

P3 Workshop 2025: Summary

Prof. Siddharth Karkare, Arizona State University

www.p3workshop.org

**Photocathode Physics for
Photoinjectors (P3)
Workshop**

Hosted by Arizona State University | November 12-14, 2025



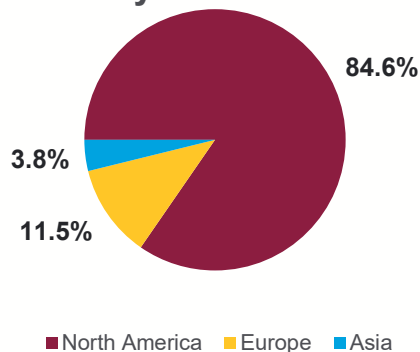
P3 Workshop overview

12–14 November 2025

Arizona State University

78 registered participants
51 talks
16 posters

Attendees by institution location



•Wednesday, November 12

- Introductory Session
- High Charge - High Average Current
- Spin Polarized Cathodes

•Thursday, November 13

- FEL session
- UED session

•Friday, November 14

- Theory Session
- Novel Concepts
- Community Perspectives and Outlook Panel Discussion

**Strong attendance given US federal funding
uncertainties in 2025:
suggests increasing interest in photocathodes!!!**

Introductory Session

Wednesday, November 12 • 2 talks

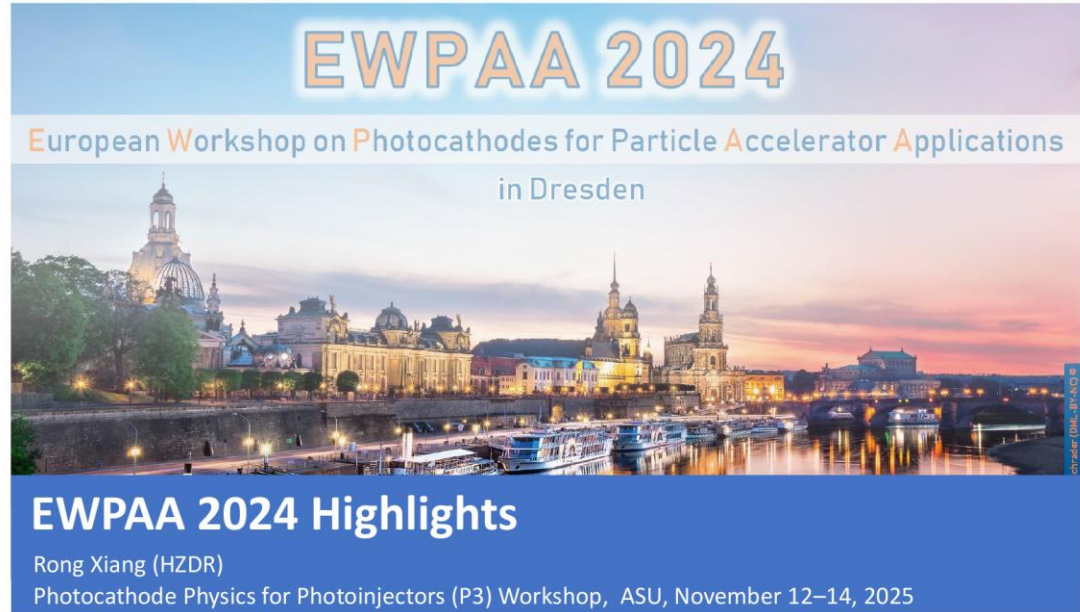
EWPA 2024 highlights

Rong Xiang (HZDR)

Introductory Session

Topics

- Photocathode Performance in Accelerator Applications
- Novel Concepts and Lasers
- Low emittance application
- 'Green' Photocathodes
- Photocathode theory and characterisation
- Cathodes for polarized electron sources



EWPA 2024 title slide
Rong Xiang (HZDR) • slide 1

Materials for Bright Beams Workshop @ Cornell

Lance Cooley (FSU / National High Magnetic Field Laboratory)

Introductory Session

Topics

- Photocathodes
- SRF materials
- High gradient RF materials



Photocathode Physics for
Photoinjectors (P3) Workshop

Hosted by Arizona State University | November 12-14, 2025

Summary of the Materials for Bright Beams Workshop

Speaking on behalf of the Organizing Committee:

Lance Cooley,
National High Magnetic Field Laboratory
Florida State University



U.S. National
Science Foundation



FLORIDA STATE
UNIVERSITY



UNIVERSITY of
FLORIDA



Los Alamos
NATIONAL LABORATORY

Materials for Bright Beams Workshop title slide

Lance Cooley (FSU / National High Magnetic Field Laboratory) • slide 1

High Charge - High Average Current (ERLs and Colliders)

Wednesday, November 12 • 9 talks

GaAs operation in the BNL SRF gun

Luca Cultrera (BNL)

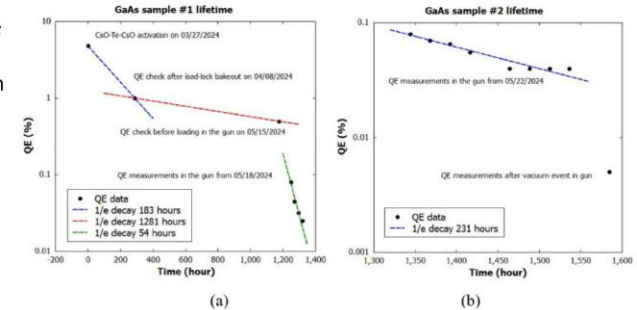
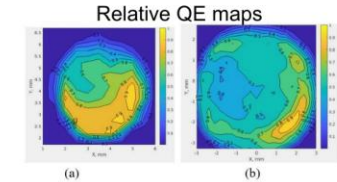
High Charge - High Average Current

- NEA-GaAs transferred to the 112 MHz SRF gun.
- Operation at 532 nm for hundreds of hours.
- Maximum field 12 MV/m; maximum bunch charge about 1.3 nC.

CsO-Te-CsO activated photocathode in SRF gun



- Cathode holder specially designed for SRF 112 MHz electron gun;
- Cathodes were transferred using a vacuum suitcase from production system to RHIC tunnel;
- Operation was only performed at 532 nm;
- **Cathodes survived transfers and were operated for hundreds of hours;**
- Max $E_{\text{field}} = 12$ MV/m
- Max Charge/bunch = 1.3 nC



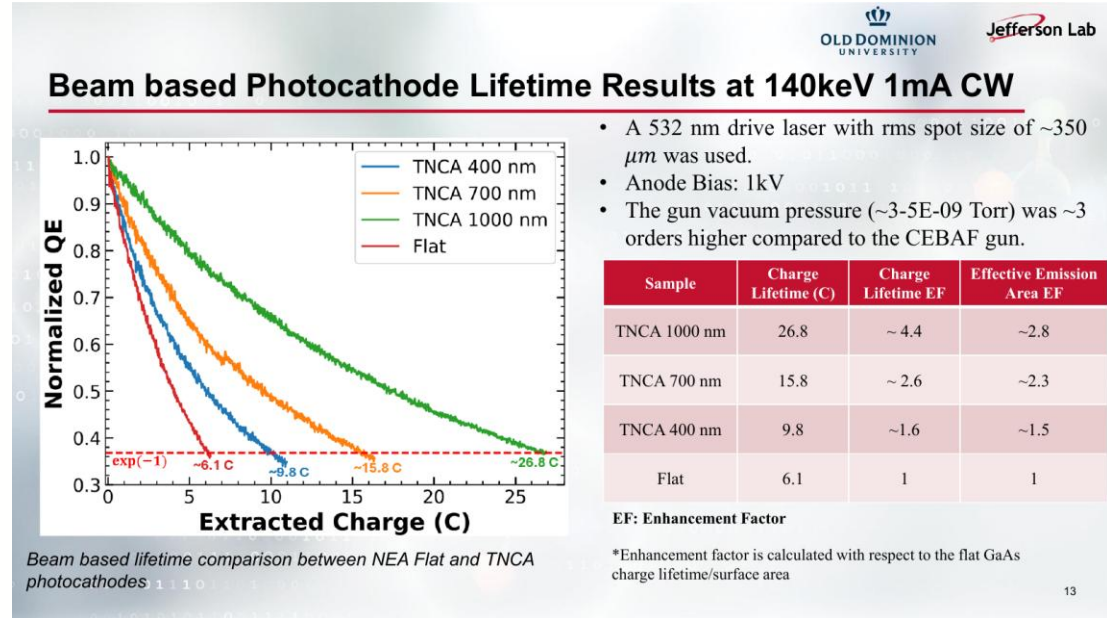
V. Litvinenko et al., "Towards a New Class of Polarized Electron Sources: An RF Gun with GaAs Photocathode", Nature Physics, accepted

Operating summary and relative QE maps
Luca Cultrera (BNL) • slide 18

Aziz Md. Rahman (JLab)

High Charge - High Average Current

- Truncated nanocone arrays tested at 140 kV and 1 mA CW.
- 1000 nm array: 26.8 C charge lifetime, 4.4× flat GaAs.
- Normalized emittance increased by 1.4–1.5×; spin tests remain future work.



Beam-based charge lifetime of flat and nanostructured GaAs
Aziz Md. Rahman (JLab) • slide 13

Paul Denham (UCLA)

High Charge - High Average Current

- Cigar-regime charge scaling experimentally verified
- Saturation mapped versus field, laser radius, duration and profile.
- Tail-emission model extends beyond saturation; emittance near saturation is next.

Summary & outlook

- $Q_{sat} \propto T(ER)^{3/2}$ cigar scaling experimental verification.
- Established method for mapping of saturation surface $Q_{sat}(E, R, T, f(r))$
- Established Tail-emission model extends beyond saturation in both pancake and cigar regimes.
- Future: Emittance near saturation in cigar regime, Optimization for FEL or UED

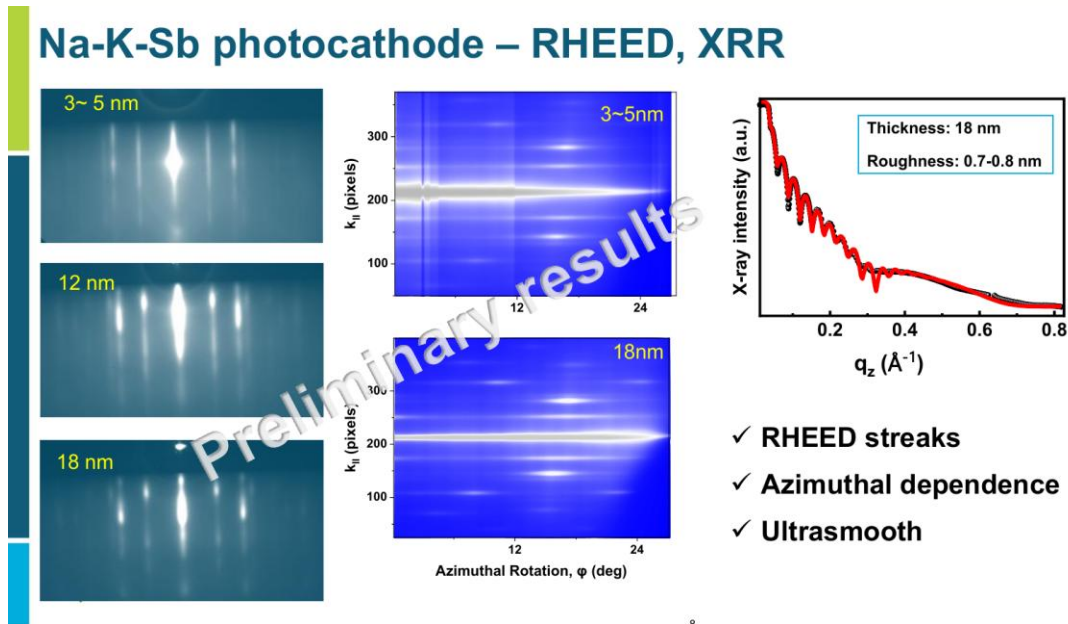
Measured saturation scaling and model summary
Paul Denham (UCLA) • slide 13

In situ X-ray studies of cathode growth

Mengjia Gaowei (BNL)

High Charge - High Average Current

- Epitaxial Na₂KSb: 18 nm film with about 0.7–0.8 nm roughness.
- RHEED, XRD, XRR and XRF track structure and composition during growth.
- Epitaxial sample: 2.8% QE at 530 nm; higher QE and CsSb activation are next.



RHEED and X-ray reflectivity during epitaxial Na–K–Sb growth
Mengjia Gaowei (BNL) • slide 8

Photocathode development for PERLE

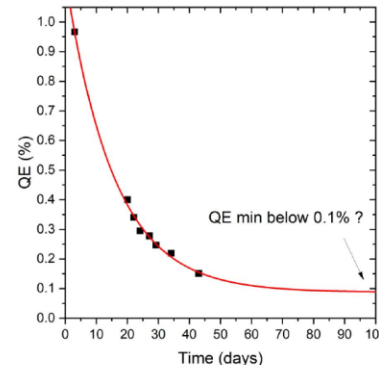
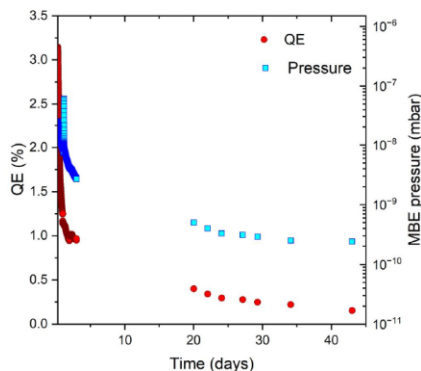
Gaël Sattonnay (IJCLab)

High Charge - High Average Current

- PERLE design: 500 pC at 40 MHz, or 20 mA; 350 kV DC gun.
- First CsK₂Sb preparation reached 3% QE.
- Lifetime studies



Photocathode preparation



After deposition the photocathode is stored in the MBE chamber :

slow decreasing of QE in one month from 3% to 0.1 % even if the pressure decreases from a few 10⁻⁸ to 2.5 10⁻¹⁰ mbar

Poor dark lifetime probably due to poor vacuum conditions during the deposition process

Perform an RGA to check the oxygen content in the MBE chamber + Redo the bake-out to restore good vacuum conditions

Cs₂Te and KCsSb for HB2TF

L. Monaco for D. Sertore (INFN Milano–LASA)

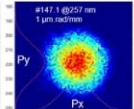
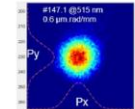
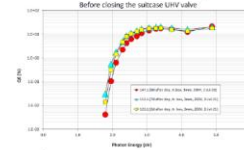
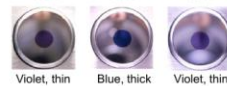
High Charge - High Average Current

- HB2TF development target: 5 mA CW from a 350 kV DC source.
- KCsSb at PITZ: about 23% lower emittance and 60% higher 4D brightness than Cs₂Te.
- Higher dark current and shorter lifetime remain trade-offs.

First batch of KCsSb photocathodes preparation

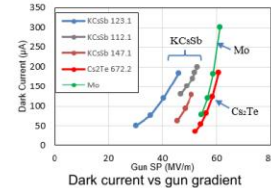
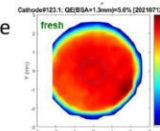
- **Successfully produced the first batch** of green photocathodes in the **New Production System** at LASA (July 2021):

- Sequential deposition with different thickness (Sb: 10nm, 5nm)
- QE: 4-8 % @ 514nm (thick and thin films respectively)
- Eg+Ea around 1.8 eV



- PITZ RF gun measurements

- Emittance reduced by ~23%, 4D brightness increased by ~60% compared to Cs₂Te cathode
- Response time: KCsSb cathode < 100 fs, Cs₂Te cathode ≈ 200 fs
- KCsSb cathodes show higher dark current and a shorter lifetime than Cs₂Te films



Photocathode Physic for Photoinjectors
INFN
LASA

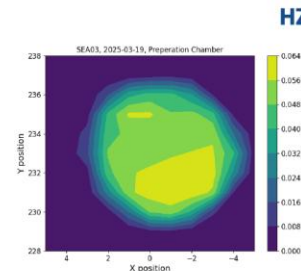
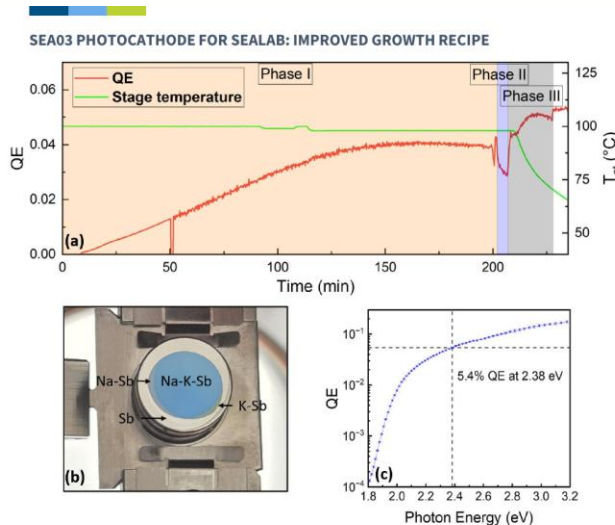
INFN / DESY–PITZ comparison of Cs₂Te and KCsSb
L. Monaco for D. Sertore (INFN Milano–LASA) • slide 21

Na-K-Sb preparation at HZB

Julius Kühn (HZB)

High Charge - High Average Current

- Triple evaporation with controlled Na, K and Sb fluxes.
- Recipe changes improve QE uniformity and robustness.
- More than 20 cathodes produced without breaking vacuum; reproducible high-QE films.



- Swap of the Na and K source + Phase II at higher temperature: **more homogenous, higher QE and more robust**

- Transfer of suitcase to SEALAB ...

2025-11-12

J. Kühn | Photocathode Physics for Photoinjectors (P3) Workshop | Arizona State University, Tempe, AZ, USA

11

QE uniformity after source-position and temperature changes
Julius Kühn (HZB) • slide 11

Na–K–Sb operation in an SRF photoinjector

Jonas Dube (HZB)

High Charge - High Average Current

- First Na–K–Sb operation in the HZB SRF photoinjector.
- QE recovers by more than $6\times$ during operation at 16 MV/m;
- Low field emission and no multipacting;
- extra emittance contributions are under study.



SEALab - Results

- We observed recovery of the QE and rejuvenation during RF operation
- Improvement of the QE more than a factor of 6 during high field operation (16 MV/m)
- Mechanism not yet fully understood

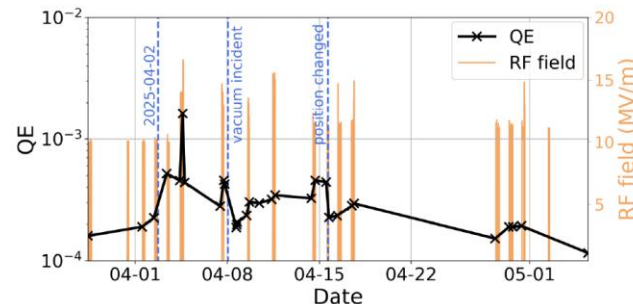


Fig 6: The photocathode SEA02 could be rejuvenated with high electric fields

T. Kamps et al., "First beam commissioning of the hzb srf photoelectron gun," in Proc. IPAC'25 (2025)

2025-11-12

Jonas Dube | Photocathode Physics for Photoinjectors workshop 2025 | Arizona State University, Tempe, USA

6

QE evolution and rejuvenation during SRF operation
Jonas Dube (HZB) • slide 6

K-rich K_2CsSb in the DC-SRF-II gun

Huamu Xie (PKU)

High Charge - High Average Current

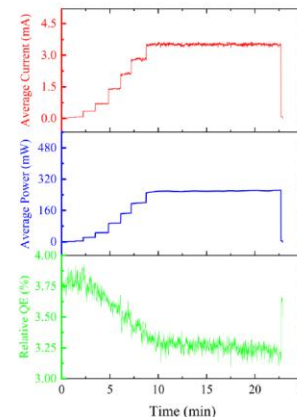
- About 10% QE at 520 nm in reflection mode.
- Stable 4 mA CW and 7 mA at 50% duty; QE about 1.4% after one month.
- At 30 K, K-rich films retain about half the room-temperature QE.

High-Current Running

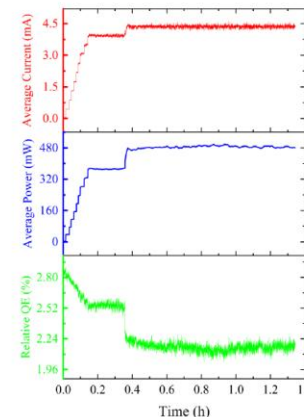
北京大学超导射频加速器实验室
Lab of Superconducting Radio Frequency Accelerator, Peking University



7 mA Operation
(50% Duty Cycle)



4 mA Continuous-Wave
(CW) Operation



16

4 mA CW and 7 mA at 50% duty in the DC-SRF-II gun
Huamu Xie (PKU) • slide 16

Spin Polarized Cathodes

Wednesday, November 12 • 7 talks

Durable NEA layers for GaAs

Maximilian Herbert (TU Darmstadt)

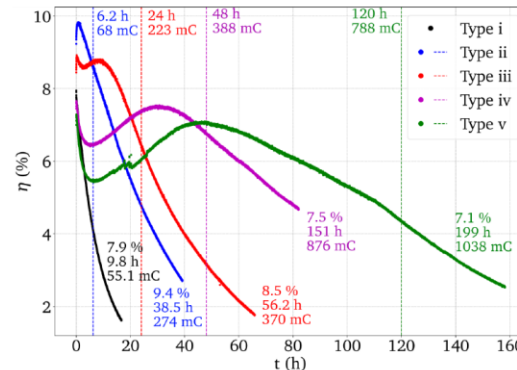
Spin Polarized Cathodes

- Pulsed Li added to Cs-O₂ co-deposition at Photo-CATCH.
- Activation-chamber tests: lifetime improved by up to 19×.
- Extracted charge improved by up to 16.5×; high-current gun tests are still needed.

Motivation - Cs-O₂-Li @ Photo-CATCH - Conclusion & Outlook



Cs-O₂-Li Lifetime (Part 1)



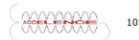
M. Herbert et al., Phys. Rev. Accel. Beams 28, 013401 (2025)
<https://doi.org/10.1103/PhysRevAccelBeams.28.013401>

- QE & Lifetime measurements in activation chamber
- $P_{\text{laser}} = (50 \pm 5) \mu\text{W}$, $\lambda = (785 \pm 2) \text{ nm}$,
 $U_{\text{bias}} = 100 \text{ V}$
- 5 types of activations:
 - Scheme 1, no prior scheme 2
 - Scheme 1, subsequent to scheme 2a
 - Scheme 2a, subsequent to scheme 1
 - Scheme 2b, subsequent to scheme 1
 - Scheme 2b, subsequent to scheme 2b
- Effect of Li on subsequent activations observed

Significant increase in τ (up to factor 19) and $Q(\tau)$ (up to factor 16.5) observed!

12.11.2025

Maximilian Herbert | Institut für Kernphysik | AG Enders | P3-Workshop



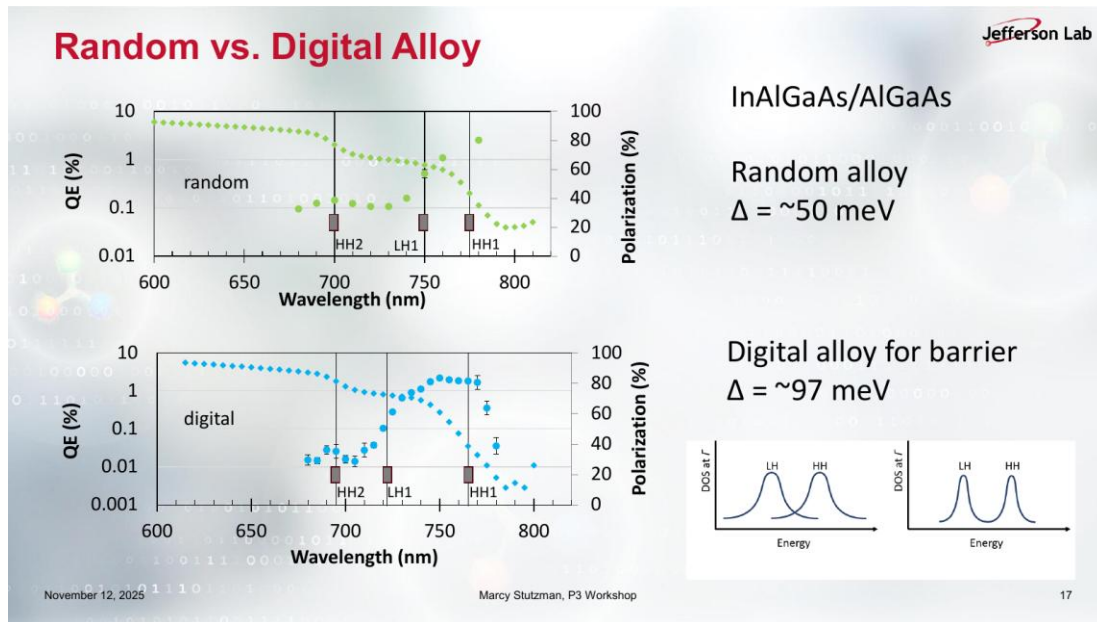
Lifetime and charge in low-bias activation-chamber tests
Maximilian Herbert (TU Darmstadt) • slide 10

MBE-grown InAlGaAs/AlGaAs cathodes

Marcy Stutzman (JLab; joint work with UCSB)

Spin Polarized Cathodes

- Nearly lattice-matched structure avoids a thick graded buffer.
- Many samples exceed 85% polarization; some exceed 0.8% QE without a DBR.
- Digital alloying increases HH–LH splitting, but QE decreases as splitting grows.



Random-alloy and digital-alloy QE / polarization spectra
Marcy Stutzman (JLab; joint work with UCSB) • slide 17

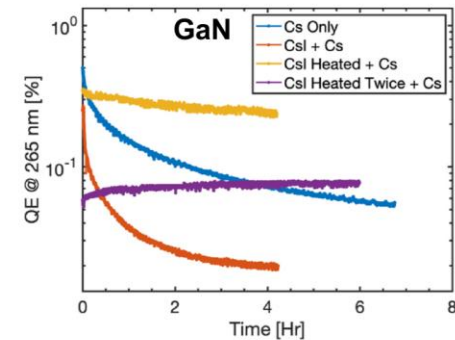
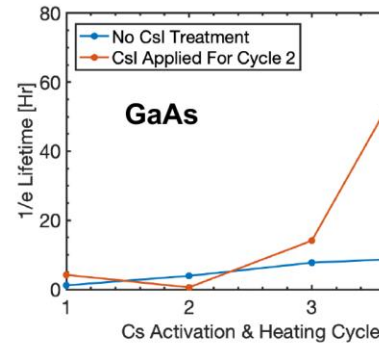
Spin-polarized cathode studies at Cornell

Jared Maxson (Cornell)

Spin Polarized Cathodes

- CsI deposition and heating improved dark lifetime by about 20× without degrading spin.
- Cs–Sb–O dark-lifetime benefit did not translate into a substantial 1 mA operating-lifetime gain.
- GaN spin emission demonstrated; strain and high-current testing are next.

CsI surface treatment of GaAs/GaN



- Improvement in lifetime NOT the result of longer heating time
- ESP is not degraded with improved lifetime
- Similar improvements observed with GaN!

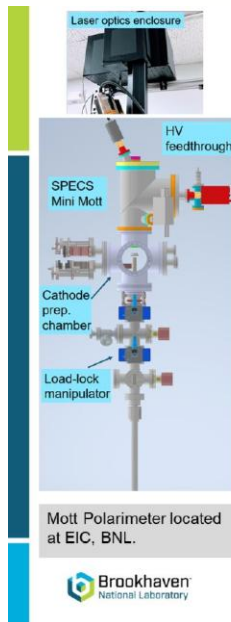
CsI treatment of GaAs and GaN: lifetime and polarization
Jared Maxson (Cornell) • slide 12

2D protection of GaAs photocathodes

Kali Prasanna Mondal (BNL)

Spin Polarized Cathodes

- Cs intercalates below monolayer graphene on GaAs.
- Graphene increases measured spin polarization by about 8%, but reduces QE by about one order.
- hBN also enables activation;



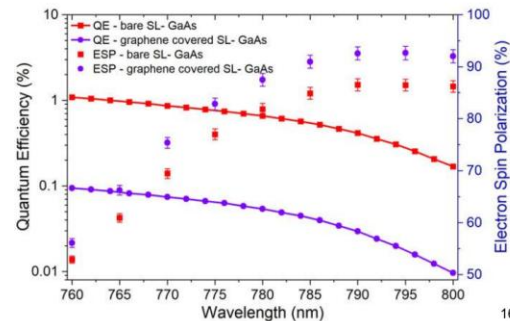
Polarisation and QE

- ❑ Two SL-GaAs samples (with / without graphene) grown on same wafer.
- ❑ Arsenic cap removed by annealing at 550 °C under UHV ($\sim 10^{-11}$ Torr).
- ❑ Cs-O activation performed at room temperature.
- ❑ QE and spin polarization measured using mini-Mott polarimeter with 760–800 nm circularly polarized laser.

Graphene offers surface protection and higher ESP, though with reduced QE.

Results

- ❑ QE $\approx 0.6\%$ (bare), drops one order with graphene.
- ❑ Electron spin polarization increases $\sim 8\%$ with graphene layer.
- ❑ Graphene increases surface work function $\rightarrow$ fewer, higher-energy electrons escape.
- ❑ Suppresses low-energy, depolarized electrons $\rightarrow$ net polarization gain.



16

Spin-polarization and QE measurements through graphene
Kali Prasanna Mondal (BNL) • slide 16

Luca Cultrera (BNL; collaboration with Sandia)

Spin Polarized Cathodes

- BNL / Sandia superlattice + DBR: 18.8% QE with 66% polarization near 775 nm.
- Second iteration: 9% QE and 72% polarization near 780 nm.
- New lattice-matched designs target about 800 nm and 1030 nm operation.

Conclusions

- Several robust activating layers yielded longer dark lifetimes
- QE and ESP tradeoffs call for higher QEs to increase operational lifetime
- Achieved record high QE from a SL DBR with high ESP
- Lattice matching on GaAs can simplify growth
 - GaAsP/InGaAs operated at ~800 nm
 - GaAsP/GaAsSb operated at ~1030 nm

Collaboration	Wavelength (nm)	QE (%)	ESP (%)	FoM (QE*ESP ²)
Nagoya/KEK/LBNL	780	1.6	92	1.35
SVT/Jlab	775	6.4	84	4.51
BNL/SNL rev.1	775	18.8	66	8.18
BNL/SNL rev.2	780	9	72	4.66



19

Measured QE / polarization and proposed growth directions
Luca Cultrera (BNL; collaboration with Sandia) • slide 19

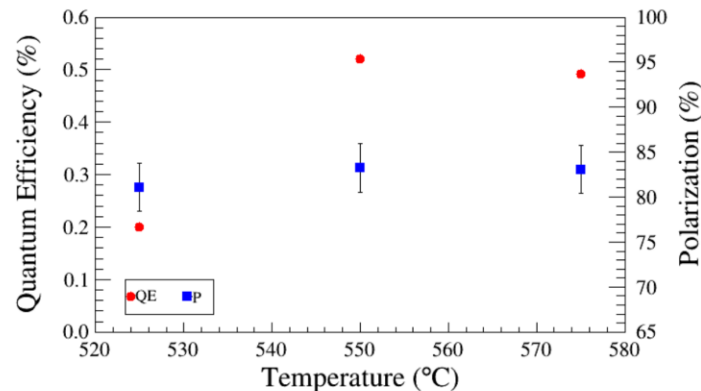
Greg Blume (ODU / JLab collaboration)

Spin Polarized Cathodes

- Surface cleaning changes QE and apparent damage susceptibility.
- High-voltage results show QE improvement above 550 °C without polarization loss.
- Need to separate contamination, low-energy sputtering and ion implantation.

Performance in a Load-Lock Photogun

- Sample heated for 1 hr at each temp then activated and evaluated
- QE increases above 550 °C while polarization remains stable



Greg Blume

Old Dominion University

November 2025

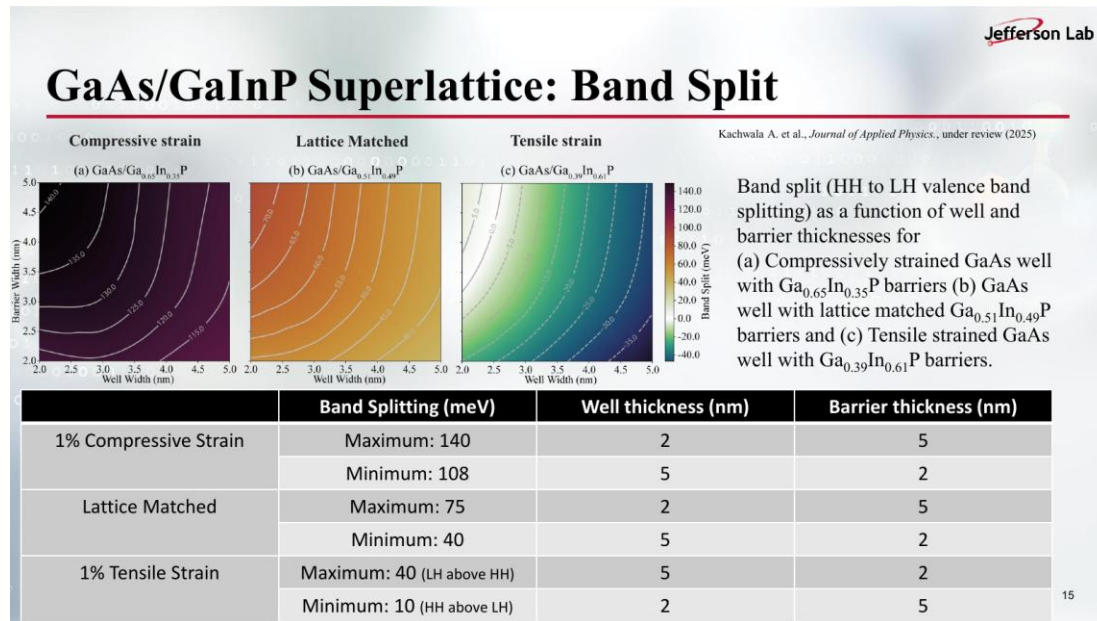
12 / 17

High-voltage QE and polarization after surface heat treatments
Greg Blume (ODU / JLab collaboration) • slide 12

Alimohammed Kachwala (JLab / ODU)

Spin Polarized Cathodes

- COMSOL envelope-function model of GaAs/GaInP wells and barriers.
- Predicted maximum HH–LH splitting: 140 meV compressive; 75 meV lattice-matched.
- Transport, defect tolerance, growth and polarization tests remain to be evaluated.



Calculated band splitting versus well and barrier thickness
Alimohammed Kachwala (JLab / ODU) • slide 15

FEL session

Thursday, November 13 • 9 talks

Ziye Yin (MSU; LCLS-II HE collaboration)

FEL session

- Required operating point: 30 MV/m, 1 MHz and MTE ≤ 184 meV.
- Quarter-wave SRF gun passed high-power tests with a Cu cathode.
- Green-cathode preparation and diagnostic beamline are in progress.

Summary and Outlook



- MTE 184meV and Gradient 30MV/m at 1MHz is needed by LCLS-II HE
- QWR SRF gun with Cu cathode is successful under high power test
- Green cathode and diagnostic beamline is being prepared
- The first green cathode high power test is around the corner

19

2025 project status and next tests
Ziye Yin (MSU; LCLS-II HE collaboration) • slide 19

LCLS cathode operation and challenges

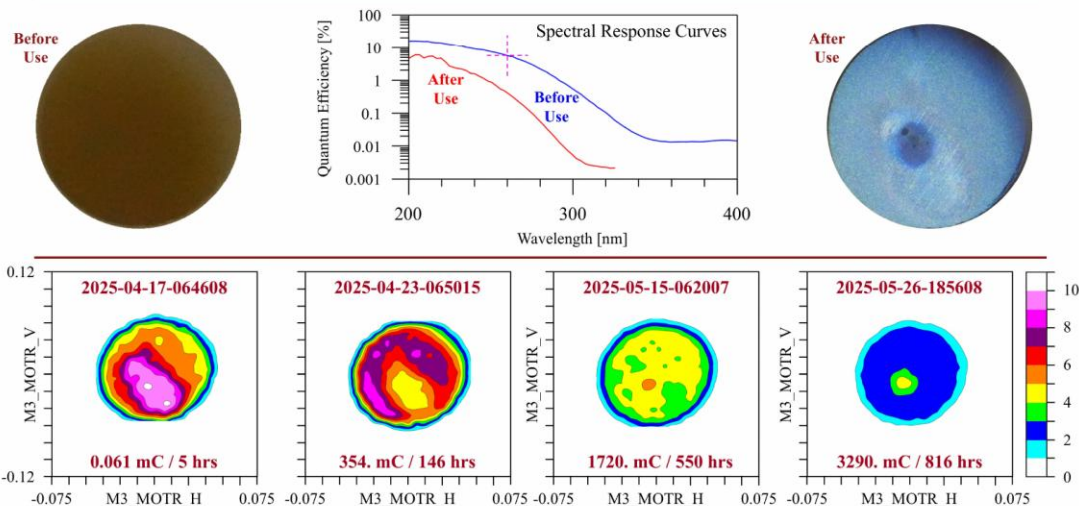
Theo Vecchione (SLAC)

FEL session

- Elliptical plug reduces dark current from about 3 μA to 4 nA.
- Cs_2Te starts with uniform QE; localized damage and a central low-QE region develop during use.
- Rapid QE changes challenge stable FEL operation; damage mechanisms remain unresolved.

Elliptical Photocathode LB04

Major advantage $\rightarrow$ **reduced dark current from $\sim 3 \mu\text{A}$ to $\sim 4 \text{ nA}$**
Small disadvantage $\rightarrow$ increased sensitivity to the laser location



Elliptical cathode and QE maps during LCLS-II operation
Theo Vecchione (SLAC) • slide 17

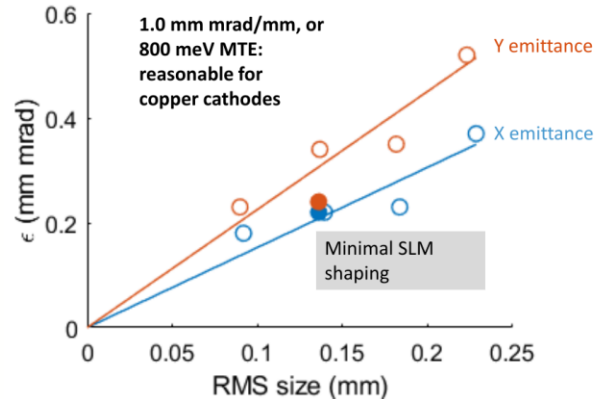
Multiphoton emission for compact sources

Samuel W. Teitelbaum (ASU)

FEL session

- 515 nm multiphoton emission replaces difficult UV delivery in the ASU X-band source.
- Charge approaches the extraction-field limit.
- Visible-light SLM shaping improves beam uniformity; first results about 0.8 eV MTE.

SLM-Corrected Beam Emittance First Results



25

First SLM-corrected emittance measurements
Samuel W. Teitelbaum (ASU) • slide 23

CLARA photocathode operation

Lee Jones (STFC Daresbury)

FEL session

- Cs₂Te depositions exceed 20% QE at 266 nm; installed cathode delivers 250 pC.
- Cathode seating and RF-contact quality are operational constraints.
- Time-lapse cathode images correlate surface defects with RF breakdowns.

Breakdown Investigation for Cathode 034 (Cs₂Te)

Data:

CLARA data archiver for gun breakdown (BD) events
Manual counting of cathode defects by eye (really!)

Results:

Strong correlation between RF BDs and defects!

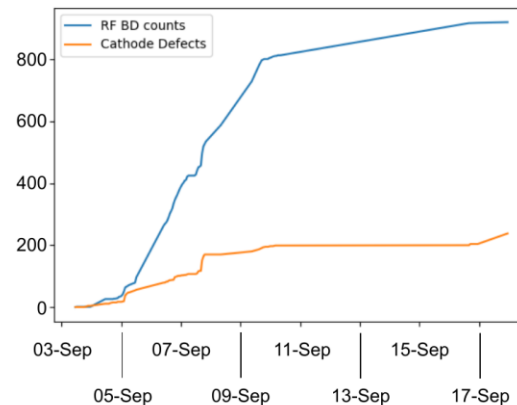
(-1 Anti Correlation → +1 Strong Correlation)

- [Pearson's Correlation Coefficient](#): 0.989
- [Spearman's Correlation Coefficient](#): 0.998
- [Concordance Correlation Coefficient](#): 0.984

- Pearson's of gradient difference: 0.427
- Spearman's of gradient difference: 0.524

For comparison, comparing against random data:

- Pearson's of gradient difference: 0.02 and -0.1
- Spearman's of gradient difference: -0.02 and -0.01



Credit: [Amelia Pollard](#)

RF-breakdown events and observed cathode defects
Lee Jones (STFC Daresbury) • slide 17

SrTiO₃ as a low-MTE photocathode

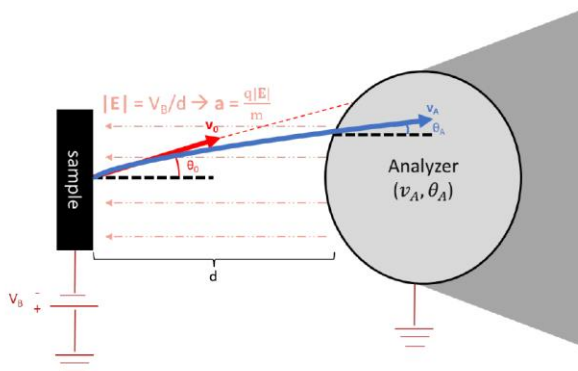
Vivek Anil (Cornell)

FEL session

- Annealed 2×1 SrTiO₃ shows narrow, intense secondary-photoemission features.
- ARPES-derived MTE about 20 meV at 8 K with 21.2 eV photons.
- QE and lower-photon-energy measurements are still needed.



How can we estimate MTEs from ARPES?



Correct for effect of applied voltage using uniform field

→ MTE ~ 20.2 meV with $h\nu = 21.2$ eV, $T = 8$ K

Photocathode	$h\nu$ (eV)	MTE (eV)
Cu (100) [1]	4.42	5
Cs ₃ Sb/Si (100) [2]	2.33	58
Cs ₃ Sb/Si (100) [3]	1.80	22
2x1 SrTiO ₃ (001) (this work)	21.2	20.2
2x1 SrTiO ₃ (001) (Hong et al.) [4]	21.2	1.6

[1] Karkare et al. *Phys. Rev. Lett.* **125**, 054081 (2020).
 [2] Owusu et al. *Appl. Phys. Lett.* **127**, 172101 (2025).
 [3] Cultrera et al. *Phys. Rev. ST Accel. Beams* **18**, 113401 (2015).
 [4] Hong et al. *Nature* **617**, 493–498 (2023).

Low MTEs at $h\nu = 21.2 \gg \phi$ are unprecedented

11/13/2025

10

MTE estimated from momentum-resolved photoemission
 Vivek Anil (Cornell) • slide 11

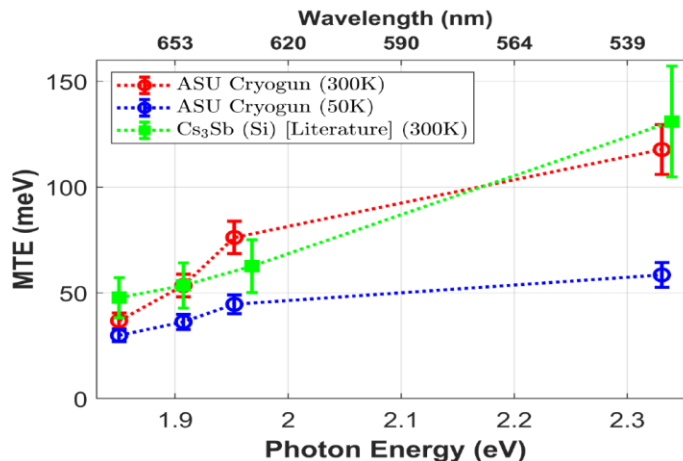
Cryogenic Cs₃Sb performance

Peter Owusu (ASU)

FEL session

- Cooling reduces MTE even above the photoemission threshold.
- 58 meV MTE with 3% QE at 532 nm: about 2× lower MTE.
- Growth phase and stoichiometry affect low-temperature QE retention.

MTE Measurements at Cryogenic Temperature



➤ MTEs measured after 200+ hours of flash-freezing



P3 Workshop, November 13th, 2025
13

Measured MTE and QE versus photon energy and temperature
Peter Owusu (ASU) • slide 13

David Garcia (UCLA)

FEL session

- Air-sensitive cathodes transported to UCLA and characterized in an S-band gun.
- RF phase scans probe work function and initial longitudinal momentum.
- Growth, transport and emission models need further refinement.

Mean Longitudinal Energy



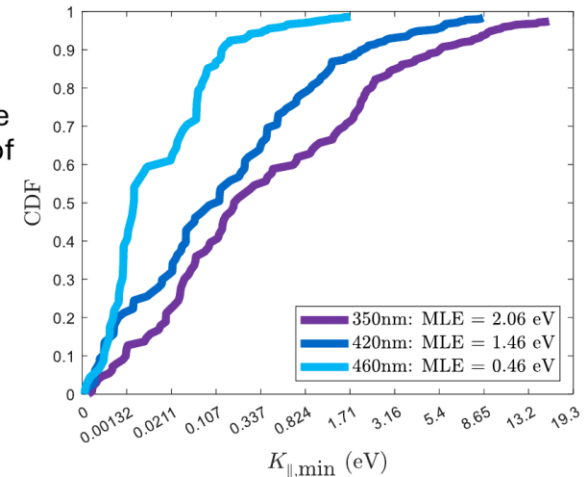
PBPL

- The phase scan for $\varphi_0 < 0$ is representative of the Cumulative Distribution Function (CDF) for the initial longitudinal kinetic energy of the electron distribution

$$F(K_{\parallel, \min}) = P(K_{\parallel} \leq K_{\parallel, \min})$$

- Analogous to the MTE we can define the MLE

$$\text{MLE} = \int_0^{\infty} [1 - F(K_{\parallel, \min})] dK_{\parallel, \min}$$



2025/11/13

16

High-gradient phase-scan characterization
David Garcia (UCLA) • slide 16

Dark-current reduction with an inserted plug

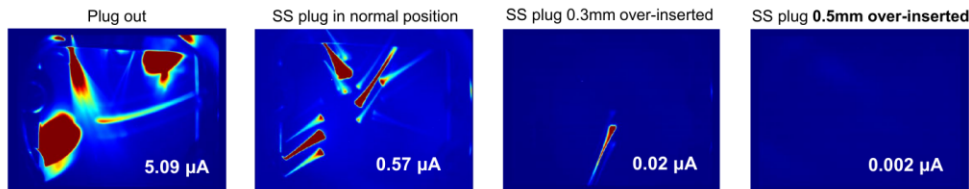
Guan Shu (Zhangjiang Laboratory electron-source team)

FEL session

- About 0.5 mm plug over-insertion reduces VHF-gun dark current from μA to nA.
- SHINE gun: <1 nA at 750 kV and 26 MV/m, maintained over months.
- No reported beam-performance penalty; preliminary S-band tests also show reduction.

Experiments with over-inserted plugs in SHINE VHF gun

- In SHINE gun (gap=3cm), 0.3mm and 0.5mm over-inserted plugs were tested



- For a 0.5mm over-inserted Mo plug w/ Cs_2Te , dark current **< 1 nA at 750kV** voltage and 26 MV/m cathode E
- Dark current **remains < 1 nA after several months beam operation**
- Beam performance with a 0.5mm over-inserted plug in SHINE injector

	Simulation	Measurement
Bunch charge [pC]		50
Transverse rms emittance [μm]	0.35	$\epsilon_x=0.3$, $\epsilon_y=0.4$ (95%)
Bunch length [mm]	0.76	~ 0.8

Page 12 / 15

SHINE VHF-gun dark current and beam measurements
Guan Shu (Zhangjiang Laboratory electron-source team) • slide 12

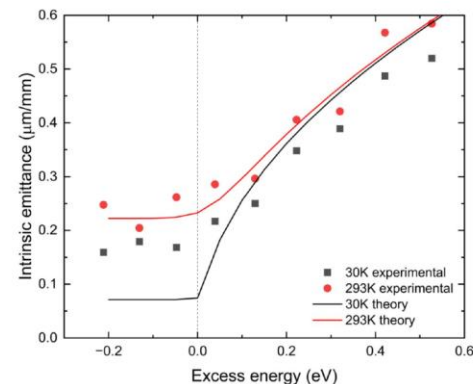
Gowri Adhikari (SLAC)

FEL session

- Compact diagnostic for photocathode intrinsic emittance.
- Measurements at 30 K show lower intrinsic emittance than at 300 K.
- Tunable illumination, grid-lensing corrections and suitcase transfer are being developed.

Preliminary Experimental Data

The Cu(001) sample was used to test the system's performance.



SLAC

Intrinsic emittance as a function of excess energy for Cu(001) cathode

Intrinsic-emittance measurements at 30 K and 300 K
Gowri Adhikari (SLAC) • slide 11

UED session

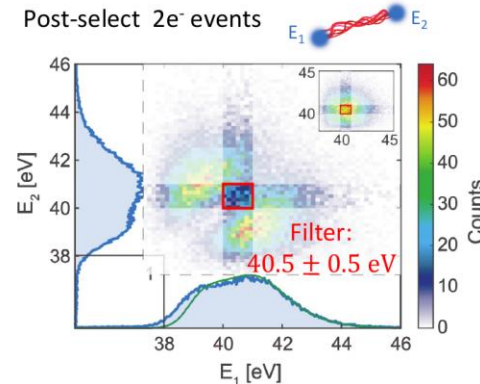
Thursday, November 13 • 7 talks

Felix López Hoffmann (FAU / Hommelhoff group)

UED session

- Gold tip arrays combine ultrafast emission with low emittance.
- Electron counts can be Poissonian while electron energies are correlated.
- Energy filtering of Coulomb-correlated pairs produces sub-Poissonian counts.

Bivariate energies and filtering



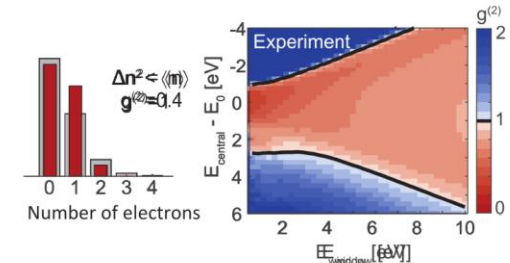
$(t, \vec{r})$ -confinement $\Rightarrow E_1 = E_2$ Coulomb-suppressed

Meier *et al.*, *Nat. Phys.* **19** (2023), 1402–1409

Related work: Haindl *et al.*, *Nat. Phys.* **19**, 10 (2023): 1410–1417

Tune number distribution via filter

$$g^{(2)} = \frac{\langle N(N-1) \rangle}{\langle N \rangle^2}, \quad N: \text{electrons per pulse}$$



$\rightarrow$ Sub-Poissonian
 $\rightarrow$ Shot noise reduction

Needle-tip emission driven by nonclassical light

Felix López Hoffmann (FAU / Hommelhoff group)

UED session

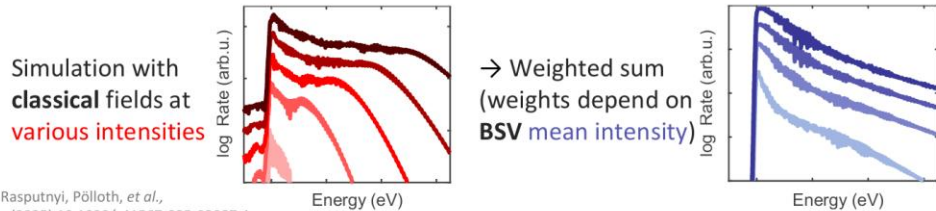
- Bright-squeezed-vacuum light drives strong-field electron emission.
- Electron counts follow broad, Γ -like distributions and depend on optical modes.
- Intensity fluctuations smear the high-energy plateau cutoff.

Understanding the spectra

Trick: describe BSV in basis of “classical” coherent states A. Gorlach et al.,
Nat. Phys. **19**, 1689-1696 (2023)

$$| \text{BSV} \rangle \approx | \alpha_1 \rangle \langle \alpha_1 | + | \alpha_2 \rangle \langle \alpha_2 | + \dots$$

[...] strong field e^- response equals weighted incoherent superposition of all “classical” responses



Heimerl, Rasputnyi, Pöloth, et al.,
Nat. Phys. (2025) 10.1038/s41567-025-03087-1

Electron spectra for coherent and bright-squeezed-vacuum illumination
Felix López Hoffmann (FAU / Hommelhoff group) • slide 10

Lianmin Zheng (Tsinghua University)

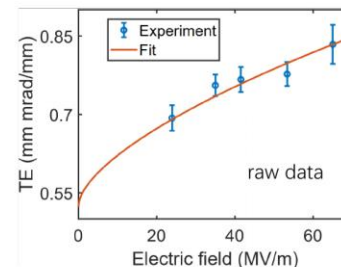
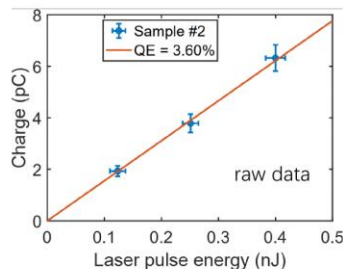
UED session

- UHV S-band gun supports alkali-antimonide operation at 100 MV/m.
- QE: 3.6% at 532 nm; 0.51% at 635 nm.
- Lifetime reported as 345 h at 532 nm; field-dependent emittance motivates smoother films.

Alkali-antimonide cathode test in S-band gun

□ K_2CsSb under 532 nm laser drive

- ◆ Under a 100 MV/m electric field gradient, the K_2CsSb sample achieved a quantum efficiency of 3.6% when driven by a 532 nm laser
- ◆ Thermal emittance increases with rising electric field strength, potentially due to transverse electric fields induced by surface roughness



19

QE and thermal-emittance measurements at high field
Lianmin Zheng (Tsinghua University) • slide 19

Nanopatterned beams by photoemission contrast

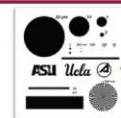
Anagha Ullattuparambil (ASU)

UED session

- Engineered photoemission contrast confines emission to about 150 nm.
- Suppressed background: extinction ratio as low as 2×10^{-7} .
- Flat patterned sources allow control of beam shape without a protruding tip.

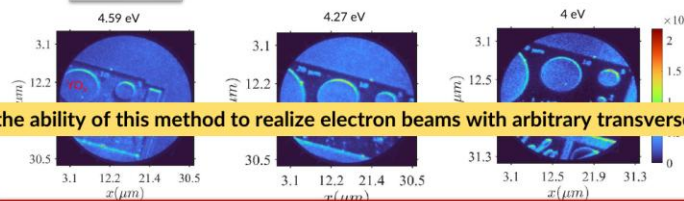


3. Yttrium Oxide on Silicon



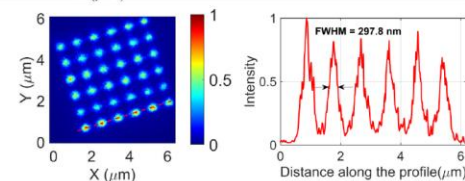
Patterns of YO_x on Silicon.

Extinction ratio in the order of 10^{-2}



This confirms the ability of this method to realize electron beams with arbitrary transverse patterns.

Nano-scale arrays of Yttrium Oxide on Silicon



aulatt@asu.edu

17

Nanopatterned source and emittance / contrast measurements
Anagha Ullattuparambil (ASU) • slide 17

Michael Kaemingk (LANL)

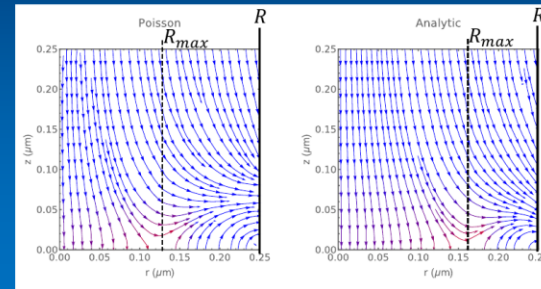
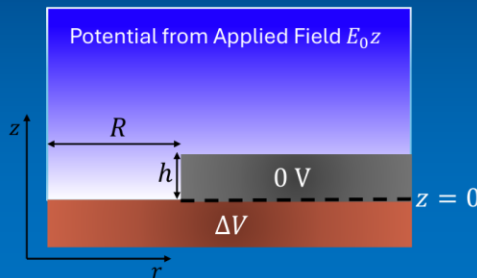
UED session

- Nanofabricated emission regions can retain QE and spin polarization.
- Local electrostatic fields change effective source size and MTE.
- Modeling and measurements test whether smaller effective beams can avoid MTE growth.

MTE from fields

- When $\Delta V - E_0 h > 0$ (e.g. $h < 0$, hole geometry)
 - Effective radius $R_{max} < R$
 - A : unitless ~~constant~~ $\rightarrow 0$ as $R_{max} \rightarrow 0$
 - $MTE \rightarrow 0$

$$MTE = A \frac{e(\Delta V - E_0 h)^2}{R E_0}$$



28

Model of local electrostatic fields and source-size effects
Michael Kaemingk (LANL) • slide 28

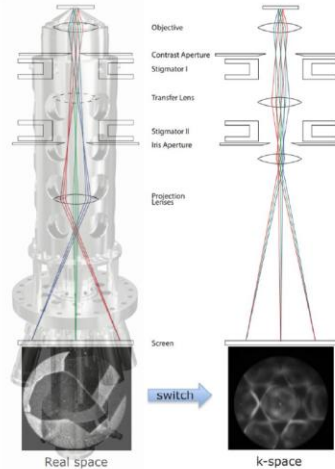
Cd₃As₂ Dirac-semimetal photocathodes

Truman Idso (ASU; growth collaboration with NREL)

UED session

- NREL-grown Cd₃As₂ transferred to ASU for QE and MTE measurements.
- Peak QE 3.37×10^{-4} at 230 nm; room-temperature MTE floor about 55 meV.
- No resolved Dirac cone in PEEM; colder, higher-resolution measurements are planned.

Photoemission Electron Microscopy Results



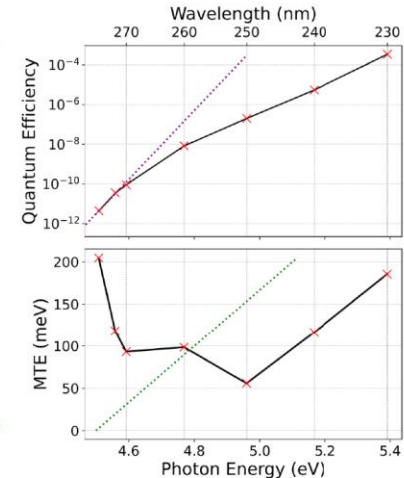
11/18/2025

- **Top:** Cd₃As₂ spectral response. The QE reaches a peak of $3.37 \cdot 10^{-4}$ at 230 nm.

• Purple: $1/k_B T$ at room temperature.

- **Bottom:** The MTE as a function of photon energy.

• Green: Dowell-Schmerge prediction of $MTE = E_{\text{excess}}/3$.



Room-temperature spectral response and MTE
Truman Idso (ASU; growth collaboration with NREL) • slide 8

Epitaxial Na–K–Sb growth and oxidation

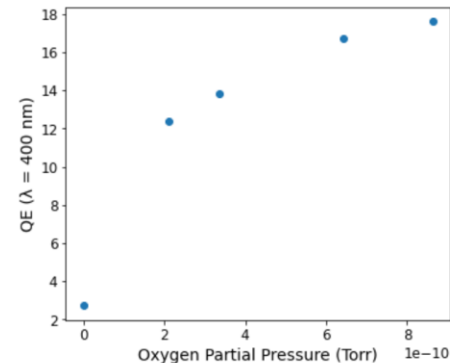
Abigail Flint (Cornell)

UED session

- Highly ordered films grown on Si, SiC, SrTiO₃ and SiN.
- Na–K–Sb is more oxygen-resilient than Cs₃Sb in the reported tests.
- Background oxygen affects QE on Si; substrate-dependent recovery needs further study.

Effect of oxygen background: NaKSb on Si

- **Background oxygen** levels are taken before deposition using RGA
- Oxygen levels are not strictly controlled in the system during deposition
- Low levels of O₂ in the system **increase** photocathode **QE**
- Based on RHEED measurements, system oxygen levels have no observable effect on crystallinity



P3 Workshop

10

Effect of oxygen background on Na–K–Sb grown on Si
Abigail Flint (Cornell) • slide 10

Theory Session

Friday, November 14 • 9 talks

Strain- and temperature-dependent GaAs bands

Joniel Mendez (NIU)

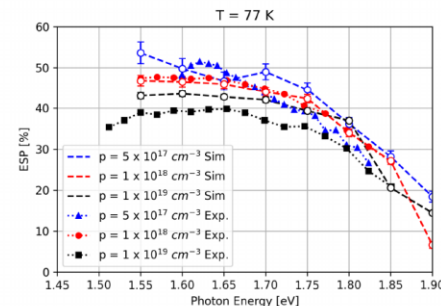
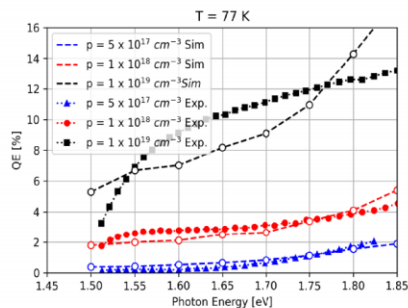
Theory Session

- DFT + U models GaAs band parameters under strain and temperature changes.
- Calculated bands improve inputs to Monte Carlo transport.
- Extend full photoemission simulations to strained, cold GaAs and III-nitrides.

Sim Results: Low-Temp Photoemission (77K)



Doping Density	EA
$p = 5 \times 10^{17} \text{ cm}^{-3}$	0.75 eV
$p = 1 \times 10^{18} \text{ cm}^{-3}$	0.67 eV
$p = 1 \times 10^{19} \text{ cm}^{-3}$	0.25 eV



Simulated low-temperature photoemission using calculated band inputs
Joniel Mendez (NIU) • slide 16

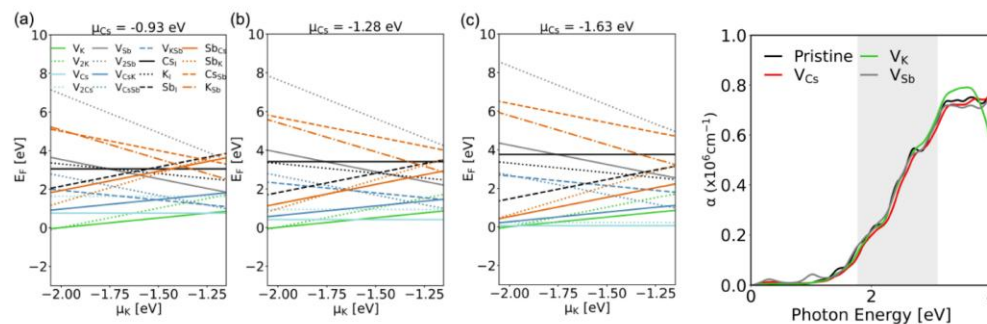
Gaoxue Wang (LANL; with Sandip Aryal and Enrique Batista)

Theory Session

- Alkali vacancies dominate studied defects in Cs_3Sb and CsK_2Sb .
- Vacancies introduce gap states; polar optical phonons limit mobility.
- Na_2O is a possible oxygen-tolerant alternative, but visible absorption and water stability are concerns.

CsK_2Sb

- Cs and K vacancies dominate, introducing mid-gap states.



Aryal et al. arXiv:2507.18933 (2025).

11/18/2025

9

Calculated vacancy defects in CsK_2Sb
Gaoxue Wang (LANL; with Sandip Aryal and Enrique Batista) • slide 9

John Petillo (Leidos; collaboration with NRL)

Theory Session

- Monte Carlo transport data converted into secondary-emission databases.
- GEANT-based databases demonstrated for several metals and graphite.
- Faster moments-model evaluation improves photoemission calculations in beam-optics simulations.

SECONDARY EMISSION MODEL (I)

- Original secondary emission model in MICHELLE is based on the post-processing of experimental (direct or published) measurements and subsequently the construction of a representative database for the measured material
 - This approach is laborious: experimental results are often not readily available and may be difficult to collect



Phonon-mediated semiconductor emission

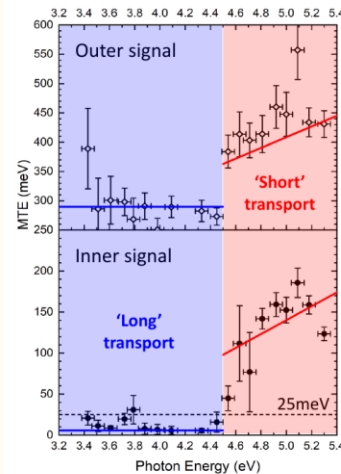
W. Andreas Schroeder (UIC)

Theory Session

- Franck–Condon emission model includes momentum-resonant phonon scattering.
- Model compared with QE and MTE data for Cs:GaAs and GaN.
- Fe:Ga₂O₃ shows a reported 6 meV component at 300 K; polaron effects are included.

Fe-doped Ga₂O₃(010): MTE

- Two emission signals evident throughout
 - Inner low MTE signal from lower CB ($\chi > 0$)
 - Outer high MTE signal from upper CB ($\chi < 0$)
- MTE is constant in ‘long’ transport regime
 - $\Rightarrow k_B T_e \approx 27\text{meV}$ is constant
- MTE increases with $\hbar\omega$ in ‘short’ transport regime
 - $\Rightarrow$ Equipartition of energy with $l = 6$ dominant optical phonon modes (c.f. Mg:GaN(001))
- Observe step increase in MTE at $\hbar\omega \approx E_g$
 - $\Rightarrow$ Evidence for T_e increase due to polaron formation energy; $g\hbar\Omega \rightarrow k_B T_e$
 - AND inner signal converts to FC emission from lower CB



Ultracold emission component reported from Fe:Ga₂O₃
W. Andreas Schroeder (UIC) • slide 15

Rapid photoemission models for beam optics

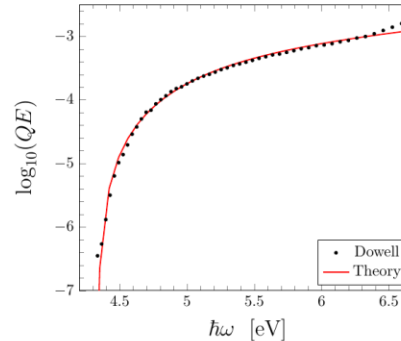
Kevin Jensen (Leidos; NRL / USNA collaboration)

Theory Session

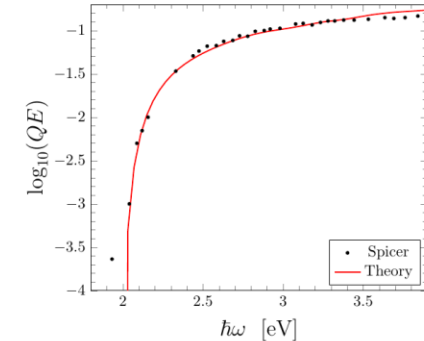
- Analytic moments model separates optical factors and emission probability.
- LDR / ADR models provide reusable optical-parameter libraries for metals and semiconductors.
- Preliminary Cu and Cs_3Sb QE comparisons; designed for rapid PIC-code evaluation.

Leidos	NRL	USNA	Background Components Simulations	Parameterization XXXX XXXX
QUANTUM EFFICIENCY				

The LDR Procedure have been extended to semiconductors through the creation of the ADR Procedure.
Preliminary QE results for both Cu and Cs_3Sb shown



Data: D.H. Dowell, et al., PRSTAB9(6), 063502 (2006).
DOI: 10.1103/PhysRevSTAB.9.063502



Data: W.E. Spicer, PR112, 114-122 (1958).
DOI: 10.1103/PhysRev.112.114

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Rapid Photoemission Models for Beam Optics and Characterization

pg 11 of 12

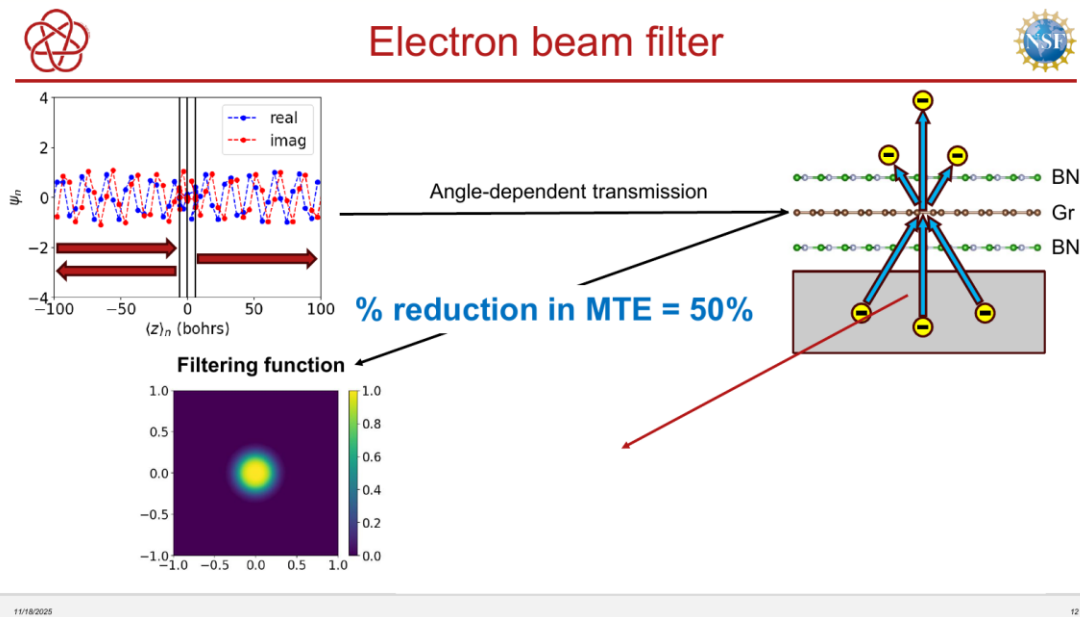
Modeled QE compared with Cu and Cs_3Sb reference data
Kevin Jensen (Leidos; NRL / USNA collaboration) • slide 11

A first-principles photoemission framework

Tyler Wu (Cornell)

Theory Session

- Vacuum Wannier functions connect DFT slabs to scattering-state calculations.
- One-step calculations give momentum distributions and MTE for layered materials.
- Illustrative BN filter: 50% MTE reduction at 25% transmission in the model.



Calculated angle-dependent transmission through a BN filter
Tyler Wu and Tomás Arias (Cornell) • slide 12

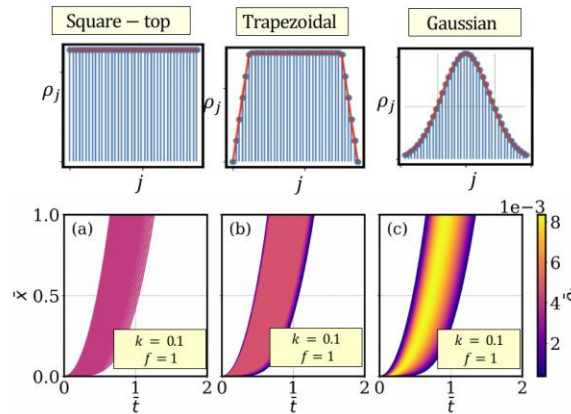
Space charge in short electron bunches

Peng Zhang (University of Michigan; with Yves Heri and Lan Jin)

Theory Session

- Multi-sheet model includes both space charge and image charges.
- Shorter pulses and larger charge produce stronger bunch distortion.
- Derived scaling laws compared with PIC; emission mechanisms are a next step.

Electron trajectories for different initial bunch profile



7 Y. Heri and P. Zhang, IEEE Trans. Electron Devices 72, 2591 (2025).

- The normalized charge density $f = \rho / (-\epsilon_0 V_0 / d)$
- The normalized pulse duration $k = \tau_p / (3d\sqrt{2eV_0/m_e})$

Model Parameters

Symbol	Meaning	Value
d	Gap distance	1.5 mm
V_0	Applied voltage	30 kV
M	Number of sheets	250
η	Electron q/m ratio	$1.76 \times 10^{11} \text{ C/kg}$

- All pulses undergo similar expansion when reaching the anode
- Significant differences in internal beam dynamics

Calculated trajectories for different initial bunch profiles
Peng Zhang (University of Michigan; with Yves Heri and Lan Jin) • slide 7

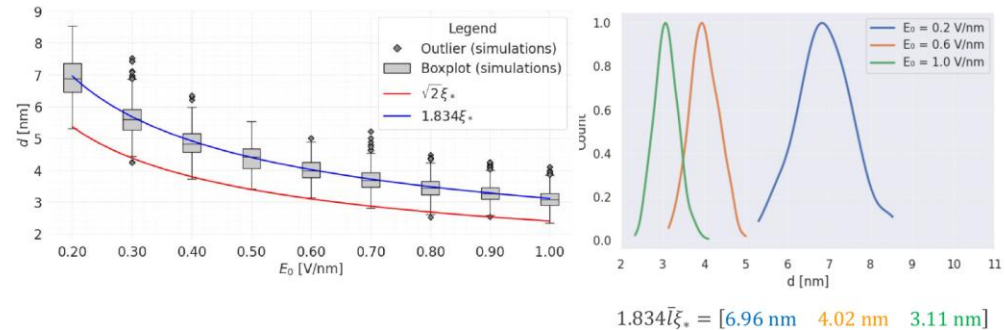
Ágúst Valfells (Reykjavík University)

Theory Session

- RUMDEED tracks individual electrons with Coulomb and image-charge forces.
- A single emitted electron inhibits emission from its immediate neighborhood.
- Very small emitters depart from continuum scaling; point-emitter current scales as $E^{3/4}$.

Spacing between emitted electrons

Distribution of spacing of nearest neighbors for space-charge limited emission.



HÁSKÓLINN Í REYKJAVÍK | REYKJAVÍK UNIVERSITY

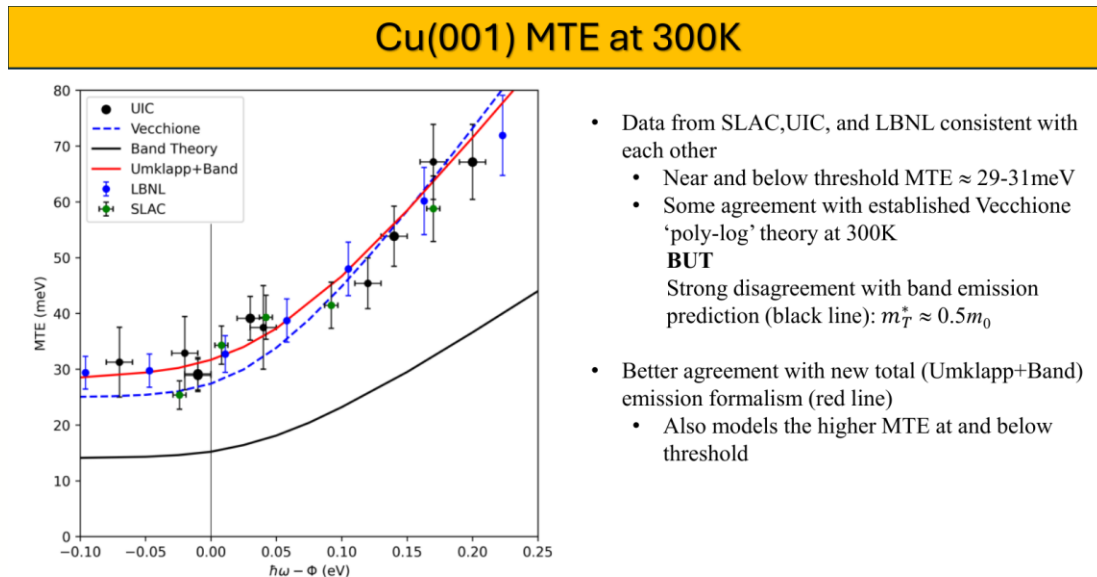
Simulated nearest-neighbor spacing under space-charge-limited emission
Ágúst Valfells (Reykjavík University) • slide 14

Umklapp scattering in metal photocathodes

Ir-Jene Shan (UIC; collaboration with SLAC)

Theory Session

- Measured near-threshold MTE exceeds simple direct-emission predictions.
- Umklapp-assisted Franck–Condon emission is a proposed explanation.
- Cu and W data show improved agreement; Nb requires additional band-structure interpretation.



- Data from SLAC, UIC, and LBNL consistent with each other
 - Near and below threshold MTE $\approx 29\text{--}31\text{ meV}$
 - Some agreement with established Vecchione ‘poly-log’ theory at 300K
- BUT**
 - Strong disagreement with band emission prediction (black line): $m_T^* \approx 0.5m_0$
- Better agreement with new total (Umklapp+Band) emission formalism (red line)
 - Also models the higher MTE at and below threshold

Cu(001) MTE: data and direct / scattering-based models
Ir-Jene Shan (UIC; collaboration with SLAC) • slide 11

Novel Concepts

Friday, November 14 • 8 talks

Zone-plate-based immersion lenses

Mansoure Moeini Rizi (ASU)

Novel Concepts

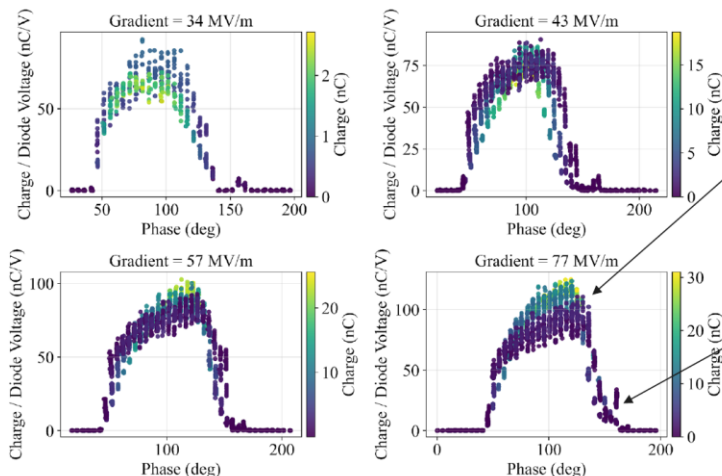
- Nanoscale electron emission using zone-plate-based immersion lenses.
- High NA lens built into substrate focuses light on cathode surface and operates in transmission mode with sub-um spot sizes

Xueying Lu (NIU / Argonne collaboration)

Novel Concepts

- AWA L-band photogun: RF phase scans and QE measurements of Cs_2Te .
- Monte Carlo emission and beam-dynamics calculations compared with data.
- Emission models used to assess intrinsic emittance and higher-gradient designs.

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.

High-field cathode measurements and simulation comparison
Xueying Lu (NIU / Argonne collaboration) • slide 14

Anika Tabassum Priyoti (USC)

Novel Concepts

- air-stable, high-gain electron-beam amplification by diamond/graphene surface engineering.
- Application: combine electron multiplication with a more robust emitter surface.

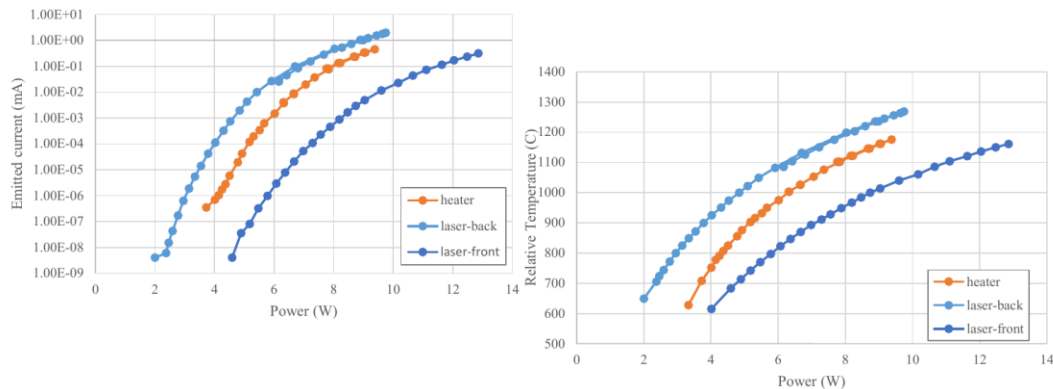
Laser-heated thermionic cathodes

Heather Andrews (LANL)

Novel Concepts

- Near-infrared lasers heat a tantalum thermionic cathode; this is not photoelectric emission.
- Ground-referenced laser heating removes the floated heater supply.
- Initial front / back heating comparisons are promising; conditioning and surface effects remain unresolved.

Heating from the back of the cathode may be more efficient than heating the front surface



Thermionic current and relative temperature versus heating power
Heather Andrews (LANL) • slide 12

Cryogenic high-field RF guns at UCLA

Fabio Bosco (UCLA)

Novel Concepts

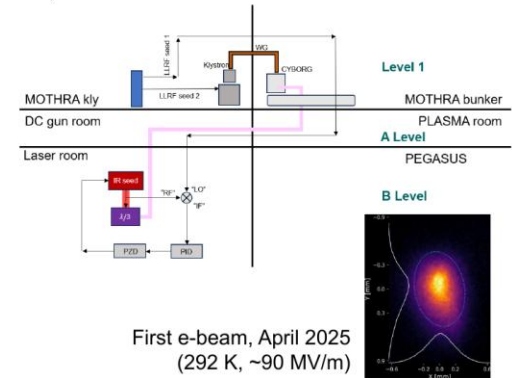
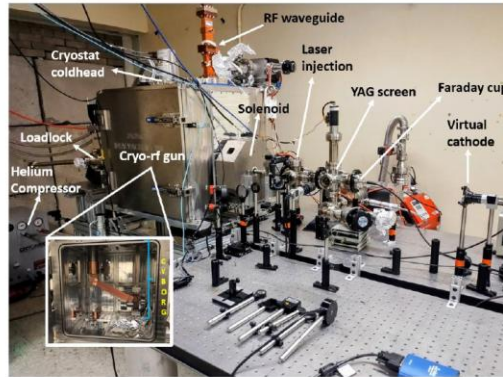
- CYBORG tests high-field cryogenic RF-photoinjector operation.
- First photoelectrons at room temperature, about 90 MV/m; synchronization and laser injection need work.
- Load-lock integration will enable tests of alternative low-MTE cathodes.



Current Status of the Beamline



- Main upgrades since the beginning of the year
 - Mirror box and optics for laser injection + Virtual cathode
 - Laser transport, timing and "synchronization" (from PEGASUS beamline)
 - First photoelectrons at the end of April (*room temperature*)



18-Nov-25

Experimental Progress in Testing High Field Cryogenic RF Photoinjectors

8

CYBORG beamline commissioning and first photoelectrons
Fabio Bosco (UCLA) • slide 8

Source 4D phase-space reconstruction

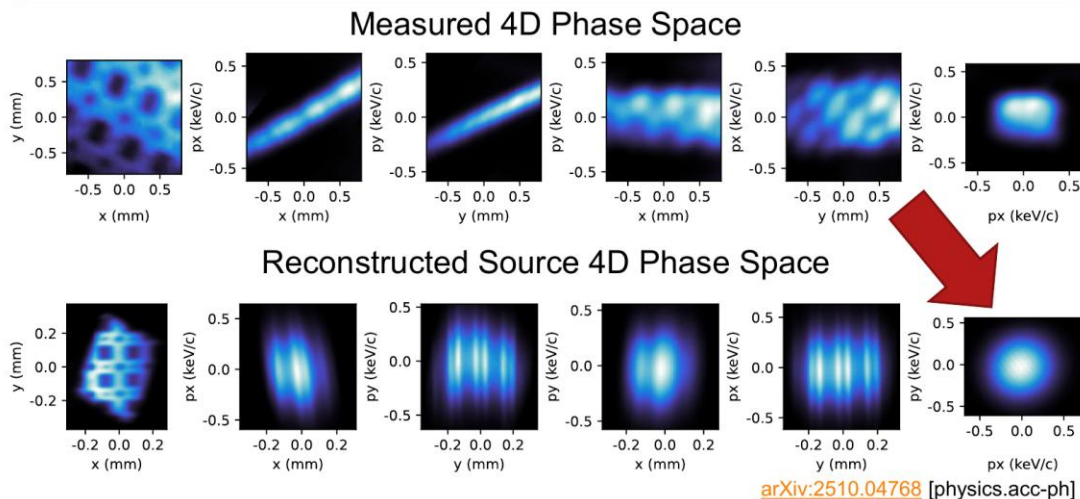
Charles Zhang (Cornell)

Novel Concepts

- Determine beamline transport from measured 4D phase space and laser-position scans.
- Patterned-cathode tests recover source structure; MTE 73 ± 2 meV versus 69 ± 2 meV independently.
- Requires linear transport and negligible space charge; no field map is needed.



Testing the Source Reconstruction



11/15/25

cz266@cornell.edu

44

Measured downstream and reconstructed source 4D phase space
Charles Zhang (Cornell) • slide 38

Rectangular-window photomultiplier tubes

Jace Beavers (LANL; work presented from Kansas State University)

Novel Concepts

- Match PMT geometry to large rectangular gamma-ray scintillators.
- Reflective design modeled; transmissive design gives a more practical fabrication path.
- Photocathode deposition exposed source leaks and contamination as major constraints.

Alternative Transmissive Photocathode Design

- A transmissive photocathode PMT was designed later
- Standard Box-and-Grid dynode design
 - Room for timing-performance improvement!
- Better collection and higher gain
 - 1st dynode opening is 12.6 mm (vs. 4.2 mm for reflective photocathode design)
 - Greater tolerance for variations in geometry
- More traditional materials and fabrication techniques are viable for this assembly

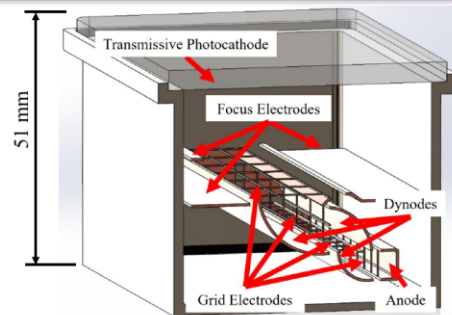


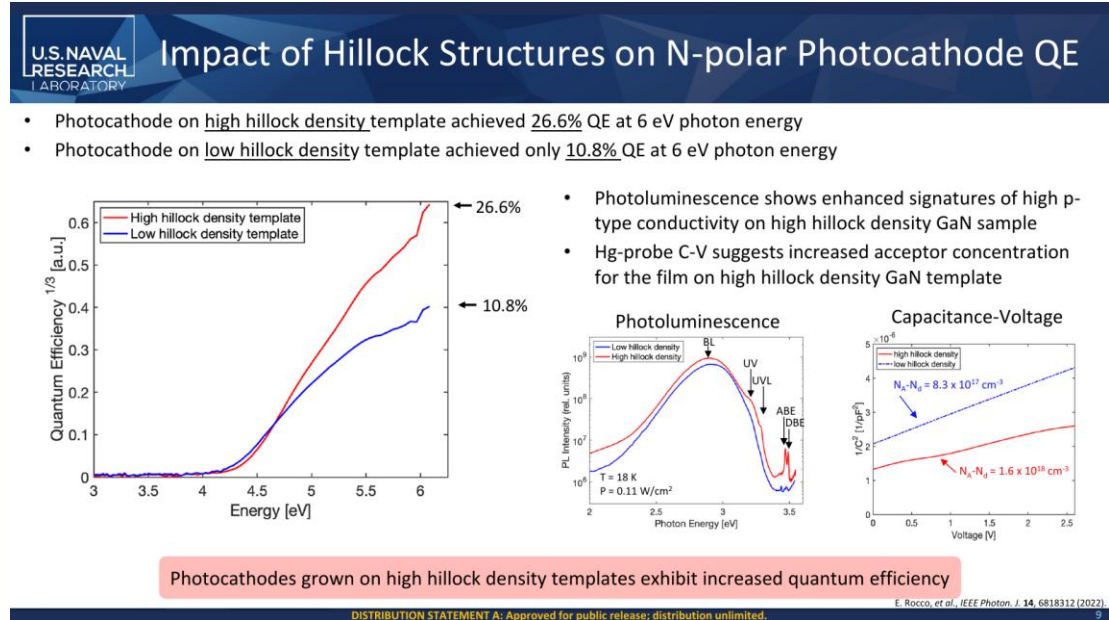
Fig. 19. 3D modeled cross section of the proposed rectangular, transmissive photocathode PMT.

Cs-free N-polar GaN photocathodes

Emma Rocco (NRL; III-nitride collaboration)

Novel Concepts

- Surface charge, cleaning and Mg doping control Cs-free GaN emission.
- Hillock-rich templates reach 26% QE at 6 eV, but increase beam defocusing and MTE.
- HCl improves QE from 3% to 12%; air degradation motivates 2D encapsulation.



QE improvement from hillock-rich N-polar GaN
Emma Rocco (NRL; III-nitride collaboration) • slide 9

Panel discussion

Howard Padmore (ASU), Dave Dowell (SLAC), Eric Montgomery (Euclid Labs),
Bruce Dunham (X-Light), Michelle Shinn (DOE)

Funding and impact

Document benefits for facilities, industry and training and consider varied funding opportunities.

Recent progress

Better understanding of NaKSb, expanding polarized-source work, and more sophisticated antimonide epitaxy studies.

Materials and nanosources

Measure QE and MTE of novel materials, theory development. Test nanosources in guns and explore optical nanostructures.

Characterization

Measure dielectric response, stoichiometry and local work function using UHV ellipsometry, XRF/EDX and PEEM.

Reliable operation

Improve reproducibility, understand heating and ion damage, and develop diagnostics inside guns.

P3 2025 summary

High field operation of High QE Cathodes

RF and SRF tests evaluate QE together with dark current, surface roughness and lifetime. Lianmin Zheng (Tsinghua), David Garcia (UCLA), Guan Shu (Zhangjiang Laboratory), Ziyi Yin (MSU), Jonas Dube (HZB).

Cryogenic operation

Cryogenic sources target lower MTE while retaining useful QE and reliable diagnostics. Peter Owusu (ASU), Huamu Xie (PKU), Gowri Adhikari (SLAC), Fabio Bosco (UCLA).

Nanostructures and patterned emission

Patterning can control the emitting area, beam shape and lifetime, with local fields and emittance as design constraints. Aziz Md. Rahman (JLab), Anagha Ullatuparambil and Mansoure Moeini Rizi (ASU), Michael Kaemingk (LANL).

Spin-polarized cathode lifetime

Work focused on activation, protective layers, high-current charge lifetime and scalable growth. Maximilian Herbert (TU Darmstadt), Jared Maxson (Cornell), Kali Prasanna Mondal and Luca Cultrera (BNL), Marcy Stutzman (JLab), Greg Blume (ODU).

Materials, theory and diagnostics

Growth and defect control are being linked to emission models and full phase-space measurements. Mengjia Gaowei (BNL), Abigail Flint and Tyler Wu (Cornell), Gaoxue Wang (LANL), Andreas Schroeder and Ir-Jene Shan (UIC), Charles Zhang (Cornell).

P3 2025 organizing committee

Thank you for organizing and hosting the workshop.

Scientific Organizing Committee

- John Smedley (SLAC)
- Marcy Stutzman (JLab)
- Jared Maxson (Cornell University)
- Oksana Chubenko (NIU)
- Dimitre Dimitrov (LANL)
- Luca Cultrera (BNL)
- Mengjia Gaowei (BNL)
- Pietro Musumeci (UCLA)
- Theodore Vecchione (SLAC)
- Kevin L. Jensen (UMD)
- Joe Grames (JLab)
- Anna Marie Alexander (LANL)
- Siddharth Karkare (ASU)

Local organizers

- Sid Karkare
- Deanna Clark
- Andrea Hamilton

P3

2027



Northern Illinois
University

Photocathode Physics for Photoinjectors

Hosted by Northern Illinois University (Chair: Prof. Oksana Chubenko)
September 14 – 16, 2027

