

Modeling and Experimental Characterization of a High-Field, High-Charge L-Band Photoinjector

Chengkun Huang¹, Xueying Lu^{2,3}, Omkar Ramachandran², Gaurab Rijal²

1. Los Alamos National Laboratory (LANL)
2. Northern Illinois University (NIU)
3. Argonne National Laboratory (ANL)

AAC 26



Acknowledgments

- A. Alexander (LANL)
- Gongxiaohui Chen (ANL)
- D. A. Dimitrov (LANL)
- Alex Ody (ANL)
- John Power (ANL)
- Omkar Ramachandran (NIU)
- Gaurab Rijal (NIU)
- E. I. Simakov (LANL)
- Gaoxue Wang (LANL)
- Eric Wisniewski (ANL)

This research was supported by:

Los Alamos National Laboratory (LANL): LDRD 20230011DR

Northern Illinois University (NIU): DE-SC0021928, DE-SC0024445.

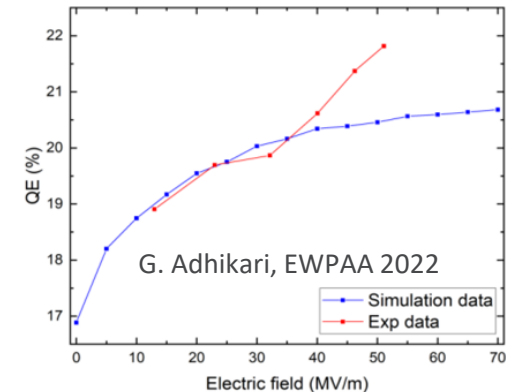
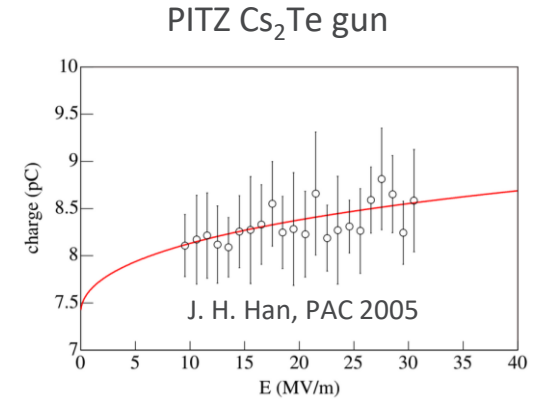
Argonne National Laboratory (ANL): DE-AC02-06CH11357

Outline

- Goal:
 - Understanding of Cs_2Te photocathode operation in a high-field photocathode gun
- Approach:
 - Modeling: DFT + Monte-Carlo + thin-film optical interference
 - Experimental benchmarking at the Argonne Wakefield Accelerator, using an L-band (1.3 GHz) high-field Cs_2Te photogun
- Application:
 - High-brightness beam generation
 - High-gradient photoguns (e.g., normal-conducting photoguns at other frequencies, such as C- or X-band, water-cooled or cryogenic; SRF guns)

Understanding semiconductor photocathode in gun operating conditions

- **High-field operation** is of advantage for increasing beam brightness but also has inherent complexity
 - Suitable photocathode materials (e.g., Cs_2Te)
 - Mitigation design and optimization
- Adequate models and knowledge of material properties to help guide the photocathode and gun design
 - No suitable existing models for **high-field photoemission**, some include Schottky and space-charge effects in emission
 - Unknown or uncertain material properties (e.g., **optical constants** for Cs_2Te)



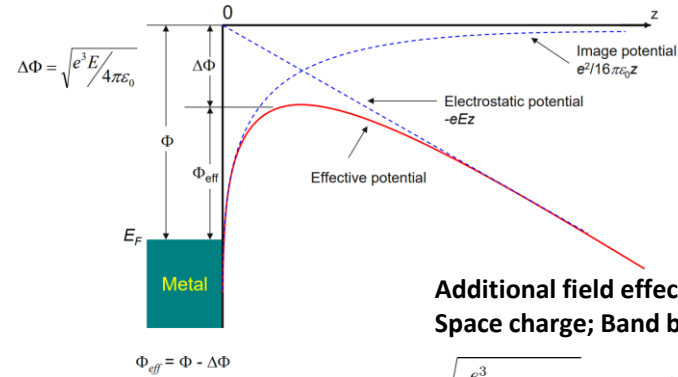
Emission models

Fowler–Dubridge $QE_F = \eta(h\nu - \Phi_\omega)^2,$

Spicer $QE_s = \frac{(h\nu - \Phi_\omega)^{1.5}}{(h\nu - \Phi_\omega)^{1.5} + \gamma}.$

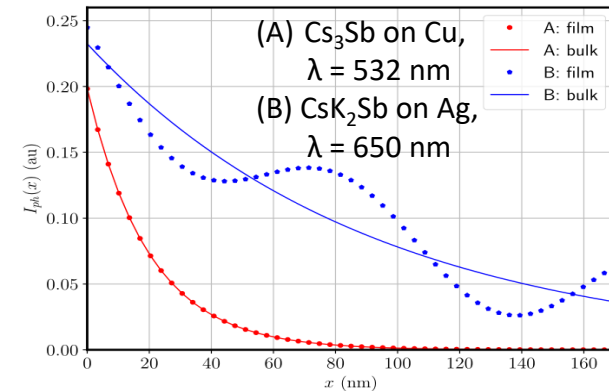
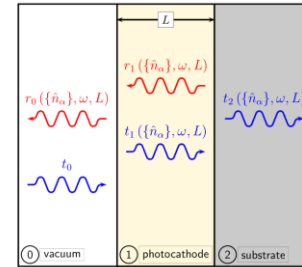
Jensen $QE_J = \frac{(1 - R_\omega) \sqrt{1 + \frac{h\nu - \Phi_\omega}{E_a}}}{2(p_0 + 1) \left(1 + \frac{E_a}{h\nu - \Phi_\omega}\right)^2}.$

Schottky effect



$$E_A = \kappa E_{A,0} - \sqrt{\frac{e^3}{4\pi\epsilon_0} \beta_{ph} E_{emit}} \quad \Delta\Phi_f(r_\perp, t) = \sqrt{\frac{q^3}{4\pi\epsilon_0} [E_{rf}(r_\perp, t) + E_{sc}(r_\perp, t)]}$$

Optical interference effect



Moment model and Monte-Carlo modeling

- Moment model for photoemission

Moments: $M_n(k_j) \equiv \langle k_j^n \rangle$ absorption (A), transport (T), emission (E)

$$M_n(k_j) = (2\pi)^{-3} \int d^3k k_j^n \times \mathbb{E} \times \mathbb{T} \times \mathbb{A}$$

for a semi-infinite photocathode

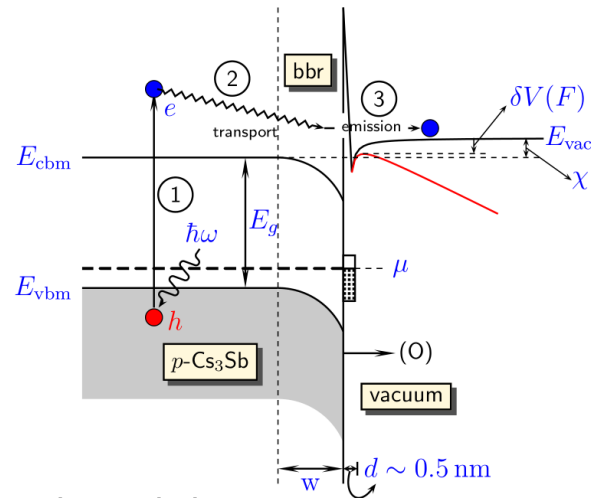
QE expressed as averages over electron energies:

$$QE = (1 - R(\omega)) \frac{\int_{E_a}^{\hbar\omega - E_g} dE E \int_{\sqrt{E_a/E}}^1 du D(Eu^2) u f_{si}(\omega, E, u)}{2 \int_0^{\hbar\omega - E_g} dE E \int_0^1 du}$$

Absorption and transport: thin film photocathode

$$f_{tf}(\omega, E, \cos(\theta)) = \frac{\int_0^L |E_{ph}(x)|^2 e^{-x/(\lambda(E) \cos(\theta))} dx}{\int_0^L |E_{ph}(x)|^2 dx}$$

- Monte-Carlo approach is suitable for detailed transport process modeling



1. Photo excitation
2. Charge transport
3. Surface emission

Informing emission model with parametrized MC transport

- We utilize a Monte Carlo simulation model and adapt the simulations for Cs₂Te semiconductor cathodes.
- Electronic properties from DFT calculation (as well as from literature/experiment)

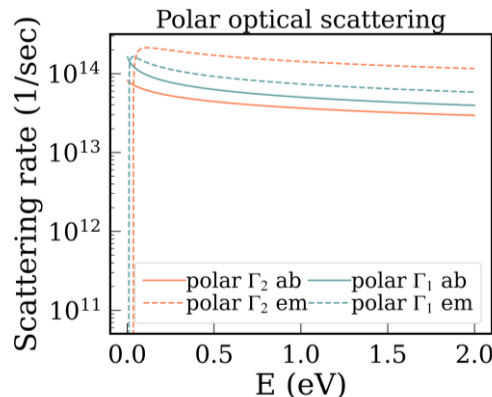
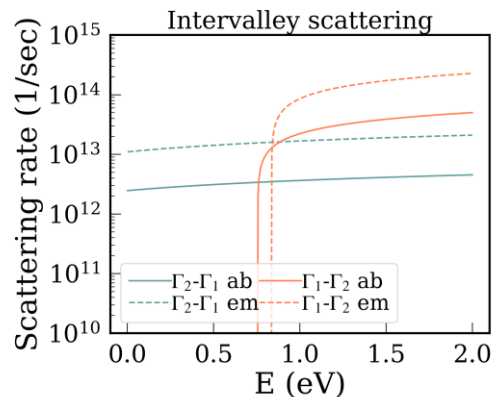


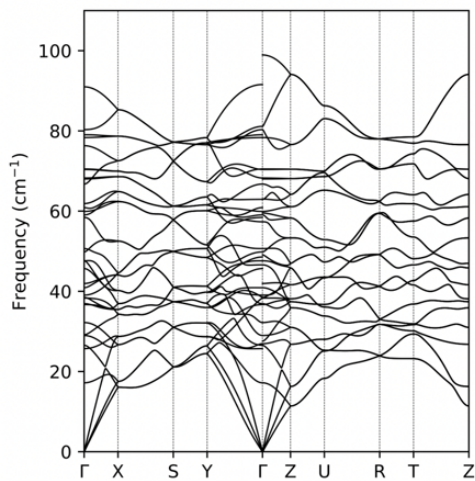
Table 1: Parameters for the Cs₂Te transport simulation. *Experimental value [4].

Parameters	Value
Band gap E_g	3.3 eV*
Γ_1 valley effective mass (m_1^*)	0.27 m_0
Γ_2 valley effective mass (m_2^*)	0.7 m_0
$\Gamma_1 - \Gamma_2$ splitting energy E_s	0.796 eV
Phonon energy E_{ph} (estimate)	0.01 eV
Deformation constant D_i (estimate)	10 ¹¹ eV/m
Dielectric constant ϵ_s	10.3 ϵ_0
High frequency dielectric constant ϵ_∞	4.3 ϵ_0
Density ρ	3.99 g/cm ³
Temperature T	300 K

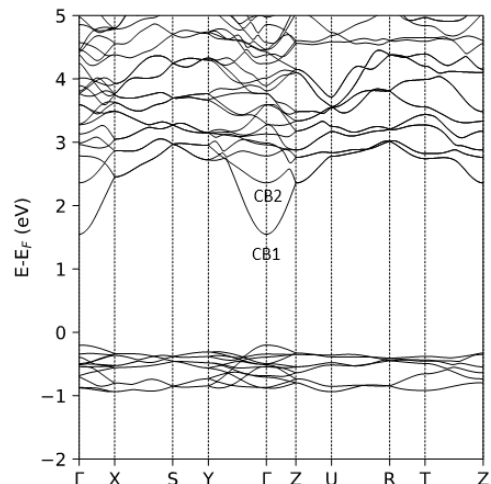
- We will use these MC simulation results to inform the thin-film photoemission model at high field

DFT modeling of Cs_2Te

- We conducted computation study of the material properties of Cs_2Te needed for high field applications: structure, optical, electronic and phonons

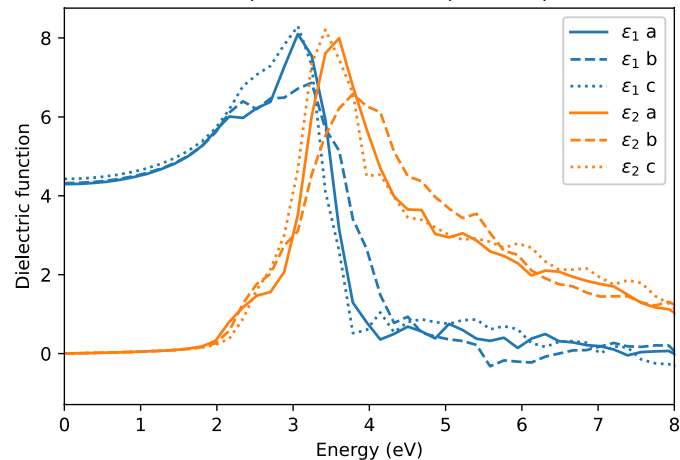


Phonon dispersion



Band structure

G. Wang et al., "First-principles study of structural, elastic, electronic, transport properties, and dielectric breakdown of Cs_2Te photocathode," Sci. Rep., vol. 15, p. 2780, 2025



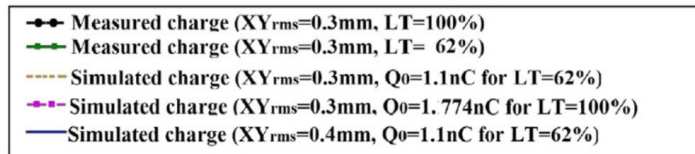
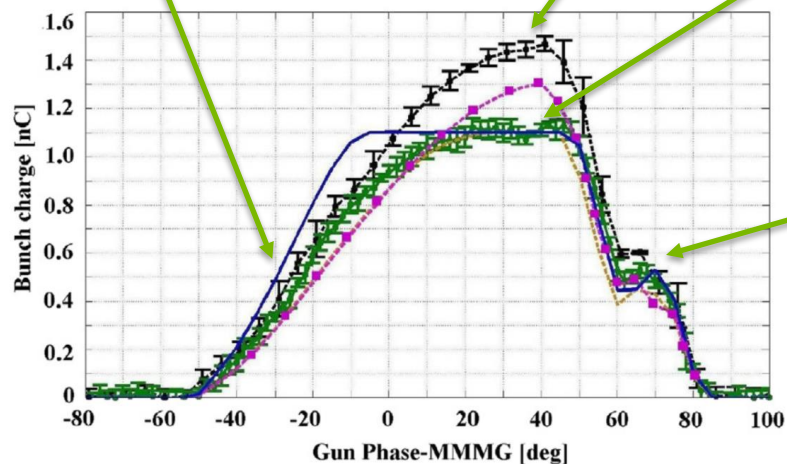
Optical properties used in the optical interference model

Gun phase scan with semiconductor photocathodes

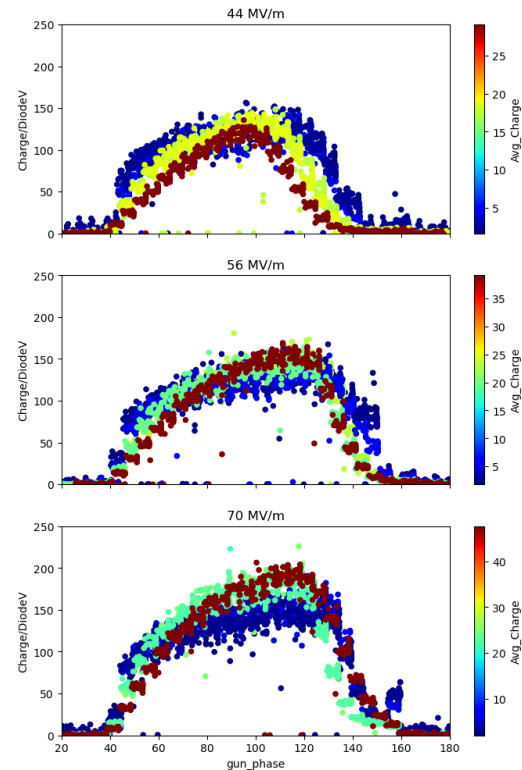
Space charge limited regime

Space charge during emission

source limited regime

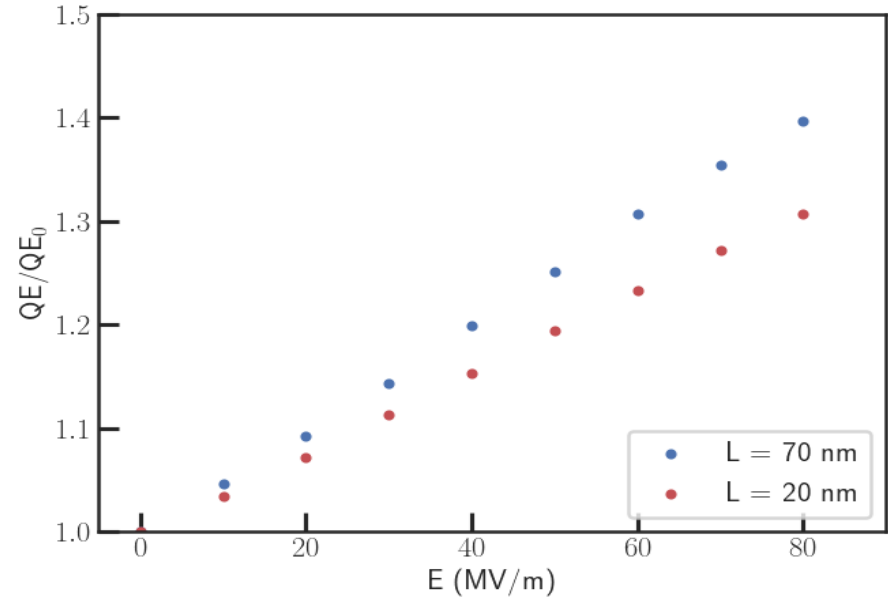
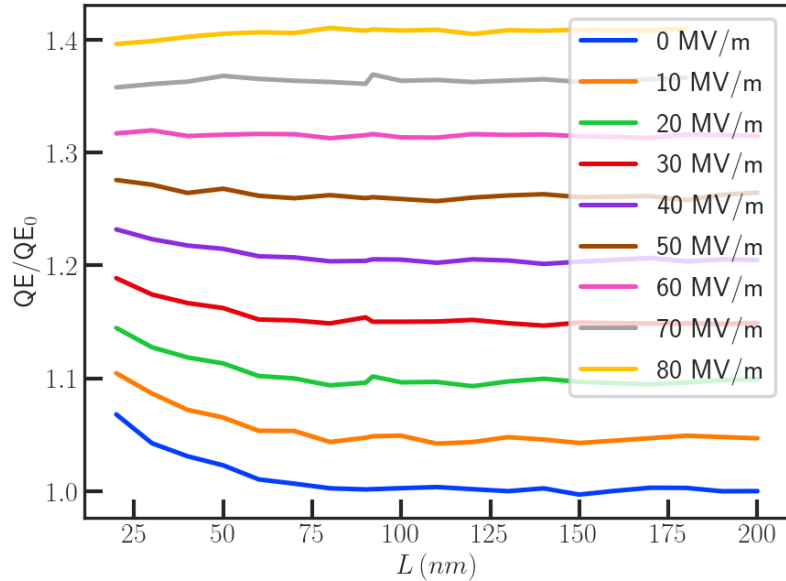


PITZ gun phase scan



AWA gun phase scan

Monte-Carlo calculation at high fields : enhancement from electron transport in Cs₂Te*

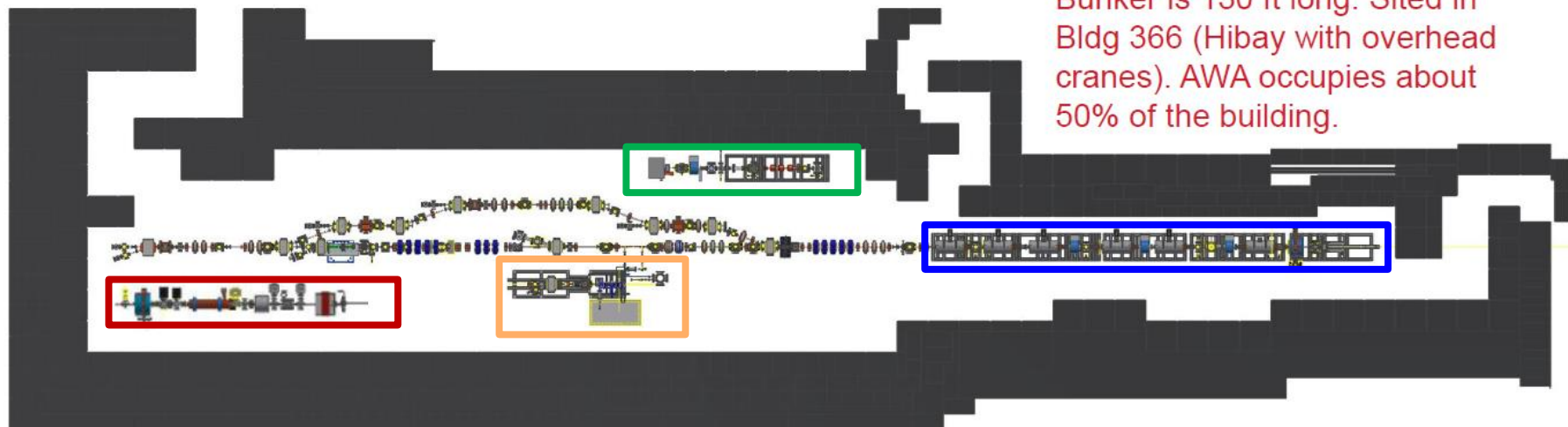


Preliminary Results : Effects from film thickness and gradients

* tunneling is included in the gun simulation

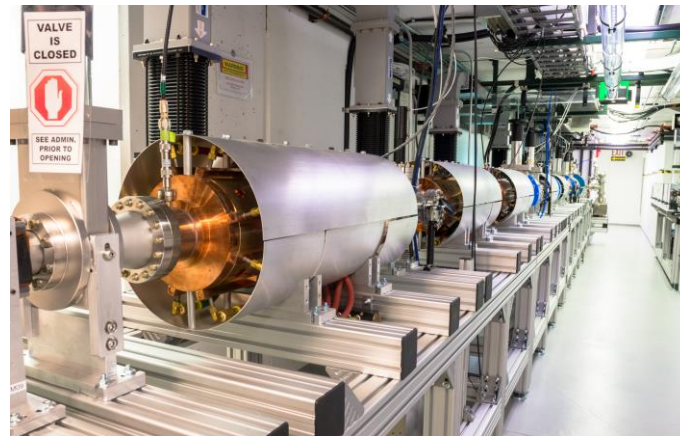
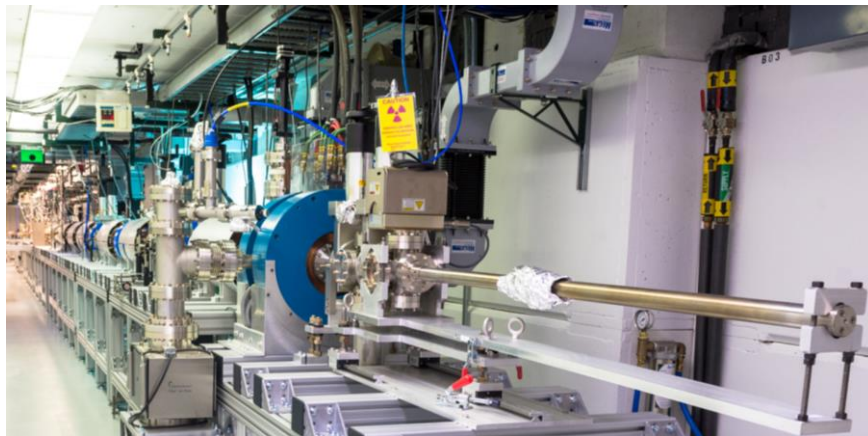
Argonne Wakefield Accelerator (AWA) Facility Overview

- 3 L-band photoinjector beamlines
 - Drive beamline (this work)
 - Witness beamline
 - Argonne Cathode Test-stand (ACT)
- 1 X-band short-pulse photoinjector powered by structure wakefield acceleration



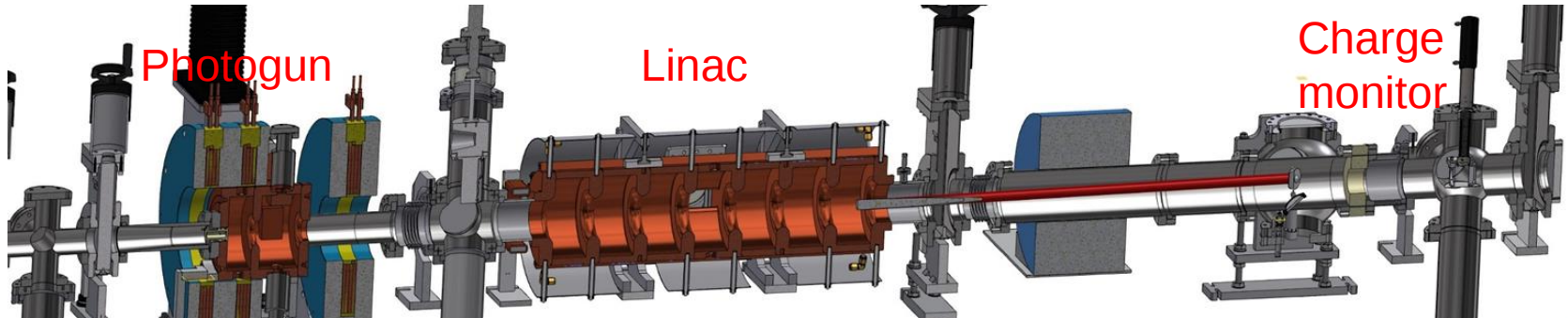
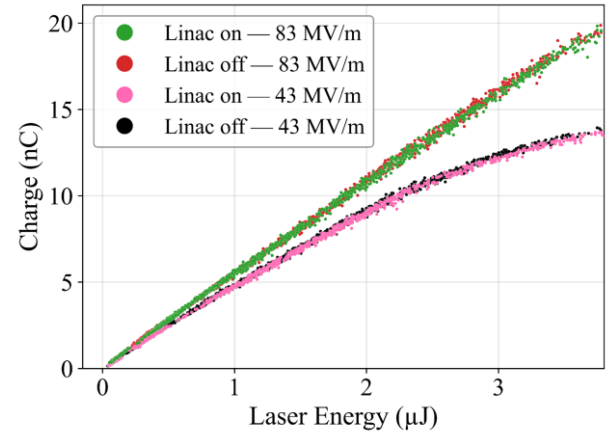
L-band drive photoinjector

- 1.5-cell, 1.3 GHz photogun with a 31 mm (diameter) **Cs₂Te cathode**
 - Laser wavelength 262 nm, laser pulse duration 1 to 8 ps
 - UHV load-lock chamber with a base pressure of 1.5E-10 Torr
- **High-field operation**
 - Cathode surface peak field over **80 MV/m**, RF pulse length 7.6 μ s
- **Wide charge range**
 - Single-bunch operation: 100 pC to **100 nC**
 - Bunch-train operation: up to **32 bunches** in a train, up to **600 nC** total charge
 - High-charge capability is the key driver behind recent breakthroughs in **high-gradient, short-pulse** acceleration using (beam-driven) structure wakefield acceleration



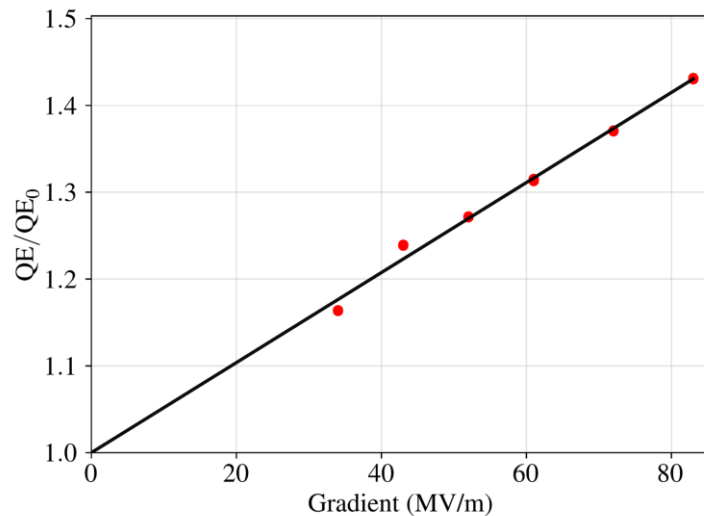
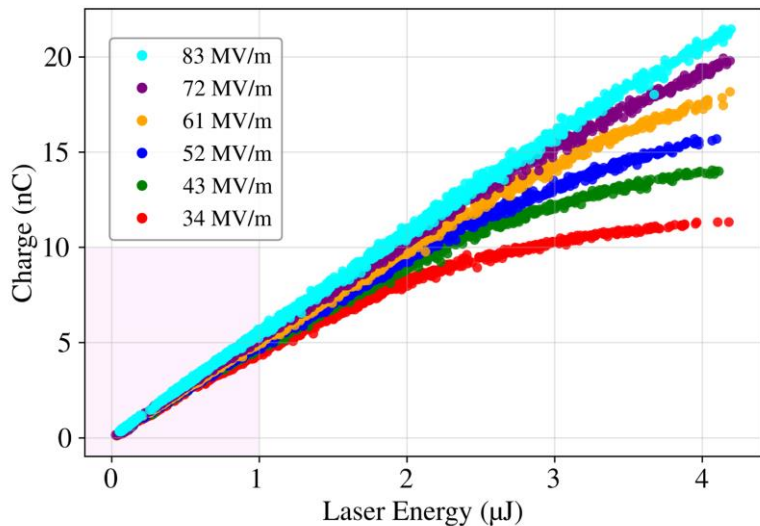
QE measurement setup

- **Challenge #1:** closest charge monitor is not immediate after the photogun exit
 - Conducted two sets of meas. w/ linac on and off
 - Same charge measured with the linac on and off at all the gradients studied
 - Complemented with beam dynamics sims
- **Challenge #2:** large laser energy jitter
 - Photodiode measurement using leakage light



Exp. results: QE vs. gradient

- Gradient and charge scan at the nominal injector operating condition
 - RF gun = 50 deg, linac = 90 deg, laser spot size 5 mm (radius)
- Charge vs. laser energy nonlinearity at low gradient & high energy due to space charge effects
- QE increases with gradient (calculated using data in the low-charge shaded region)

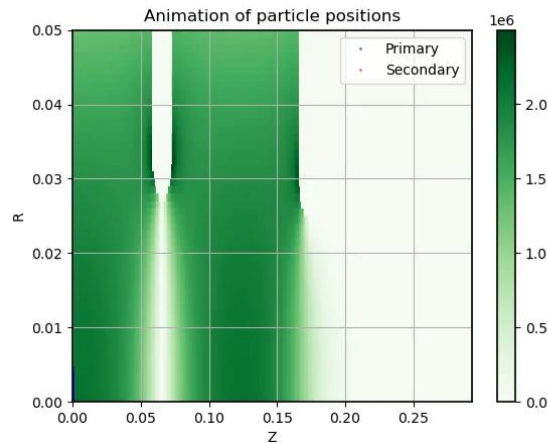


Beam-dynamics simulations w/ MC emission model

Code development

To simulate transport through the gun and linac, we developed a tracking code with the following features:

1. Initializes distributions using the Monte-Carlo photoemission model (incl. Schottky effect).
2. Beamline elements are modeled with 3D field-maps.
3. 3D space charge is modeled using with a rest-frame Poisson solve at each timestep.
4. Secondary electron emissions are modeled on the photocathode surface.



$$\delta(E_p) = \delta_{\max} \frac{E_p}{E_{p,\max}} \frac{s}{s - 1 + \left(\frac{E_p}{E_{p,\max}}\right)^s}$$

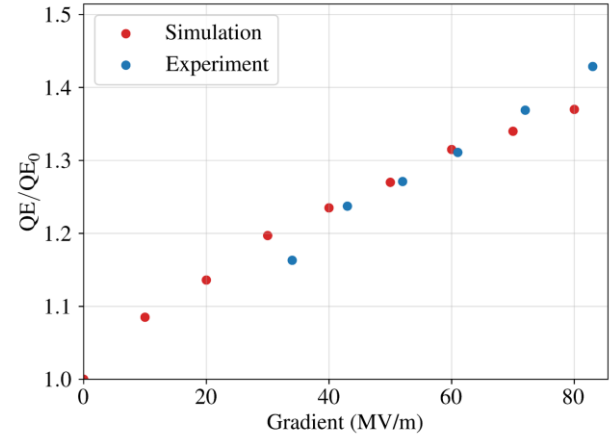
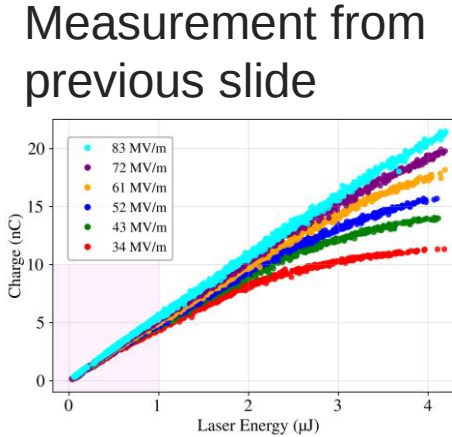
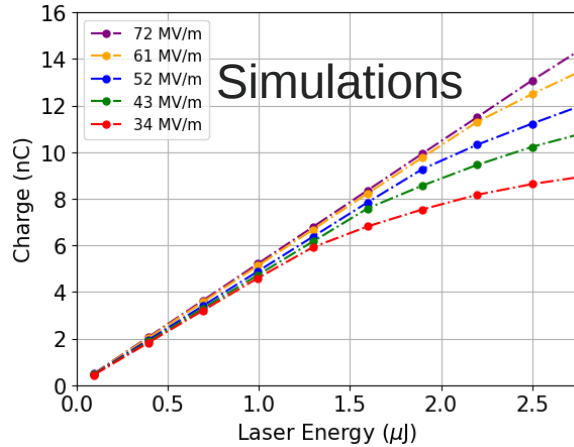
$$\delta_{\max} = 7.0$$

$$s = 1.5$$

$$E_{p,\max} = 2.2 \text{ eV}$$

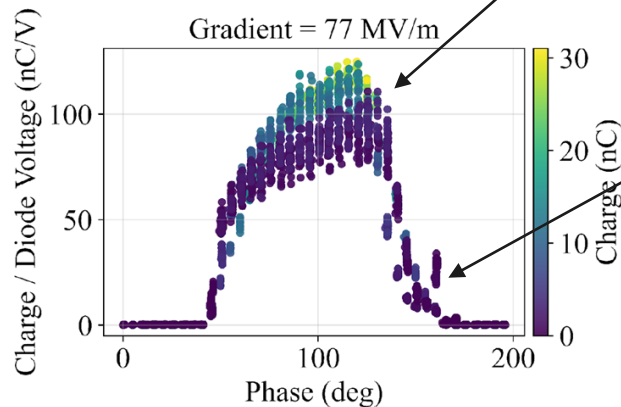
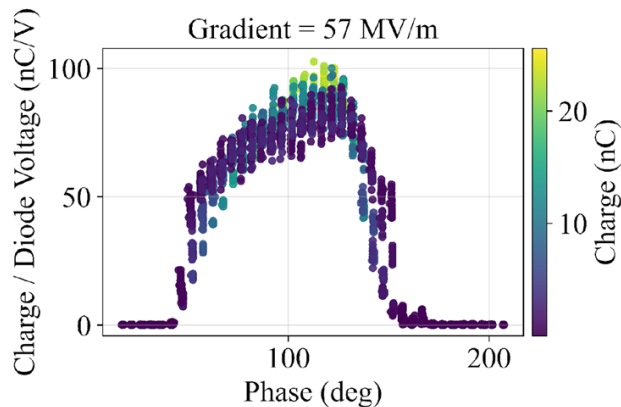
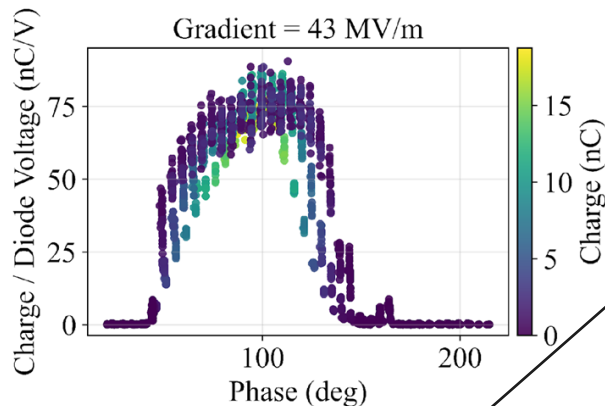
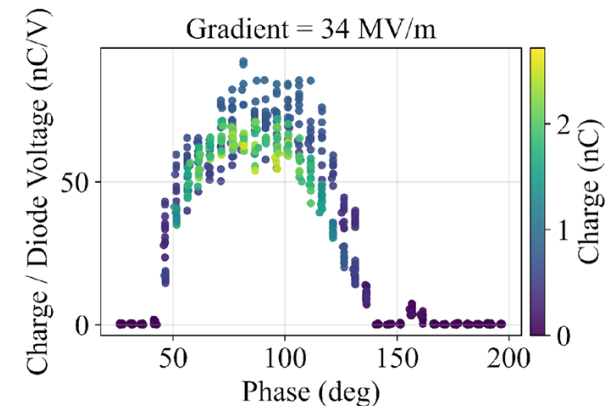
Beam-dynamics simulations w/ MC emission model

Preliminary Results



- At low gradient & high charge, space charge effect leads to beam loss at the charge monitor location.
- Beam dynamics simulations performed with distributions obtained from the MC Model predict ~40% increase from 0 to 80 MV/m.
- These results are largely in line with experimental data.

RF phase scan at various gradient & charge

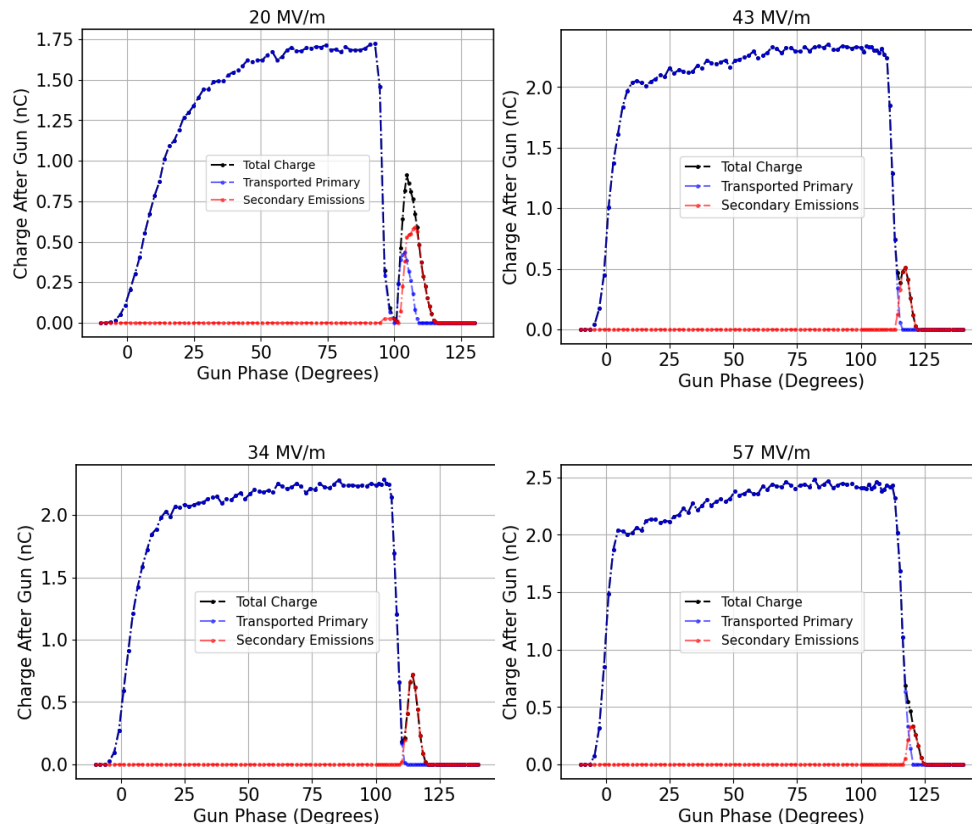


The phase scans from experiment all demonstrate the increase in charge due to QE from 0-100 deg.

All 4 gradients have secondary bumps after around 120 degrees.

RF phase scan at various gradient & charge

Preliminary Results

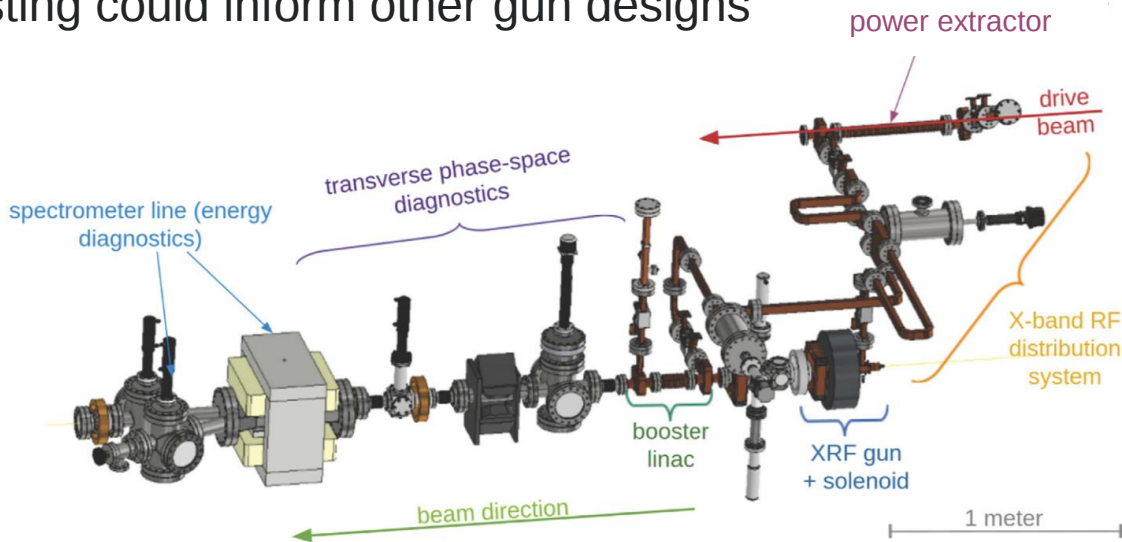
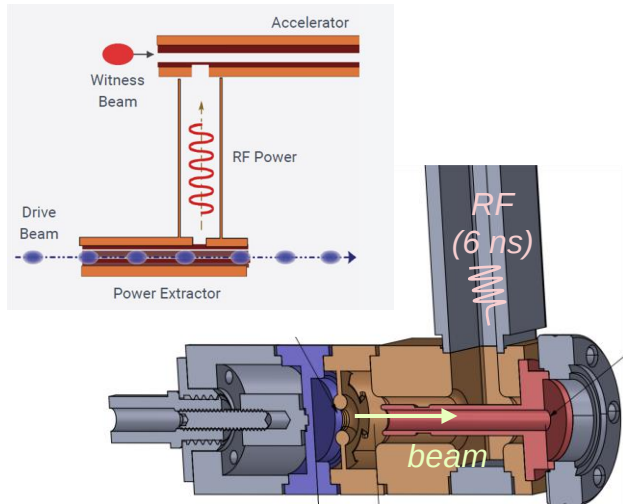


At the exit of the gun,

- The gradual increase in charge from 0-100 degrees is explained by increases in QE due to gradient.
- The bump at ~120 deg can be explained by a combination of transport and secondary emission at low gradients, and pure secondary emission at high gradients.

X-band short-pulse photogun

- Close to **400 MV/m** measured on an X-band photocathode surface in a photogun driven by 6 ns RF pulses, **two-beam acceleration**
 - Rapid RF conditioning, low dark current, reliable operation
 - A reduction of emittance expected; detailed beam characterization in progress
- A new photogun with removable cathode plug expected in the near future
 - High-gradient cathode testing could inform other gun designs



Conclusion

- Phase-scan and Cs_2Te cathode QE measurements of the AWA L-band high-field photogun are performed to characterize semiconductor-cathode behavior under various operating conditions.
- Monte Carlo and beam-dynamics simulations are compared with experimental measurements and show reasonable agreement.
- The Monte Carlo emission model can be used to study intrinsic emittance and beam brightness.
- As future high-brightness photoguns move toward even higher gradients, this approach can support their design and optimization.