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

Cathodes to produce ultra-bright beams for accelerators (including XFELs and UED)

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Snowmass Electron Source Workshop 2/16/22

Intro

- Main message: the photocathode needs and goals of future HEP facilities are **highly synergistic** with other applications, such as UED/UEM and XFELs.

- Main difference: NP and HEP machines often want polarized e-
- Above applications span a huge range of charge/bunch and hence emittance. $1 - 10^{10}$ electrons/bunch.
- Even so, all the above applications are brightness hungry (*voracious?*)
- Small note: I'll be concentrating on space charge dominated operation in UED/UEM (not single electron).

Photoinjector Brightness

- In UED: more 5D brightness means access to higher resolution in real and reciprocal space.
- In XFEL: more 5D brightness means more photon output for a given XFEL, or a smaller XFEL for a given output.
- On paper, easy to state the parameters for higher brightness:

more extraction field, less intrinsic emittance.

(source density) (source coherence)

State of the art intrinsic emittance

- My preferred units of intrinsic emittance are MTE: $$\frac{\sigma_{px}}{mc} = \sqrt{\frac{MTE}{mc^2}}$$

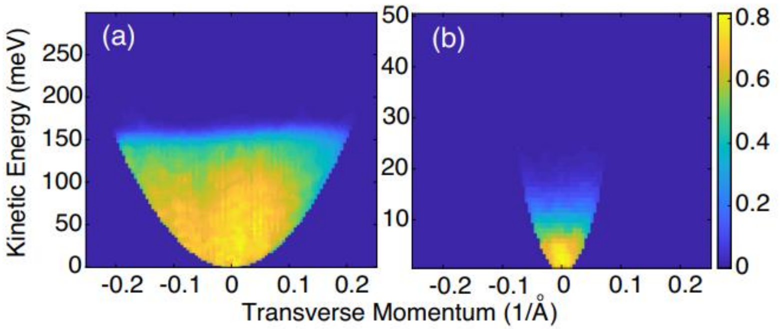
  MTE = 130 meV → 0.5 micron/mm rms.

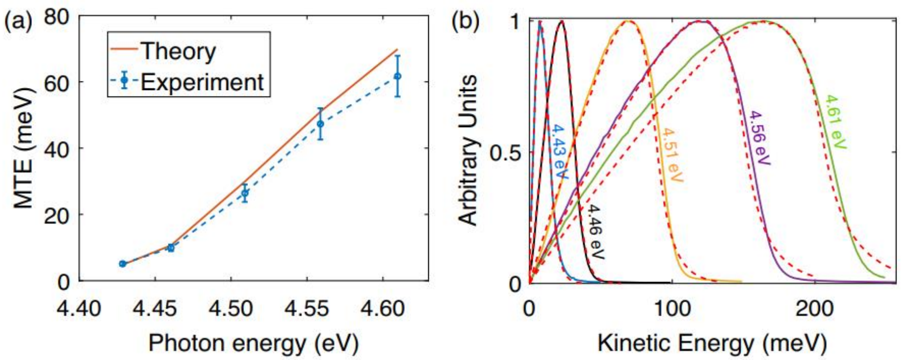
- State of the art: **cryo-cooled**, atomically ordered Cu (100), with photon energy tuned to **threshold**. Single digit meV, 0.1 micron/mm rms! Karkare et al.:

PHYSICAL REVIEW LETTERS **125,** 054801 (2020)

Editors' Suggestion | Featured in Physics

Ultracold Electrons via Near-Threshold Photoemission from Single-Crystal Cu(100)





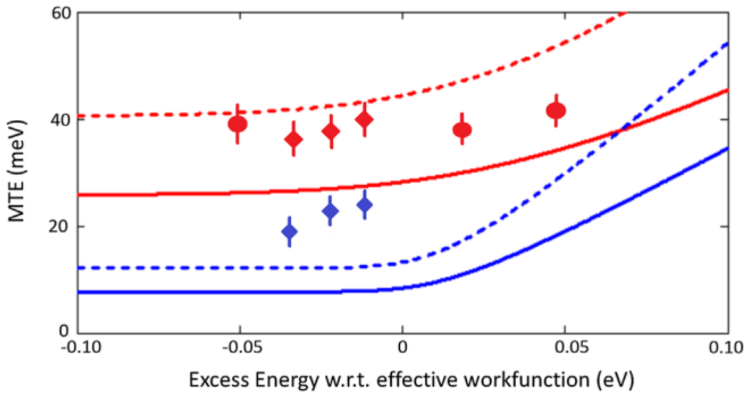
- Threshold photoemission and cryo-cooling reduce QE (here ~10^{-8}). Nonlinear photoemission would likely be dominant in space charge applications.

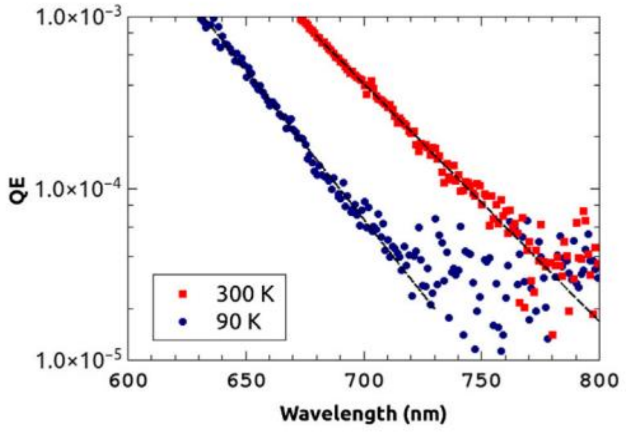
Low MTE with high QE cathodes?

- Need high QE to avoid multiphoton photoemission (how much?)
- Look to the most robust high QE cathodes: Cs-Te (UV) and alkali antimonides (Visible)
- Cryogenic MTE measurements of Cs-Sb, Cultrera et al.:

PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18,** 113401 (2015)

Cold electron beams from cryocooled, alkali antimonide photocathodes





Larger MTE than expected (solid lines)!

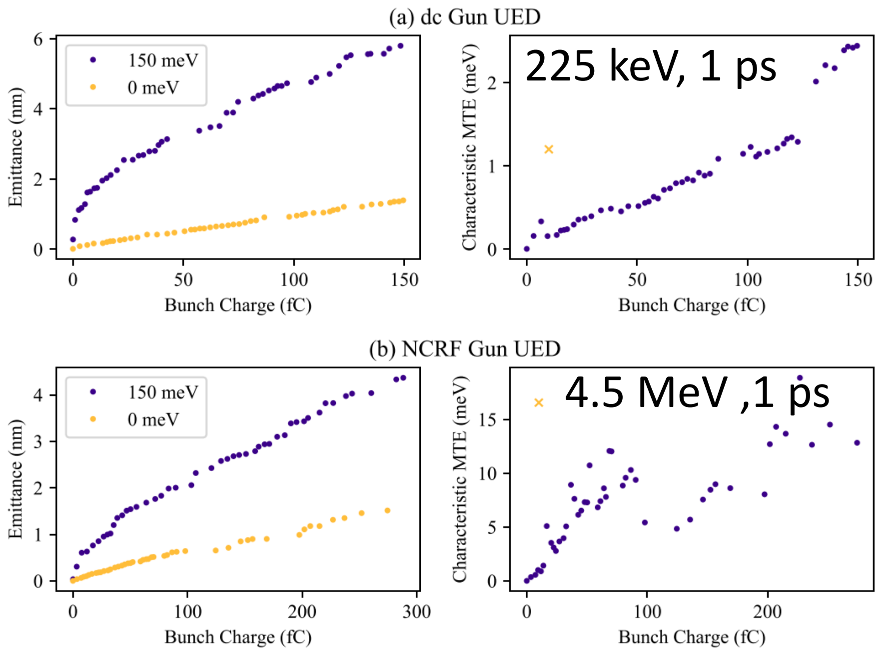
This all alkali antimonides in use are polycrystalline.
Chemical roughness?
Defect states?
Something else?

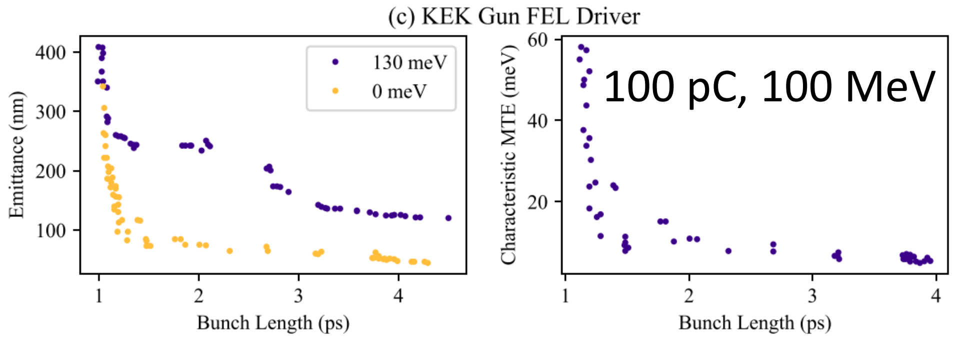
MTE and Space Charge

- How useful is low MTE in space charge dominated applications (here UED and XFEL)? Pierce et al, 2020:
- One simple way to determine is to optimize beam dynamics with zero MTE. Finite final emittance → convert to a “characteristic MTE” using optimum spot size.

PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 070101 (2020)

Low intrinsic emittance in modern photoinjector brightness





Final emittance can benefit from MTE down to the scale of 10 meV with existing gun/injector technology.

Low MTE with high QE cathodes?

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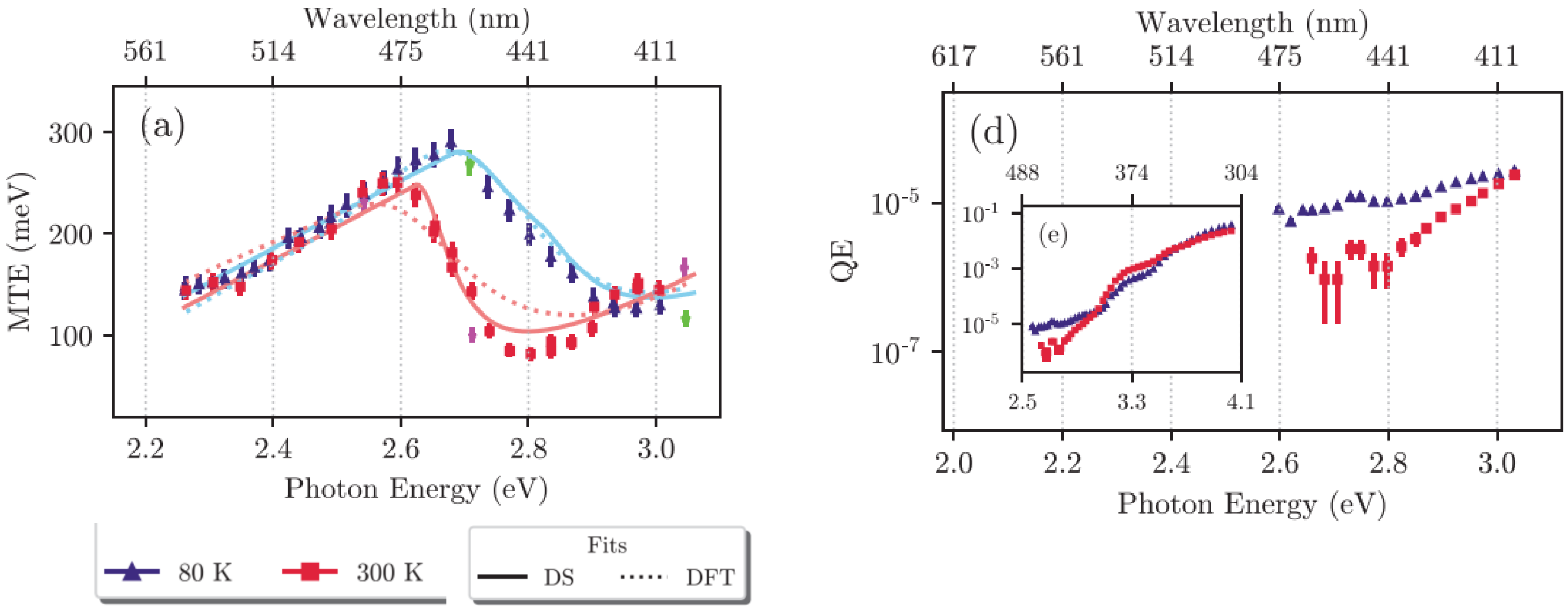
- Look to the most robust high QE cathodes: Cs-Te (UV) and alkali antimonides (Visible)
- Cryogenic MTE measurements of Cs-Te, Pierce et al.:

Beam brightness from Cs–Te near the photoemission threshold

Appl. Phys. Lett. **118**, 124101 (2021);



Visible response, non-monotonic, And strong temperature dependence!

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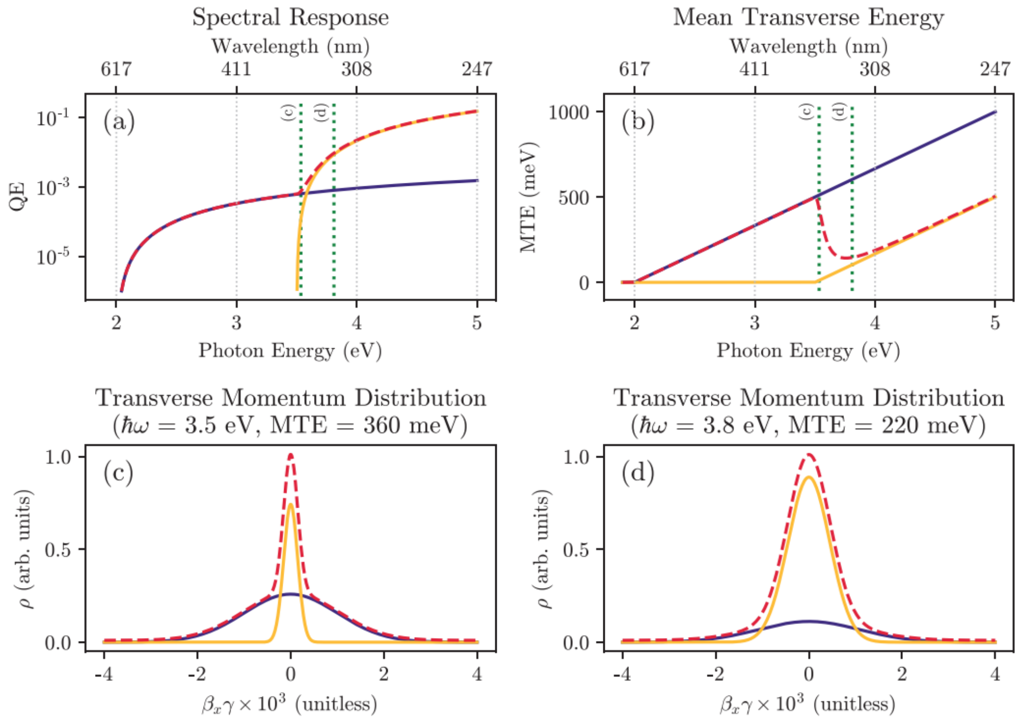
Non-monotonicity can be explained by the existence of at least one ***lower work function phase in the photocathode***. *For example,* Cs_5Te_3 has a lower work function (and but likely lower peak QE) than the target phase Cs_2Te.

Here's a cartoon for a two-phase cathode:

UV photocathodes may be very important for high field operation! However, we **need precision growth techniques** to ensure phase purity.



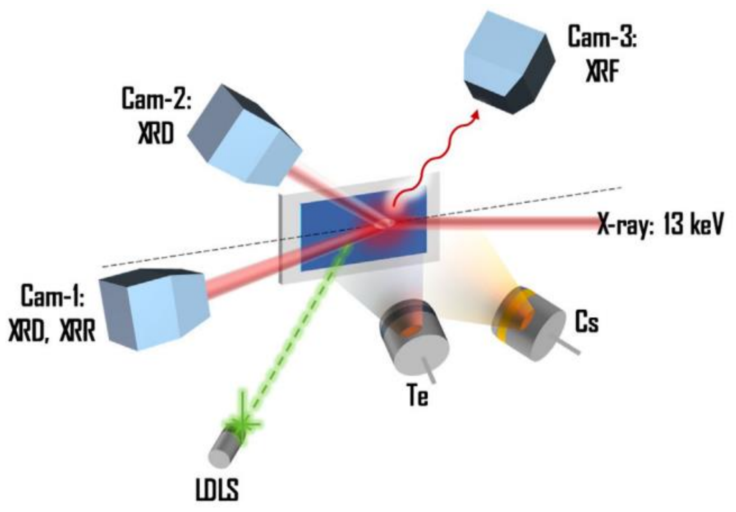
Precision Growth: Cs-Te

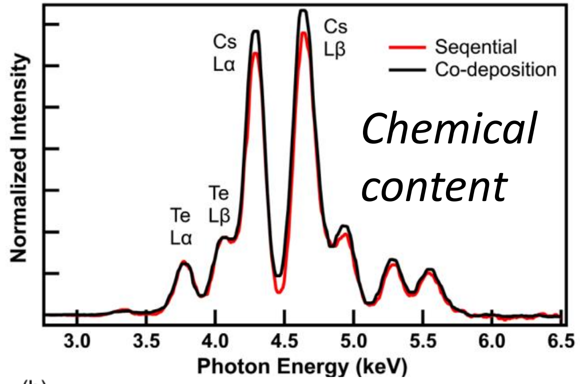
- One example of the kind of precision needed: M. Gaowei et, al.
- Cathode growth with a ***whole suite*** of x-ray diagnostics at a synchrotron

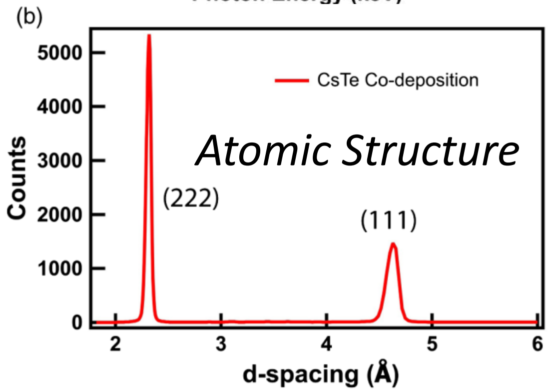
PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 073401 (2019)

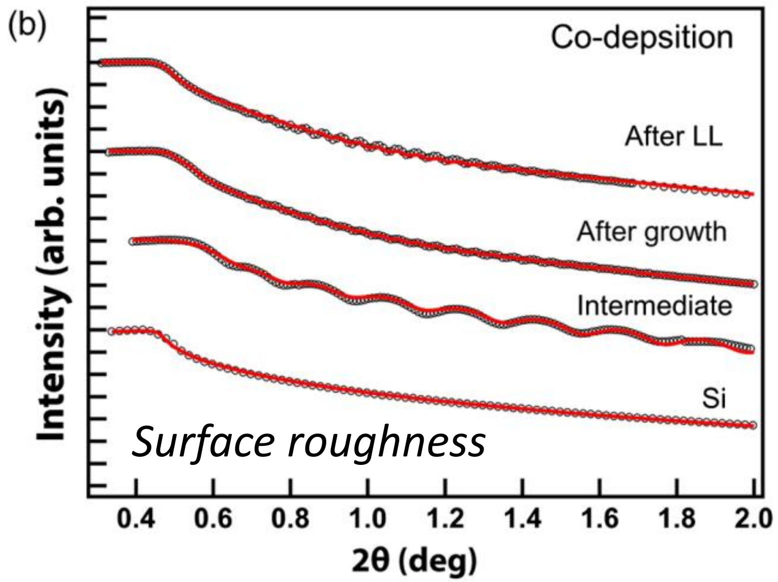
Editors' Suggestion

Codeposition of ultrasmooth and high quantum efficiency cesium telluride photocathodes









Precision Growth: Cs_3Sb

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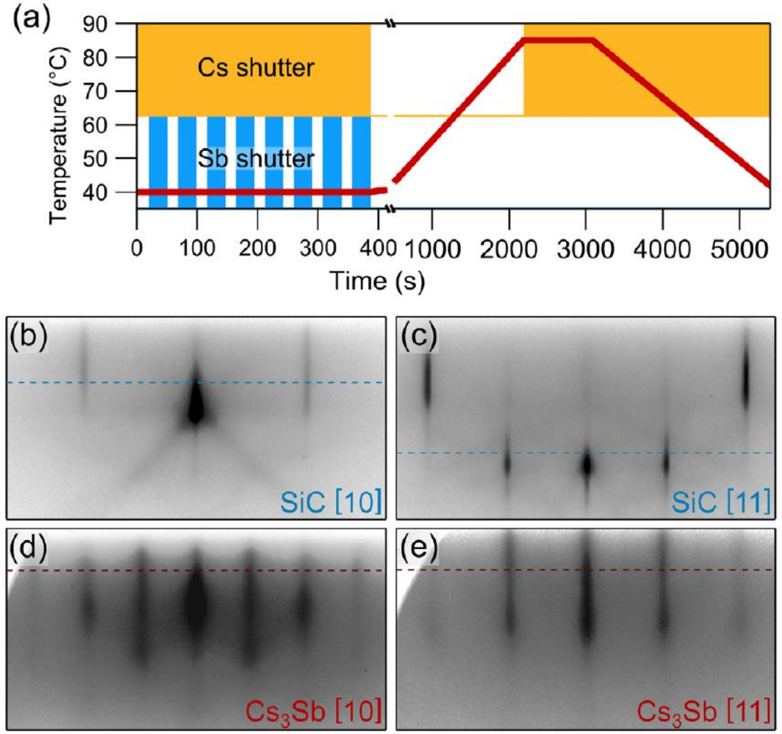
- Another example: Parzyck, Galdi, et. al. PRL in press.
- Molecular beam epitaxy of Cs_3Sb with RHEED, XPS, ARPES. The first single crystal alkali antimonide.

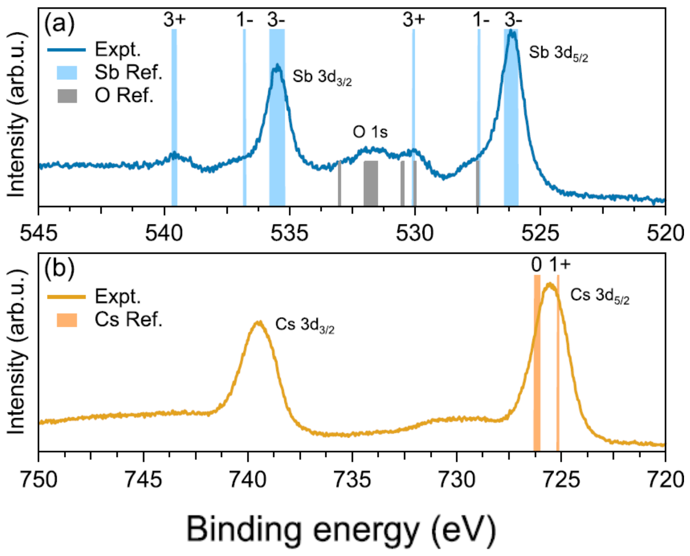
AN NSF MATERIALS INNOVATION PLATFORM

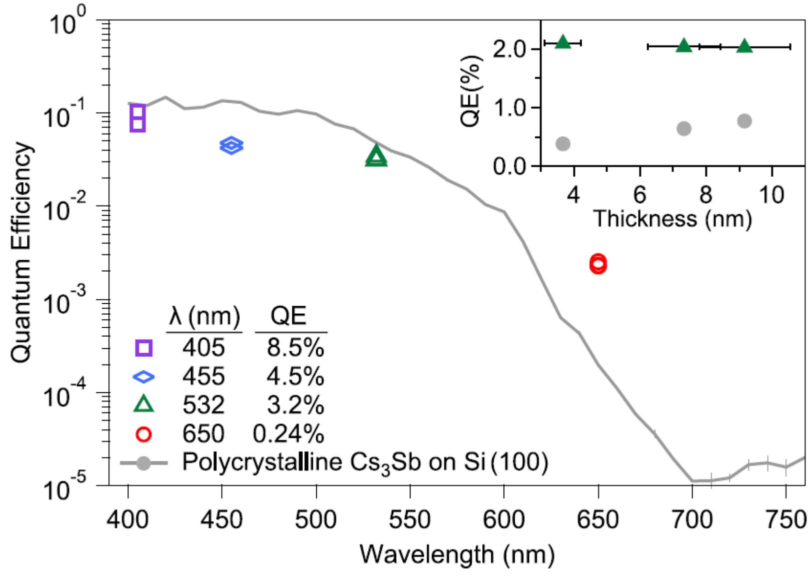
PHYSICAL REVIEW LETTERS **VOL..XX,** 000000 (XXXX)

Single-Crystal Alkali Antimonide Photocathodes: High Efficiency in the Ultrathin Limit



XPS Spectra





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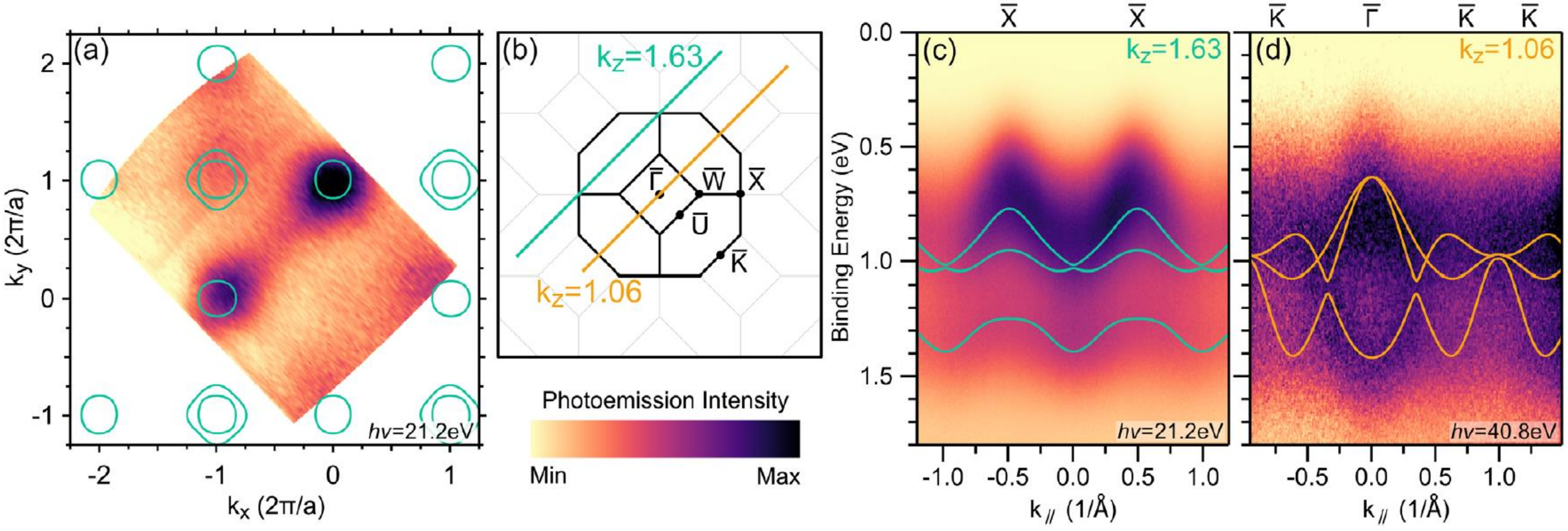
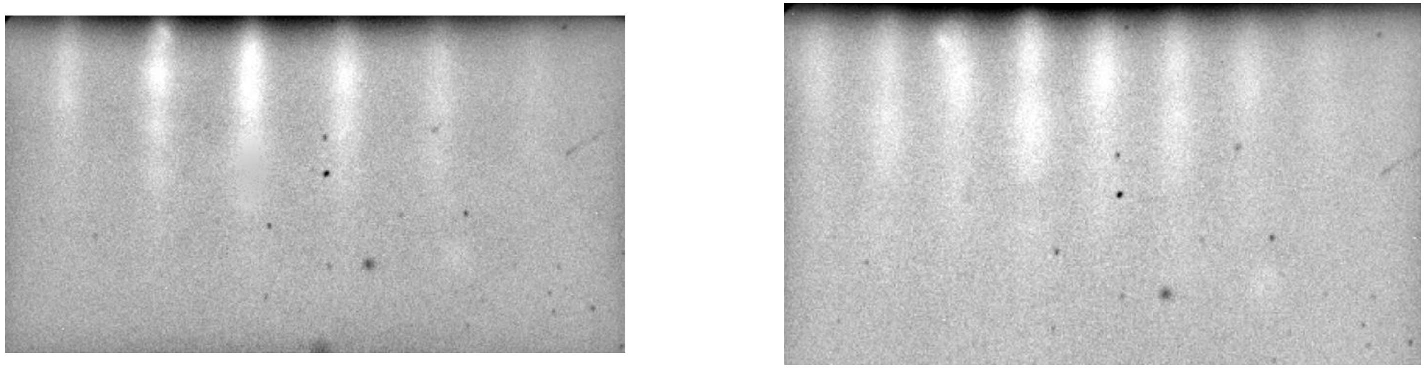
ARPES Spectra: in agreement with DFT



New lab @ Cornell: PHOEBE

Meet **PHOEBE**: **PHO**tocathode **E**pitaxy and **B**eam **E**xperiments laboratory

First epitaxial Cs_3Sb sample grown in **PHOEBE**-MBE



- MTE measurements on epitaxial Cs_3Sb samples
- Epitaxial growth of other alkali antimonide compounds
- Study of strain effects on different substrates
- Photocathode heterostructures

We are excited about collaboration! Have a growth experiment in mind that might be good for PHOEBE? Let us know!

Low MTE at work: UED @ MEDUSA

- A new UED beamline @ Cornell using alkali antimonides (polycrystalline) driven at threshold.

https://arxiv.org/abs/2111.07922

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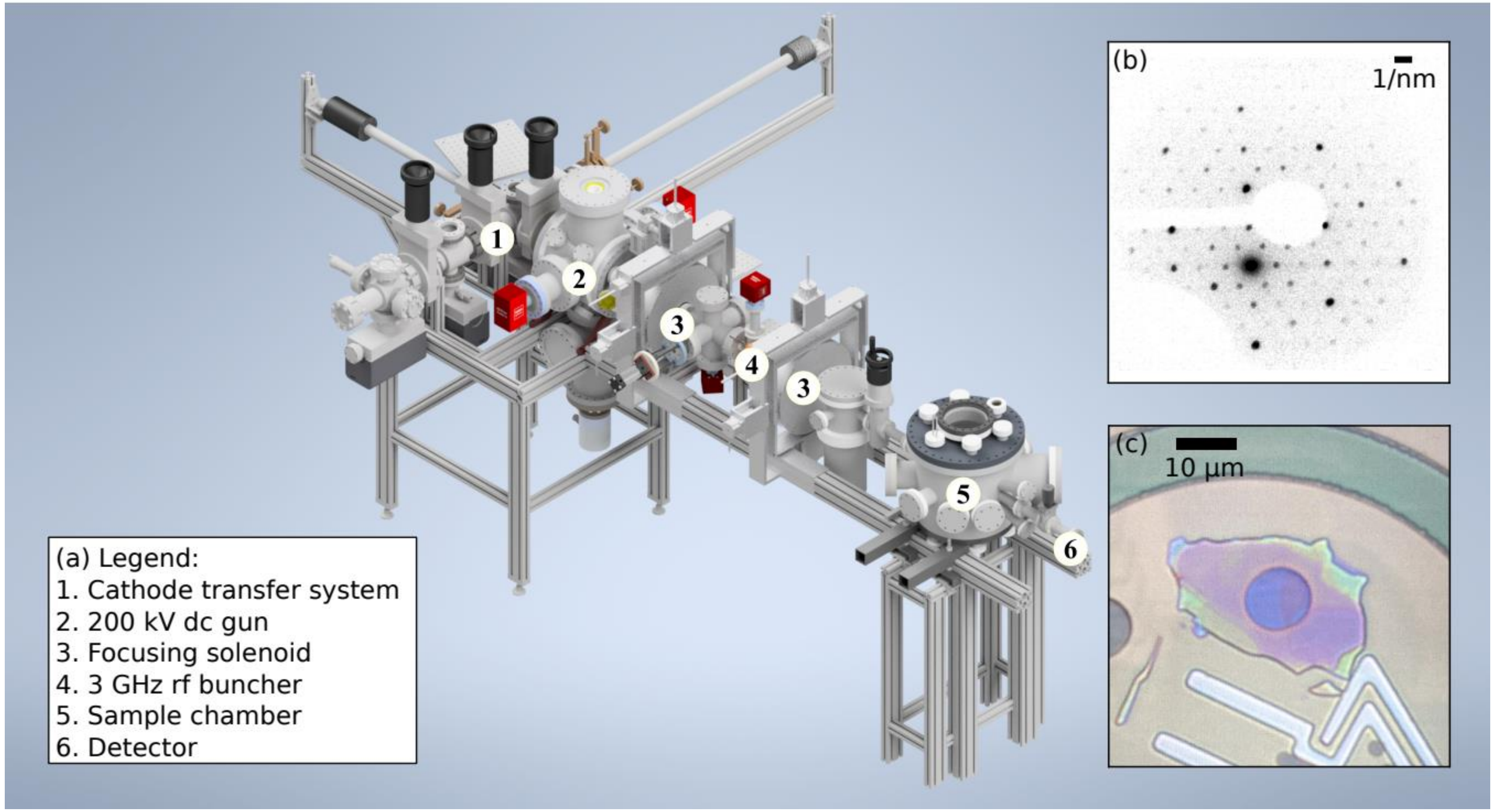
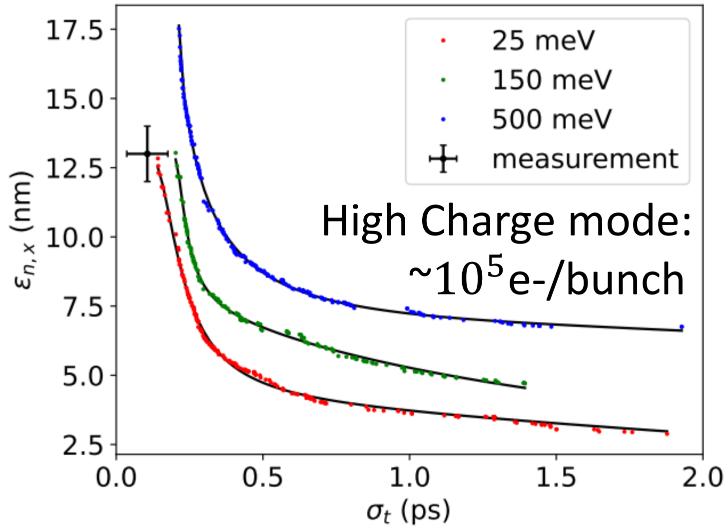
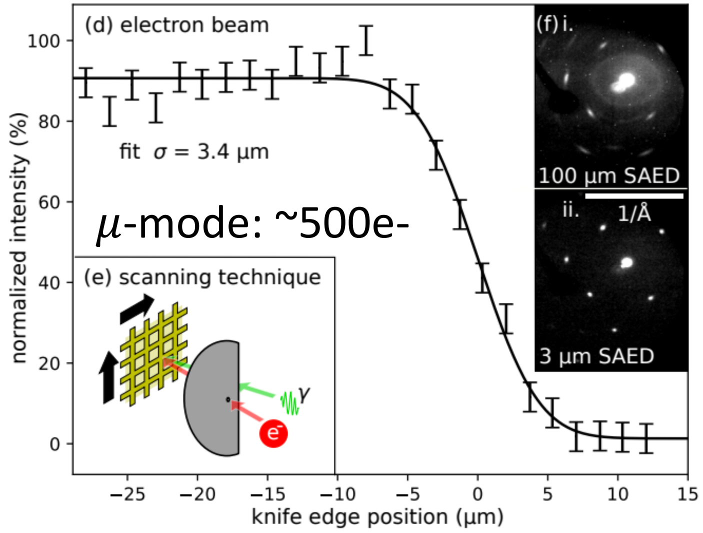


Ultrafast tunable light source drives the photocathode at threshold.

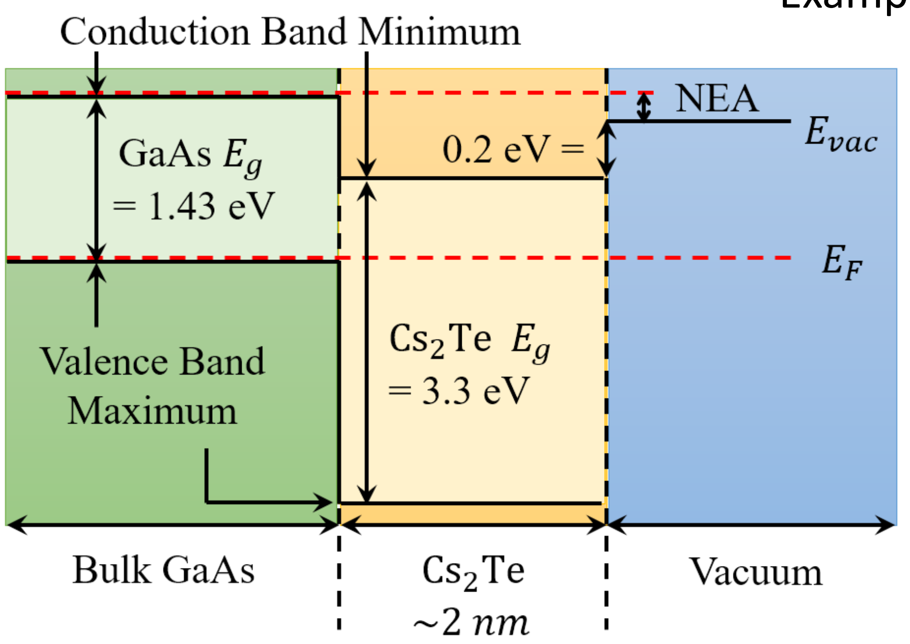


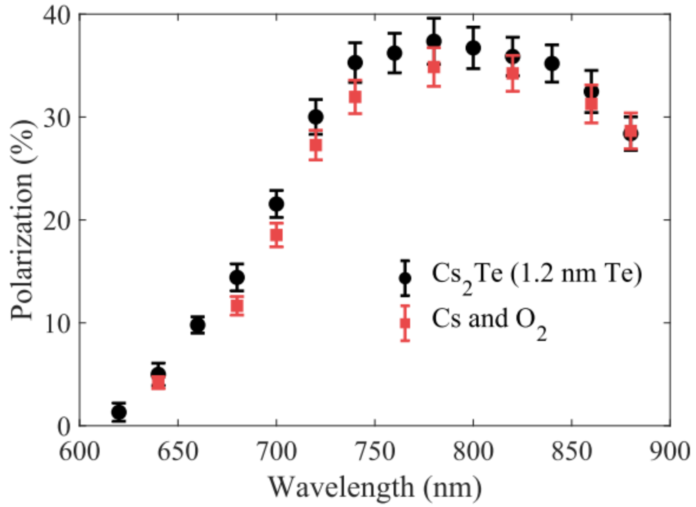


What about polarized electrons?

- What do CsTe and alkali antimonides have to do with polarized sources?
- Both can activate GaAs to negative electron affinity!

Example: CsTe activation





Bulk GaAs

Bae, et al. Applied Physics Letters 112.15 (2018): 154101.

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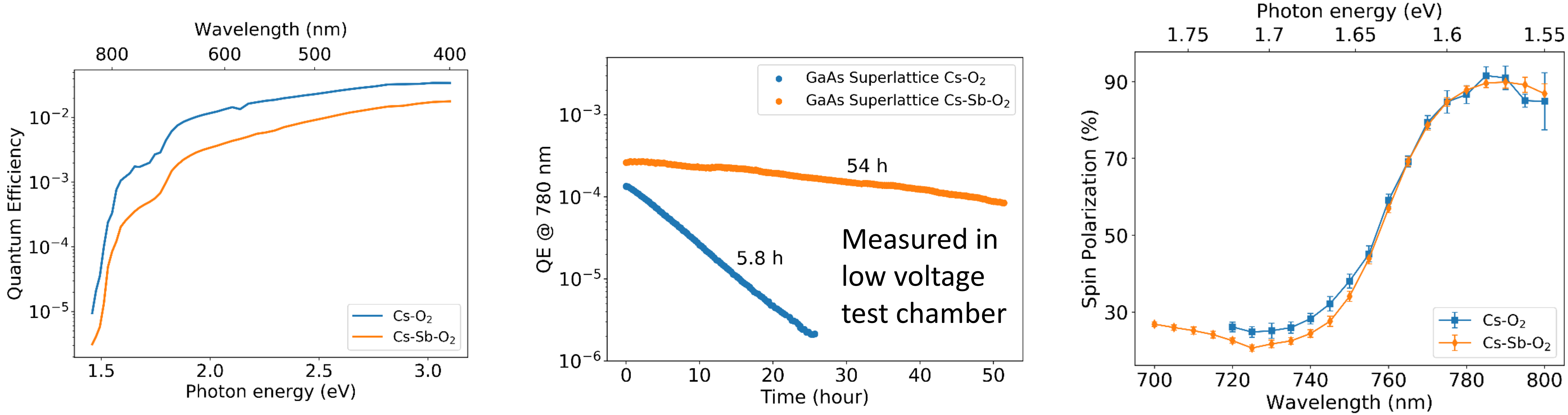
Example: Cs-Sb-O activation with superlattice GaAs



Bae *et al*, *Journal of Applied Physics*. **127**, 124901 (2020)

The lifetime of the CsSb or CsTe layer will be critical for high field or current polarized sources!

Summary and Big Questions

Advanced photocathode materials have benefits across accelerator physics: HEP, NP, XFEL, UED/UEM.

Lots of exciting materials science developments in high QE photocathodes—we now need to translate them to the gun.

Critical studies needed along a few axes:

- QE and MTE at low temperature
- Nonlinear photoemission yields
- Lifetime at high fields (100 MV/m and above!), and high currents.
- Protection coatings to make these materials easier to use!

Thanks!

The Cornell Polarized Photocathode Team: Jai Kwan Bae, Alice Galdi (now at U. Salerno), Luca Cultrera (now at BNL), Matthew Andorf, Jared Maxson, Ivan Bazarov

Thanks to The Center For Bright Beams, NSF, DOE HEP, and DOE NP for funding!

PARADIM
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