The Quantum Efficiency and Thermal Emittance of Metal Cathodes

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Theory Seminar
June 2, 2006

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Surface Roughness Measurements
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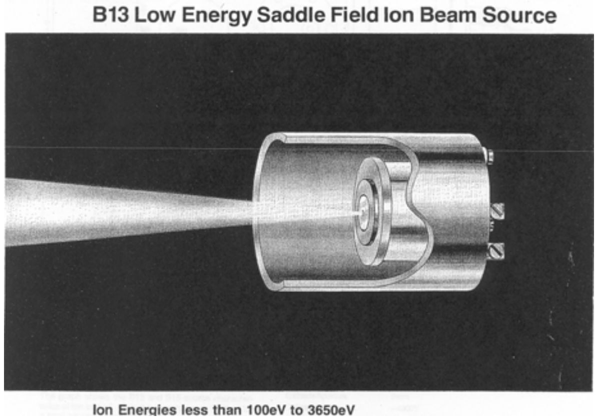

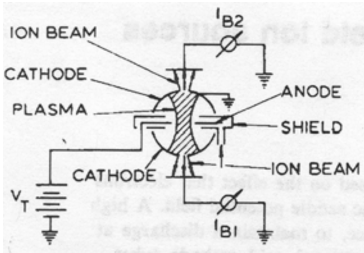

Collaborators: E. Colby, B. Kirby, J. Schmerge, J. Smedley

Some general introductory comments

- *The QE is obviously important to reduce the size and cost of the drive laser*
- *The connection between QE and the thermal emittance is not always appreciated*
- *The beam quality from future electron sources for LCLS-like applications will be dominated by the thermal emittance*
- *Therefore improvements in beam brightness will require a detailed understanding of physics near the cathode.*

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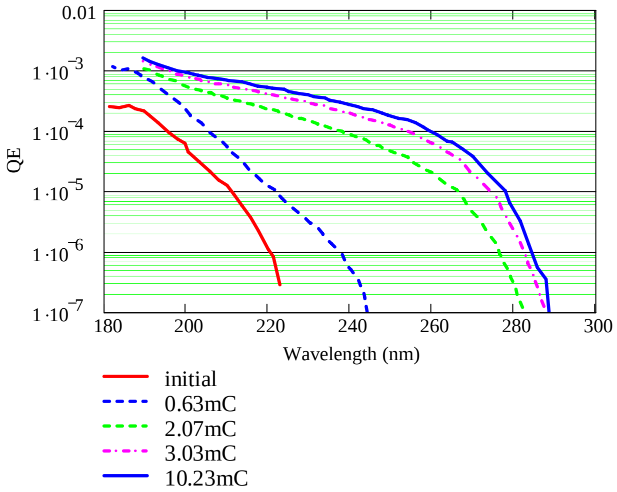
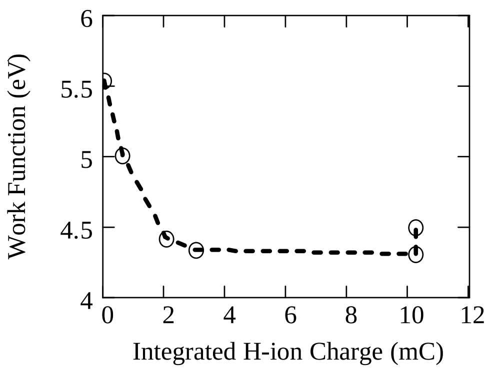
We can now produce atomically clean surfaces which can be used for theoretical studies





QE can be computed using the three-step photo-emission model (Spicer):

1. ***Photon is absorbed by electron (reflectivity and absorption depth)***
2. ***Electron travels to surface (electron-electron, electron-phonon scattering)***
3. ***Electron escapes to vacuum (energy and barrier penetration)***

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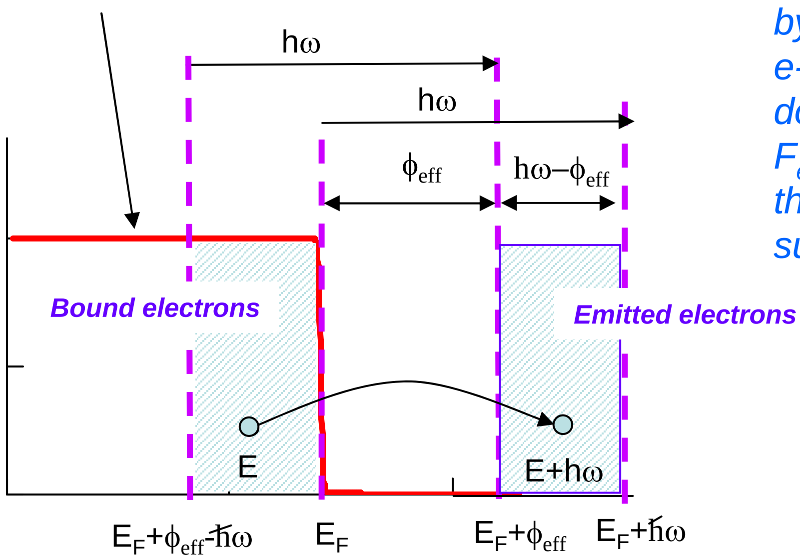
Derivation of the QE assuming the free electron gas model of a metal

Step 1: Absorption of photon

Fermi-Dirac distribution at 300degK

$$f_{FD}(E) = \frac{1}{1+e^{(E-E_F)/k_BT}} \qquad \phi_{eff} = \phi - \phi_{schottky}$$



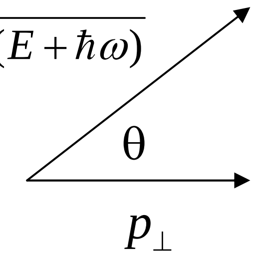
Step 2: Transport to surface

Electrons lose energy by scattering, assume e-e scattering dominates, F_{e-e} is the probability the electron makes it to the surface without scattering

Step 3: Escape over barrier

Escape criterion: $\frac{p_\perp^2}{2m} > E_F + \phi_{eff}$

$$p_{total} = \sqrt{2m(E+\hbar\omega)}$$



$$\cos\theta_{max} = \frac{p_\perp}{p_{total}} = \sqrt{\frac{E_F+\phi_{eff}}{E+\hbar\omega}}$$

$$QE(\omega) = (1-R(\omega)) \frac{\int_{E_F+\phi_{eff}-\hbar\omega}^{\infty} dE\; N(E+\hbar\omega)(1-f_{FD}(E+\hbar\omega))N(E)f_{FD}(E) \int_{\cos\theta_{max}(E)}^{1} d(\cos\theta) F_{e-e}(E,\omega,\theta) \int_0^{2\pi} d\Phi}{\int_{E_F-\hbar\omega}^{\infty} dE\; N(E+\hbar\omega)(1-f_{FD}(E+\hbar\omega))N(E)f_{FD}(E) \int_{-1}^{1} d(\cos\theta) \int_0^{2\pi} d\Phi}$$

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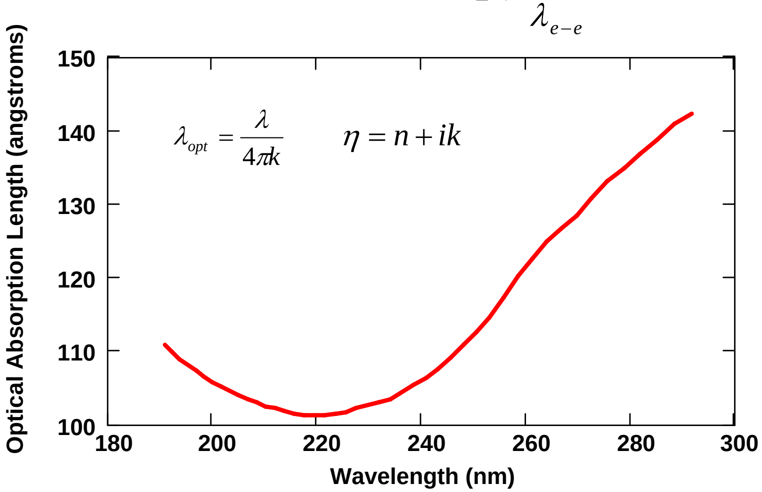
Assuming the three-step model the previous relation can be separated into three factors and integrating over angles and initial electron energy gives:

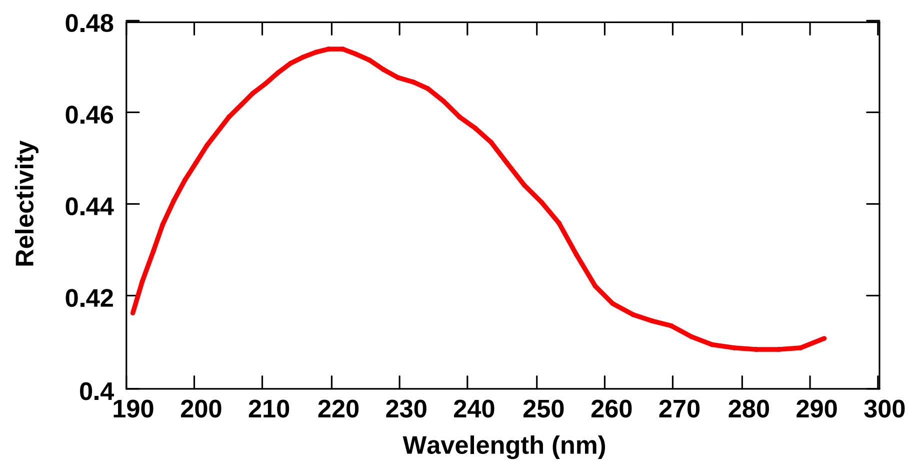
$$QE(\omega)=\left(1-R(\omega)\right)F_{e-e}(\omega)\frac{\int\limits_{E_F+\phi_{eff}-\hbar\omega}^{E_F} dE \int\limits_{\sqrt{\frac{E_f+\phi_{eff}}{E+\hbar\omega}}}^{1} d(\cos\theta)\int\limits_0^{2\pi} d\Phi}{\int\limits_{E_F-\hbar\omega}^{E_F} dE \int\limits_{-1}^{1} d(\cos\theta)\int\limits_0^{2\pi} d\Phi} \Rightarrow QE(\omega)=\left(1-R(\omega)\right)F_{e-e}(\omega)\frac{\left(E_F+\hbar\omega\right)}{2\hbar\omega}\left[1+\frac{E_F+\phi_{eff}}{E_F+\hbar\omega}-2\sqrt{\frac{E_F+\phi_{eff}}{E_F+\hbar\omega}}\right]$$

Probability electron at depth s, absorbs a photon and escapes without scattering:

$$f(s)=\frac{1}{\lambda_{opt}}e^{-s\left(\frac{1}{\lambda_{opt}}+\frac{1}{\lambda_{e-e}}\right)} \Rightarrow F_{e-e}=\int\limits_0^{\infty} f(s)ds=\frac{1}{1+\frac{\lambda_{opt}}{\lambda_{e-e}}}$$

$$QE(\omega)=\frac{1-R(\omega)}{1+\frac{\lambda_{opt}}{\lambda_{e-e}}}\frac{E_F+\hbar\omega}{2\hbar\omega}\left[1+\frac{E_F+\phi_{eff}}{E_F+\hbar\omega}-2\sqrt{\frac{E_F+\phi_{eff}}{E_F+\hbar\omega}}\right]$$





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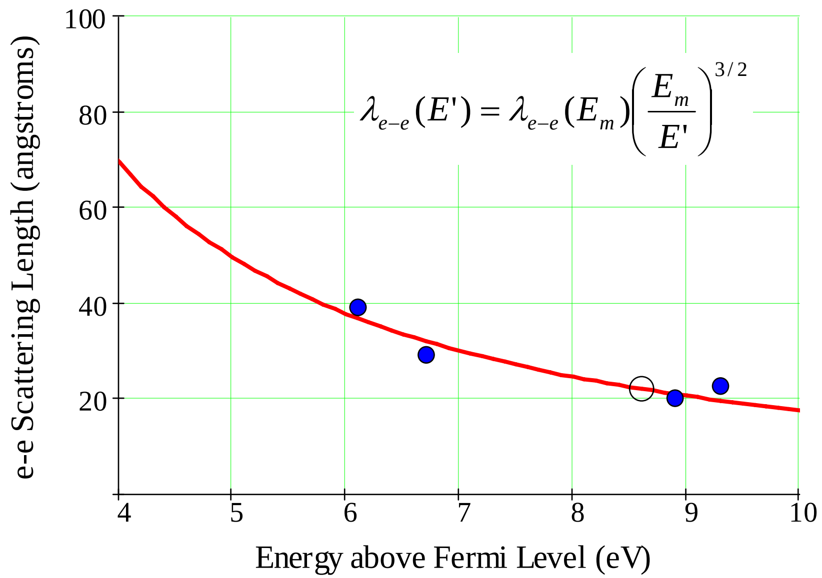
$$QE(\omega) = \frac{1-R(\omega)}{1+\dfrac{\lambda_{opt}}{\lambda_{e-e}}}\frac{E_F+\hbar\omega}{2\hbar\omega}\left[1+\frac{E_F+\phi_{eff}}{E_F+\hbar\omega}-2\sqrt{\frac{E_F+\phi_{eff}}{E_F+\hbar\omega}}\right]$$

Assume the electron-electron scattering length can be averaged over energy:

$$\bar{\lambda}_{e-e}(\hbar\omega) = \frac{\int_{\phi_{eff}}^{\hbar\omega}\lambda_{e-e}(E)dE}{\int_{\phi_{eff}}^{\hbar\omega}dE} = \frac{2\lambda_m E_m^{3/2}}{\hbar\omega\sqrt{\phi_{eff}}}\frac{1}{\left(1+\sqrt{\dfrac{\phi_{eff}}{\hbar\omega}}\right)}$$

$$\phi_{eff} = \phi - \phi_{schottky}$$



The QE is then given by:

$$QE(\omega) = \frac{1-R(\omega)}{1+\dfrac{\lambda_{opt}(\omega)}{2\lambda_{e-e}(E_m)}\dfrac{\hbar\omega\sqrt{\phi_{eff}}}{E_m^{3/2}}\left(1+\sqrt{\dfrac{\phi_{eff}}{\hbar\omega}}\right)}\frac{(E_F+\hbar\omega)}{2\hbar\omega}\left[1+\frac{E_F+\phi_{eff}}{E_F+\hbar\omega}-2\sqrt{\frac{E_F+\phi_{eff}}{E_F+\hbar\omega}}\right]$$

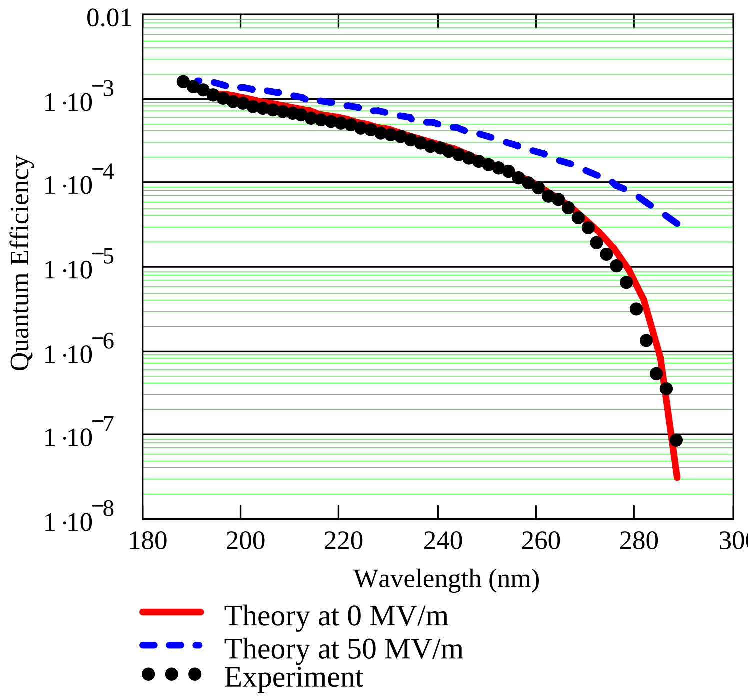
Final expression for QE and comparison with experiment

$$QE(\omega) = \frac{1-R(\omega)}{1+\frac{\lambda_{opt}}{2\lambda_{e-e}(E_m)}\frac{\hbar\omega\sqrt{\phi_{eff}}}{E_m^{3/2}}\left(1+\sqrt{\frac{\phi_{eff}}{\hbar\omega}}\right)} \frac{(E_F+\hbar\omega)}{2\hbar\omega}\left[1+\frac{E_F+\phi_{eff}}{E_F+\hbar\omega}-2\sqrt{\frac{E_F+\phi_{eff}}{E_F+\hbar\omega}}\right]$$

$$\phi_{eff} = \phi - \phi_{schottky}$$

$$\phi_{schottky} = 3.7947\times 10^{-5}\sqrt{E(V/m)}\ \text{eV}$$

Fermi Energy, E_F	7eV
Work Function, ϕ	4.31eV
$\phi_{schottky}$ @50MV/m	0.268eV
e-e scattering length @8.6eV	22 angstroms



http://www.slac.stanford.edu/pubs/slacpubs/11750/slac-pub-11788.pdf , submitted to PRST-AB

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So for metals there is excellent agreement between the free electron gas model and experiment, but what about the thermal emittance?

The problem is both theoretical and experimental:

> ***No thermal emittance measurements at low field with clean cathode***
> ***No QE vs. wavelength at high field to verify the QE theory***

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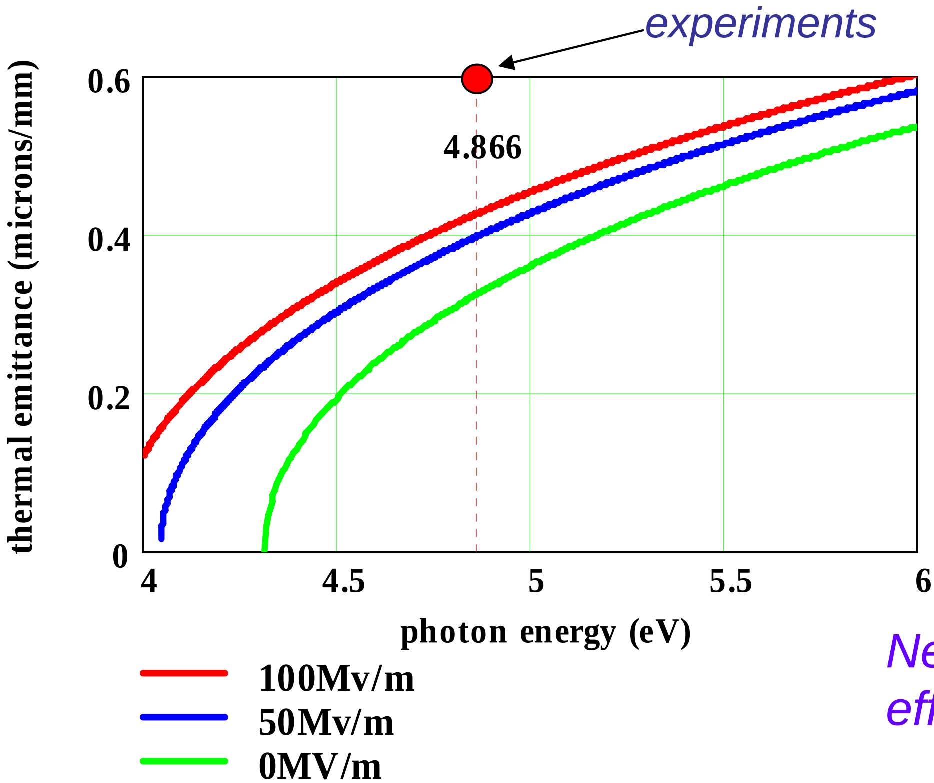
An expression for the thermal emittance can also be derived using the free electron gas model

$$\varepsilon_{thermal} = R_c \left[\frac{ \frac{E_F + \hbar\omega}{3}\left(1 - r^2\right) - \frac{2}{3}\hbar\omega\left(1 + 3r - \left(3 - \frac{E_F + \hbar\omega}{\hbar\omega}\right) r^{1/2} - \left(1 + \frac{E_F + \hbar\omega}{\hbar\omega}\right) r^{3/2}\right) }{ 2\left(1 + r - 2r^{1/2}\right) mc^2 } \right]^{1/2}$$

where R_C is the cathode (laser) radius and

$$r = \frac{E_F + \phi_{eff}}{E_F + \hbar\omega}$$



Experimental emittance is larger by factor of 1.5 even after taking into account the Schottky reduction of the barrier

Need to understand the effects of high field emission

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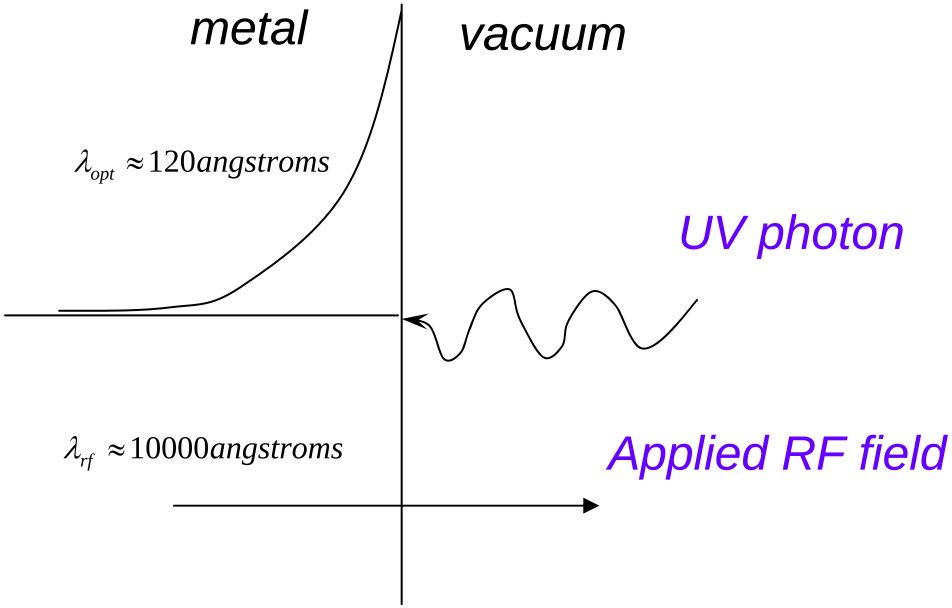
The optical skin depth is much less than the RF skin depth,
this means the electrons are accelerating inside the metal before being emitted



Theory (and simulation codes) ignore this effect, but it can be significant.

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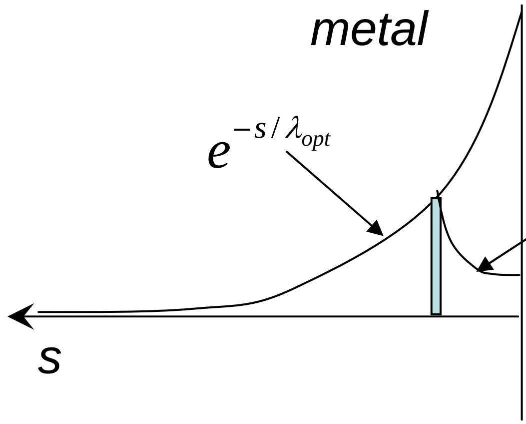
A crude estimate of the effect can be made by computing the energy spread of the electrons when they reach the surface,



$$e^{-s/\lambda_{opt}} e^{-s/\lambda_{e-e}} = e^{-s\left(\frac{1}{\lambda_{opt}}+\frac{1}{\lambda_{e-e}}\right)} = e^{-s/\lambda_{eff}}$$

probability an electron at depth s, escapes

Each electron coming from a depth s, will gain $eE_{ext}s$ as it moves to the surface. The average energy gain and rms energy spread are,

$$\mu_E = \frac{\int_0^\infty eE_{ext} s e^{-s/\lambda_{eff}} ds}{\int_0^\infty e^{-s/\lambda_{eff}} ds} = eE_{ext}\lambda_{eff}$$

$$\sigma_E^2 = \frac{\int_0^\infty \left(eE_{ext}s - \mu_E\right)^2 e^{-s/\lambda_{eff}} ds}{\int_0^\infty e^{-s/\lambda_{eff}} ds}$$

$$\sigma_E = eE_{ext}\lambda_{eff} = \frac{eE_{ext}\lambda_{opt}\lambda_{e-e}}{\lambda_{opt}+\lambda_{e-e}}$$

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$$\sigma_E = eE_{ext}\lambda_{eff} = \frac{eE_{ext}\lambda_{opt}\lambda_{e-e}}{\lambda_{opt}+\lambda_{e-e}}$$

Estimate magnitude of energy spread at 255 nm,

$$\lambda_{opt} = 117 angstroms; \lambda_{e-e} = 52 angstroms; E_{ext} = 100 MV/m \Longrightarrow \sigma_E \cong 0.36 eV$$

Use this for crude estimate of emittance:

$$\varepsilon \approx \beta\gamma\sigma_{x'}\sigma_x$$

$$\sigma_{x'} = \frac{\sqrt{2m\sigma_E}}{\beta\gamma mc} = \frac{1}{\beta\gamma}\sqrt{\frac{2\sigma_E}{mc^2}}$$

For a uniform radial distribution: $\sigma_x = \frac{R}{2}$

And the thermal emittance is:

$$\varepsilon \approx \beta\gamma\sigma_{x'}\sigma_x = R\sqrt{\frac{\sigma_E}{2mc^2}} \quad \text{or} \quad \varepsilon / R \approx 0.6 microns/mm$$

which roughly agrees with the high field measurements

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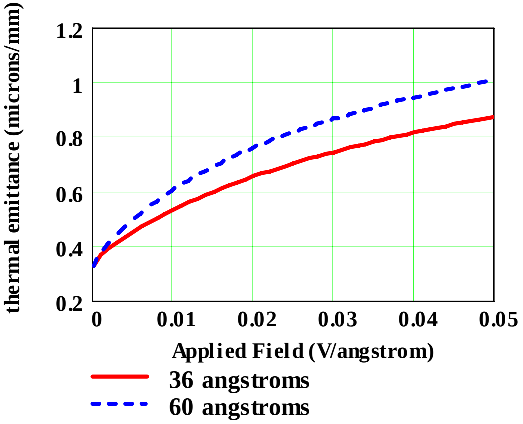
A better calculation of the emittance begins with the transverse momentum:

$$\left\langle p_T^2 \right\rangle = \frac{\int_{E_F+\phi-\hbar\omega}^{E_F} dE \int_{\cos\theta_{\max}}^{1} d(\cos\theta) \int_0^\infty ds \int_0^{2\pi} d\Phi\, p_T^2 e^{-s/\lambda_{eff}}}{\int_{E_F+\phi-\hbar\omega}^{E_F} dE \int_{\cos\theta_{\max}}^{1} d(\cos\theta) \int_0^\infty ds \int_0^{2\pi} d\Phi}$$

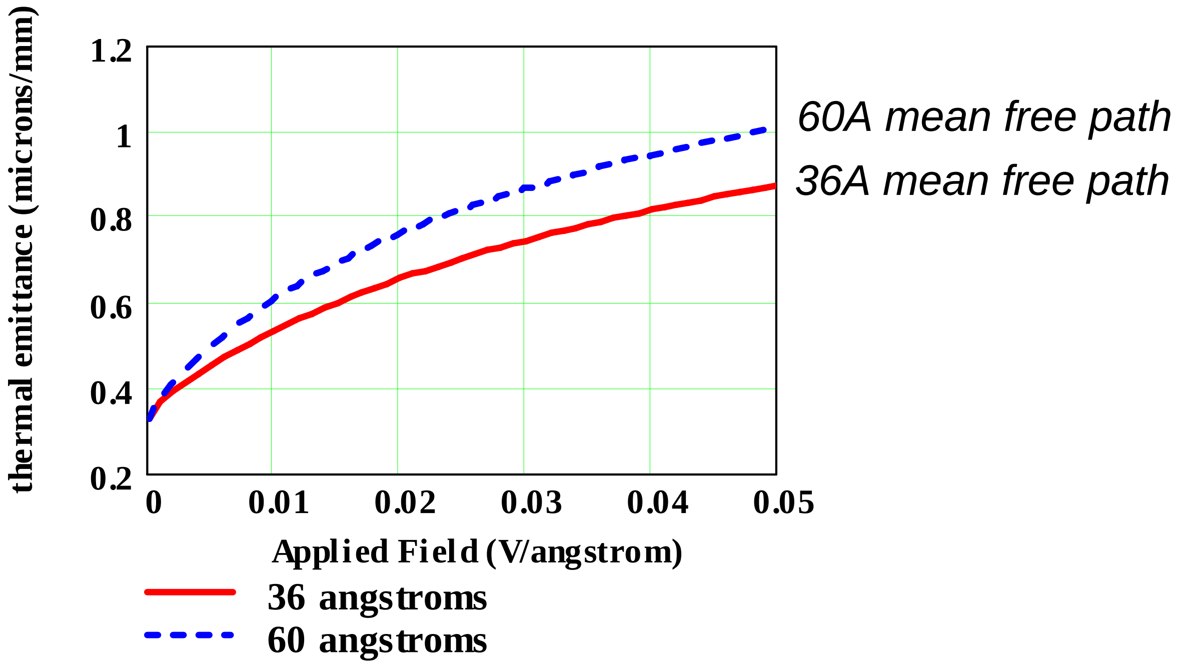
$$\left\langle p_T^2 \right\rangle = \frac{4\pi m \int_{E_F+\phi-\hbar\omega}^{E_F} EdE \int_0^\infty e^{-s/\lambda_{eff}} \left[\frac{2}{3} + \left(\frac{E_F+\phi}{3\left(E+\hbar\omega+eE_{ext}s\right)} - 1 \right) \sqrt{\frac{E_F+\phi}{E+\hbar\omega+eE_{ext}s}} \right] ds}{2\pi \int_{E_F+\phi-\hbar\omega}^{E_F} dE \int_0^\infty e^{-s/\lambda_{eff}} \left(1 - \sqrt{\frac{E_F+\phi}{E+\hbar\omega+eE_{ext}s}} \right) ds}$$

Numerically integrate to obtain the emittance:

$$\varepsilon_{thermal} = \beta\gamma\sigma_x\sigma_{x'} = \frac{R_c}{2} \frac{\left\langle p_T^2 \right\rangle^{1/2}}{mc}$$



Including acceleration inside the metal increases the emittance about 50% for 100MV/m (0.01V/angstrom).
But to obtain agreement with experiment requires a much longer effective mean free path. Or higher field enhancement.



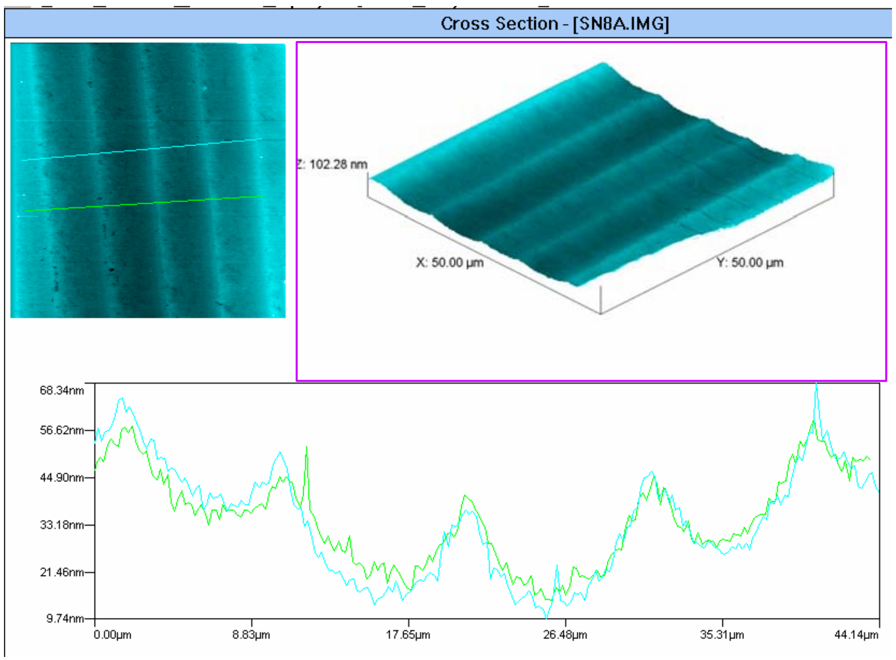
Clearly high fields will significantly increase the thermal emittance

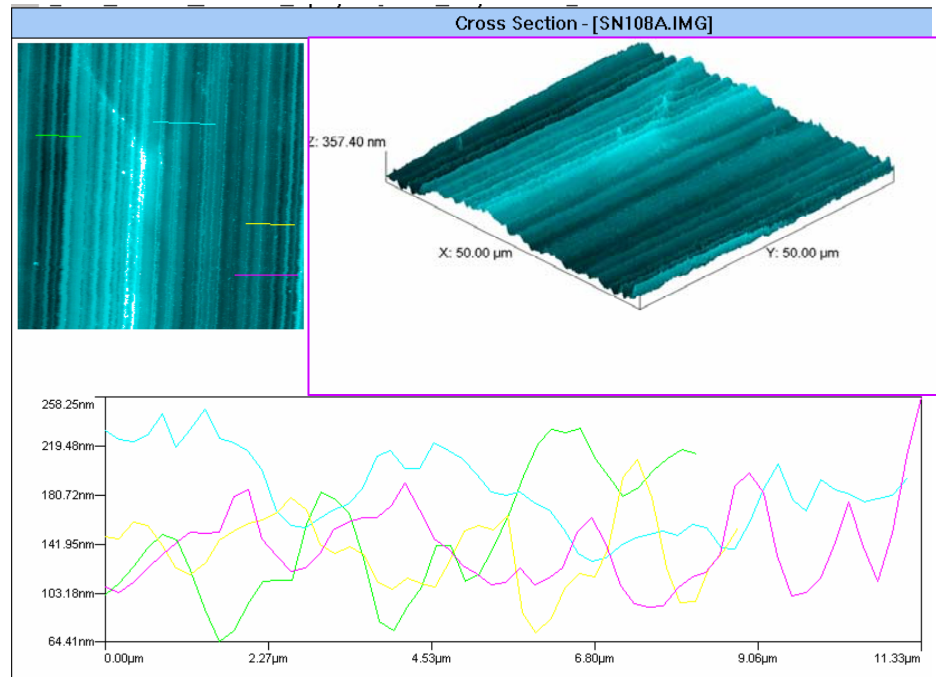
Surface Physics of Real Cathodes Can be Very Complex

Vendor vs. klystron dept. diamond-turned samples

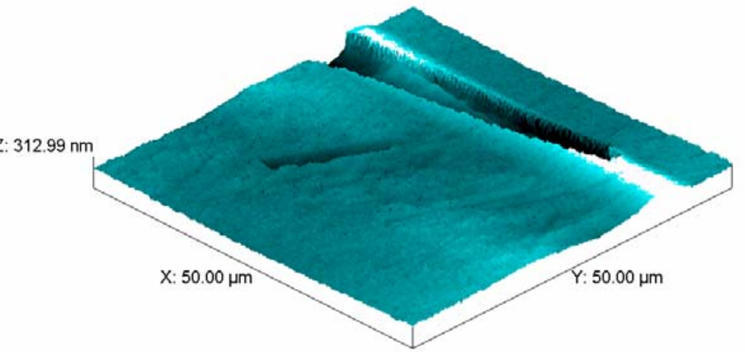
Fly cut with single-crystal diamond tool by Diamond Turning, Inc.

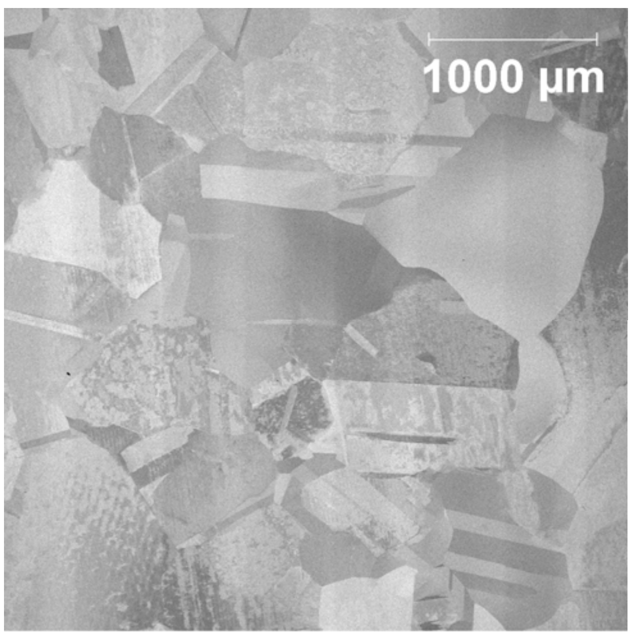
Fly cut with polycrystalline diamond tool in Klystron Shop

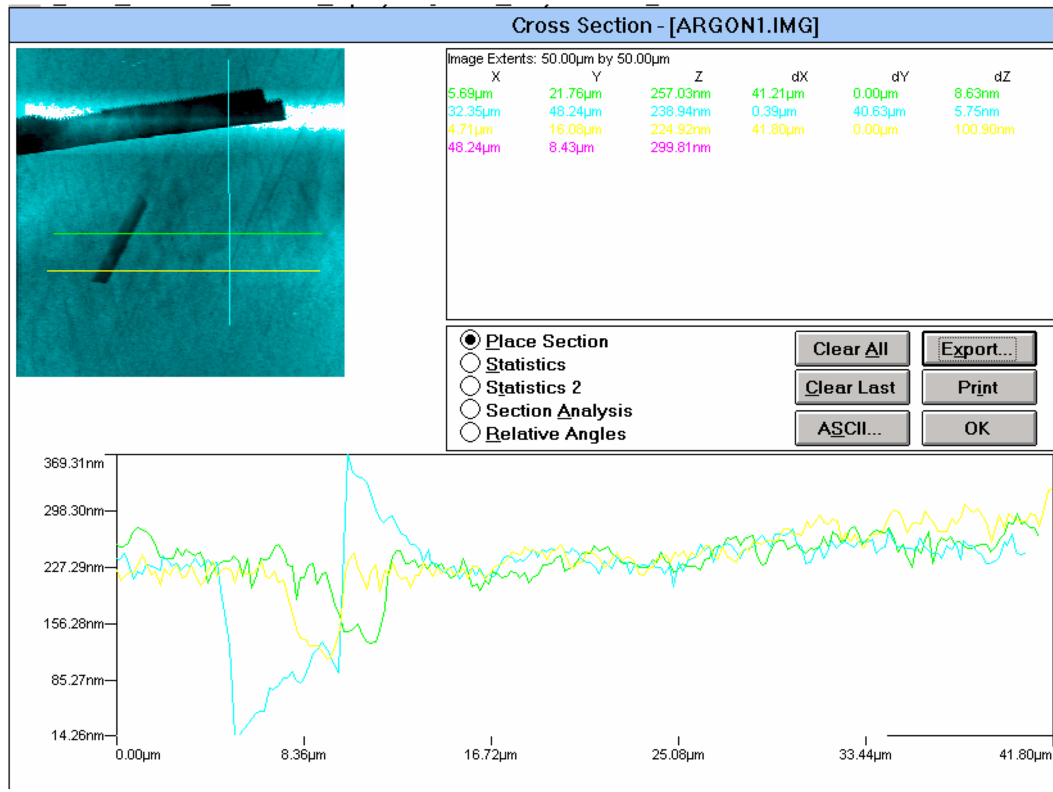




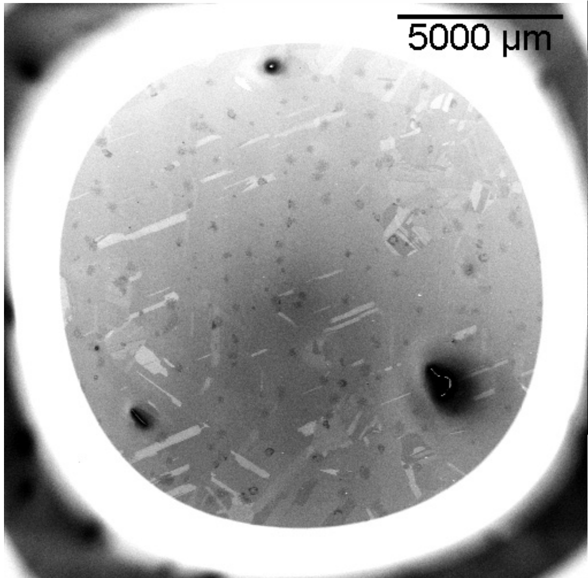
Ar-Ion cleaning preferentially mills out particular grains (single crystals), producing high-contrast canyons in the surface

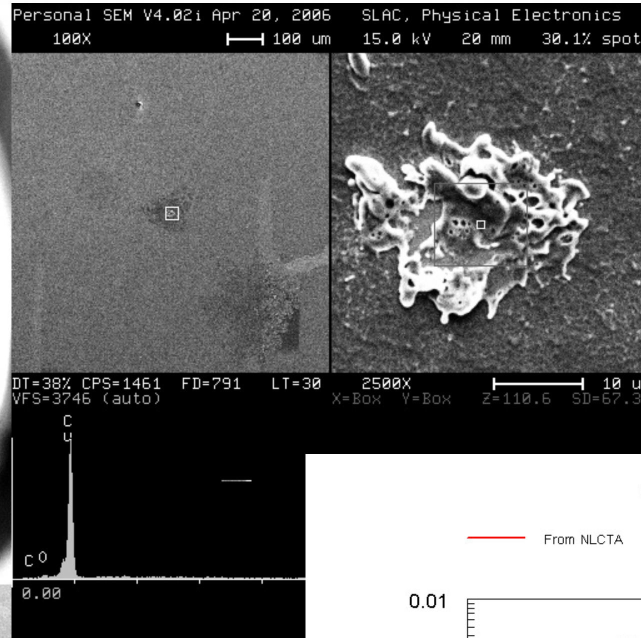


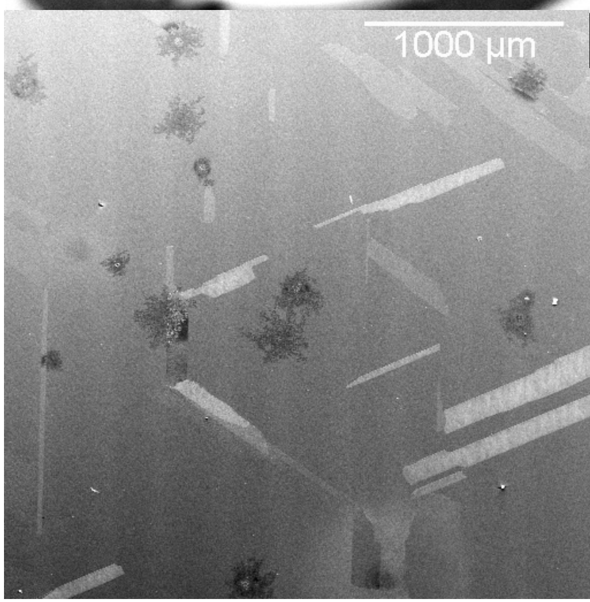


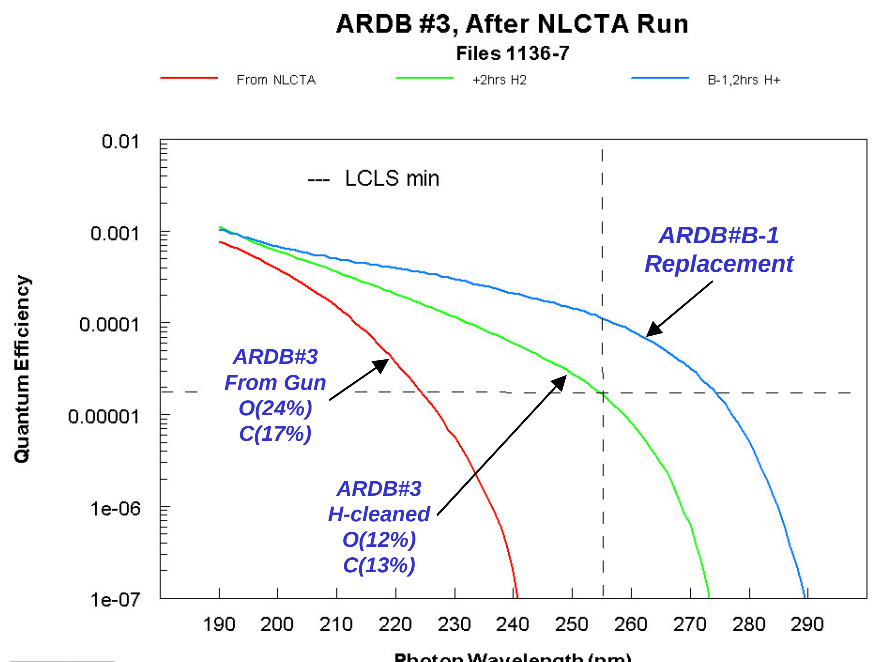


Cleaning of a damaged cathode









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Summary and Conclusions

- Theory developed for QE and thermal emittance
  - Great* agreement between QE theory and expt.
  - Thermal emittance theory requires inclusion of acceleration inside the metal to improve agreement with theory

- But not all the possible effects of surface roughness and material properties have been included

- The interaction of the electrons with the near cathode fields needs study
  - Dynamical (time-dependent) image charge fields
  - etc.

- These phenomena need to be included in simulation codes

*B. Kirby quote

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