# Photocathode Endeavors at SLAC National Accelerator Laboratory

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Photocathode Physics for Photoinjectors
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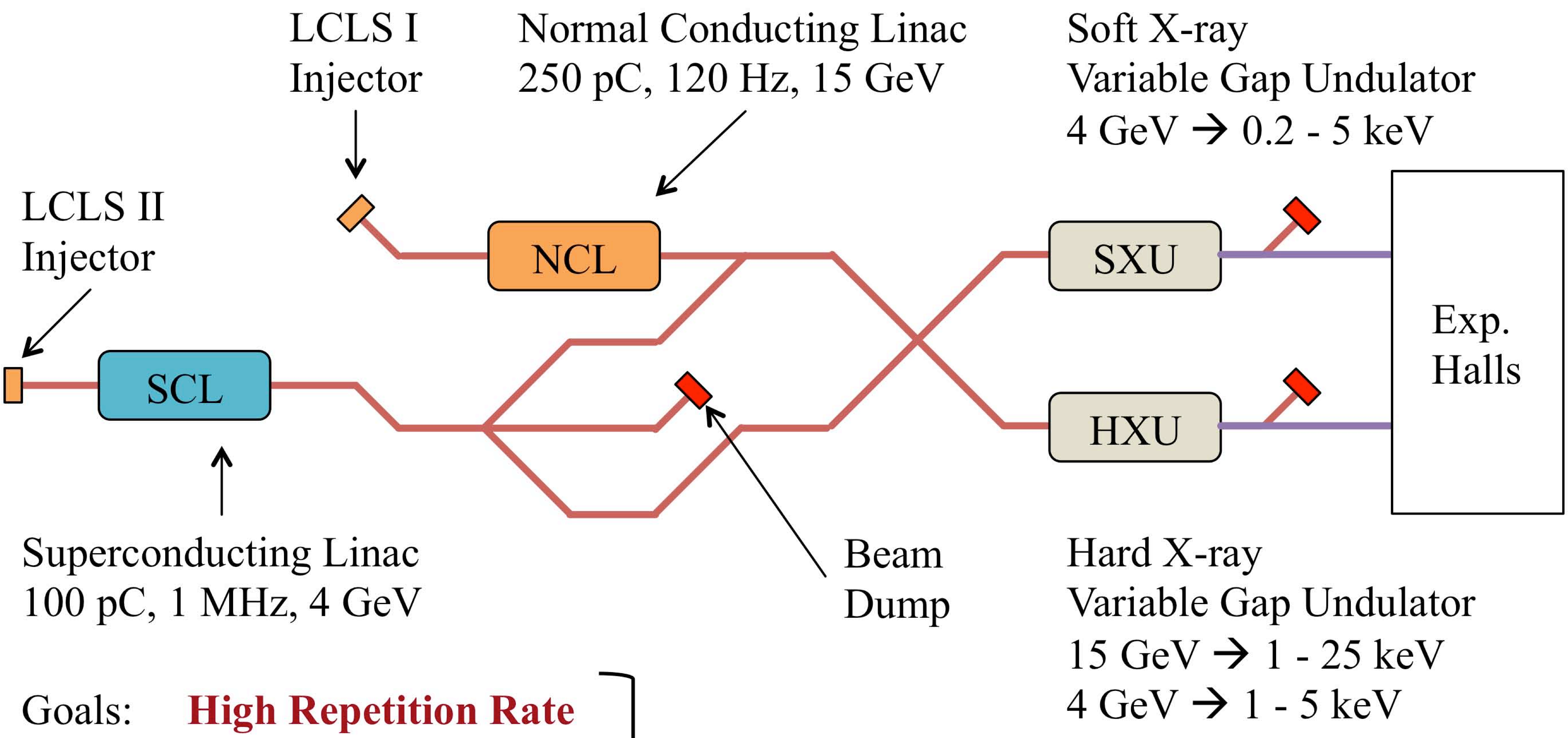
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

# Outline

- **Supplying Photocathodes for the LCLS II**
- Modest Photocathode Optimization for Future FELs
- Simulations for Predicting Significant Photocathode Improvements

# LCLS II




Goals:
- **High Repetition Rate**
- **Large Spectral Range**
- **Spectral Tunability**
- **Increased Coherence**

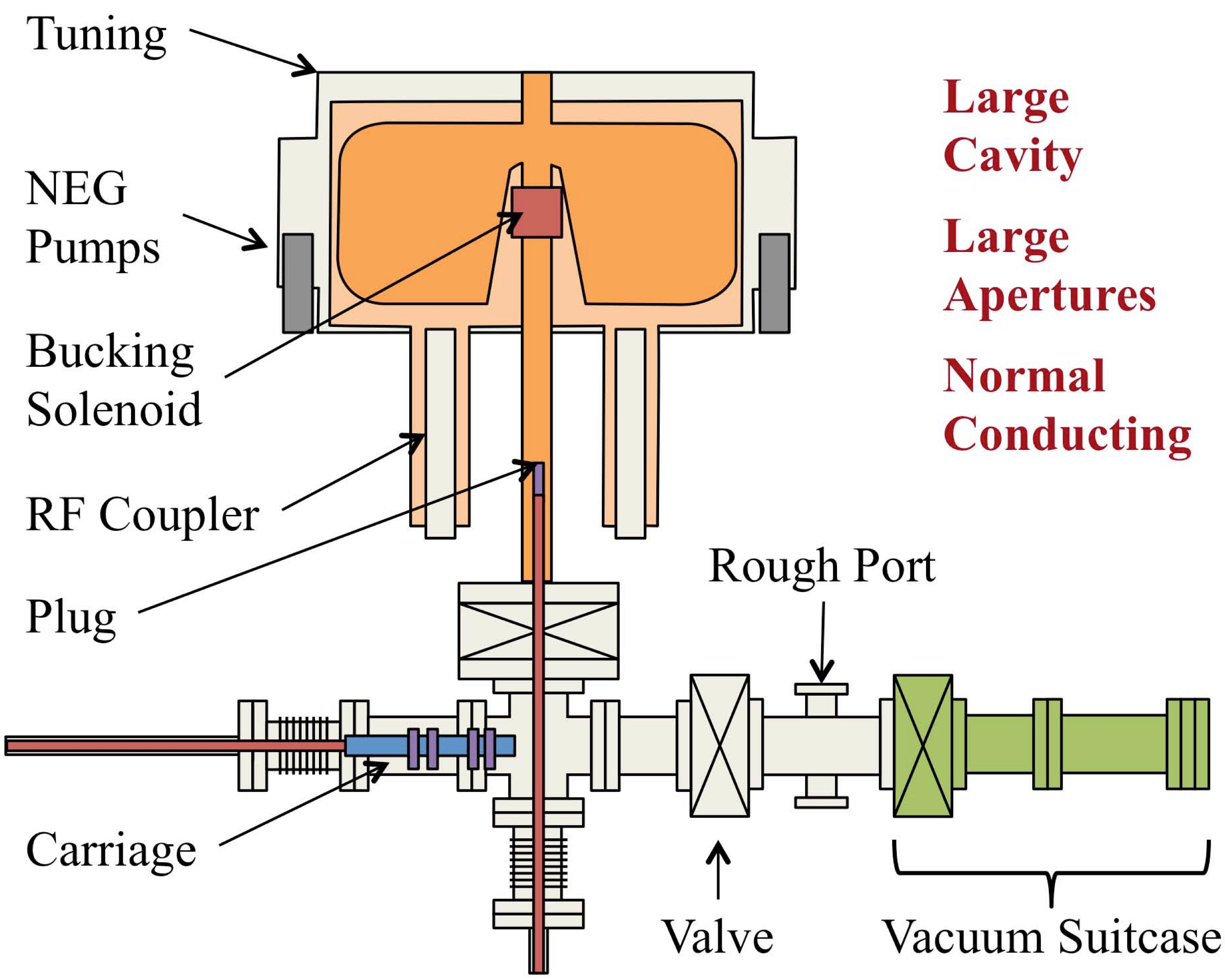
Scientific case laid out in 2013 BESAC report

# LCLS II Injector


| | |
|---|---|
| Repetition Rate | 0.929 MHz |
| Bunch Charge | 100, 10 - 300 pC |
| Peak Current | 12, 4 - 50 A |
| 95% Slice Emittance | 0.4, 0.2 - 0.6 μm |
| Bunch Length | 0.3 - 10 mm |
| Slice Energy Spread | 1 - 5 keV |

| | |
|---|---|
| **Photocathode QE** | **> 0.5 %** |
| **Intrinsic Emittance** | **< 1 μm/mm** |
| **1/e Lifetime** | **> 10 days** |
| UV @ Photocathode | 300 nJ |
| 1 nJ → 1 pC @ 0.5% QE | |
| IR @ Laser Heater | 15 μJ |
| 15 μJ, 30 ps → 20 keV | |

# LCLS II VHF Normal Conducting RF Gun




**Large Cavity** → Dissipate CW heat load

**Large Apertures** → High vacuum conductivity, High QE photocathodes

**Normal Conducting** → Reliability

| | |
|---|---|
| Frequency | 186 MHz |
| Gradient | 20 MV/m |
| Energy | 750 keV |
| Vacuum | $< 5 \times 10^{-10}$ torr |

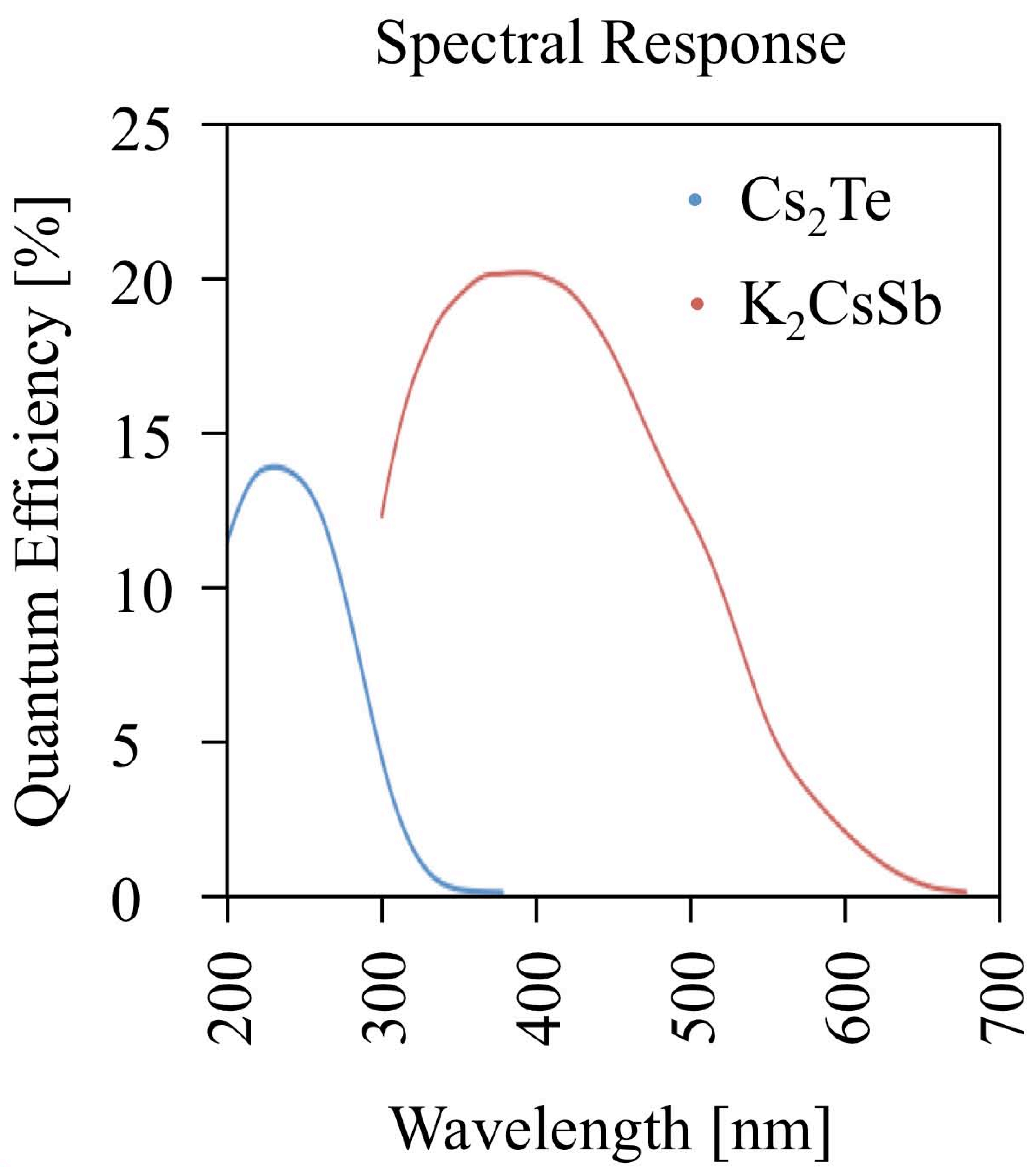
K. Baptiste et al., NIMA 599, 9 (2009)
F. Sannibale et al., PRST-AB 15, 103501 (2012)

# Photocathodes for the LCLS II

Performance summary of photocathodes at APEX

| | | $Cs_2Te$* INFN | $K_2CsSb$ LBNL |
|---|---|---|---|
| Vacuum Requirement | [torr] | $< 10^{-9}$ | $< 10^{-10}$ |
| Laser Wavelength | [nm] | 263 | 526 |
| Initial QE | [%] | > 10 | ≤ 8 |
| Intrinsic Emittance | [μm/mm] | 0.7-0.8 | < 0.60 |
| Service Life | [days] | 50 | |
| Storage Life | [days] | ∞ | > 30 |

*D. Filippetto et al., APL 107, 042104 (2015)

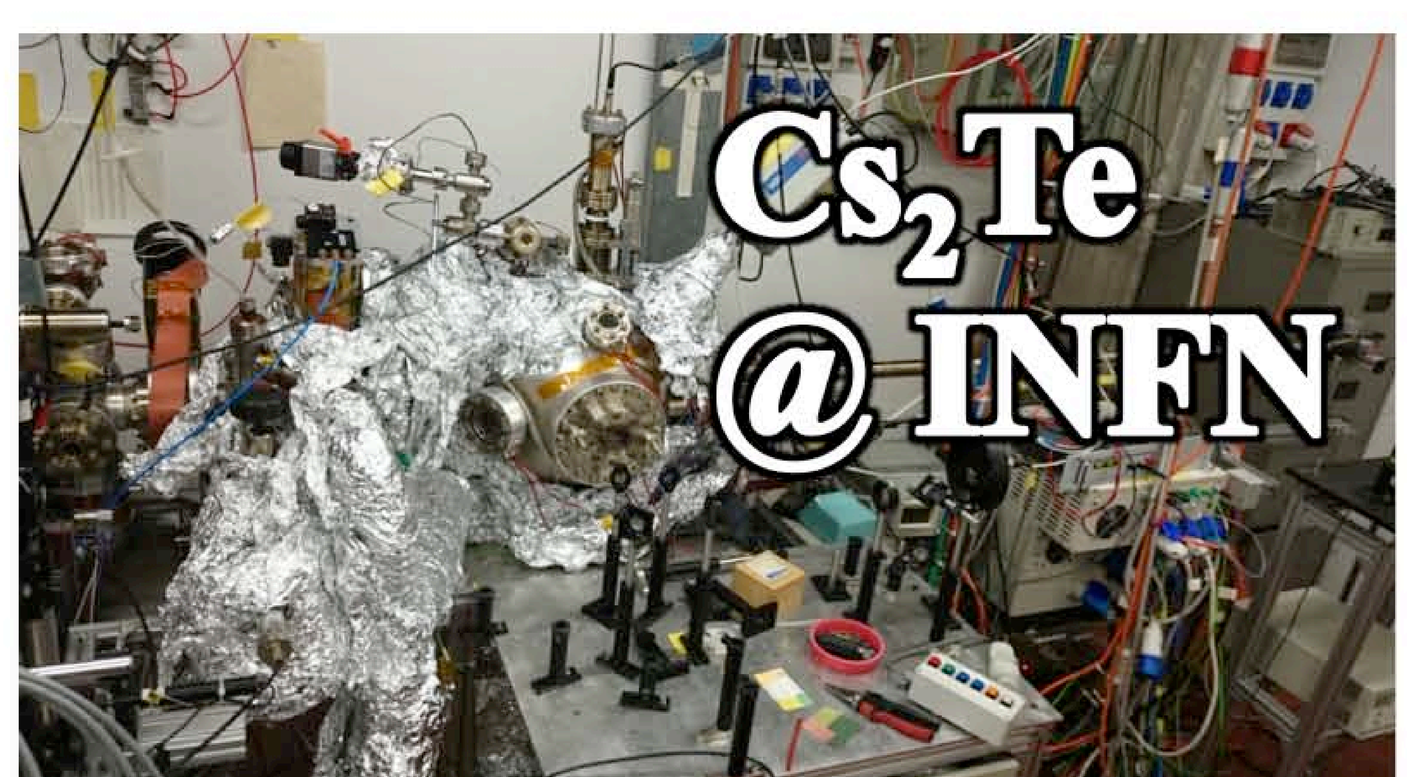



**Conservative approach →**
**$Cs_2Te$ was chosen as the LCLS II baseline**

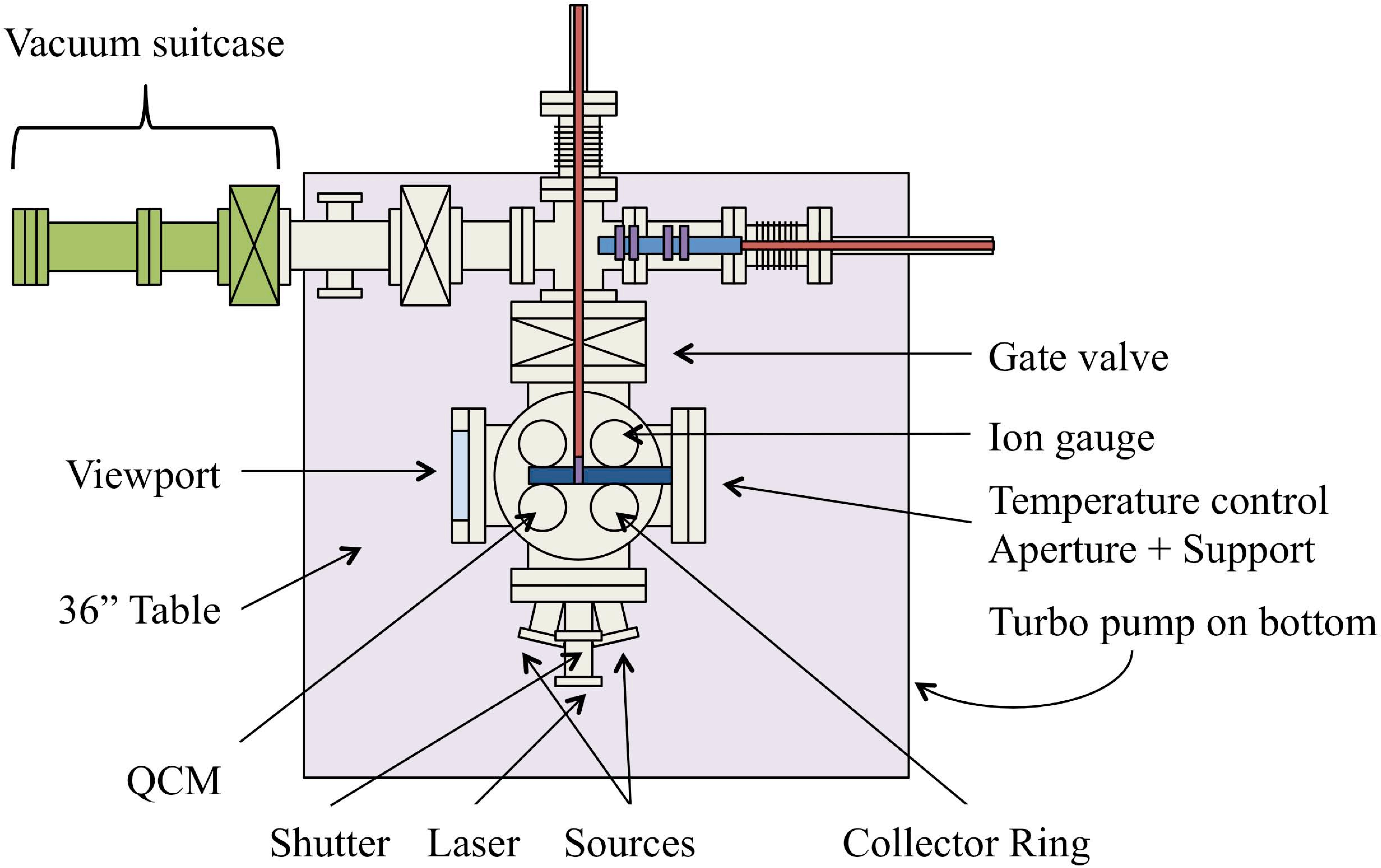
# Providing Photocathodes for the LCLS II

| Calendar Year | 17 | | | | 18 | | | | 19 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Quarter | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| LCLS Shutdown | ■ | ■ | | | | | ■ | ■ | ■ | ■ | | |
| Injector Installation | | | ■ | ■ | | | | | | | | |
| Injector Commissioning | | | | ■ | ■ | ■ | | | | | ■ | ■ |
| **Purchase Photocathodes** | | ■ | ■ | ■ | ■ | ■ | | | | | | |
| Appropriate Lab Space | | | | ■ | ■ | | | | | | | |
| Diagnostic System Commissioning | | | | | ■ | ■ | ■ | | | | | |
| Deposition System Commissioning | | | | | | | ■ | ■ | ■ | | | |
| **Photocathodes Produced at SLAC** | | | | | | | | | ■ | ■ | ■ | ■ |

Suppliers



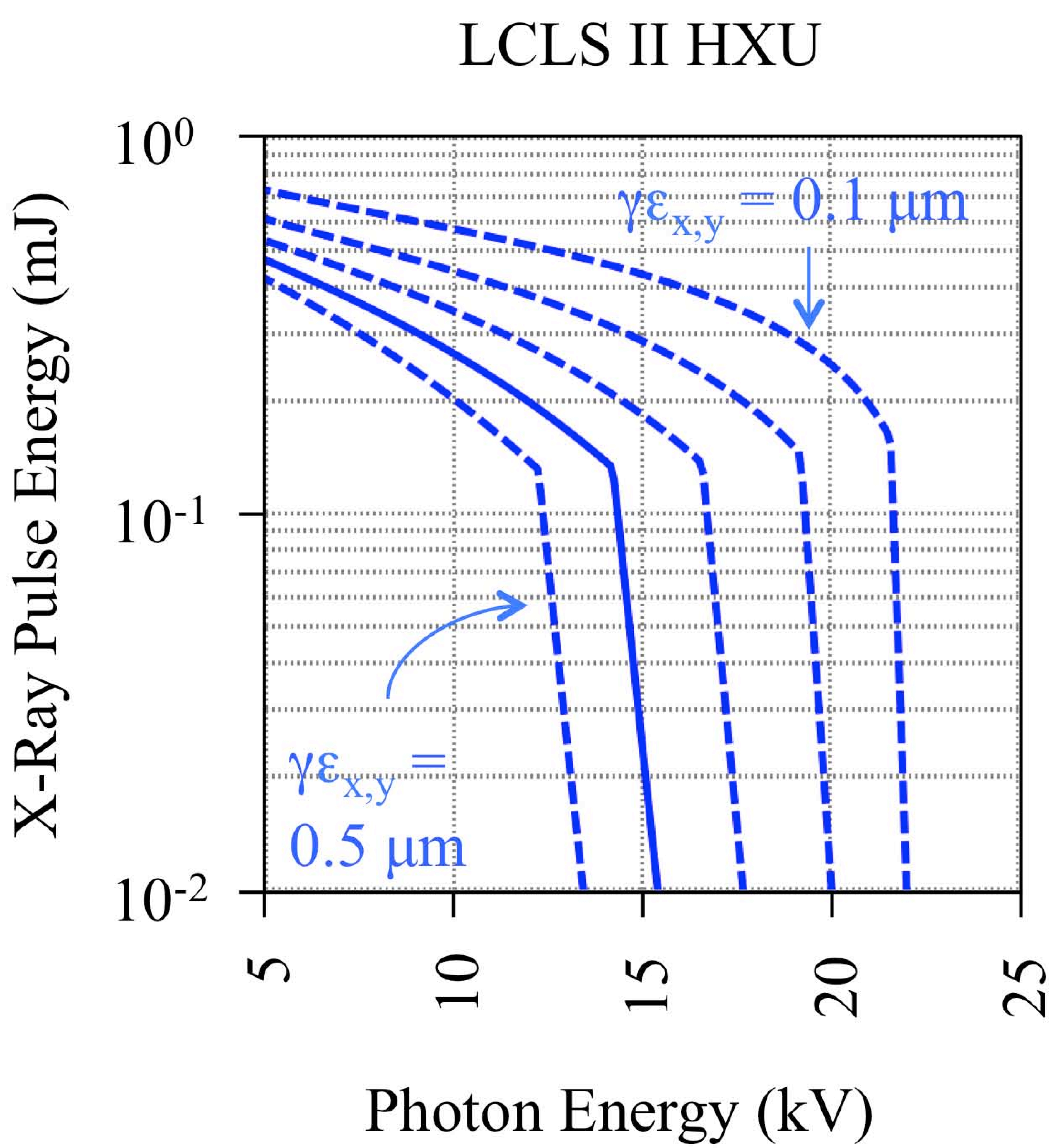

# Initial Conceptual Design of a Deposition System for LCLS II Photocathodes



# Outline

- Supplying Photocathodes for the LCLS II
- **Modest Photocathode Optimization for Future FELs**
- Simulations for Predicting Significant Photocathode Improvements

# Future FELs Need Lower Emittance




| | | | |
|---|---|---|---|
| $I_{pk}$ | = 1 kA | E | = 8 GeV |
| Q | = 100 pC | $\sigma_E$ | = 0.5 MeV |
| $L_u$ | = 140 m | $\langle\beta_{x,y}\rangle$ | = 20 m |
| $\lambda_u$ | = 26 mm | $p_f$ | = 0.8 |

FEL radiated power is a function of the FEL parameter, ρ, which in turn depends implicitly on emittance, $\varepsilon_x$, through $\sigma_x$.

$$\rho[\varepsilon_x]=\left(\left(\frac{I}{I_A}\right)\left(\frac{\lambda_u}{2\pi\sigma_x[\varepsilon_x]}\right)^2\left(\frac{K}{\sqrt{2}}\left(J_0\left[\frac{K^2}{4+2K^2}\right]-J_1\left[\frac{K^2}{4+2K^2}\right]\right)\right)^2\left(\frac{1}{2\gamma}\right)^3\right)^{1/3}$$

M. Xie, PAC'95, Dallas, USA, 183-185.

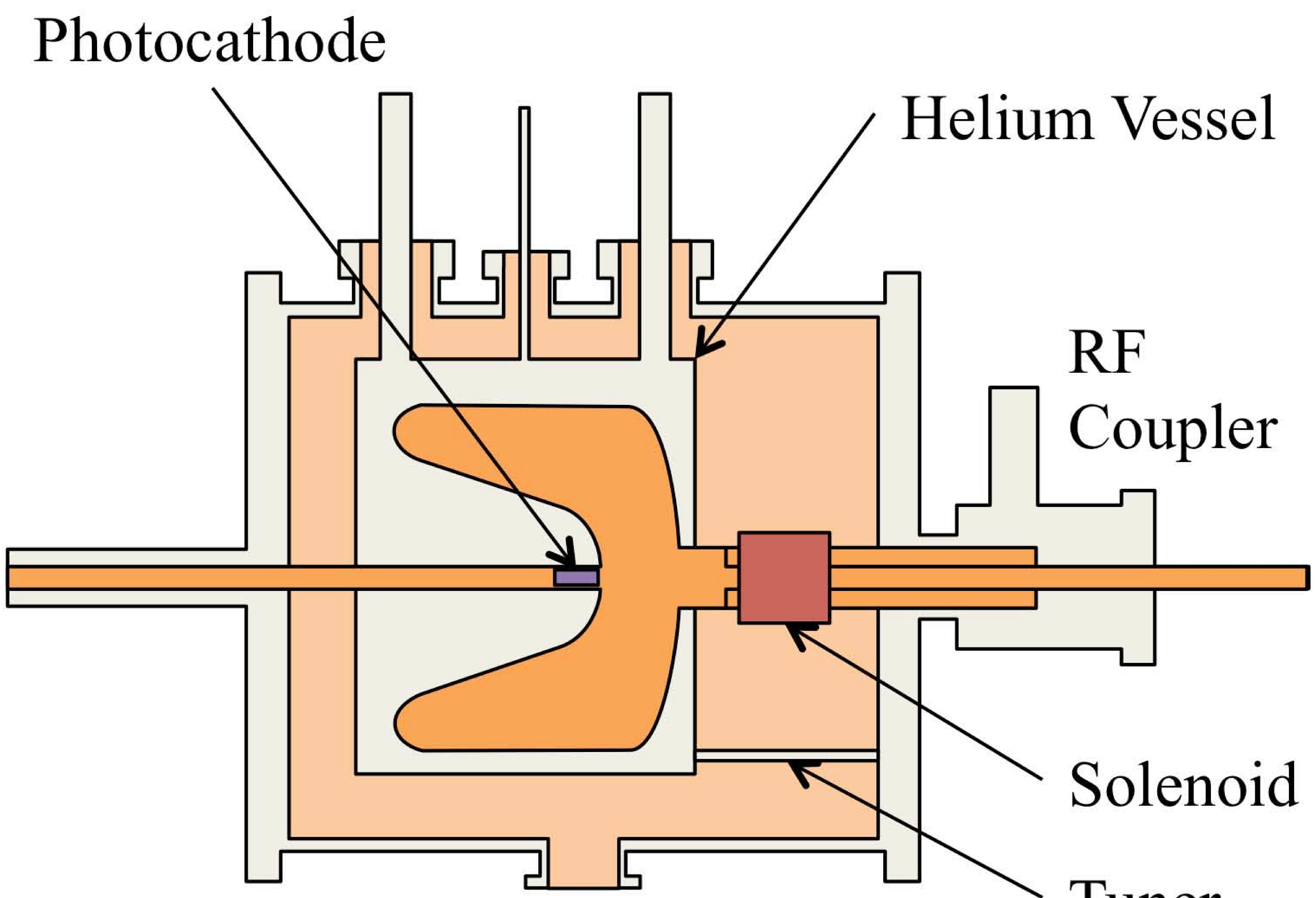
Reducing emittance:

- Increases photon pulse energy
- Extends accessible spectral range
- Increases transverse coherence

LCLS II: 0.4 μm @ 100-pC

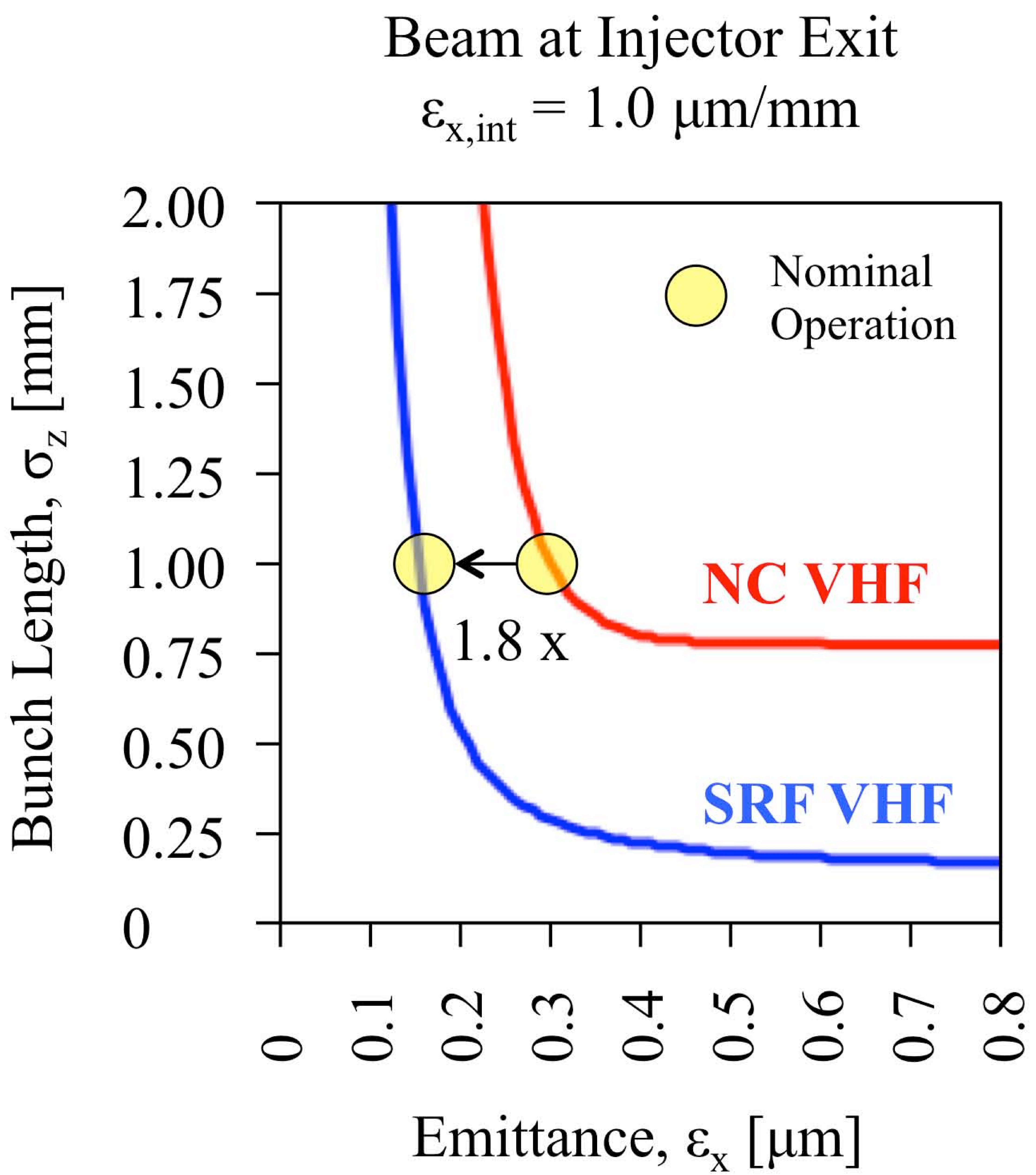
**Factor of 4 reduction needed for**
**> 20-keV radiation from 8 GeV linac**

# WiFEL VHF SRF Gun




J. Bisognano et al., PAC'13, TUPMA19

| | |
|---|---|
| Frequency | 200 MHz |
| Gradient | 45 MV/m |
| Energy | 4.0 MeV |




R. Li, DOE Injector Workshop

# Photoemission from Free Electron Like Metals

Sommerfeld Free Electron Model

Electronic states and occupational probabilities

1.) Electrons bound by uniform potential

2.) Constant density of states

3.) Occupation from Fermi-Dirac statistics

**Intrinsic Emittance**

$$\frac{\varepsilon_n}{\sigma_{x,y}} = \sqrt{\frac{m^*}{m}\frac{kT}{mc^2}}\sqrt{\frac{Li_3\left[-Exp\left[\frac{\hbar\omega-\phi+\Delta\phi}{kT}\right]\right]}{Li_2\left[-Exp\left[\frac{\hbar\omega-\phi+\Delta\phi}{kT}\right]\right]}}$$

Spicer 3-Step Photoemission Model

Identifies a sequence of steps in photoemission

1.) Absorb photons, ΔE normal to surface

2.) Diffuse to surface

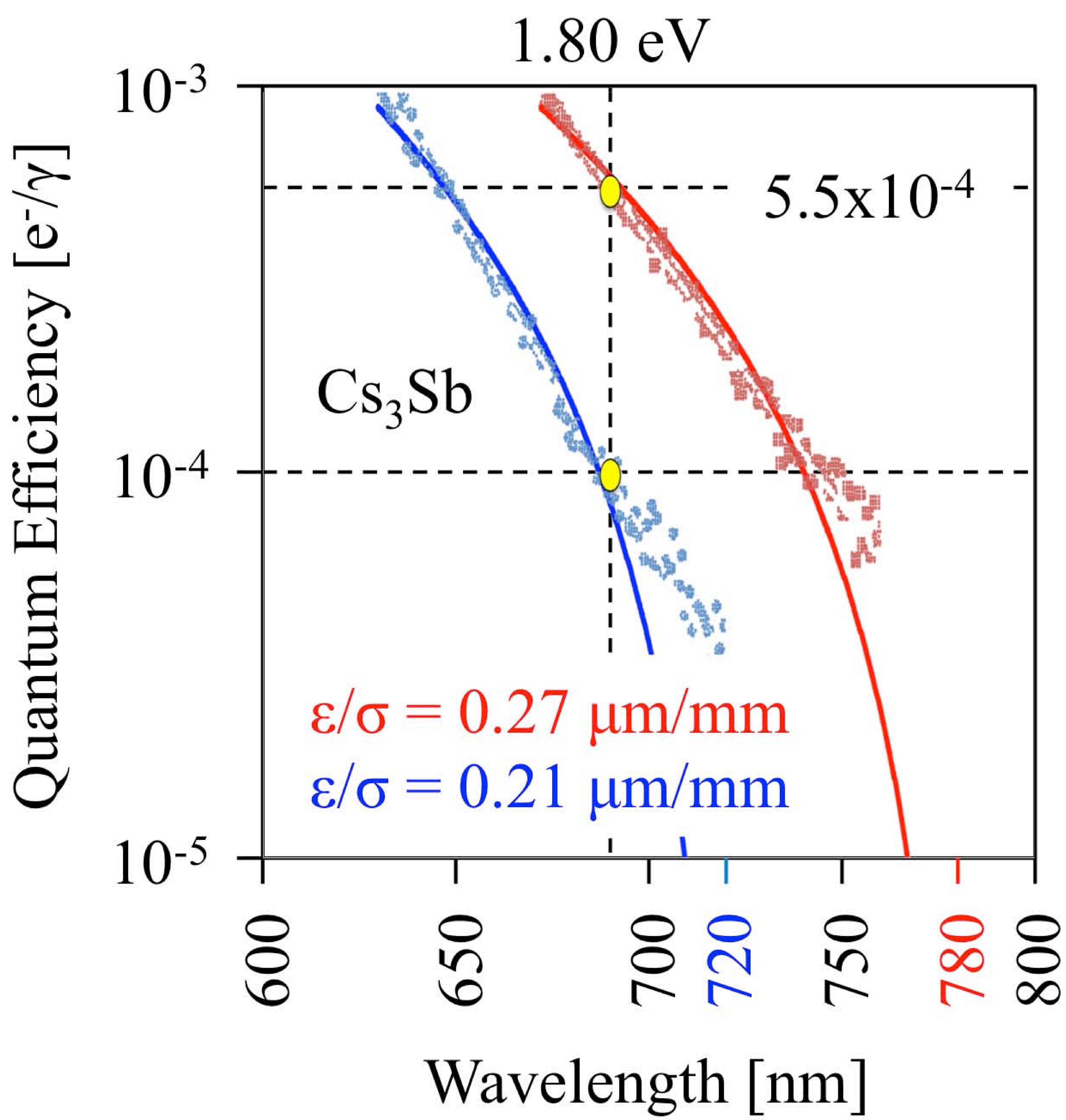
3.) Escape, ΔE = μ+ϕ-ħω normal to surface

**Quantum Efficiency**

$$QE \propto Li_2\left[-Exp\left[\frac{\hbar\omega-\phi+\Delta\phi}{kT}\right]\right]$$

D. Dowell and J. Schmerge, PRSTAB 12(11), 074201 (2009).
T. Vecchione et al., Proc. of the 2013 Int. FEL Conf., Manhattan, USA, TUPSO83.

# Optimizing Wavelength and Temperature for Modest Reductions in Intrinsic Emittance




L. Cultrera et al., PRSTAB 18(11), 113401 (2015)

| | Temp K | QE | Emittance μm/mm | Excess eV |
|---|---|---|---|---|
| $Cs_3Sb$ | 300 | $5.5\times10^{-4}$ | 0.27 | 0.21 |
| (measured) | 90 | $1\times10^{-4}$ | 0.21 | 0.08 |
| Metals | 300 | $2\times10^{-5}$ | 0.39 | 0.21 |
| (predicted) | 90 | $3\times10^{-6}$ | 0.23 | 0.08 |

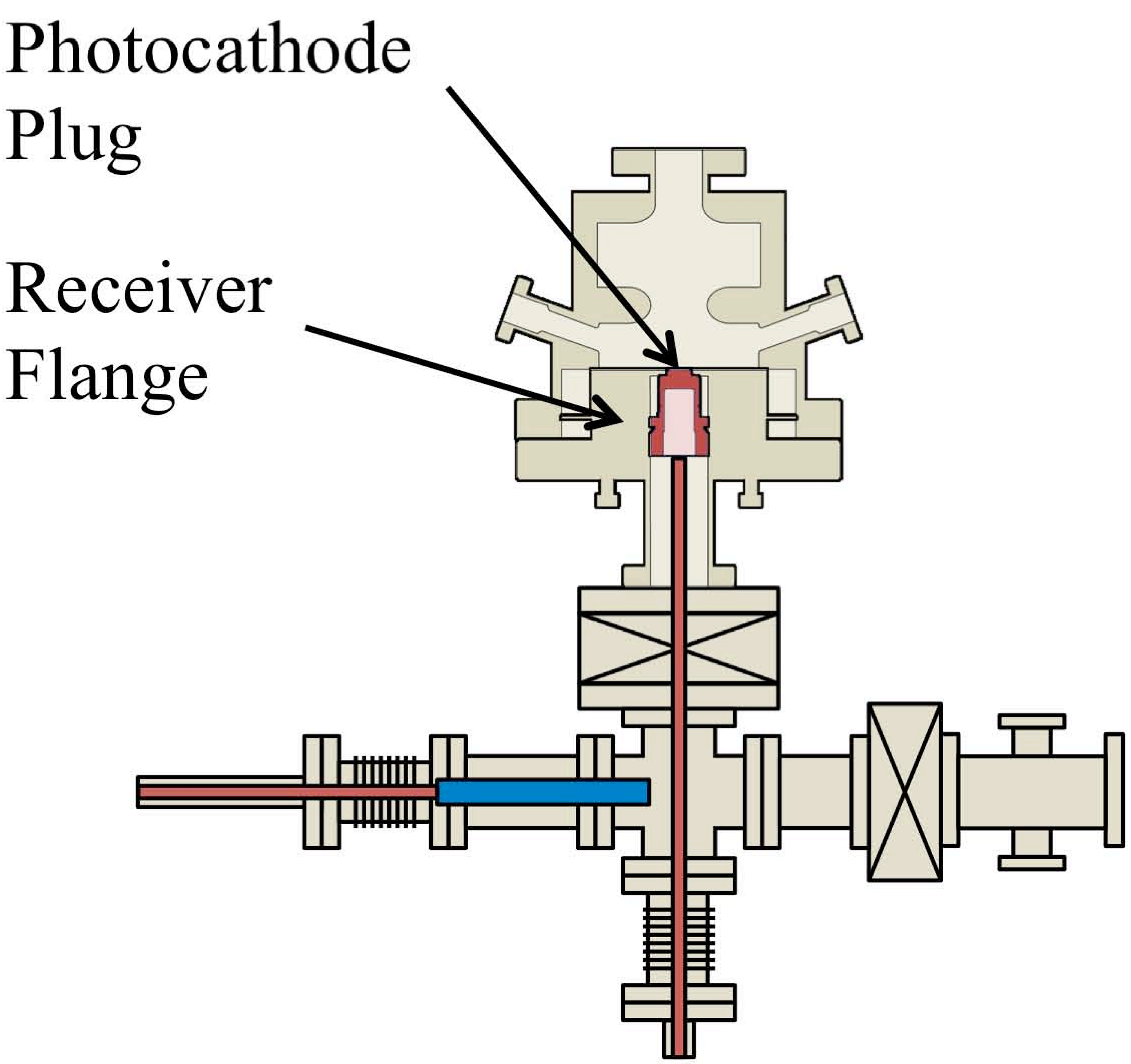
Similar emittance but 30x QE

**Semiconductors may dramatically outperform metals operating at cryogenic temperatures close to the photoemission threshold**

# Conceptual Designs of Photocathode Diagnostics

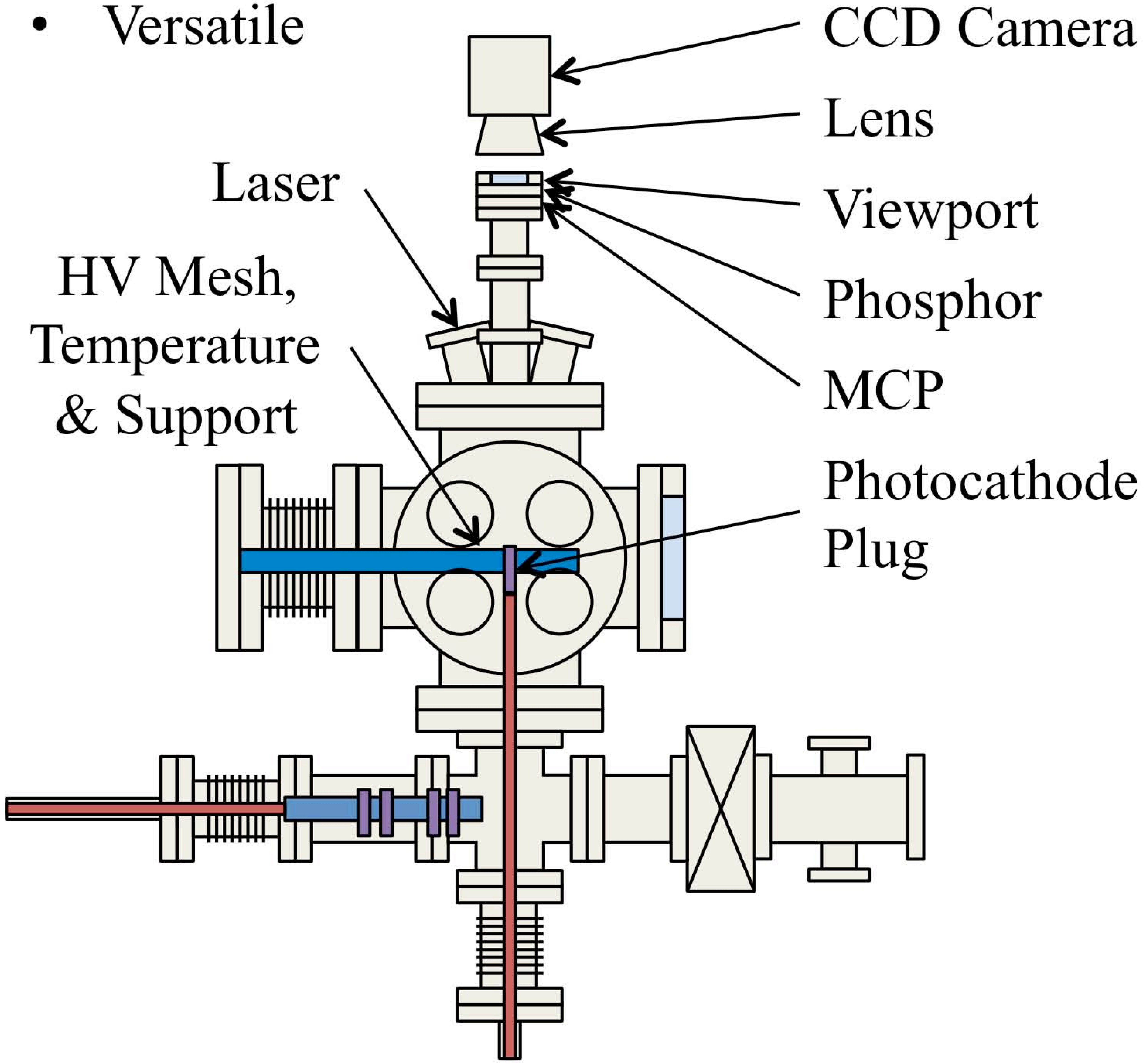
**High Gradient Diagnostic**

- S-Band NC RF test facility
- Results from 30 – 120 MV/m
- Decouples Photocathode R&D from Injector R&D




**Low Gradient Diagnostic**

- Cost effective small scale apparatus
- Results from 0 – 30 MV/m
- Versatile




Both can be used to study the effects of wavelength, temperature and surface roughness

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# Integrating Density-Functional Theory (DFT) into Photoemission Models to Improve Performance Predictions

Goal: Identify photocathodes with low intrinsic emittance and high QE

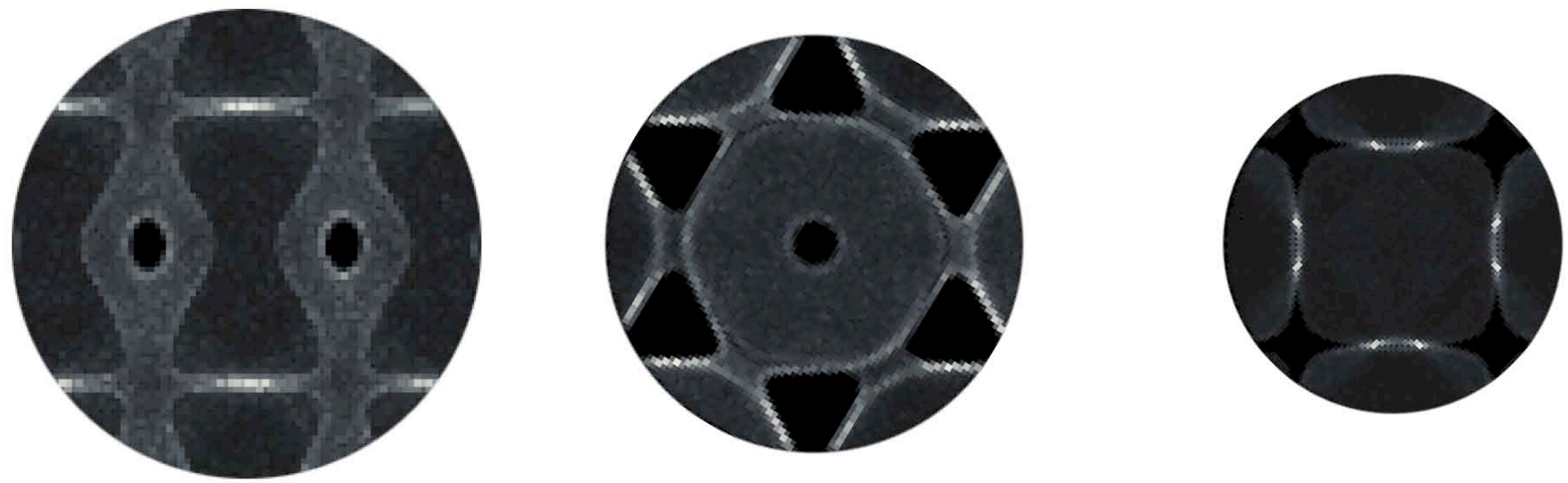
Approach: Use DFT to calculate photocathode electronic structure
Valid for metals and semiconductors
Can include the effects of finite temperatures, work function shifts in the presence of surface dipole layers and contributions from surface states

Method: DFT results → Supply function → Photoemission model
1) K-space is populated by interpolating between DFT eigenstates
2) K-space is searched until enough occupied states w/ sufficient energy and momentum for emission are found
3) States undergo excitation and emission following photoemission model

ABINIT: Plane wave basis and periodic boundary conditions
Troullier-Martins norm-conserving pseudopotentials replace ion cores
Exchange-correlation given by LDA Teter-Pade parameterization
Slab supercells w/ relaxed atomic positions give surface electronic structure

# Photoemission Simulations Need Verification Whenever Possible to Prevent Inaccuracy

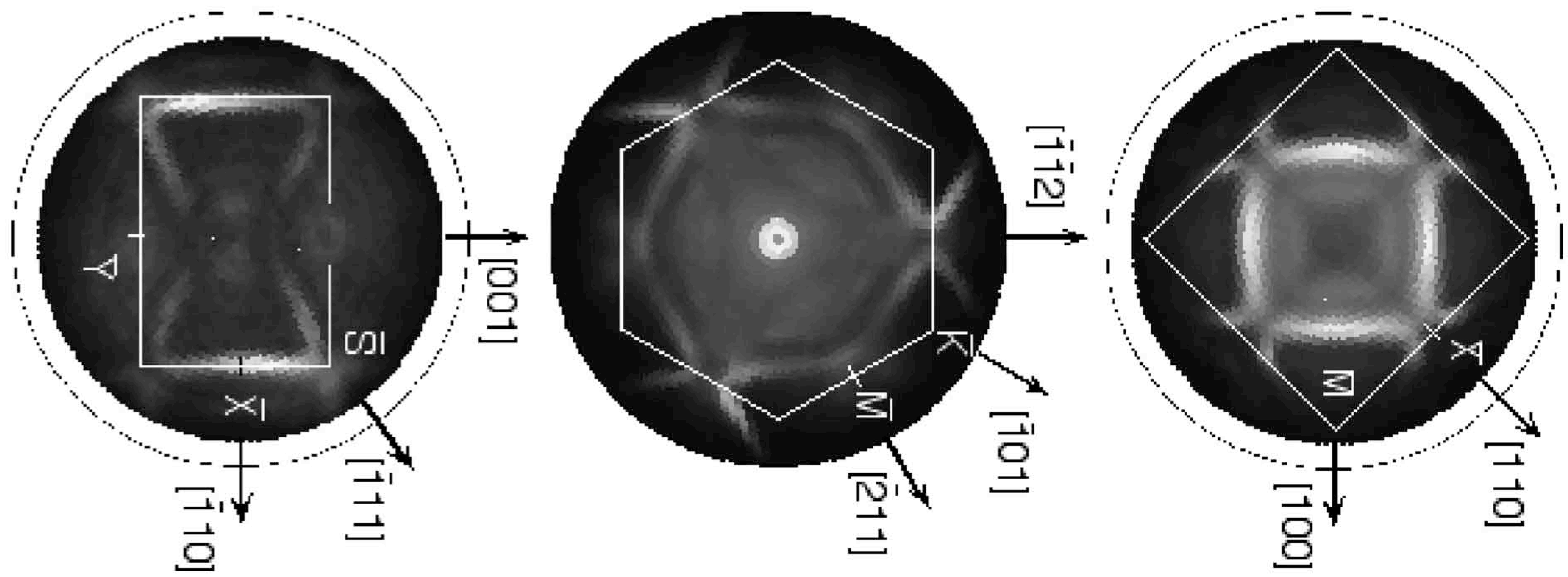
Simulations [1]



ħω = 21.2 eV
ΔE = 0.1 eV

(100) (111) (110)

ARPES Experiments [2]




**Pretty good agreement!**

1.) T. Vecchione et al., Proc. of 2015 Int. FEL Conf., Daejeon, Korea, WEP002.
2.) Reproduced from P. Aebi et al., Surf. Sci. 307, 917-921 (1994).

# Work Function & Intrinsic Emittance from Copper

| φ [eV] | Lit. [1] | Sim. [2] |
|---|---|---|
| (100) | **4.73** ± 0.10 | **4.78** |
| (110) | **4.56** ± 0.10 | **4.64** |
| (111) | **4.90** ± 0.02 | **5.01** |


[1] G. N. Derry et al., JVSTA 33(6), 060801 (2015).
[2] T. Vecchione et al., FEL'15, Korea, WEP002.

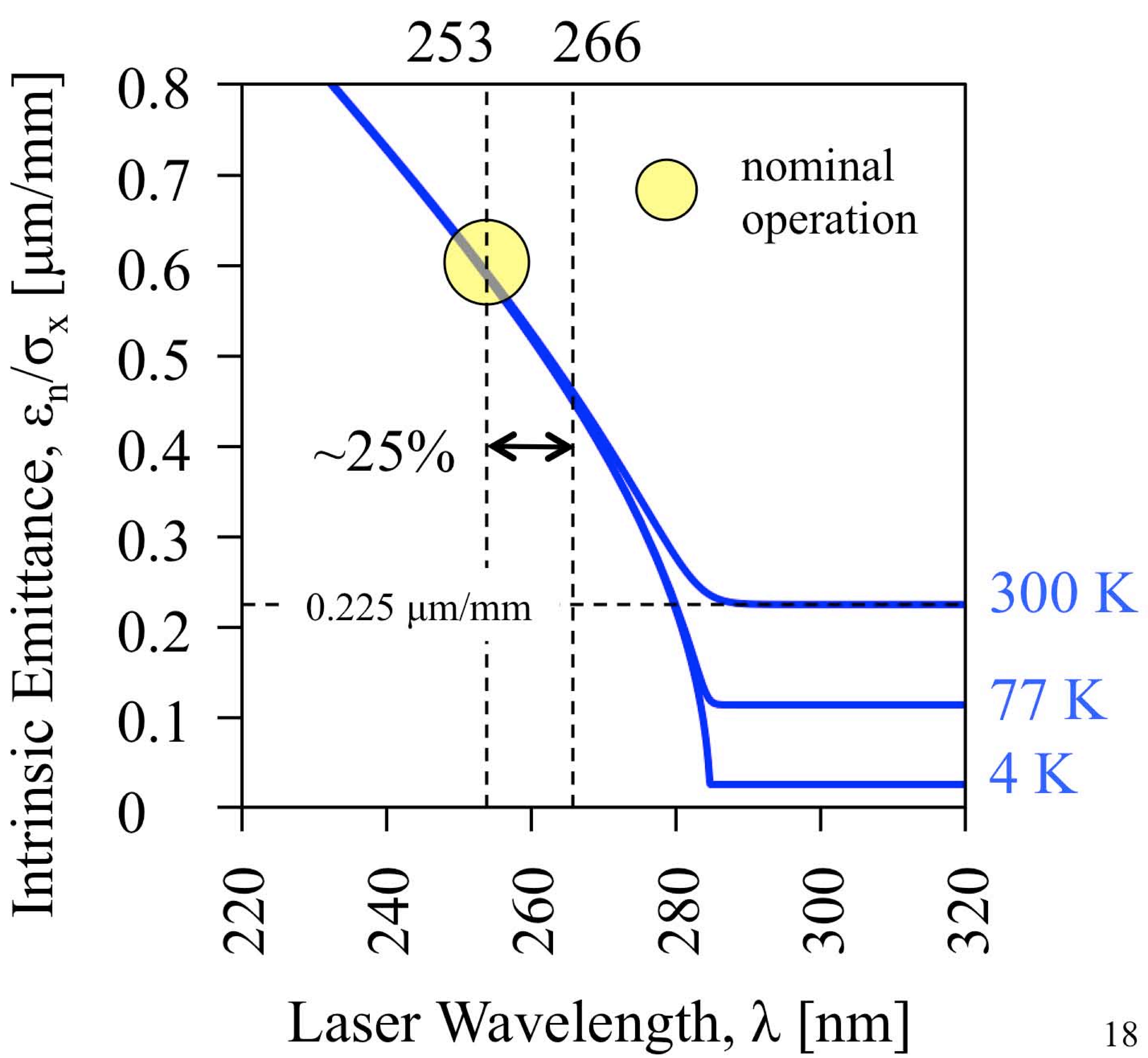

φ = 4.64 eV, 120 MV/m, 30° phase

**Results are consistent with literature**

Cu (110) has lowest work function. It should dominate emission from polycrystalline Cu photocathodes.

**Reasonable agreement with values measured at the LCLS I**

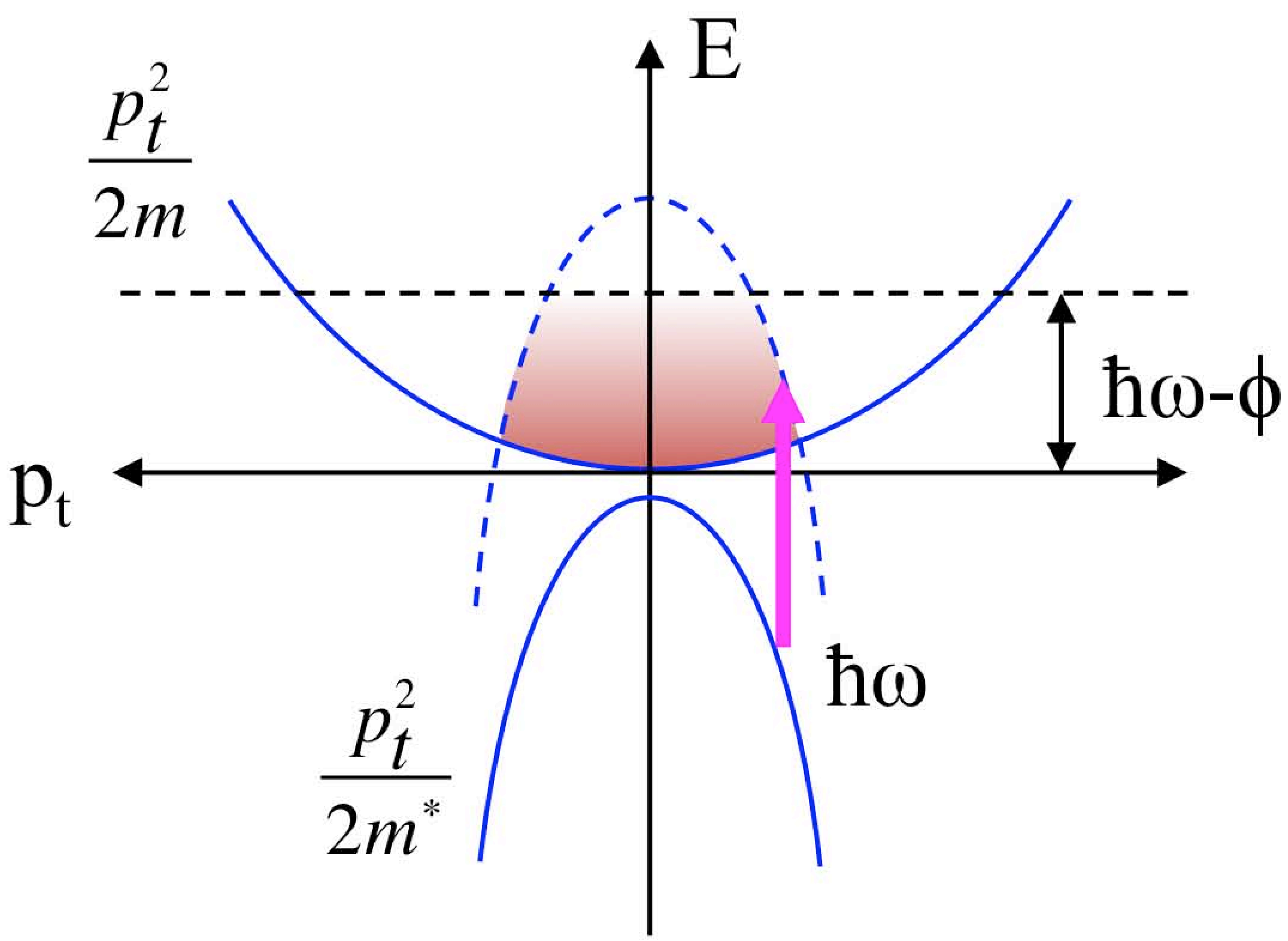
Changing laser from 253 to 266 nm reduces intrinsic emittance by 25% but requires enough laser power to compensate for a 70% drop in QE.



# Low Intrinsic Emittance is Expected When $-m < m^* < 0$

$$-m < m^* < 0$$

- Lower $p_t$ at high excess energy
- Emittance may decrease w/ temperature




Initially looking for single crystal surfaces with isolated emitting states that have small effective mass

(100) surfaces of BCC metals

(111) surfaces of FCC metals

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Li | Be | | | | | | | | | |
| Na | Mg | | | | | | | | | |
| K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu |
| Rb | Sr | Y | Zr | Nb | Mo | Tc | Ru | Rh | Pd | Ag |
| Cs | Ba | | Hf | Ta | W | Re | Os | Ir | Pt | Au |

Plans also include semiconductors with small effective masses at their band gaps

# Conclusions

Supplying Photocathodes for the LCLS II

- Purchasing photocathodes from 2017 until the middle of 2018
- Be ready to produce photocathodes by the start of 2019

Modest Photocathode Optimization for Future FELs

- Use high QE semiconductors operating near the emission threshold
- Optimize laser wavelength and temperature, minimize surface roughness
- Goal is to reduce intrinsic emittance by a factor of two

Simulations for Predicting Significant Photocathode Improvements

- Need to develop reliable, cost-effective, time-efficient simulation codes
- Longer term, more ambitious effort but the benefits could be significant
- Goal is to reduce intrinsic emittance to below the thermal limit

**Thank you all very much for your attention!**

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