Low-MTE Photocathode Test at AWA

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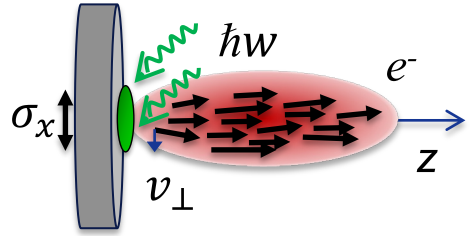
Outline

- *High-quality photocathodes and their impact*
- *Alkali antimonide photocathodes: high Quantum Efficiency (QE) and low Mean Transverse Energy (MTE)*
- *Photocathode development at NIU*
- *Testing photocathodes at AWA*
- *Conclusions and future steps*

Motivation

High-quality electron beams =

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



Photocathode

$$N_{bunch} \propto \sigma_x \sigma_y (E_z)^k$$
$$1 \leq k \leq 2$$
$$\epsilon_{x,y} = \sigma_{x,y}\sqrt{MTE/m_e c^2}$$

High-quality photocathodes =

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

  MTE ~ k_BT ~ 25 meV at room temperature → MTE ~ few 100s meV

  Factors, limiting MTE:
  - requirements of the high charge density
  - disordered nature of photocathode materials
  - surface roughness and work function variations

- high quantum efficiency $QE = \frac{N_{e^-}}{N_{\hbar w}}$

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

Capabilities of accelerator applications are limited by capabilities of electron sources!

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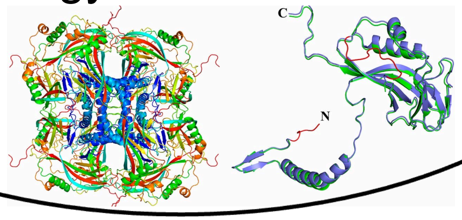
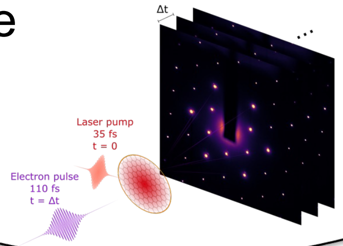
X-ray Free Electron Laser (XFEL)
- protein crystallography
- cell biology

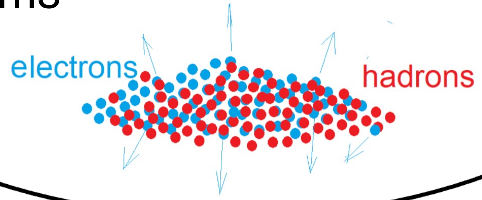


Ultrafast Electron Diffraction (UED)
- dynamical changes of material structure

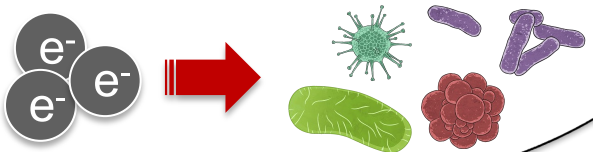


High-quality photocathodes

Electron cooling of hadron beams
- reduction of emittance of hadron beams



Industrial electron accelerators
- sterilization of medical devices, municipal sludge, and waste water



Cesium antimonide photocathodes

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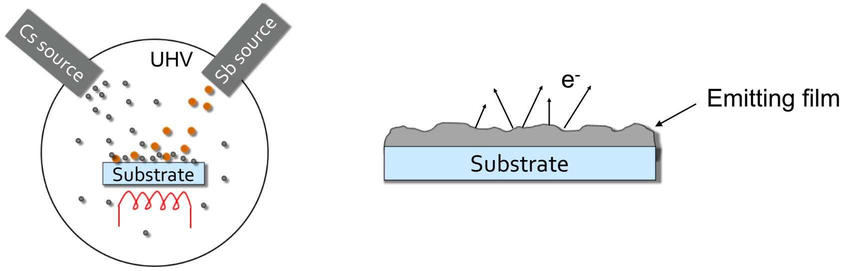
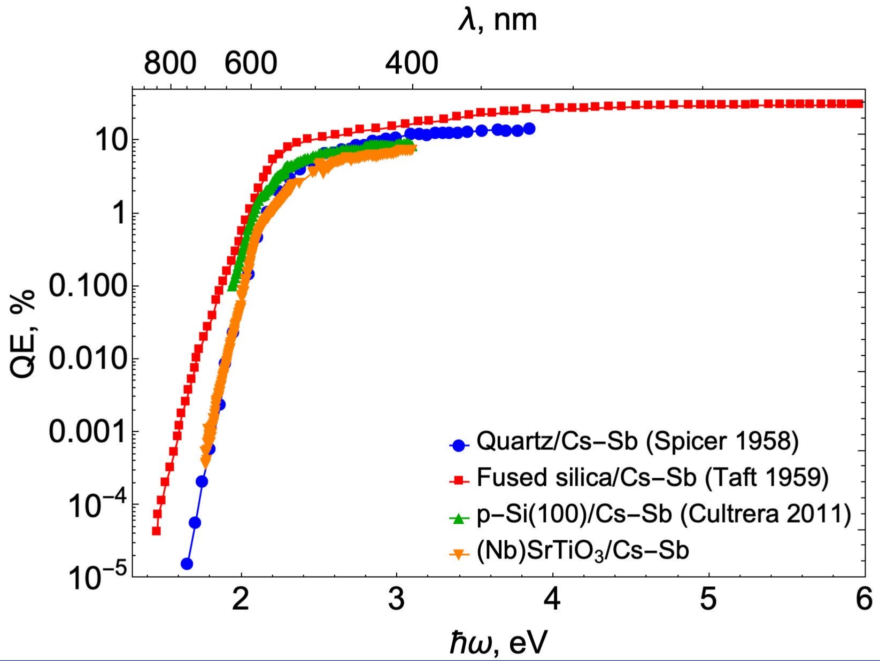
(Bi)Alkali antimonides (Cs_3Sb, CsK_2Sb, etc.) belong to a class of bright electron sources.

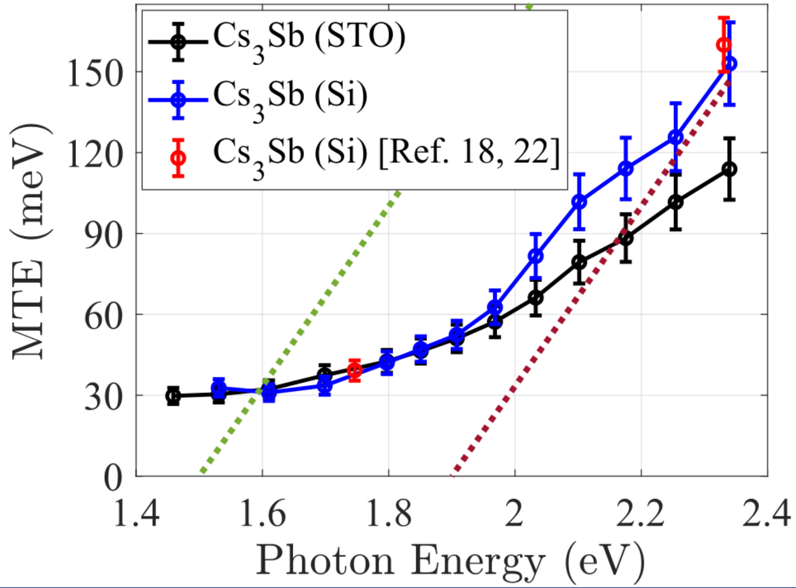
Cesium antimonide photocathodes:

- can be easily deposited through thermal evaporation at moderate temperatures
- photoemit in a visible wavelengths range





Kachwala et al., 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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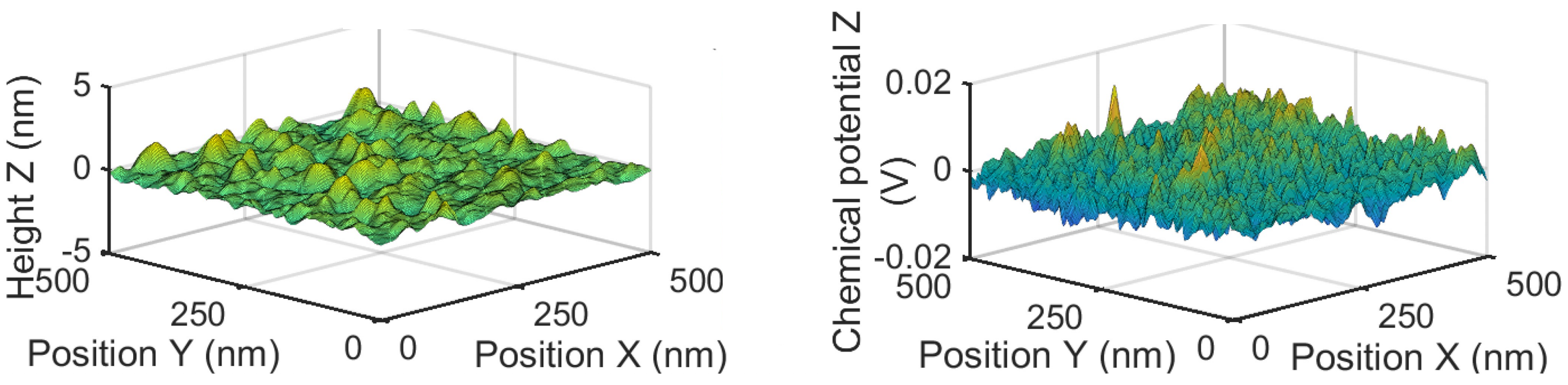
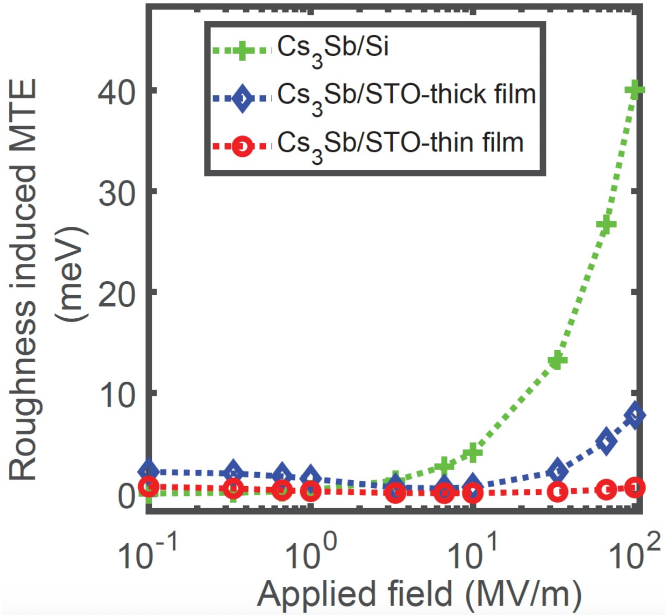
Surface roughness and work function variation can limit MTE!





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

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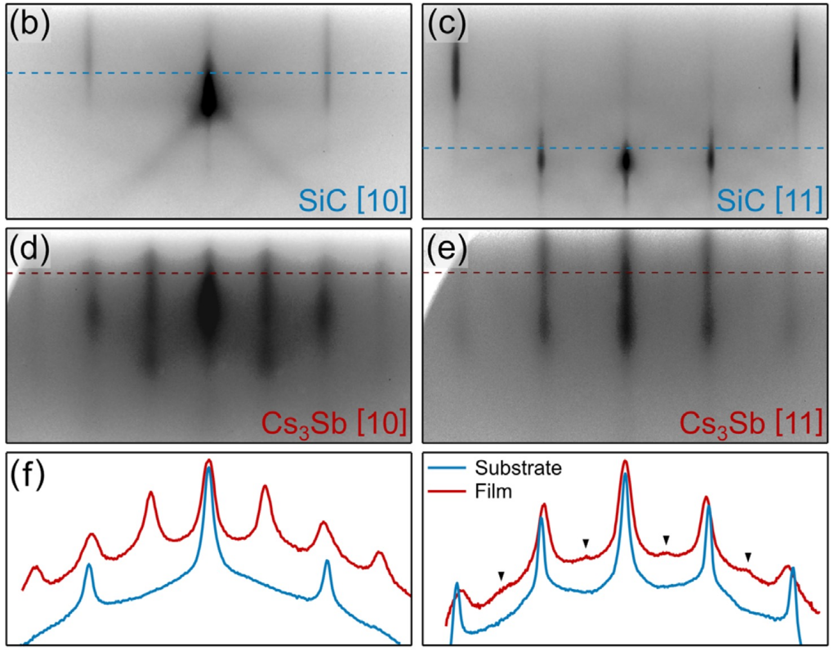
Disordered crystal structure can limit MTE!



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

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

First-to-date demonstration of epitaxial growth of cesium-antimonide films on lattice-matched single crystal SiC substrates.

Testing cesium antimonide photocathodes in accelerators

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Cesium antimonide photocathodes:

- Low MTE ✅
- High QE ✅
- robustness + long operational lifetime under realistic photoinjector conditions ?

Previous experience:

- many tests in DC guns
- very few tests of bialkali antimonides in high field RF/SRF guns
- CBB: attempts to test Cornell-grown photocathodes at UCLS's Pegasus

CBB Strategic Plan:

Deliverable 2.1 (Priority): Photocathode that can operate for >1 week with MTE <35 meV at 50 mJ/cm^2 laser fluence and high field (>100 MV/m) for high peak current applications such as XFELs (**Summer 2025**)

Deliverable 2.2 (Priority): Photocathode that can operate for >1 week with MTE <100 meV and QE>1% under high average current (>50 mA) conditions (**Summer 2026**)

Grow cesium antimonide photocathodes at NIU and test them at AWA facility.

Growth of Cesium Antimonide Photocathodes

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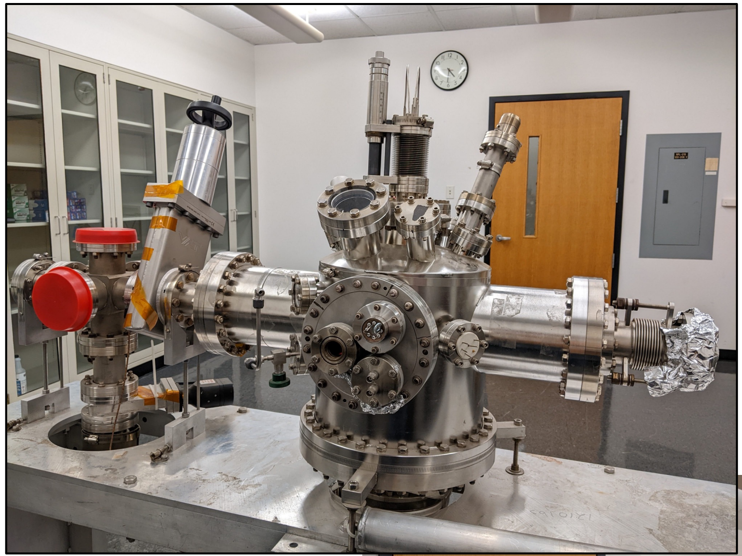
Option 1: NIU Photoemission Research Lab



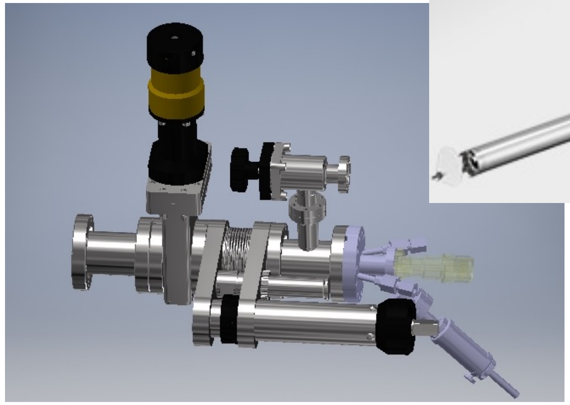
Growth system previously used to grow Cs-Te at Fermilab

INFN-type photocathode plug

Option 1: NIU Photoemission Research Lab

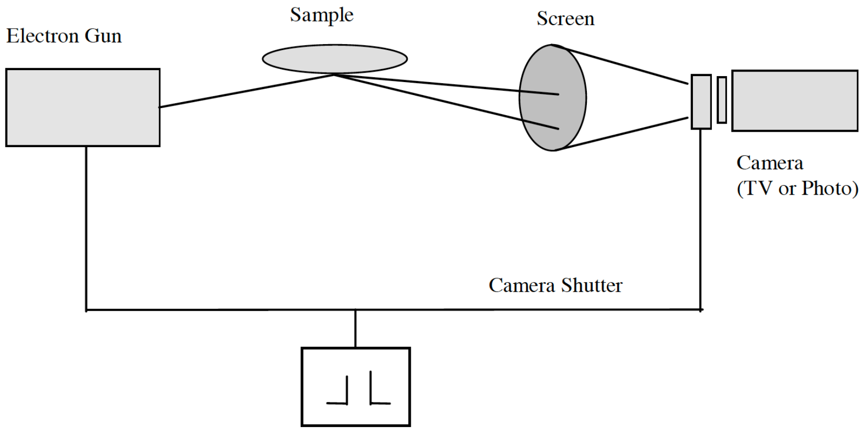
Growth system updates

- Replace SAES strip Cs sources with long-lasting effusion cells (MBE Komponenten) with cesium molybdate pellets (SAES Getters)
  - Evaporation of metals, compounds and organic materials between 80° C and 1000° C
  - Crucible capacities from 2 to 200 cm³
  - Excellent temperature stability and controllability
  - Gate valve + bellow system for a faster "recharge"



- *In situ/operando* characterization with the RHEED system required for the epitaxial growth of cesium antimonide photocathodes

- Develop the load-lock and photocathode transfer systems compatible with AWA



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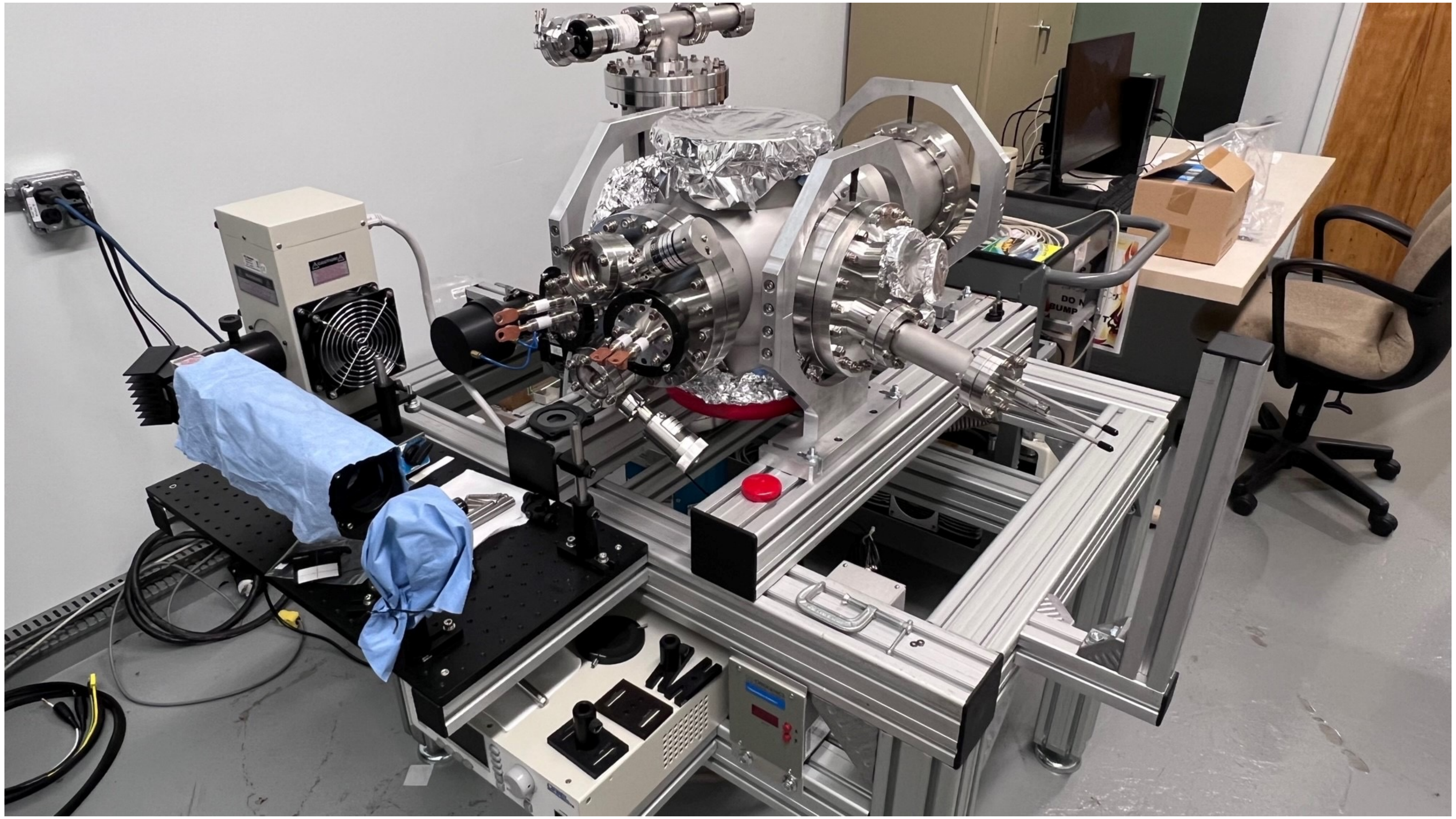
Option 2: Brand-new, unused (but unfinished) cathode deposition system at AWA



Picture courtesy of Scott Doran

Growth of Cesium Antimonide Photocathodes

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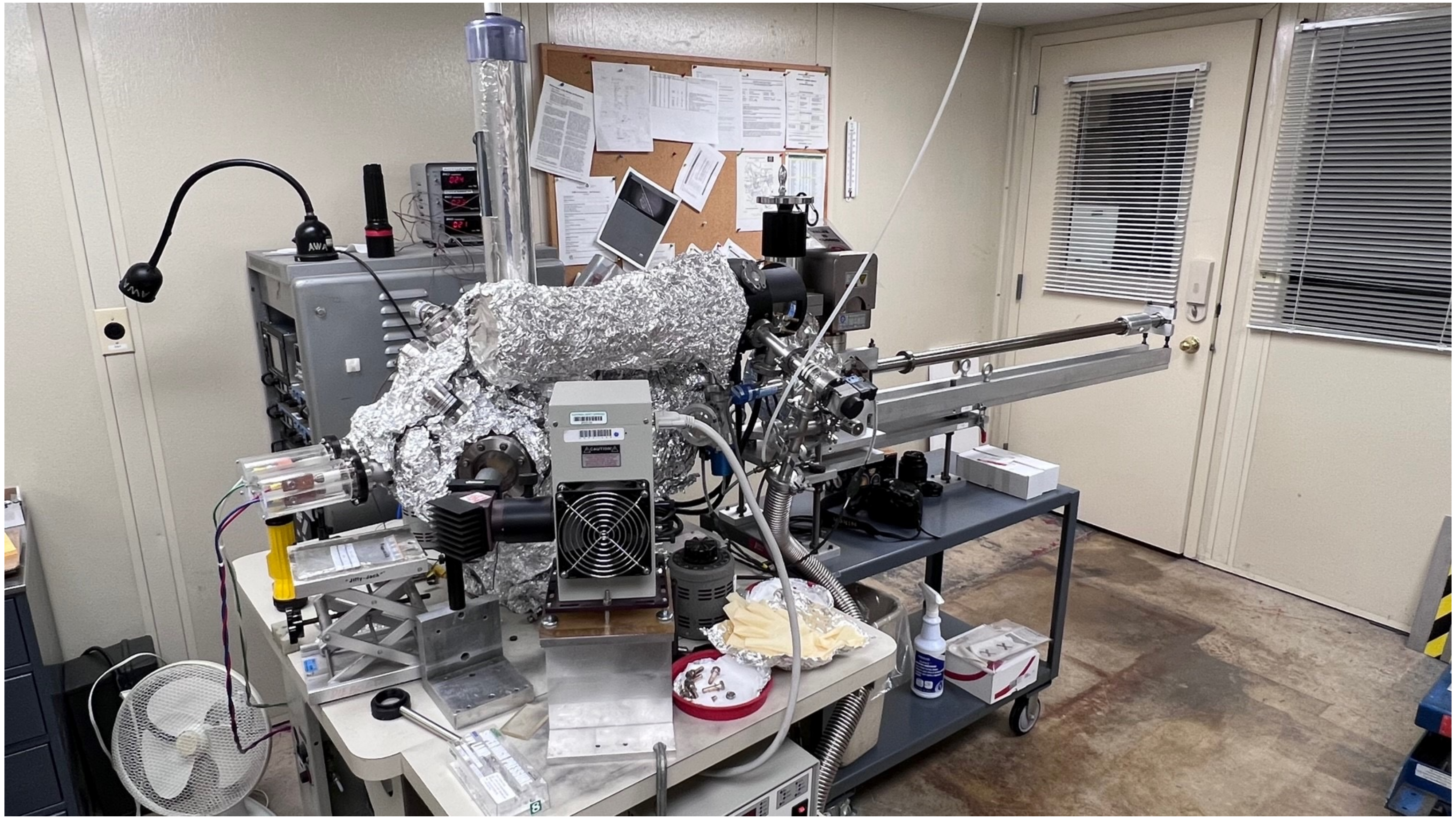
Option 3: Cs-Te growth system at AWA



Picture courtesy of Scott Doran

Testing Cesium Antimonide Photocathodes at AWA Facility

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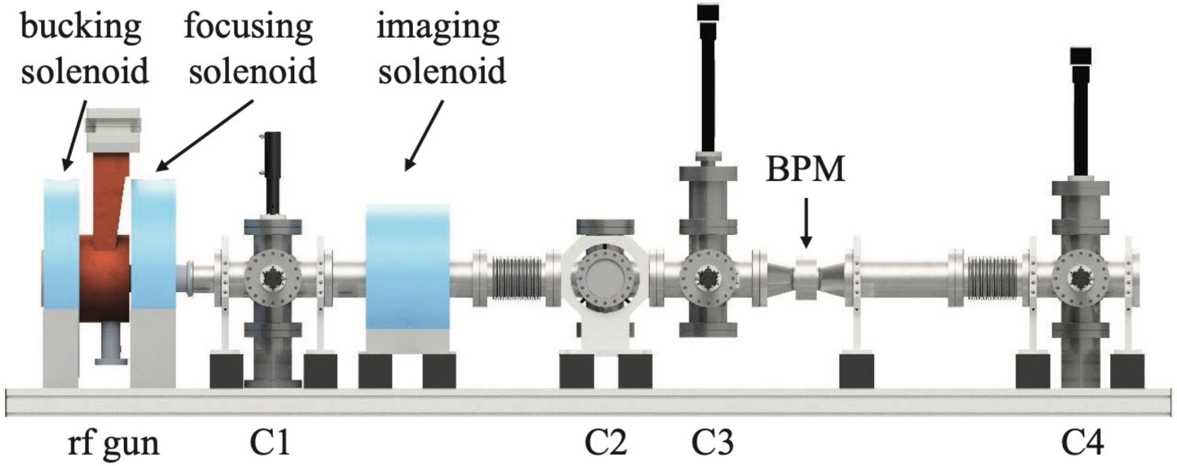
Option 1: Argonne Cathode Teststand (ACT) beamline:

- L-band 1.3 GHz single-cell photocathode RF gun
- includes field emission (FE) imaging system to locate emitters with a resolution of ~20 μm
- currently suitable for testing air-stable materials only
- not in often use
- photocathode plug is suitable for testing different photocathode substrates
- intention of adding a load-lock system for testing Cs-containing photocathodes
- intention to update the pump system for ~10^{-10} Torr
- intention of adding the deflecting cavity for photocathode response time measurements



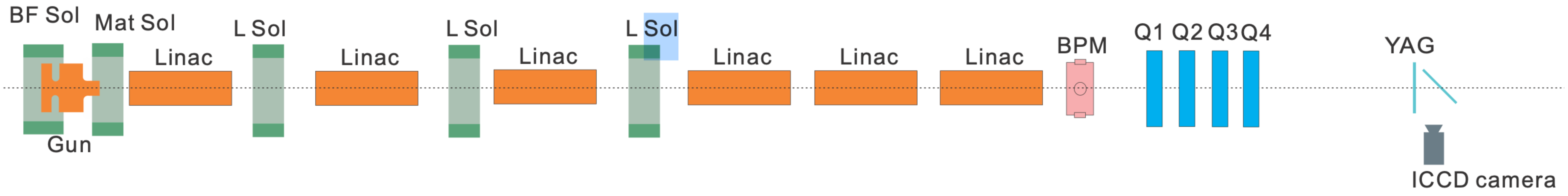
Shao et al, IPAC 2018 https://accelconf.web.cern.ch/ipac2018/papers/tupml006.pdf

Option 2: AWA drive gun

- L-band 1.3 GHz 1.5-cell photocathode RF gun
- Cs_2Te photocathodes
- quadrupole-scan method for measuring thermal emittance

$$\varepsilon_{T,x} = \sigma_x \frac{\sqrt{\langle p_\perp^2 \rangle}}{m_e c} = \sigma_x \frac{\sqrt{MTE}}{m_e c^2}$$

- has a load-lock system for testing Cs-containing photocathodes
- main facility gun = busy + concern regarding inserting new photocathodes



Zheng et all, IPAC 2017 https://accelconf.web.cern.ch/ipac2017/papers/tupab074.pdf

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Option 3: AWA witness gun

- RF gun, prototype of the new AWA drive gun
- provides more flexibility
- some modifications are required to perform our tests

Conclusions and future steps

- AWA possesses both the capabilities and the willingness to test alkali antimonide photocathodes.
- Task 1: Identify the beamline(s) most suitable for achieving our goals.
- Task 2: Complete the growth system so that it is compatible with the selected beamline(s).
- Task 3: Develop the load-lock and photocathodes transfer systems compatible with the selected beamline(s).
- Task 4: Develop the plug that uses semiconductor substrates.