QE and Emittance from Free Electron Metals

Photocathode Physics for Photoinjectors 2012

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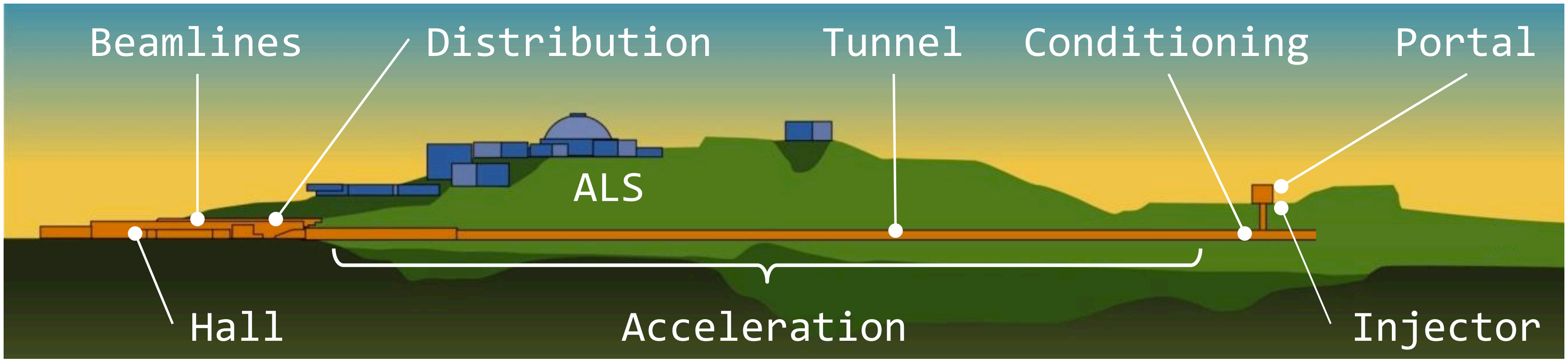
Background for Bi-Alkali Antimonide Research

NGLS: 2.5 GeV CW SC Linac producing ultrafast coherent X-rays
High brightness (≤ 1 mm-mrad, ≤ 1 nC)
High rep rate (MHz), synchronized with photocathode



Cu	fast, relatively robust, 5e-5 QE in UV 1 nC @ 1 MHz reprate -> ~ KW of IR
GaAs:Cs:O	slow depending on λ, hyper-reactive, 10% QE in visible 1 nC @ 1 MHz reprate -> ~ mW of IR
Cs_2Te	fast, relatively robust at ~ 10^{-9} Torr, 10% QE in UV 1 nC @ 1 MHz reprate -> ~ W IR
K_2CsSb	fast, somewhat reactive at 10^{-9} Torr, 1% QE in visible 1 nC @ 1 MHz reprate -> ~ mW of IR

Choice made to study K_2CsSb
based on work by D. Dowell et al., NIM 356 2-3, 167 1995

Initial QE Measurements on K_2CsSb

Basic Recipe (current):

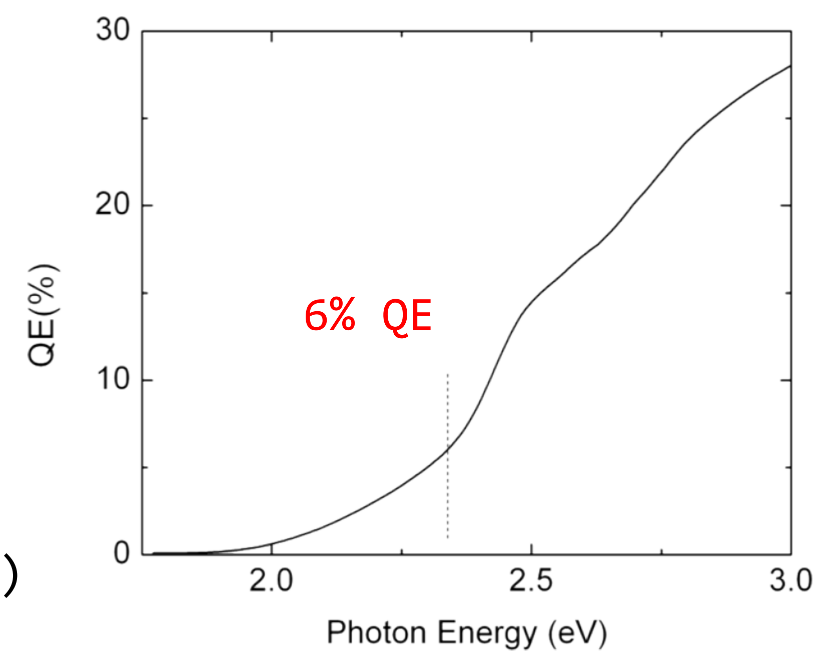
1) HF Dipped Si substrate heat cleansed at 600° C
2) 200 Å Sb deposited at 160° C
3) K deposited at 140° C till max QE
4) Cs deposited at 120° C till max QE
5) 3 + 4 are repeated as needed

Different recipes produce similar results wrt QE
High temp step + rapid cooling work but not necessary

Results:

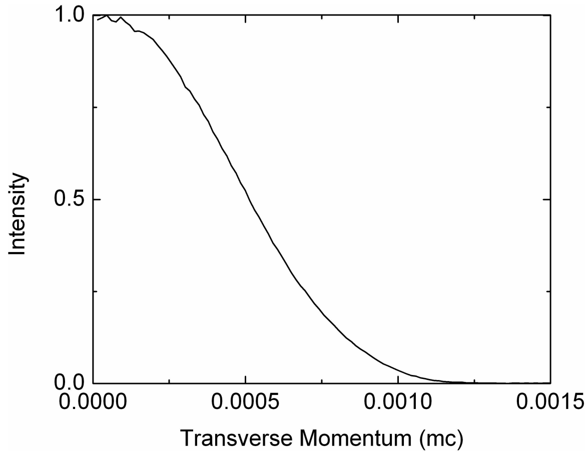
1) Nominally 6% QE at 532
2) 100 μm focused green laser maintained current density of 1 mA/mm^2 for weeks w/o decay
3) 50% decay time of QE at 5e-9 torr pp H_2O around 17 h

Vecchione et al., APL 99, 034103 (2011)



Initial Transverse Emittance Measurements on K_2CsSb

Transverse momentum distribution for K_2CsSb measured at 543 nm
Simple model: Dowell et al., NIM Phys. Res. A 622, 685 (2010)

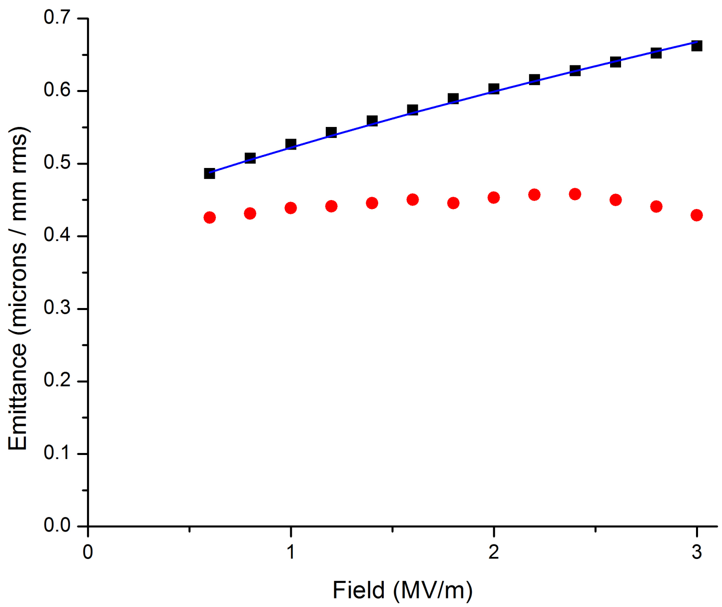


$$\frac{\varepsilon_n}{\sigma_x} = \sqrt{\frac{\hbar\omega - E_g - E_A + \phi_s}{3mc^2}}$$

Threshold = 1.9 eV
Band Gap = 1.2 eV
Affinity = 0.7 eV
Schottky (2 MV/m) = 0.053 eV

Predict ε_n = 0.39 μm / mm rms beam size
Measured ε_n = 0.37 μm / mm rms beam size

Emittance vs Gradient



red dots = thin and smooth cathode

black squares = thicker cathode consisting of several layers

blue line = fit to a model of field dependent emittance growth

Growth in emittance wrt field is believed to be observed

Vecchione et al., FEL2011, TUOC3
Vecchione et al., IPAC2012, MOPPP041

Theoretical Quantum Efficiency, Free Electron Metal

Free Electron Model

$$\vec{p} = \hbar \vec{k} \qquad E = \frac{\vec{p}^2}{2m} \qquad f[\vec{p}] = \frac{1}{1 + Exp\left[\frac{\vec{p}^2}{2mkT} - \frac{\mu}{kT}\right]}$$

Generic Current Density

$$J = \frac{e}{4\pi^3\hbar^3 m}\int_0^\infty \int_0^\infty \int_0^{2\pi} D[p_z] \frac{p_z p_r}{1 + Exp\left[\frac{p_z^{\ 2} + p_r^{\ 2}}{2mkT} - \frac{\mu}{kT}\right]} d\theta\, dp_r dp_z$$

Escape Probability

$$D[p_z] = \begin{cases} 1 & p_z \geq \sqrt{2m(\mu + \phi - \hbar\omega)} \\ 0 & \text{Otherwise} \end{cases}$$

Hypothetical Current Density

$$J_h = \frac{ekT}{2\pi^2\hbar^3}\int_0^\infty Log\left[1 + Exp\left[\frac{\hbar\omega - \phi}{kT} - \frac{p_r^{\ 2}}{2mkT}\right]\right] p_r dp_r$$

$$J_h = -\frac{em(kT)^2}{2\pi^2\hbar^3} Li_2\left[-Exp\left[\frac{\hbar\omega - \phi}{kT}\right]\right]$$

Polylogarithm Definition

$$Li_n[z] = \sum_{k=1}^{\infty} \frac{z^k}{k^n} = \frac{z}{\Gamma[n]}\int_0^\infty \frac{t^{n-1}}{Exp[t] - z} dt$$

Richardson-Dushman

Approx: $$J_R \approx \frac{emk^2}{2\pi^2\hbar^3} T^2 Exp\left[-\frac{\phi}{kT}\right]$$

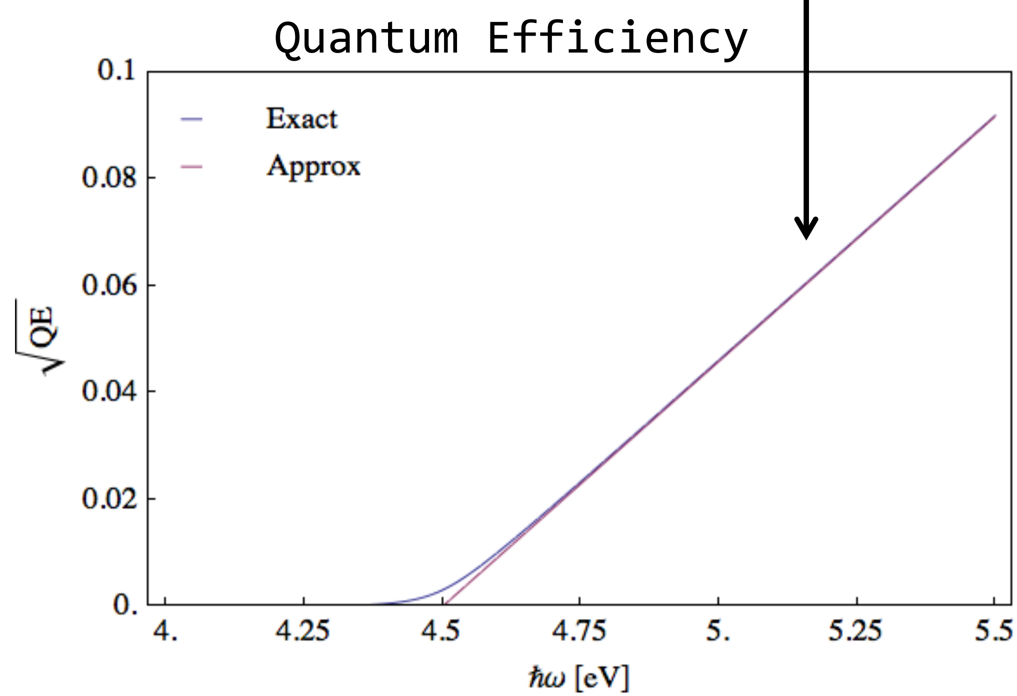
Quantum Efficiency

$$QE \propto \frac{(\text{current density escaping})}{(\text{current density arriving})} = \frac{J_h}{J_0}$$

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

Fowler-Dubridge

Approx: $$QE \propto -\frac{1}{2Li_2\left[-Exp\left[\frac{\mu}{kT}\right]\right]}\left(\frac{\hbar\omega - \phi}{kT}\right)^2$$



Note: External coordinates produce identical results

$$P_z = p_z - \sqrt{2m(\mu + \phi - \hbar\omega)}$$

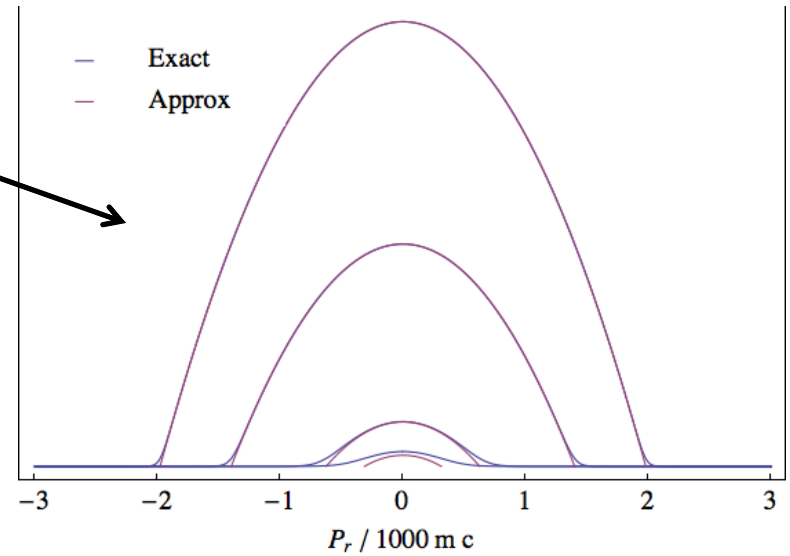
Theoretical Transverse Emittance, Free Electron Model

Radial Momentum Distribution

$$dJ = \frac{ekT}{4\pi^3\hbar^3} Log\left[1 + Exp\left[\frac{\hbar\omega - \phi}{kT} - \frac{p_r^{\,2}}{2mkT}\right]\right] p_r dp_r d\theta$$

Approx: $dJ \approx \frac{e}{4\pi^3\hbar^3}\left(\hbar\omega - \phi - \frac{p_r^{\,2}}{2m}\right) p_r dp_r d\theta$

Transverse Momentum Distribution

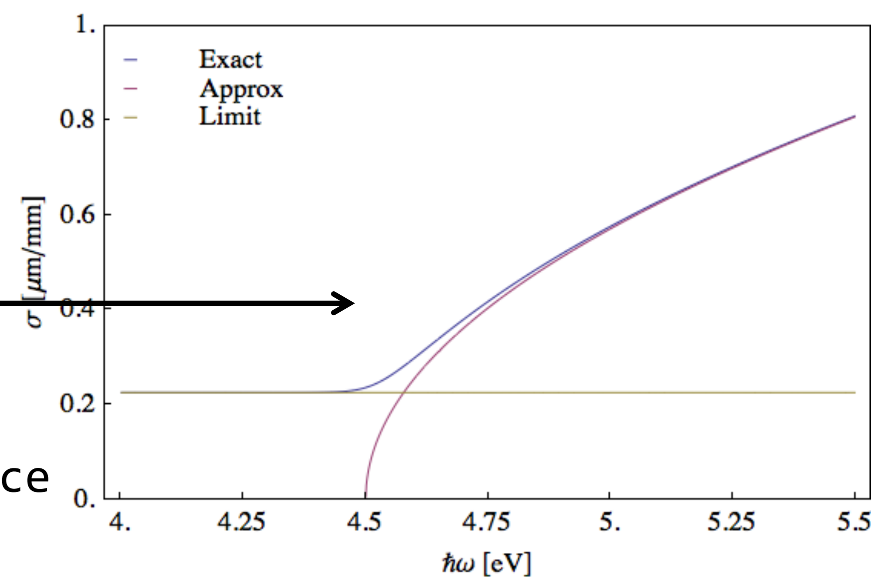


RMS Radial Momentum

$$P_{r,rms} = \sqrt{\frac{\frac{ekT}{4\pi^3\hbar^3}\int_0^\infty \int_0^{2\pi} Log\left[1 + Exp\left[\frac{\hbar\omega - \varphi}{kT} - \frac{p_r^2}{2mkT}\right]\right] p_r^3 d\theta\, dp_r}{\frac{ekT}{4\pi^3\hbar^3}\int_0^\infty \int_0^{2\pi} Log\left[1 + Exp\left[\frac{\hbar\omega - \varphi}{kT} - \frac{p_r^2}{2mkT}\right]\right] p_r d\theta\, dp_r}}$$

$$P_{r,rms} = \sqrt{2mkT}\sqrt{\frac{Li_3\left[-Exp\left[\frac{\hbar\omega - \varphi}{kT}\right]\right]}{Li_2\left[-Exp\left[\frac{\hbar\omega - \varphi}{kT}\right]\right]}}$$

Transverse Emittance



Normalized Emittance Definition

$$\sigma_x = \left(\frac{1}{mc}\right)\sqrt{\langle P_x^{\,2}\rangle - \langle P_x\rangle^2}$$

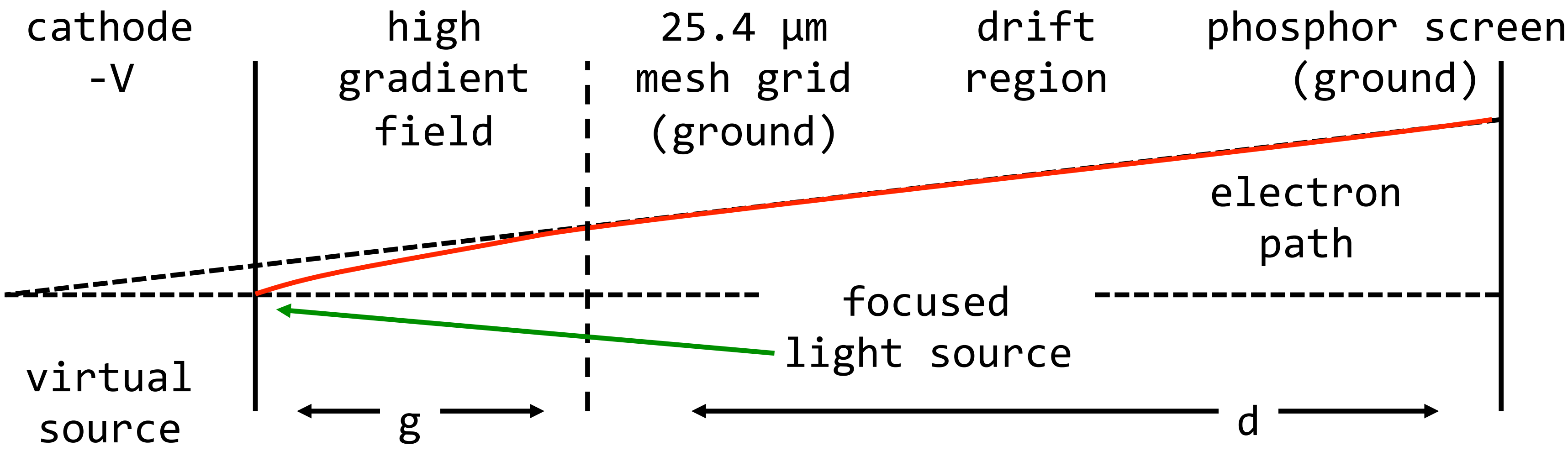
$$\sigma_{x,rms} = \left(\frac{1000}{\sqrt{2}}\right)\frac{P_{r,rms}}{mc}$$

$$\sigma_{x,rms} = 1000\sqrt{\frac{kT}{mc^2}}\sqrt{\frac{Li_3\left[-Exp\left[\frac{\hbar\omega - \phi}{kT}\right]\right]}{Li_2\left[-Exp\left[\frac{\hbar\omega - \phi}{kT}\right]\right]}}$$

Approx: $\sigma_{x,rms} \approx 1000\sqrt{\frac{kT}{mc^2}}$ Thermionic Emittance

$\sigma_{x,rms} \approx 1000\sqrt{\frac{\hbar\omega - \phi}{3mc^2}}$ Dowell Emittance

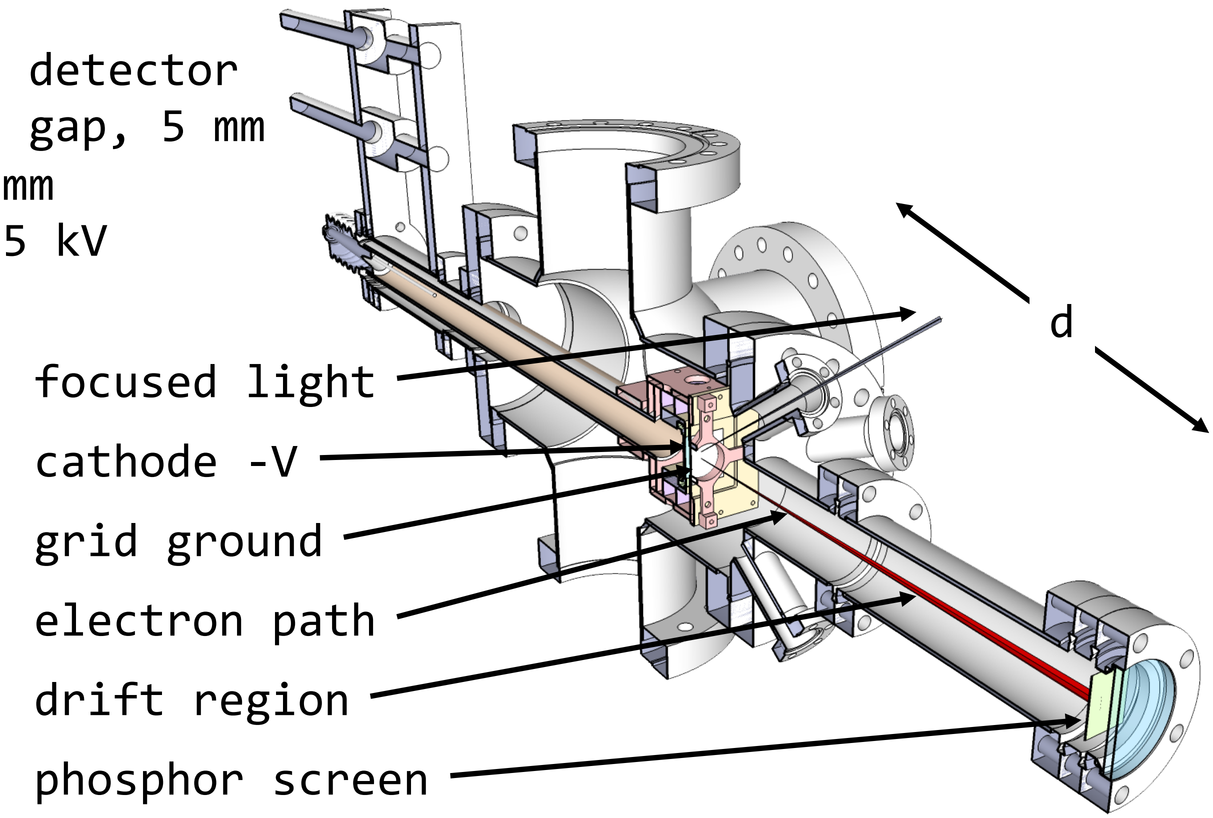
“Momentatron” Apparatus Measuring Transverse Momentum



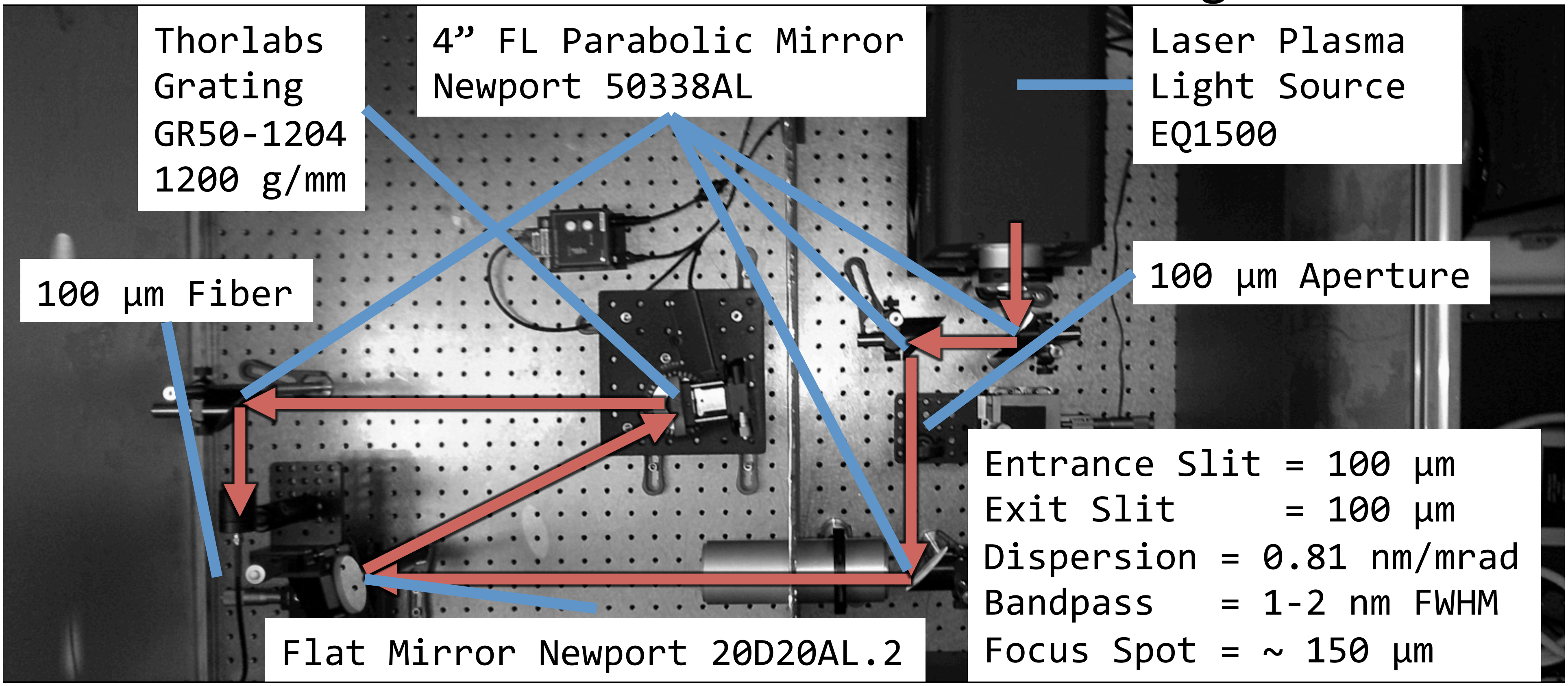
r = radial coordinate on detector
g = cathode-grid (anode) gap, 5 mm
d = drift distance, 244 mm
V = applied voltage, 1-15 kV

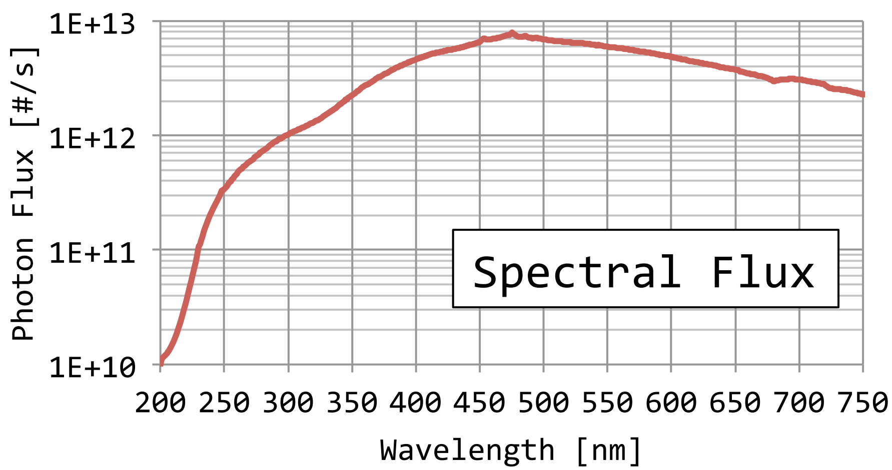
$$r = \sqrt{\frac{mc^2}{2eV}}(2g + d)\left(\frac{p_x}{mc}\right)$$

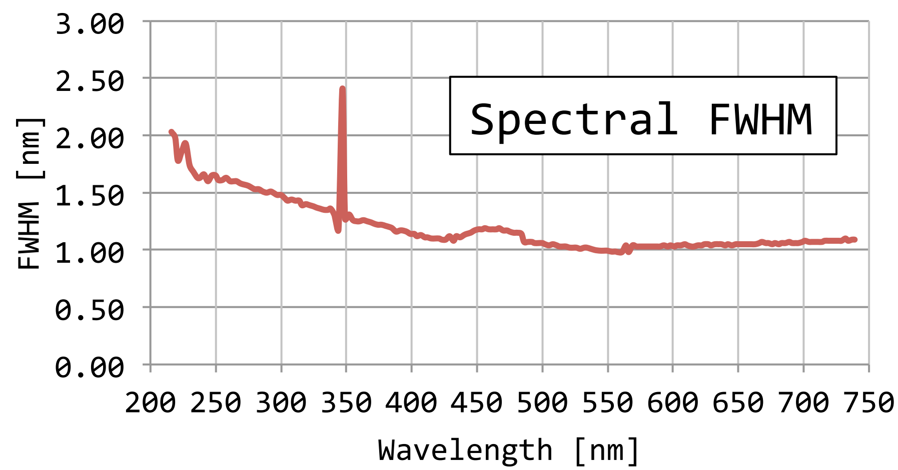
$$\sigma_x = \frac{\langle p_x^2 \rangle^{1/2}}{mc}$$



Monochromated UV-VIS Broadband Fiber Light Source







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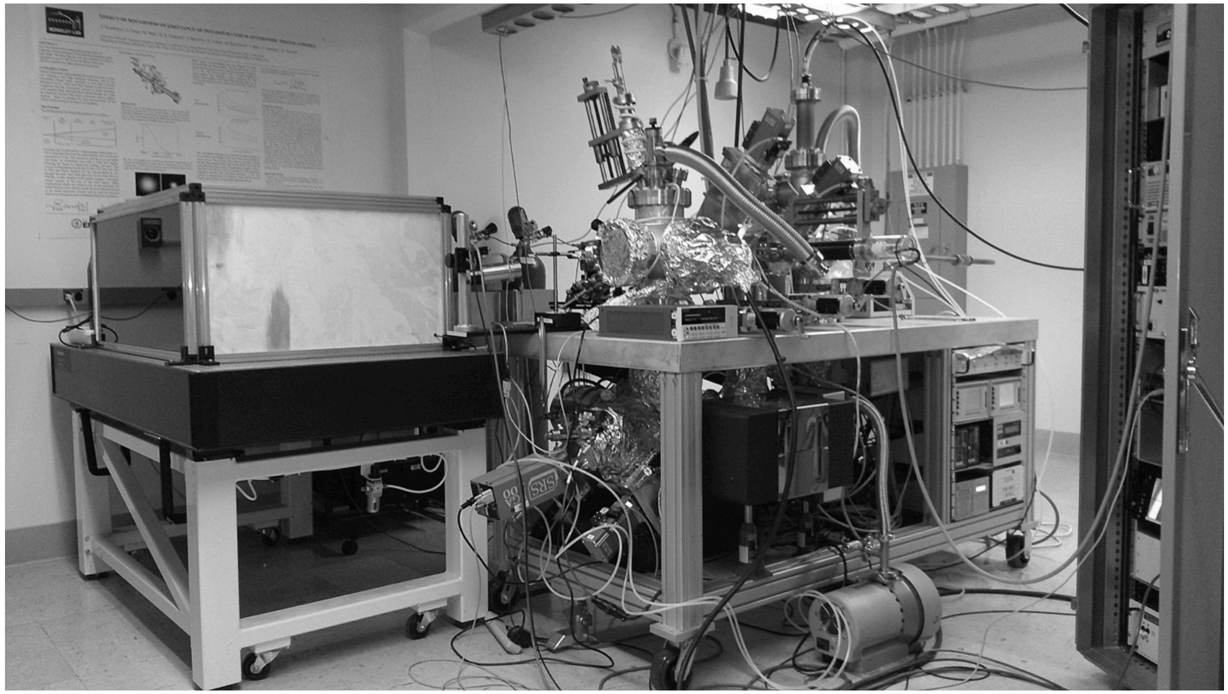
Experimental Methods (Brief)

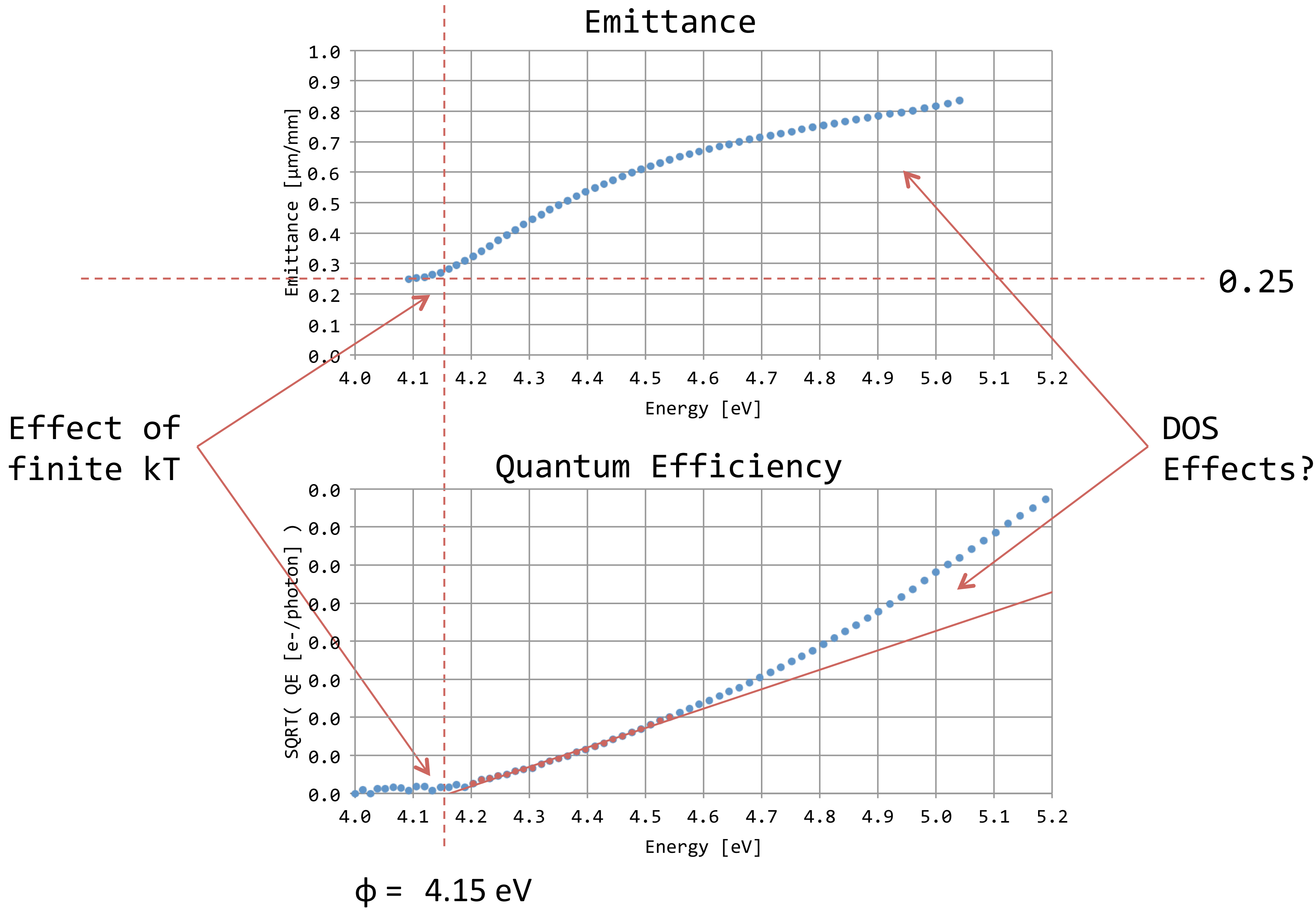


Work Function: Biased -10V emission recorded w/ Keithley 6517B (noise ~ 10s fA)
~10 mm^2 collimated beam normal incident via fused quartz viewport
Photon flux calibrations performed using AXUV photodiode

Emittance: 900 V channel plate before beam accelerated 3.1 kV into phosphor
Lens coupled CCD camera imaged using 0.1 – 10 s exposures
Convergent light focused through grid at 30° into 0.1-0.2 mm spot
*** Instrumental resolution estimated to be less than kT

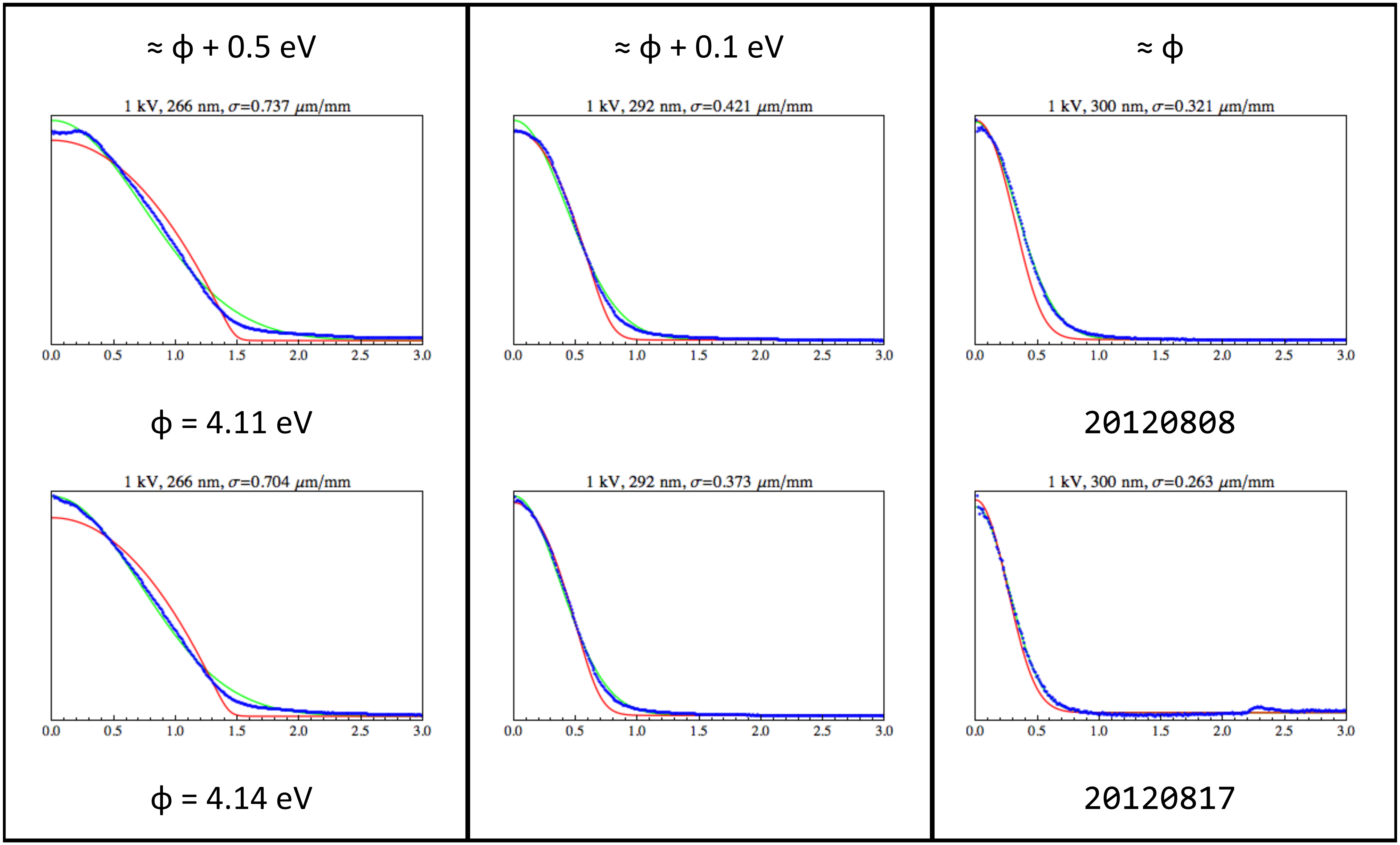
Sample Prep: HF Dipped polished Si substrate phosphor doped <100> $1x10^{-12}$ Ω-cm
Films deposited using low temperature effusion or DC sputtering
Monitored using quartz monitor, base pressures ~ $1\text{-}2x10^{-10}$ torr

Best Guess* of Results from Oxidized Antimony



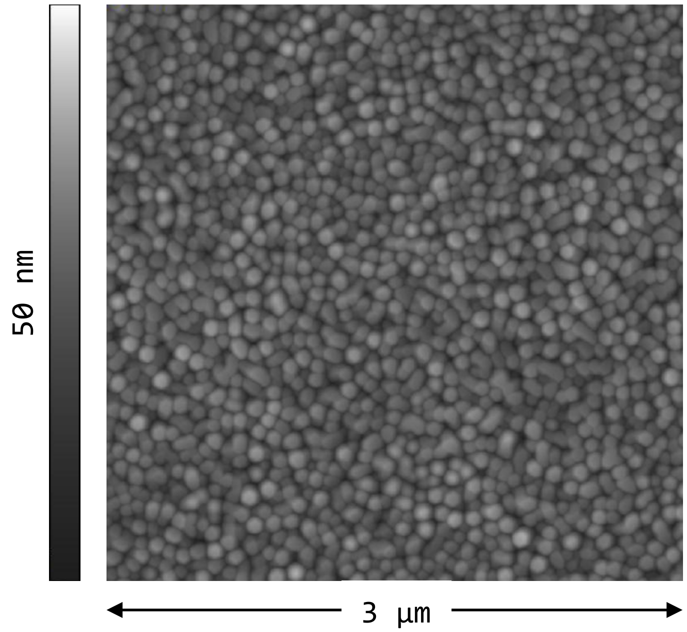
*Data slightly processed

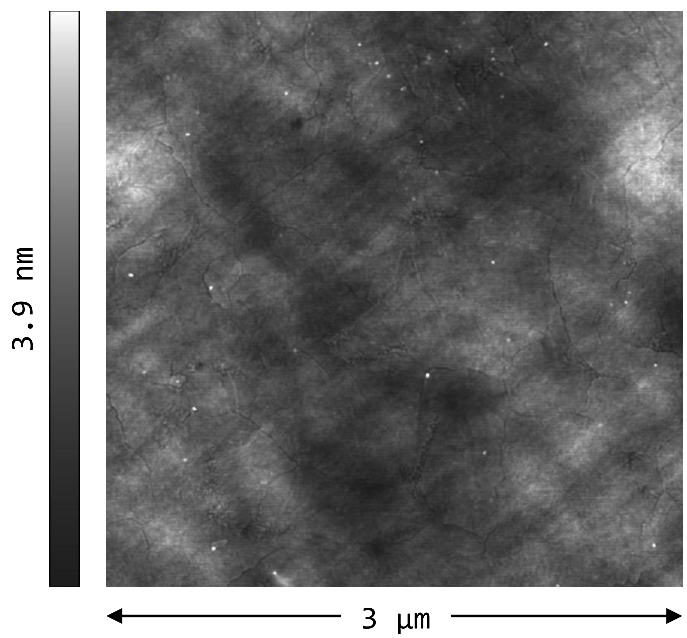
Transverse Momentum Distributions - Oxidized Antimony

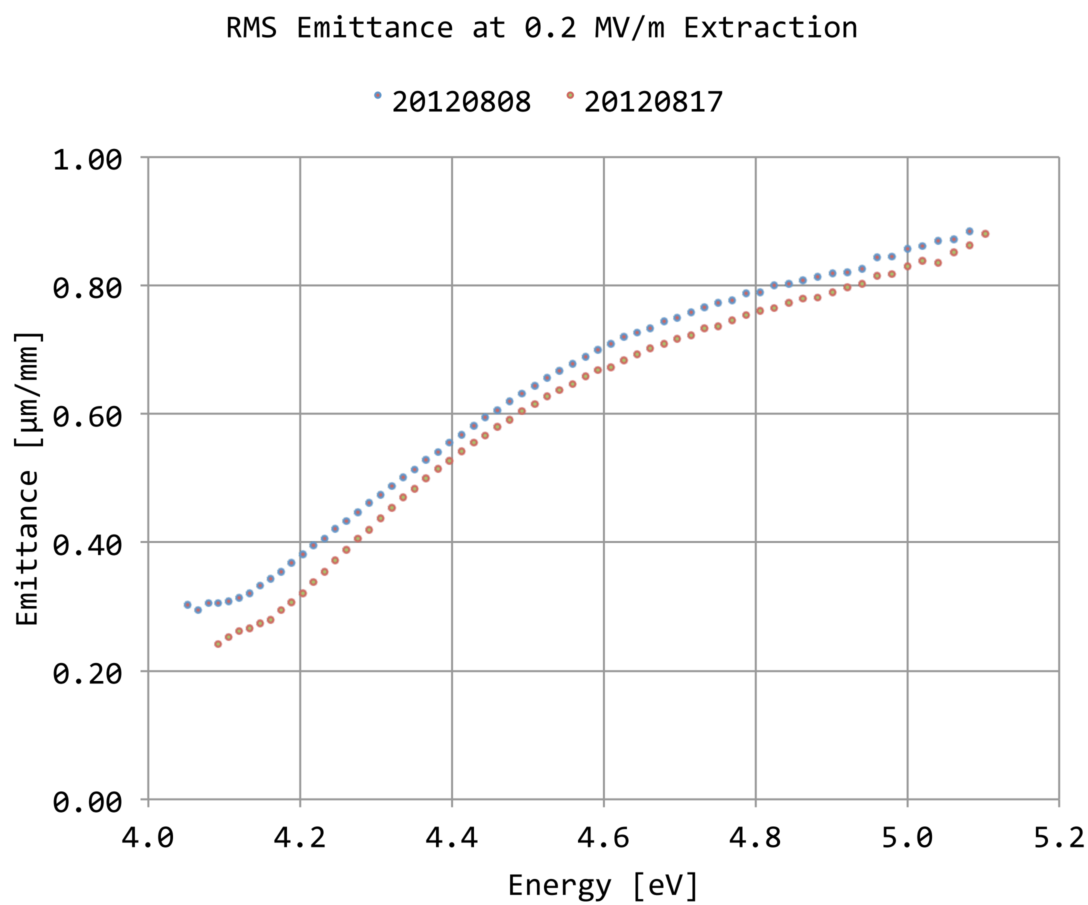


Disclaimer: Systematic fitting of > 1 million images is ongoing process
Results presented today may change a bit before publication

Quantifying the Effects of Roughness?







General recipe:
1) Preheat HF dipped substrate to 500 C
2) Cool to RT
3) Sputter at room temperature or evaporate at ~ 160 C
4) Sample oxidized before taking data

0808: exposed to wet air and then re-heated to 125 °C
0817: exposed to oxygen and water via ambient vacuum

Conclusions

1) QE experiences a gradual onset of emission at work function
   Effect originates from finite temperature of cathode
   i.e. Fermi-Dirac distribution not modeled by step function

2) Emittances measured plateau at a finite value of ~ 0.23 μm/mm
   Value conventionally referred to as "thermal emittance"
   Effect also originates from finite temperature of cathode

3) Predictions are close to measurements but inconsistencies remain
   Fitting may be complicated by non-flat density of states
   Averaging of crystallographic grains also needs consideration

4) Roughness effects are believed to have been observed
   At most ~ 20% increase in overall emittance
   Theory focused on including power-spectral density of surface

5) Efforts continue to refine experimental measurements
   Currently focused on making a wide range of samples
   May be time to reboot experiment to refine each measurement aspect

6) Questions are fundamentally important + interesting
   Hope is future experiments will increase our understanding!