $MTE = \frac{m\langle v_\perp^2 \rangle}{2}$

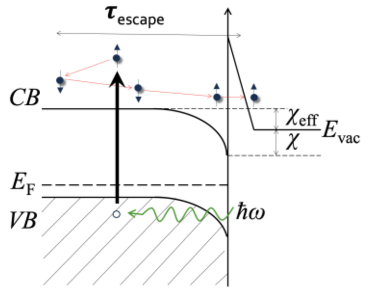
  MTE ~ k_BT ~ 25 meV at room temperature

  Factors, limiting MTE:
  - requirements of the high charge density
  - disordered nature of photocathode materials → MTE ~ few 100s meV
  - surface roughness and work function variations



Frame, Marzouk, Chubenko et al, Instruments **7**, 48 (2023).

- high quantum efficiency, $QE = \frac{N_{e^-}}{N_\gamma}$



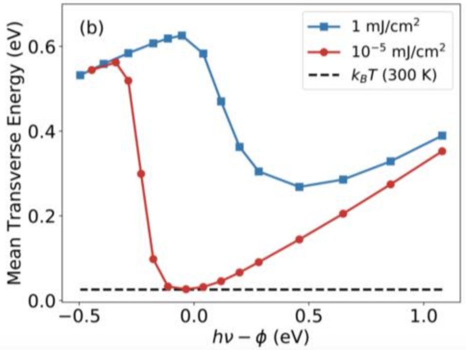
NEA GaAs

- prompt response time

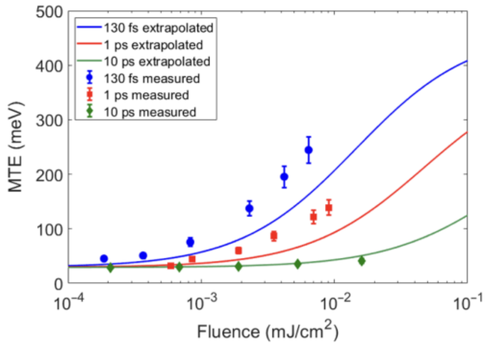
- robustness + long operational lifetime under realistic photoinjector conditions (5-100 MV/m to extract ~ 50-1000 pC/mm^2 of charge densities/bunch)

Low-electron-affinity semiconductor photocathodes

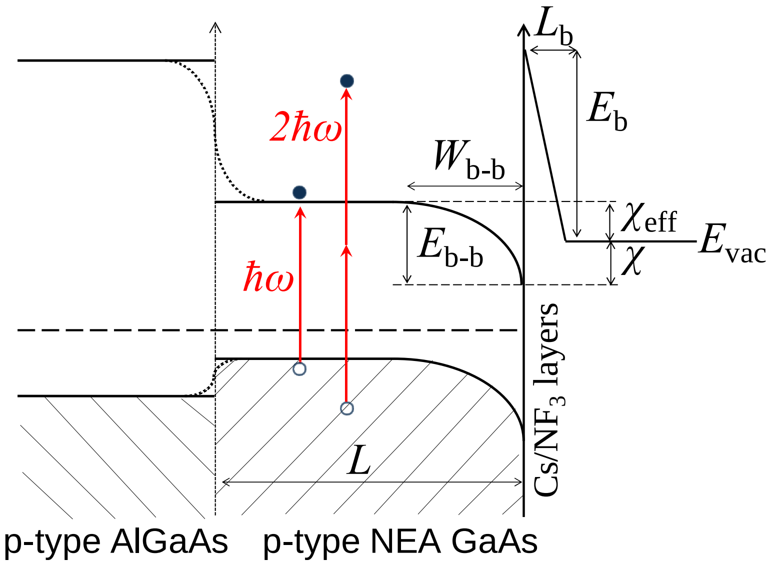
- Multi-photon absorption limits MTE!

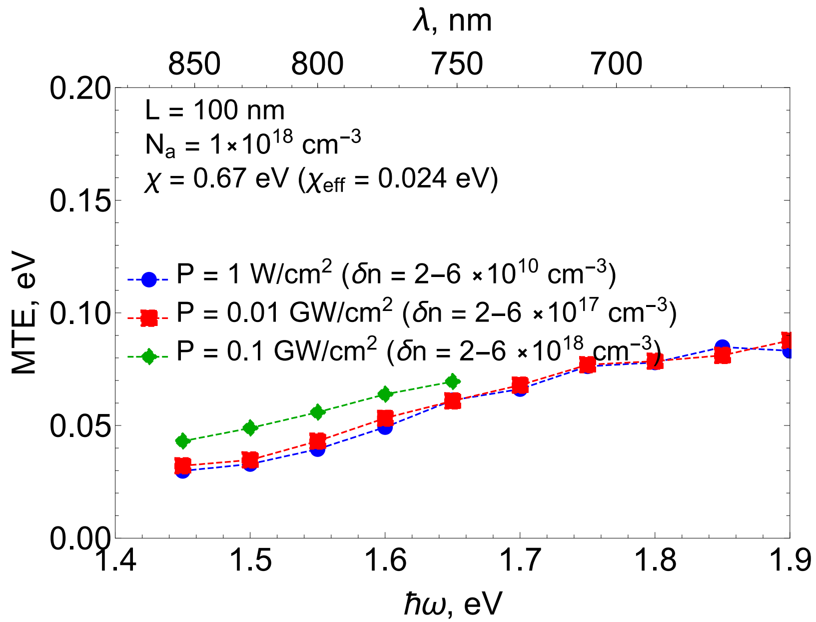


Bae et al. J. App. Phys. **124**, 244903 (2018)



Knill et al., Phys. Rev. Accel. Beams **26**, 093401 (2023)

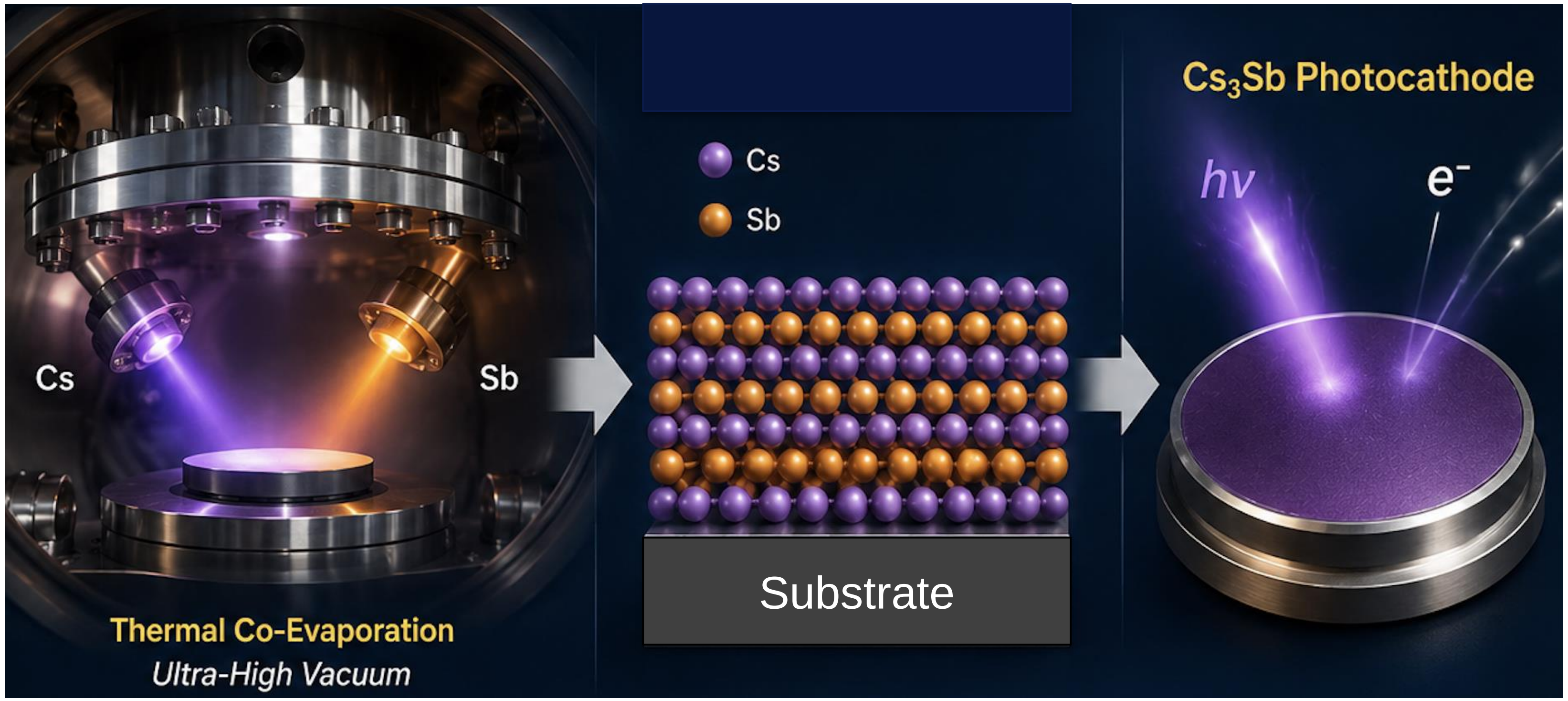


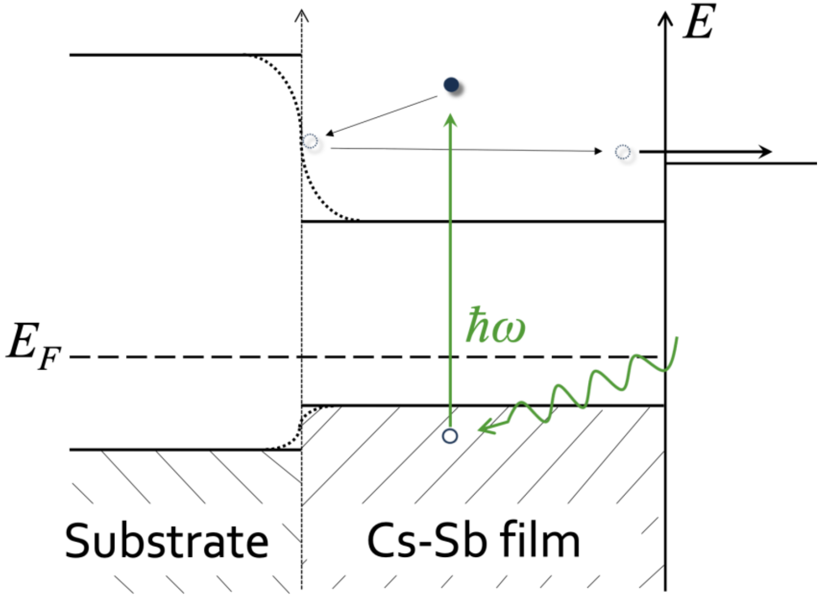


Low-electron-affinity semiconducting photocathodes are better candidates to operate under high laser fluences.

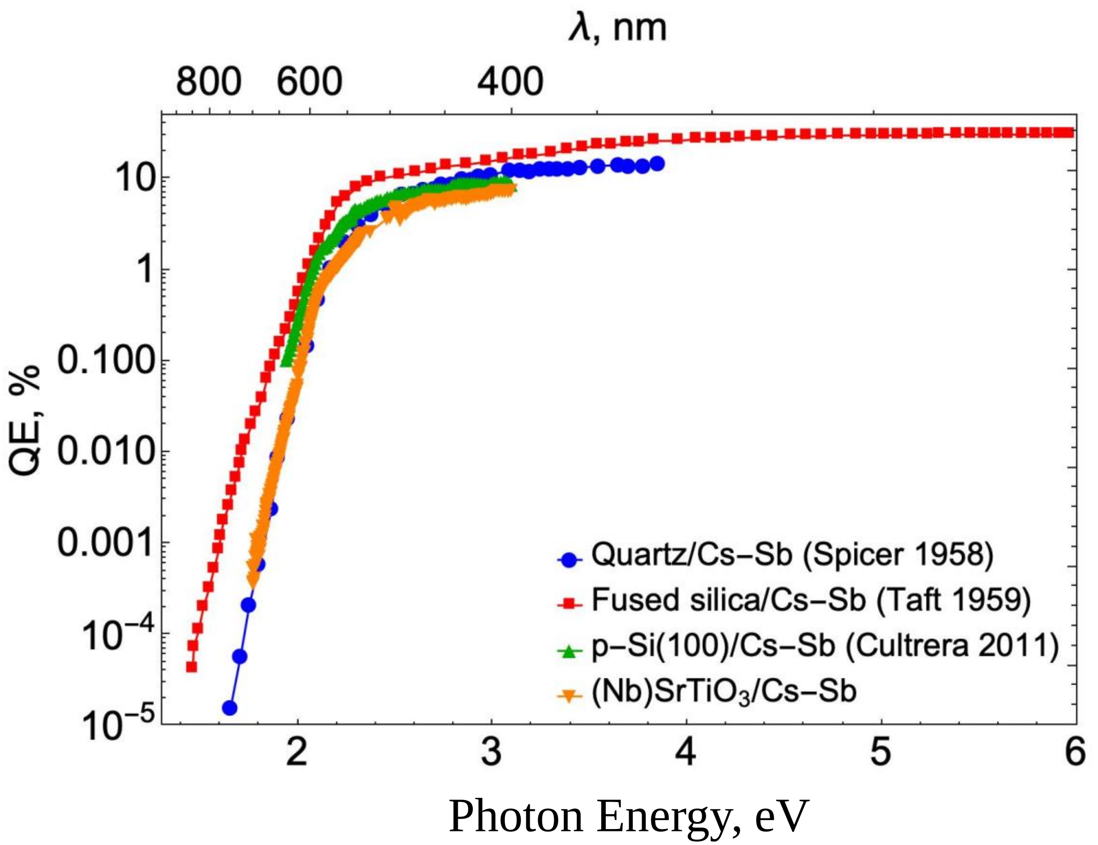
Cesium-antimonide photocathodes (Cs-Sb):

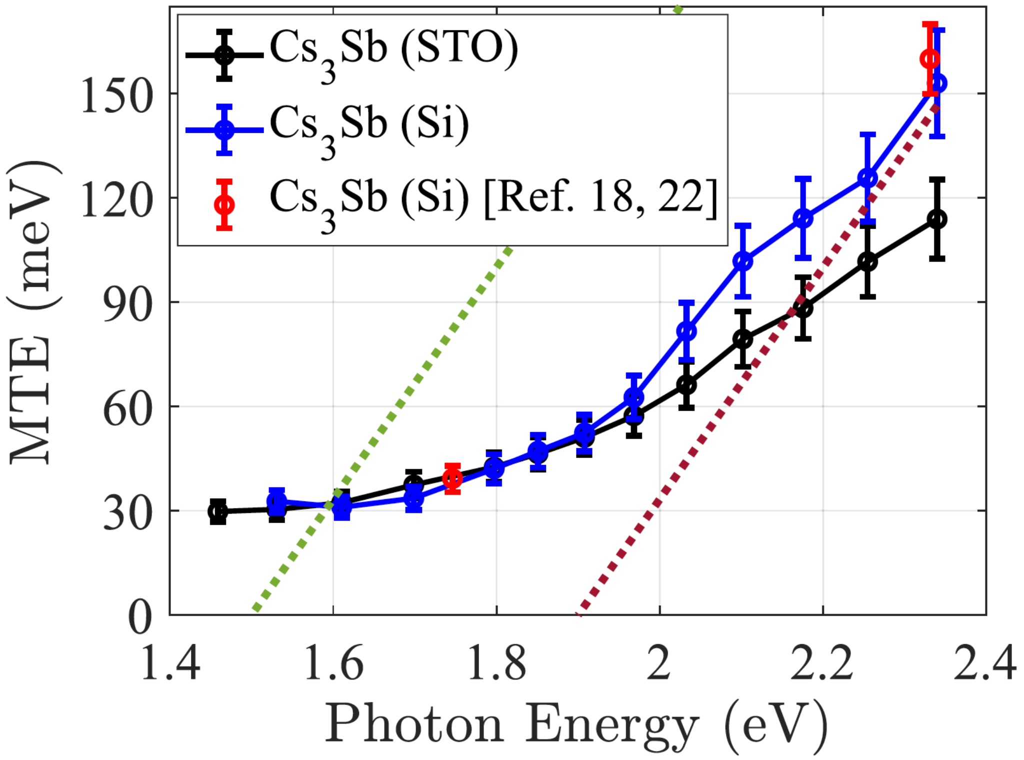
- promising candidates for generating extremely bright electron beams for XFELs, UED, and UEM.
- can be easily deposited through thermal evaporation at moderate temperatures.
- thin films (several 10s of nm).





- Operational photon energy affects MTE!





A. Kachwala, P. Saha, P. Bhattacharyya, E. Montgomery, O. Chubenko, and S, Karkare, Appl. Phys. Lett. 123, 044106 (2023)

Cesium-antimonide photocathodes demonstrate thermal-limit MTE and relatively high QE at photoemission threshold.

Cesium-antimonide photocathodes

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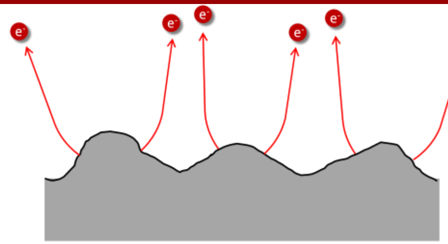
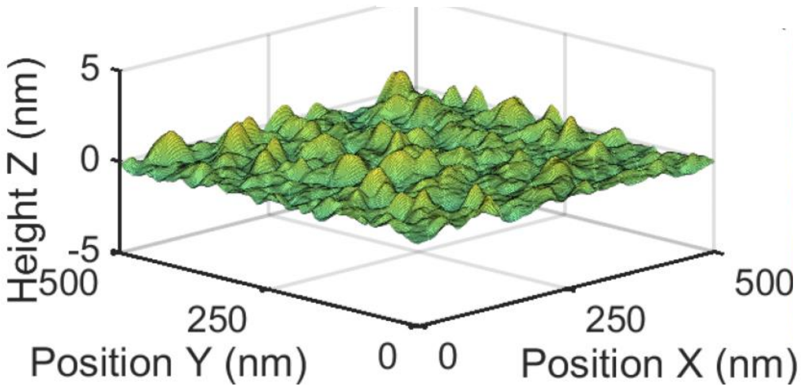
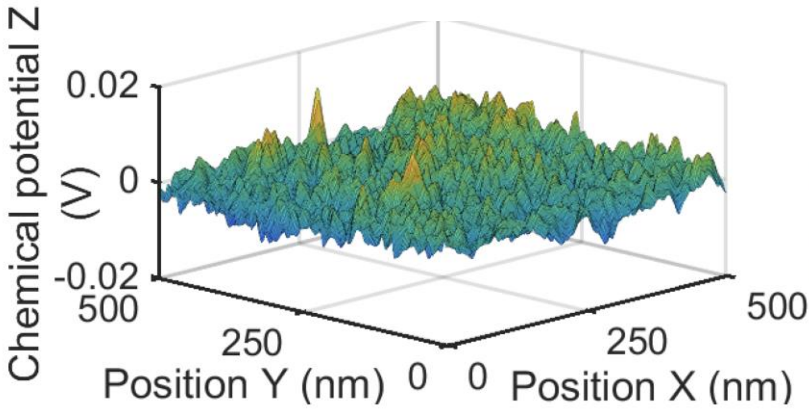
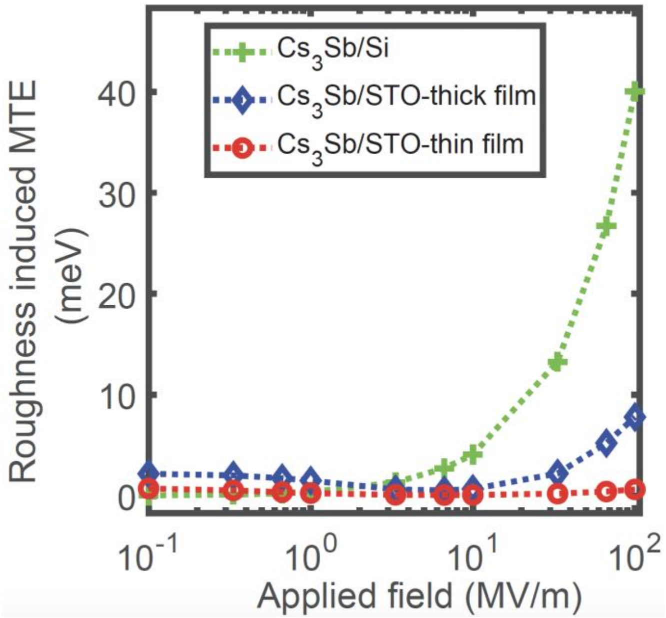
- Surface roughness and work function variation limit MTE!









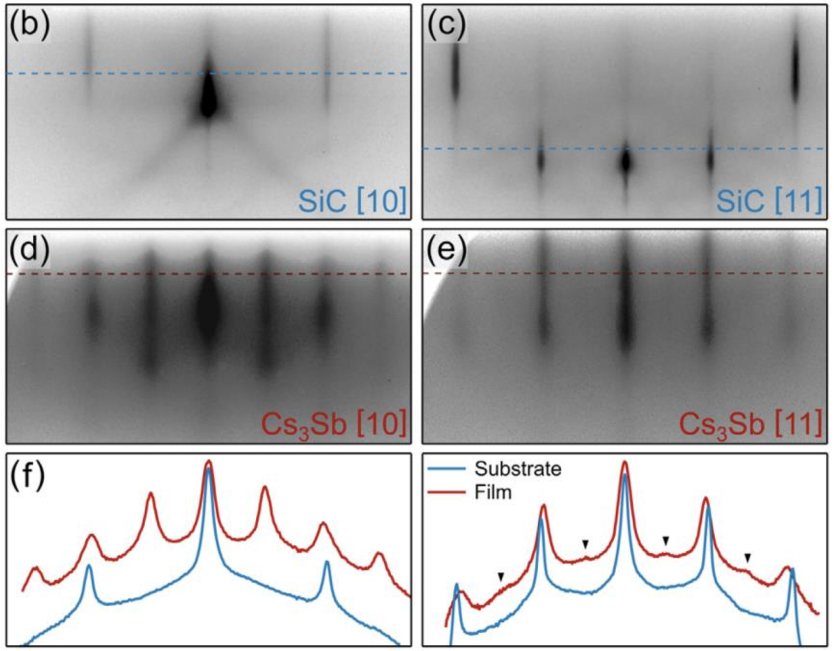
Saha, Chubenko et al, Appl. Phys. Lett. **120**, 194102 (2022).

Cesium-antimonide films grown on lattice-matched single crystal strontium titanate (STO) substrates demonstrate roughness-induced MTE < 10 meV even at large applied fields.

Cesium-antimonide photocathodes

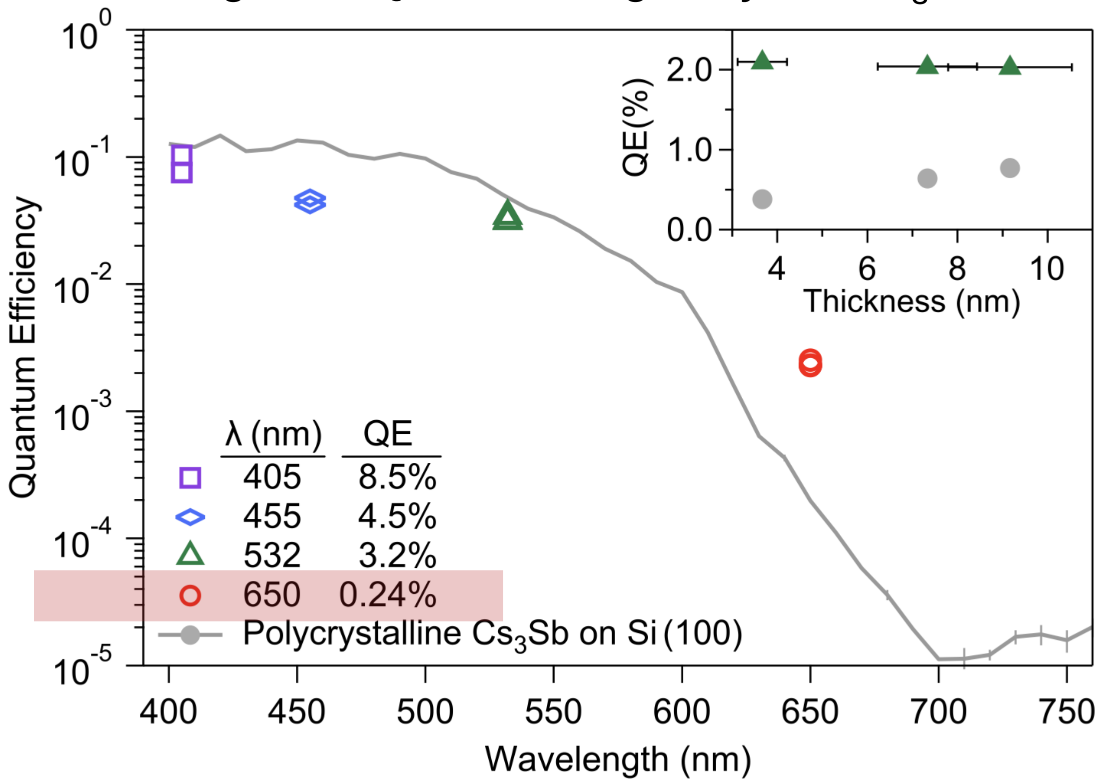
- Disordered crystal structure limits MTE!

RHEED images of an annealed SiC substrate and a 10 u.c. Cs_3Sb film.



Parzyck et al, Phys. Rev. Lett. **128**, 114801 (2022).

High red QE from single crystal Cs_3Sb

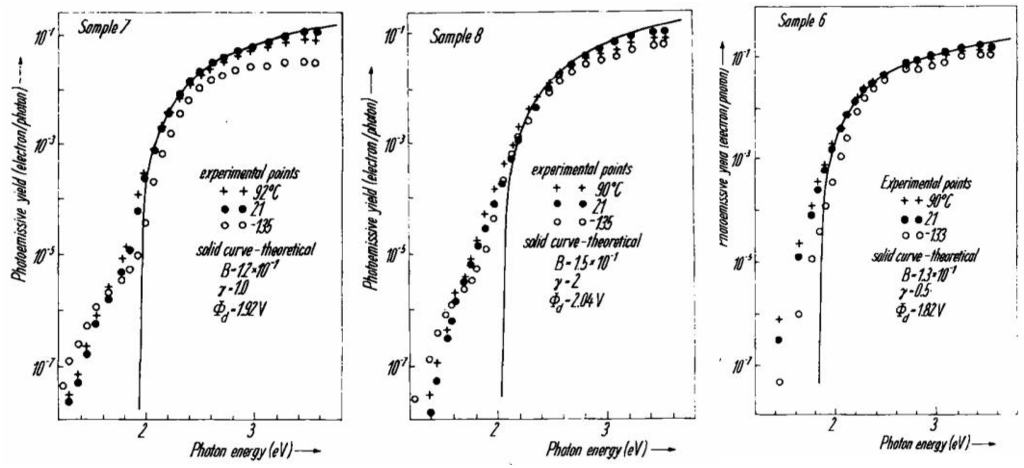


Epitaxial growth of cesium-antimonide films on lattice-matched single crystal SiC substrates.

Cesium-antimonide photocathodes

- Stoichiometry influences photoemission!

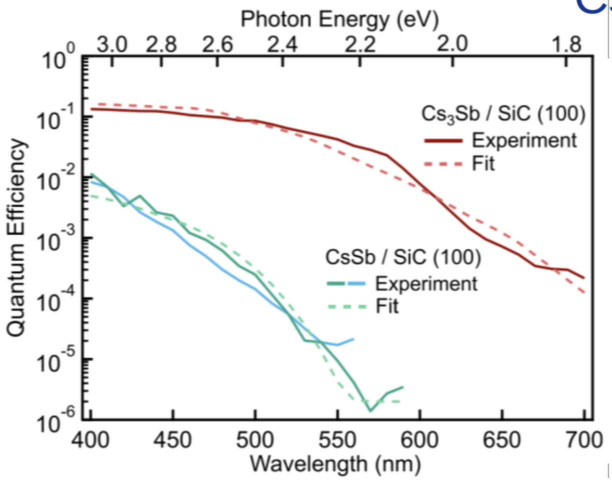
Stoichiometric variation

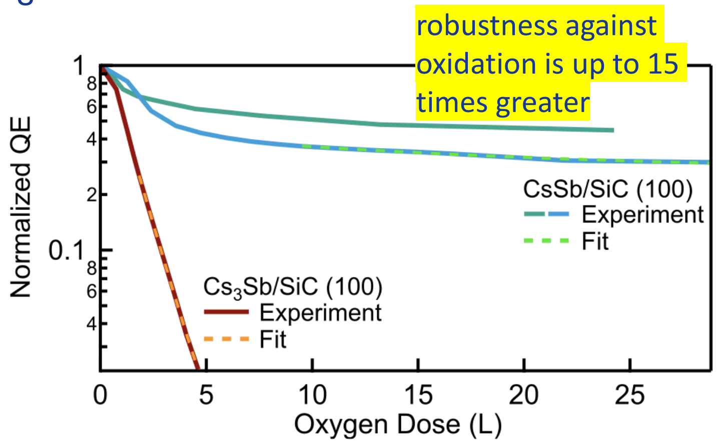


Near Cs_3Sb Cs-rich High yield

Hagino et al, Phys. Stat. Sol. **17**, 609 (1966).

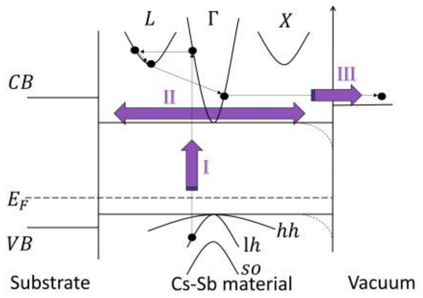
Cs_3Sb vs CsSb

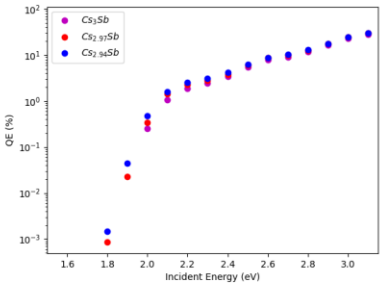




Parzyck et al., APL Mater. 11, 101125 (2023)

DFT + Monte Carlo investigation of stoichiometry influence on photoemission





Daniel Franklin, T21 (Tuesday)

Detailed modeling and advanced growth and characterization are required to achieve desired stoichiometry.

Testing alkali-antimonide photocathodes in accelerators

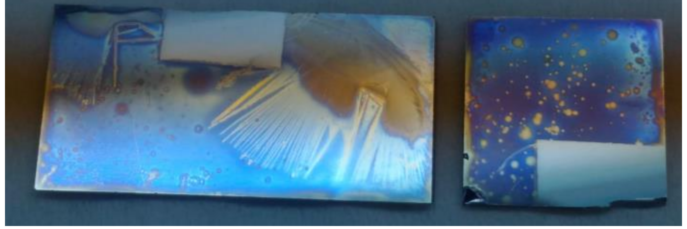
Alkali-antimonide photocathodes (Cs-Sb, Na-K-Sb):

- Low MTE ☑
- High QE ☑
- Thin films → prompt response time ☑
- Robustness + long operational lifetime under realistic photoinjector conditions ?

Testing alkali-antimonide photocathodes in accelerators

Previous experience:

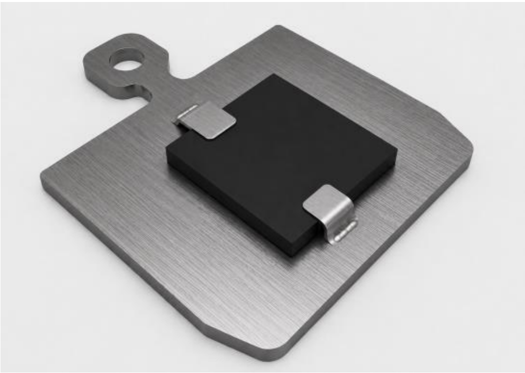
- many tests in DC guns
- very few tests of bialkali-antimonides in high field RF/SRF guns
- no RF tests of Cs-Sb films grown on SC substrates.


Oxidation of Cs-Sb films after ~ 5 min in air

Complications:

- photocathode sensitivity to vacuum conditions
- incompatibility between photocathode growth systems and photoinjectors

Flag-style sample holder



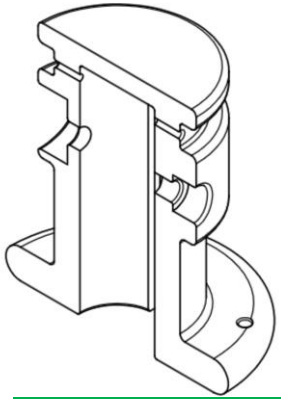
University labs

Old INFN-style

New INFN-style

FermiLab, SLAC, UCLA, Cornell

AWA drive gun



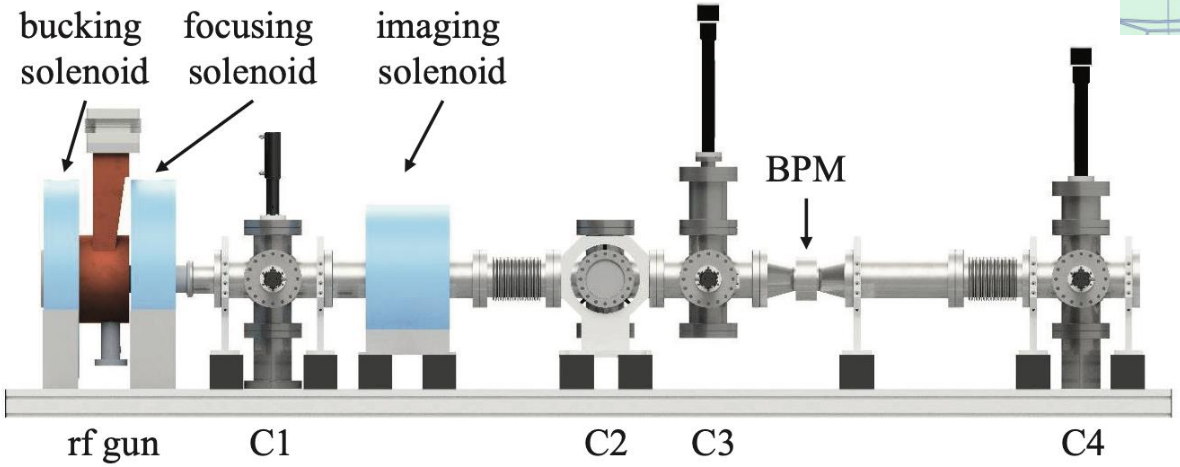
ACT gun

Witness gun

Argonne

Argonne Cathode Teststand (ACT):

- L-band 1.3 GHz single-cell photocathode RF gun.
- Emittance measurement capability.
- Close proximity to NIU.
- Currently suitable for testing air-stable materials only.
- Unique plug design.

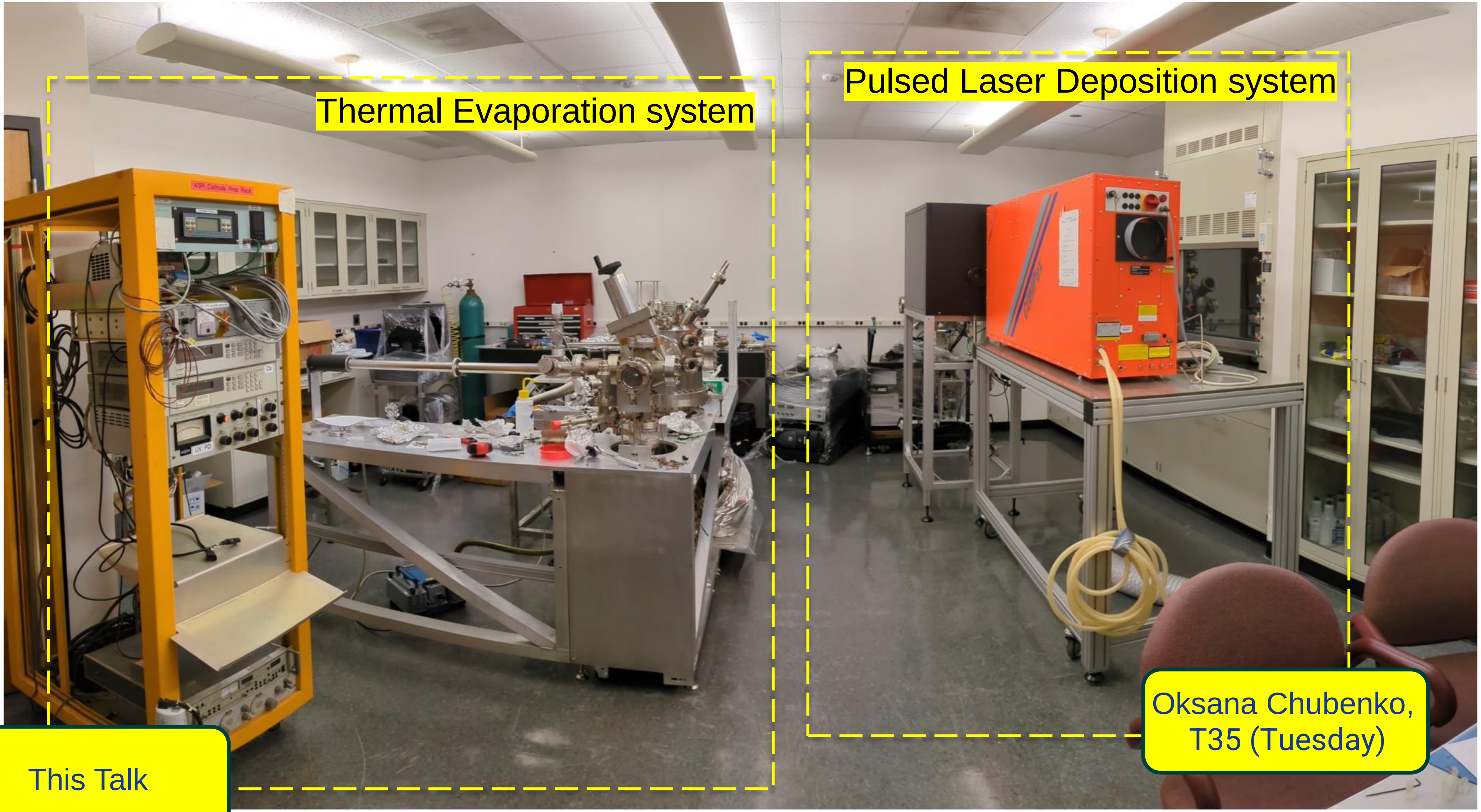


Shao et al, IPAC 2018

Planned ACT updates:

- Update the pump system to achieve ~10^{-10} Torr.
- Integrate NIU-compatible photocathode plug suitable for testing different photocathode substrates.
- Possibility of adding the deflecting cavity for photocathode response time measurements.

NIU Photoemission Research Lab

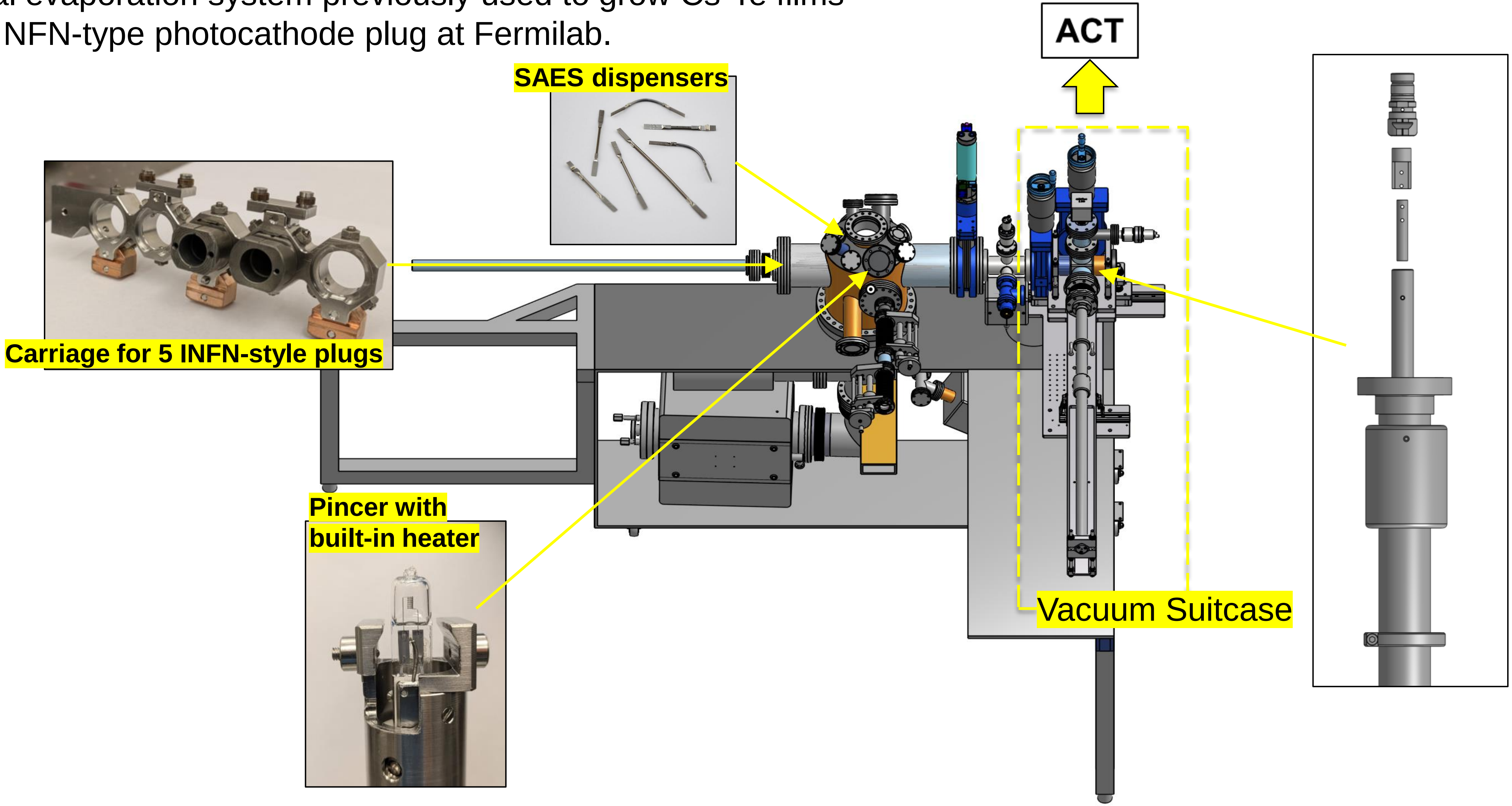


This Talk

Oksana Chubenko, T35 (Tuesday)

Growth of alkali-antimonide films at NIU

Thermal evaporation system previously used to grow Cs-Te films on old INFN-type photocathode plug at Fermilab.



Growth of alkali-antimonide films at NIU

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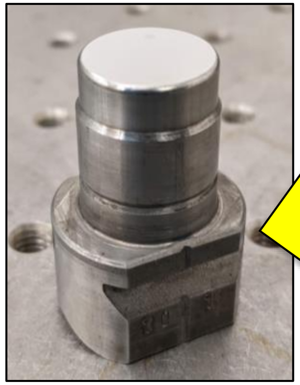
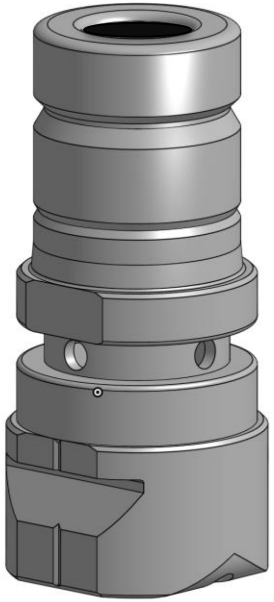
- New plug enables growth of low-MTE Cs_3Sb films on semiconductor substrates.
- Compatible with ACT

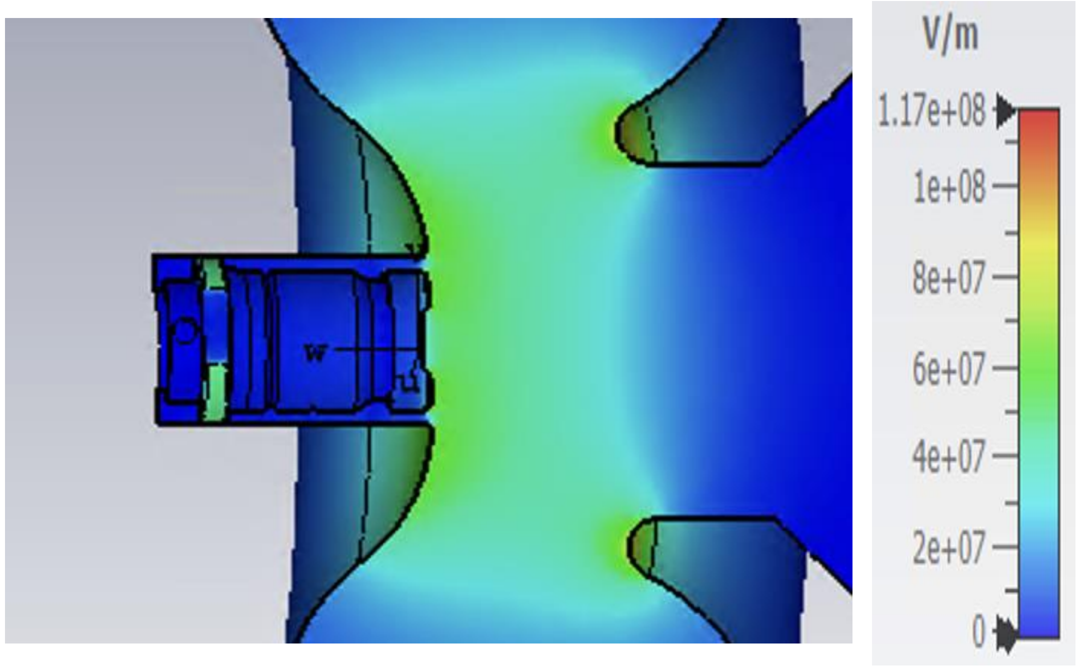
Old INFN-style plug



ACT plug

New NIU plug

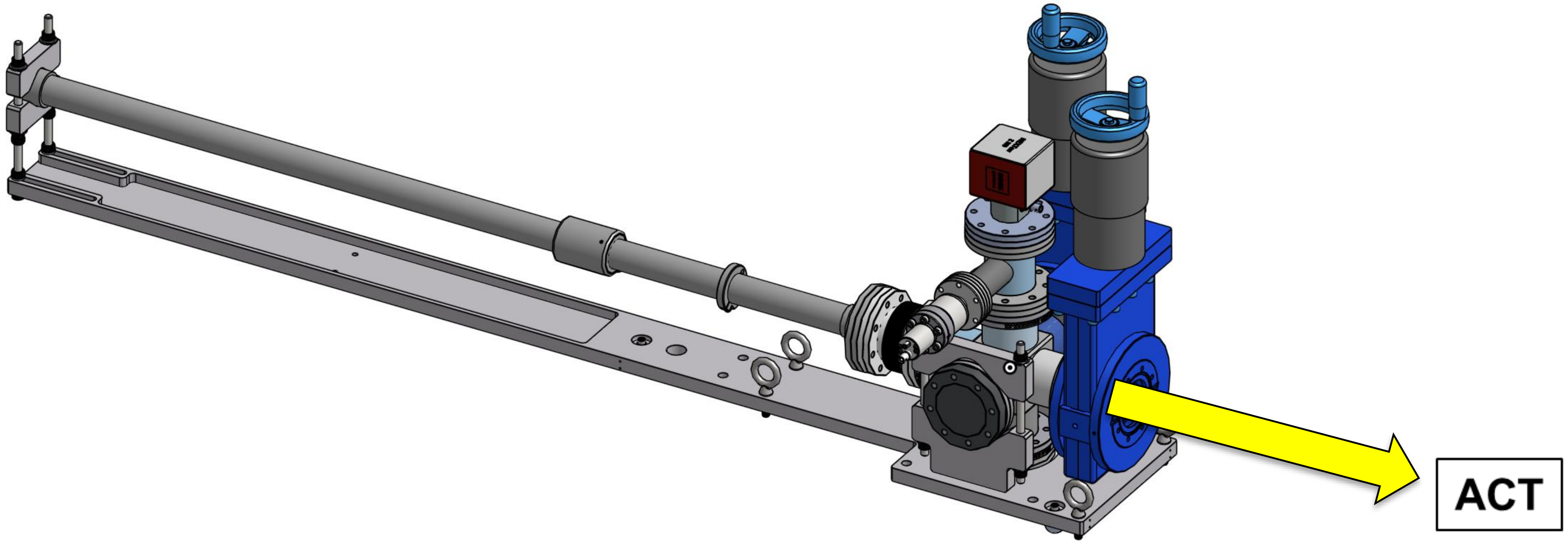




NIU plug in ACT

Developed vacuum suitcase compatible with ACT.

- K. J. Lesker sample transfer device with rolling metal & ceramic bearings for smooth, low friction actuation, with minimal outgassing.
- NEXTorr® UHV pump.
- Two VAT GVs.



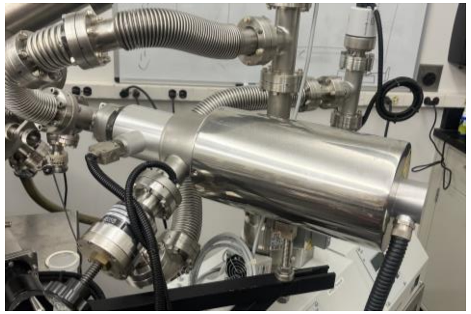
Further system upgrades:

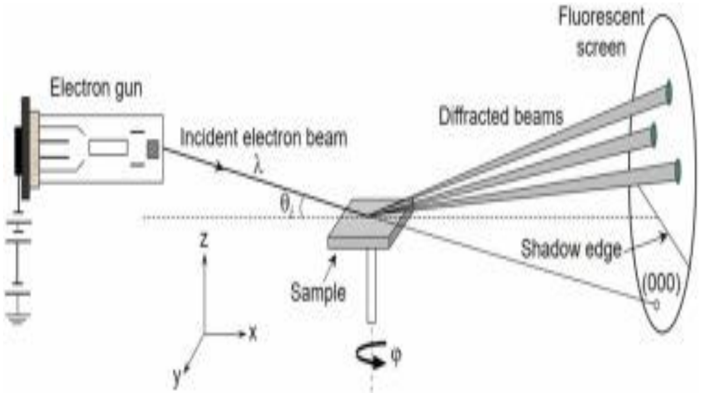
- More efficient particle sources

SAES dispensers

Effusion cell

- Implement RHEED system or other mechanism for controlled epitaxial growth of alkali antimonide photocathodes with desired stoichiometry.





Summary

- High-quality photocathode development through epitaxial growth of atomically smooth crystalline materials.

- Developed experimental setup for the epitaxial growth of alkali antimonide photocathodes on lattice-matched substrates.

- Extensive testing and characterization of photocathodes will be carried out in the L-band RF gun of ACT.

- This project aims to bridge the gap between university-based photocathode R&D and the reliable deployment of high-quality photocathodes in accelerator facilities.

Acknowledgements

Undergrad students:

Grace Straub (NIU)

Grad students:

Tariqul Hasan (NIU)

Collaborators:

John Power (ANL)
Scott Doran (ANL)
Eric Wisniewski (ANL)
Gongxiaohui Chen (ANL)
Philippe Piot (ANL)

Funding agencies:

The Center for Bright Beams (CBB), NSF award PHY-1549132.
Launching of Early-Career Academic Pathways in the Mathematical and Physical Sciences (LEAPS-MPS), NSF Award Number 2532996.

Thank you!