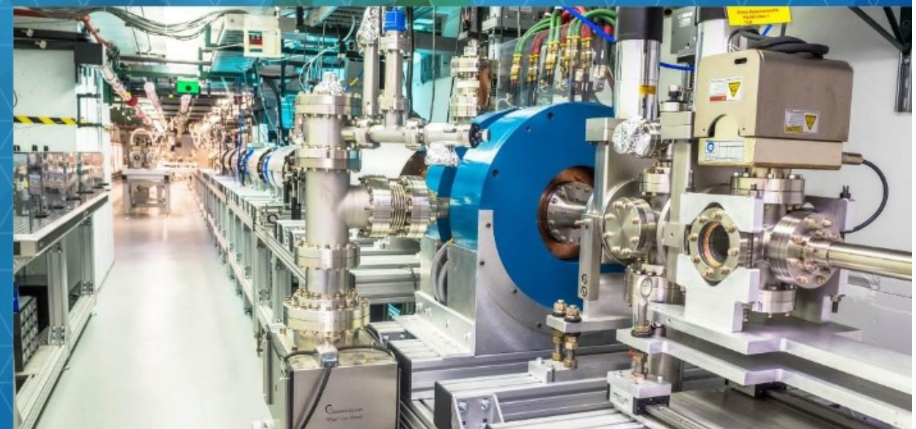
FEBRUARY 27, 2025

CBB BDC Meeting

High Brightness Beam Generation with Low-MTE Photocathodes



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OVERVIEW

- Introduction & Motivation:
  - CBB integrated photocathode tests
  - Generating bright beams at the Argonne Wakefield Accelerator
- Results
- Next Steps
- Summary
- Tariqul Hasan update on Alkali Antimonide Photocathodes Testing and Characterization at Argonne Cathode Test-Stand (ACT)

CBB integrated photocathode tests

- Integrated test of low-MTE photocathode in a photoinector; collaboration between NIU, Cornell, UCLA
- Share methods and ideas
- Test CBB photocathodes at 3 different facilities (inc. Argonne Wakefield Accelerator [AWA])

Deliverable 1.2: low-MTE photocathodes integration in existing photoinjectors

Identification of beamlines for a potential experimental demonstration of the simultaneous generation of low-emittance and high-charge (~100 pC) bunch, using CBB low-MTE photocathodes and diagnostics, that when coupled with a bunch-compression beamline would produce beams with 5D normalized brightness $I/\varepsilon^2 > 10^{15}$ A/m^2.

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Bright beams at AWA

- Initial goal: generate 100-pC beam with ~100-nm transverse emittance
- Simulation:
  - find optimal configurations of AWA's upgraded drive-beam photoinjector to generate bright beams
- Experiment:
  - utilize lower-MTE photocathodes in the beamline, contingent on prior characterization at high-gradients

Impact of the photocathode

- Investigate impact of photocathode type on transverse emittance (varying mean transverse energy [MTE])

$$\varepsilon_x = \sigma_x \sqrt{\frac{\mathrm{MTE}}{m_e c^2}}$$

- Test three different photocathodes:
  - 250 meV (Cs_2Te)
  - 60 meV (Cs_3Sb)
  - ~5 meV (TBD, CBB goal)
- Also test the case of a SiC dielectric photocathode, at
  - 45 meV
  - 60 meV

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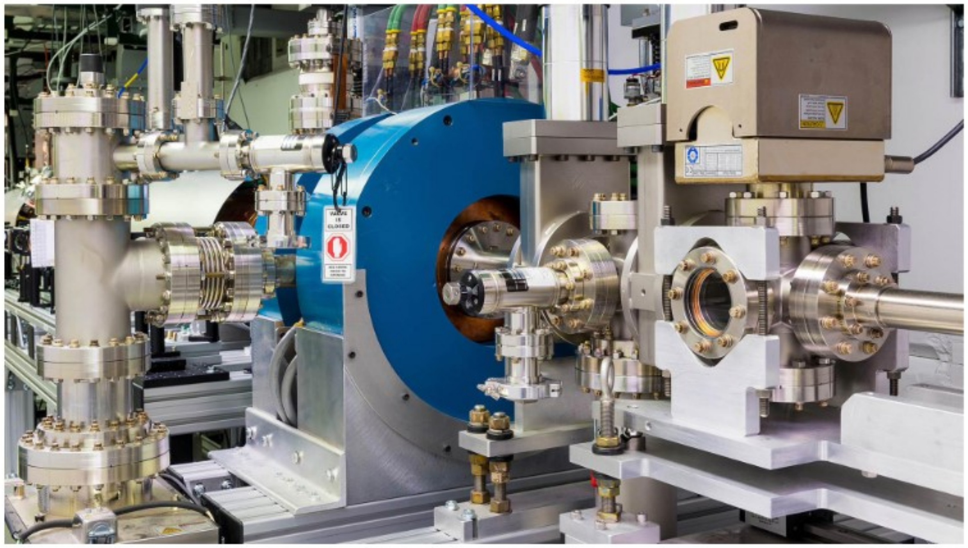
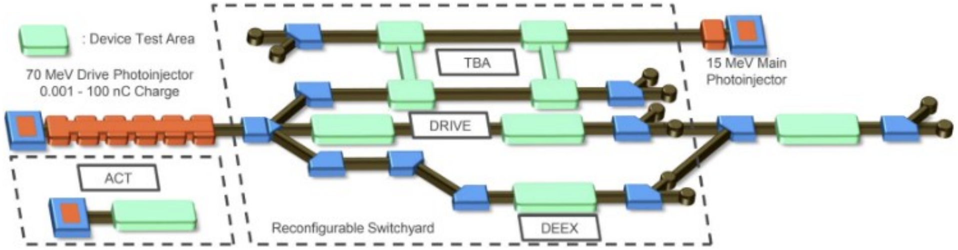
Overview of AWA

- Areas of research:
  - Structure wakefield acceleration
  - Underlying beam dynamics, beam manipulation and control, and developing advanced accelerating structures
- AWA has three accelerators:
  - The drive photoinjector
    - Up to 70 MeV bunches
  - The main photoinjector
    - Up to 15 MeV bunches
  - Cathode test-stand
    - A few MeV bunches





(Courtesy of Scott Doran)

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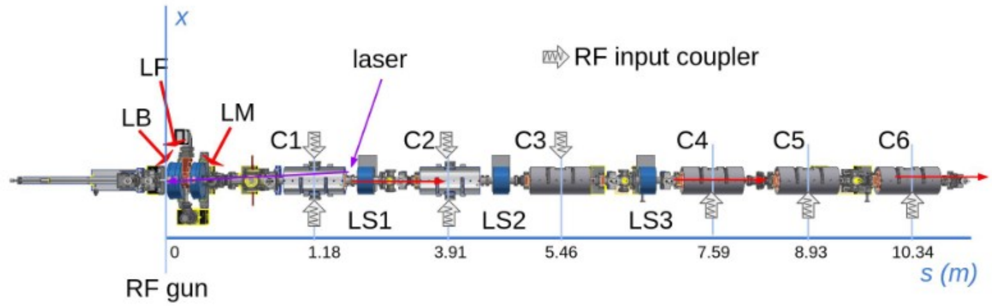
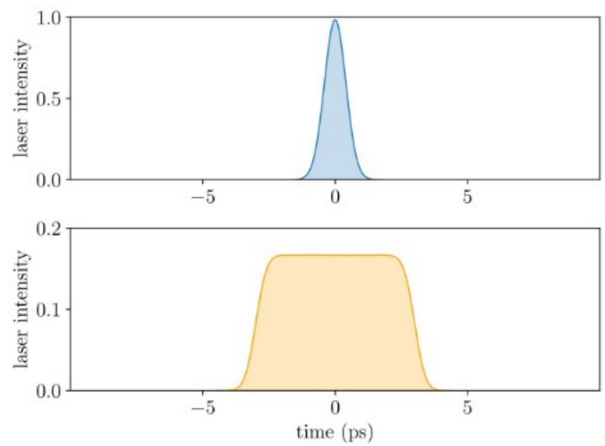
The upgraded drive-beam linac

- The drive-beam linac can reach bunch charges of 100 pC - 100 nC
- Consists of an RF photoinjector with a 1 + ½ cell resonant cavity operating at 1.3 GHz and a Cs2Te photocathode
- The cavity is surrounded by three solenoids: the bucking (LB), focusing (LF), and matching (LM) magnets
- Six accelerating cavities C1-C6; the first two will have a dual-coupler design and the remaining four will keep the single-coupler design. There are also focusing solenoids LS1-LS3. The shaded arrow indicate the RF input couplers locations





Photoemission is driven by a UV laser (292 nm) with two laser pulse profiles: (a) short pulse Gaussian distribution (“1G”; 170-fs RMS) and (b) long pulse flat-top distribution (“FT”, 6-ps duration)

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Multi-objective Optimization

- Goal:
  - perform a multi-objective optimization to minimize transverse emittance and bunch duration
  - generate a 100-pC particle bunch in Astra
    - Vary MTE
    - Vary laser pulse distribution

Control Parameter	Range of values
Laser rms spot-size	(0.02, 0.5) mm
laser launch phase	(-40, 40)°
peak field on photocathode	(40, 80) MV/m
linac C1 and C2 phase	(-50, 50)°
linac C1 and C2 peak field	(10, 20) MV/m
solenoid LM peak magnetic field	-(0, 0.4) T
solenoid LF peak magnetic field	-(0.1804, 0) T
solenoid LB peak magnetic field	LF*(0.85, 1.15) T
solenoid LS1 Peak magnetic field	(0, 0.4458) T

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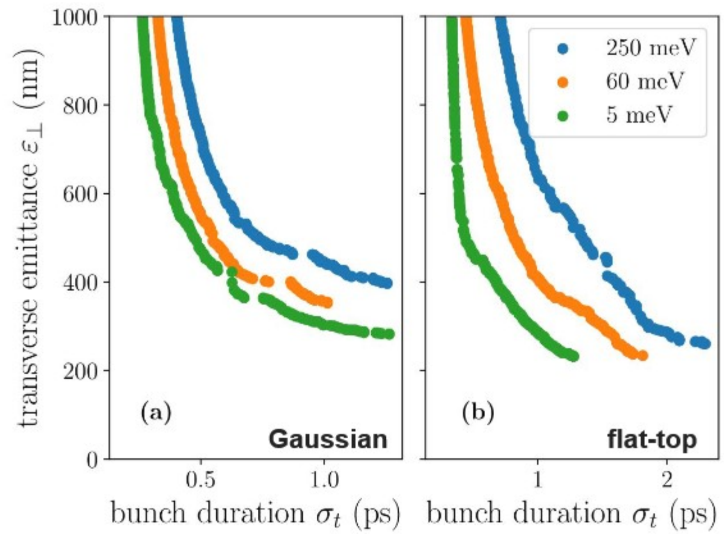
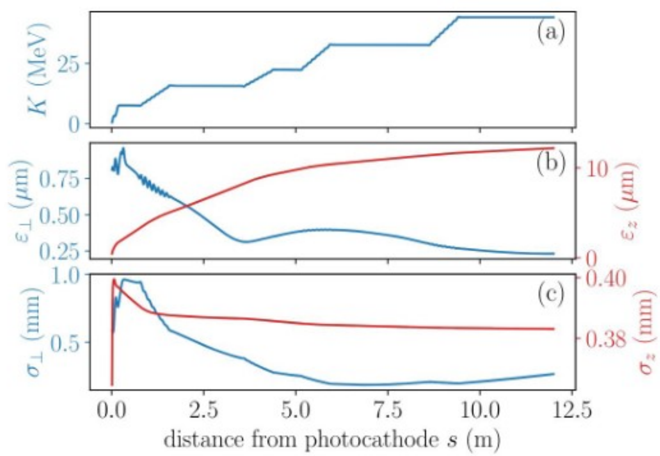
Results

Pareto Front

- The lowest emittance cases were obtained using the flat-top laser pulse and decreased with decreasing MTE, yielding
  - $\varepsilon\perp$ = 260.5 nm for 250 meV,
  - $\varepsilon\perp$ = 233.8 nm for 60 meV, and
  - **$\varepsilon\perp$ = 232.0 nm for 5 meV** (lower right plot)





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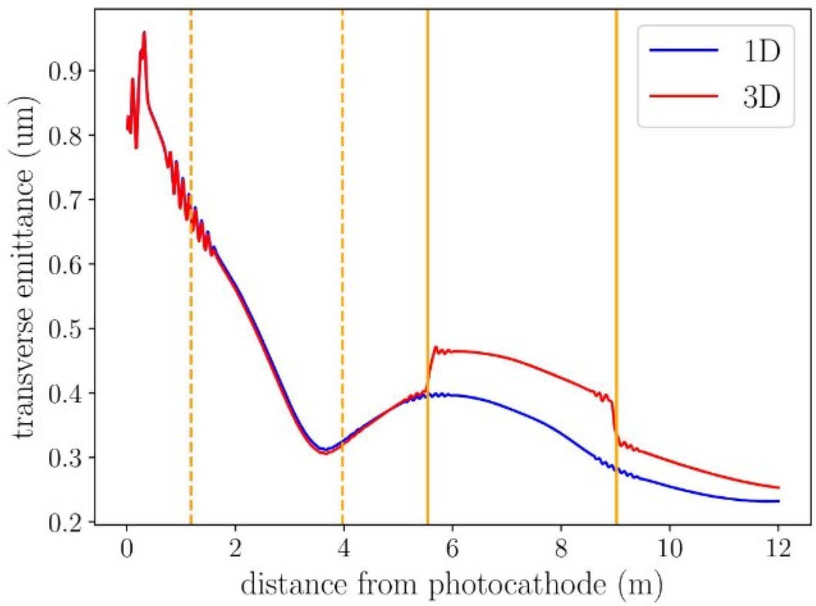
Results

Impact of 3D fields

- The 3D field maps for the upgraded gun and linacs were generated to investigate the impact of these realistic electromagnetic fields on emittance compared to the idealized axi-symmetric field
- Emittance evolution comparison using the 1D (blue) and 3D (red) field maps. The dashed and solid orange lines indicate the position of the upgraded dual-coupler linacs and the single-coupler linacs, respectively. [5 meV, FT laser pulse]



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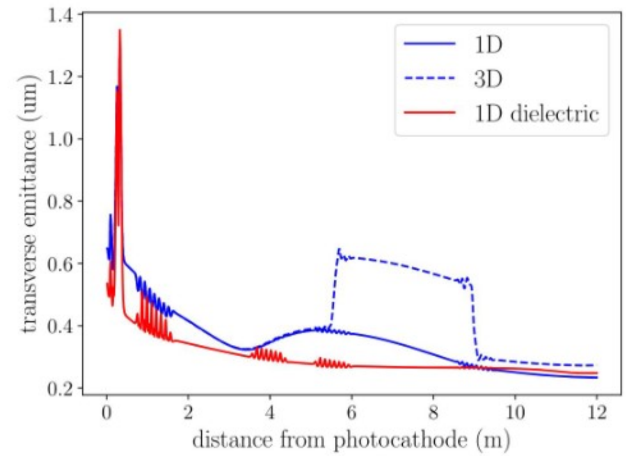
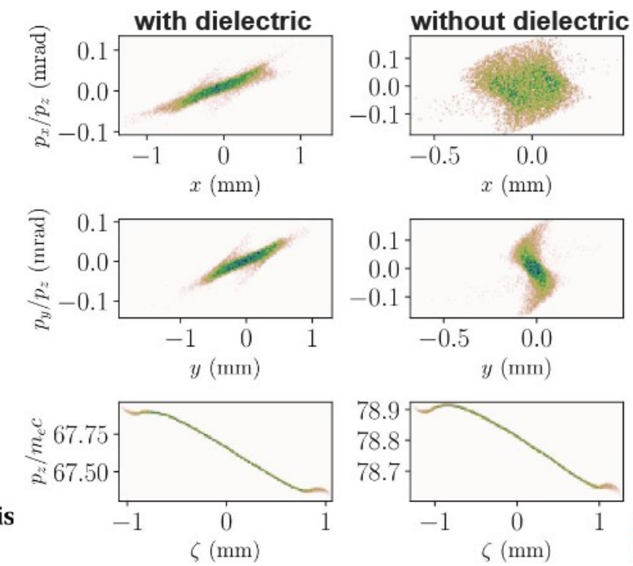
Results

Dielectric Photocathode

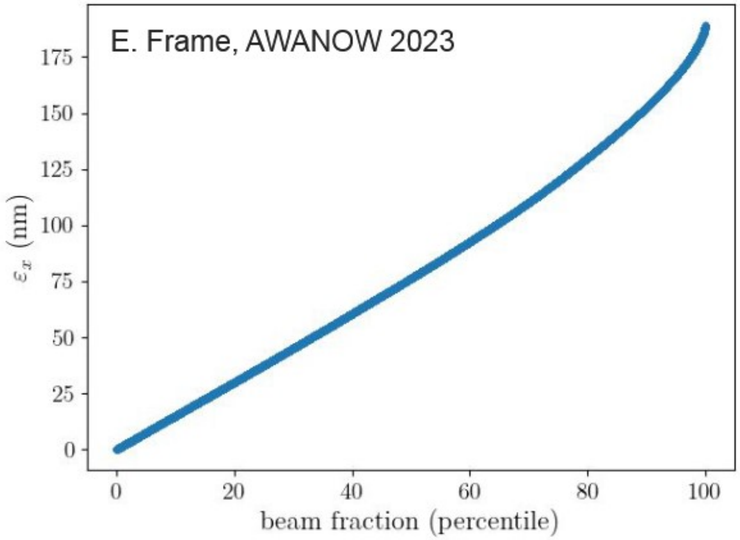
- Optimization for the case of a photocathode consisting of a thin film deposited on a SiC substrate (for flat-top laser pulse).
- Two possible MTEs were explored (45 and 60 meV), but to directly compare the performance of the photoinjector with and without the dielectric substrate, a common MTE of 60 meV was used.
- Emittance evolution along the beamline for the case of a photocathode with a dielectric substrate (red) and the nominal metallic boundary using the 1D (solid blue) and the 3D field (dashed blue).
- Horizontal, vertical, and longitudinal phase space with (left column) and without (right column) the dielectric photocathode





Next Steps
Simulations

- Further simulation work will be done:
  - implement a measured laser distribution
  - model full 3D field map of dielectric cathode to use in simulations
  - alignment map: use optics to steer the beam, compensating for the coupler kick
- We also want to try to implement selective collimation - see J. Maxson's work
  - insert an aperture into the beamline to select the bright core of the electron beam
  - start with simulations:
    - perform an optimization of the beam starting at a higher charge, then dynamically select a 100-pC subpopulation and see the attainable emittance
  - from previous results (see plot) and J. Maxson's work, we expect a reduction in transverse emittance using this technique



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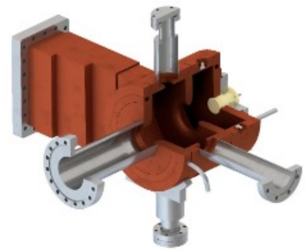
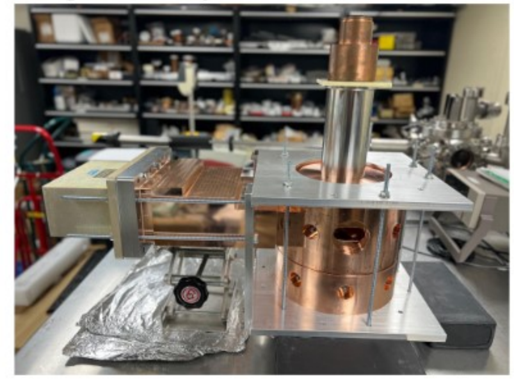
Next Steps

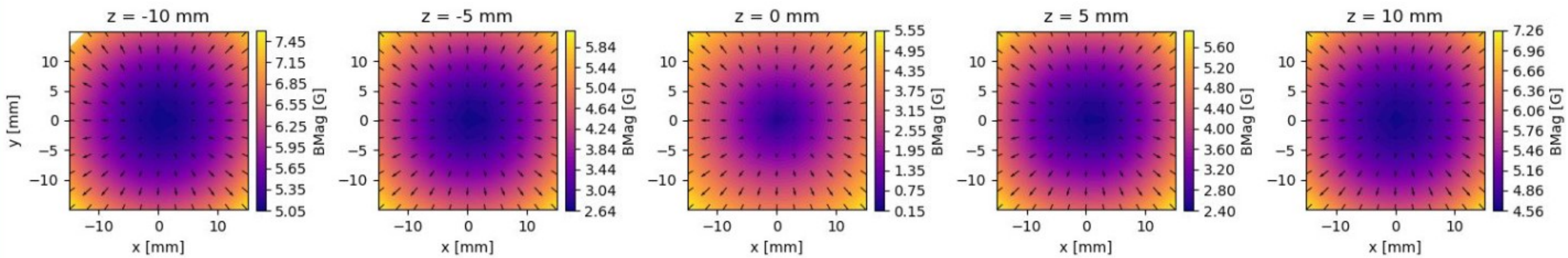
Experiment: photoinjector upgrade

- Installation of the new, symmetrized RF gun starting in March
- New solenoid also being installed at this time
  - I am helping with measuring the transverse map which can then be used in simulations
- Also would like to implement an alignment map:
  - optics to inject the beam at an angle/offset to compensate for emittance growth induced by the single-coupler linacs



Images courtesy of Scott Doran at ANL.





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Next Steps

Experiment: Cs2Te photocathodes in the upgraded injector

- Benchmark our model and validate optimum configuration
- Emittance measurement downstream of linac:
  - measuring sub-micrometer emittances will be challenging as it will most likely rely on a multi-shot method (scanning slit or quadrupole/solenoid scan)
    - shot-to-shot stability
    - high-resolution diagnostics
- Expected timeline: summer 2025

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Next Steps

Experiment: low-MTE photocathodes

- Install the lower-MTE cathodes in the upgraded drive-beam RF gun
- This is contingent on prior high-gradient cathodes testing and characterization on a different beamline
  - see Tariqul's talk at the end!

- The lower-MTE photocathodes to increase the brightness will be utilized by Oksana's students later; my focus will be on the Cs_2Te photocathode measurements due to the timescale of these experiments.

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Summary

- Collaboration with CBB participants to demonstrate substantial emittance reduction from lower-MTE photocathodes integrated in a photoinjector
- Simulations indicate that AWA's drive-beam accelerator can achieve low emittance.
- Further simulations will be done, including refining the current model, making an alignment map, and investigating selective collimation as an emittance-reduction technique.
- Experiments will first focus on optimizing the upgraded injector with the nominal AWA photocathode to gain experience with diagnostics and model validation; this will occur this summer at AWA!
- Once ready, lower-MTE photocathode(s) will be inserted in the drive-beam RF gun.
- Now, on to Tariqul's talk!

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