Factors Affecting QE and Dark Current in Alkali Cathodes

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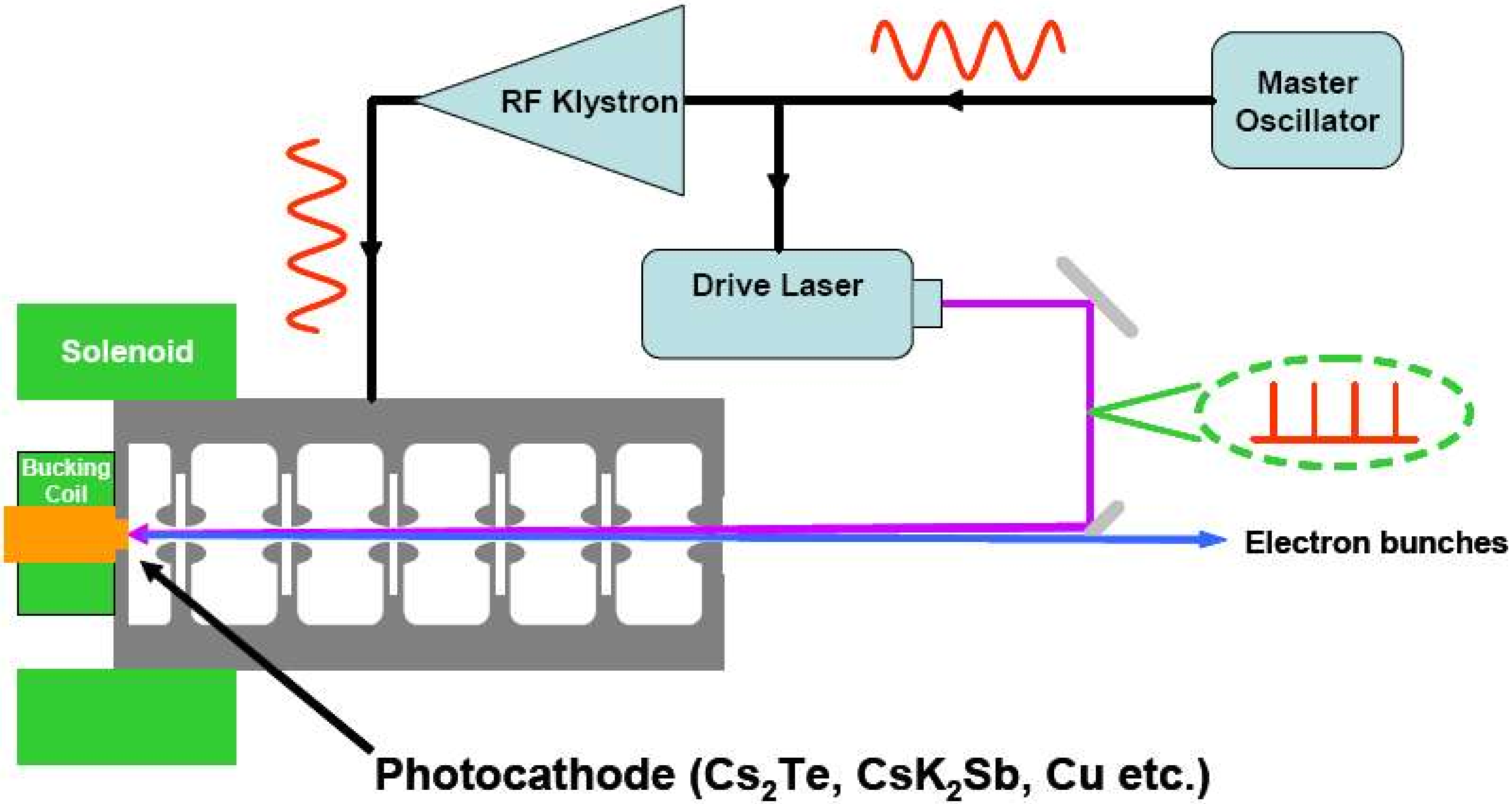
Outline

- Desirable Photocathode Properties
  – Low light detection
  – Accelerator cathodes
- Factors Affecting Performance
- Practical Experience with K_2CsSb
  – Monte Carlo modeling
  – Cathode studies

Photoinjector



Slide compliments of P. O'Shea, UMd

What makes a good photocathode?

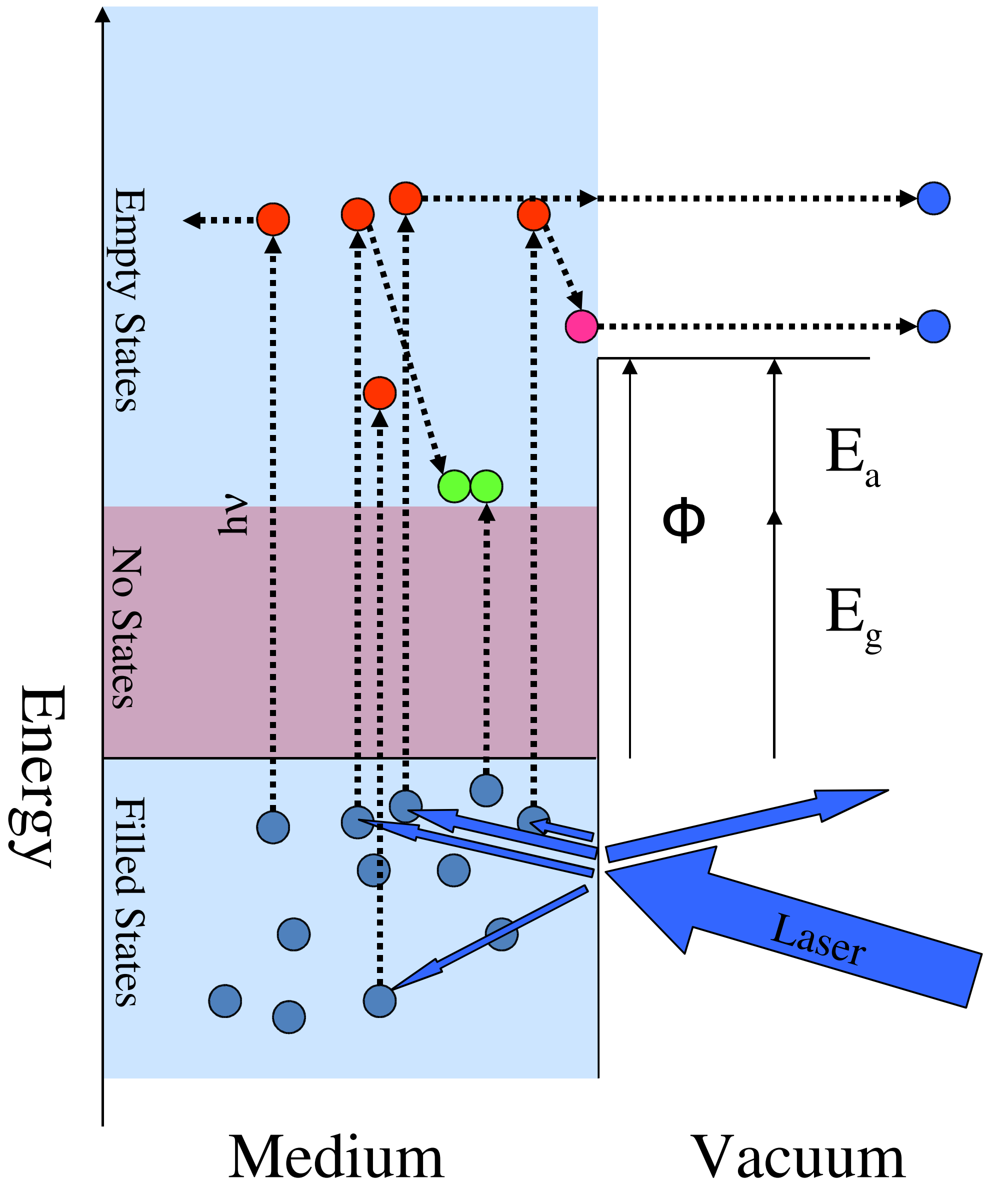
Photoinjector

- High QE at a convenient λ
- Low dark current
  - Dominated by field emission
- Spatially Uniform
- Long lifetime in challenging vacuum environment
  - Chemical poisoning
  - Ion bombardment
- Low intrinsic energy spread (thermal emittance)
- Typical pulse length of 10-50 ps
- Peak current density can be >10kA/cm^2

Photodetector

- High QE in range of interest
- Low dark current
  - Dominated by thermal emission
- Spatially Uniform
- Large area
- Low response to “stray” light
- Reproducible
- Long lifetime in sealed system
- Cheap, easily manufactured

Three Step Model - Semiconductors



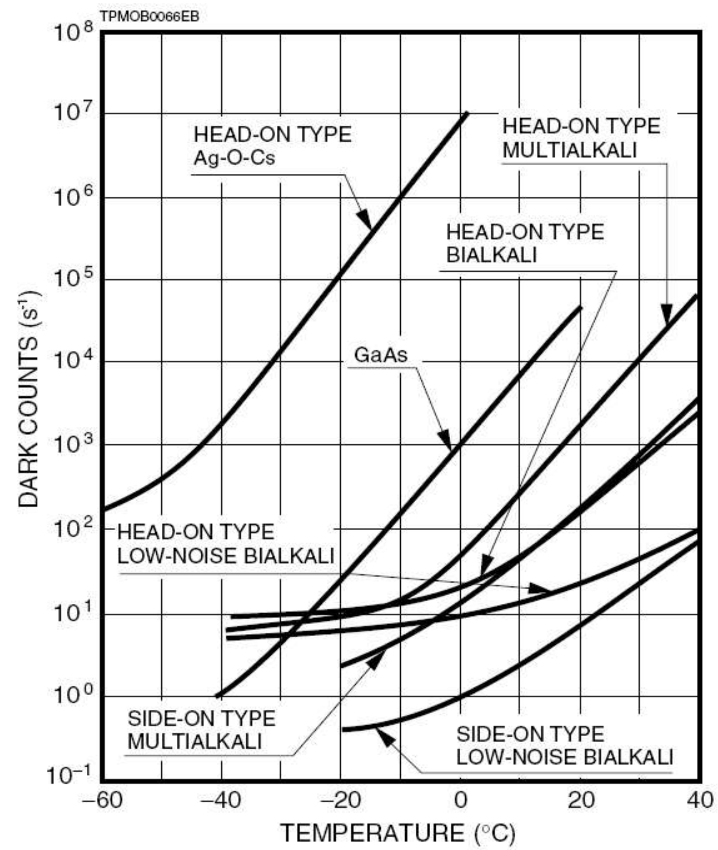
1) Excitation of e^-
   - Reflection, Transmission,
     - Interference
   - Energy distribution of excited e^-
2) Transit to the Surface
   - e^--lattice scattering
     - mfp ~100 angstroms
     - many events possible
   - e^--e^- scattering (if $h\nu > 2E_g$)
     - Spicer's Magic Window
   - Random Walk
     - Monte Carlo
     - Response Time (sub-ps)
3) Escape surface
   - Overcome Electron Affinity

Factors Affecting QE

Reflection	Choice of polarization and angle of incidence Light traps (microstructures)
Nonproductive absorption	Semiconductor cathodes (especially NEA materials) Narrow valence band Work function reduction (Schottky effect, dipole layers)
Electron scattering (electron mfp)	Stay within the “magic window”, $\phi<E_{\gamma}<2E_{gap}$ Minimize photon absorption length (surface plasmons) Good crystals – minimize defect and impurity
Deposition parameters	Substrate material, cathode thickness, sequential vs co-deposition, substrate temperature, cooling time, oxide layer formation
Vacuum environment	Ion back-bombardment, electron stimulated desorption, chemical poisoning
Operating environment	Thermal stability, space charge

Factors Affecting Dark Current

Field emission	Electric field at cathode Surface morphology (field enhancement) Work function
Thermal emission	Temperature Work Function $I = A\,T^2 \exp[-e\phi/(kT)]$
Ion bombardment	Vacuum Work function



Hamamatsu Tech Not

Low work function reduces the threshold photon energy and improves QE, especially near threshold

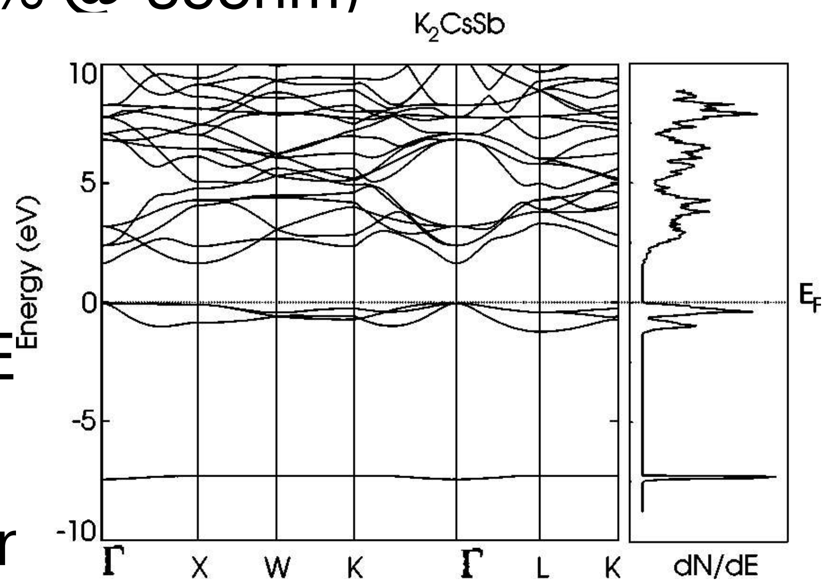
But, it increases dark current

=> Optimal work function depends on application

K_2CsSb (Alkali Antimonides)

Work function 1.9-2.1eV, E_g= 1.1-1.2 eV

Good QE (4% -12% @ 532 nm, >30% @ 355nm)



Deposited in <10^{-10} Torr vacuum

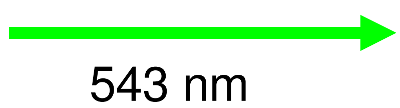
- Typically sequential (Sb->K->Cs)
- Cs deposition used to optimize QE
- Oxidation to create Cs-O dipole
- Co-deposition increases performance in tubes

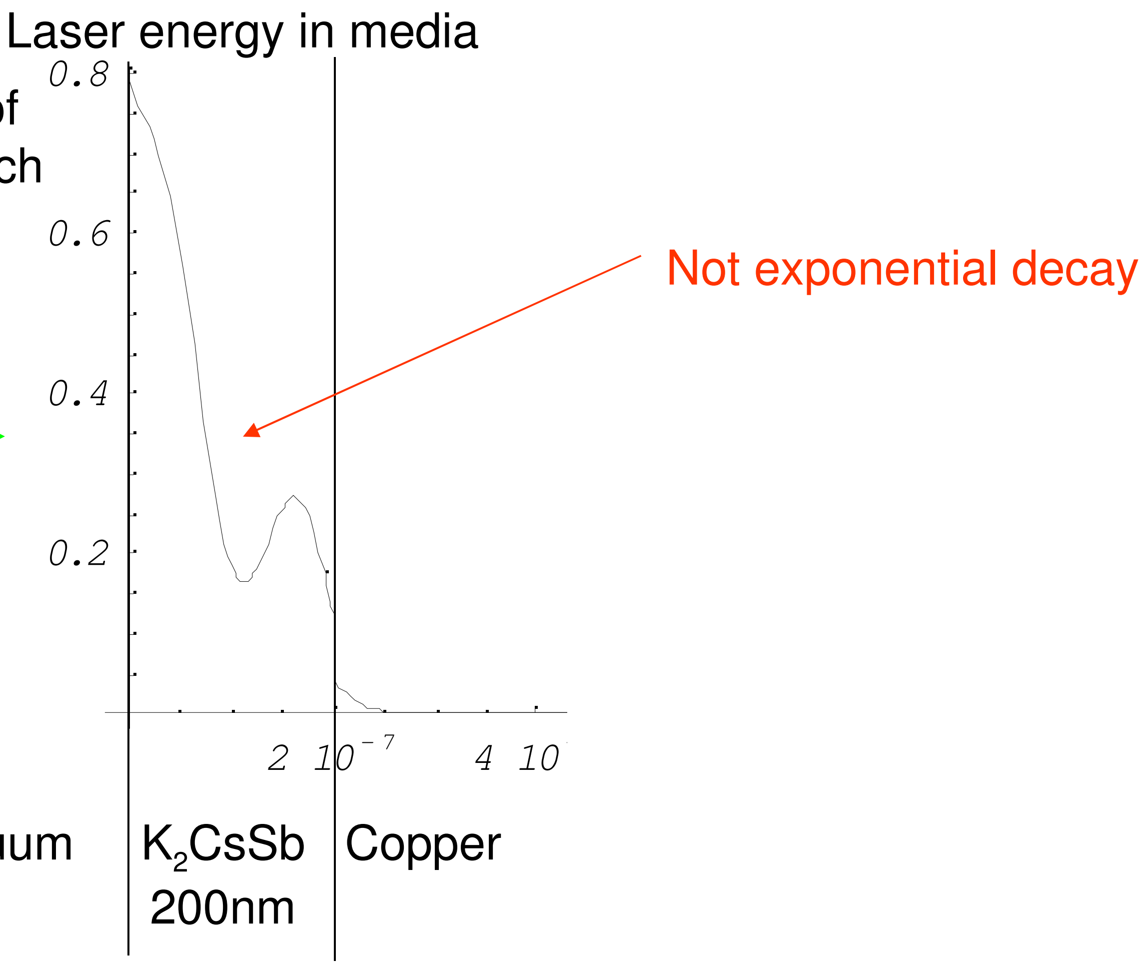
Cathode stable in deposition system (after initial cooldown)

D. H. Dowell *et al.*, *Appl. Phys. Lett.*, **63**, 2035 (1993)
C. Ghosh and B.P. Varma, “*J. Appl. Phys.,* **49**, 4549 (1978)
A.R.H.F. Ettema and R.A. de Groot, Phys. Rev. B **66**, 115102

Laser Propagation and Interference

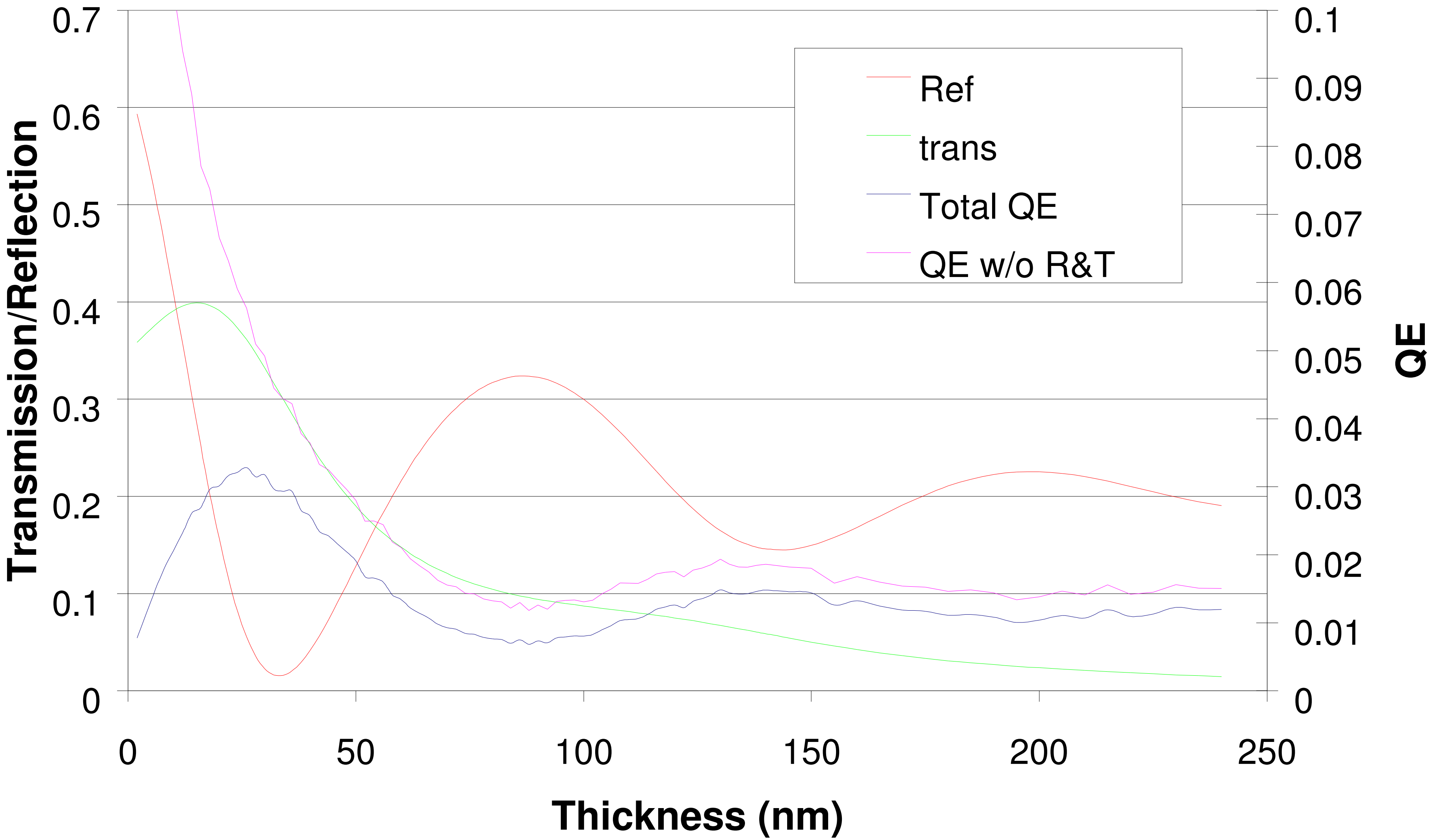
Calculate the amplitude of the Poynting vector in each media



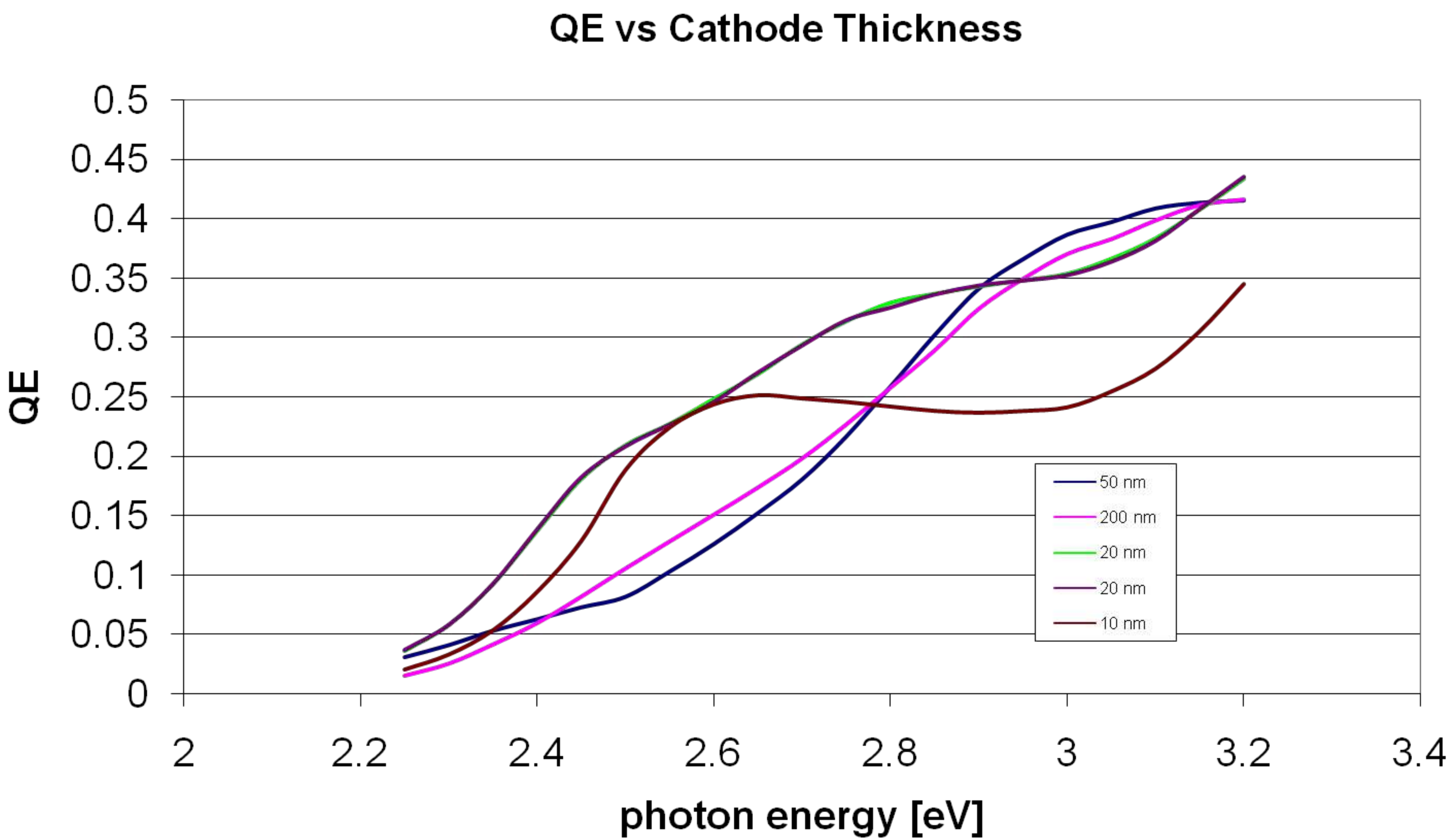


Monte Carlo Modeling

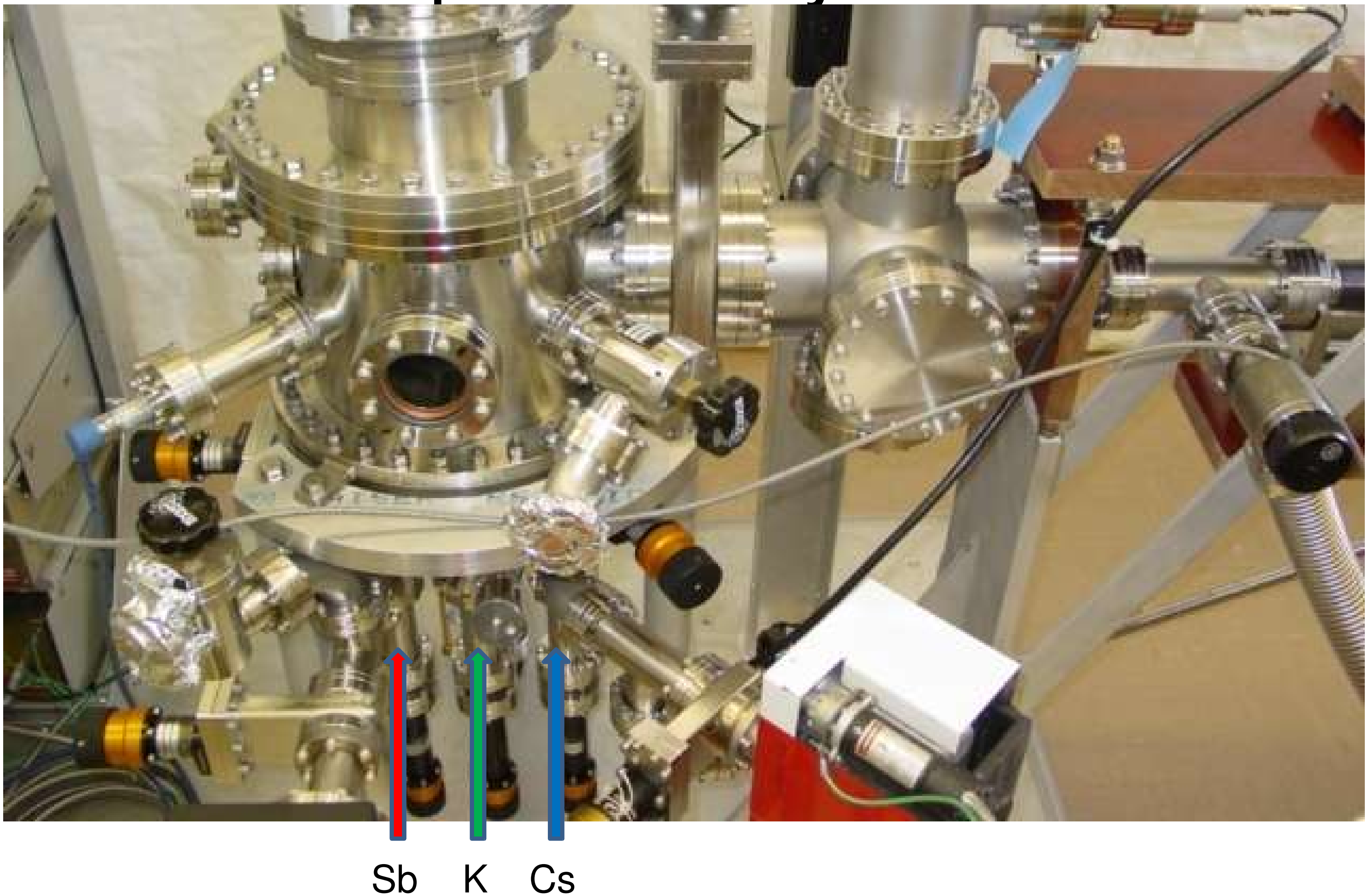
Thickness dependence @ 543 nm



Monte Carlo Modeling



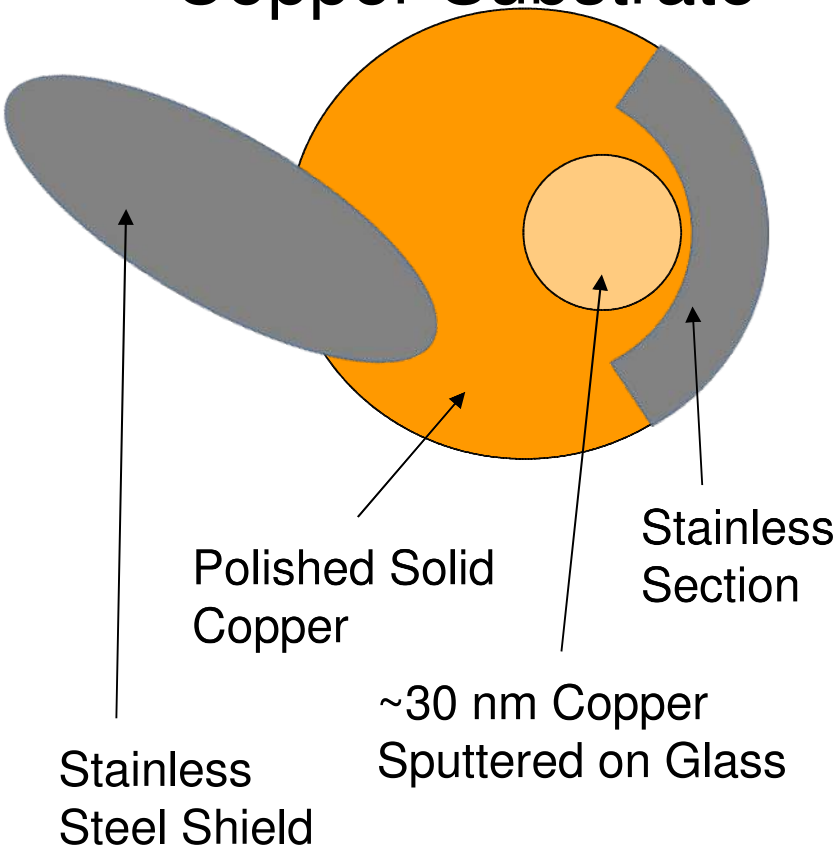
Deposition System



Sequential deposition with retractable sources (prevents cross-contamination)
Cathode mounted on rotatable linear-motion arm
Typical vacuum 0.02 nTorr (0.1 nTorr during Sb deposition)

Substrate & Recipe

Copper Substrate

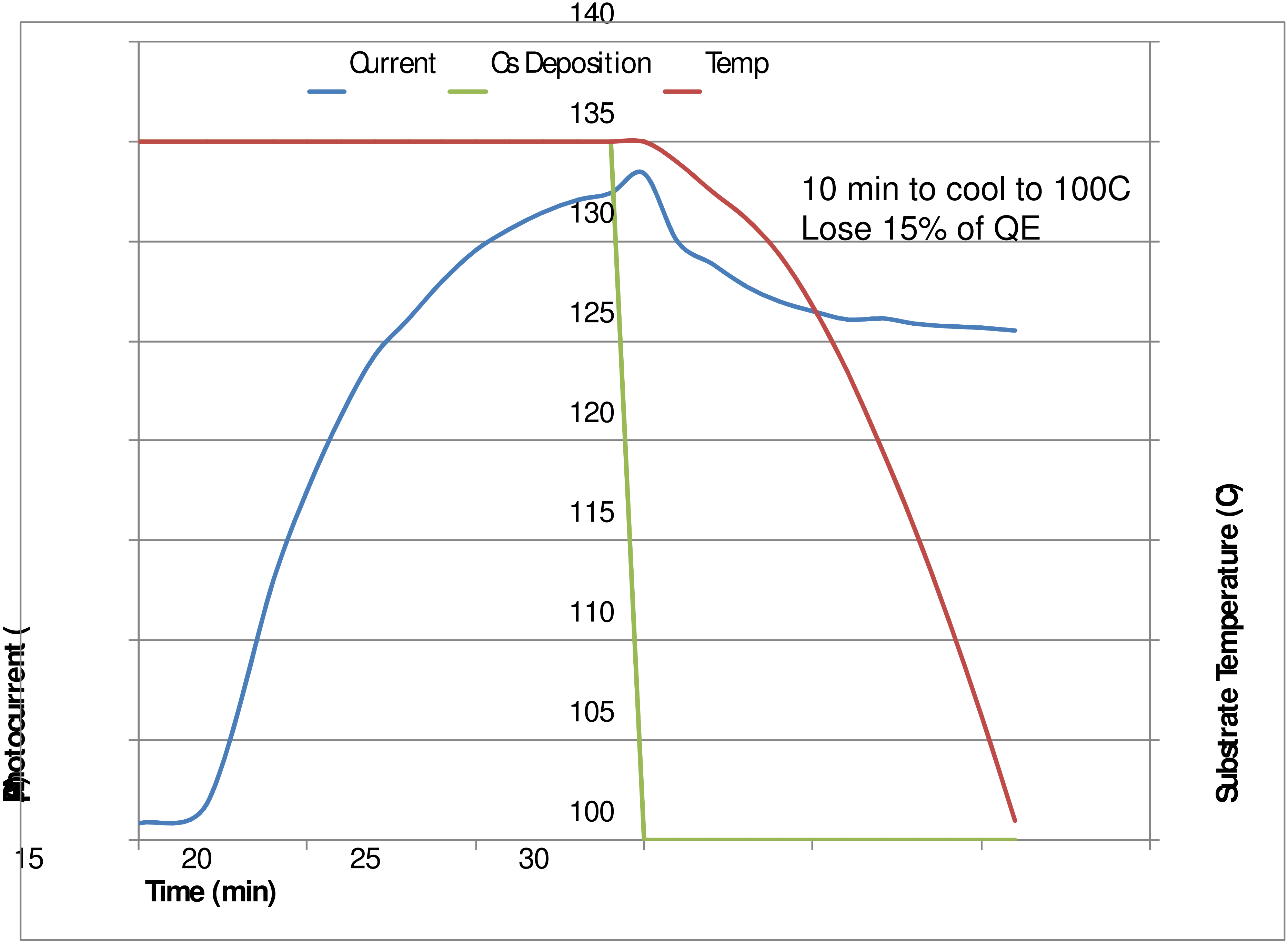


Recipe

Following D. Dowell (NIM **A356** 167)

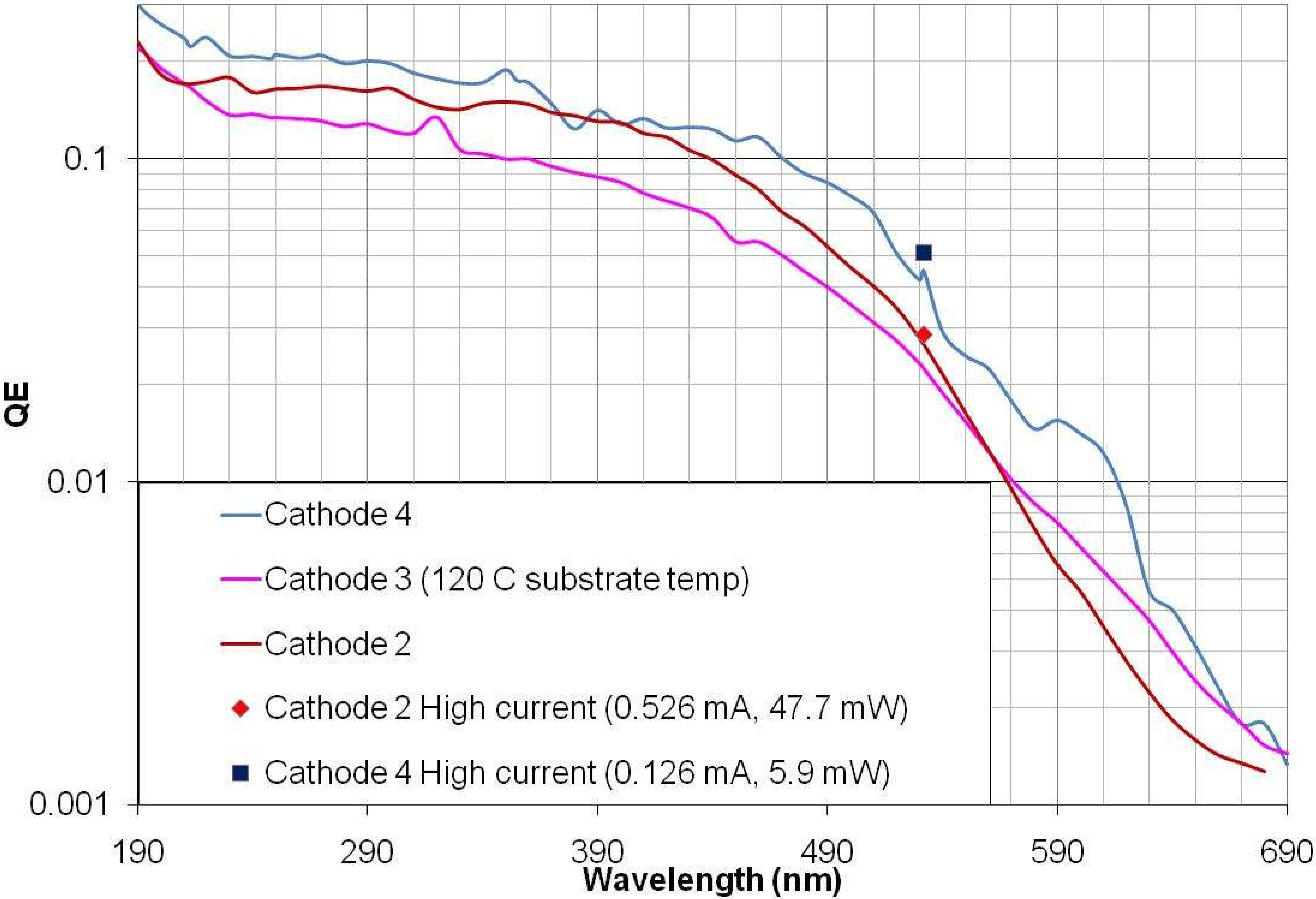
	Substrate Temperature
100 Å Sb	150 C
200 Å K	140 C
Cs to optimize QE	135 C

Cool to room temperature as quickly as possible (~15 min)

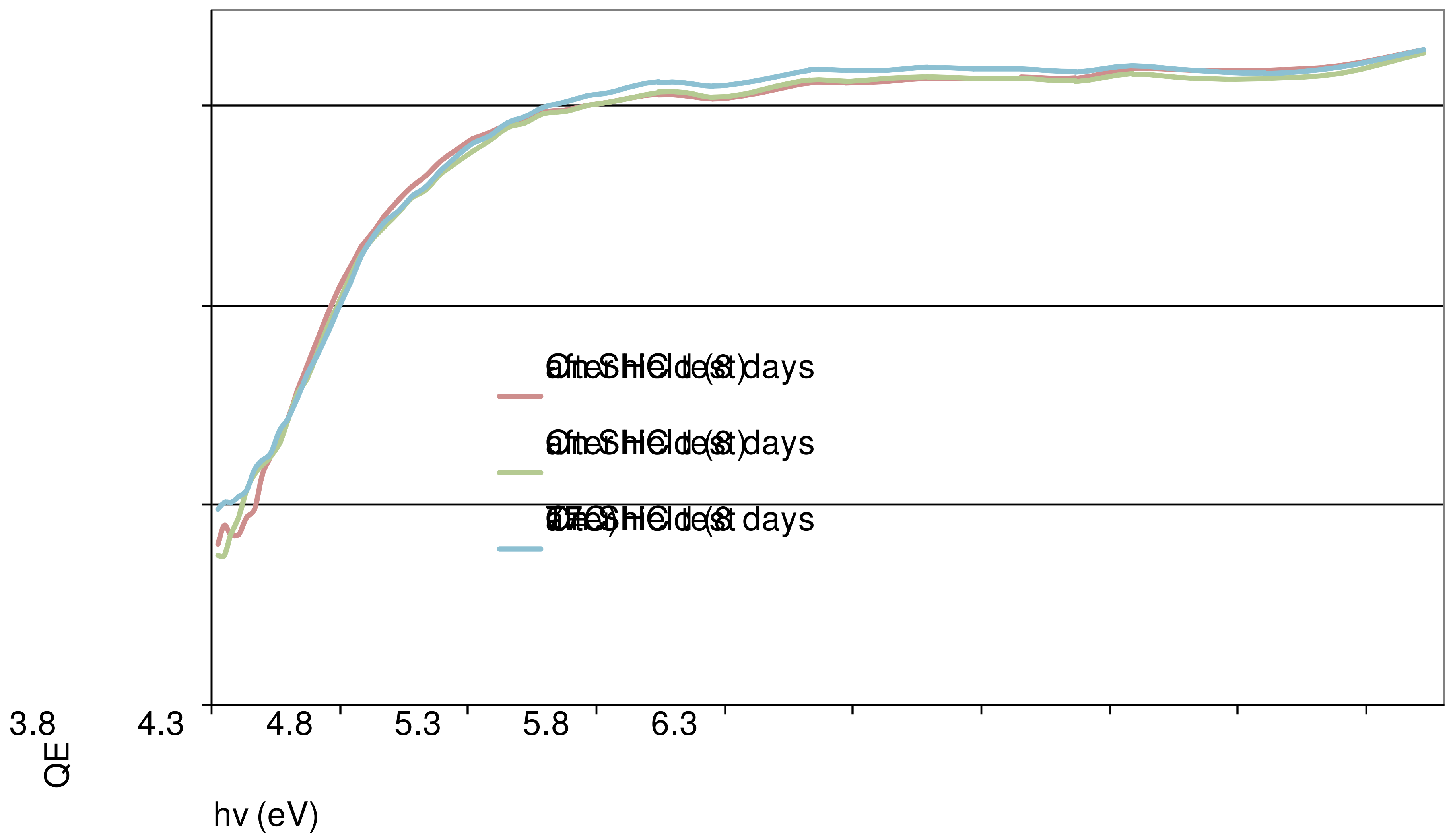


Current
Cs Deposition
Temp
140
135
130
125
120
115
110
105
100
15
20
25
30
Time (min)
Photocurrent (
Substrate Temperature (C)
10 min to cool to 100C
Lose 15% of QE

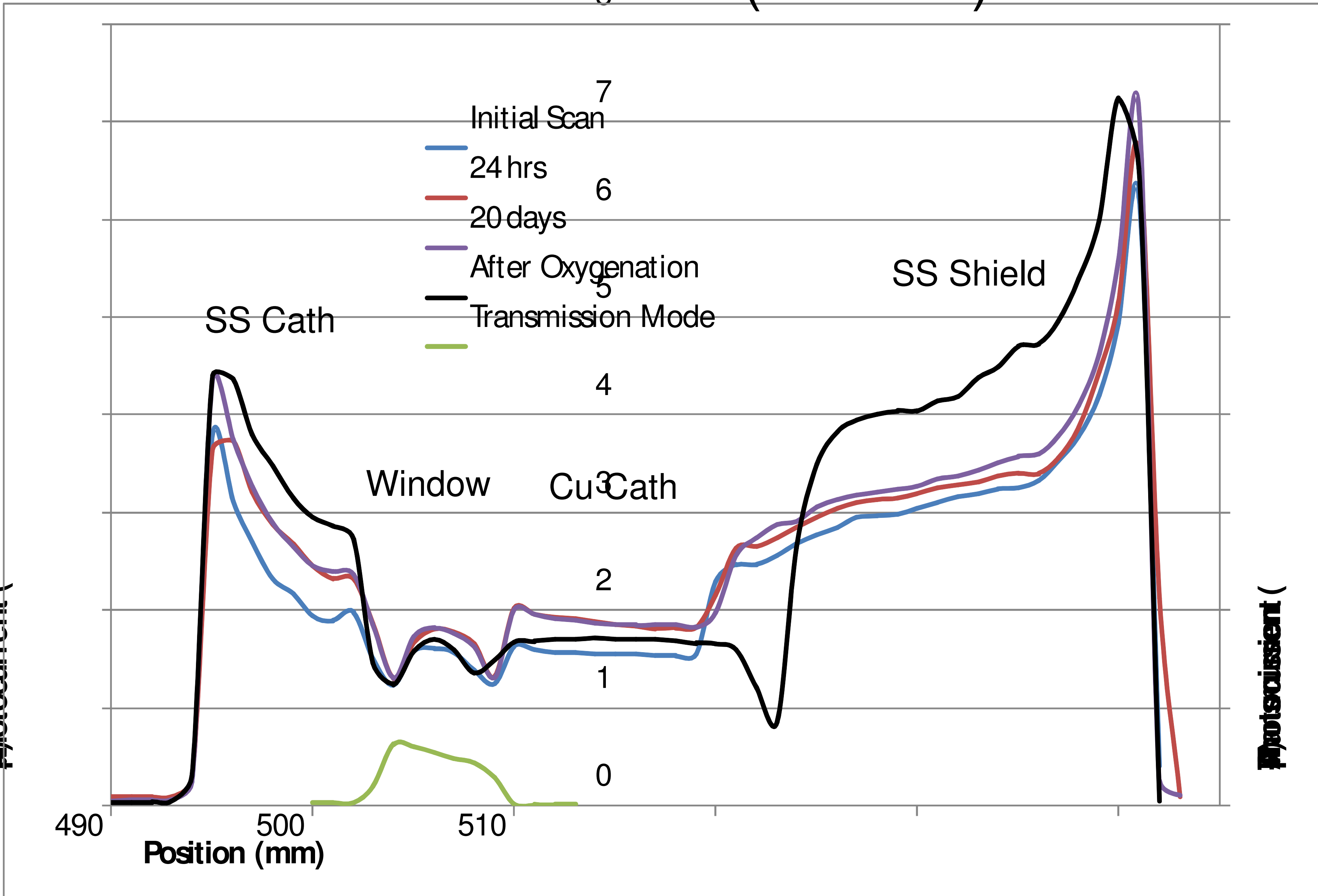
Spectral Response



Temperature Dependence

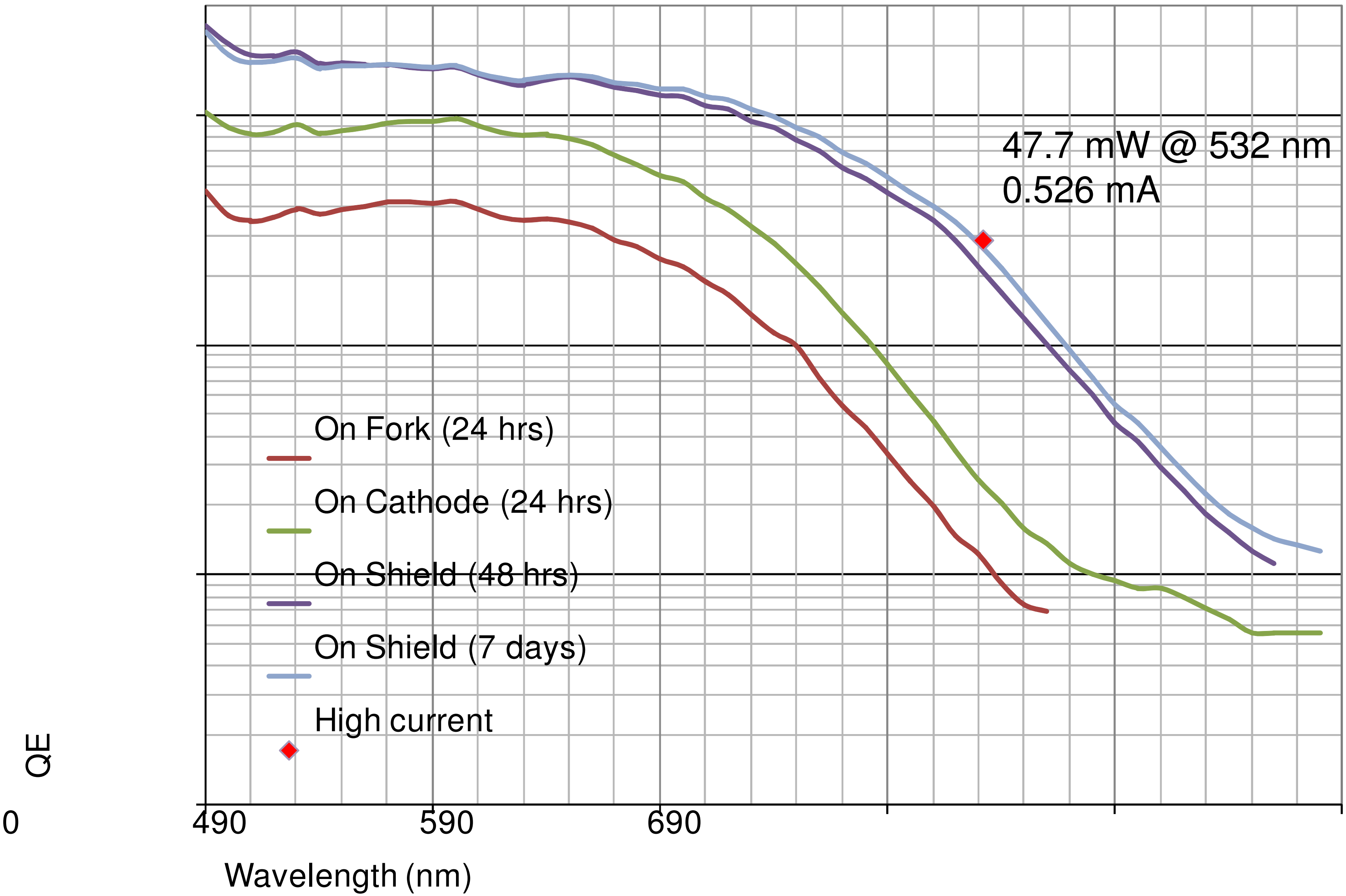


Position Scan (532 nm)



Cu transmission ~20%

Copper vs Stainless



Summary

- Alkali Antimonide cathodes have good QE in the visible and near UV
  - Narrow valance band from Sb 5p level
  - Band gap depends on which alkali metals used
  - Work function depends on surface termination (and metals used)
  - May be room for improvement by growing better crystals
- Optimal work function depends on wavelength range of interest
- For thin cathodes, it may be possible to enhance the QE by tailoring the thickness to improve absorption near emission surface
- Practical aspects, such a choice of substrate material, surface finish of substrate, and cooling rate after deposition can have a dramatic effect on the QE

Thanks for your attention!

Additional Slides

Photoinjector Basics

Why use a Photoinjector?

Electron beam properties determined by laser
- Timing and repetition rate
- Spatial Profile
- Bunch length and temporal profile (Sub-ps bunches are possible)

High peak current density

10^5 A/cm^2

Low emittance/temperature

<0.2 µm-rad

Cathode/Injector Properties

Quantum Efficiency (QE)

$$QE = \frac{¿e^{-}_{emitted}}{¿\gamma_{incident}} = h\nu \frac{I}{P}$$

Lifetime: time (or charge) required for QE to drop to 1/e of initial

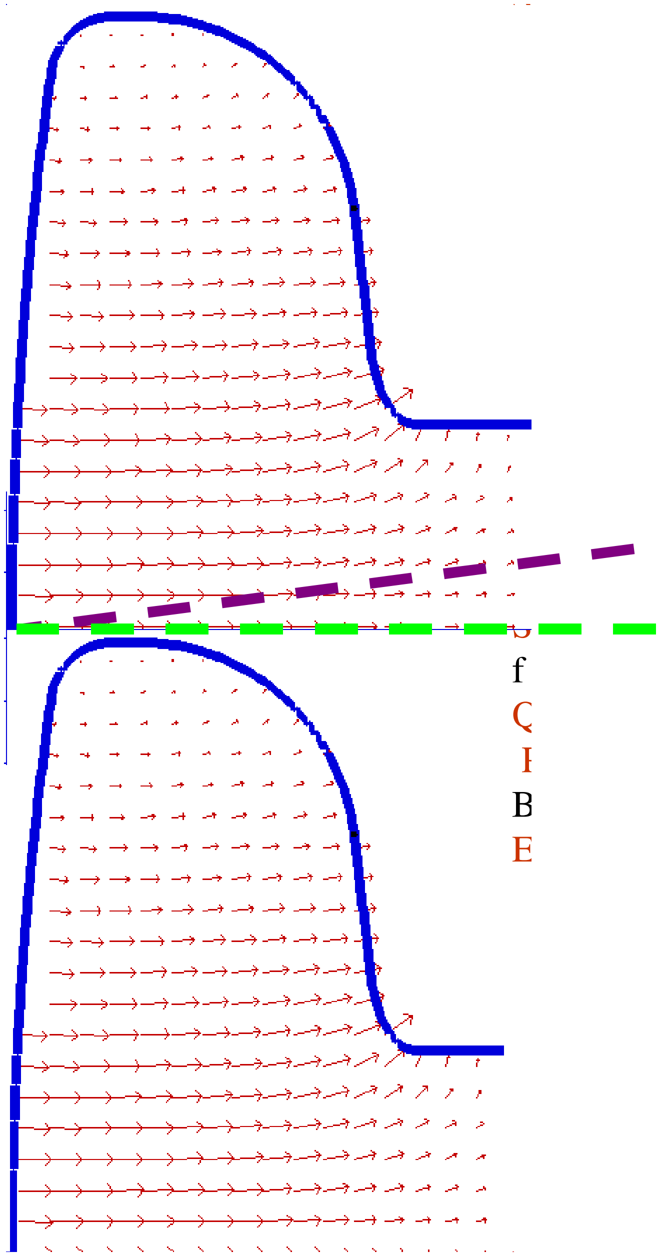
Response Time: time required for excited electrons to escape

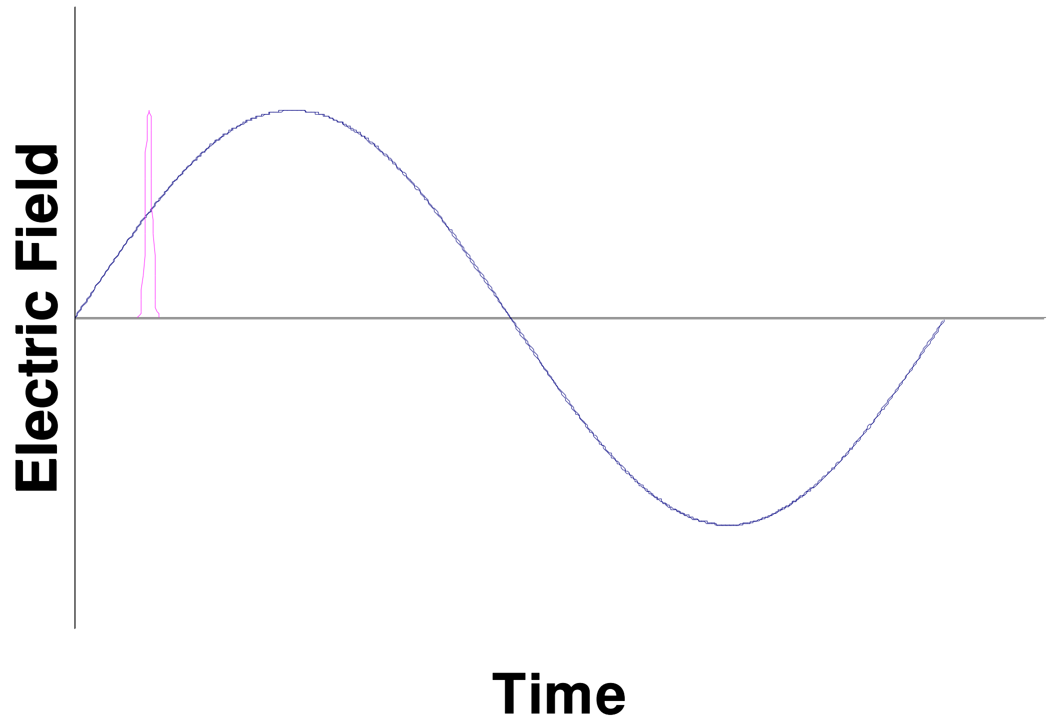
$$I_p = \frac{Q_{bunch}}{\tau_{bunch}}$$

Peak Current:

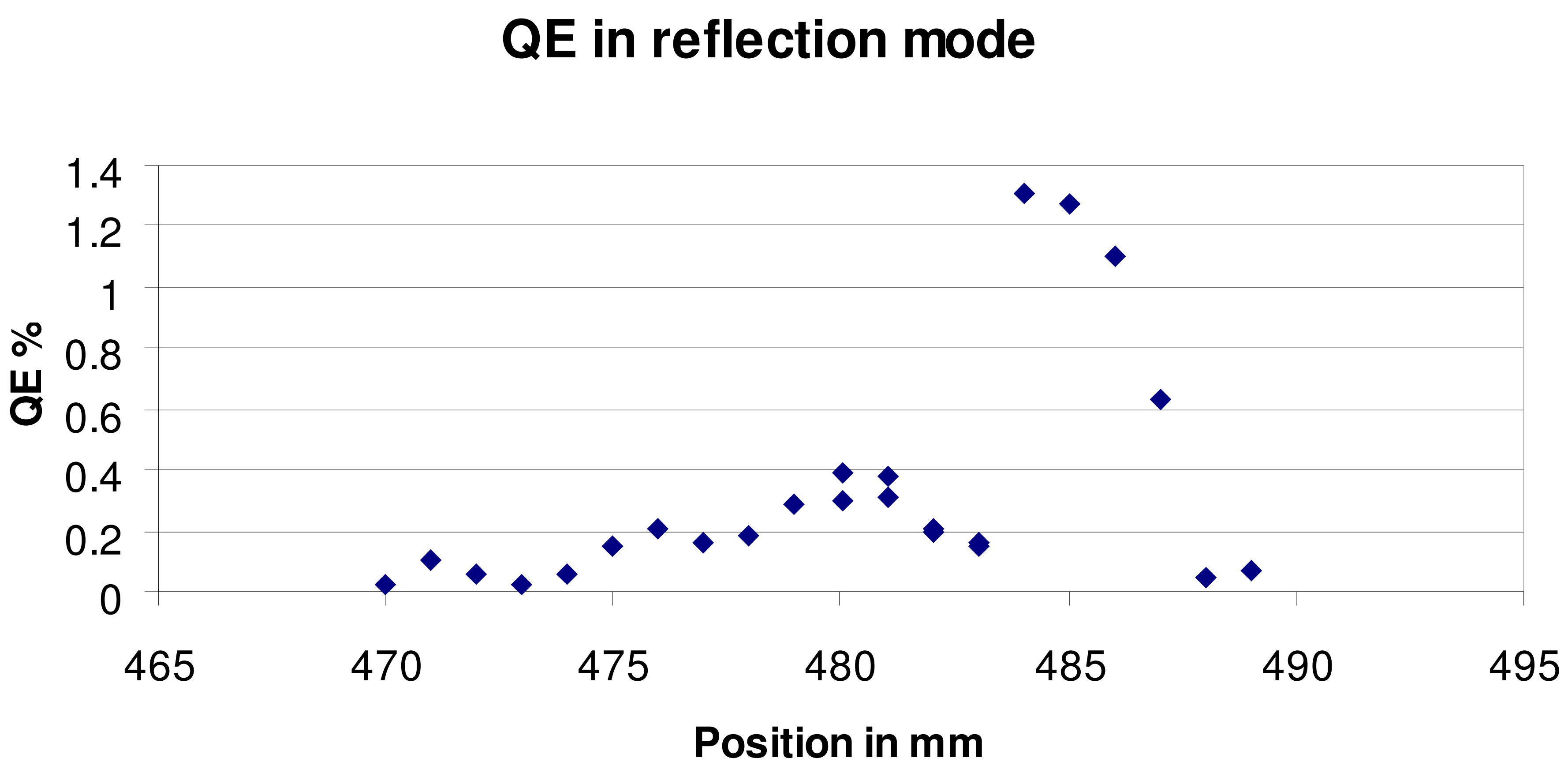
G. Suberlucq, EPAC04, 64
JACoW.org

Photoinjector

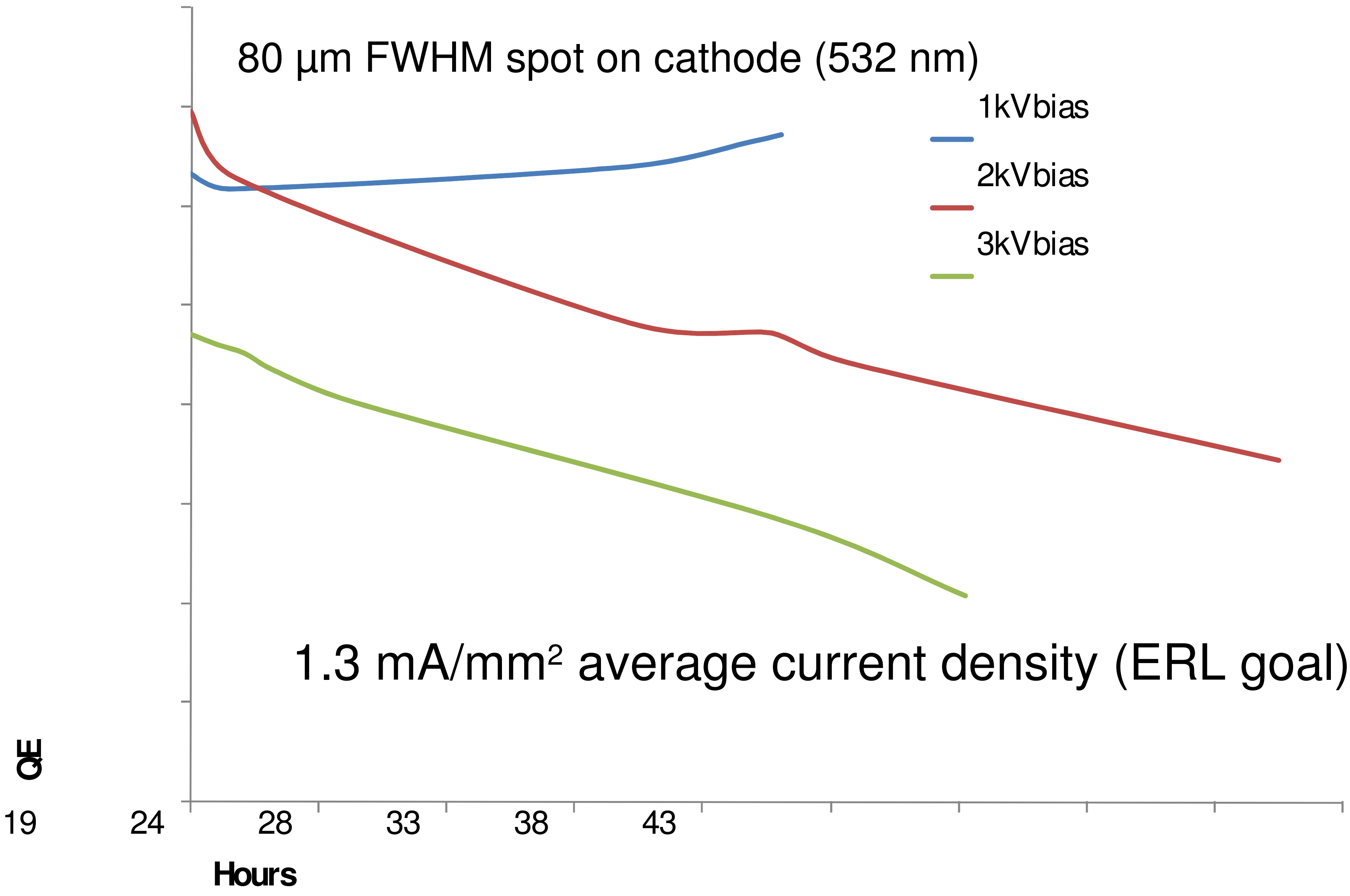




Thin Cathode



QE Decay, Small Spot



Linearity and Space Charge