Photocathode Performance at the LCLS-II

+ Extra Stuff

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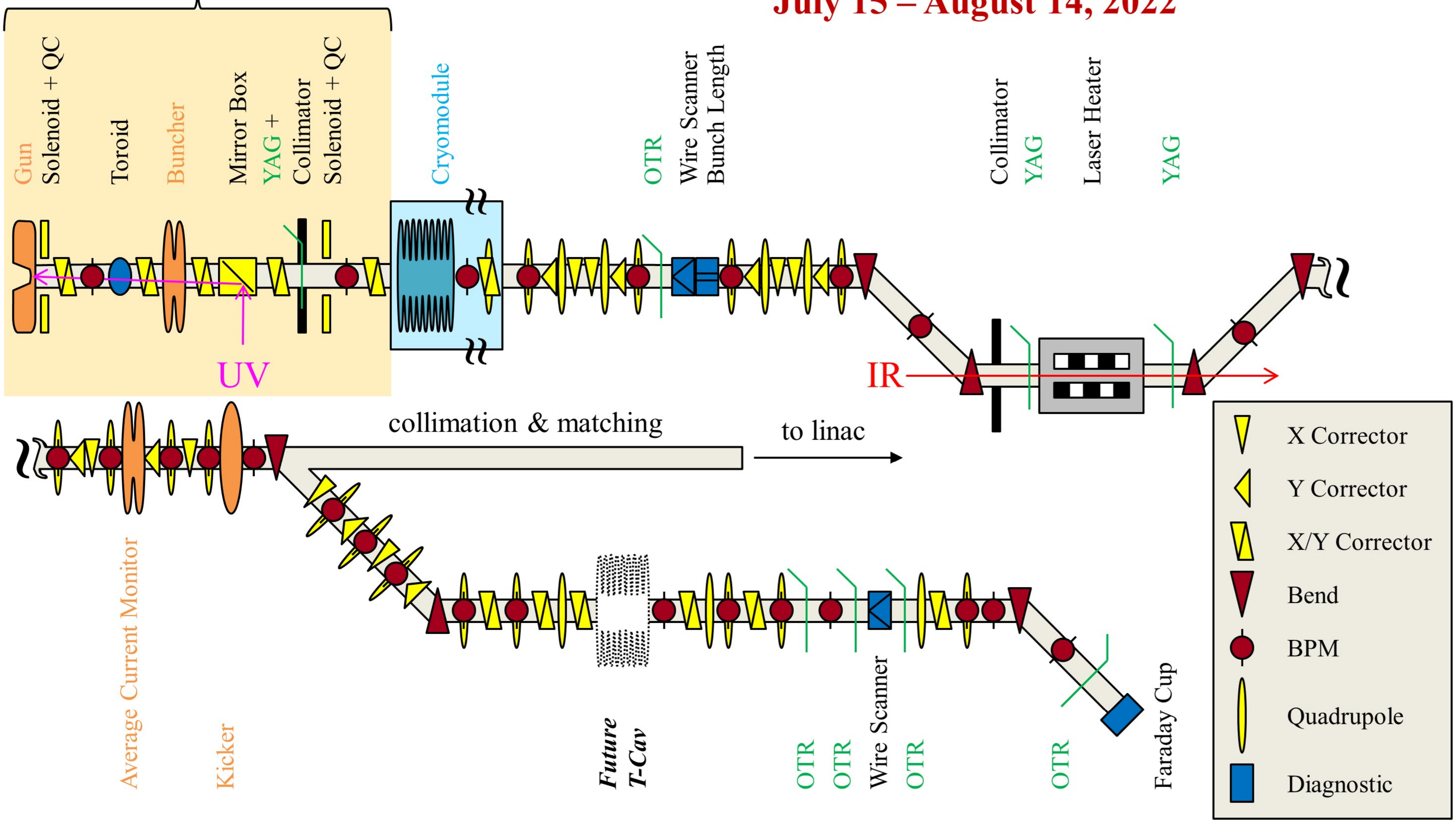
EWPAA: September 20, 2022

SLAC NATIONAL ACCELERATOR LABORATORY

LCLS-II Photoinjector Commissioning

0.75 MeV electron source (2018-2020)

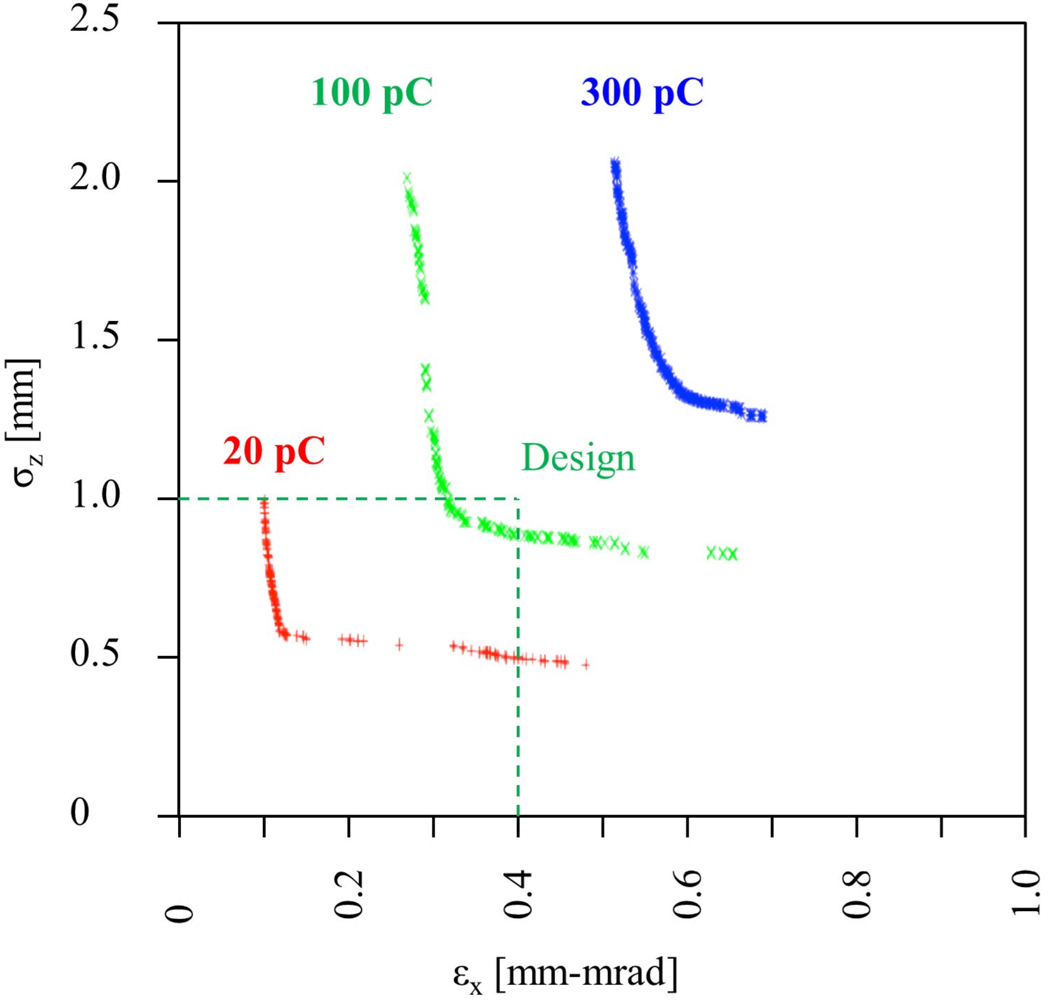
100 MeV diagnostic line commissioned
July 15 – August 14, 2022



LCLS-II Photoinjector Design Specifications

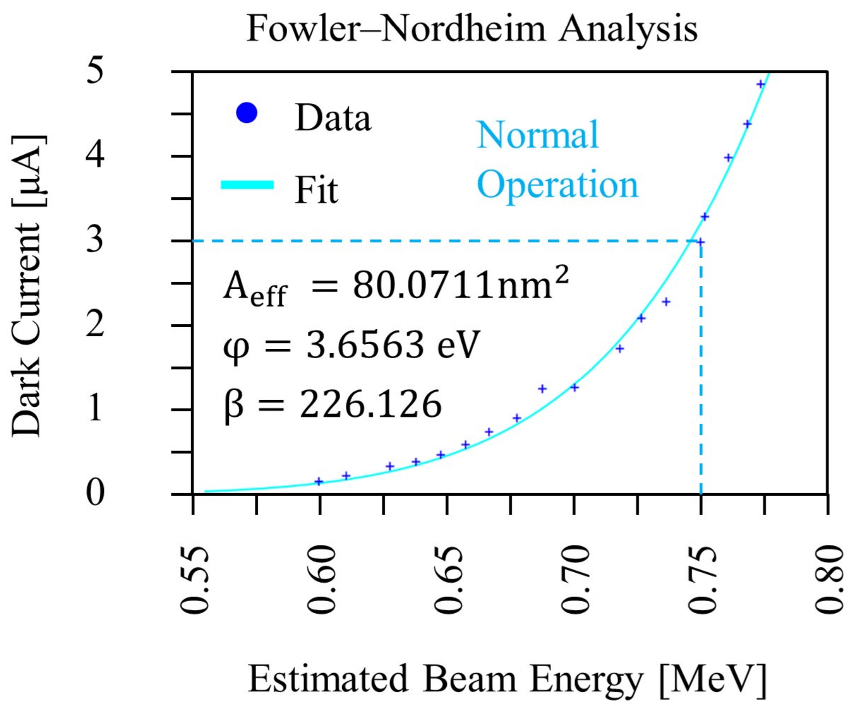
Cs_2Te was a conservative choice to meet these specifications

Simulations at 100 MeV
using $\varepsilon_{ix} = 1.0$ µm/mm

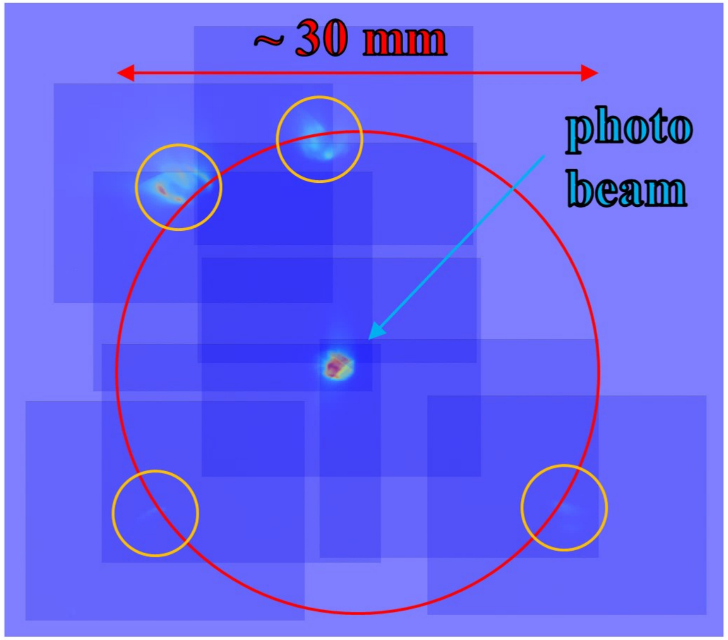


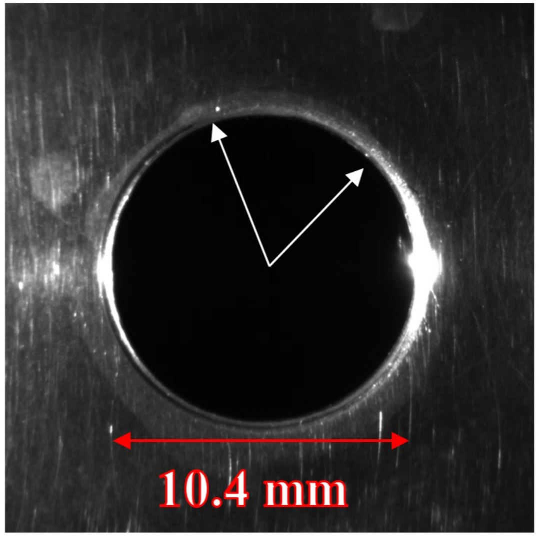
Bunch Charge	100 pC
Maximum Repetition Rate	0.929 MHz
Photoinjector Energy	100 MeV
Photoinjector Bunch Length	1 mm, 3 ps
Photoinjector Peak Current	12 A
Photoinjector Slice Emittance	0.4 mm-mrad
Photoinjector Slice Energy Spread	≤ 5 keV
Gun Energy	750 keV
Gun Gradient	19.5 MV/m
Gun Dark Current	≤ 400 nA
Gun vacuum w/ RF	≤ 1x10^{-9} torr
Intrinsic Emittance	**≤ 1 µm/mm**
Quantum Efficiency	**≥ 0.5 %**
1/e Lifetime	**≥ 10 days**
IR Delivered to Laser Heater (20 keV heating)	15 µJ / 30 ps pulse
UV Delivered to Photocathode (0.5% QE → 300pC)	≥ 0.3 µJ / 30 ps pulse

LCLS-II VHF Gun Dark Current



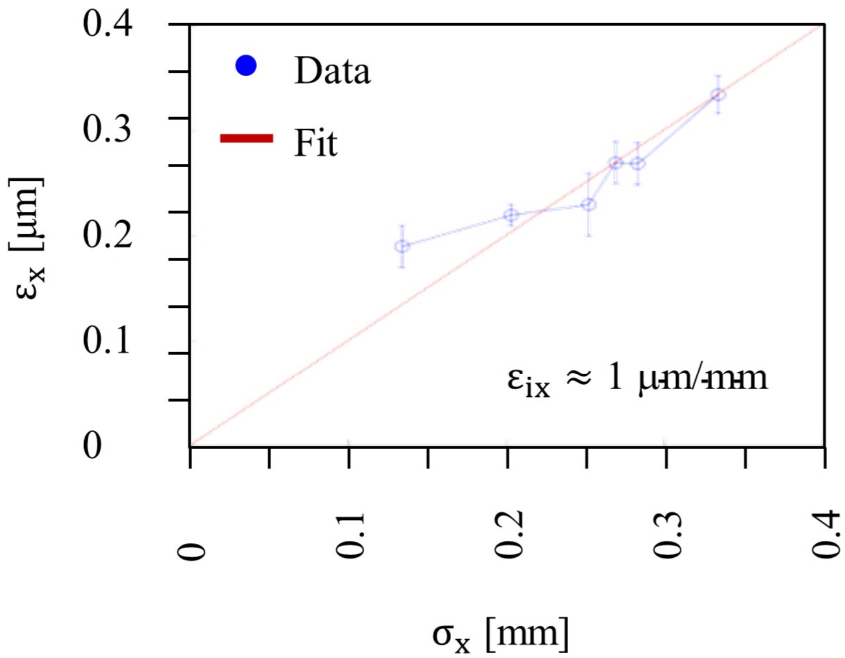
Zhou et al., PRAB **24**, 073401 (2021)





- There are two large sources and two small sources of dark current
- Dark current may originate from the inner lip of the gun nose cone
- Dark current generation seems to be stable over time
- **Spatial collimator added to remove > 95% of dark current**
- Typical: e-beam 16-18 mm diameter, 20 mm aperture (3μA →100nA)

Performance of First Two Cs_2Te Photocathodes Used

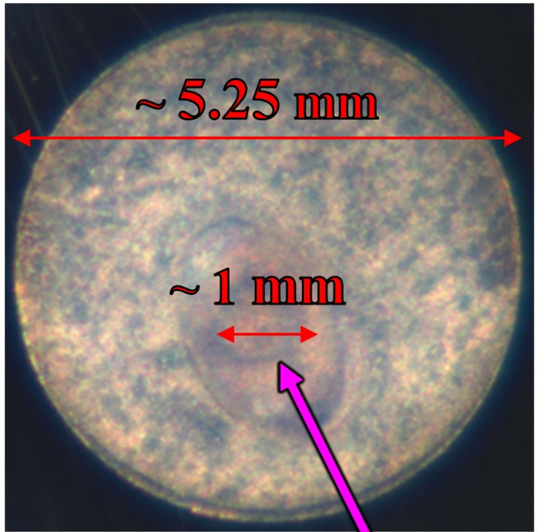


Zhou et al., PRAB **24**, 073401 (2021)

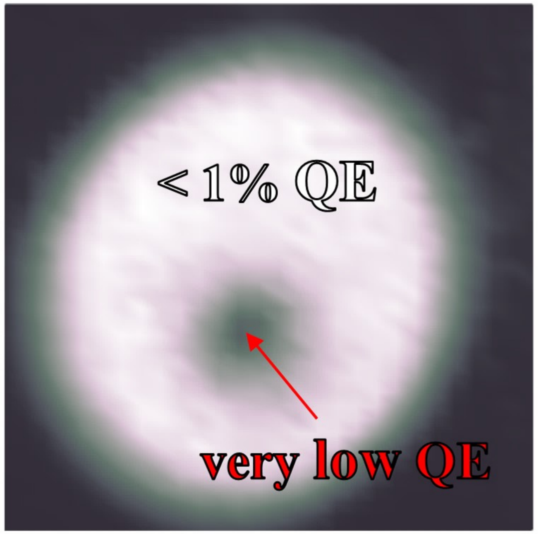
- The first two Cs_2Te photocathodes used were produced by INFN/LASA. ***Thank you!***
- Unfortunately the QE was low due to a problem with SLAC's *original* suitcase - but OK for commissioning
- The intrinsic emittance measurement above is from the first Cs_2Te photocathode used
- **The intrinsic emittance matched the value assumed when designing the photoinjector**
- The measurement used the gun solenoid with the buncher turned off and < 1 pC of charge in the beam

Postmortem Analysis of 1st Photocathode

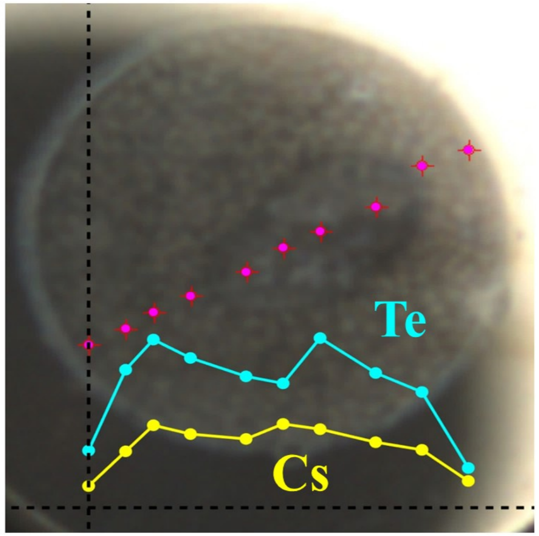
Optical Image



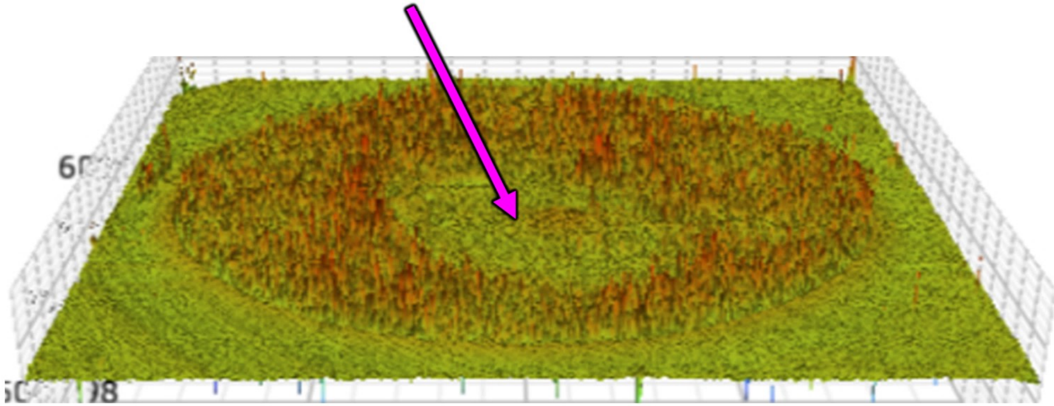
QE Map



Uncalibrated XRF Signals



Visible damage where QE degradation occurred

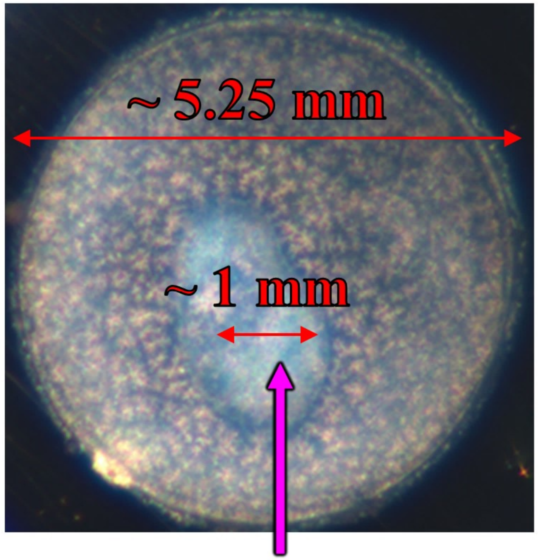


Optical Profilometry

- ~ 500 hours of operation, mostly at low rep rate
- Studies: profilometry, XRF, RBS + PIXE
- Homogeneous Cs:Te ratio of 1.8:1
- Thickness 0.05 ± 0.02 µm
- Slight bulge at defect but no clear step
- Defect is smoother than surrounding area
- **No evidence for material loss**

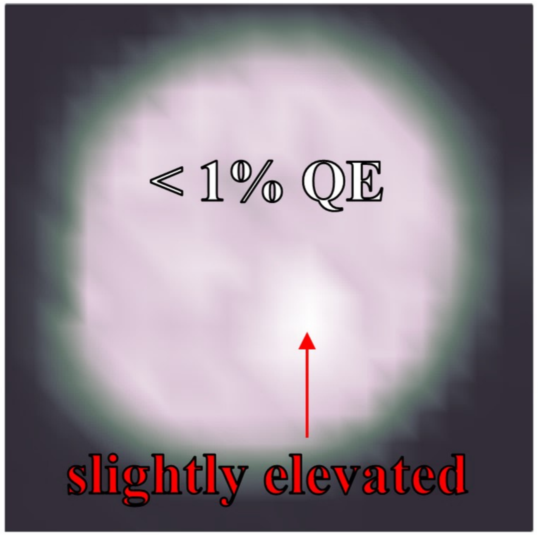
Postmortem Analysis of 2nd Photocathode

Optical Image

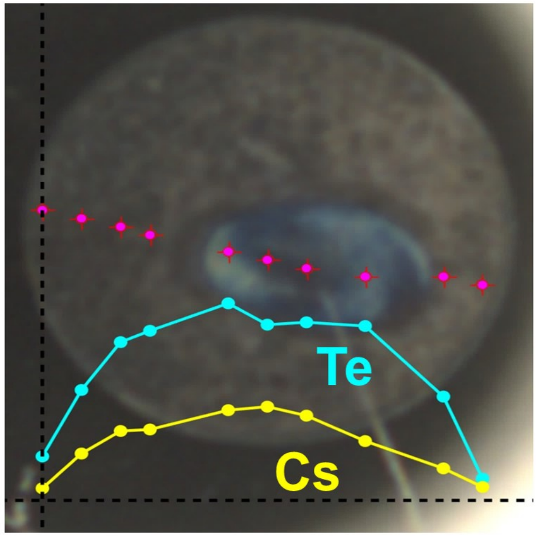


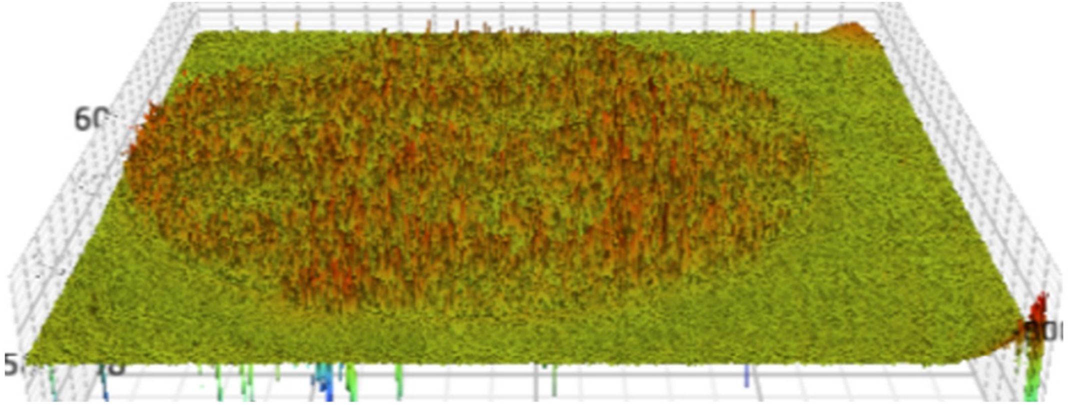
Visible damage

QE Map



Uncalibrated XRF Signals

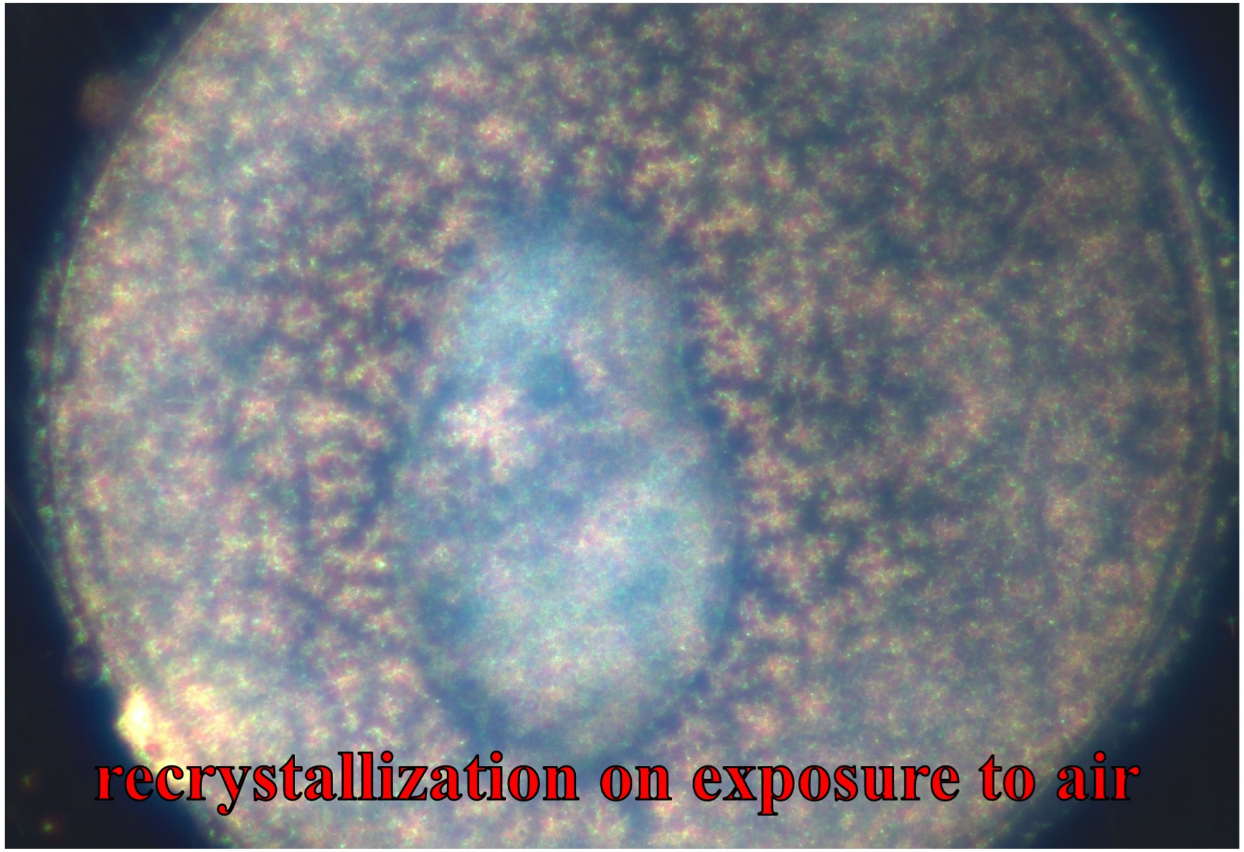




Optical Profilometry

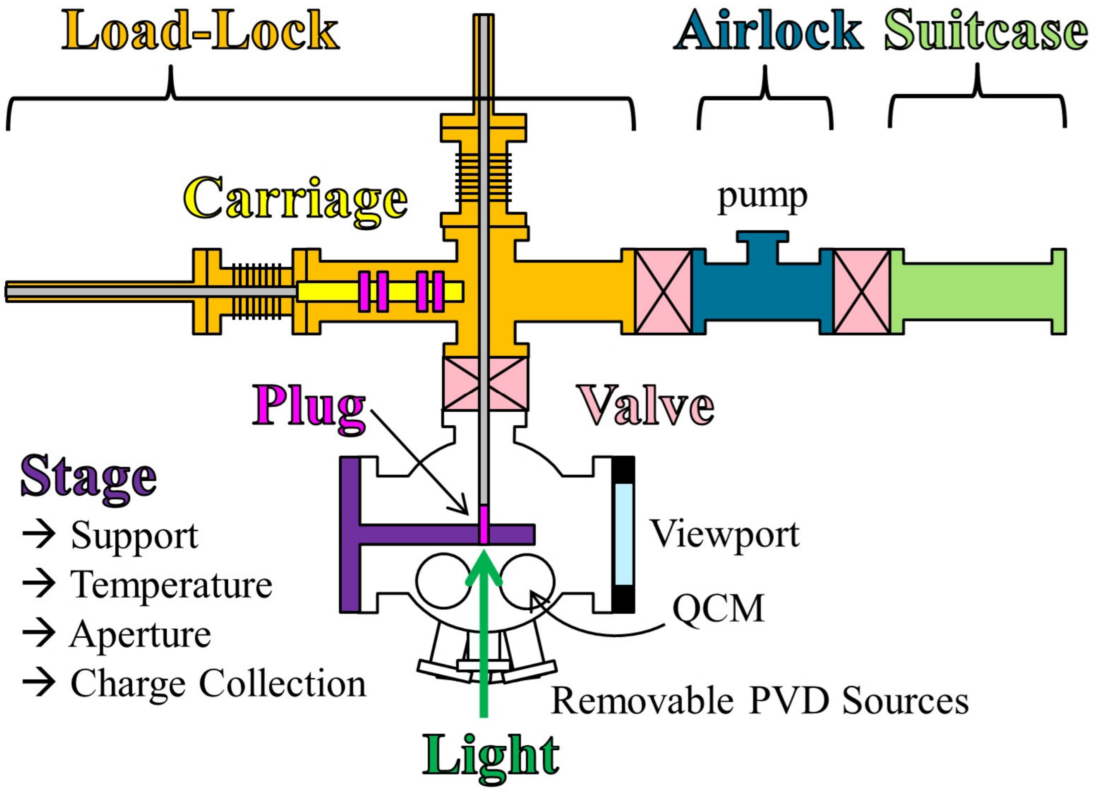
- ~ 200 hours of operation, mostly at low rep rate
- Studies: profilometry, XRF, RBS + PIXE
- Homogeneous Cs:Te ratio of 1.9:1
- Thickness 0.05 ± 0.02 μm
- Defect is similar to surrounding area
- **No evidence for material loss**

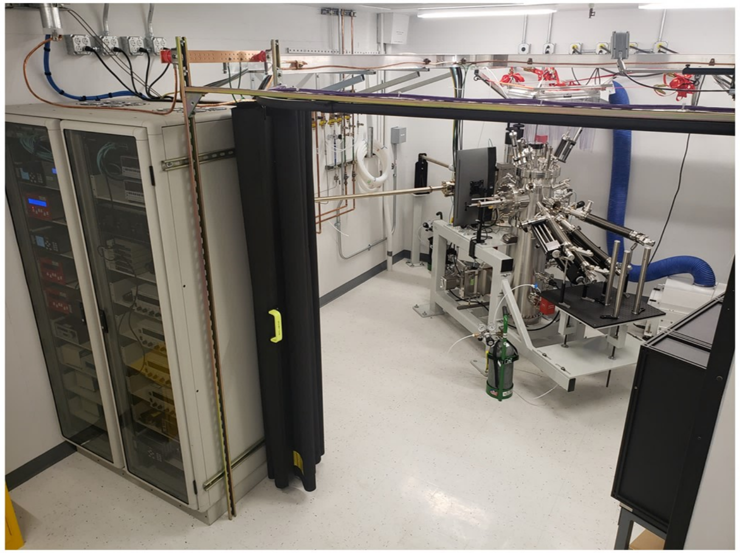
Future LCLS-II Photocathode Post-Mortem Analyses

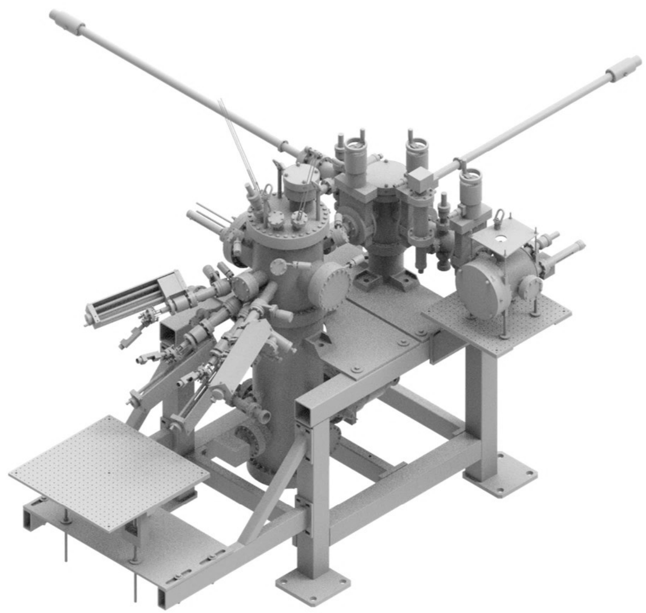


- Goal is to map chemical composition and to correlate this with performance
- Problem is that new compounds are produced when the photocathodes are exposed to air (understatement)
- **To do better will likely require capping in an inert layer to preserve the surface chemistry**
- Future analysis techniques will likely be destructive to the underlying plugs, e.g. FIB + TEM

LCLS-II Photocathode Deposition System

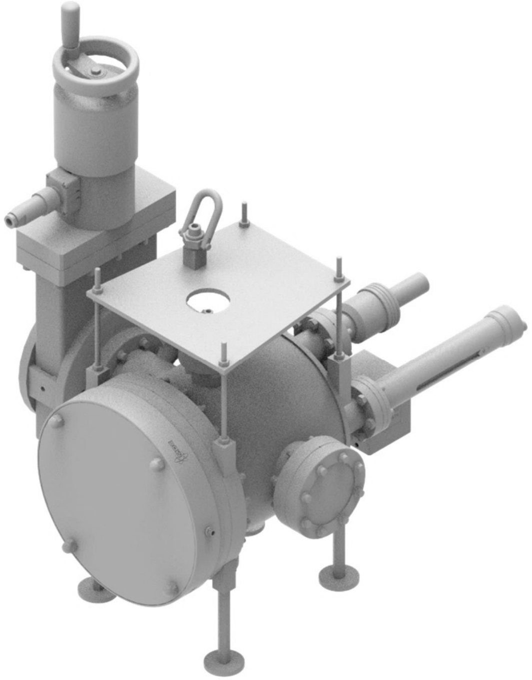


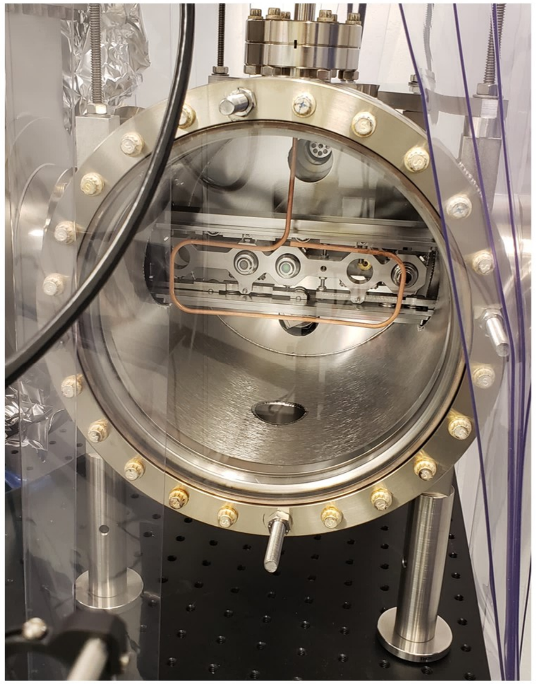




- SLAC has grown ~20 photocathodes since 2020
- System has four physical vapor deposition sources that are reconfigurable to produce different materials following either sequential or co-deposition recipes (Cs_2Te, K_2CsSb or other)
- Load-Lock, Airlock and Suitcase are maintained "particle free"
- Initial QE of Cs_2Te photocathodes at 258 nm is 5-15%, with > 10% typical
- Efforts are underway to improve uniformity with better PVD source overlap

LCLS-II Photocathode Suitcases





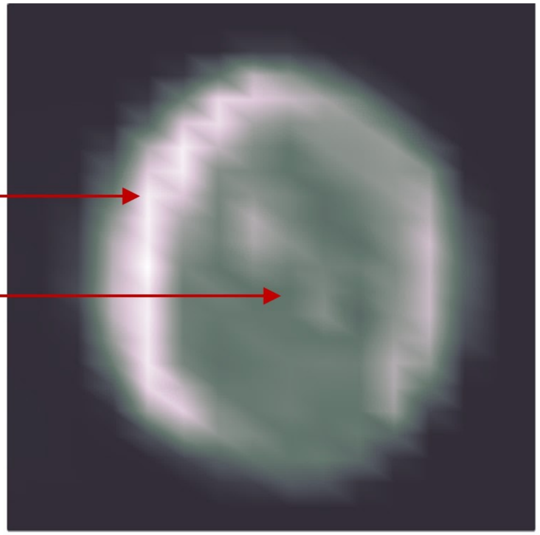
- UHV transport suitcases were redesigned to improve photocathode visibility (for characterization) and inter-system transferability (for exchange with collaborators). This is different from SLAC's *original* suitcase.
- Cs_2Te QE appears to be stable for months in a 'clean' suitcase
- If a suitcase doesn't have a hydrogen dominated vacuum of $1x10^{-10}$ torr or better then the Cs_2Te QE decays over time (e.g. from 10% to 1% in ~6 months, then a very slow decay from 1% to 0.5%)
- Minimum useful QE for LCLS-II operations is 0.5%.

Current LCSL-II Photocathode

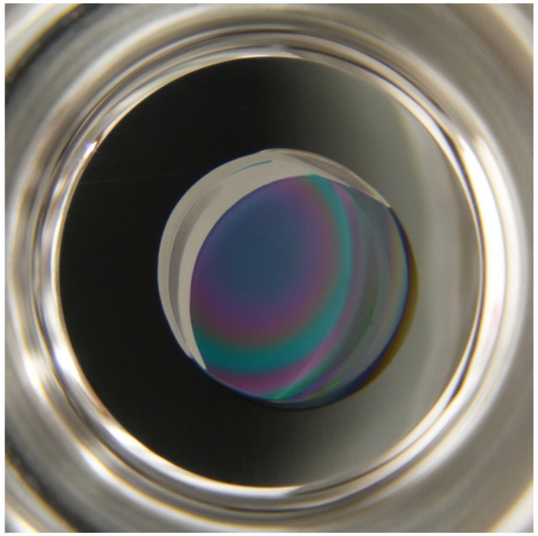
QE map of photocathode A008

15% max QE

8% QE on center



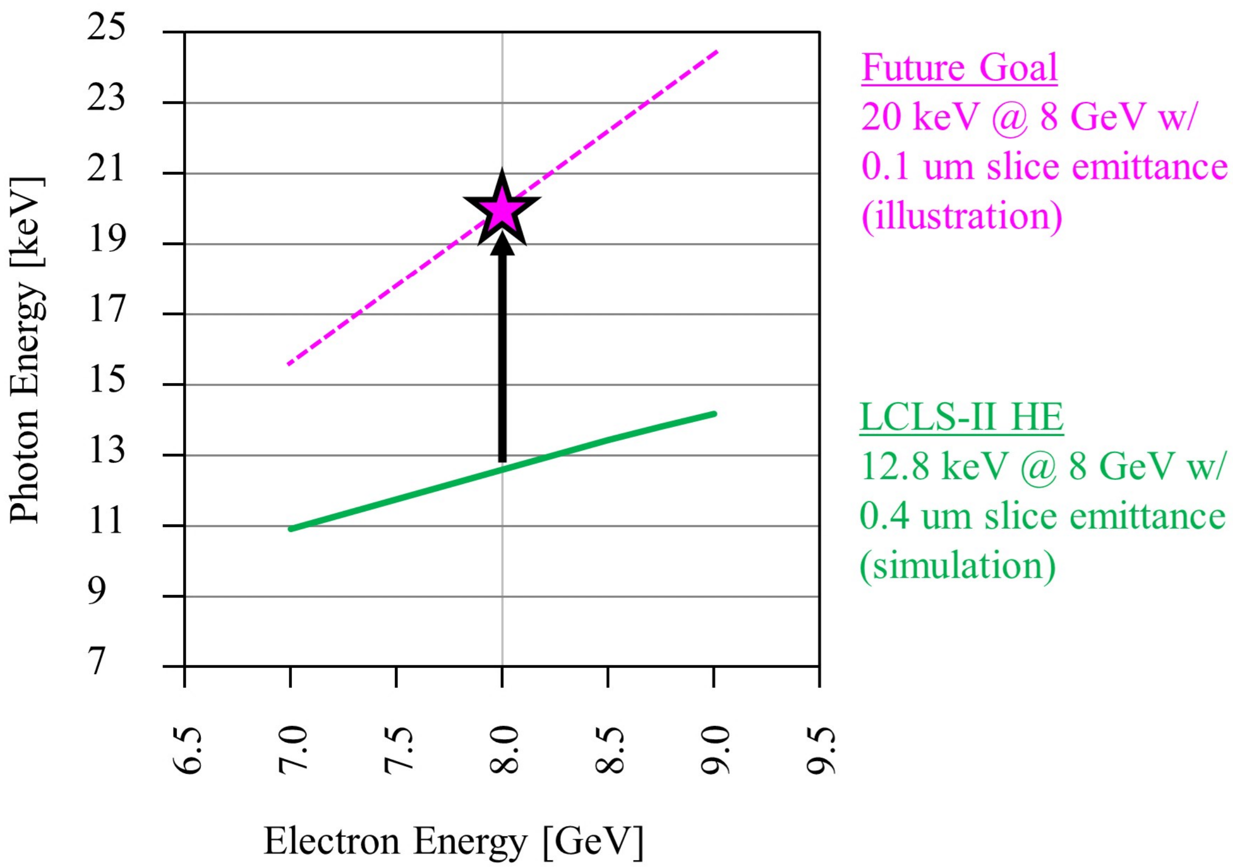
Optical image of photocathode A008



- Photocathode A008 was produced using Cs and Te codeposition
- Non-uniform QE may arise from non-uniform PVD source overlap (will be improved)
- Photocathode A008 has 400 hrs of operation at low rep rate and no obvious QE decay has been observed
- Intrinsic emittance measurement coming soon…

FEL Output as a Function of Electron Beam Emittance

Maximum wavelength for producing 100 uJ X-ray pulse energy



Achieving this requires a factor of 4 reduction in slice emittance at the undulator (100 pC in 1 mm bunch)

No single approach to achieve this → requires multiple parallel efforts

… starting with the photoinjector

$$\boldsymbol{\varepsilon}_{\mathbf{nx}} = \sqrt{\boldsymbol{\varepsilon}_{\mathrm{sc}}^2 + \boldsymbol{\varepsilon}_{\mathrm{rf}}^2 + \boldsymbol{\varepsilon}_{\mathrm{ix}}^2 + \cdots}$$

Layout

Electron source (> 20 MV/m)

Photocathode

current: $\boldsymbol{\varepsilon_{ix} > 0.6\ \mu m/mm}$

target: $\boldsymbol{\varepsilon_{ix} < 0.3\ \mu m/mm}$

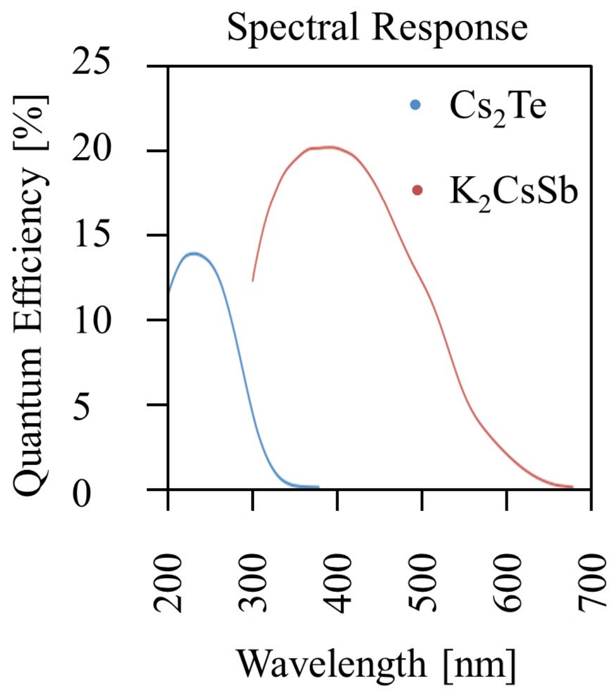
- Photocathodes are only a part … *but they are the most cost effective to improve*
- Photocathodes may achieve up to ½ of the desired emittance reduction overall

The Grand Photocathode Challenge

- A large contribution to emittance comes from the photocathode
- **Problem is, very few new photocathodes have been discovered in the last 50 years**

Desired →

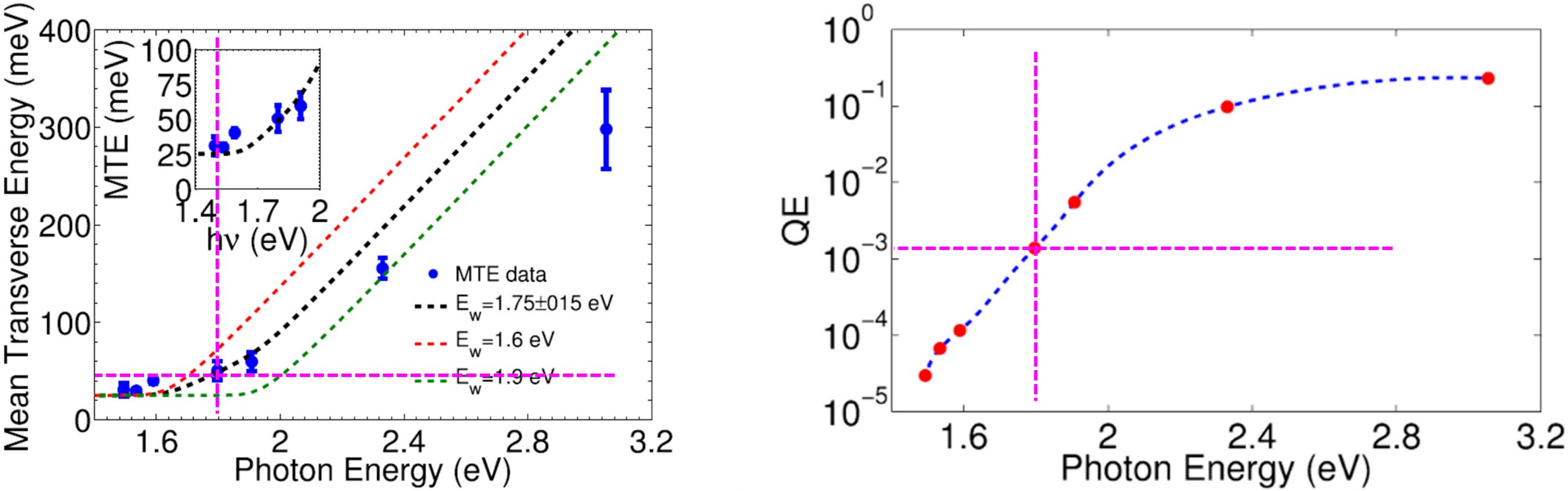
- Intrinsic emittance $\varepsilon_{int} < 0.3$ μm/mm → $\varepsilon_n < 0.1$ μm at 100 pC, 1 mm, 100 MeV
- QE sufficient to generate 100 pC, expected to be > 0.1% to minimize multiphoton effects
- Visible or IR wavelength (500-700 nm) operation for spatial laser shaping
- Temporal response time < 3 ps for longitudinal phase space manipulation
- Longitudinal energy spread $< 10^{-3}$
- 1/e QE lifetime > the lesser of 60 Coulomb or 1 week of operation at 1 MHz
- < 1 nA dark current when operated at 25 MV/m



	Cs_2Te	K_2CsSb	units
Required Vacuum	$< 10^{-9}$	$< 10^{-10}$	Torr
Laser Wavelength	263	526	nm
Initial QE	≥ 10	≤ 8	%
Intrinsic Emittance	0.7-0.8	0.60	μm/mm
1/e Lifetime	17		days
Service Life (10% to 0.5%)	50		days
Storage Life (suitcase)	∞	> 30	days

S20 Photocathode → Simultaneous 0.3 μm, 0.1% QE

- "S20" photocathode = Cs_3Sb on Na_2KSb → **best known candidate ???**
- Demonstrated 0.3 μm/mm intrinsic emittance (50 meV) at 690 nm and 300 K while maintaining a QE > 0.1%
- K_2CsSb has also had success in the BNL SRF gun; many relevant details to discuss in this case though…

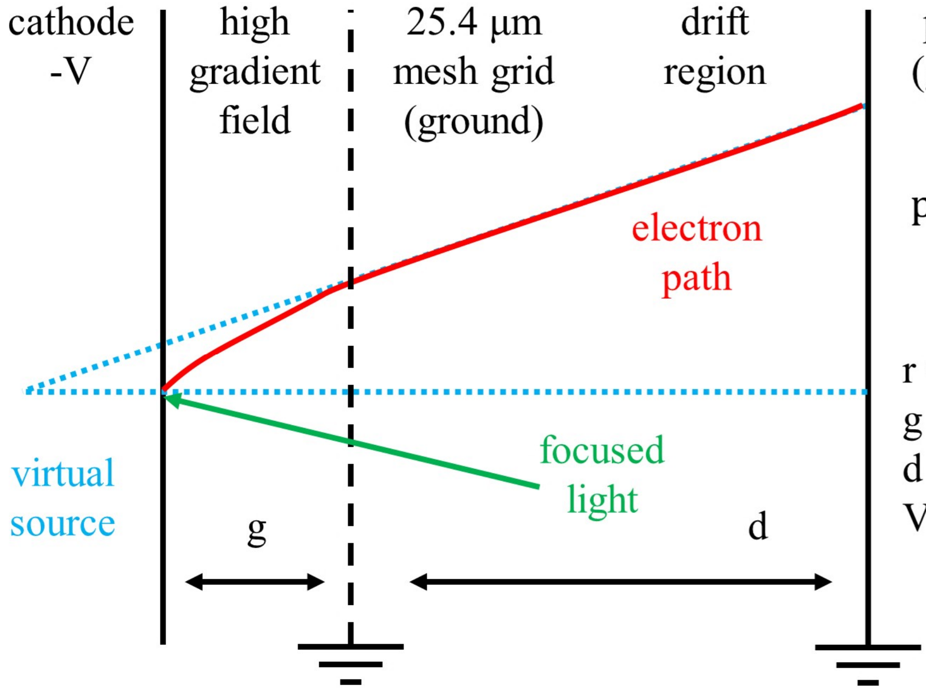


Cultrera et al. APL 108, 134105 (2016)

Only credible strategy at present for reducing intrinsic emittance (*in my opinion*):

- Use high QE semiconductor photocathodes
- Reduce surface roughness and increase chemical uniformity by optimizing epitaxial growth methods
- Operate as near the threshold for emission and at as low a temperature as multiphoton effects allow
- <u>Hope</u> secondary electron yield doesn't generate too much dark current

Momentatron: Transverse Momentum Measurement System



$$p_x = \sqrt{2\,m_0\,e\,V}\left(\frac{r}{2g+d}\right)$$

r = radial coordinate on detector, 0-5 mm
g = cathode-grid (anode) gap, 0.020 m
d = drift distance, 0.960 m
V = applied voltage, 20 kV max → 1 MV/m

Normalized emittance

$$\varepsilon_{nx} = \left(\frac{1}{m_0 c}\right)\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle x p_x\rangle^2}$$

$$\varepsilon_{nx} = \sqrt{\langle x^2\rangle}\sqrt{\frac{2\,V}{(2g+d)^2}\left(\frac{e}{m_0 c^2}\right)}\sqrt{\langle r^2\rangle}$$

Intrinsic emittance

$$\varepsilon_{ix}\left[\frac{\mu m}{mm}\right] \equiv \frac{\varepsilon_{nx}}{x_{rms}} \approx 0.063\,\sqrt{V[kV]}\,r_{rms}[mm]$$

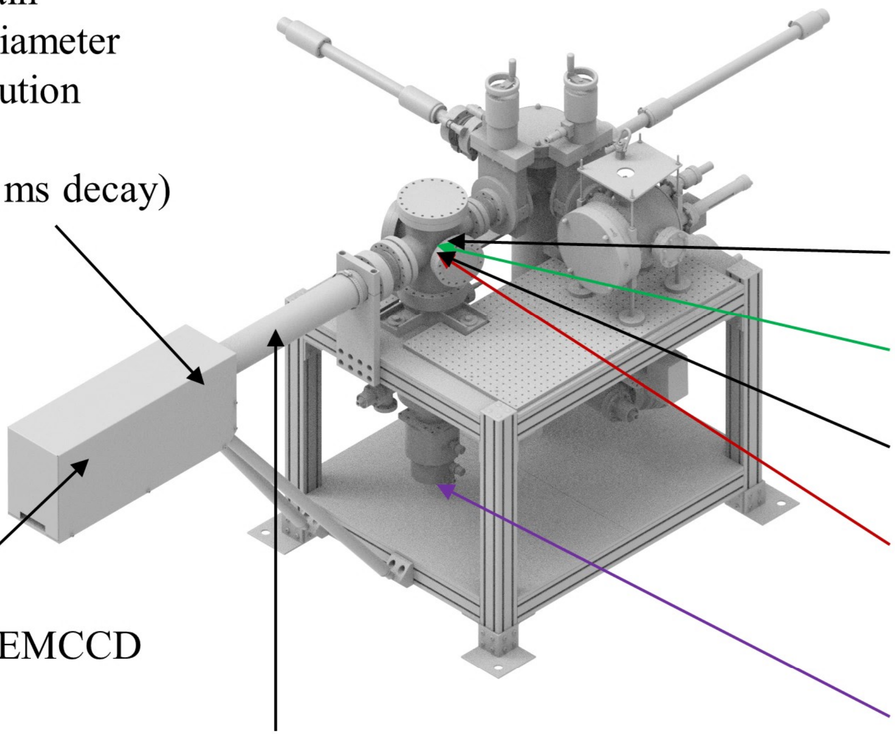
Cryogenic Momentatron being Commissioned at SLAC

- Characterize the performance of LCLS-II photocathodes at 300K prior to operational use
- Study general photocathode properties at temperatures between 300K and 4K
- Provide data that is essential to facilitate future theoretical model developments
  e.g. the inclusion of phonons, carriers, physisorption of gas, etc.

F2225-21PGF
Hamamatsu Microchannel Plate (MCP)
two stage, 10^6 gain
12 um channel diameter
80-100 μm resolution
P43 phosphor
(545 nm peak, 1 ms decay)

NKT Supercontinuum Laser

SuperK COMPACT	450-2400 nm Pulse Length: < 2 ns Rep Rate: 1 Hz - 20 kHz
VARIA	400-840 nm
UV Extend	350-480 nm
DUV Extend	265-345 nm



Photocathode Plug

Focused Laser

Mesh Grid

Sapphire Isolator

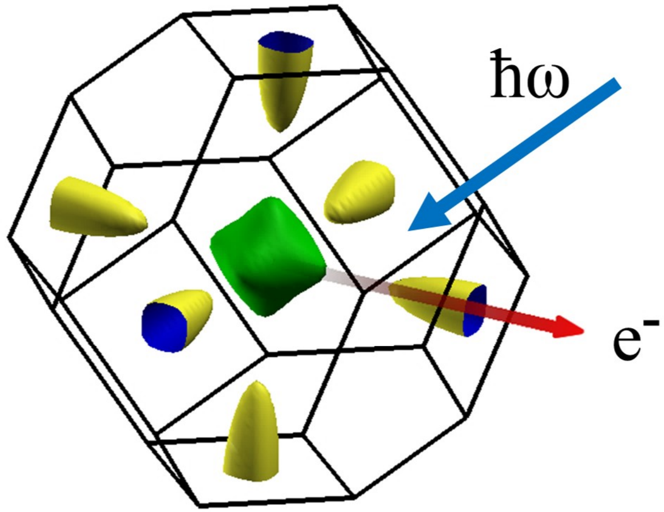
Andor Xion 888 EMCCD

Mu-metal shielded drift

Advanced Research Systems
DE-215 Cryocooler
30 W at 45 K
1.5 W at 4.2 K

US DOE ARDAP Accelerator Stewardship Effort

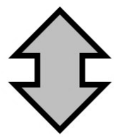
From Theory to Practical High-Brightness Photocathodes
W. Andreas Schroeder (UIC) + SLAC



Objectives

- Use photoemission modeling based on *ab initio* band structure calculations to find an appropriate single-crystal material predicted to have < 0.2 μm/mm intrinsic emittance at 300 K
- Demonstrate < 0.3 μm/mm intrinsic emittance and a QE > 0.1% using the operational test facility at the University of Illinois at Chicago (UIC)

Ab initio
Theory



MTE(ħω)
QE(ħω)

Current and future work

- Experimental studies single-crystal (-----) photocathodes
- *Ab initio* theoretical and experimental studies of (-----) photocathodes

US DOE BES Low Emittance Photoinjector Effort

Multi-lab/multi-university collaboration to determine the best photocathode to reach 0.3 μm/mm or less intrinsic emittance with a QE of 0.1% or better for use in the LCLS-II HE low emittance photoinjector

Materials Selection: All

1. Identify candidates
   Conventional: Cs_3Sb
   More exotic: Cs_3Sb:Na_2KSb
   Novel: Na_2O
   others (-----)

DC Studies: SLAC, ASU and Cornell

2. Measure the temperature and wavelength dependence of QE and intrinsic emittance using existing systems (Cornell and ASU) that are capable of reaching a few MV/m
   Cross check for consistency and reproducibility

3. Measure temporal response

4. Assess the importance of multi-photon effects (high laser power required for low QE)

5. SLAC DC high gradient field emission tests
   15 MV/m achievable w/ LEEM
   30 MV/m (300V over 10μm) w/ STM or nanoprobe

6. ASU is also looking into a modified INFN plug with removable tip to increase substrate options and to improve compatibility w/ surface science systems

RF Studies: UCLA and LBNL

7. Produce photocathodes
   Evaluating options now:
   1) SLAC using either an existing or a new system
   2) RMD commercial sealed capsule approach

8. Transfer photocathodes amongst collaboration
   * UCLA and LBNL accept INFN style plugs

9. Measure dark current generation using existing systems that are capable of reaching > 20 MV/m

10. Assess the importance of physical and/or chemical roughness

Summary

- The LCLS-II photoinjector has been successfully commissioned
  2018-2020: 1 MeV — Measured 1 μm/mm of intrinsic emittance
  July–August 2022: 100 MeV — Measured ~0.5 μm emittance w/ 50 pC, already close to design
  New collimator blocks 95% of dark current generated by the VHF gun

- Three Cs_2Te photocathodes have been used during photoinjector commissioning
  The 1st one operated for 500 hours and damage was observed near the center
  The 2nd one operated for 200 hours with similar but less pronounced results
  The 3rd one has operated for 400 hrs and there has been no obvious damage observed so far

- Ion back-bombardment did not cause the damage observed in the first two LCLS-II photocathodes.
  Other options: e-beam or laser?

- The LCLS-II deposition system and transport suitcases have been successfully commissioned

- A cryogenic momentatron system will be commissioned at SLAC over the next year

- SLAC is engaged in BES & ARDAP funded collaborations aiming for significant reductions in intrinsic emittance. Goal is to achieve ≤ 0.3 μm/mm with $\geq 0.1\%$ QE

Thank you very much for your attention!