Some of the Photocathode Science at SLAC

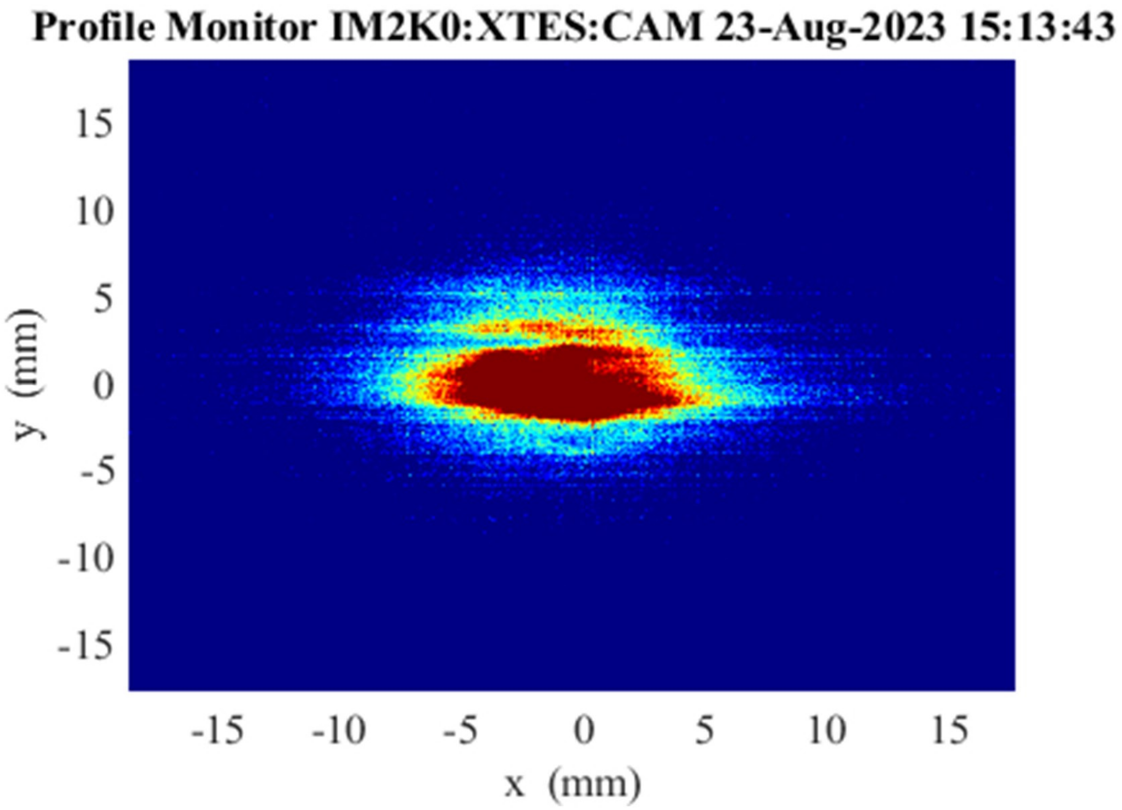
2023 Photocathode Physics
for Photoinjectors Workshop

Theodore Vecchione
October 4, 2023

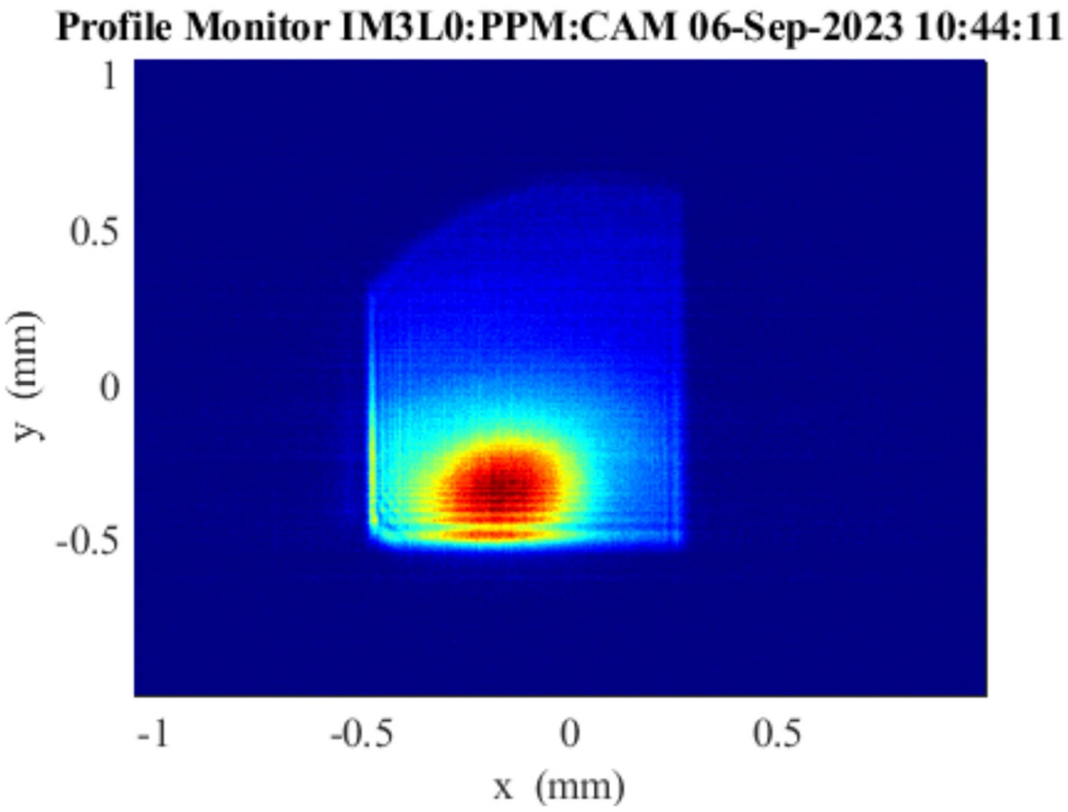
SLAC NATIONAL ACCELERATOR LABORATORY

LCLS-II First Light

8/23/23
Soft X-ray Undulator, 450 eV


Profile Monitor IM2K0:XTES:CAM 23-Aug-2023 15:13:43

9/6/23
Hard X-ray Undulator, 1050 eV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LCLS-II

Injector

Cryoplant

SC Linac

NC Linac

Spreader

Bypass

Beam Transport

Undulators &
X-Ray Transport

X-Ray Experimental Area
(NEH and FEH)

BERKELEY LAB

Fermilab

Argonne
NATIONAL LABORATORY

Jefferson Lab

CORNELL UNIVERSITY FOUNDED A.D. 1865

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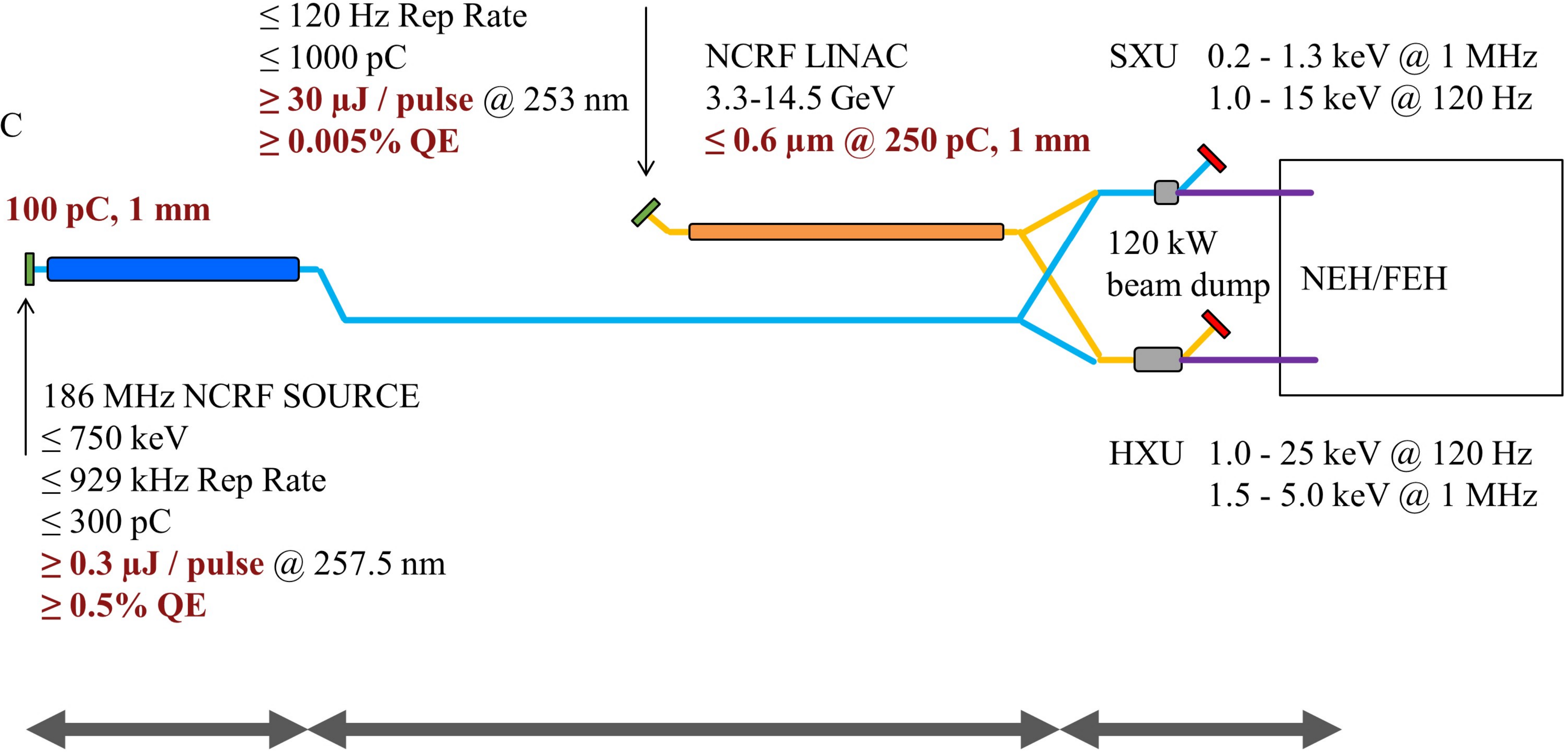
CD-0: 2010
TTO: 2023
→ 13 years

~ 5M hours
~ $1B

LCLS-II



SCRF LINAC
2-4 GeV
≤ 0.4 µm @ 100 pC, 1 mm

2856 MHz NCRF SOURCE
≤ 6 MeV
≤ 120 Hz Rep Rate
≤ 1000 pC
≥ 30 µJ / pulse @ 253 nm
≥ 0.005% QE

NCRF LINAC
3.3-14.5 GeV
≤ 0.6 µm @ 250 pC, 1 mm

SXU 0.2 - 1.3 keV @ 1 MHz
1.0 - 15 keV @ 120 Hz

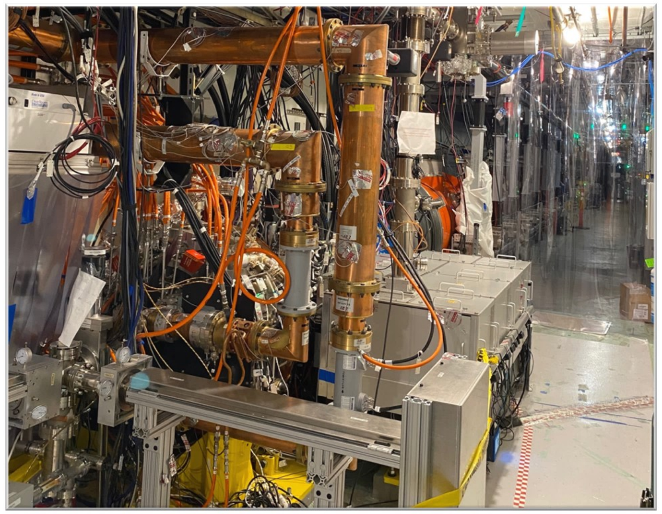
120 kW
beam dump

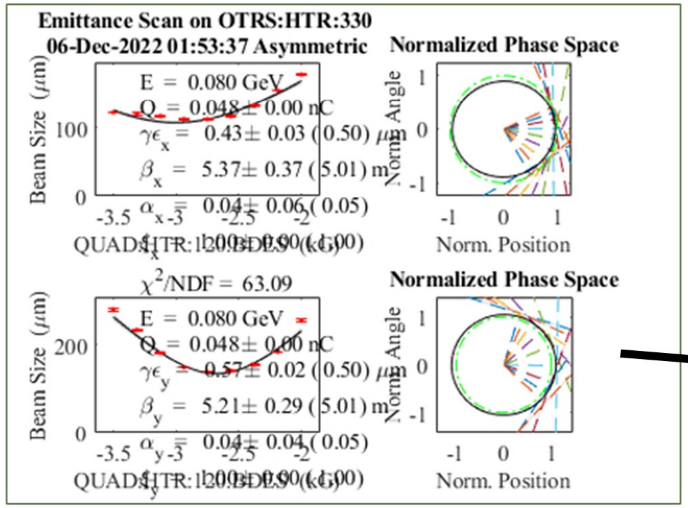
NEH/FEH

HXU 1.0 - 25 keV @ 120 Hz
1.5 - 5.0 keV @ 1 MHz

186 MHz NCRF SOURCE
≤ 750 keV
≤ 929 kHz Rep Rate
≤ 300 pC
≥ 0.3 µJ / pulse @ 257.5 nm
≥ 0.5% QE

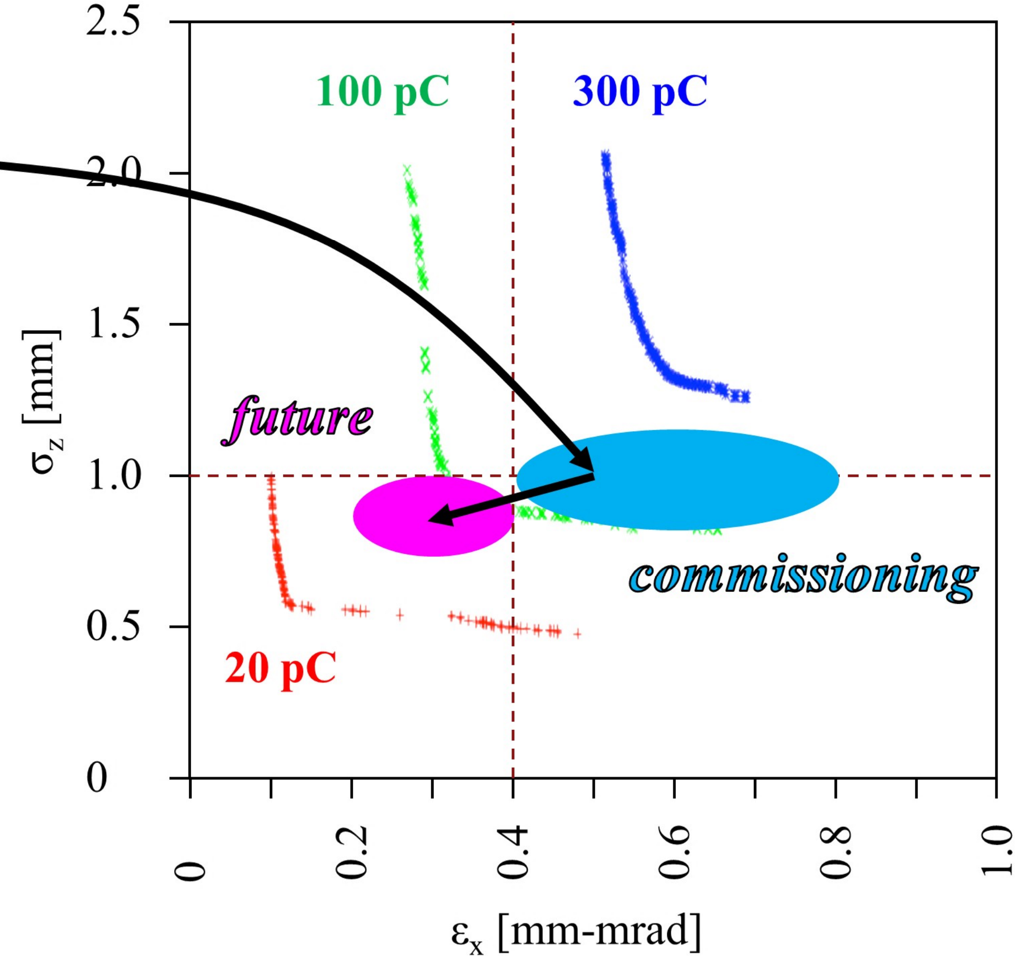
LCLS-II Photoinjector



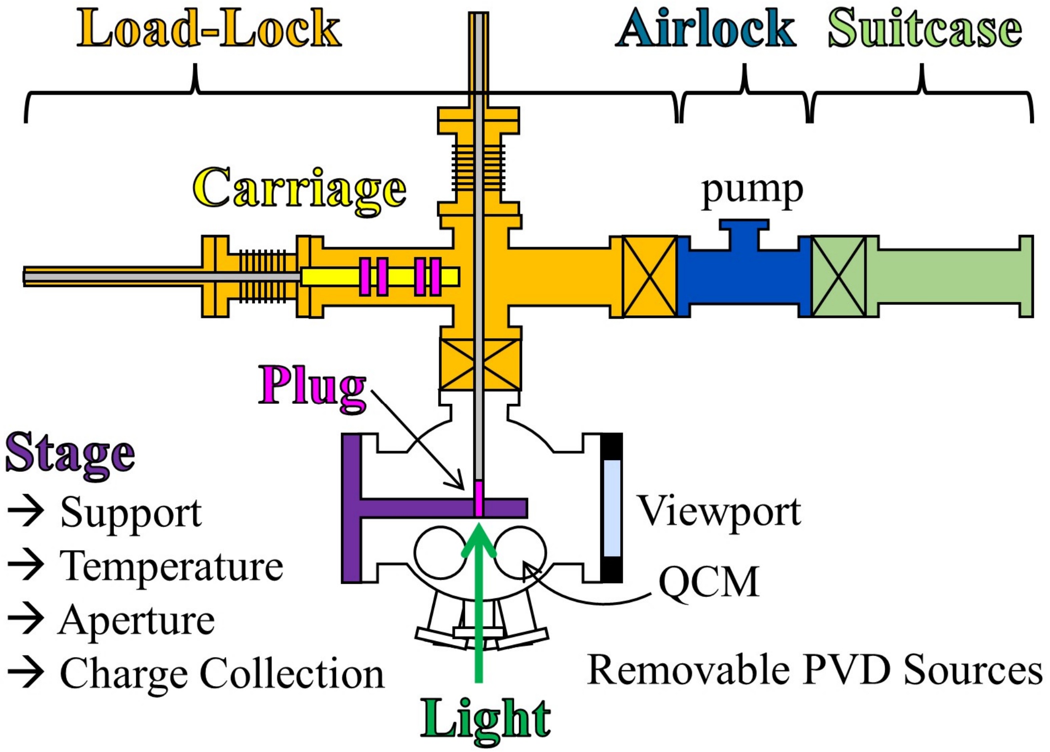


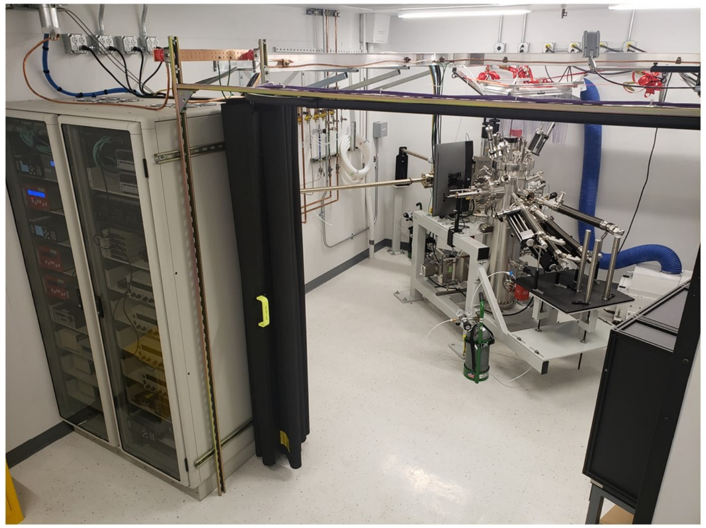
	Specification	**Commissioning**
Bunch Charge	10-300 pC	**20-100 pC**
Beam Energy	100 MeV	**80-90 MeV**
Bunch Length	0.3-10 mm	**~ 1 mm**
Slice Emittance	0.2-0.6 μm	**0.4-1.0 μm (projected)**
Gun Energy	750 keV	**650 keV**
Gun Gradient	19.5 MV/m	**17 MV/m**
Gun Dark Current	≤ 400 nA	**3-5 μA**
Gun vacuum w/ RF	≤ 1x10^{-9} torr	**~ 3x10^{-9} torr**
Quantum Efficiency	≥ 0.5 %	**1-2 %**
1/e Lifetime	≥ 10 days	**~ 2 years**
UV on Photocathode	≥ 0.3 μJ / 30 ps pulse	**≥ 0.3 μJ / 16 ps pulse**

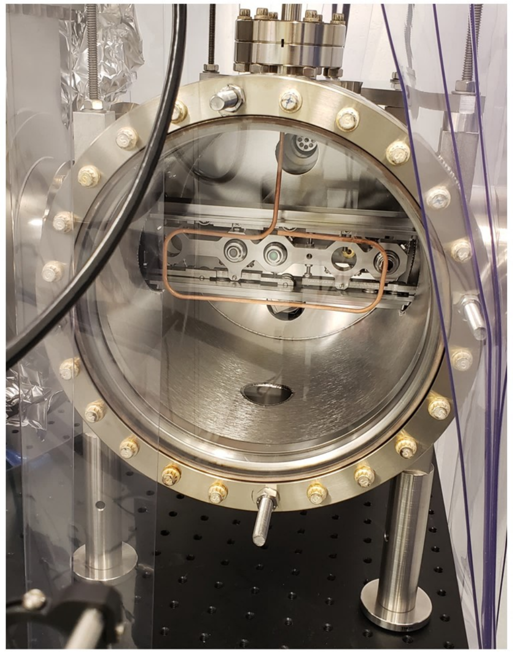
Pareto front optimizations at injector exit (100 MeV) using ε_{int} = 1.0 μm/mm



LCLS-II Photocathode Deposition System







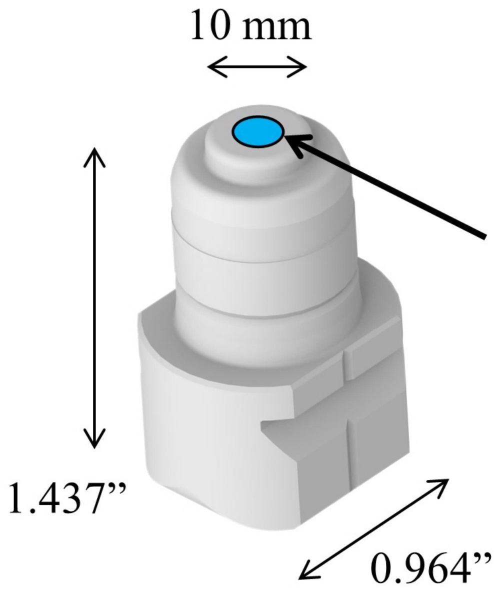
- System has four physical vapor deposition sources that are reconfigurable to produce different materials following either sequential or co-deposition recipes
- Load-Lock, Airlock and Suitcase are maintained “particle free”
- Initial QE of Cs_2Te photocathodes at 258 nm is 5-15%, with > 10% typical
- Cs_2Te QE is stable for months in a ‘clean’ suitcase

Current LCSL-II Photocathode

Current LCLS-II Cs_2Te photocathode has be used for ~ 2 years

QE has degraded and the QE map has changed, but the current QE is sufficient to support the beam program

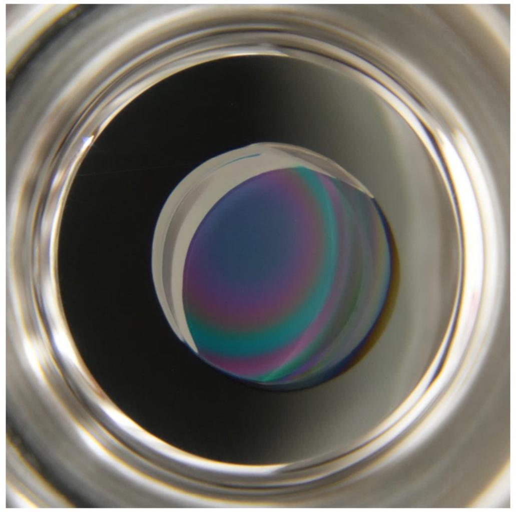
Cause of QE decay is a mystery: ~~ion back-bombardment~~, ~~back-propagating~~ or secondary electrons, laser heating?

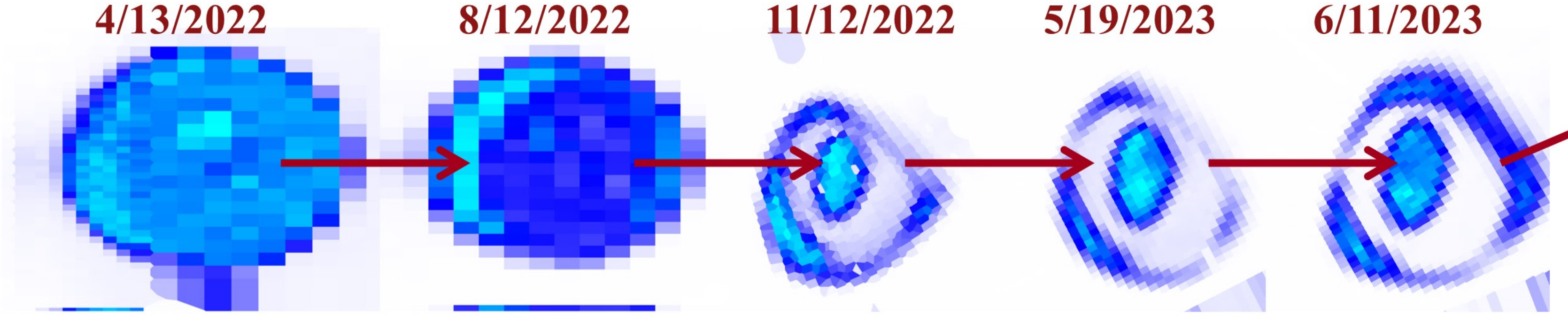


5 mm diameter
Cs_2Te photocathode

Molybdenum Plug

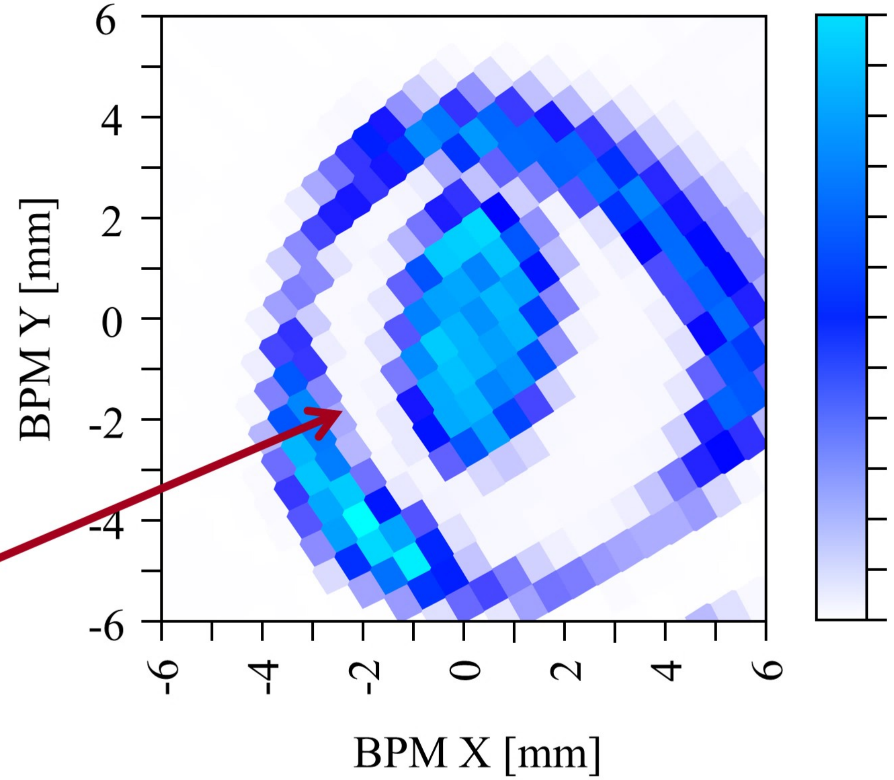
Optical image of photocathode A008 produced using Cs and Te co-deposition



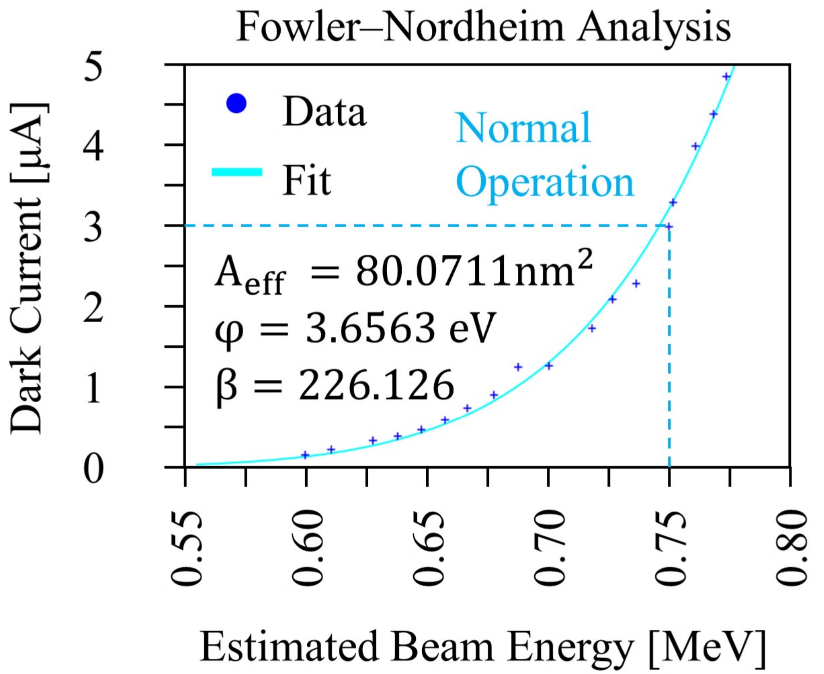


Maupiti?

QE map of photocathode
A008 on **9/24/2023**



LCLS-II VHF Gun Dark Current



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

$$f[F,\varphi] = \frac{e^3}{4\pi\epsilon_0}\frac{\beta F}{\varphi^2} = 1.439964\times10^{-3}\left[\frac{\mathrm{m\,eV}^2}{\mathrm{MV}}\right]\frac{\beta F}{\varphi^2}$$

$$v[f] \approx 1 - f + (1/6)\, f\, \mathrm{Log}[f]$$

$$i = A_{\mathrm{eff}}\left(\frac{a\,\beta^2F^2}{\varphi}\right)\mathrm{Exp}\left[-\left(\frac{b\,\varphi^{3/2}}{\beta\,F}\right)v[f[F,\varphi]]\right]$$

$$a = 1.541434\times10^6\left[\frac{\mathrm{A\,eV}}{\mathrm{MV}^2}\right] \quad b = 6.830890\times10^3\left[\frac{\mathrm{MV}}{\mathrm{m\,eV}^{3/2}}\right]$$

Dark current is indeed an issue

Dark current may originate from the inner lip of the gun nose cone

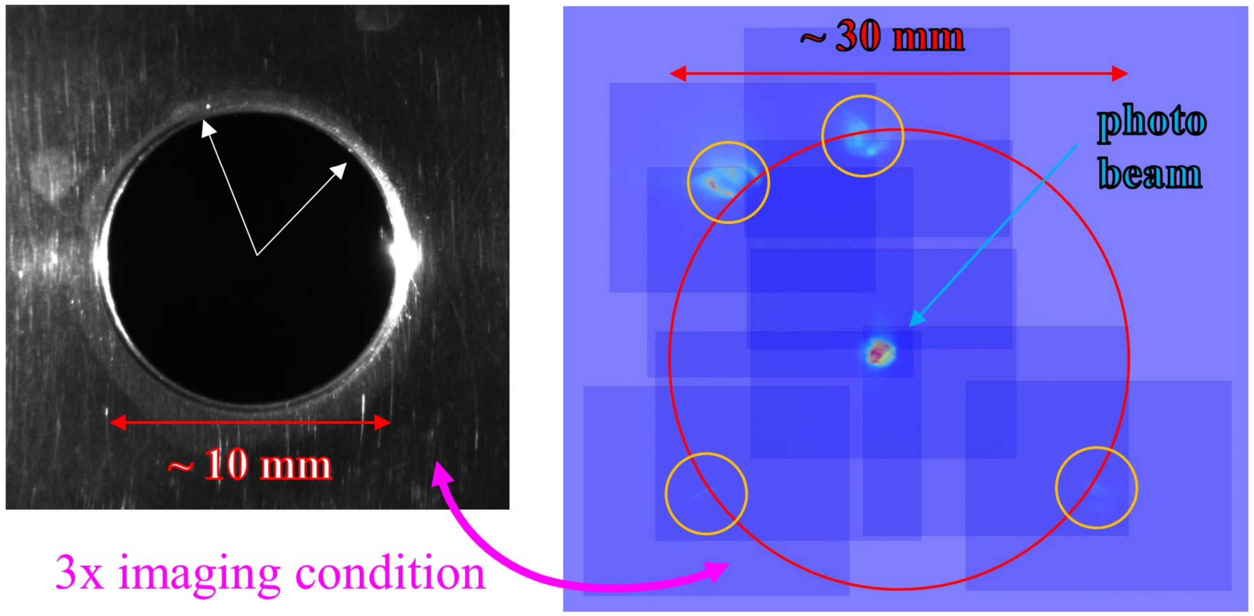
Dark current generation may be stable over time

→ *run at reduced gradient to minimize dark current generation*

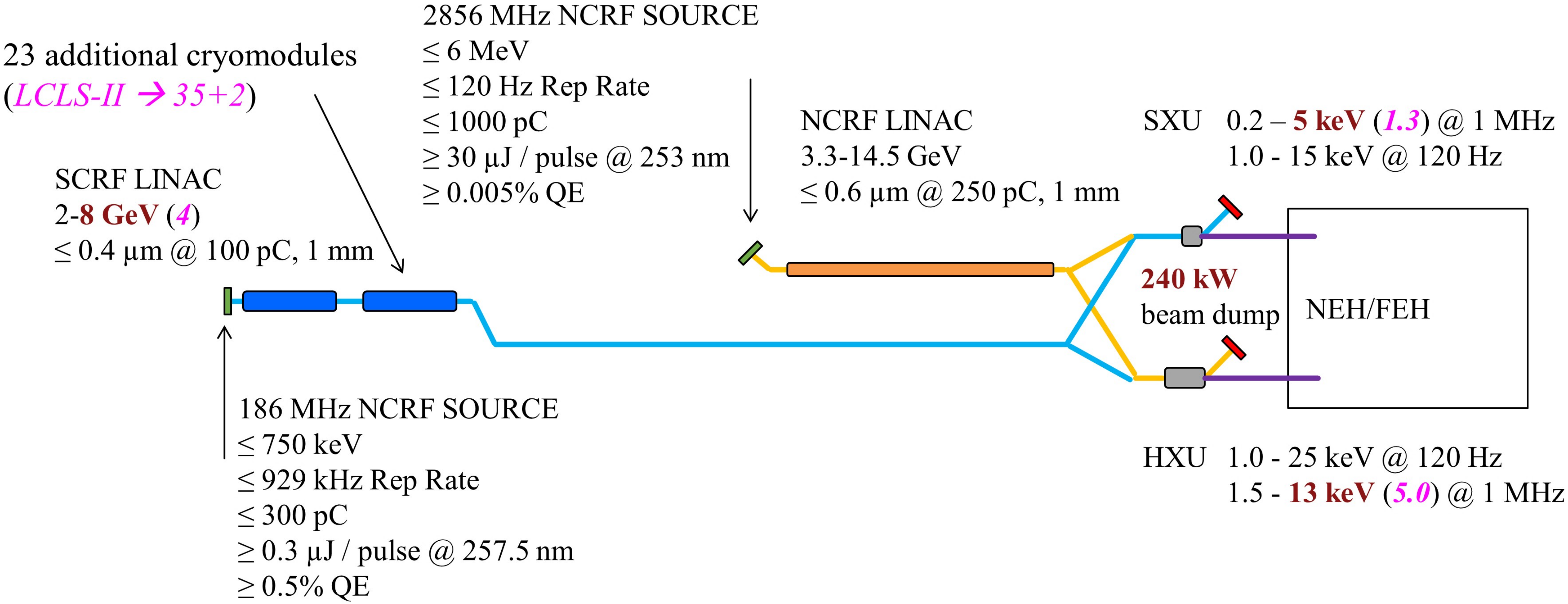
Spatial collimator removes > 95% of dark current

Typical: e-beam 16-18 mm diameter, 20 mm aperture (3µA →100nA)

→ *detune the photoinjector to prevent dark current propagation*



LCLS-II-HE



23 additional cryomodules
(*LCLS-II → 35+2*)

SCRF LINAC
2-**8 GeV** (*4*)
≤ 0.4 µm @ 100 pC, 1 mm

2856 MHz NCRF SOURCE
≤ 6 MeV
≤ 120 Hz Rep Rate
≤ 1000 pC
≥ 30 µJ / pulse @ 253 nm
≥ 0.005% QE

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HXU 1.0 - 25 keV @ 120 Hz
1.5 - **13 keV** (*5.0*) @ 1 MHz

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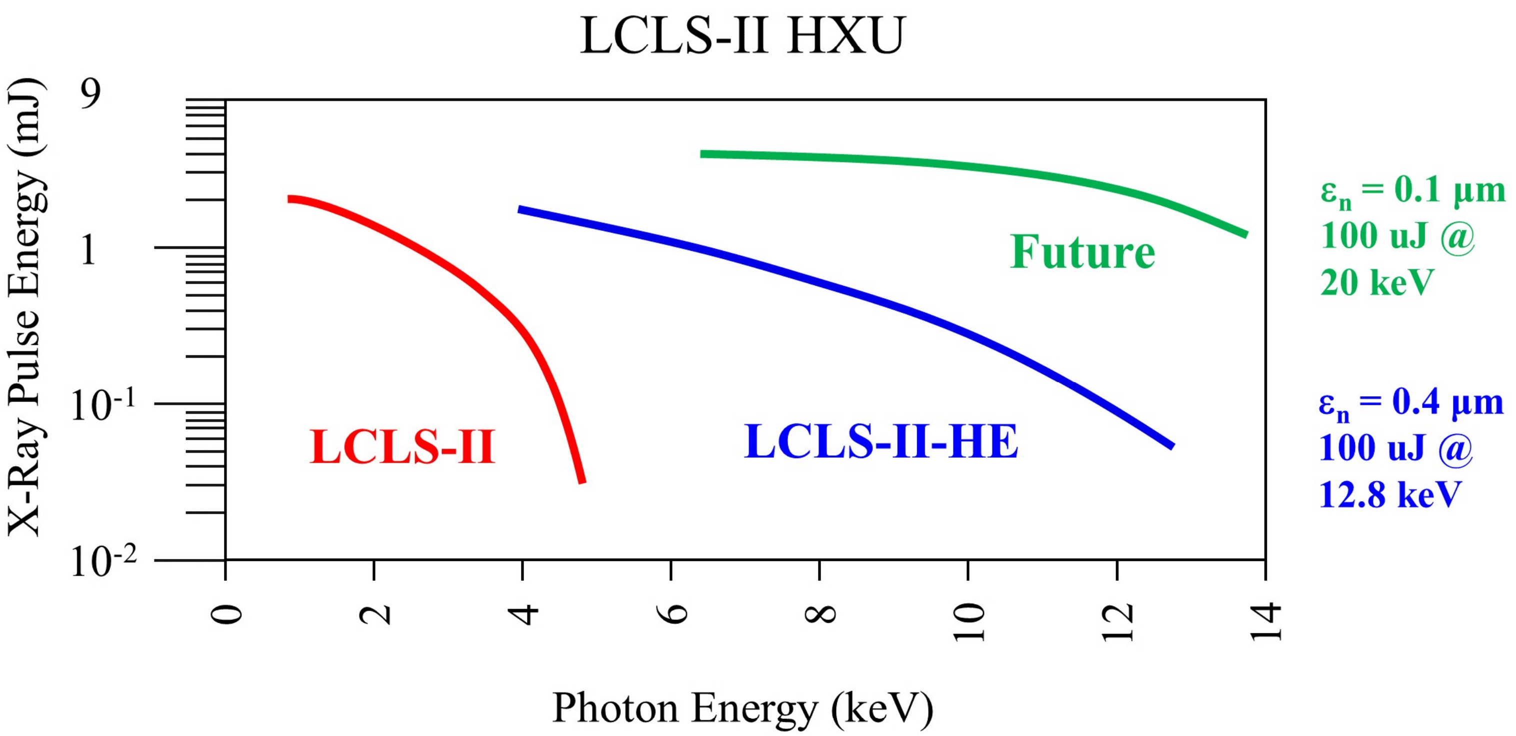
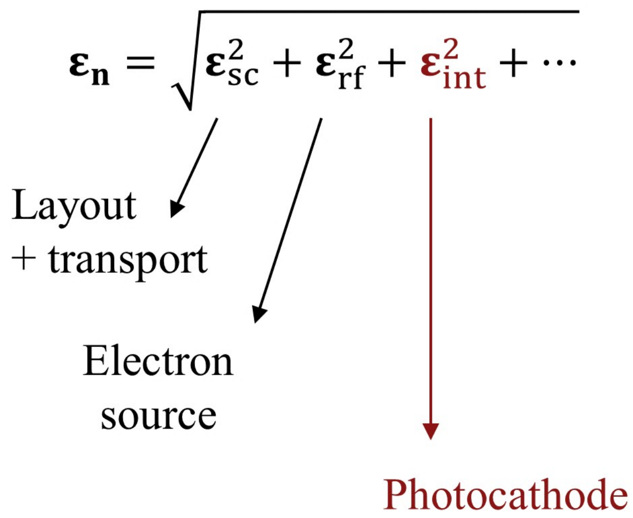
Jefferson Lab EXPLORING THE NATURE OF MATTER
BERKELEY LAB
FRIB
Argonne NATIONAL LABORATORY
Fermilab
CORNELL UNIVERSITY
HZDR

FEL Output as a Function of Electron Beam Emittance





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

current: $\boldsymbol{\varepsilon}_{\mathbf{int}} \geq \mathbf{0.6\ \mu m/mm}$

target: $\boldsymbol{\varepsilon}_{\mathbf{int}} \leq \mathbf{0.3\ \mu m/mm}$

A factor of 4 reduction in slice emittance at the HXU will extend the spectral range to > 20 keV

No single approach to achieve this → multiple parallel efforts … starting with the photocathode

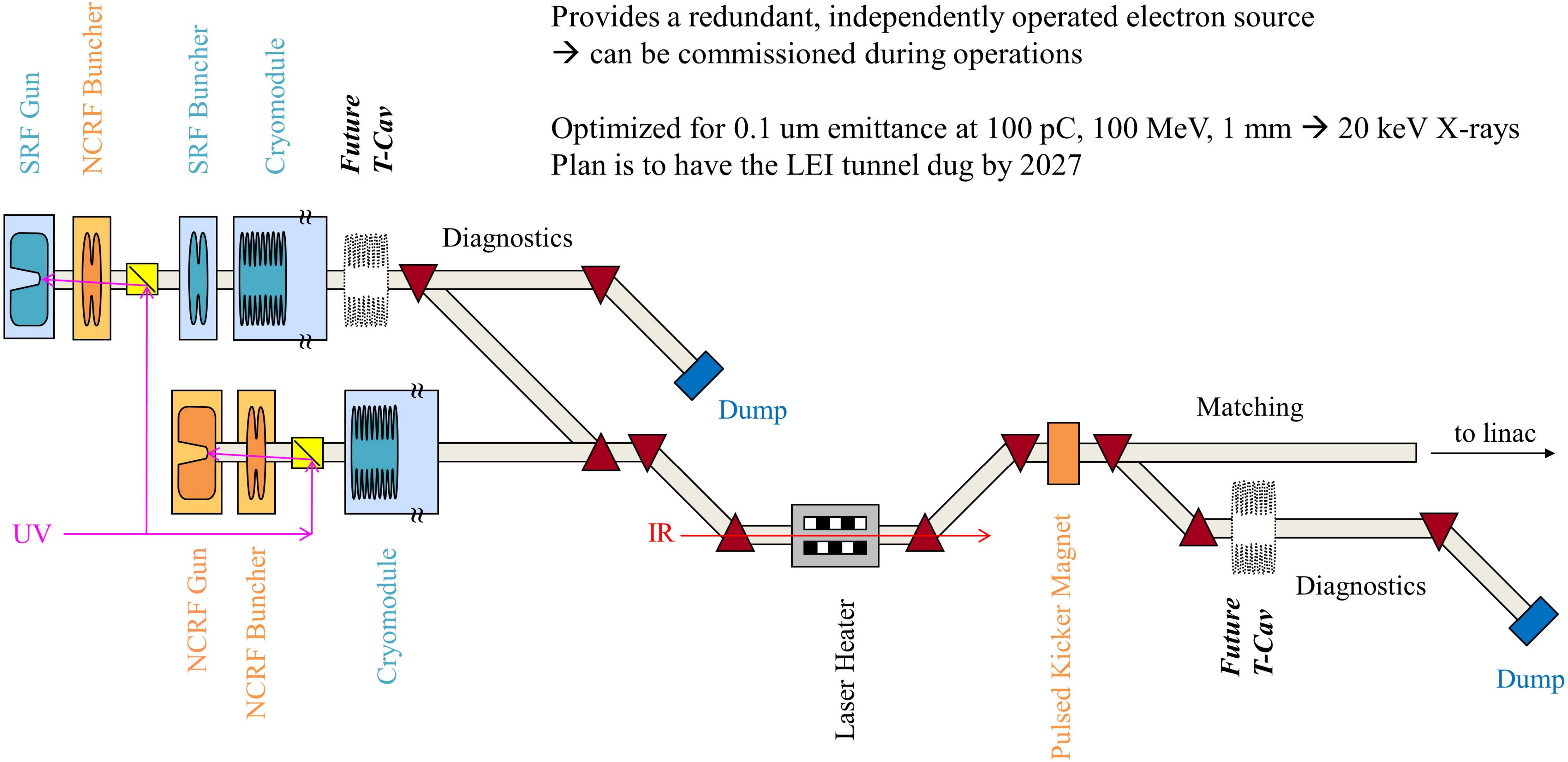
Photocathodes may only be a part … but they are the ***most cost effective*** component to improve

Photocathode improvements may achieve a significant fraction of the desired emittance reduction

LCLS-II-HE Low Emittance Injector (LEI)

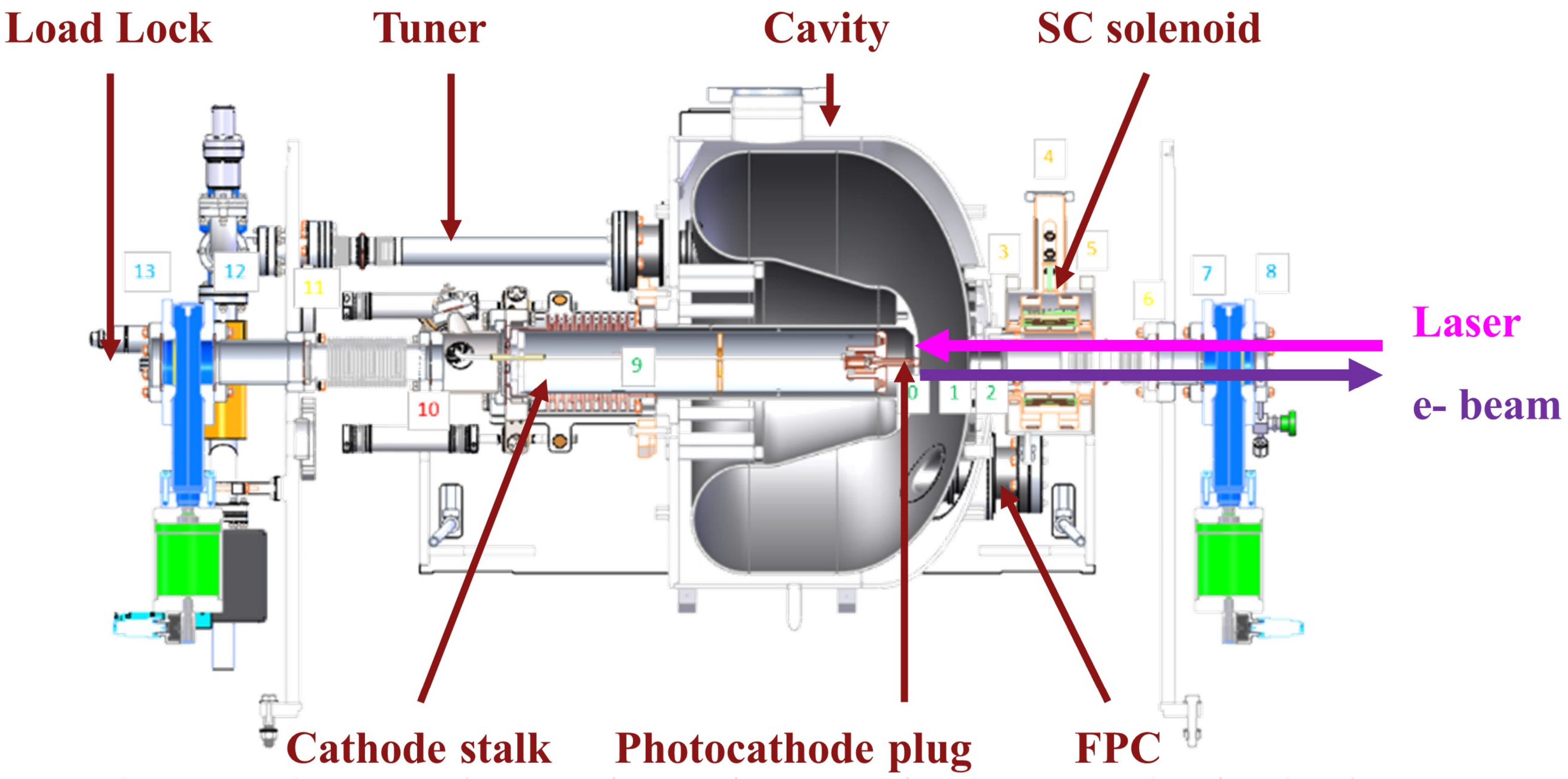
Provides a redundant, independently operated electron source
→ can be commissioned during operations

Optimized for 0.1 um emittance at 100 pC, 100 MeV, 1 mm → 20 keV X-rays
Plan is to have the LEI tunnel dug by 2027

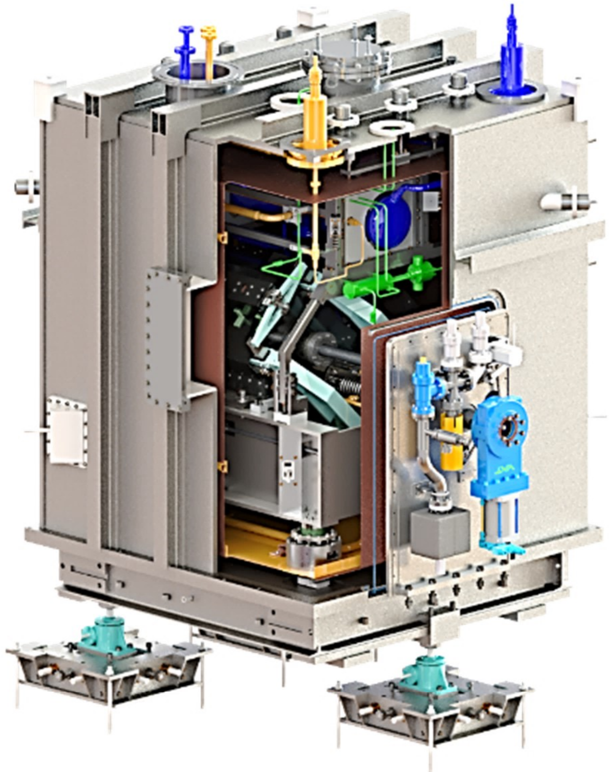


LCLS-II-HE QW SRF Electron Source

Electric field on photocathode ≥ 30 MV/m, 1.8 MeV beam energy
→ optimization represents a significant fraction of the desired emittance reduction
Tested with a metal photocathode at MSU, delivered to SLAC in 2025
Backup: LCLS-II-HE can still meet goals using existing NCRF gun(s)



Load Lock
Tuner
Cavity
SC solenoid
Laser
e- beam
Cathode stalk
Photocathode plug
FPC

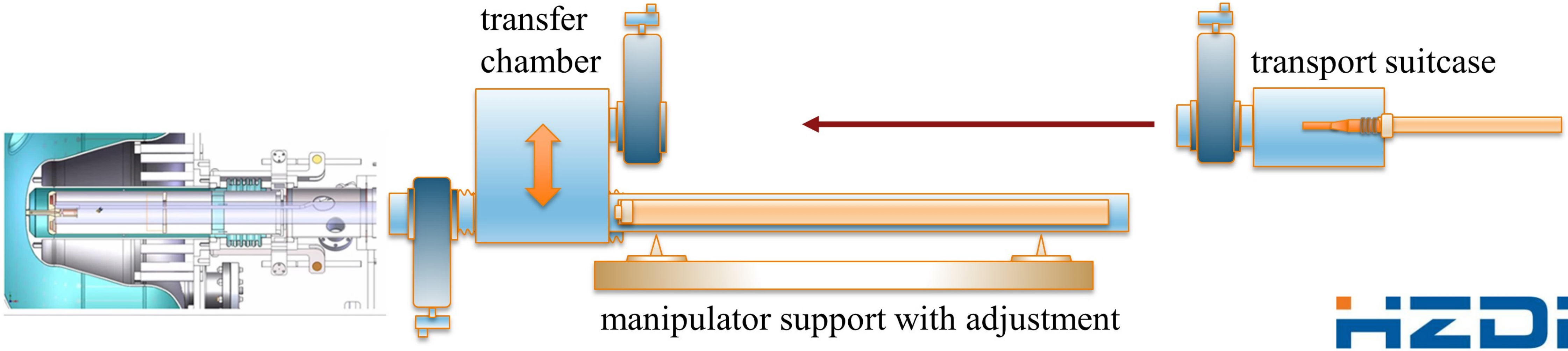


LCLS-II-HE SRF Electron Source Photocathode Exchange System

Photocathode exchange system is being developed by HZDR - both design and prototype demonstration

Tests included:
- Alignment and mechanical fit
- High-power RF + stalk DC bias
- Particle free exchange and insertion

Long plugs are incompatible with the existing LCLS-II growth system
SLAC needs to develop plans for operating with this type of photocathode
… could transport single cathodes from HZDR - but not optimal solution.



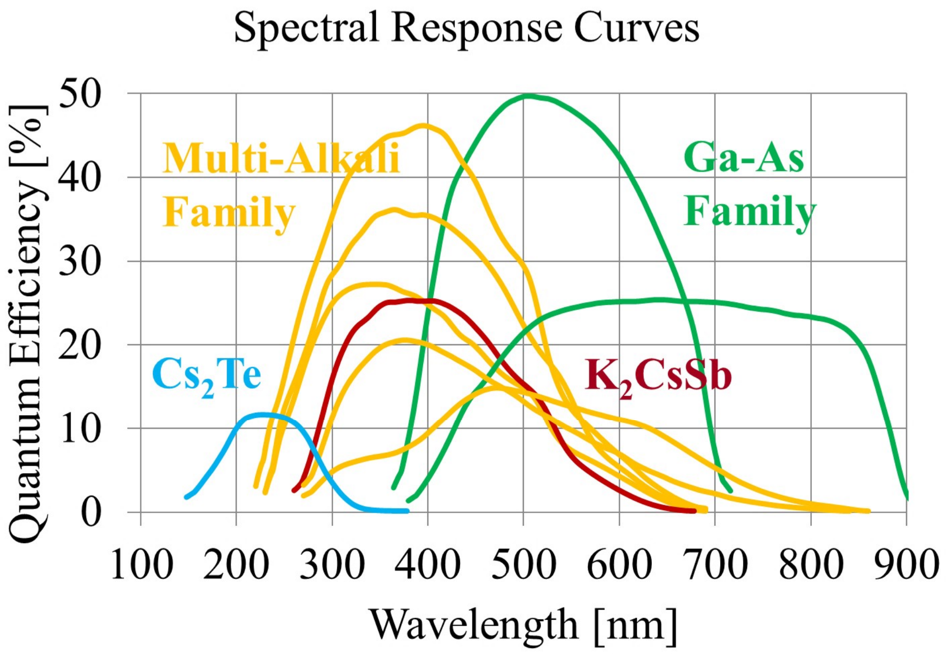
HZDR

SLAC’s Grand SRF Photocathode Challenge

We have $\varepsilon_n = 0.4$ μm at 100 pC, 1 mm, 100 MeV (*in theory*)
We want $\varepsilon_n < 0.1$ μm at 100 pC, 1 mm, 100 MeV

Intrinsic emittance	Operate near threshold for emission
$\varepsilon_{int} \approx 0.6$ μm/mm now	Operate at low temperature
$\varepsilon_{int} \leq 0.3$ μm/mm future	Reduce surface roughness
$\varepsilon_{int} \leq 0.2$ μm/mm eventually	Increase chemical uniformity
Dark current	≪ 1 μA
Quantum Efficiency	Use semiconductor photocathode
QE drops near threshold	QE must be sufficient to generate 100 pC
QE drops with temperature	without multiphoton contributions
	but QE > 0.1% is not strictly a requirement
	Visible or IR wavelength preferred for laser shaping
Temporal Response	< 50 ps, bunched downstream to ≪ 1 ps
	≪ 1 ps at the photocathode is not necessary
1/e Lifetime	> 1 week (*operational issue*)

Photocathode must also not generate particles or contaminate the cavity



Motohiro Suyama, Hamamatsu

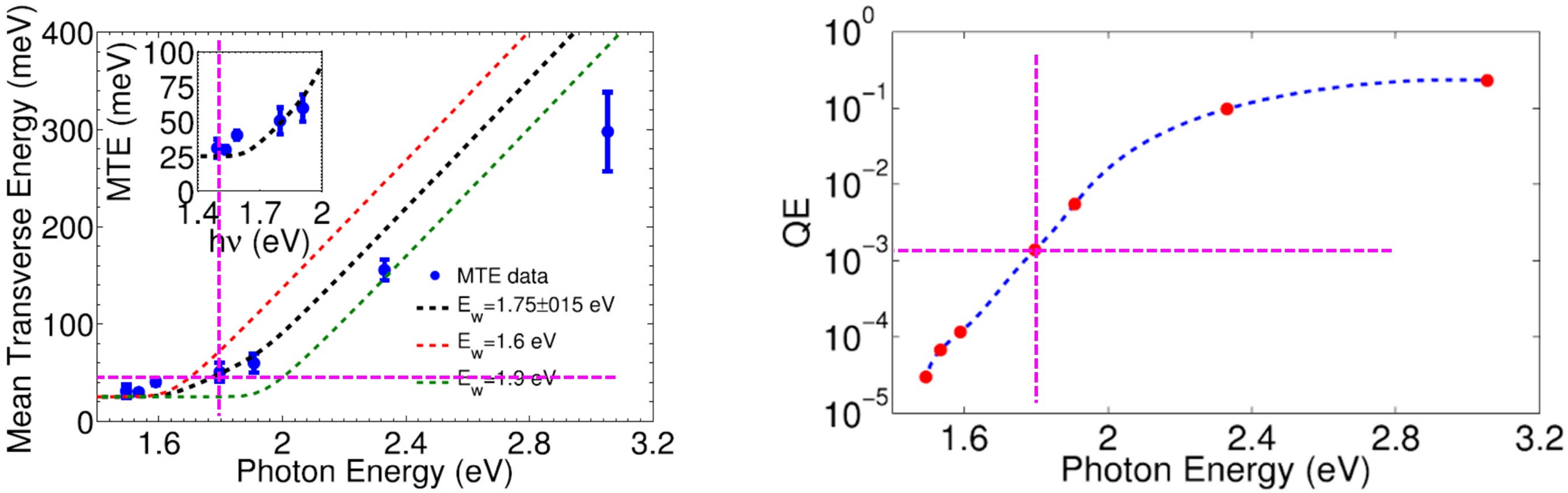
Challenge: Which to use?

Conventional: Cs_3Sb
More exotic: $Cs_3Sb{:}Na_2KSb$
Novel: Na_2O

S20 Photocathode

“S20” photocathode = Cs_3Sb on Na_2KSb

Demonstrated 0.3 µm/mm intrinsic emittance (50 meV) at 690 nm and 300 K while maintaining a QE > 0.1%



Cultrera et al. APL 108, 134105 (2016)

Questions:

Are these results robust?
Do they translate to high gradient?
Is a significant amount of dark current generated?
Can these results be improved with single crystal epitaxial growth?
Are there other candidates like this?

US DOE BES funded LEI Photocathode Effort

Work supported under contract number DE-AC02-76SF00515 through FWP100903

Multi-institution collaboration to determine the best photocathode to achieve $\varepsilon_{int} \leq 0.3$ µm/mm with QE ≥ 0.1% for the LCLS-II HE
Use high gradient facilities to demonstrate the applicability of low gradient laboratory successes for improved photocathode performance

High Gradient Characterization

UCLA and LBNL photoinjectors both use LCLS-II style plugs

1. Produce photocathodes
    - Baseline: LCLS-II $CsTe_2$ production system at SLAC
    - Evaluate RMD’s sealed capsule photocathodes
    - ASU is also evaluating a modified INFN plug with removable tip to increase substrate options and to improve compatibility with surface science systems
2. Transfer photocathodes to high gradient facilities
3. Measure dark current and lifetime at ≥ 20 MV/m

**** BONUS ****

SLAC field emission tests
30 MV/m DC (300V over 10µm) w/ proximal probe systems (STM, nanoprobes)

Low Gradient Characterization

Cornell and ASU both have in-house materials science facilities

1. Reduce surface roughness and increase chemical uniformity with epitaxial growth on smooth single crystal substrates.
   Note: epitaxial growth may also help with ‘particle free’ and cavity contamination concerns.
2. Measure the temperature and wavelength dependence of QE and intrinsic emittance. Cross check results at Cornell and ASU for consistency and reproducibility
3. Assess multi-photon and laser heating effects at low QE

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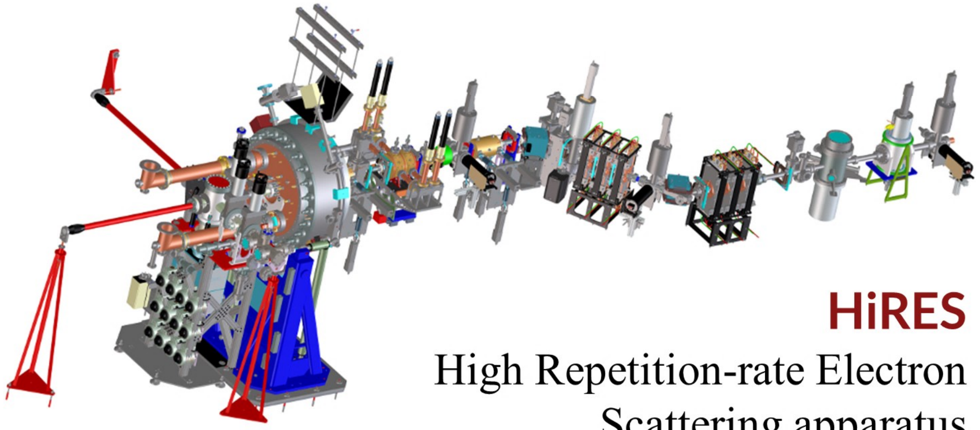
ASU ARIZONA STATE UNIVERSITY

BERKELEY LAB

High Gradient Photocathode Studies at LBNL

‘Medium’ gradient CW 186 MHz photoinjector

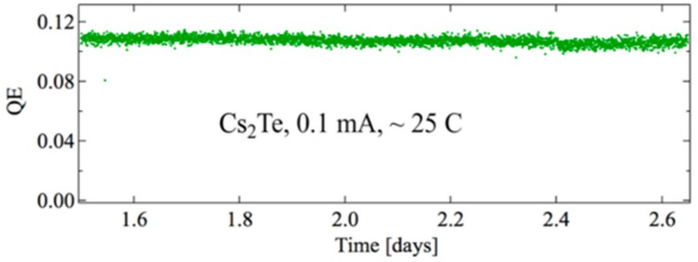
Able to fully characterize the photoemitted electron beam



HiRES

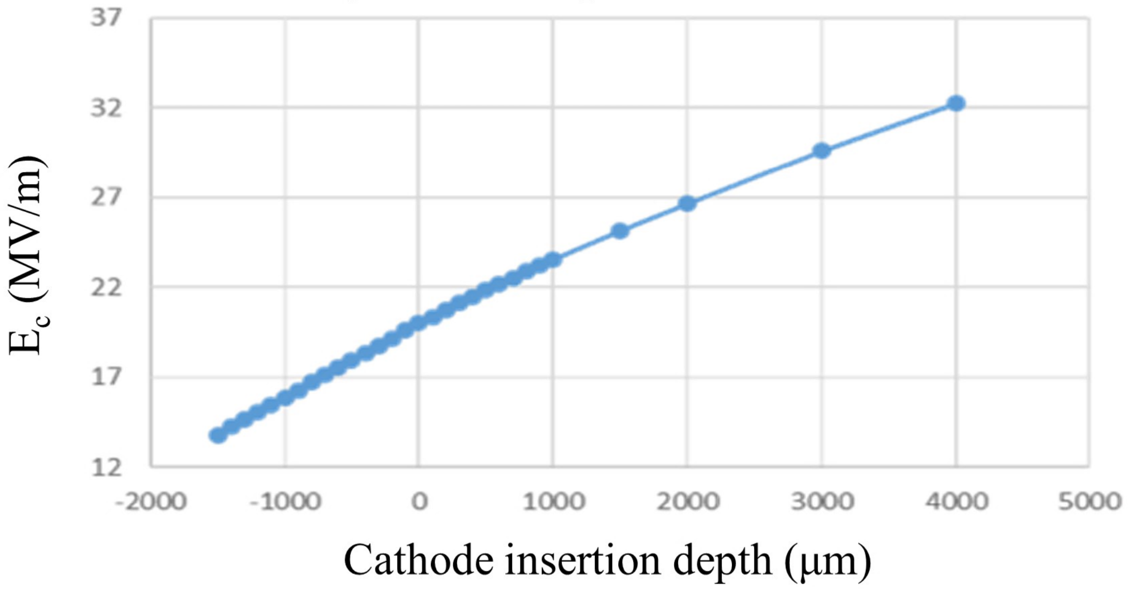
High Repetition-rate Electron Scattering apparatus

Lifetime measurements of different photocathodes produced by partner labs

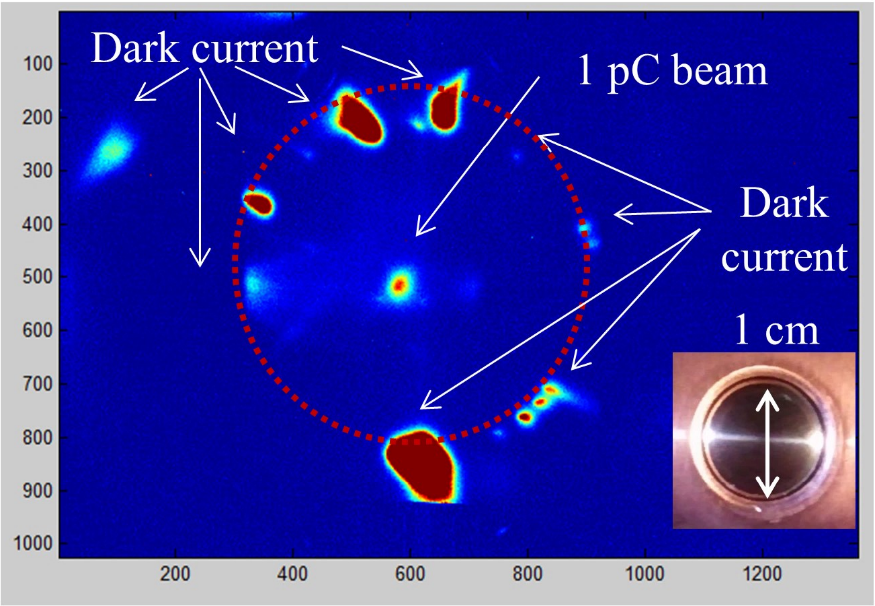


LCLS-II compatible photocathode plug and exchange system

Can optimize plug geometries to increase the accelerating field at the photocathode to ≥ 25 MV/m



Characterization of dark current from cathode source imaging and average current transmitted



High Gradient Photocathode Studies at UCLA

High gradient S-band gun photoinjector (40-100 MV/m)

Pulsed @ 10 Hz

Operating vacuum ≤ 1×10^{-9} torr

Wavelength tunable, spatially shapeable laser

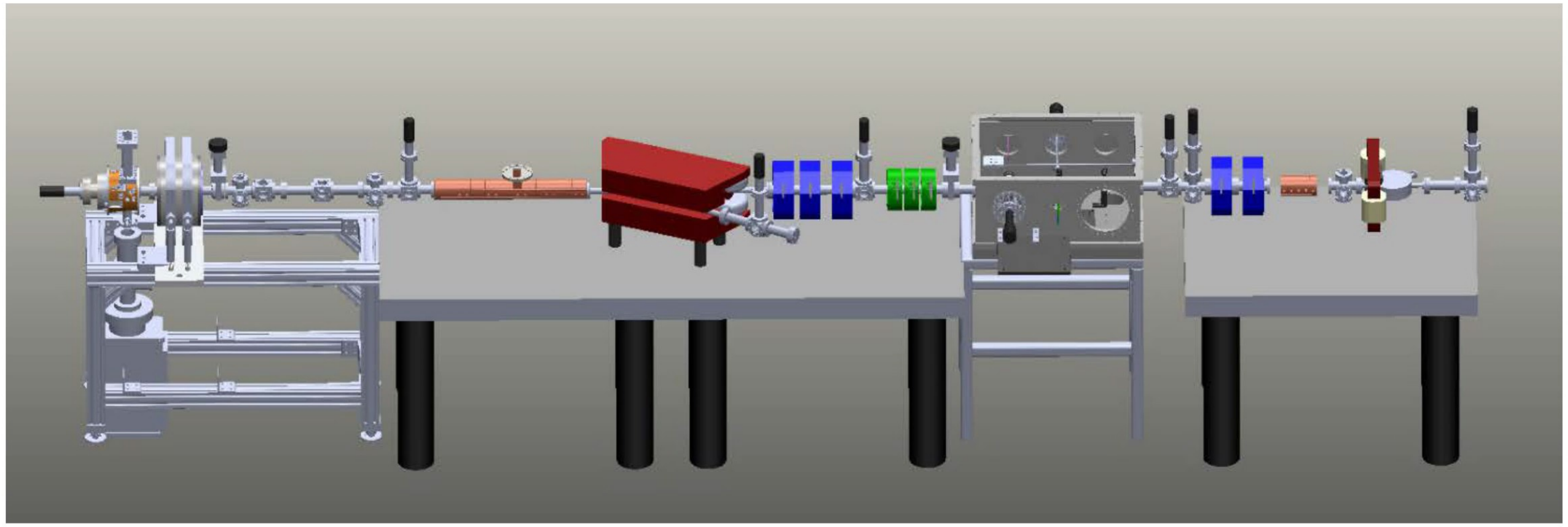
Well-characterized beamline

- Study novel photocathode concepts
- Study surface roughness effects

LCLS-II compatible photocathode plug and exchange system

PEGASUS

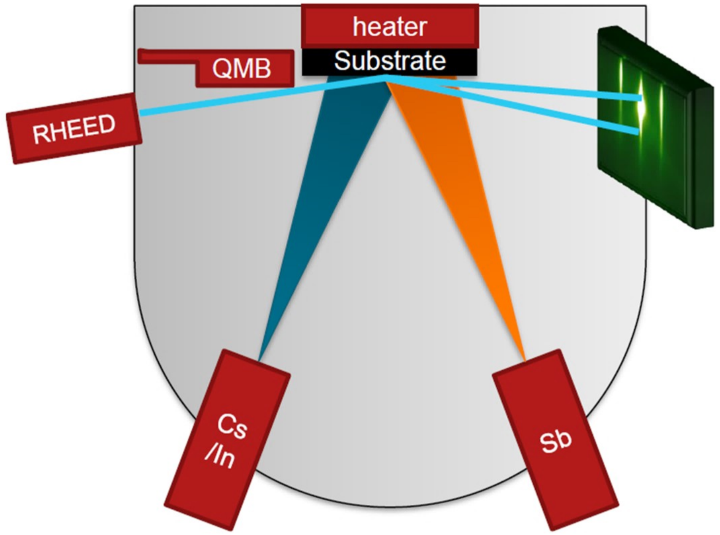
Photoelectron Generated Amplified Spontaneous Radiation Source



Low Gradient Photocathode Studies at Cornell

Meet **PHOEBE**: **PHO**tocathode **E**pitaxy and **B**eam **E**xperiments laboratory

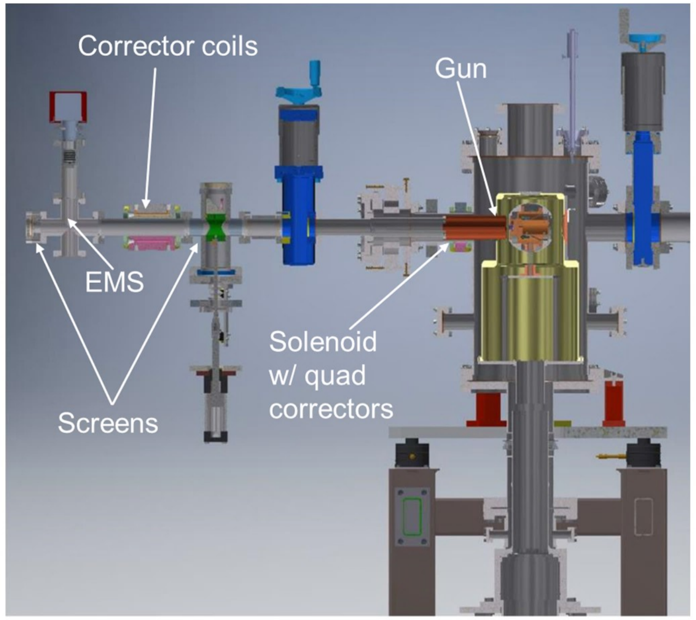
Photocathode MBE system

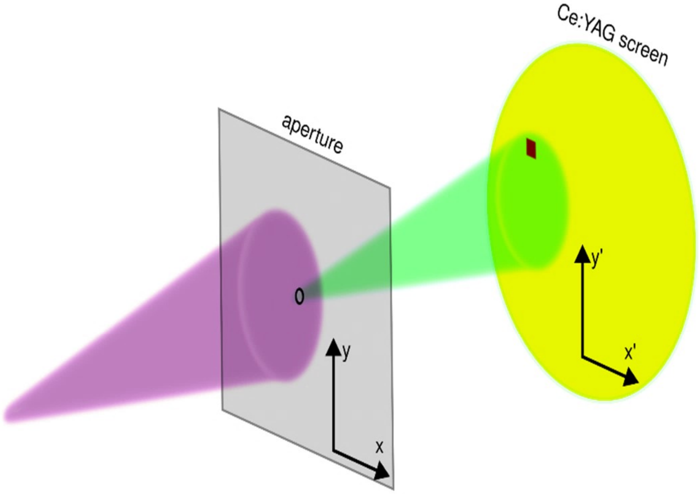


Cryo-TE meter

A 10 keV gun cooled to 18 K with diagnostic beamline

Accepts cathodes via suitcase

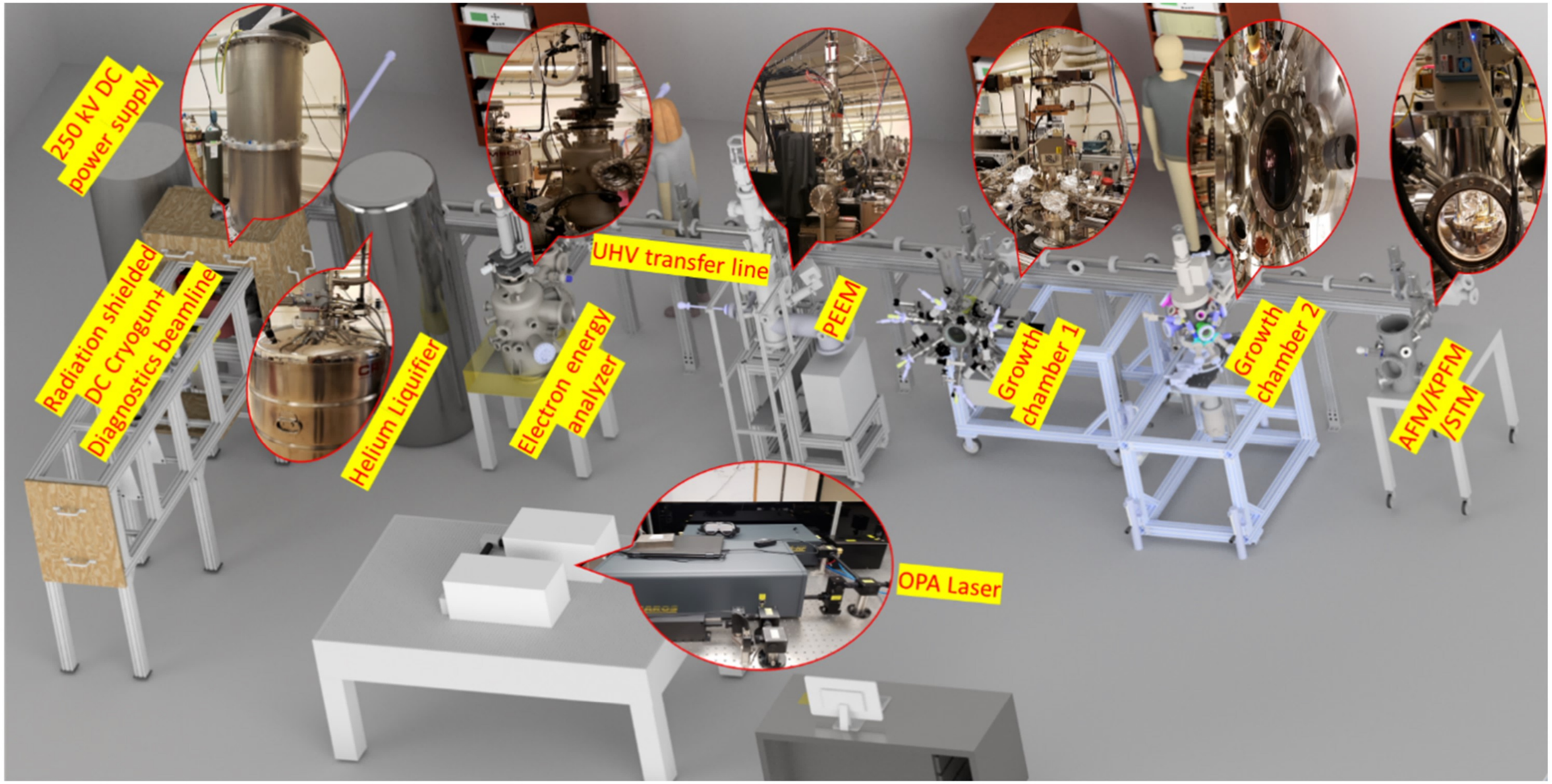




Transverse phase space diagnostic

Low Gradient Photocathode Studies at ASU

200 kV cryocooled DC gun for detailed photoemission characterization
Atomic scale surface characterization to study the effects on physical and chemical roughness on intrinsic emittance

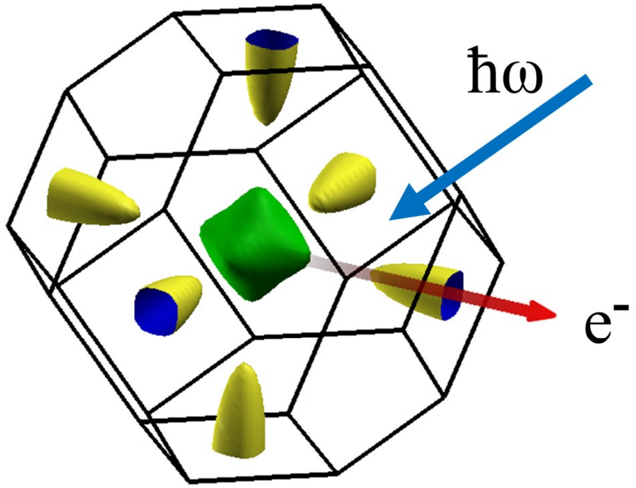


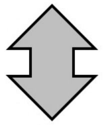
US DOE ARDAP Accelerator Stewardship Funded Effort

From Theory to Practical High-Brightness Photocathodes

PI: W. Andreas Schroeder @ UIC under grant DE-SC0020387
In collaboration with SLAC under FWP 100917

- 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)
- Demonstrate ≤ 0.3 μm/mm intrinsic emittance and a QE ≥ 0.1% at ≤ 300 K using a soon-to-be commissioned cryogenic transverse momentum measurement system at SLAC



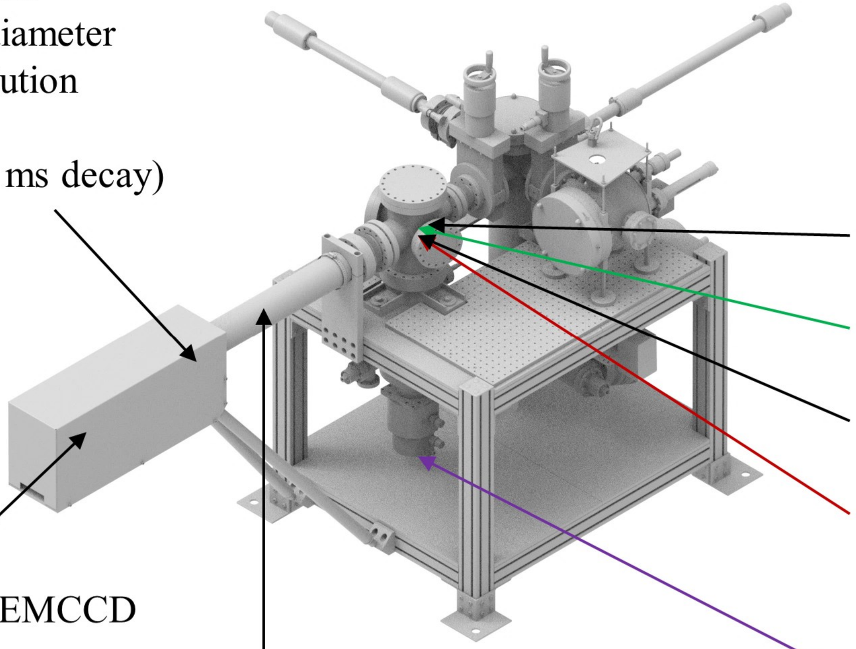


***Ab initio* Theory**

MTE(ħω)
QE(ħω)

Cryogenic Momentatron being Commissioned at SLAC

- Characterize the performance of LCLS-II photocathodes 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)

Quantity 2 of
TDK-Lambda
PHV 20 kV

Andor Xion 888 EMCCD

Mu-metal shielded drift

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

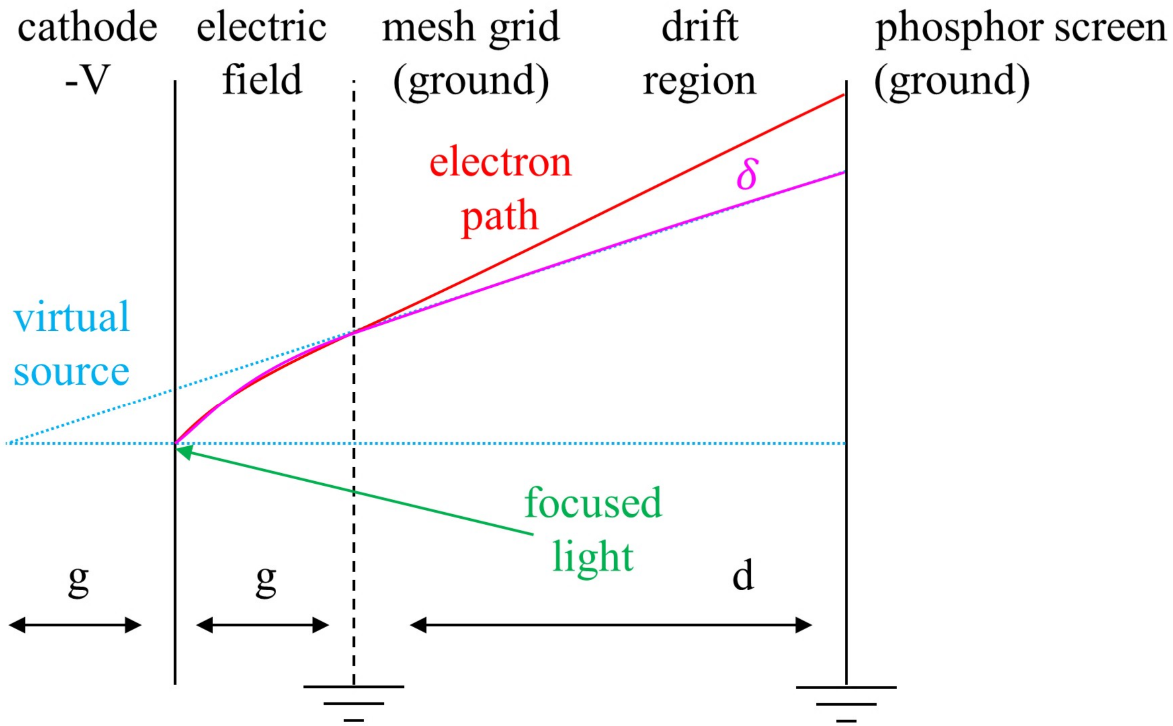
Advanced Research Systems
DE-215 Cryocooler
30 W at 45 K
1.5 W at 4.2 K

SAFETY FIRST!

Highest priority at SLAC

Enhanced WPC has delayed system commissioning a ‘little’

Momentatron: Transverse Momentum Measurement System



r_d = radial coordinate on detector, < 5 mm
r_g = radial coordinate on grid w.r.t. nearest grid hole center
g = cathode-anode (grid) gap, 0.020 m
d = drift distance, 0.980 m
δ = angular kick from mesh-lensing effect
V = applied voltage, 20 kV max → 1 MV/m

Mesh Grid
Pitch = 50.8 μm
Support = 0.9 μm
Hole = 41.8 μm

Davisson and Calbick Lens, Mesh-Lensing Effect
Yu et al., RSI 92, 013302 (2021).

$$\delta = \frac{r_g}{8\,g}$$

Vecchione et al., APL 99.3 (2011).

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

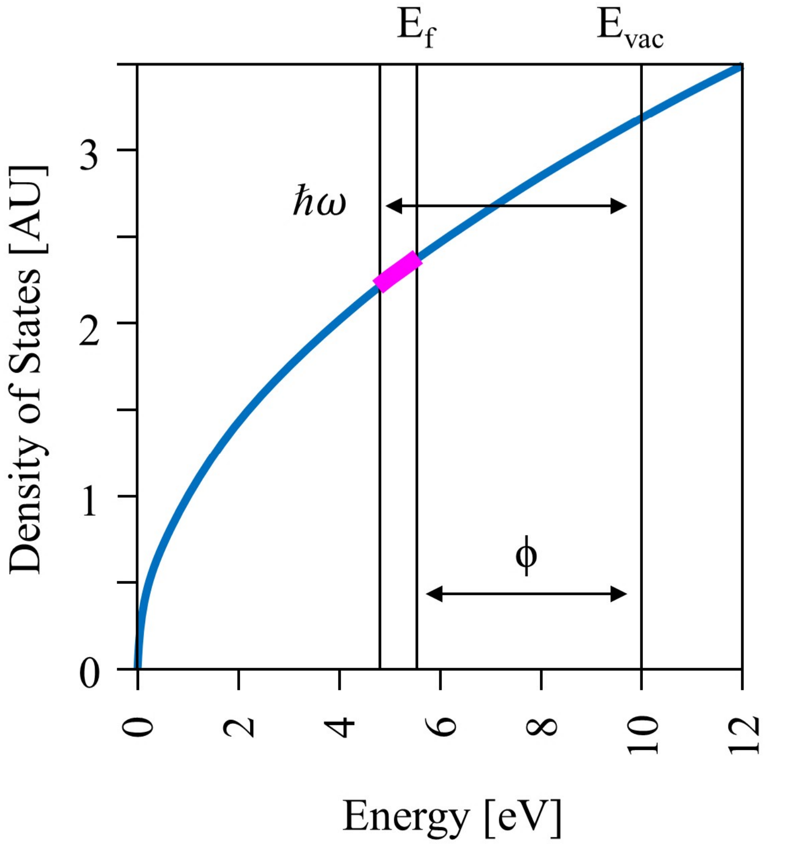
$$\downarrow$$

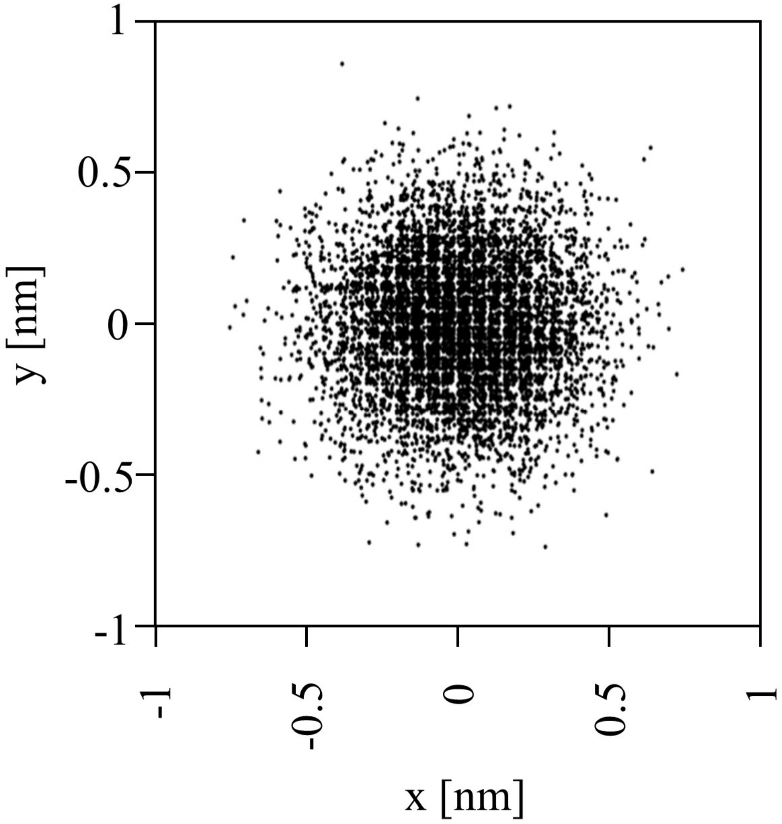
Normalized emittance $$\varepsilon_{nx} = \left(\frac{1}{m_0 c}\right)\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \cancelto{0}{\langle x p_x\rangle^2}}$$

$$\downarrow$$

Intrinsic emittance $$\varepsilon_{int}\left[\frac{\mu m}{mm}\right] \equiv \frac{\varepsilon_{nx}}{\sqrt{\langle x^2\rangle}} \approx 0.061\,\sqrt{V[kV]}\;r_{rms}[mm]$$

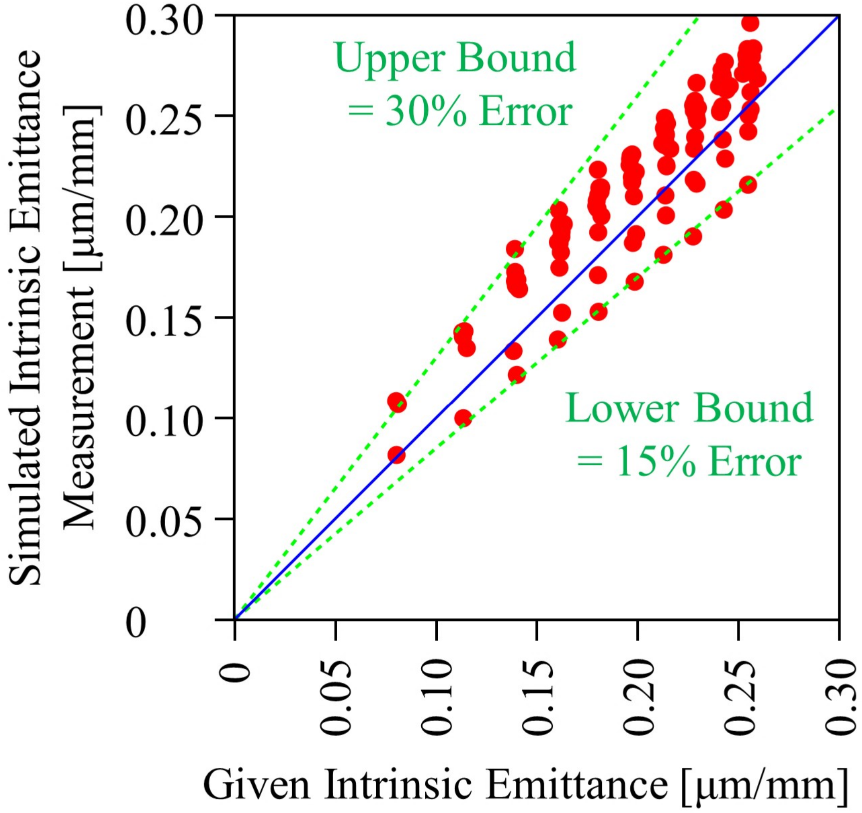
Momentatron: System Resolution





Simulated electron pattern on the detector

Analysis by Gowri Adhikari



Free-electron model:

Fermi energy	$E_f = 5.49$ eV
Photon energy	$\hbar\omega = 4.84$ eV
Work function	$\phi = 4.64$ eV

Condition for credible data:

$$\varepsilon_{\mathrm{int}}\left[\frac{\mu\mathrm{m}}{\mathrm{mm}}\right] \geq 0.61\sqrt{V[\mathrm{kV}]}\,\sigma_{\mathrm{rms}}[\mathrm{mm}]$$

$$\sigma_{\mathrm{rms}}[\mathrm{mm}] \leq \frac{1}{10}\,r_{\mathrm{rms}}[\mathrm{mm}]$$

Summary: use small laser spot and low voltage

Summary

- The LCLS-II has been successfully commissioned
  ~0.5 µm emittance @ 80 MeV w/ 50 pC, 1 mm bunch length
  ~0.4 µm emittance @ 90 MeV w/ 20 pC, < 1 mm bunch length
  Lots of opportunity to improve – stay tuned!

- Current LCLS-II Cs_2Te photocathode has be used for ~ 2 years
  QE has degraded and the QE map has changed, but the current QE is sufficient to support the beam program
  Cause of QE decay is a mystery: ion ~~back-bombardment~~, ~~back-propagating~~ or secondary electrons, laser heating?

- SLAC is engaged in BES funded collaboration to reduce intrinsic emittance.
  Goal is to achieve ≤ 0.3 µm/mm with ≥ 0.1% QE, good lifetime and minimal dark current production.
  This would **help** to bring the normalized emittance at the FEL undulator down from ~ 0.4 µm to ~ 0.1 µm.
  Effort addresses the question of which photocathode should be used in SLAC's future SRF gun.

- SLAC is engaged in an ARDAP funded collaboration with UIC.
  Goal is to use photoemission modeling based on ab initio band structure calculations to find a single-crystal materials with ≤ 0.2 µm/mm intrinsic emittance and then to demonstrate at least ≤ 0.3 µm/mm with ≥ 0.1% QE at UIC.
  A cryogenic momentatron system is being commissioned at SLAC which will replicate these results on LCLS-II plugs.

Thank you for your attention!

Questions?