Low Intrinsic Emittance in Space Charge Dominated Photoinjectors

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

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Outline

- Brightness and intrinsic emittance of photocathodes
- Cathode materials and emission approach
- Is low intrinsic emittance actually useful in the face of space charge?
- A brief experimental example of low intrinsic emittance at work

Primary Figure of Merit: Brightness

- Transverse brightness is a critical figure of merit across many electron linac applications.
  - Electron linear colliders: Luminosity! Also: Can we eliminate the need for an e- damping ring?
  - XFELs: Can we make the XFEL dramatically shorter, or more powerful?
- The transverse brightness of a photoinjector is constrained by its source.

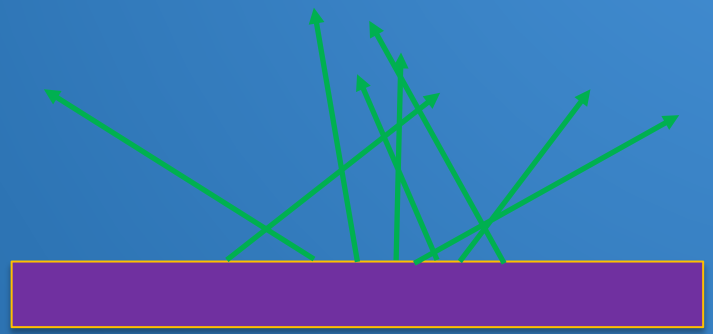
$$B_{4D,Max} = B_{source} \propto \frac{Q_{bunch}}{(\sigma_{laser})^2 (\sigma_{px})^2}$$

Recasting the Max Brightness

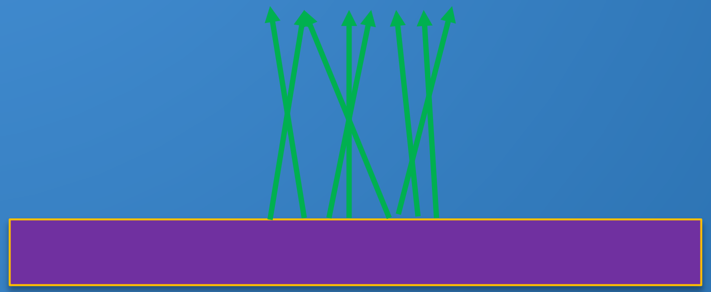
- The maximum charge density achievable is ultimately constrained by the source acceleration field, E_{acc}
- We often characterize the transverse momentum spread of photoemission in energy units, called the Mean Transverse Energy, *MTE*, $\sigma_{p_x} \propto \sqrt{MTE}$

Analagous to a "transverse temperature"

High MTE cathode



Low MTE cathode



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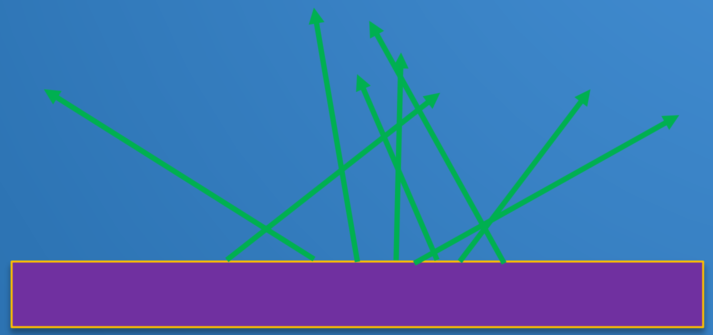
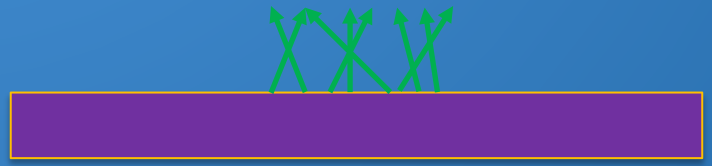


Low MTE cathode (more realistic)



Recasting the Max Brightness

- The maximum charge density achievable is ultimately constrained by the source acceleration field, E_{acc}
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- Putting it all together:

$$B_{max,4D} = \frac{E_{acc}^{n}}{MTE}$$

1<n<1.5 depends on the bunch aspect ratio—larger for more “cigar” shaped beams.

Semiconductor Photocathodes

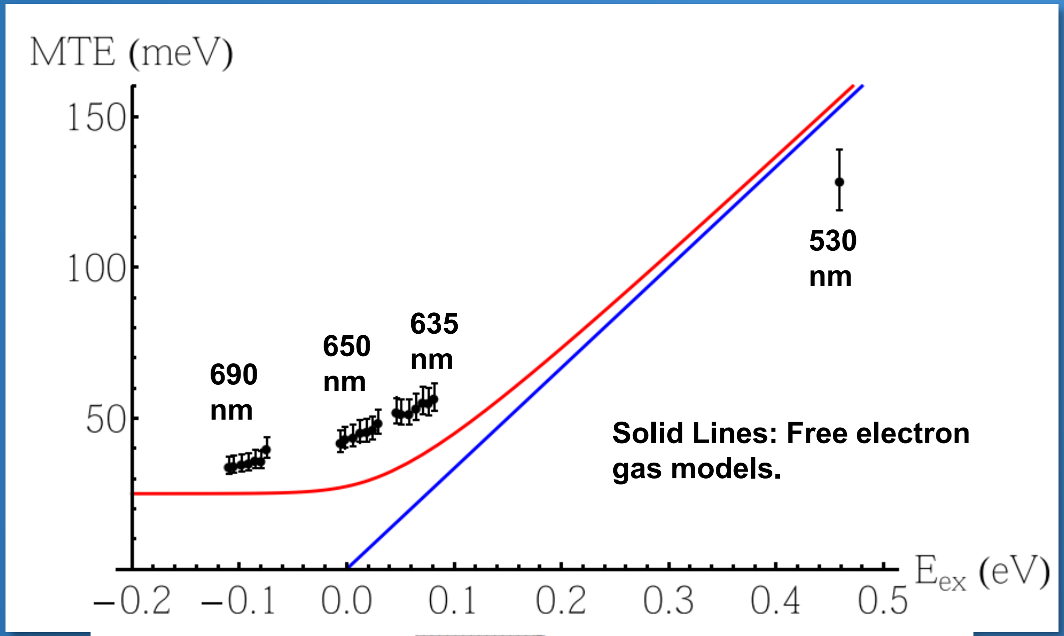
All next generation electron linear accelerators (XFELs and colliders alike) plan the use of high QE semiconductor photocathodes. The three main choices in use today are:

GaAs:Cs	Alkali Antimonides	Cesium Telluride

• Go-to polarized electron source
• Extremely vacuum sensitive (dc guns only, $\ll 10^{-10}$ torr)
• Percent level quantum efficiency in the green (520-530 nm)
• In green: MTE = 120 meV, or 0.48 um/mm rms.
	• Vacuum sensitive ($< 10^{-9}$ torr)
	• Percent level quantum efficiency in the green (520-530 nm)
	• In green: MTE = ~130 meV, or ~0.5 um/mm rms.
	• Multiple species to choose from: Cs-K-Sb, Na-K-Sb, Cs-Sb
	• *Very few tests of this photocathode in high field RF guns* (many tests in dc guns)
	• In use at BNL QWR SRF gun, planned for LCLS-II-HE low emittance injector (> 30 MV/m)
		• Vacuum sensitive ($< 10^{-9}$ torr), but less so than alkali antimonides
		• Percent level quantum efficiency in the **UV (~260 nm)**
		  • High work function good for dark current
		  • Adds significant laser complexity
		• In UV: MTE = ~500 meV, or ~1 um/mm rms.
		• *Well-tested in high RF fields (FAST, PITZ, EU-XFEL…)*

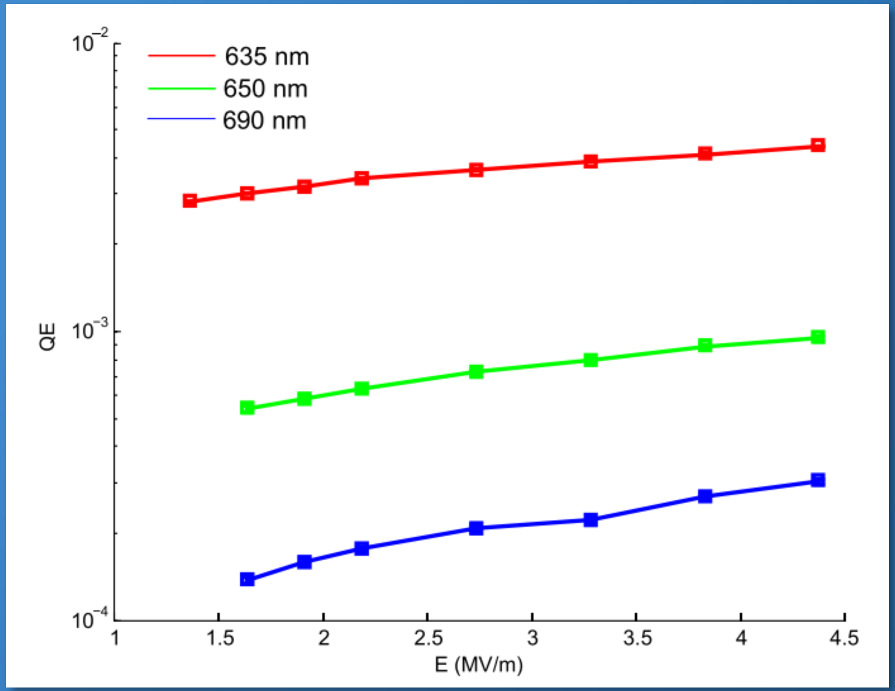
In search of Low MTE

- By reducing the **excess energy ($h\nu - \phi$)** of photoemission, one can *trade* quantum efficiency for lower MTE.
- 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 Cu in normal operation.
- Lower QE must be balanced against increased laser energy—ultimate limit is multiphoton photoemission, which spoils low MTE (more later)



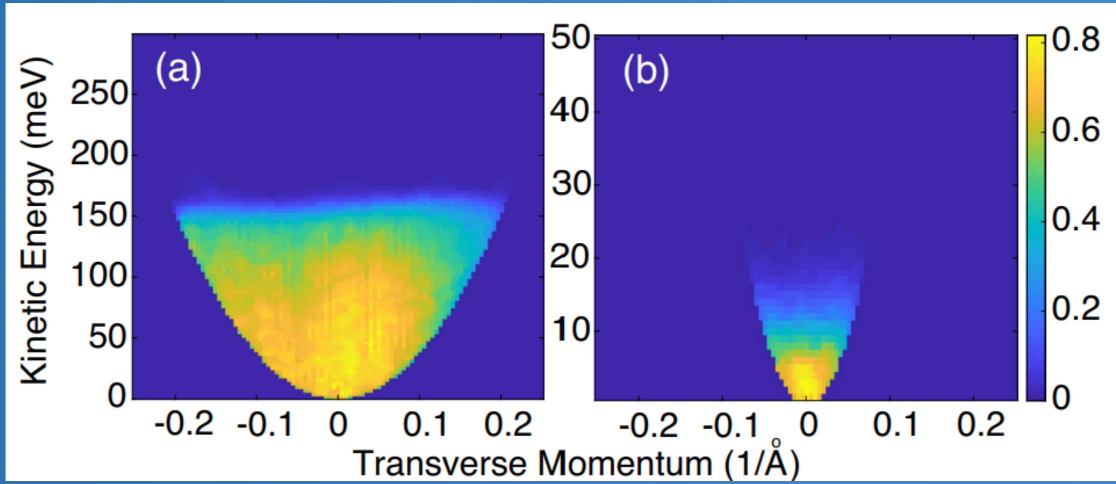
$E_{ex} = h\nu - (\phi - e\sqrt{eE/4\pi\epsilon_0})$. We assume $\phi = 1.95$ eV.

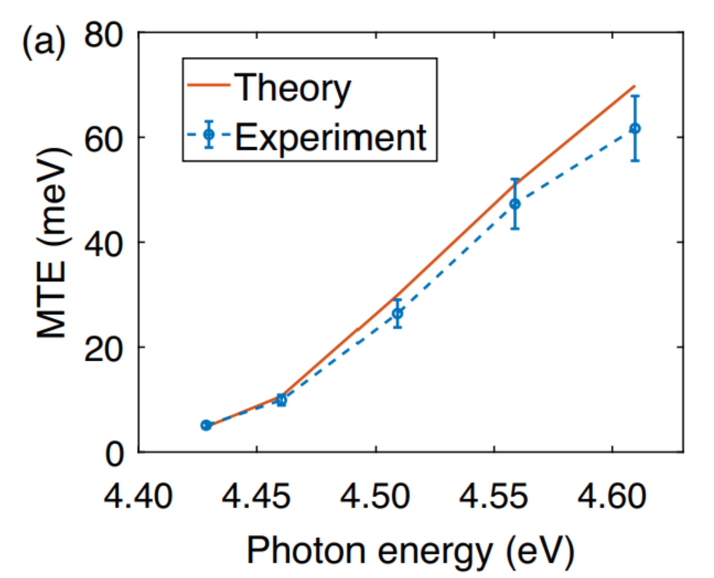
APPLIED PHYSICS LETTERS 106, 234102 (2015)



The record low MTE: 5 meV

- Demonstrated at LBNL by Karkare and Padmore et al.
- Used pristine Cu(100) crystal, cryo-cooled and tuned wavelength





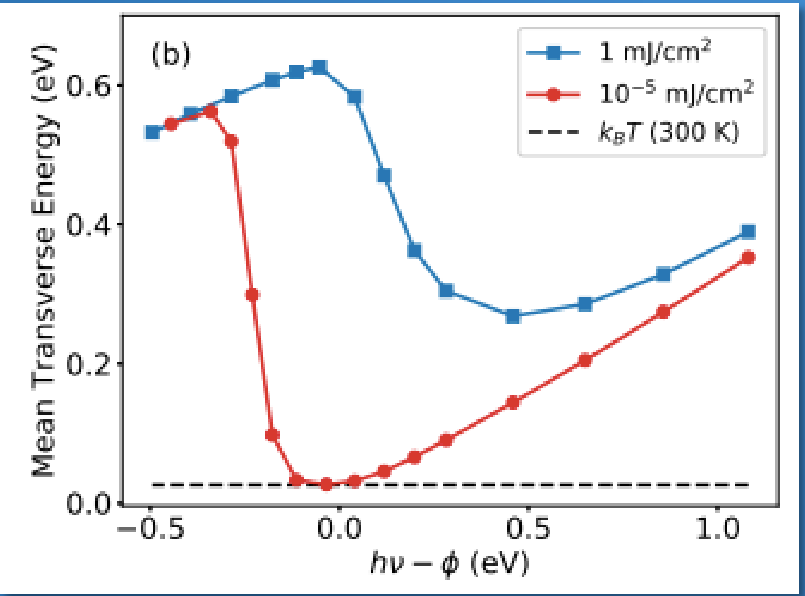
- However, very low QE$\sim 10^{-8}$.

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

QE is necessary to overcome multiphoton photoemission

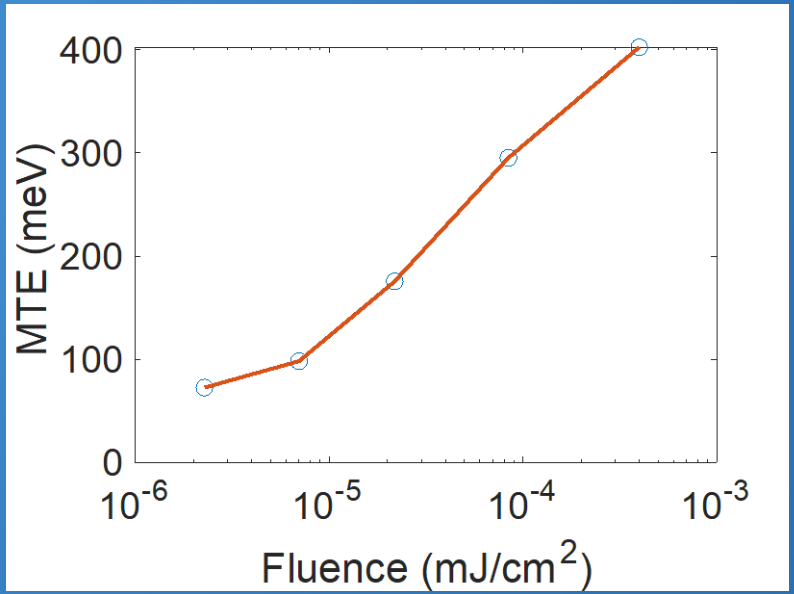
- Even with infinite laser power, low MTE requires high QE.
- How high? One needs to beat *multiphoton photoemission,* $Q \propto \left(I_{opt}\right)^n$, *for n photon photoemission.*
- Absorption of more than one photon at a time increases the excess energy.

Cu Cathode: Calculation



J.K. Bae et al, J. Appl. Phy. 124, 244903 (2018).

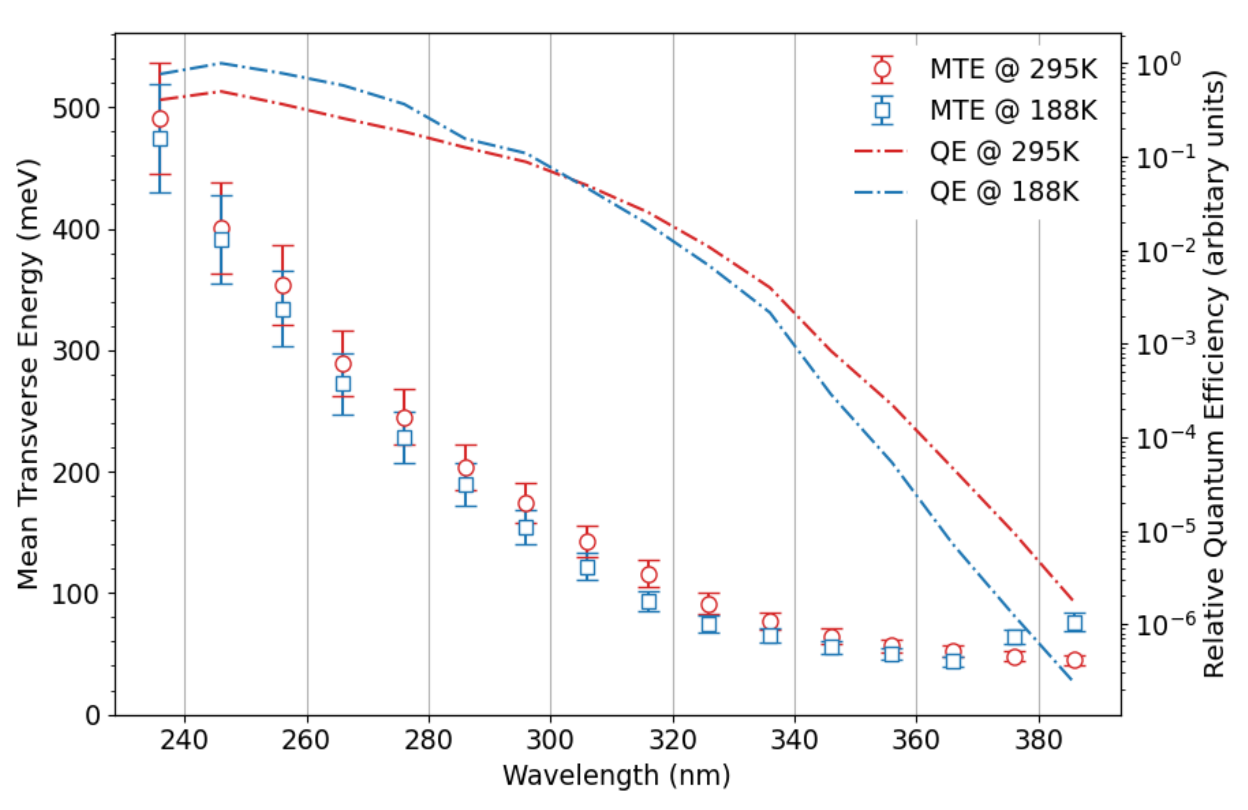
Cu Cathode: Experiment



C. Knill, P3 workshop, SLAC, 2021

Cs-Te at threshold: the same as the others?

- Alkali antimonides, GaAs, and metals have been studied at threshold in many contexts.
- How about Cs-Te? Some recent results from Daresbury/Liverpool + Cornell

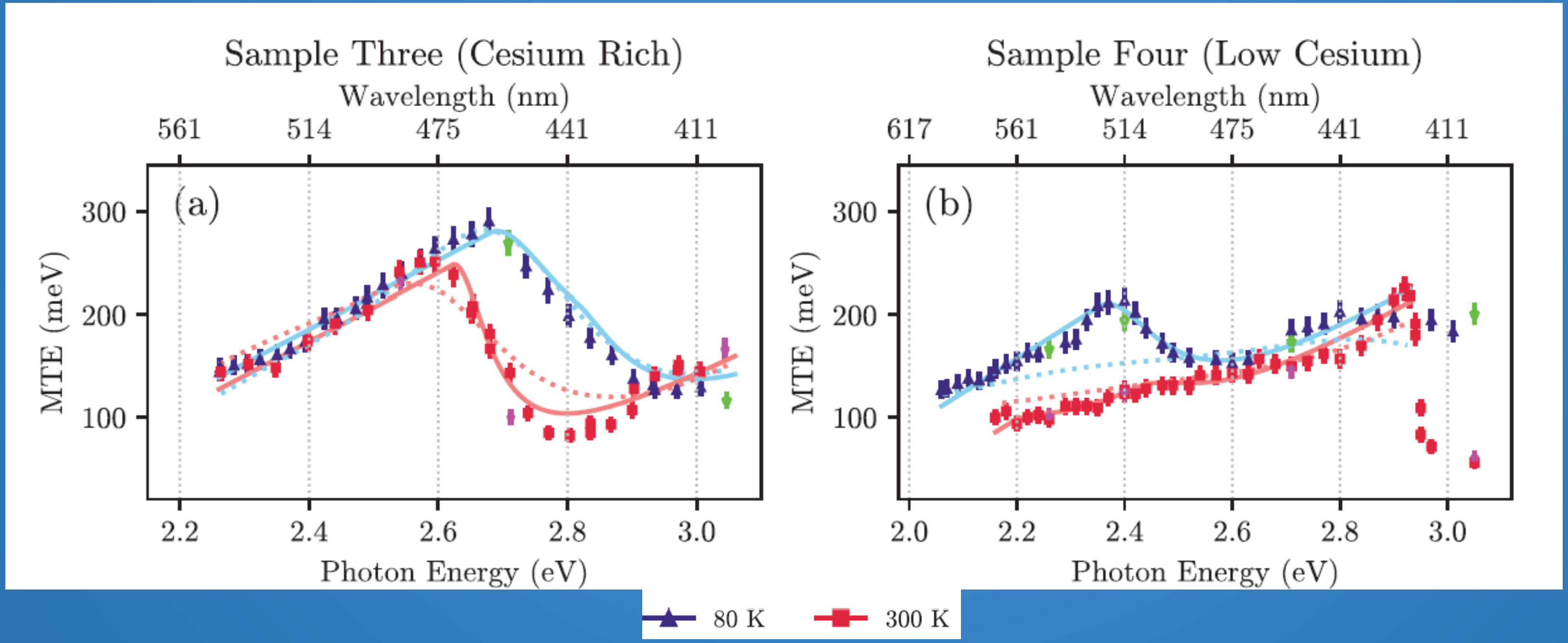


L. Soomary et al, P3 workshop, SLAC 2021.

- Initially we observe the classic trend in QE, MTE vs wavelength.
- MTE response dramatically depends on Cs-content (only one cathode shown here)
- Some cathodes get close to the thermal limit! Some show an **uptick in MTE?**

Cornell Studies: in search of the Cs-TE threshold

- We looked at the Cs-Te response in the visible (picks up where previous plot leaves off)
- We similarly observe that MTE is very sensitive to Cs-content during growth
- We observe significant non-monotonicity in the MTE.

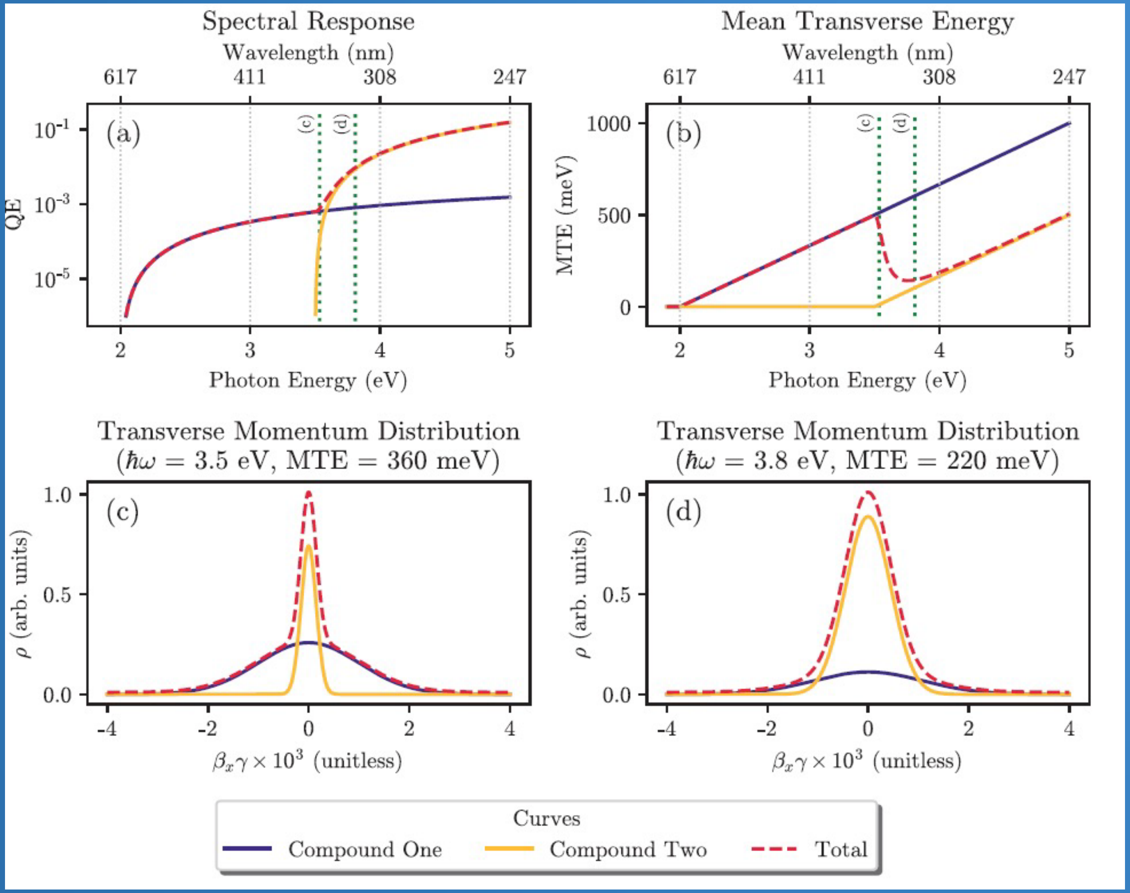


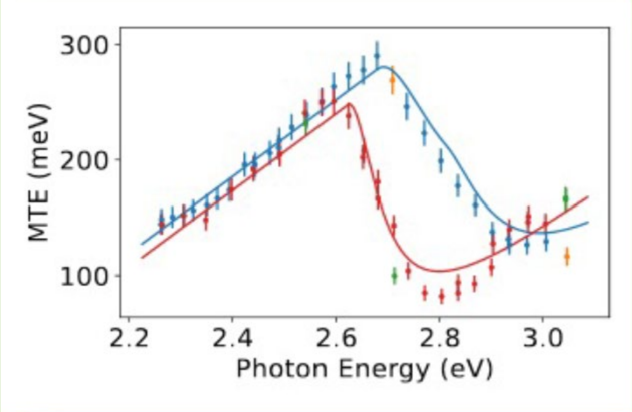
Note: this uptick is not due to multiphoton effects!

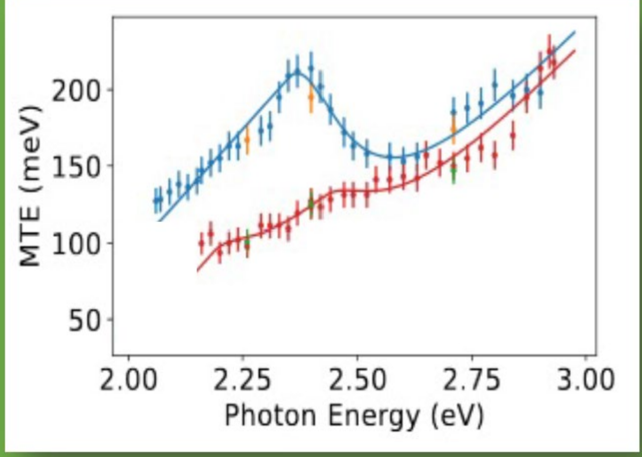
Appl. Phys. Lett. **118**, 124101 (2021)

Our hypothesis: low work function phases

- One model that fits the data well is the existence of several material phases, some with *lower work function* than Cs_2Te
  - Ex: metallic Cs, Cs_5Te_3. →they may form spontaneously!







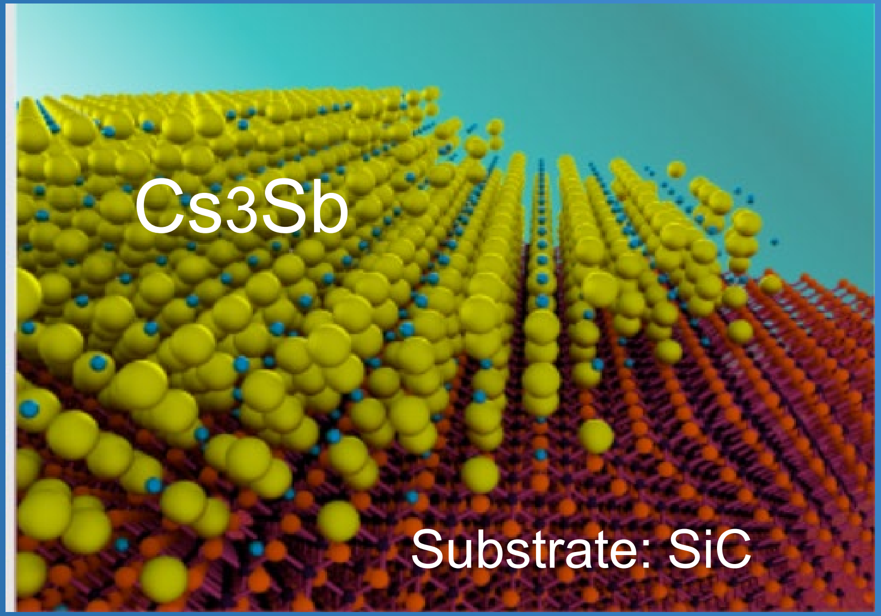
Solid curves: Multi-phase modelling

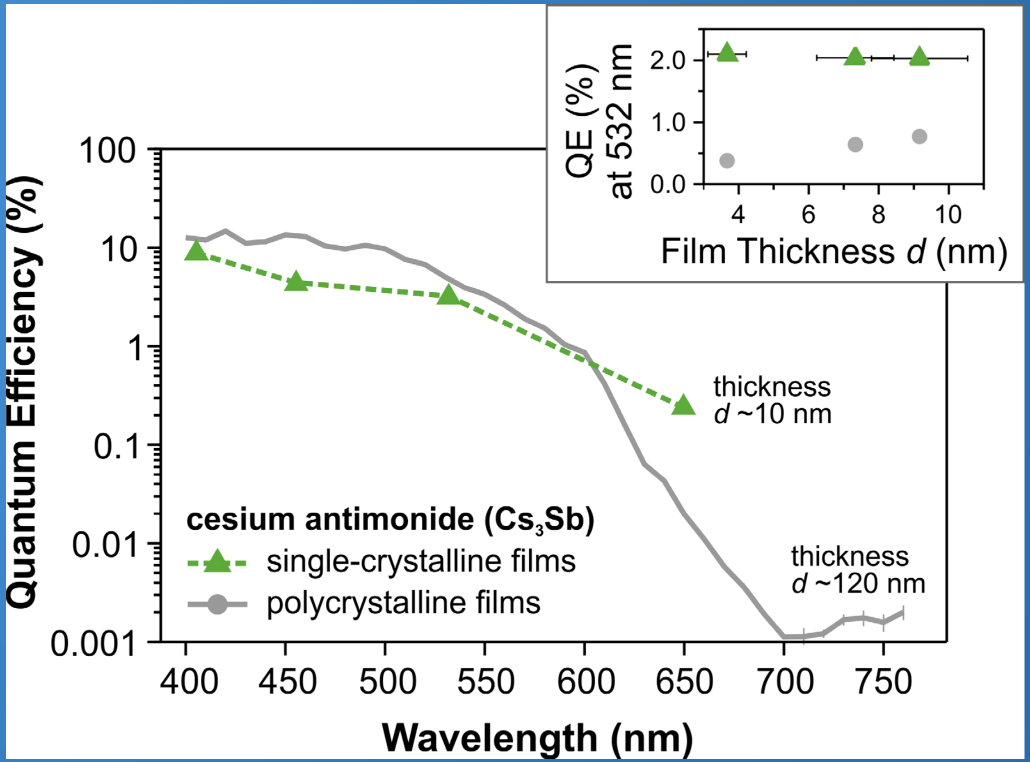
Appl. Phys. Lett. **118**, 124101 (2021)

The answer: precision growth for phase purity

- The need is then to grow *single-phase* Cs_2Te.
- Growth via Molecular Beam Epitaxy might be the answer.
- Example: The first single crystalline Cs_3Sb

Concept:





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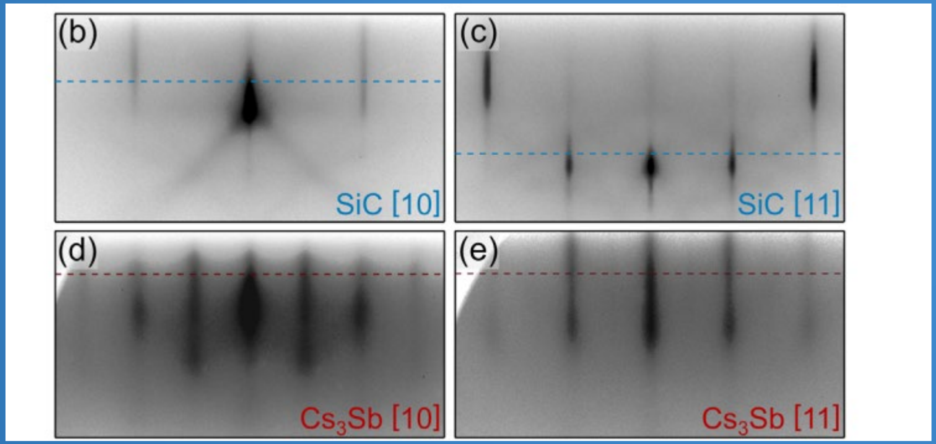
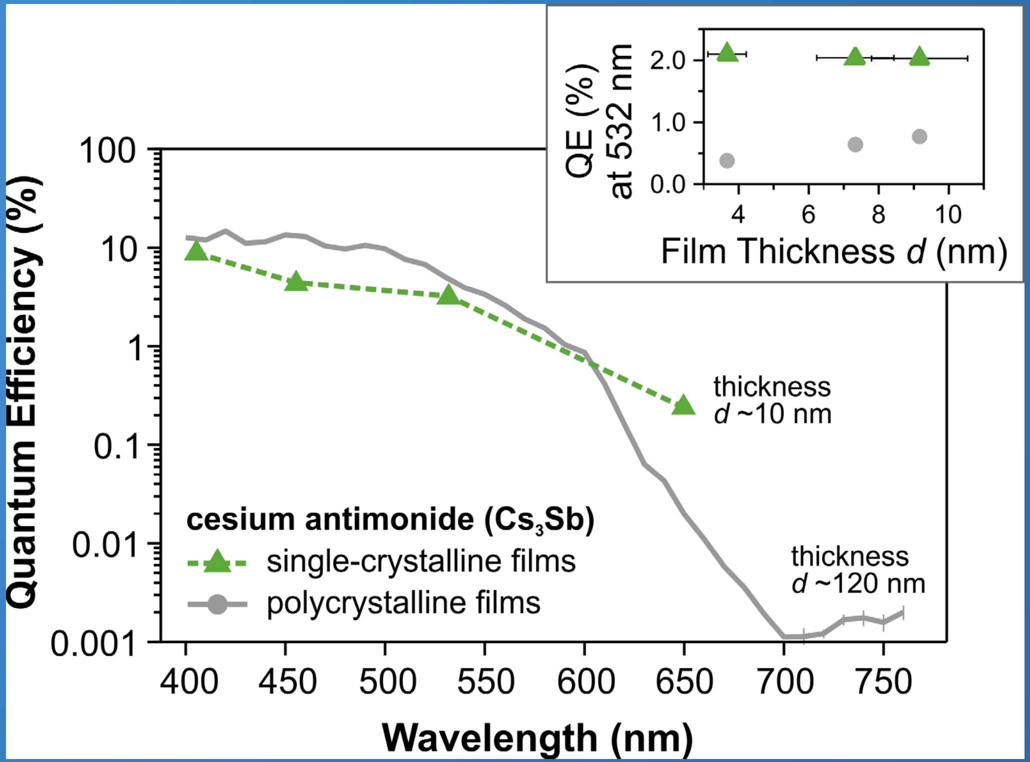
RHEED Images:

Substrate: 3C-SiC>

Photocathode -> Cs3Sb



PHYSICAL REVIEW LETTERS **128,** 114801 (2022)

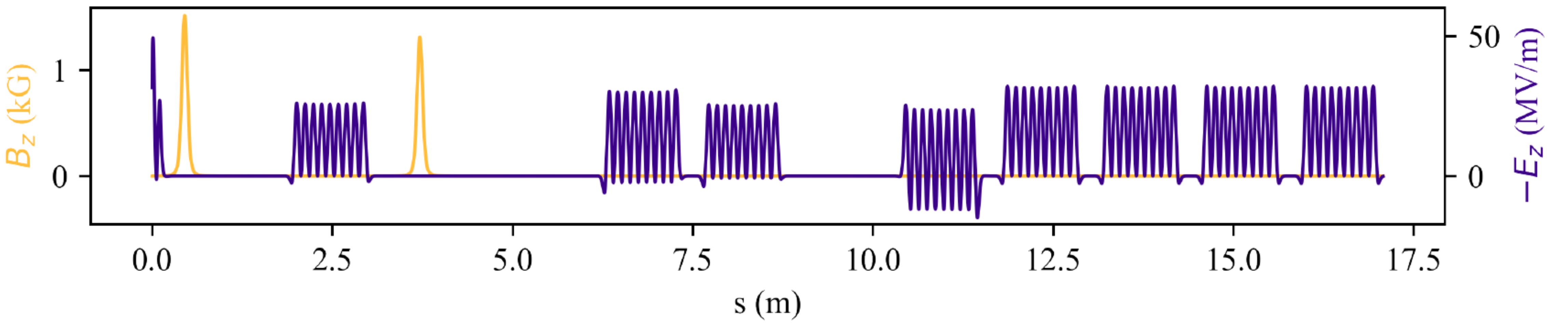


Does low MTE actually matter in space charge beam dynamics?

We'll look at the case of a hypothetical XFEL injector.

Does MTE Matter? Strategy

- The general strategy we'll adopt is to simulate beam dynamics with zero photocathode momentum spread→ zero MTE.
- What is the minimum possible emittance? Once we know this, we can ask what MTE *would have mattered* (and resimulate).
- Hypothetical injector: intentionally ambitious



KEK-style SRF gun, 1.5 Cells, 1.3 GHz,
Allowed to go up to 50 MV/m cathode field, or 3.5 MeV output.

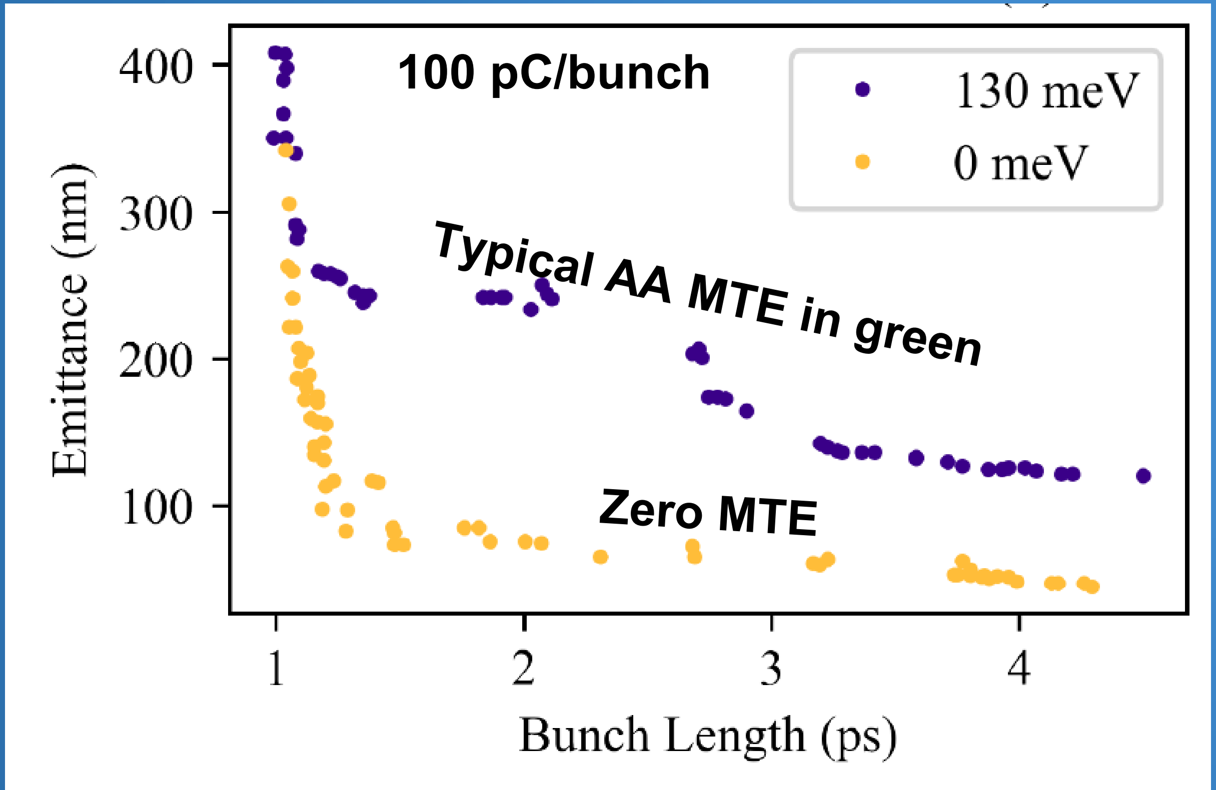
9 cell 1.3 GHz capture cavity, and then linac, output > 90 MeV

Use genetic optimization, vary nearly everything: gradients, phases, positions, solenoid strength, and 3-d laser shape. Many thousands of simulations.

PHYS. REV. ACCEL. BEAMS **23,** 070101 (2020)

Does MTE matter? Example results

- Optimize emittance and bunch length to generate an optimal front:



Significant reduction in emittance going from MTE= 130 meV -> zero. (Note Cs-Te at 266nm has >300 meV MTE).

How much does the initial MTE matter? Introduce the metric "characteristic MTE"

Characteristic MTE= $\left(\frac{\epsilon_{final}}{\sigma_{laser}}\right)^2 mc^2$

Roughly speaking this is the MTE scale that matters—much below won't change final the emittance.

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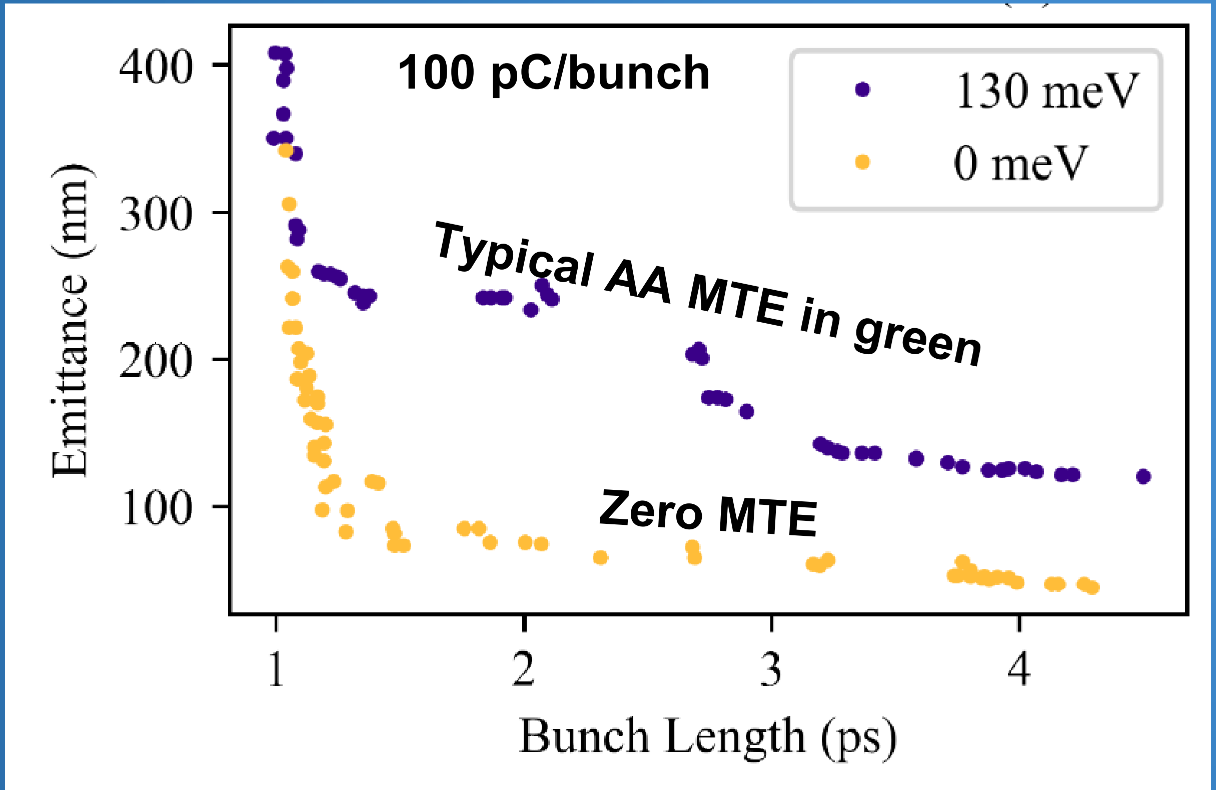

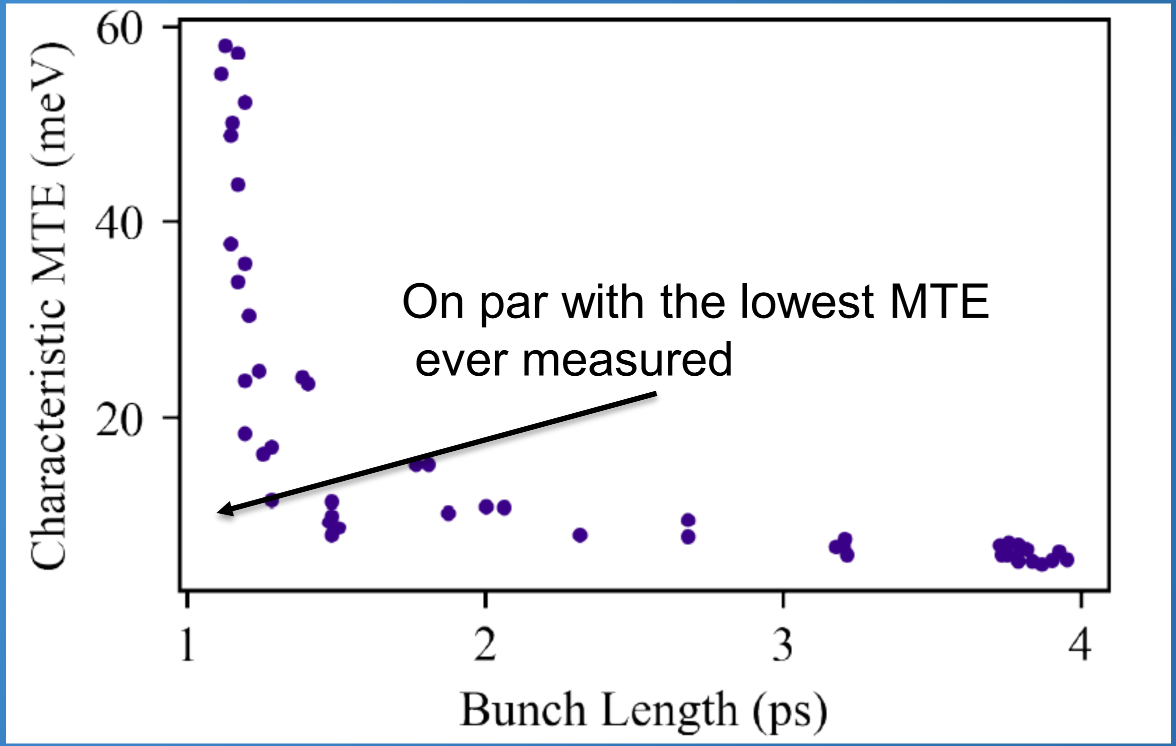

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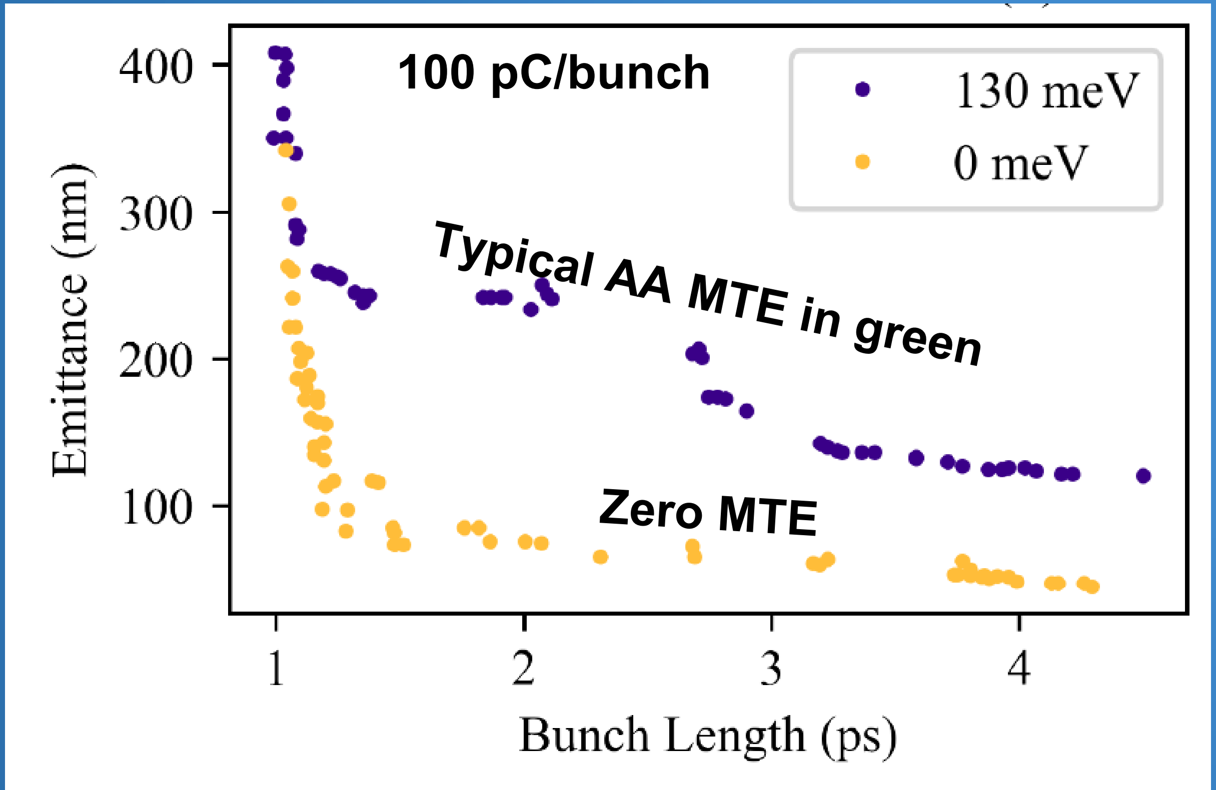
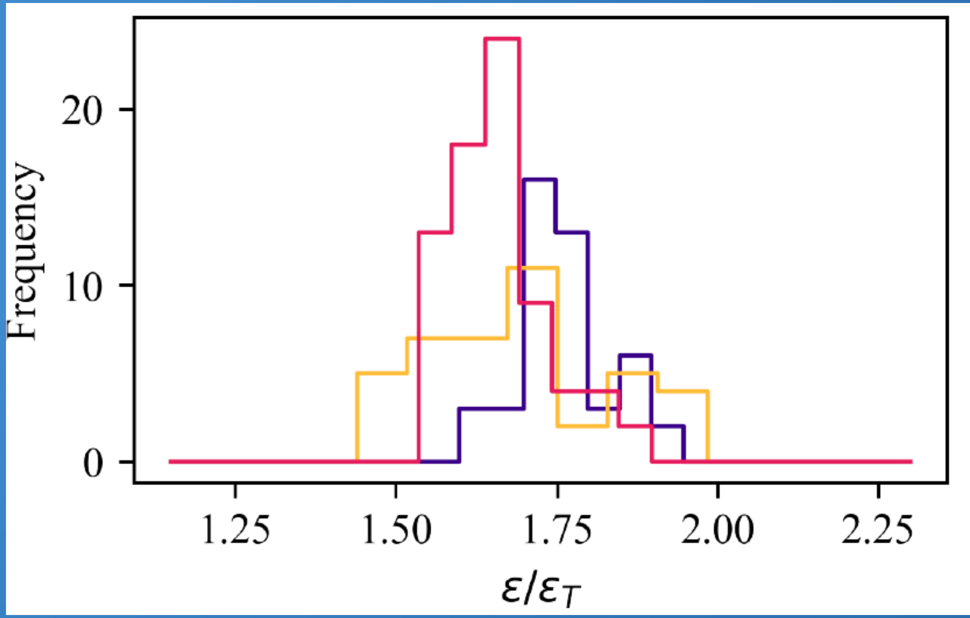


Insert back in the effective MTE– emittance grows by a factor between 1.5-1.7. As expected!

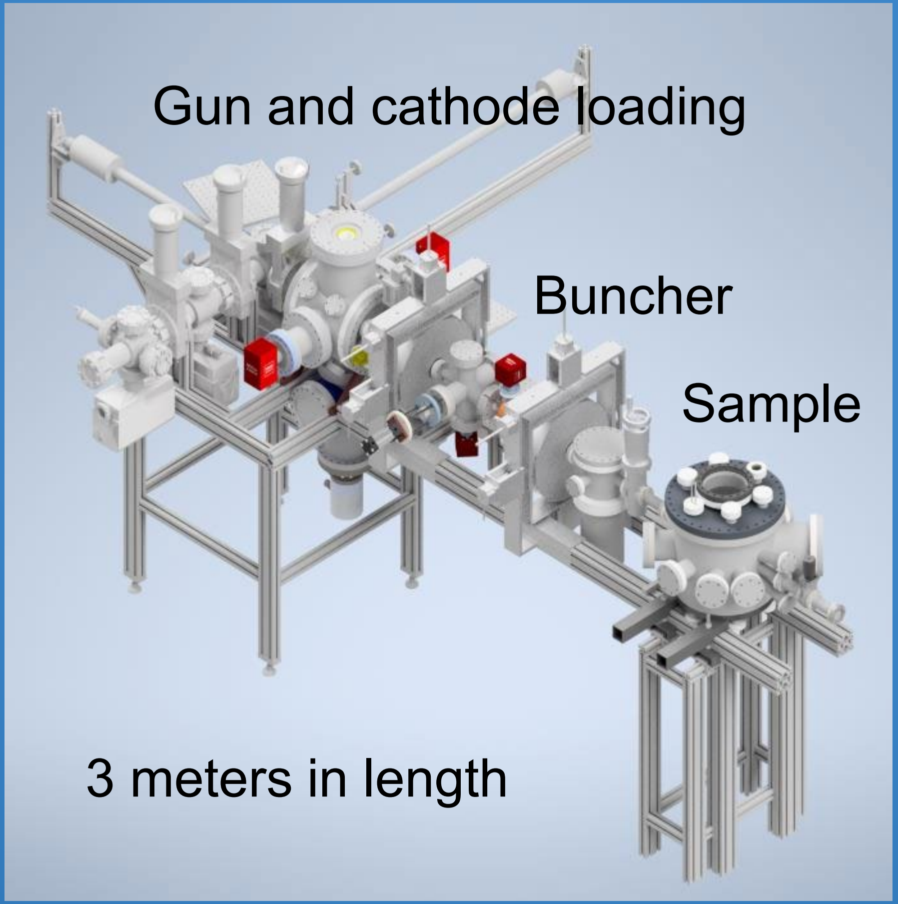


Does low MTE matter?

- The short answer is yes, down to the level of approximately 10 meV for *many applications!*
- We've done this study for many other injectors too: MeV UED, FAST photoinjector at FNAL @ 100 pC, UCLA Pegasus, UCXFEL injector—the order of magnitude of the effective MTE is **10 meV.**
- Pushing the limit of what photocathodes have done to date!
- Tuning the drive wavelength of a photoinjector facility isn't trivial.
- One experimental example of this effect at work: UED @ Cornell using alkali antimonides emitting at threshold.

UED@Cornell: device called MEDUSA

- 150 keV beam from alkali antimonides driven by ultrafast, tunable *red laser light (650 nm).*



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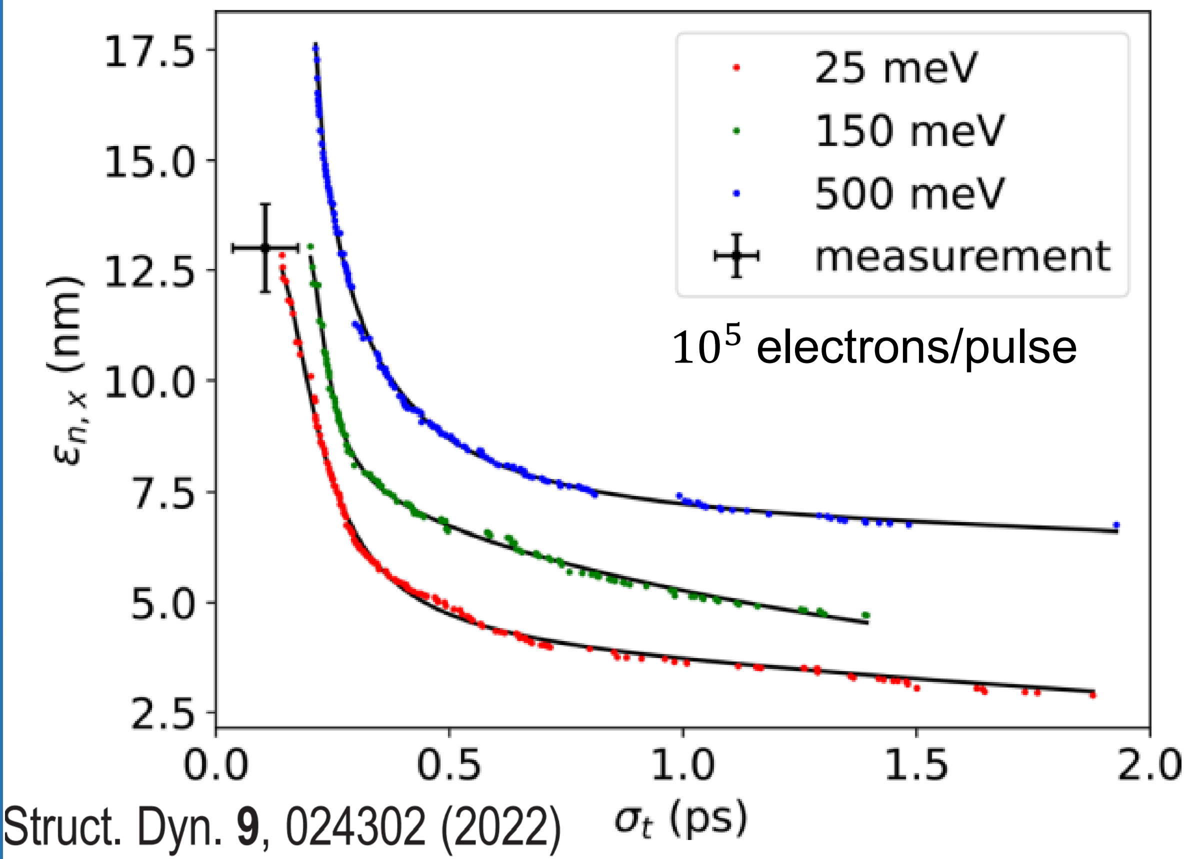
Emittance at MEDUSA

- Emittance measurements at MEDUSA vs optimization



Struct. Dyn. **9**, 024302 (2022)

Optimization shows that low MTE gets you either lower emittance for a given bunch length, or **vise versa!**

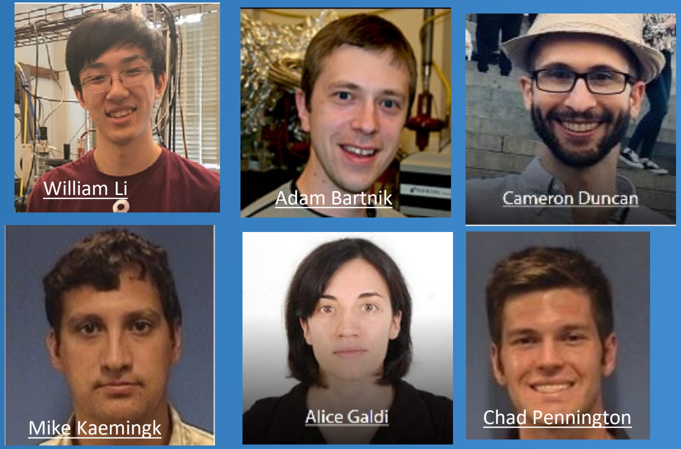
Our emittance measurements suggest our MTE is well below 100 meV, as expected.

Challenge for greater precision is emittance diagnostics on the nm scale!

Low MTE for us is then the key to short pulse lengths (few hundred fs) with high coherence.

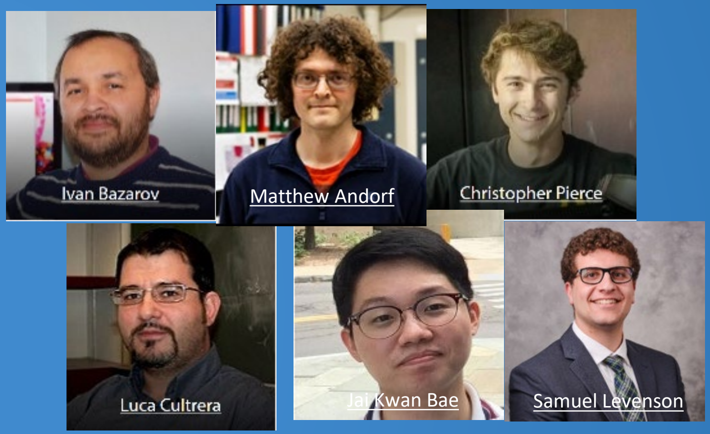
Acknowledgements

Maxson Group



Now at U. Salerno.

Bazarov Group



Now at BNL

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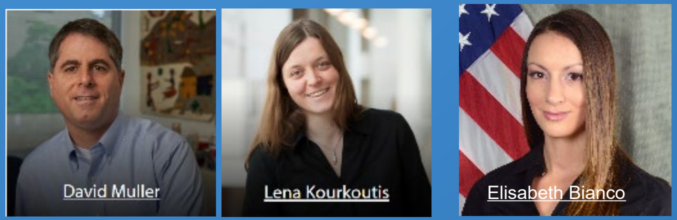
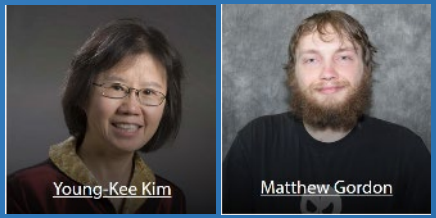
Cornell Electron Microscopy



U. Chicago Beam Dynamics



Conclusions

- I hope I have convinced you that the role of the photocathode intrinsic emittance remains **critical** for modern and future photoinjectors.
- Cross talk between between photocathode (materials science) community and the beam physics community as as important as ever.
- There is rich physics in the photoemission from high efficiency photocathodes– expect many more exciting updates in the next few years.