High-Efficiency and Low-Emittance Electron Sources

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Introduction

The Center for BRIGHT BEAMS
A National Science Foundation Science & Technology Center

Beam Production

theme leaders

Richard Hennig U. Florida | Jamie Rosenzweig UCLA | Melissa Hines Cornell | Kyle Shen Cornell | Ivan Bazarov Cornell | Pietro Musumeci UCLA | Jared Maxson Cornell | Siddharth Karkare ASU | Oksana Chubenko NIU | Tomas Arias Cornell

Optimal outcome: Methods for x100 brighter electron sources through better photocathodes, enabling better X-ray sources, colliders and electron imaging.

Introduction

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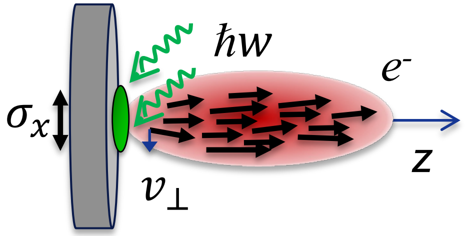
High-quality electron beams =

- 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 =

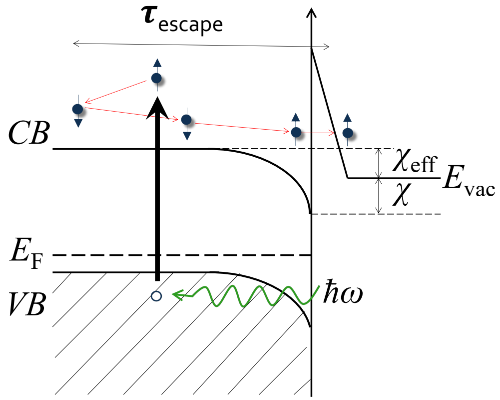
- low mean transverse energy $MTE = \frac{m\langle v_\perp^2 \rangle}{2}$

MTE ~ $k_B T$ ~ 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 $QE = \frac{N_{e^-}}{N_{\hbar w}}$
- prompt response time



NEA GaAs

- 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!

Metal vs. semiconductor photocathodes

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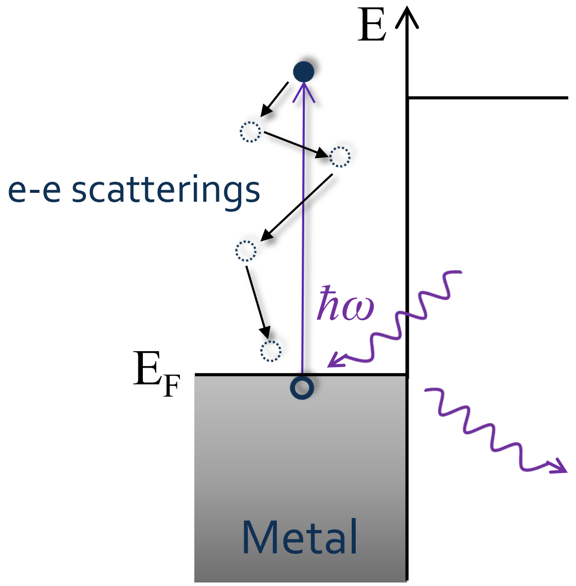
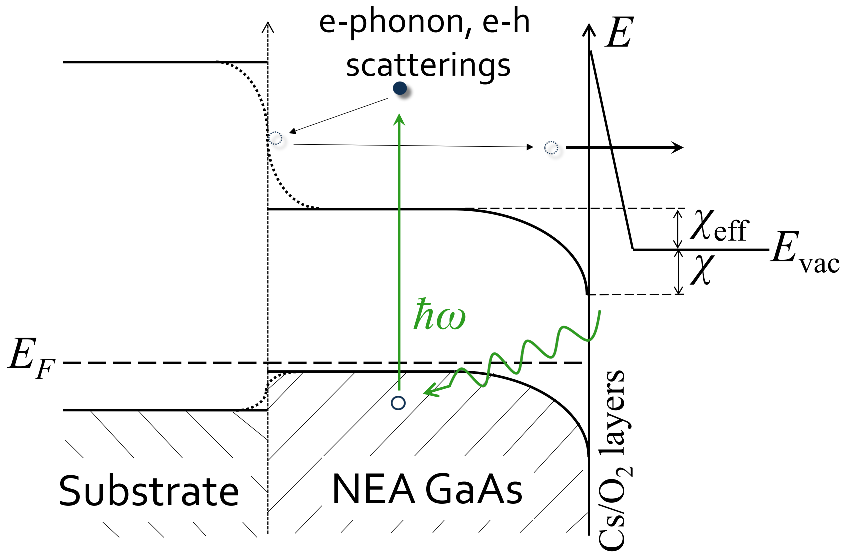
Metals

- Prompt response time
- Low QE (high reflection coefficient, enhanced e-e scattering events)



Semiconductors

- High QE (less reflective surfaces, fewer e-phonon, e-h scattering events, NEA GaAs:Cs)
- Can be tuned and optimized for specific wavelength ranges and applications
- Prompt response time can be achieved (thin films)



Semiconductor photocathodes

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All next-generation electron linear accelerators (XFELs and colliders alike) plan the use of high-QE semiconductor photocathodes. The three main choices in use today are:

GaAs:Cs

- Go-to polarized electron source (Jlab's CEBAF, SLAC, BNL's EIC)
- Extremely vacuum sensitive (DC guns only, ≪ 10^{-10} Torr)
- Percent-level QE in green (520-530 nm)
- MTE ≈ 120 meV (or 0.48 um/mm rms) in green

Cesium Telluride

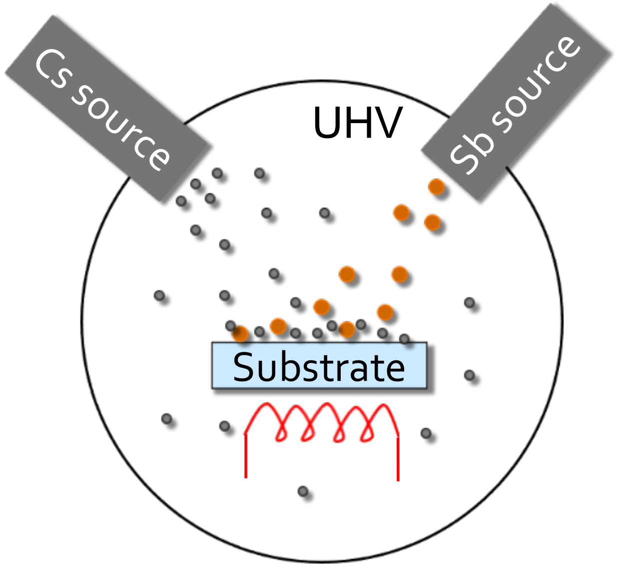
- Vacuum sensitive (< 10^{-9} Torr), but less so than alkali antimonides and GaAs:Cs
- Well-tested in high RF fields (FAST, PITZ, EU-XFEL)
- Percent-level QE in UV (~260 nm)
- High work function good for dark current
- Adds significant laser complexity
- MTE ≈ 500 meV (or 1 um/mm rms) in UV
- Non-monotonic MTE due to presence of low-threshold compounds

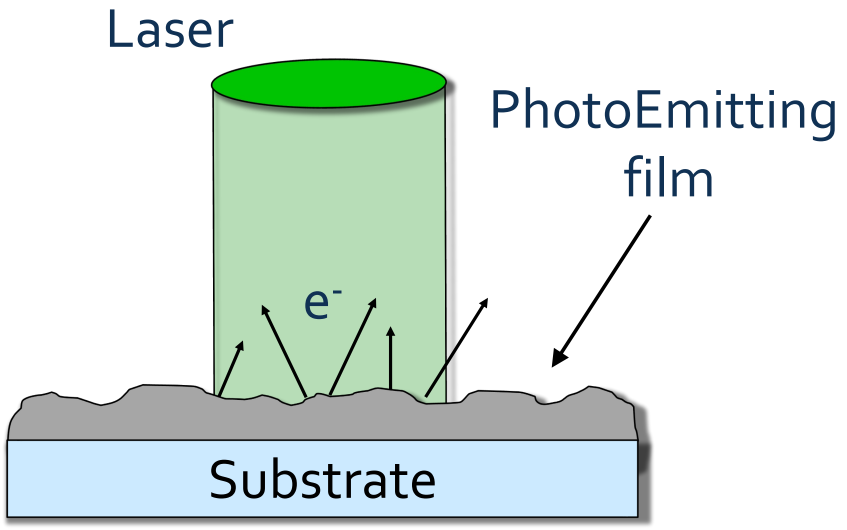
Alkali Antimonides

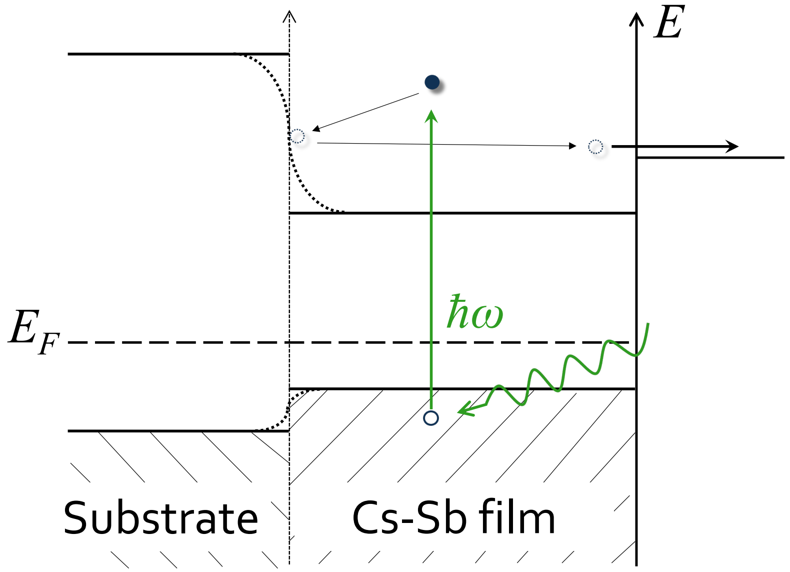
- Vacuum sensitive (< 10^{-10} Torr)
- Percent-level QE in green (520-530 nm)
- MTE ≈ 130 meV (or 0.5 um/mm rms) in green
- In use at BNL QWR SRF gun, planned for LCLS-II-HE low emittance injector (> 30 MV/m)
- Very few tests in high-field RF guns (many tests in DC guns)
- Multiple species to choose from Cs-Sb, Cs-K-Sb, Na-K-Sb, …

Cesium-antimonide photocathodes:

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

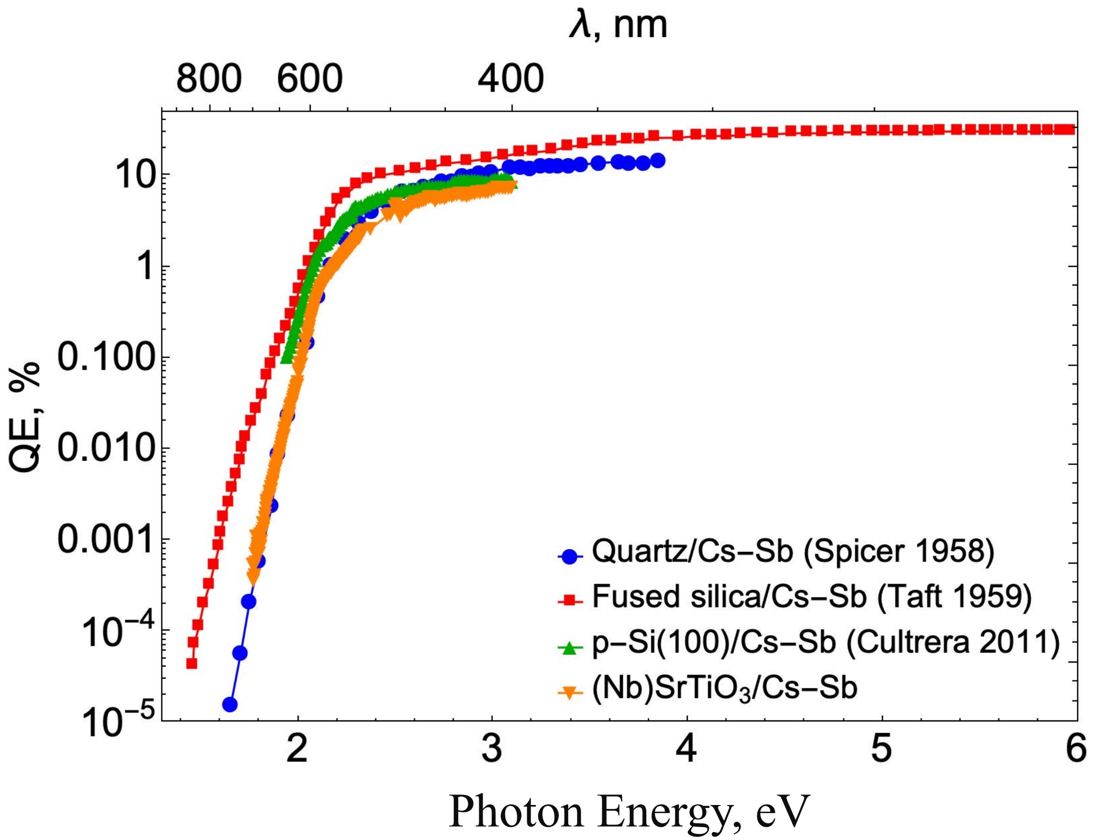




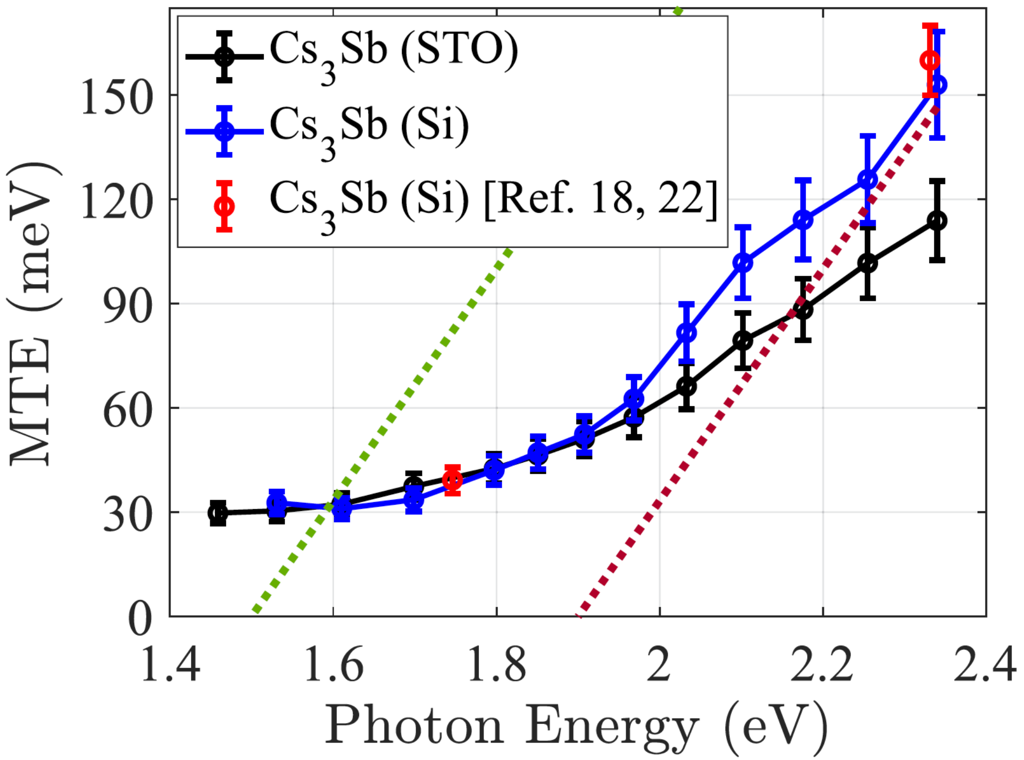


Cesium-antimonide photocathodes

- By reducing the photoexcitation energy, one can trade QE for lower 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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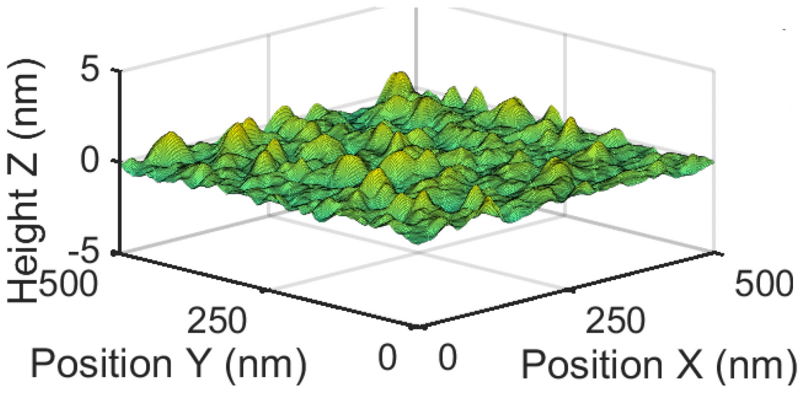
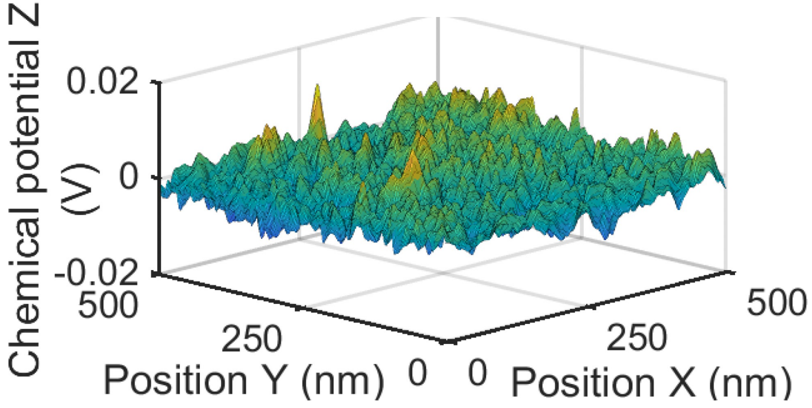
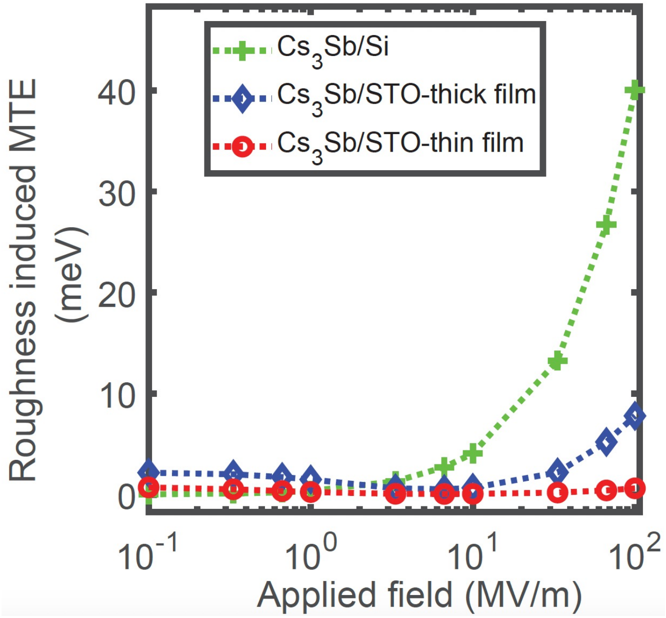
- Surface roughness and work function variation can limit MTE!







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

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

Cesium-antimonide photocathodes

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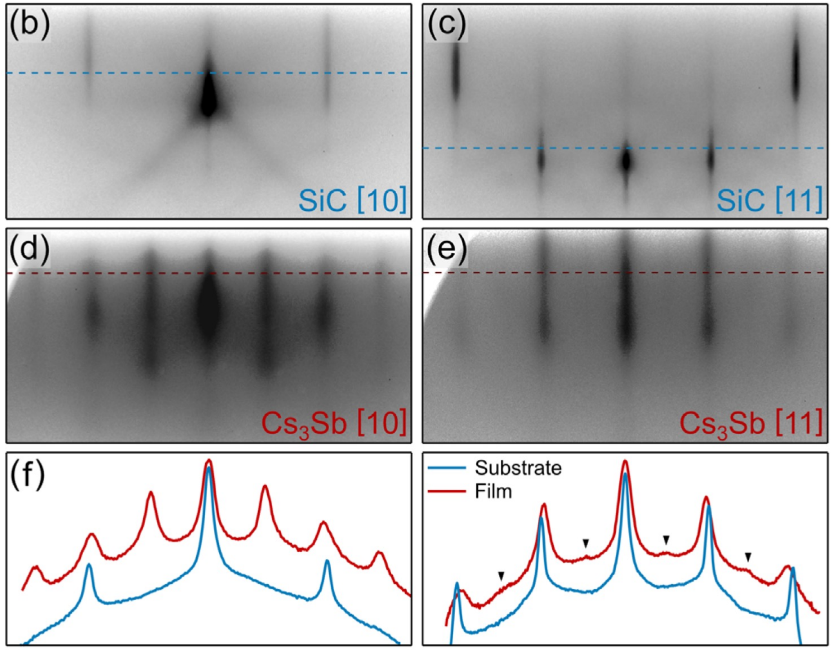
- Disordered crystal structure can limit MTE!



RHEED images of an annealed SiC substrate and a 10 u.c. Cs3Sb film.

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

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

Sodium-potassium-antimonide photocathodes

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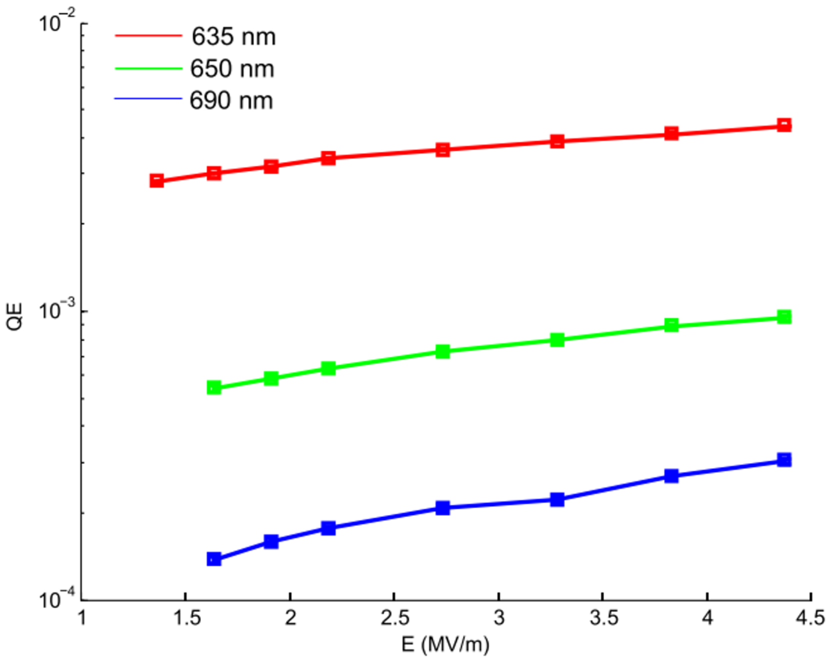
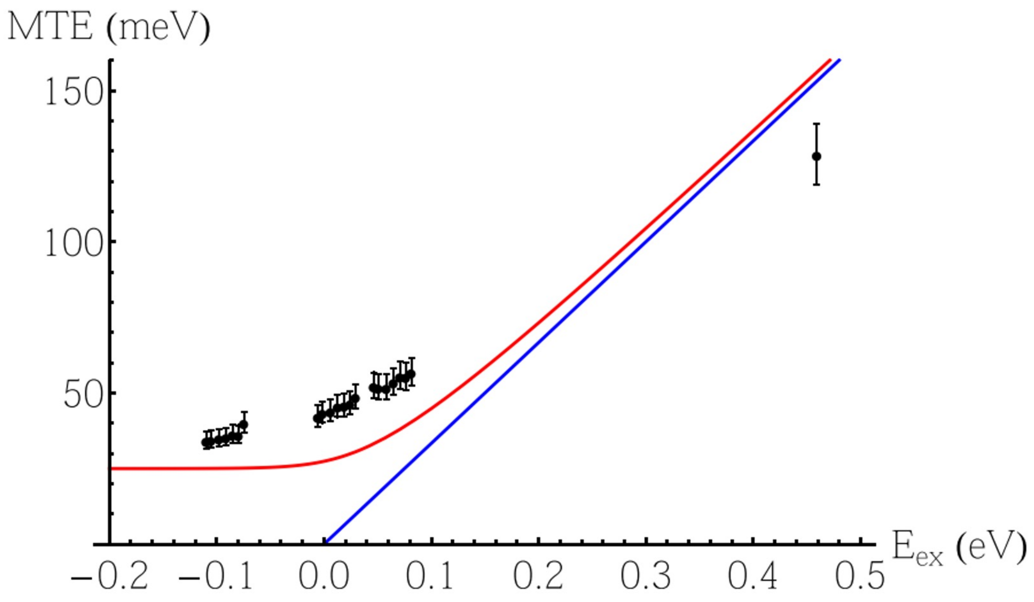
- Alkali antimonides achieve as low as ~30 meV (shown below: Na-K-Sb, min MTE of 35 meV) with photon energy tuning (>10x max. brightness as compared to Cs-Te in normal operation).
- Lower QE must be balanced against increased laser energy - ultimate limit is multiphoton photoemission, which spoils low MTE.





$E_{ex} = h\nu - (\phi - e\sqrt{eE/4\pi\epsilon_0})$. We assume $\phi = 1.95$ eV.

Na-K-Sb photocathodes demonstrate thermal-limit MTE and relatively high QE at photoemission threshold.

Maxson et al, Appl. Phys. Lett. 106, 234102 (2015)

Testing alkali-antimonide photocathodes in accelerators

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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 ?

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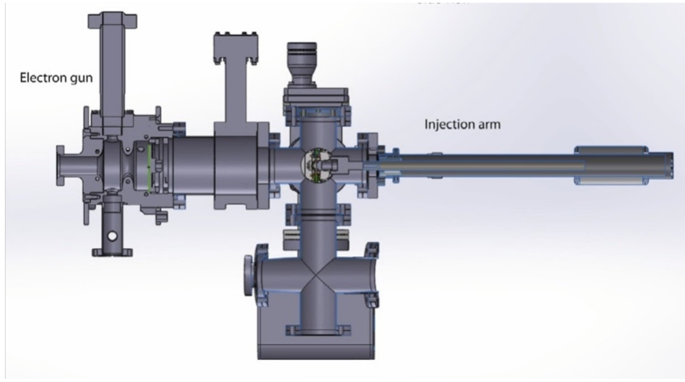
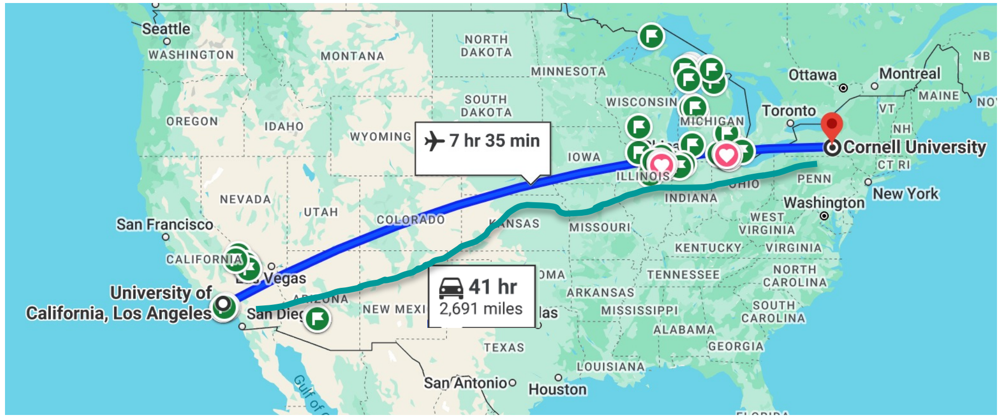
Previous experience:

- many tests in DC guns
- very few tests of bialkali-antimonides in high field RF/SRF guns; no tests of Cs-Sb
- **CBB efforts: testing Cornell-grown photocathodes at UCLA**

  - UCLA's Pegasus is compatible with Cornell's photocathode growth system.
  - (Relatively) successful deployment of photocathode grown at Cornell to UCLA: beam delivered with multiple orders of magnitude higher QE than baseline Cu photocathode.
  - Due to long transit time from NY → CA, the cathode suffers QE degradation below percent level in the suitcase.





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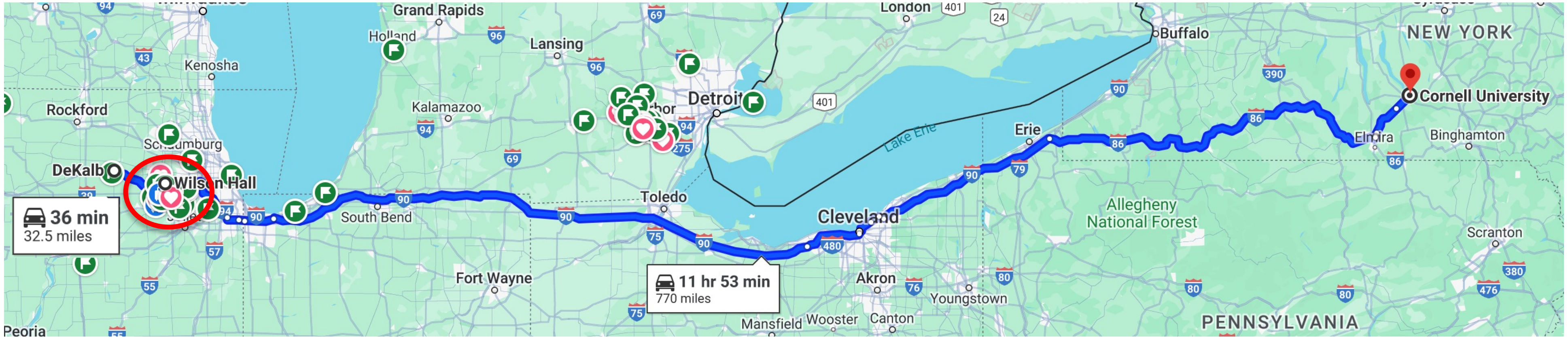
CBB Strategic Plan:

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

We propose to grow alkali-antimonide photocathodes and test them at FAST facility.



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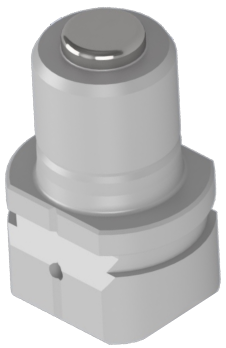
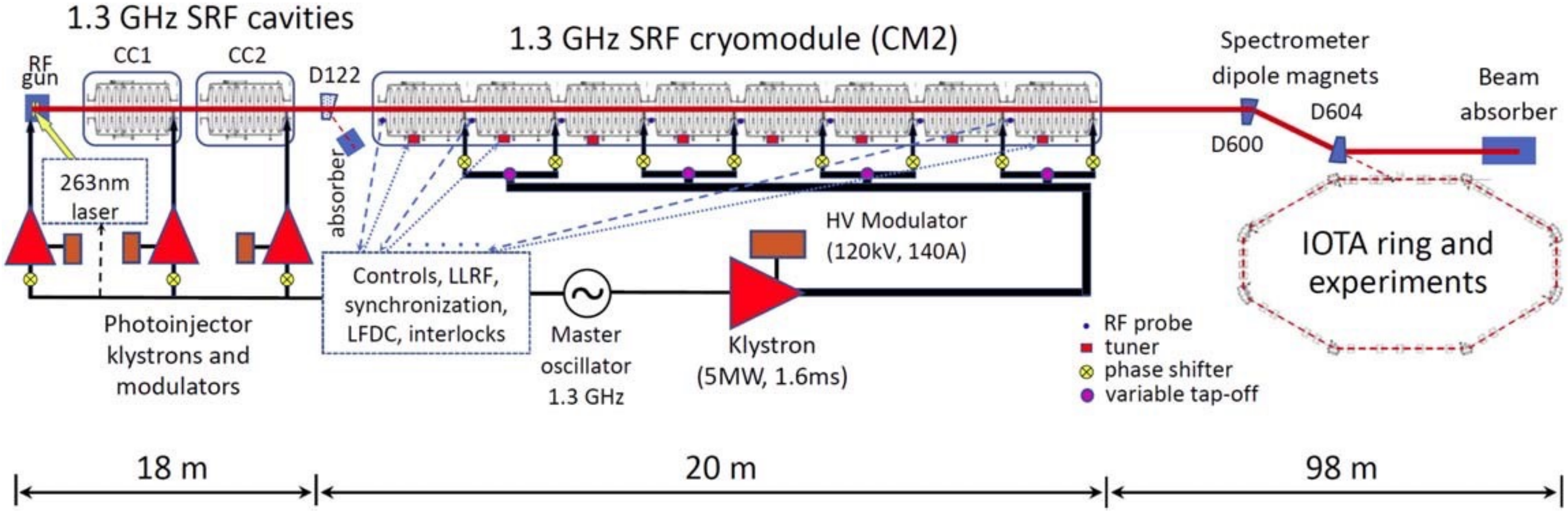
FAST electron injector:

- Photoinjector-based 1.3 GHz SRF linear accelerator.
- Production of 150 MeV electrons for IOTA ring.
- Main facility electron gun.
- Cs-Te-coated Mo photocathode.
- INFN-type photocathode plug.



INFN-type plug



Broemmelsiek et al, New J. Phys. 20, 113018 (2018) https://doi.org/10.1088/1367-2630/aaec57

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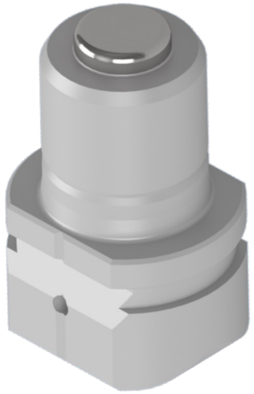
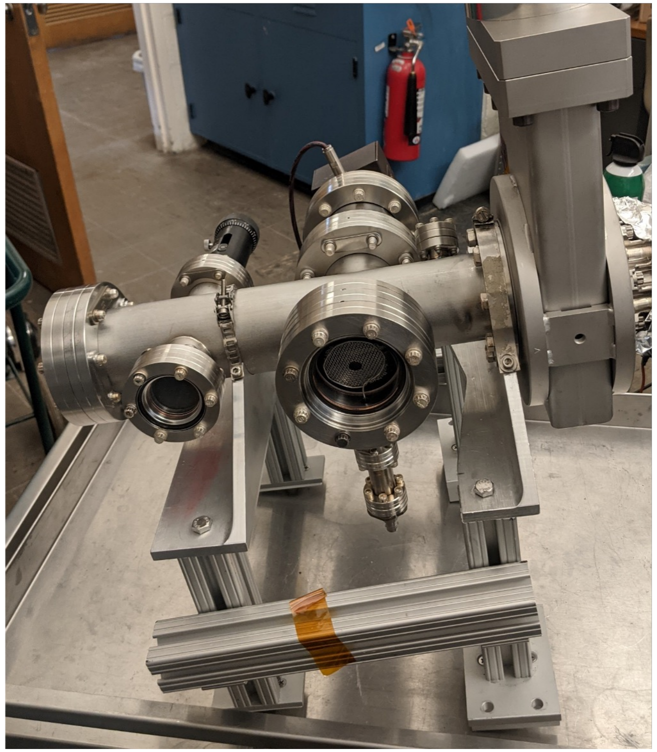
Cornell photocathode growth system:

- Used to grow Na-K-Sb films. Other compounds also possible.
- Uses INFN-type photocathode plug.
- Cornell also has an INFN-style suitcase system for vacuum transfer (also compatible with FAST).



INFN-type plug

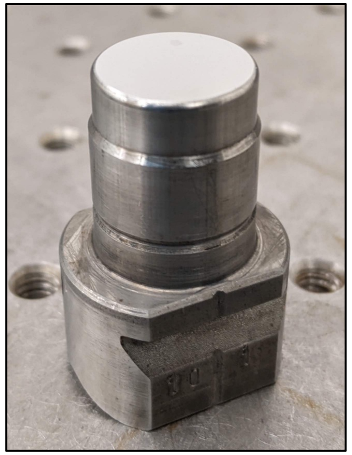


NEG and ion pump achieve pressure below 1e-10 torr

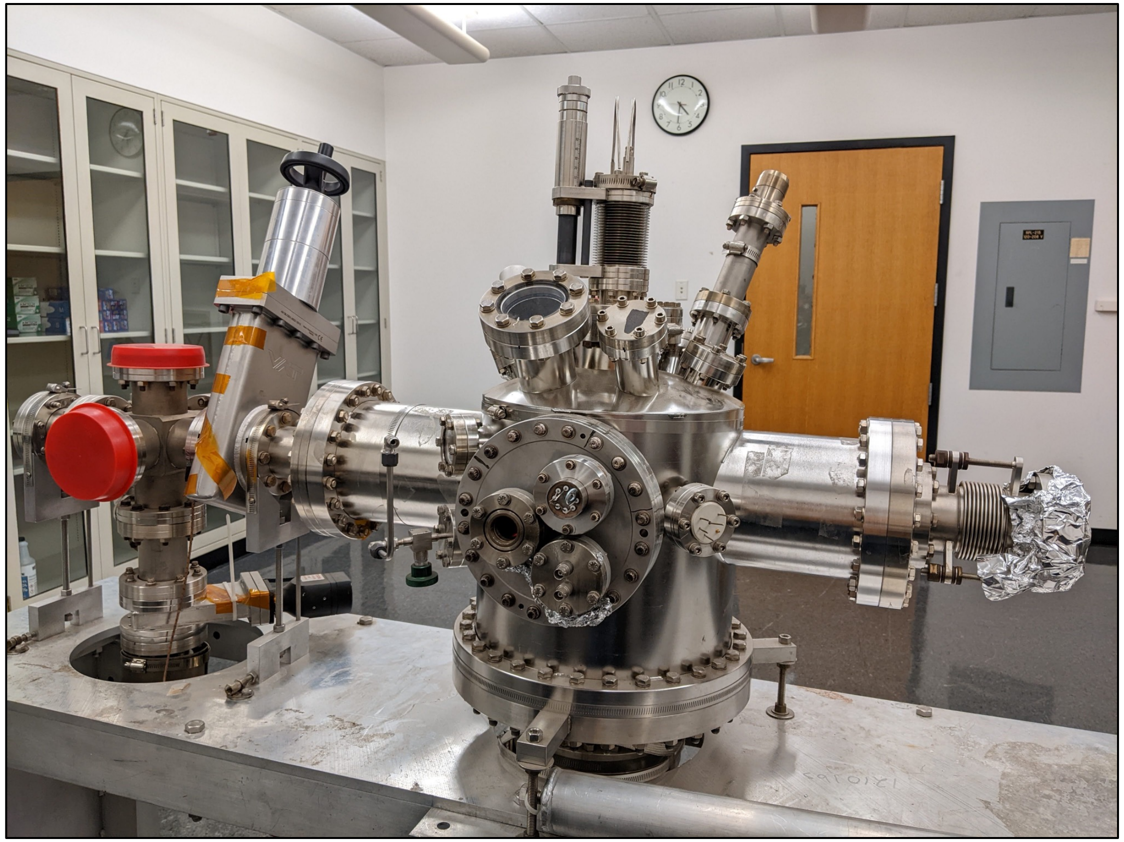
Collection grid diagnostic for QE measurements

NIU photocathode growth system:

- Was previously used to grow Cs-Te at Fermilab.
- Uses old INFN-type photocathode plug.



Old INFN-type plug



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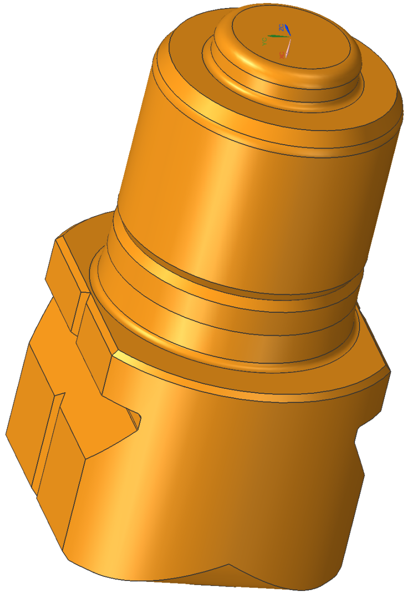
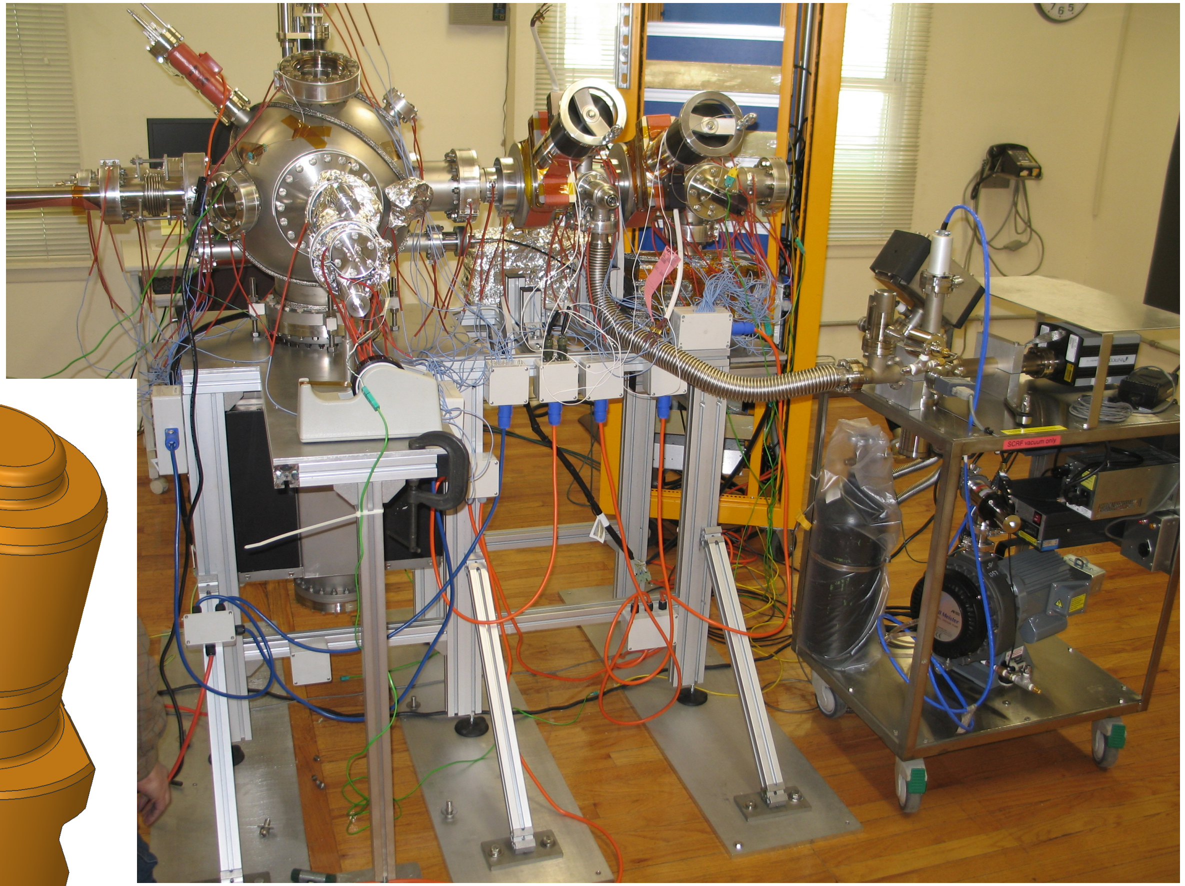
FAST photocathode growth system:

- Used to grow Cs-Te films.
- Can be easily modified to grow Cs-Sb films.





Picture courtesy Jamie Santucci

Testing alkali-antimonide photocathodes at FAST

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Tasks:

- Mechanical compatibility checks (not required if photocathode grown at FAST)
- Develop/deploy thermal emittance measurement capability (solenoid scans)
  - ➢ First emittance measurements can be done with existing Cs-Te cathodes (expect MTE ≈ 500 meV with ≈ 300 nm emittance)
- Demonstrate successful transfer of CBB-grown cathodes
- Possibility of wavelength tuning for testing CBB cathodes (emittance + lifetime at ≥ 50 MV/m)
  - ➢ Initial tests can be performed with UV (266 nm, already set up)
  - ➢ Possibility of converting drive laser to green (527 nm) (expect MTE ≈ 130 meV with ≈ 150 nm emittance)
  - ➢ Possibility of generating near-threshold light (~650 nm) to minimize emittance (alternatively, test new compounds that may have low MTE in the green).
- Possibility of testing CBB films grown on SC substrates (SiC) (expect MTE ≈ 40 meV at threshold)
  - ➢ Plug modification
  - ➢ Compatibility of semiconductor with gun environment

Comments and questions welcome:

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