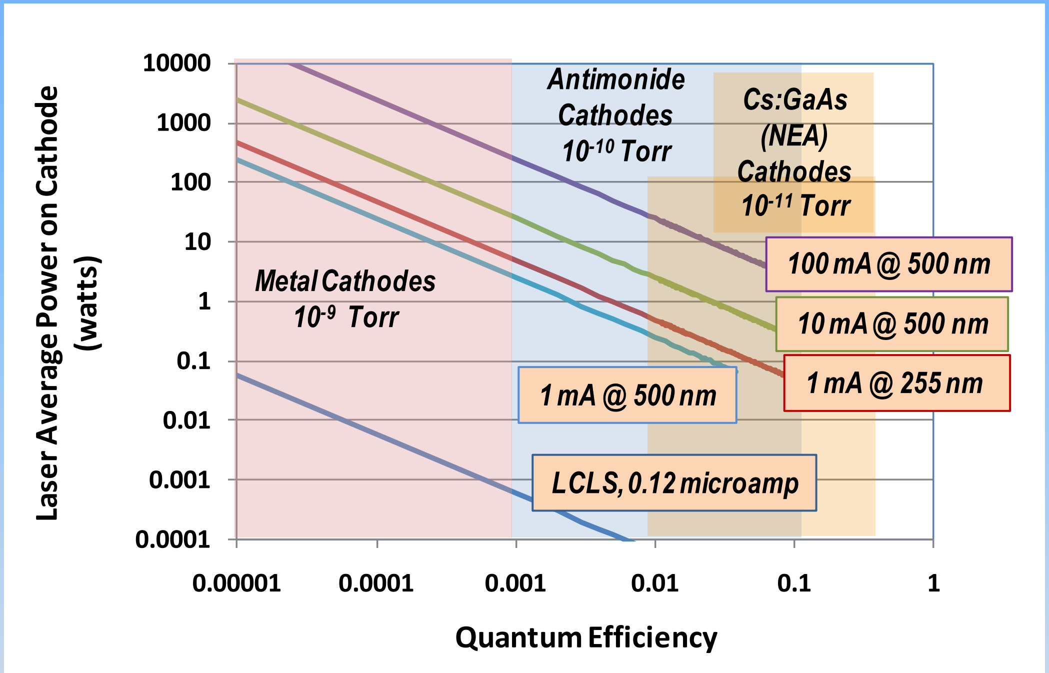
Lecture 13
*Practical Cathodes**

*Talk given at Future Light Sources 2010

Laser Power Requirements

Average laser power vs. quantum efficiency to produce various average beam currents. The QE ranges for the general cathode types are shown along with their vacuum requirements.

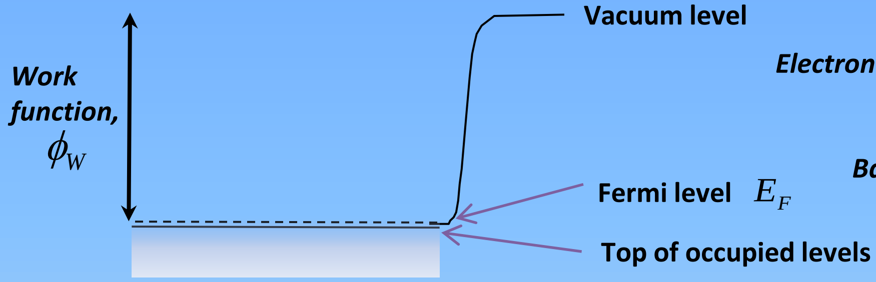


UV Wavelength good for high QE however:

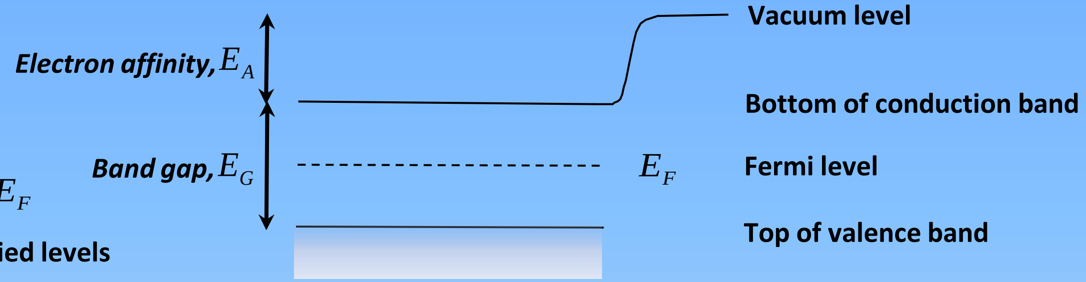
- *UV laser is difficult but possible*
    - *Careful design mitigates optical damage*
- *UV light decomposes hydrocarbons in vacuum which attach to cathode*
    - *Electron beam also decomposes vacuum constituents*

Estimating metal and semiconductor thermal emittances

Metal energy levels
T ~ 300 degK



Semiconductor energy bands
T ~ 300 degK



$$\frac{\varepsilon_n}{\sigma_x} = \frac{\sqrt{\langle p_x^2 \rangle}}{mc}$$

$$\frac{\varepsilon_{metal,n}}{\sigma_x} = \sqrt{\frac{\hbar\omega - \phi_W}{3mc^2}}$$

$$E_{excess,metal} = \hbar\omega - \phi_W$$

$$E_{excess,semi} = \hbar\omega - E_G - E_A$$

$$\frac{\varepsilon_{semi,n}}{\sigma_x} = \sqrt{\frac{\hbar\omega - E_G - E_A}{3mc^2}}$$

Due to electron-phonon scattering the excited electrons can thermalize with the lattice, giving GaAs a thermal-like emission component:

$$\frac{\varepsilon_{GaAs,n}}{\sigma_x} = A_{slow}\sqrt{\frac{k_B T}{mc^2}} + A_{fast}\sqrt{\frac{\hbar\omega - E_G - E_A}{3mc^2}}$$

This gives rise to a slow thermionic-like emission and a fast prompt photoelectric emission which is dependent upon wavelength band gap energy and affinity.

Thermionic Cathodes

Thermionic emittance: $$\frac{\varepsilon_{th,n}}{\sigma_x} = \sqrt{\frac{k_B T}{mc^2}}$$

Some properties of the SCSS Thermionic Cathode

Thermionic Cathodes	Typical Temperature, T (°K), (eV)	Emission Radius (mm)	Surface Current Density (A/cm²)	Work Function, ϕ_W (eV)	Thermal Emittance (microns /mm(rms))
CeB_6 single crystal	1723K, 0.15 eV	1.5	42	2.3	0.54

For a desired bunch charge, Q, the required bunch length can be estimated from the Richardson-Dushman eqn. for the thermionic current density,

$$j_{thermal}(T) = AT^2 e^{-\frac{\phi_{eff}}{k_B T}} \qquad A \equiv \frac{-em}{2\pi^2\hbar^3} = 120 A/cm^2 K^2$$

$$Q(T, t_{bunch}) = j_{thermal}(T)\Delta t_{bunch}$$

$$\Delta t_{bunch} = \frac{Q}{\pi R_c^2 \, j_{thermal}(T)} = \frac{Q}{4\pi\sigma_x^2 \, j_{thermal}(T)}$$

SCSS example: A 250 pC bunch requires a bunch length of 83 ps from the cathode which is then compressed to ~10 degRF before accelerating in linac.

Metal Cathodes

Metal photocathodes are commonly used in high gradient, high frequency RF guns and are the mainstay of the BNL/SLAC/UCLA and the LCLS s-band guns. Due to the high work function UV photons are needed for reasonable QE, which makes them impractical for high average current applications such as ERLs. However, they are the most robust of all the photoemitters and can survive for years at the high cathode fields required to produce a high brightness beam. The current copper cathode in the LCLS gun has operated for the x-ray FEL for over a year.

Metal Cathodes	**Wavelength & Energy: λ_{opt} (nm), $\hbar\omega$(eV)**	**Quantum Efficiency (electrons per photon)**	**Vacuum for 1000 Hr Operation (Torr)**	**Work Function, ϕ_W (eV)**	**Thermal Emittance (microns/mm(rms))**	
					Theory	**Expt.**
Bare Metal						
Cu	250, 4.96	1.4×10^{-4}	10^{-9}	4.6 [34]	0.5	1.0±0.1 [39] 1.2±0.2 [40] 0.9±0.05 [3]
Mg	266, 4.66	6.4×10^{-4}	10^{-10}	3.6 [41]	0.8	0.4±0.1 [41]
Pb	250, 4.96	6.9×10^{-4}	10^{-9}	4.0 [34]	0.8	?
Nb	250, 4.96	$\sim 2\ 10^{-5}$	10^{-10}	4.38 [34]	0.6	?
Coated Metal						
CsBr:Cu	250, 4.96	7×10^{-3}	10^{-9}	~2.5	?	?
CsBr:Nb	250, 4.96	7×10^{-3}	10^{-9}	~2.5	?	?

The thermal emittances are computed using the listed photon and work function energies in eqn. on previous slide and expresses the thermal emittance as the normalized rms emittance in microns per rms laser size in mm. The known experimental emittances are given with references.

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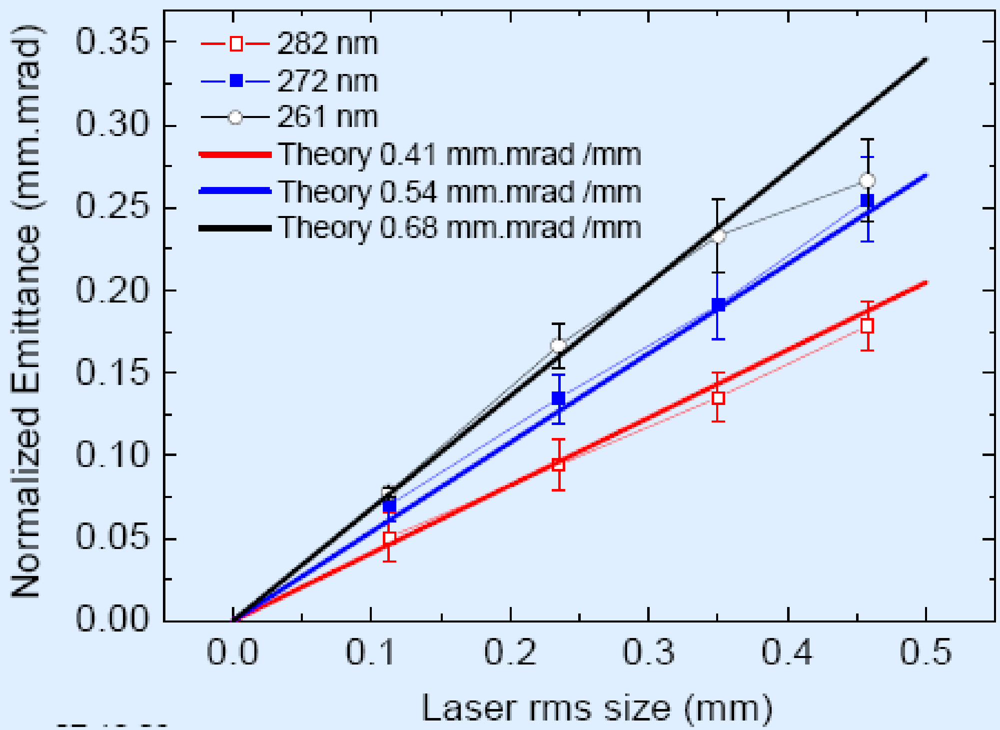
Intrinsic Emittance versus Laser Wavelength



261 nm: 0.68 mm.mrad / mm

272 nm: 0.54 mm.mrad / mm

282 nm: 0.41 mm.mrad / mm

$$\varepsilon_{Intrinsic} = \sigma_x \sqrt{\frac{h\nu - \Phi_0 + e^{3/2}\frac{F_{eff}^{1/2}}{(4\pi\varepsilon_0)^{1/2}}}{3mc^2}}$$

Φ_{Cu}= 4.35 eV

With F_{eff} = 25 MV/m

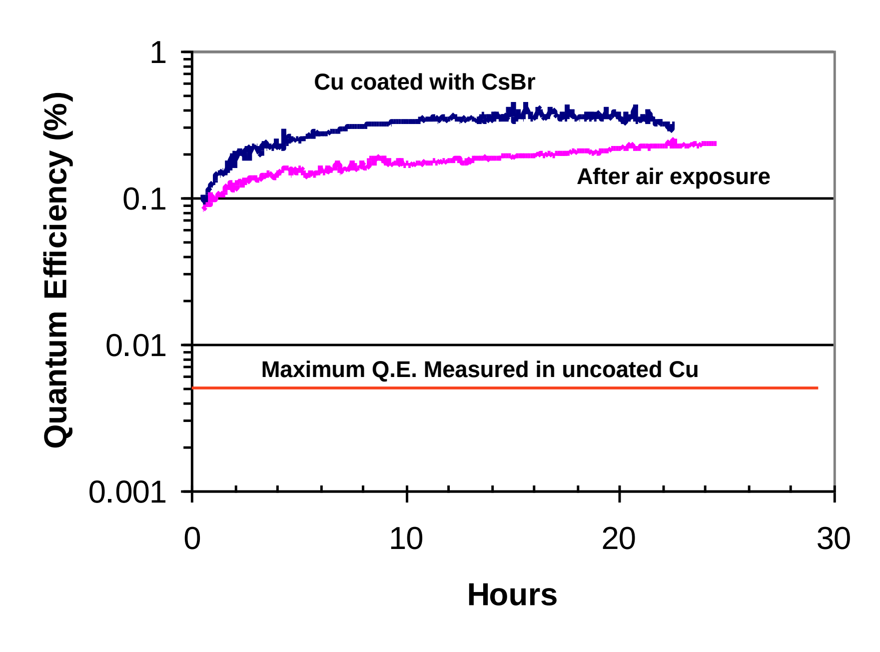
Exp. Cond.:
Q < 1 pC; 5.2 MeV
$\sigma_{t,laser}$= 4 ps rms; 25 MV/m
Copper Cu
Solenoid Scan

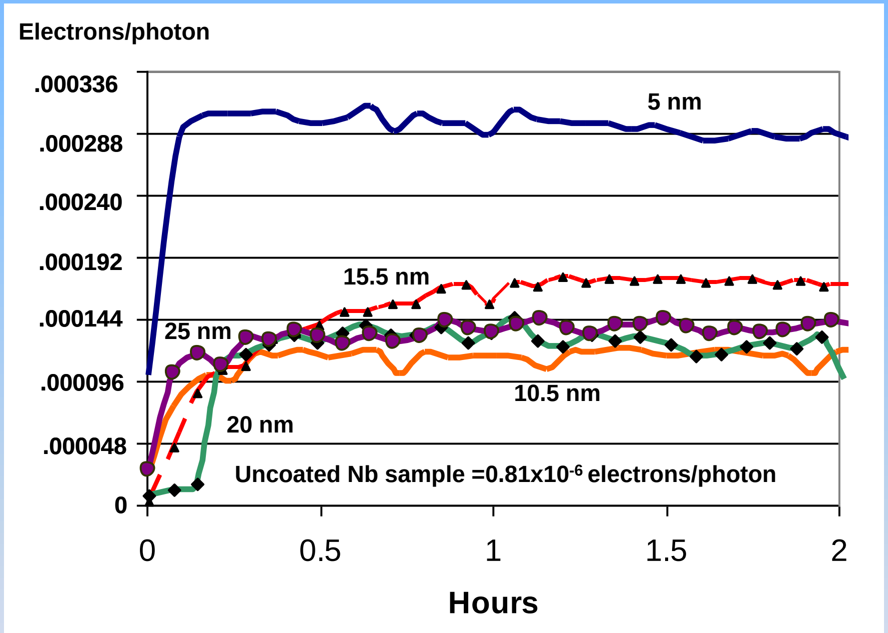
Slide compliments of H. Braun and R. Ganter, PSI

Coated Metal Cathodes

Quantum efficiency(%) at 257nm of CsBr/Cu sample as deposited and after exposure to air for 1 minute and pumped down to low pressure without bake out.

Depositing a thin layer of CsBr increases Nb QE a factor of 350!
Possibility of a superconducting cathode as thin layer maintains super conductivity of Nb-substrate.





J. Maldonado et al., "A Robust CsBr/Cu photocathode for the LINAC COHERENT LIGHT SOURCE (LCLS)", Phys. Rev. ST Accel. Beams 11, 060702 (2008)

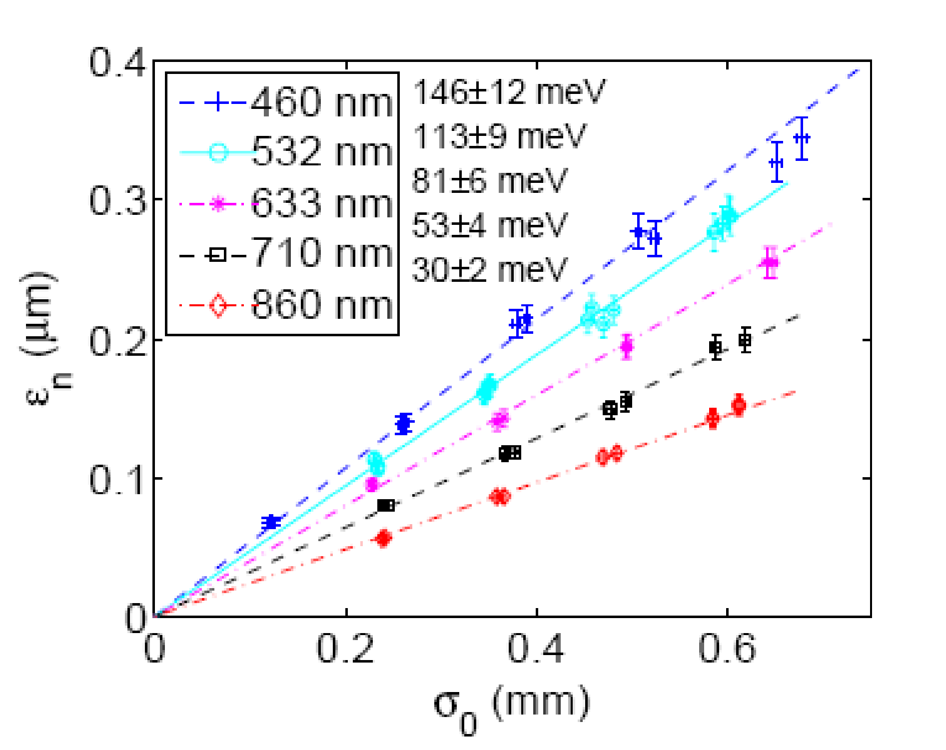
J. Maldonado et al., "Performance of a CsBr coated Nb photocathode at room temperature", JAP 107, 013106 (2010).

Semiconductor Cathodes

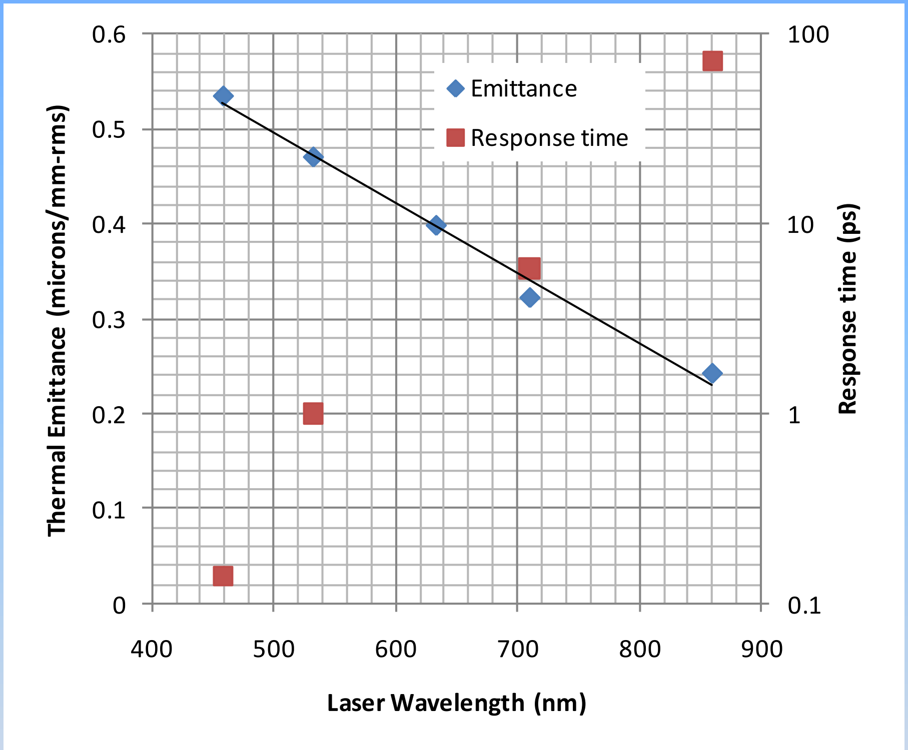
The thermal emittances are computed using the listed photon, gap and electron affinity energies and expresses the thermal emittance as the normalized rms emittance in microns per rms laser size in mm.

Cathode Type	*Cathode*	*Typical Wavelength, λ_{opt}(nm), (eV)*	*Quantum Efficiency (electrons per photon)*	*Vacuum for 1000 Hrs (Torr)*	*Gap Energy + Electron Affinity, $E_A + E_G$ (eV)*	*Thermal Emittance (microns/mm(rms))*	
						Theory	*Expt.*
PEA: Mono-alkali	Cs_2Te	211, 5.88 264, 4.70 262, 4.73	~0.1 - -	10^{-9} - -	3.5 [42] “ ”	1.2 0.9 0.9	0.5±0.1 [35] 0.7±0.1 [35] 1.2 ±0.1 [43]
	Cs_3Sb	432, 2.87	0.15	?	1.6 + 0.45 [42]	0.7	?
	K_3Sb	400, 3.10	0.07	?	1.1 + 1.6 [42]	0.5	?
	Na_3Sb	330, 3.76	0.02	?	1.1 + 2.44 [42]	0.4	?
	Li_3Sb	295, 4.20	0.0001	?	?	?	?
PEA: Multi-alkali	Na_2KSb	330, 3.76	0.1	10^{-10}	1+1 [42]	1.1	?
	$(Cs)Na_3KSb$	390, 3.18	0.2	10^{-10}	1+0.55 [42]	1.5	?
	K_2CsSb	543, 2.28	0.1	10^{-10}	1+1.1 [42]	0.4	?
	$K_2CsSb(O)$	543, 2.28	0.1	10^{-10}	1+<1.1 [42]	~0.4	?
NEA	GaAs(Cs,F)	532, 2.33 860, 1.44	~0.1 -	? ?	1.4±0.1 [42] ”	0.8 0.2	0.44±0.01 [44] 0.22±0.01 [44]
	GaN(Cs)	260, 4.77	-	?	1.96 + ? [44]	1.35	1.35±0.1 [45]
	GaAs(1-x)Px x~0.45 (Cs,F)	532, 2.33	-	?	1.96+? [44]	0.49	0.44±0.1 [44]
S-1	Ag-O-Cs	900, 1.38	0.01	?	0.7 [42]	0.7	?

Thermal Emittance and Response Time of GaAs



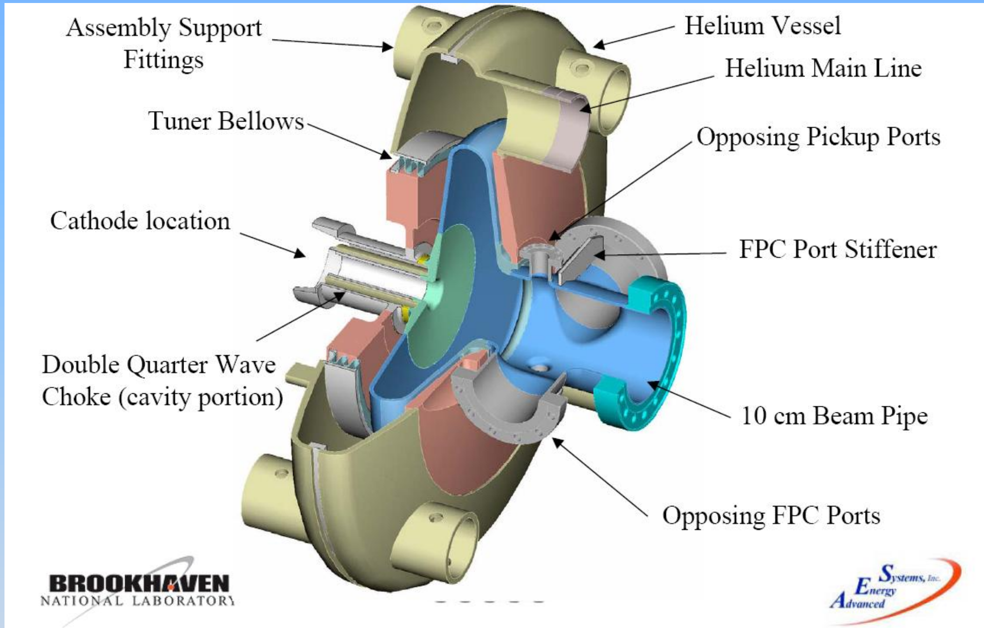
I. V. Bazarov et al., Proceedings of PAC07



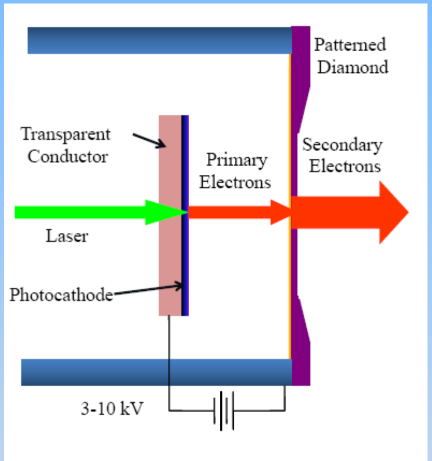
Plot of data taken from I.V. Bazarov et al., APL (2008) and Proceedings of PAC07

Cathodes by Design

Warm cathodes in SRF gun require a technically challenging RF choke for thermal isolation



Advanced Diamond Amplified Cathode Being Developed at BNL for SRF Gun



J. Smedley, I. Ben-Zvi, J. Bohon, X. Chang, R. Grover, A. Isakovic, T. Rao, Q. Wu, "Diamond Amplified Photocathodes", in Diamond Electronics—Fundamentals to Applications II, Mater. Res. Soc. Symp. Proc. 1039, Warrendale, PA, 2007, 1039-P09-02.

X. Chang, I. Ben-Zvi, A. Burrill, J. Kewisch, T. Rao, J. Smedley, Y-C. Wang, Q. Wu, "First Observation of an Electron Beam Emitted from a Diamond Amplified cathode, PAC 09, Vancouver, Canada

Cathode Design and Engineering: Tunable Cathodes

Fabrication of S1-cathode over a structured substrate to induce photoemission from plasmon surface states

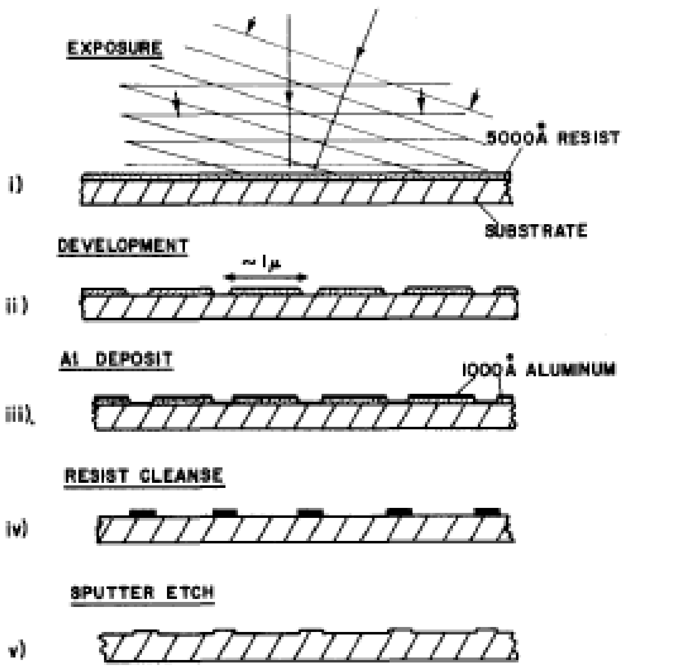


FIG. 2. Method for producing shallow-etched gratings. A split laser beam is used to expose striped areas of precise period in a resist. The resist is developed, aluminum coated, and cleaned off leaving Al stripes. An easily controlled 100—300-Å sputter etch is carried out, followed by removal of residual aluminum.

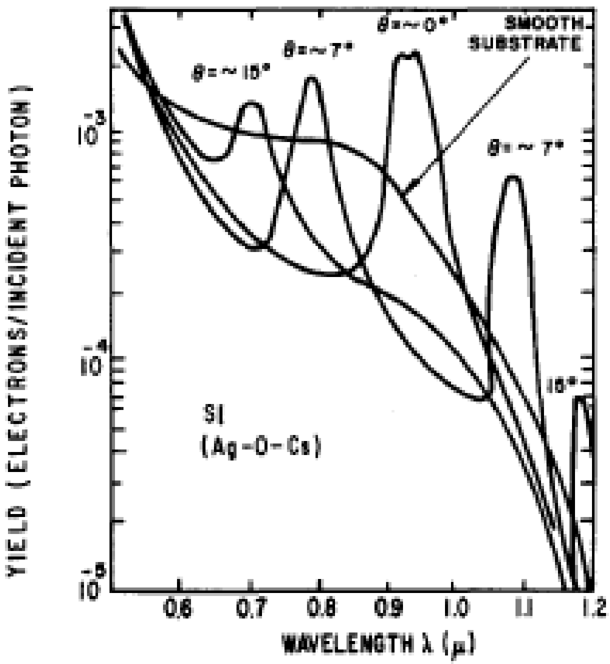


FIG. 3. Quantum efficiency of a grating-tuned S1 cathode. Shown are quantum efficiency curves vs free-space wavelength for p-polarized light at normal and at 7° and 15° angles of incidence. Response of a similar S1 on a smooth substrate is shown for comparison.

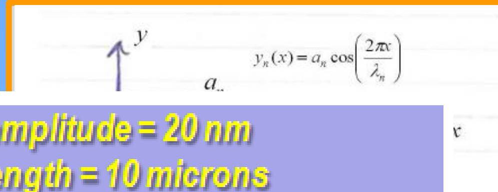
J.G. Endriz, Applied Physics Letters, 25,1974 p261
T. Tsang, T. Srinivasan-Rao, J. Fischer, Phys. Rev. B Vol. 43, pp. 8870-8878, 1991
F. Sabary et al., "Silver-covered diffraction gratings as possible high-efficiency laser driven photoemitters", Applied Physics Letters, 1991. 58(12): p. 1230-1232

Cathode Surface Roughness

Emittance Growth Due to Non-Uniform Emission & Field Enhancement

-Highest cathode field not necessary best emittance-

Emittance Growth Due to Field Enhancement



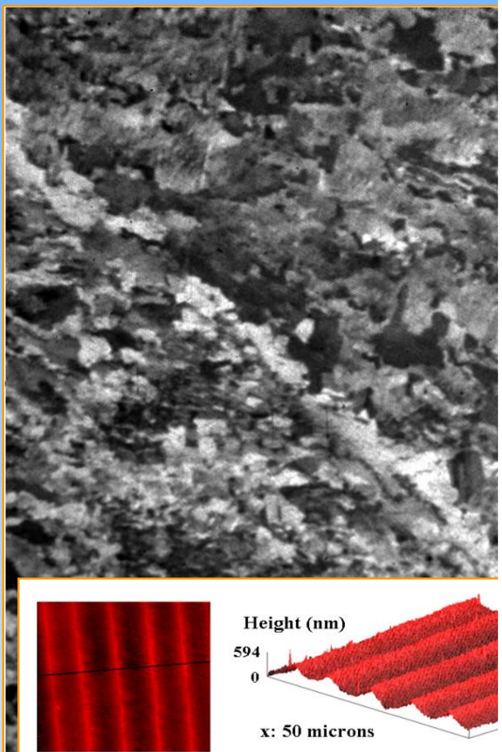
$$\gamma\varepsilon_{n,s} = \sqrt{\frac{e\pi^2 a_n^2 E_{RF}\sin\theta_{RF}}{2mc^2\lambda_n}}$$

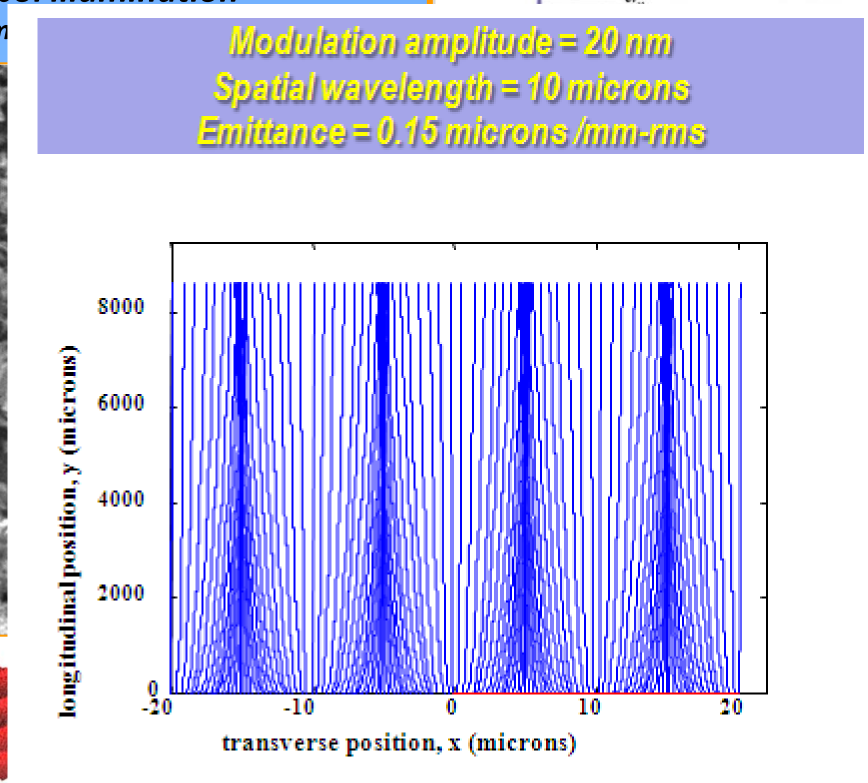
Xiang et al., PAC07, pp. 1049-1051

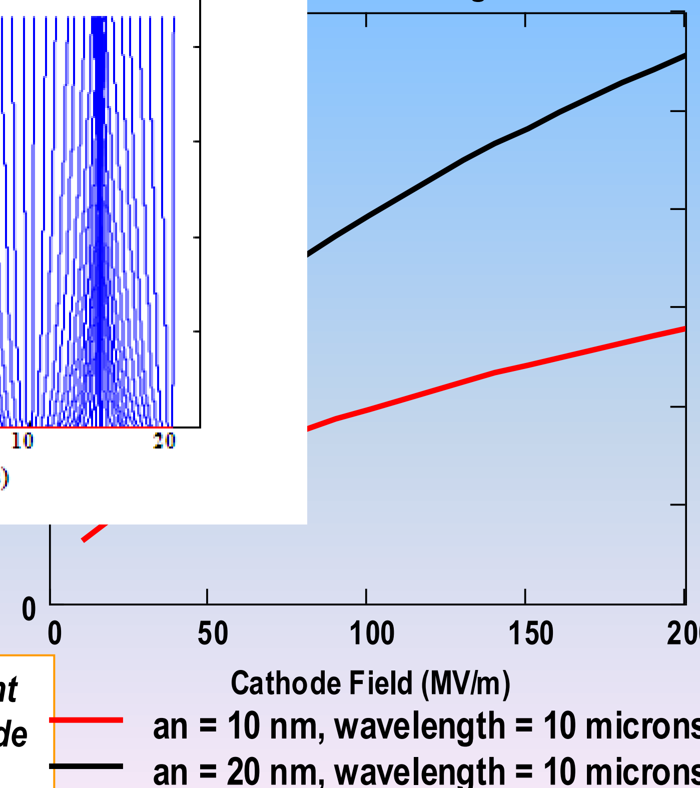
266 nm PEEM image of polycrystalline Cu sample

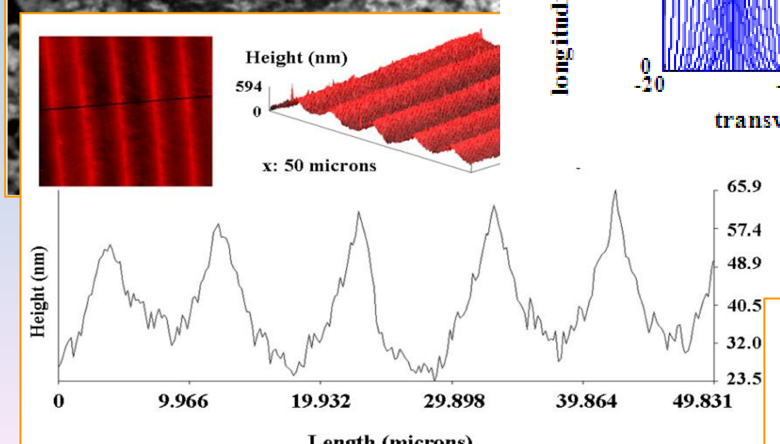
~ 14 micron field of view, p-pol illumination

Image compliments of H. Padm









AFM measurement of a sample cathode surface

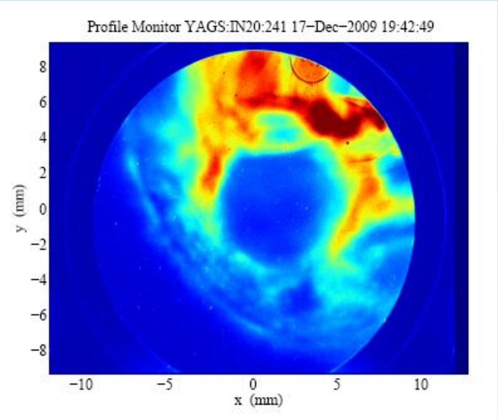
Cathode Contamination

Three sources of cathode contamination

- *Residual contaminants left by fabrication, handling and storage*
- *Contamination by the gun vacuum*
    - *Ambient vacuum*
    - *Operating vacuum*
- *Contamination during operation due to molecular cracking:*
    - *By the laser*
    - *By the electron beam*

For LCLS contamination by molecular cracking (?) is problematic.

Electron beam emission image of the cathode after >1 year of operation. The UV laser beam has left a QE hole at its location.



Estimates of the rate of molecular cracking can be done using the ideal gas law and the cross sections for electron-impact bombardment and photoionization of molecules.
The ideal gas law gives the molecular density (molecules/unit volume) at temperature T and pressure P.
For example, C_6H_6 (benzene) at ambient temperature (300 degK) and P = 10^{-9} Torr,

$$n_{molecules} = \frac{P}{k_B T} = 3.2\times10^{7}\, molecules/cm^{3}$$

The cross sections gives the number of ions produced per electron or UV photon over some interaction length $L_{interaction}$. The interaction length for electrons is the distance over which the cross section is large (see fig). In this case,

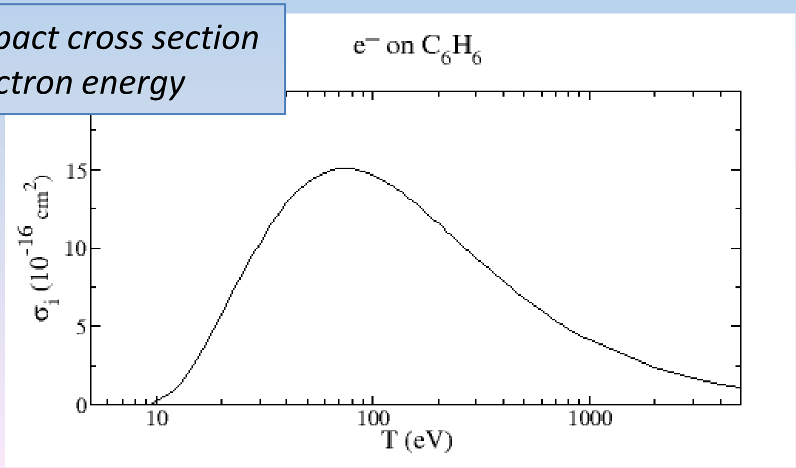
$$L_{interaction} = \frac{T(eV)=1KeV}{50MV/m} \approx 20 microns$$

$$N_{ions,e} = N_e \sigma_{C_6H_6} n_{molecules} L_{interaction}$$

$$= 6.25\times10^{9} e^{-} \times 10^{-15} cm^{2} \times 3.2\times10^{7} molecules/cm^{3} \times 20 microns$$

$$N_{ions,e} \approx 0.4\, ions/nC$$

Electron-impact cross section vs. electron energy



The calculation for photoionization gives an even lower ion production rate.

For LCLS operating at 120 nC/s the ion contamination due to electron-impact and photoionization is too small to explain the QE hole. Thus it appears the monolayer of adsorbed molecules is what is being photoionized into its constituents which then strongly bind to the surface and increase the work function.

The molecular flux on the cathode surface is $\Gamma = n\sqrt{\frac{kT}{2\pi m}}$

Where n is molecular volume density, m is the mass of the C_6H_6 *molecule. At* 10^{-9} *Torr,*

$$\Gamma = 3.2\times10^{13} molecules/m^3 \sqrt{\frac{1.38\times10^{-23} J/\deg K \times 300\deg K}{2\pi\times78\times1.67\times10^{-27} kg}} = 2.3\times10^{11} molecules/(cm^2 s)$$

Monolayer formation time is then (assuming area occupied by each deposited molecule is d_0^2*~(10 angstroms)*^{2}

$$t_{ml} = \frac{1}{\Gamma d_0^2} = \frac{1}{2.3\times10^{11}\times\left(1\times10^{-7}\right)^2} \approx 430\,\text{seconds} \Rightarrow$$ *monolayer has* 10^{14} *molecules/cm*^{2}

The ion yield at the surface with 100 μJ *(for ~1nC) of laser at 4.8 eV is then,*

$$n_{ion} = 2\times1.3\times10^{14}\gamma's/100\mu J\times10^{-26}cm^2\times10^{14} molecules/cm^2 = 260\, ions/100\mu J$$

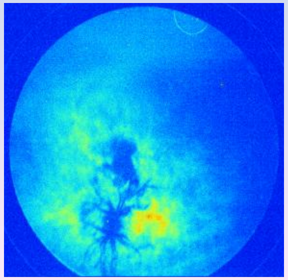
Since laser runs at 30 Hz and beam size is 1.2 mm dia, the time to decompose 10% of the monolayer is

$$\frac{10^{14}/cm^2\times\pi\times(0.06cm)^2(0.1\,\text{coverage})}{260 ions\times30Hz} \approx 1.5\times10^7 s = 174 days$$

Thus in the LCLS case, it is more likely that the monolayer is being photo-dissociated rather than the free molecules in the vacuum.

Summary and Conclusions

- *Reviewed Laser Requirements for cathodes at low and high average current*
- *Developed heuristic theory of thermal emittance for comparing metal and semiconductor cathodes*
- *Listed QE and thermal emittance properties for thermionic, metal and semiconductor cathodes*
- *Described the impact of surface roughness on thermal emittance*
- *Argued contamination of LCLS cathode is due to dissociation of monolayer rather than cracking vacuum constituents*
- *The lack of commercial interest forces us to do our own cathode R&D*
- *Cathode R&D should be directed into three basic aspects of cathode physics and technology*
    - *Fundamental Physics of cathodes and electron emission*
    - *Electron Dynamics near the cathode*
    - *Operational Testing in the gun and injector (two regimes)*
        - *Low average current, ultra-low emittance beams*
        - *High average current, low emittance beams*



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*Cathode R&D for Future Light Sources**

D. H. Dowell[1], I. Bazarov[2], B. Dunham[2], K. Harkay[3],
C. Hernandez-Garcia[4], R. Legg[5], H. Padmore[6], T. Rao[7], J. Smedley[7] and W. Wan[6]
[1]SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
[2]Cornell University, Cornell Laboratory for Accelerator-Based Sciences and Education (CLASSE)
Wilson Laboratory, Cornell University, Ithaca, NY 14853, USA
[3]Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, Il 60439, USA
[4]Thomas Jefferson Laboratory, 12000 Jefferson Ave, Free Electron Laser Suite 19
Newport News, VA 23606, USA
[5]University of Wisconsin, SRC, 3731 Schneider Dr., Stoughton, WI 53589, USA
[6]Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, CA 94720, USA
[7]Brookhaven National Laboratory, 20 Technology Street, Bldg. 535B, Brookhaven National Laboratory
Upton, NY 11973 USA

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