Cathodes

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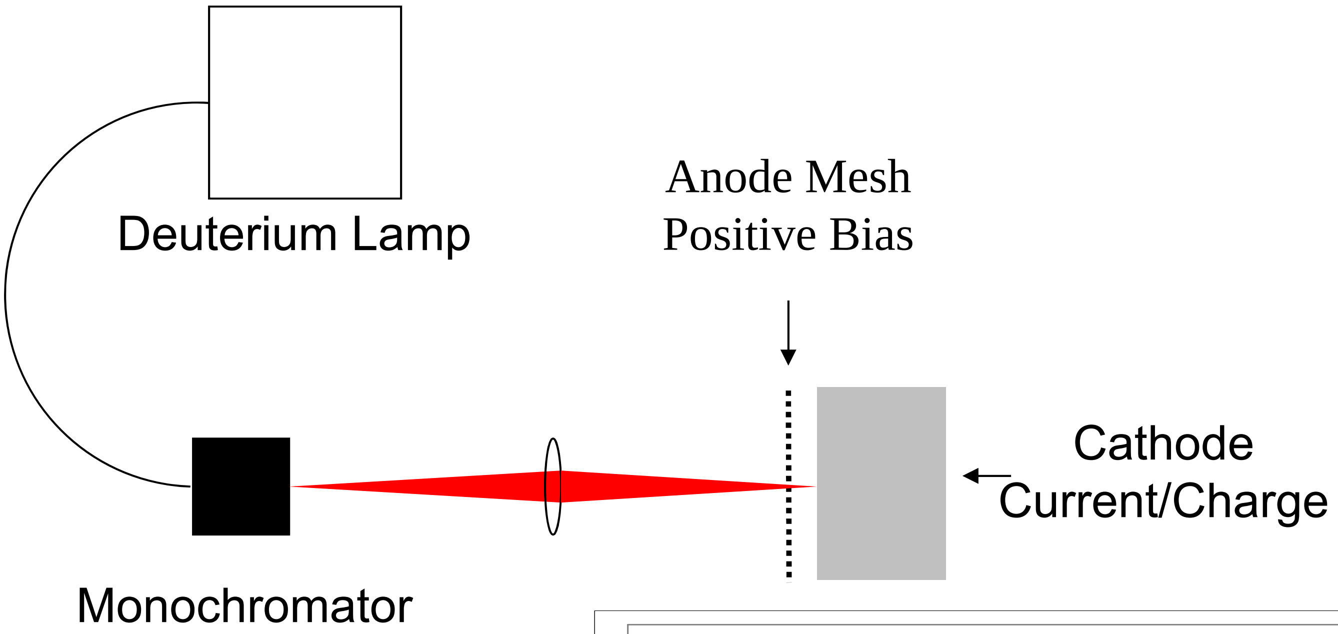
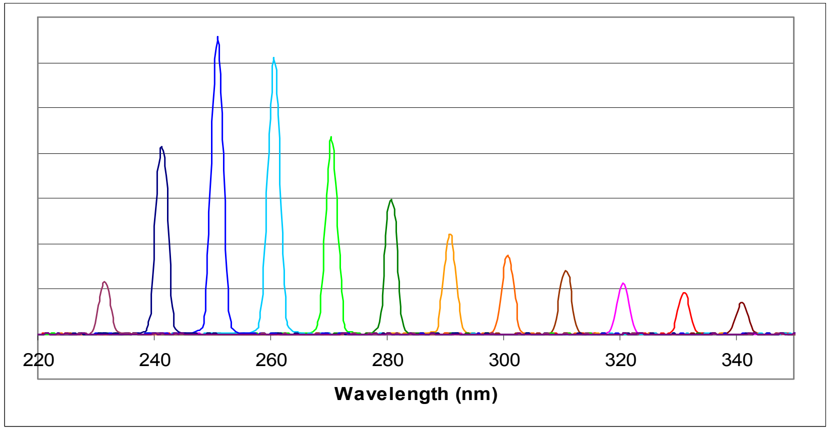
Overview

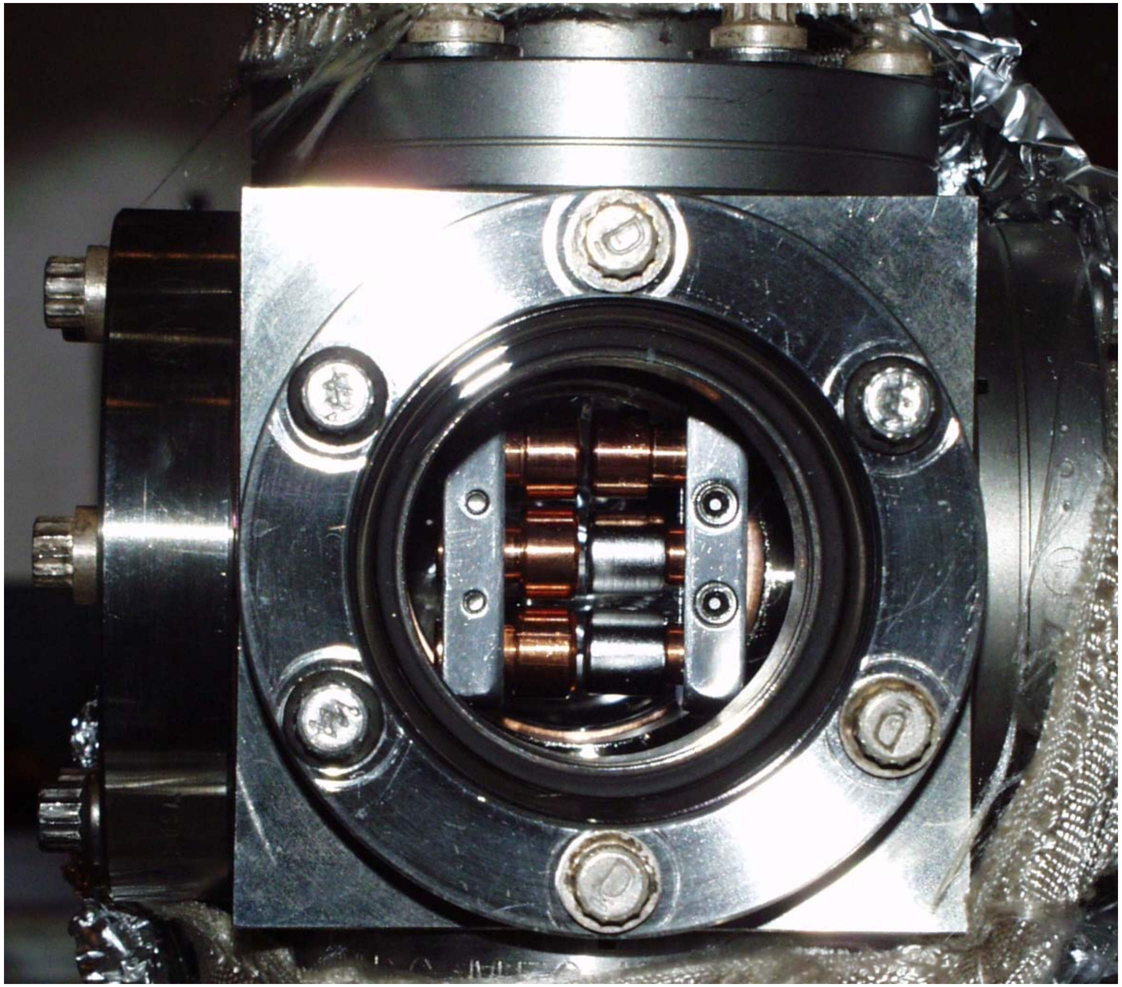
- QE Measurement
- Metallic Photocathodes
  - Normal Conductors (LCLS Copper)
  - Superconductors (Lead)
    - Lab tests
    - SRF Gun measurements at TJNAF
- Semiconductor Photocathodes
  - Positive Electron Affinity (K_2CsSb)
    - Deposition Systems
    - Gun tests at TJNAF
    - In-situ X-ray analysis
- Diamond Electron Amplifier
  - Amplifier tests
  - ARPES on diamond

QE Measurements



Advantages of Lamp Source
- QE can be measured at any wavelength
- Material workfunction can be established
- Measurement source does not affect QE





QE Measurement Notes

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

Good QE measurement requires four things:

- High resolution current or charge measurement
  - Electrometer (Keithley 6517 or similar)
  - Charge sensitive preamp (pulsed measurement)
- Variable photon energy source
  - White light + Monochromator
  - Array of lasers (made more feasible with cheap diode lasers and doubled Nd:YAGs)
- Precision optical power/energy meter
  - QE measurement is only as accurate as the measurement of photons in!
- Sufficient bias to overcome space charge!
  - Always plot charge/current vs pulse energy/optical power

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.

D. H. Dowell, I. Bazarov, B. Dunham, K. Harkay,
C. Hernandez-Garcia, R. Legg, H. Padmore, T. Rao, J. Smedley and W. Wan, NIM **A622**(2010)685-697.

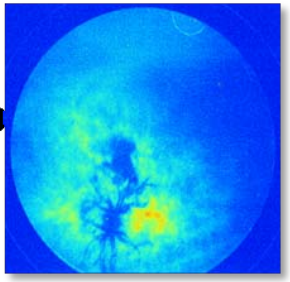
Clean Metal Surfaces

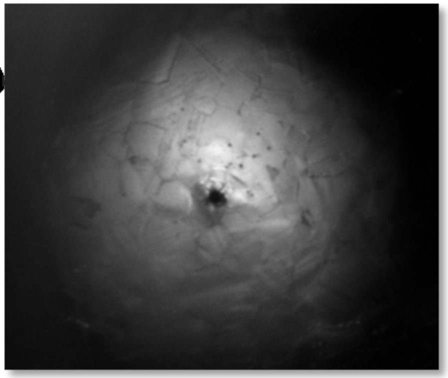
- We like metals because they are easy
  - They are not as sensitive to vacuum
  - The support high fields (low dark emission)
  - They do not risk compromising the cavity
- However, all is not roses…
  - As we saw earlier, surface adsorbates can change (typically raise) the surface dipole and the workfunction
  - To mitigate this, metal cathodes typically have to be cleaned
  - There are three ways to do this:
    - Heat treatment
    - Laser Cleaning
    - Ion cleaning
  - Typically laser cleaning is the most practical in a gun, however care must be taken to avoid damage
    - It *does not* always pay to use the drive laser

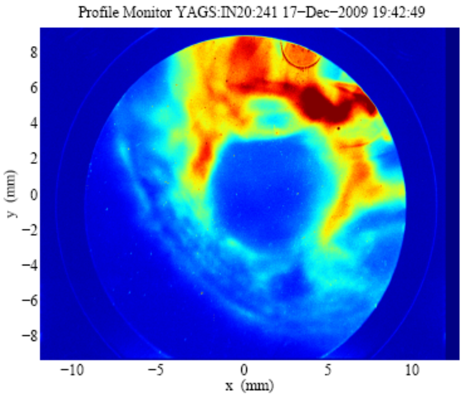
Survivability and Lifetime: Cathode Contamination

Three sources of cathode contamination

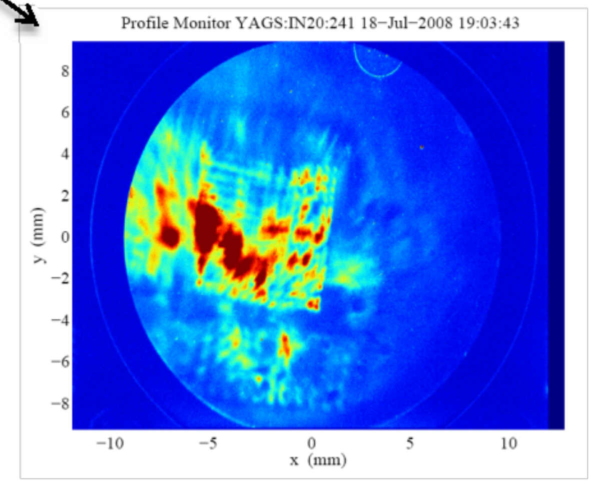
- *Residual contaminants left by fabrication, handling and storage*
- *Contamination and damage by the gun RF and laser*
    - *Ambient vacuum*
    - *Operating vacuum*
    - *Cathode cleaning*
- *Contamination during operation due to molecular cracking:*
    - *By the laser*
    - *By the electron beam*







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



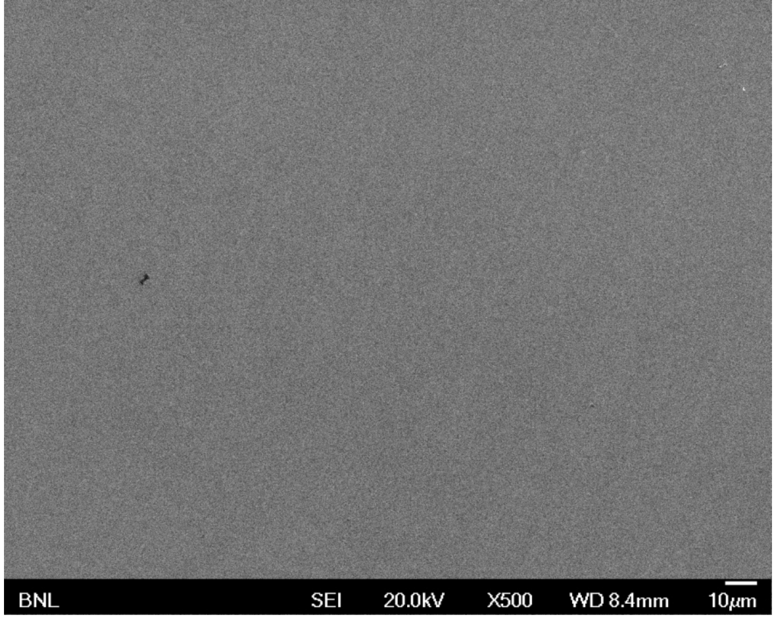
For LCLS contamination by molecular cracking (?) is problematic.

Optimum Energy Density for Cleaning

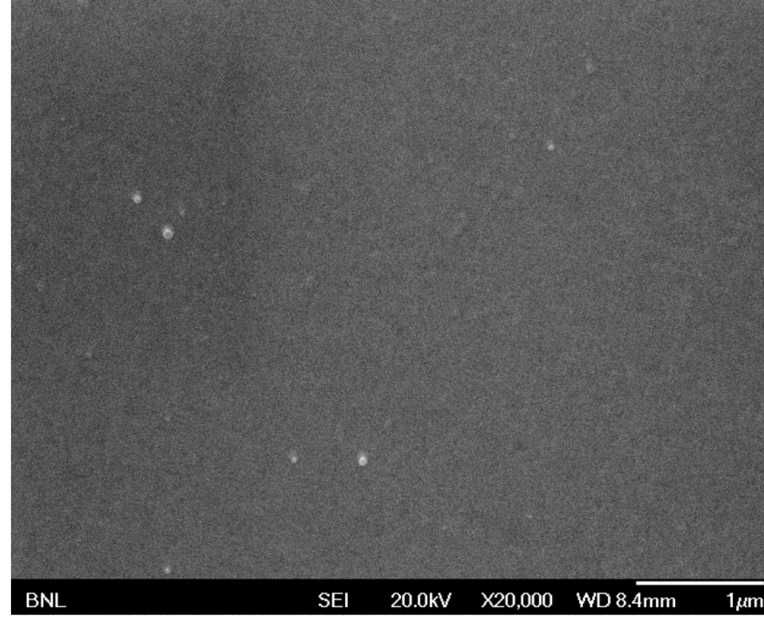
- Two lasers:
  - 266 nm, 35 ps laser (YAG, 4th harmonic, with saturatable absorber)
  - 248 nm, 5 ns laser (KrF excimer)

Metal	Energy Density of Cleaning Laser (mJ/mm^2)
Copper	1
Magnesium	0.1
Niobium	0.6
Lead	0.2

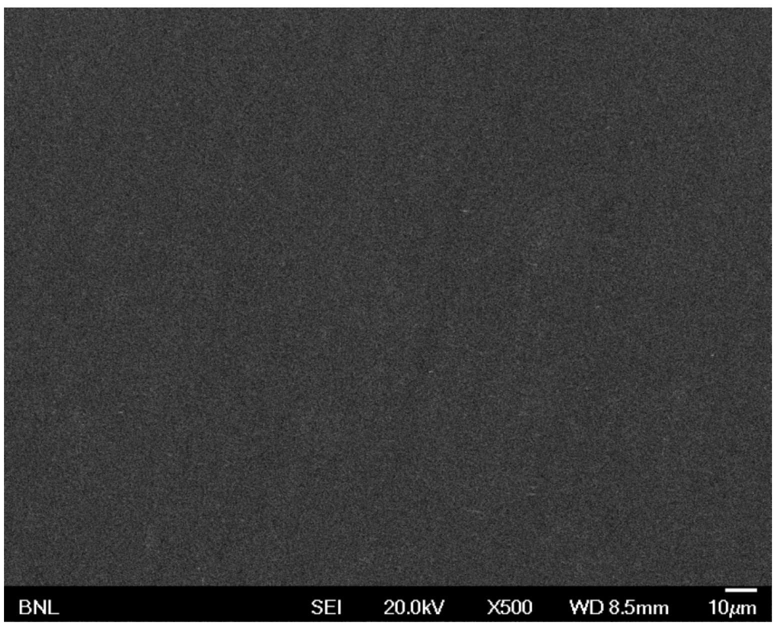
- Not much difference; damage slightly more likely with ps lasers
- Typically raster scan laser to get more uniform coverage
- Some improvement from cw lamp sources
- Systematic investigation of mechanism needed
  - Chemical desorption (should only depend on $\hbar\omega$)
  - Thermal desorption (Should depend on energy deposited, ω, and timescale/cooling)



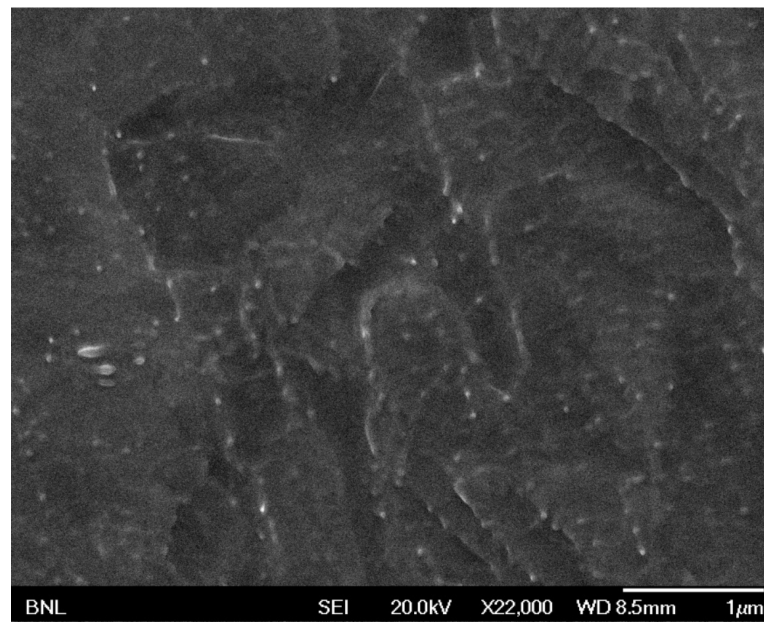
Before, x500



Before, x20k



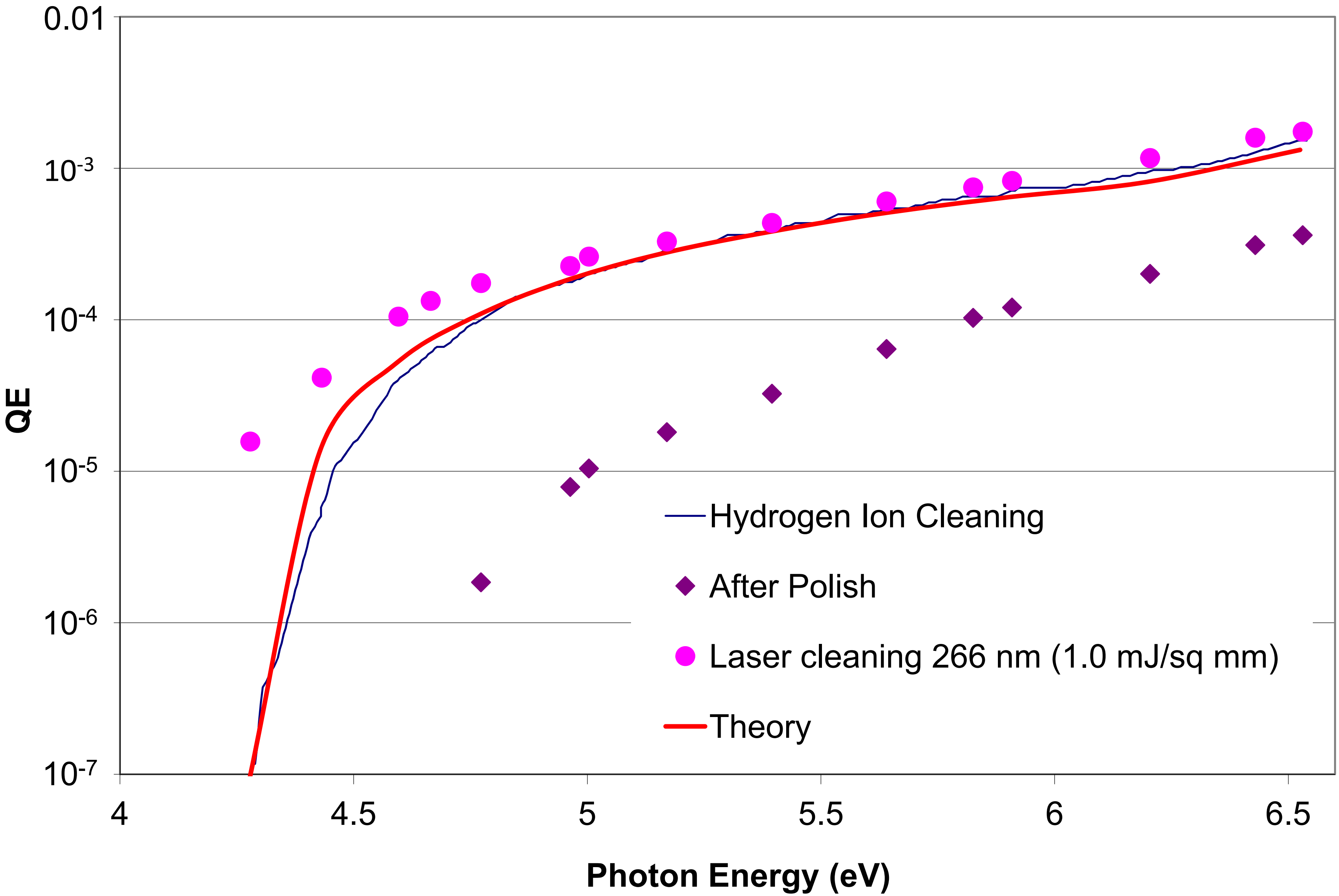
After, x500



After, x20k

1.3 mJ/mm^2

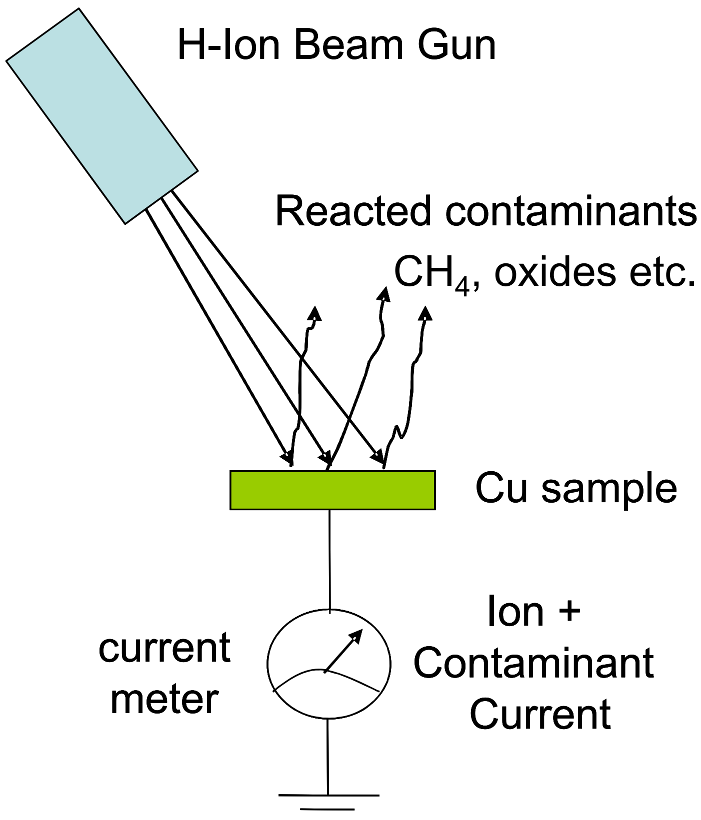
LCLS Copper Cathodes



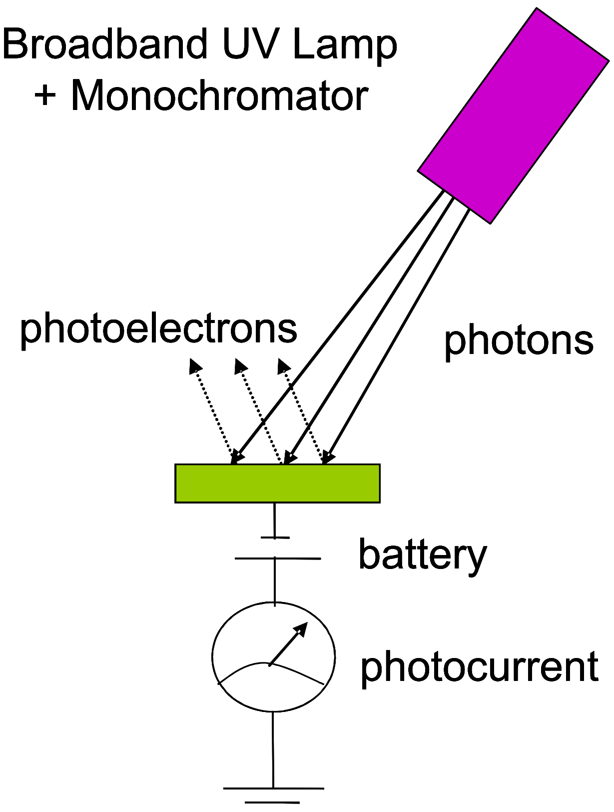
D. H. Dowell *et al.*, Phys. Rev. ST Accel. Beams 9, 063502 (2006)

Ion cleaning and QE measurements

H-Ion Cleaning

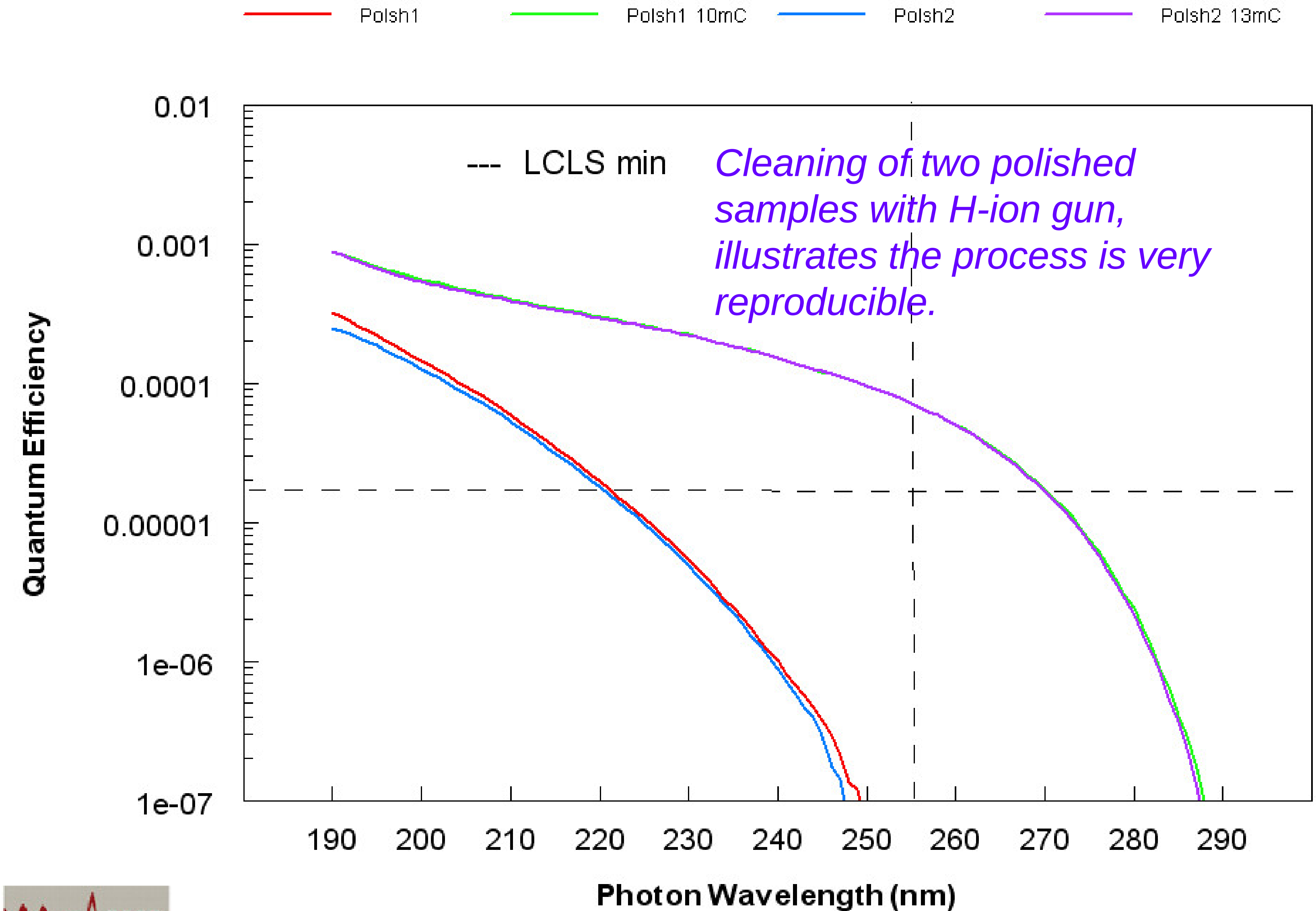


QE vs. Wavelength Measurement

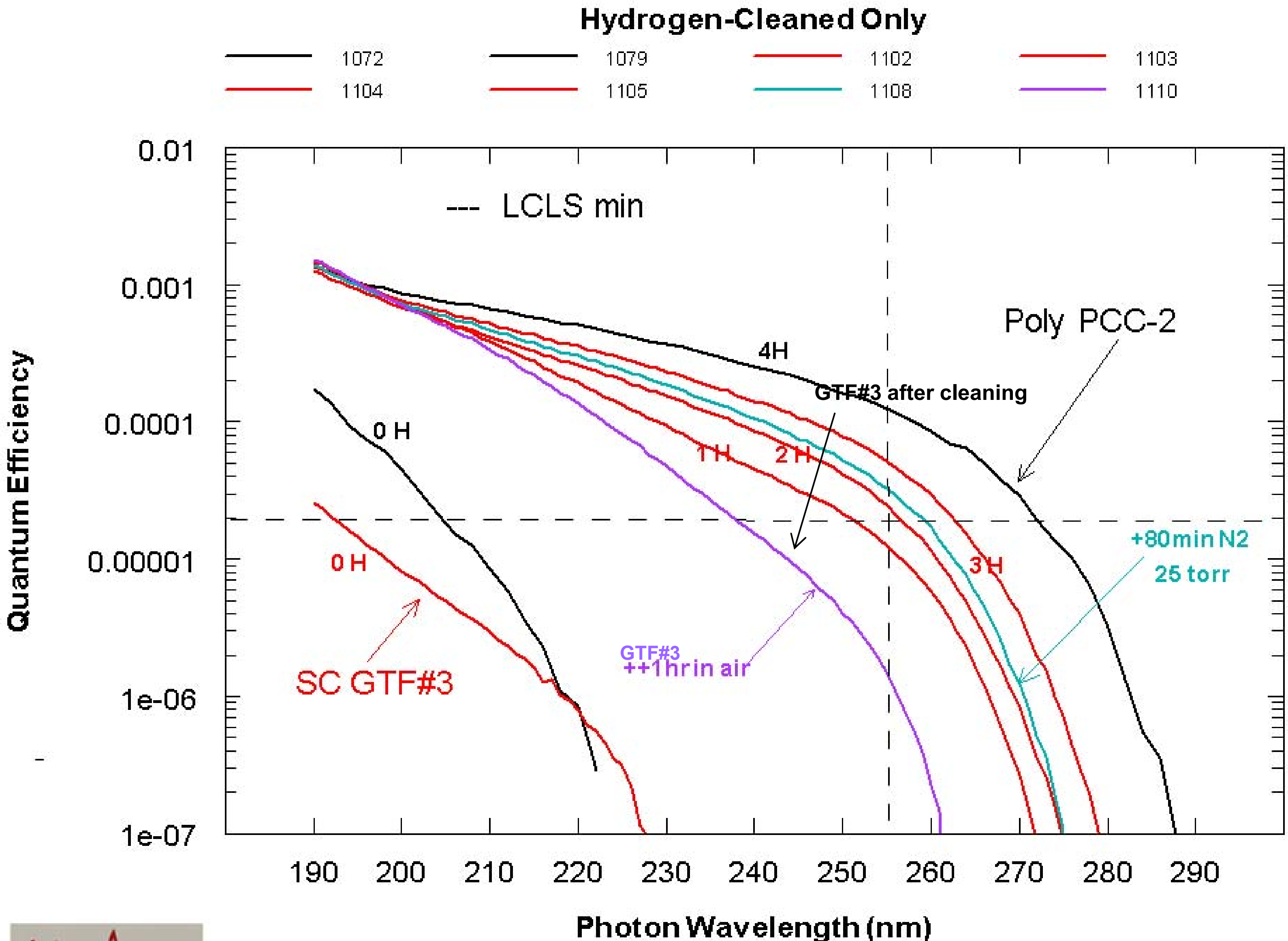


LCLS Test Coupons

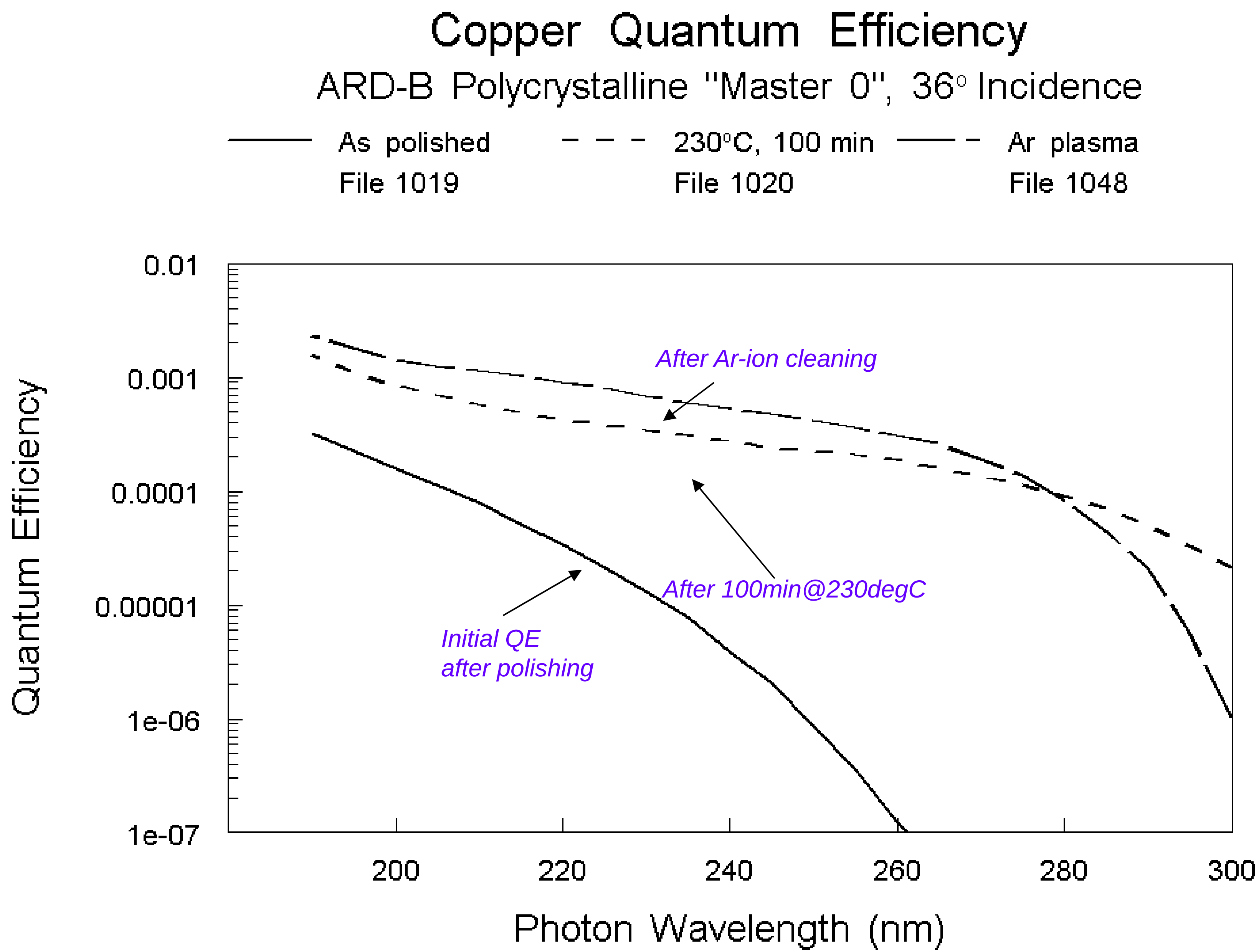
H2 Ion Bombardment



Single Crystal GTF#3 vs. Poly PCC-2

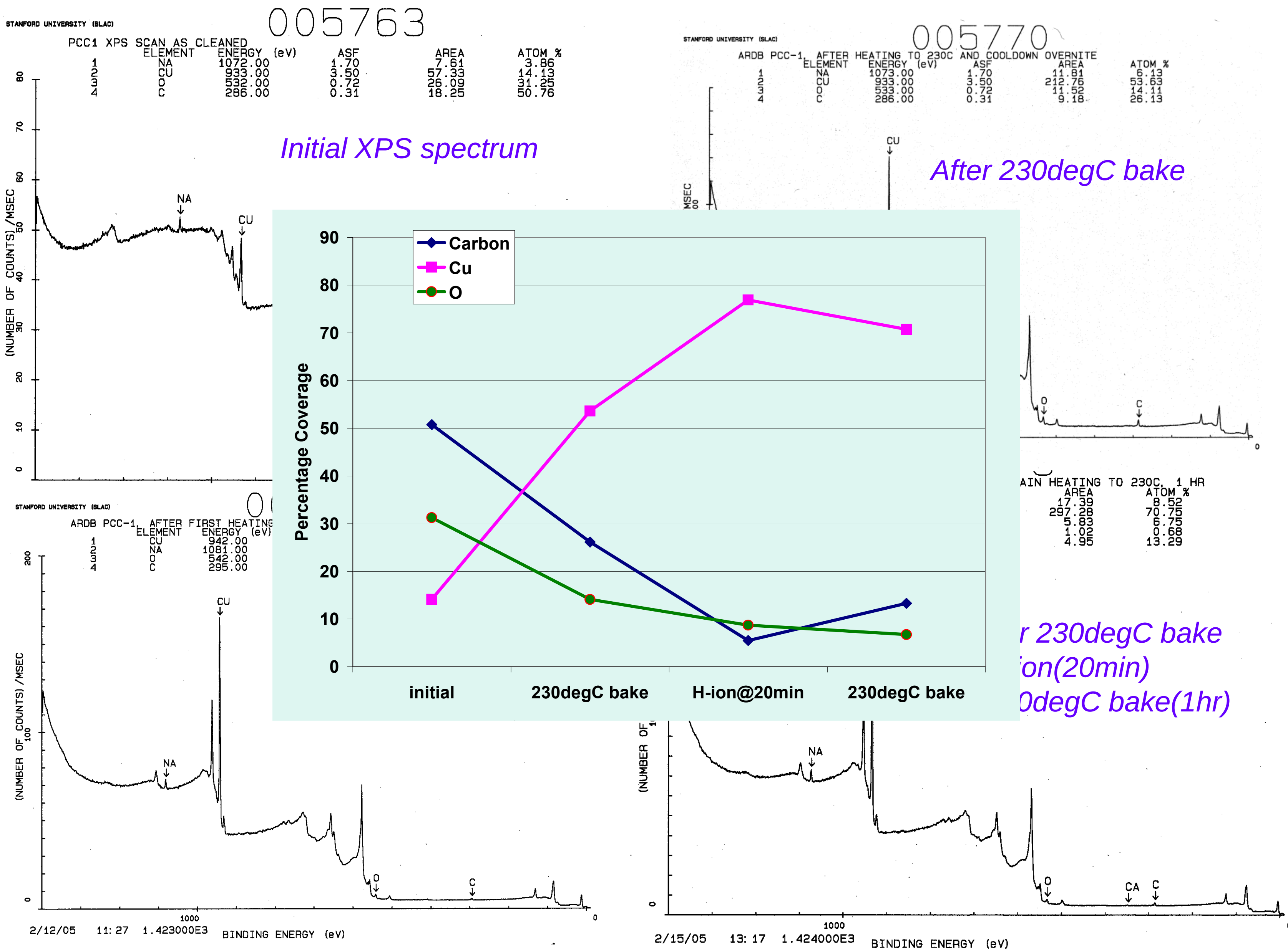


Measurements show even exposure to N_2+0.5ppm H_2O reduces QE, an additional hour in air reduces the QE another factor of ~500

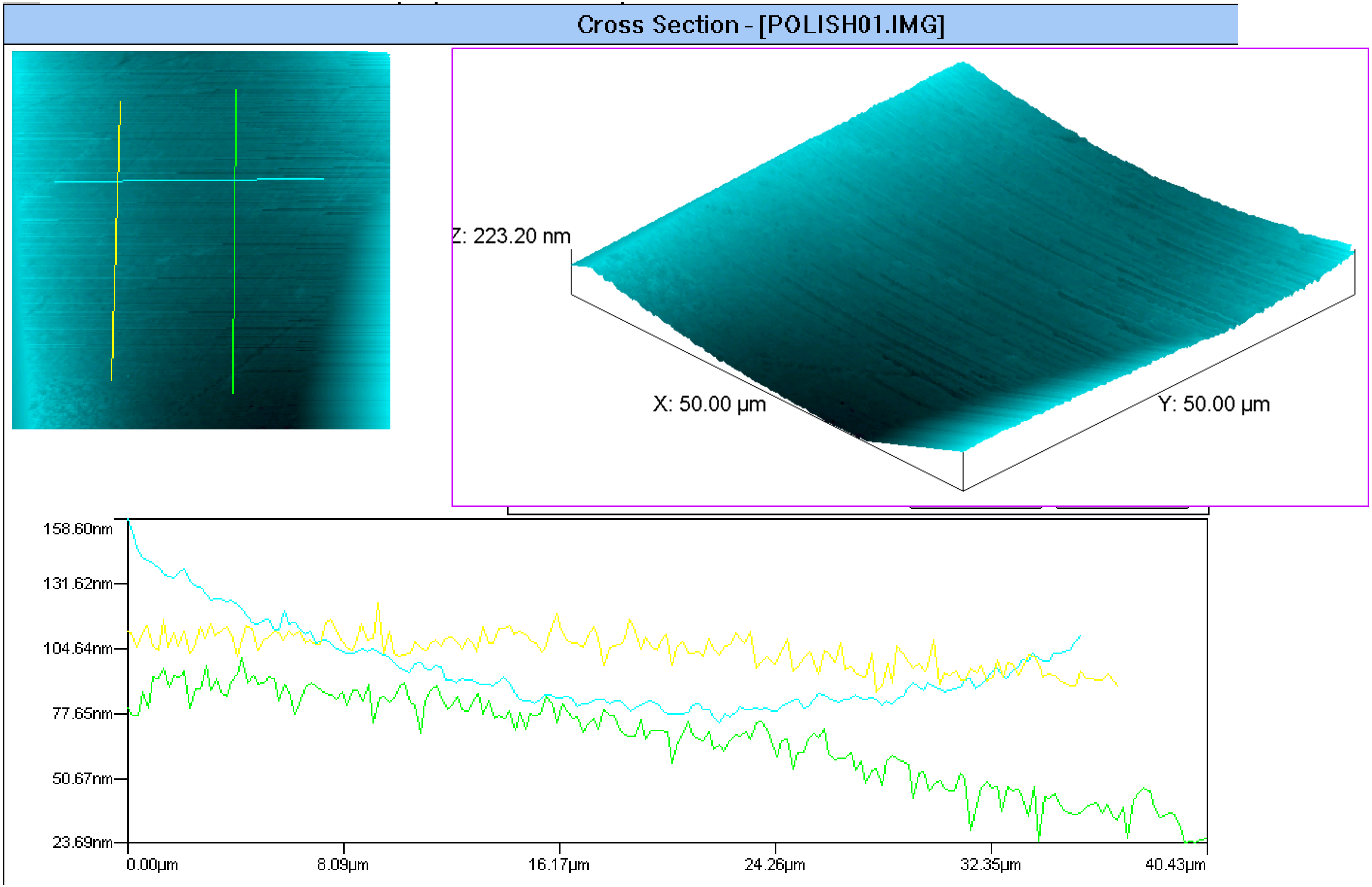


Comparison of heat cleaning and cleaning with Ar-Ions

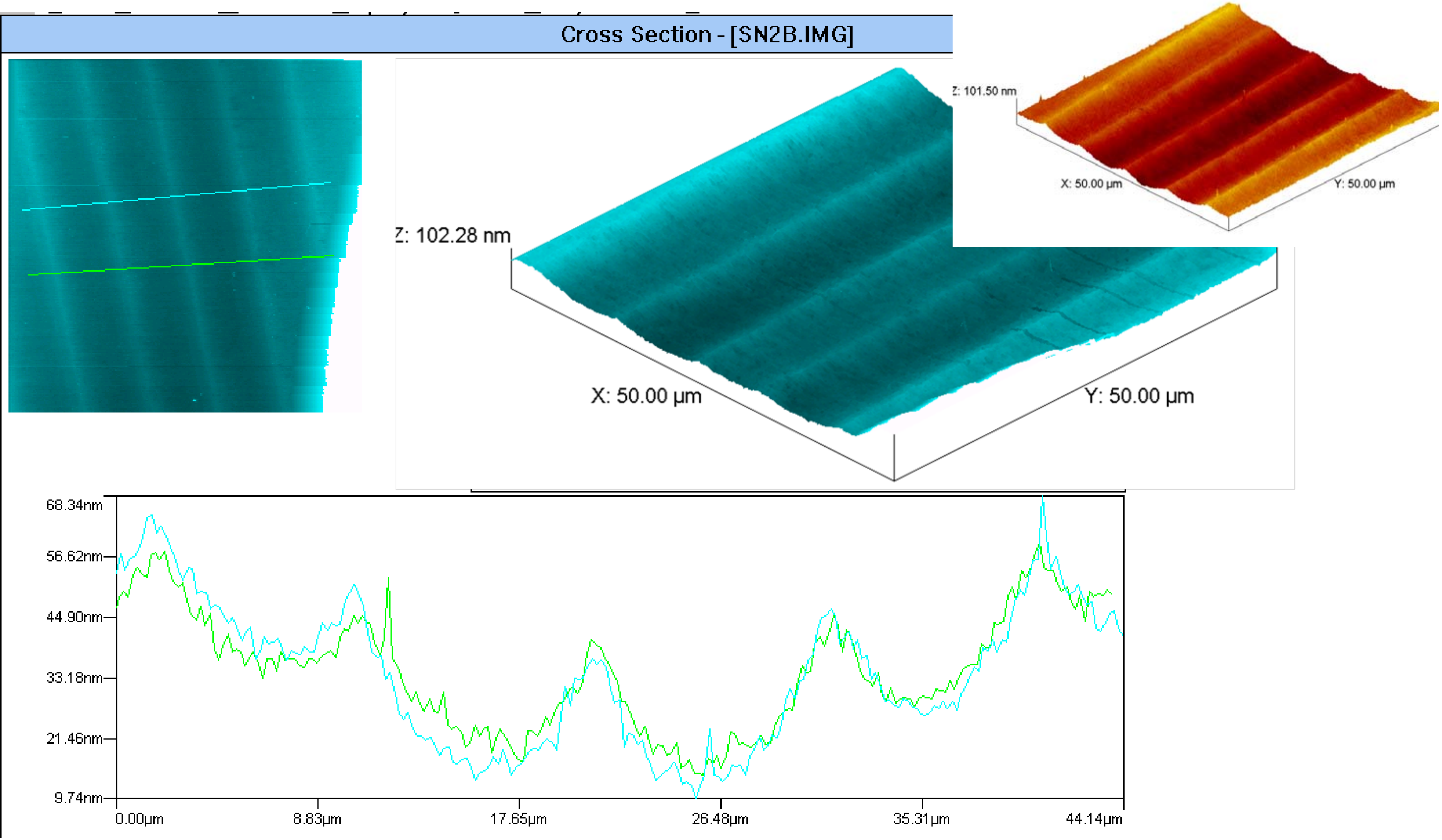
X-ray Photo-electron Spectroscopy (XPS) gives the surface coverage of contaminants



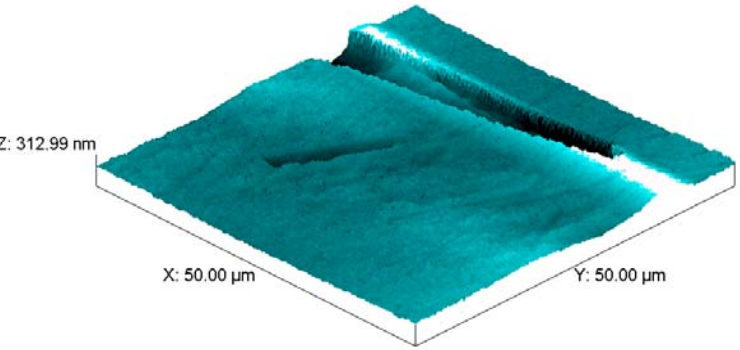
Atomic Force Microscope (AFM) measurement of a hand-polished sample

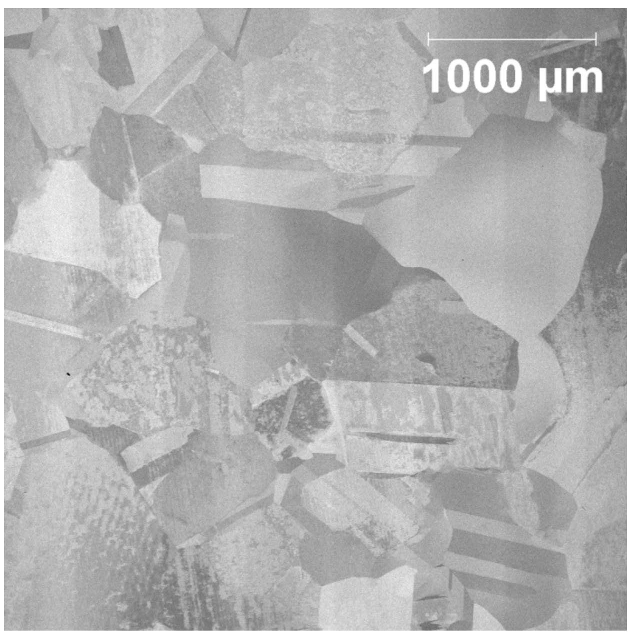


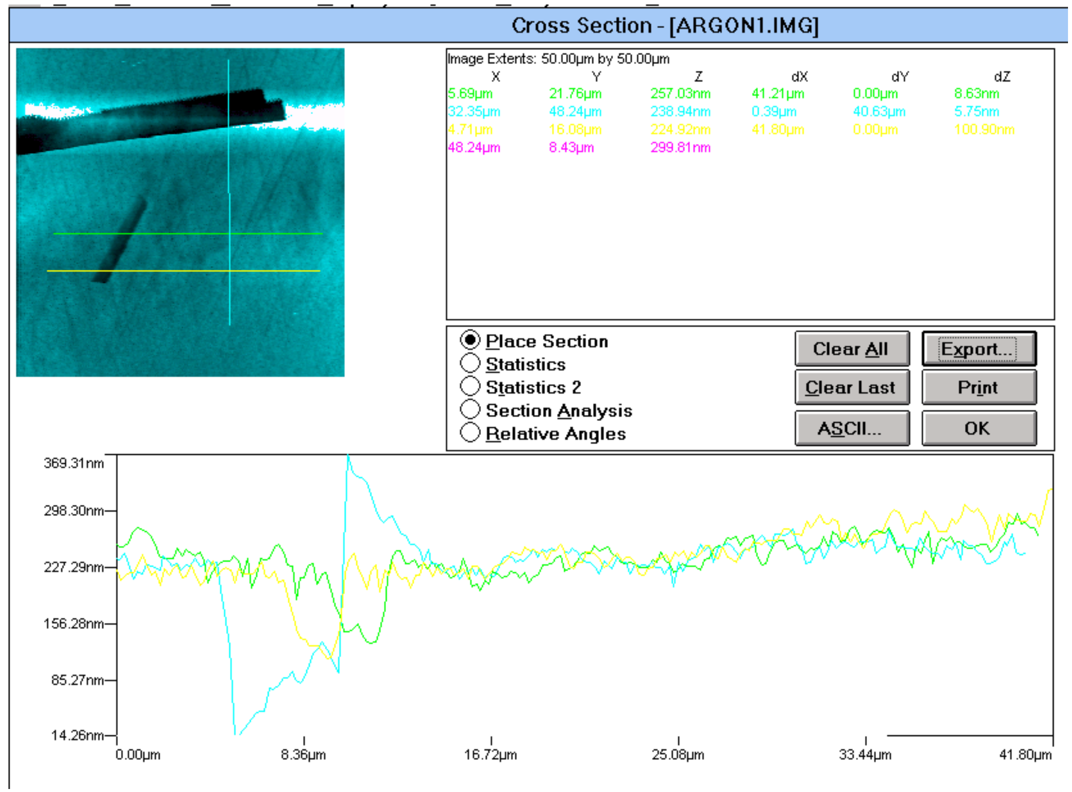
AFM measurements show diamond-turned samples have grating-like ridges



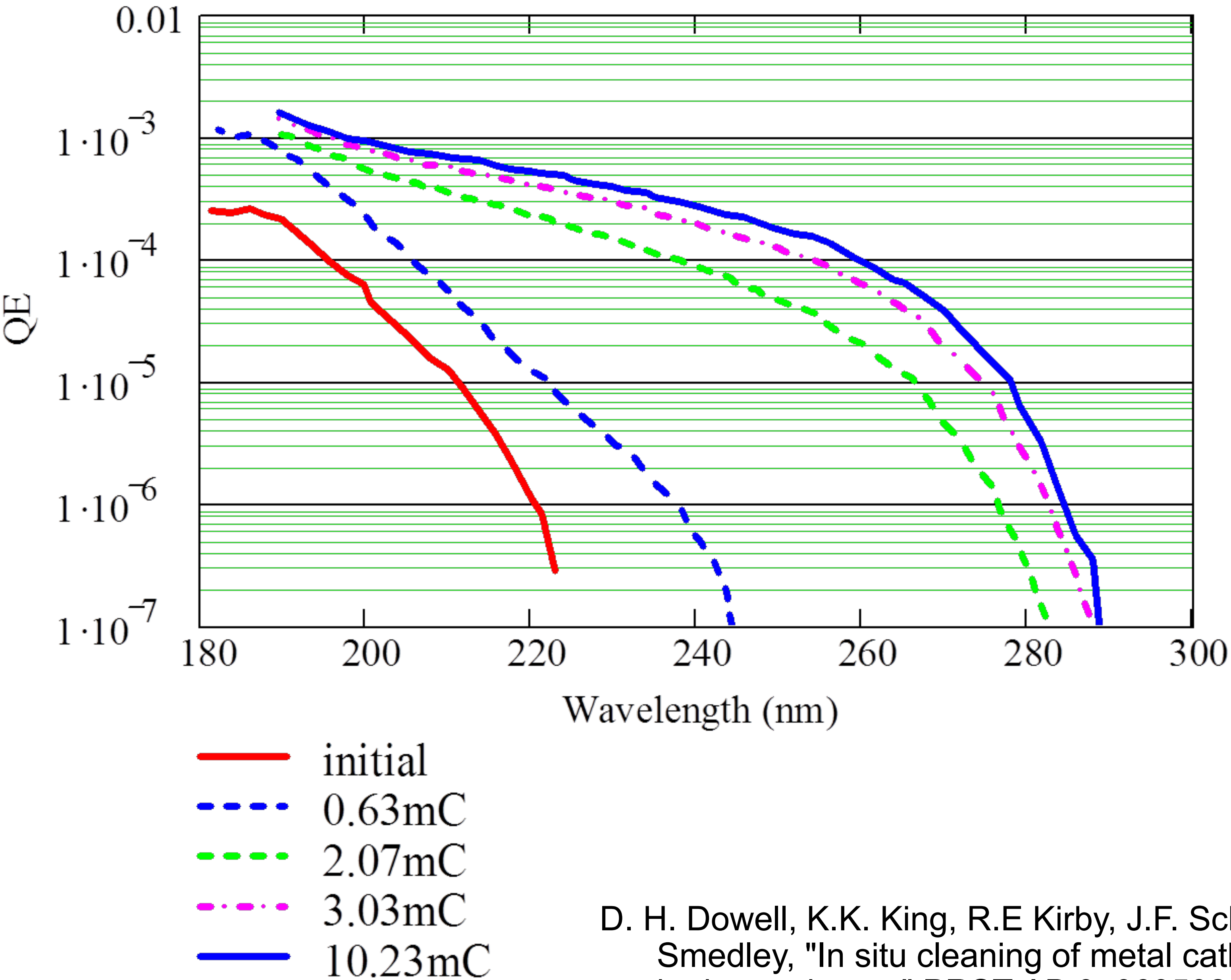
Ar-Ion cleaning preferentially mills out particular grains (single crystals), producing high-contrast canyons in the surface







QE vs Ion Dose



D. H. Dowell, K.K. King, R.E Kirby, J.F. Schmerge and J. Smedley, "In situ cleaning of metal cathodes using a hydrogen beam," PRST-AB 9, 063502 (2006)

Ion Cleaning Conclusions

•H-ion cleaning is reproducible and robust in lab experiments, but disappointing in gun tests

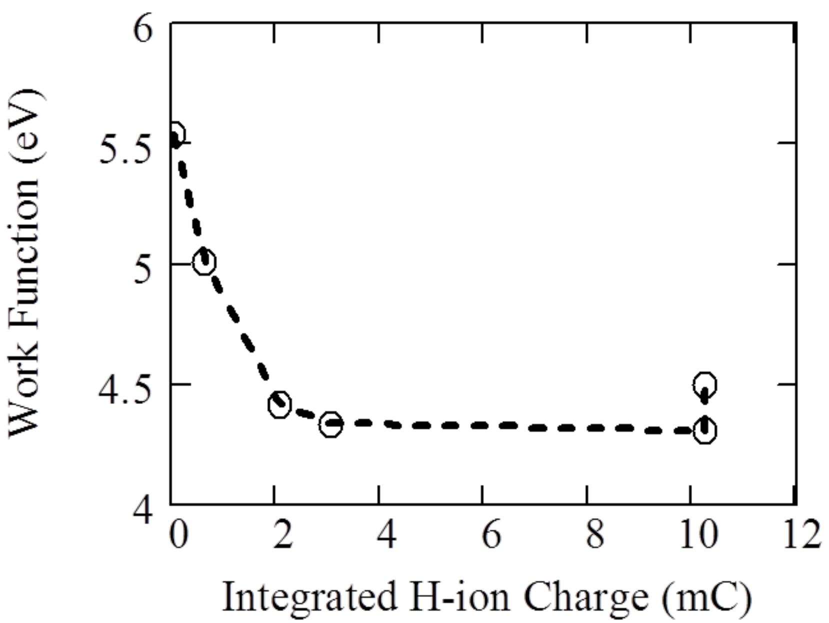
•Even copper cathodes are sensitive to contamination

- •QE dies a factor of ~500 with 1 hour exposure to air

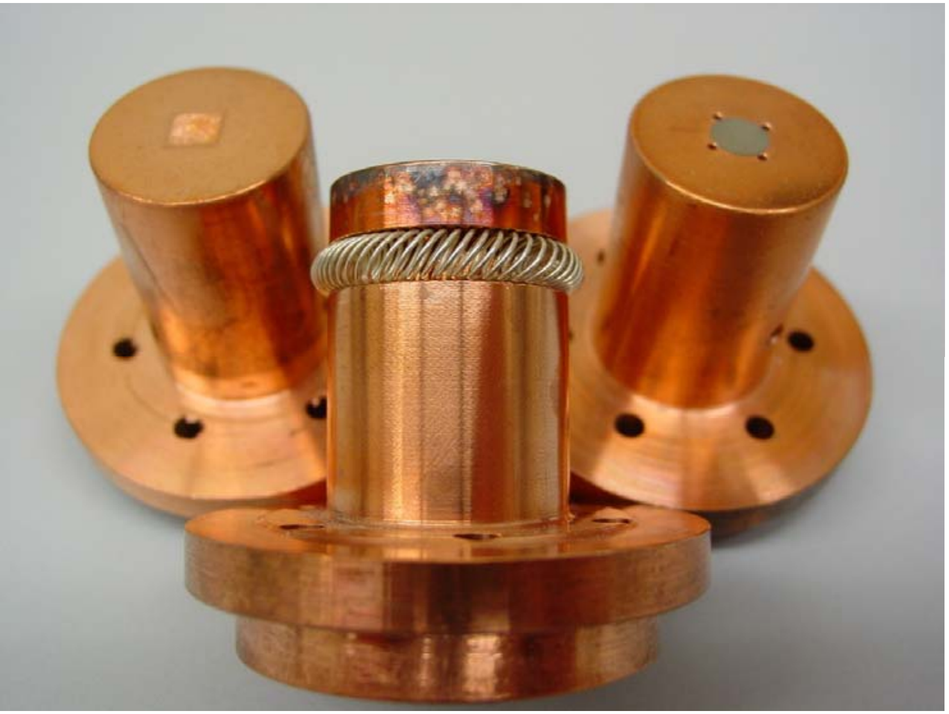
•Ar-ions and 230degC baking also clean but,

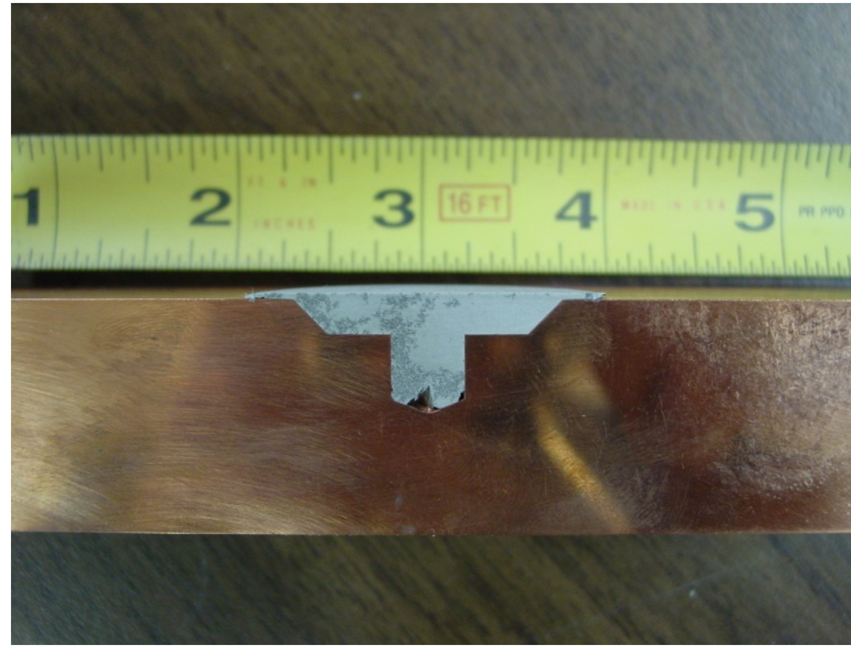
- •Ar-ions can erode the surface leading to high dark current
- •Baking can re-contaminate and is less effective at removing carbon
- •Some combination of H-ion and baking maybe best

•Current LCLS cathode process is laser cleaning



Putting the Cathode in the Gun

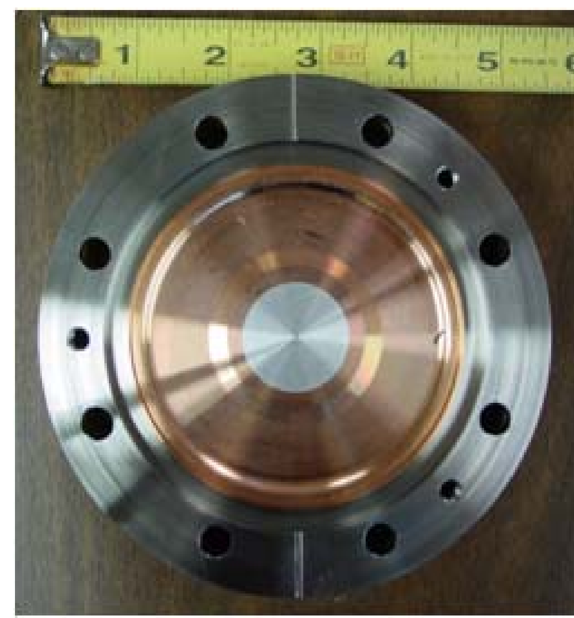




Contiguous black planes or plugs

Plugs are convenient, but the joint provides field enhancement and RF breakdown at high field

Mg is friction welded into copper



Superconducting Photocathodes

- The cathode-cavity interface is the most difficult part a superconducting injector
- Using a superconductor as a cathode removes the need for a RF choke, and may allow higher gradients
- Niobium is a poor photocathode -> use Lead
- Two ½ cell cavities (1.3 & 1.42 GHz) have been tested
  - Both reached 40 MV/m; RF performance unaffected by lead
  - 1.6 Cell reached 46 MV/m with lead
  - Lead cathode QE comparable to room temperature values
  - Peak laser power of 3 MW/cm^2 (@ 248 nm) did not quench the cavity

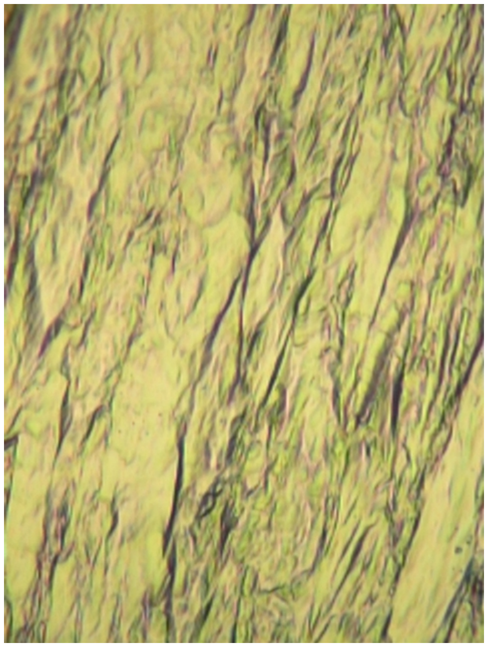
J. Smedley, T. Rao, and Q. Zhao, J. Applied Physics 98, 043111 (2005)
J. Sekutowicz, et al.; *Phys. Rev. ST Accel. Beams,* **8**, 010701 (2005)
J. Smedley, T. Rao , J. Sekutowicz, Phys. Rev. ST Accel. Beams 11, 013502 (2008)
J. Smedley *et al.*, PAC07, 1365; J. Sekutowicz *et al.*, PAC07, 962

Cathode Preparation - Niobium

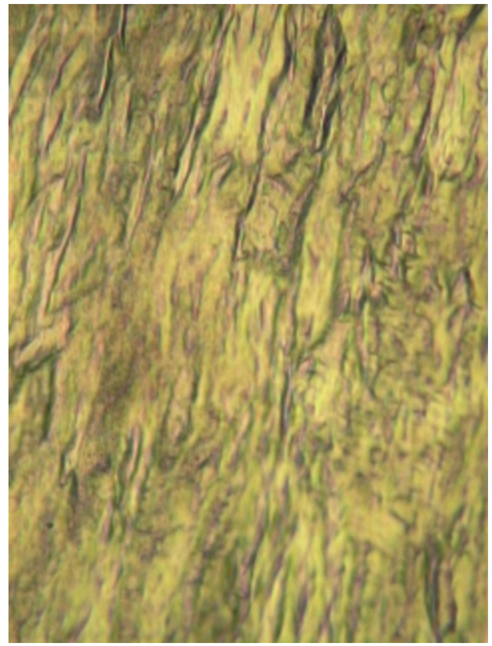
- Amorphous, RRR 250 Nb Cathodes used
- Three surface preparations:
  - Mechanical polish (with diamond slurry)
  - Electropolishing
  - Buffered chemical polish
- In situ laser cleaning
  - Nd:YAG 4th harmonic (266 nm), 12 ps pulse, ~0.2 mJ/mm^2
  - KrF Excimer (248 nm), 12 ns pulse, ~2 mJ/mm^2

Nb Surface Finish

Buffered Chemical Polish

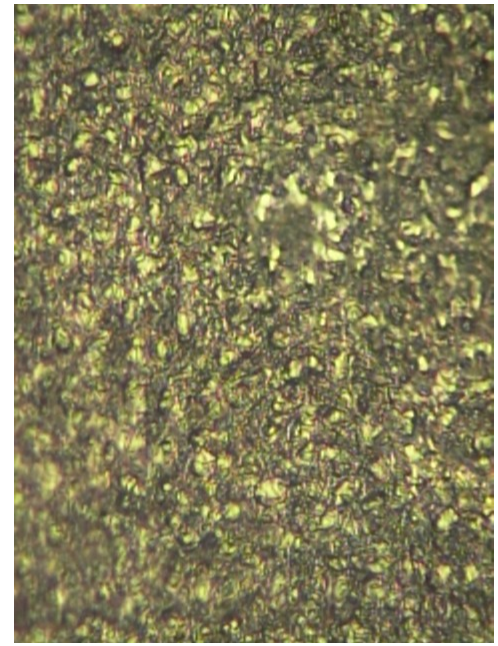


no laser cleaning



0.25 mJ/mm^2

12 ps Nd:YAG (266 nm)



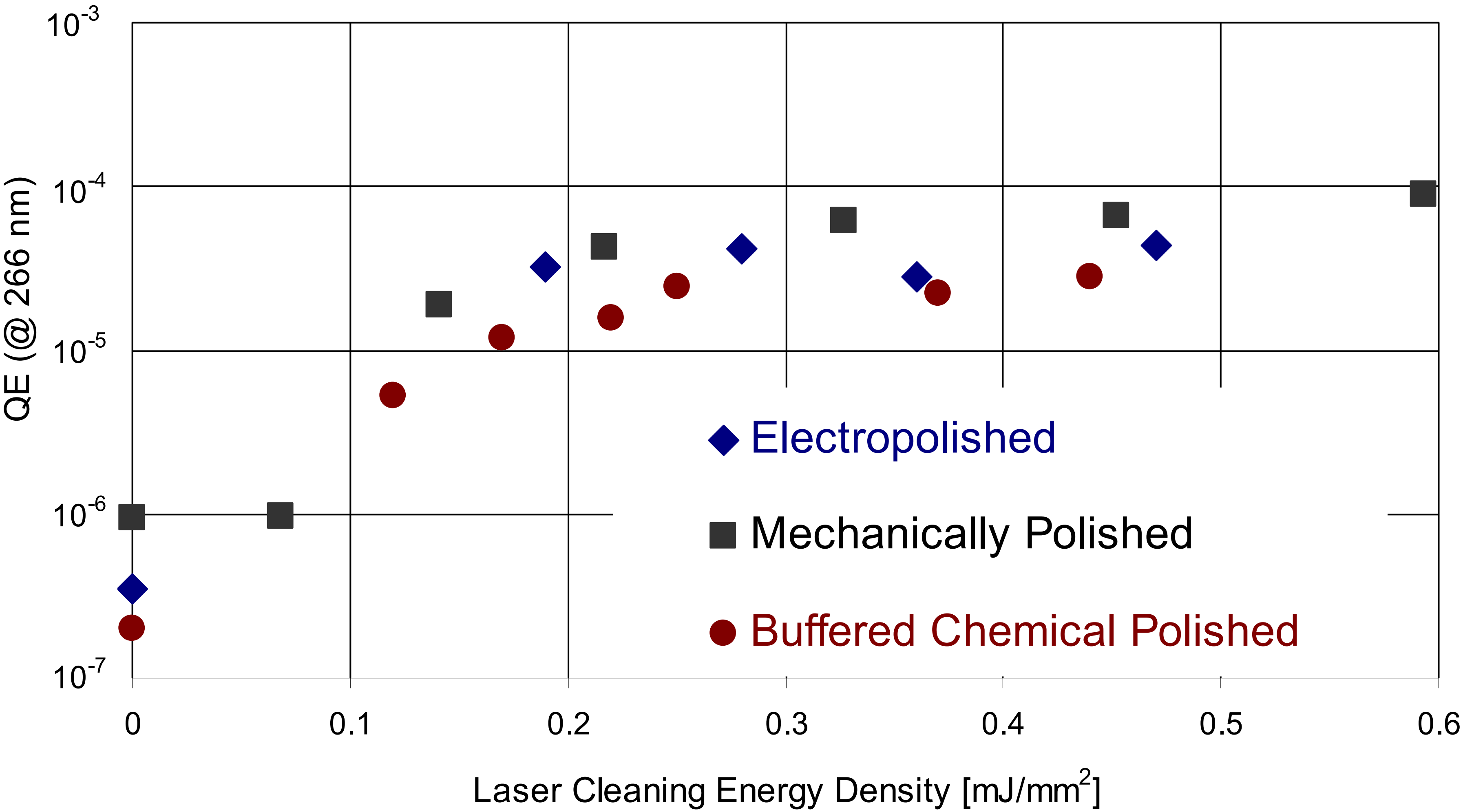
0.67 mJ/mm^2

12 ps Nd:YAG (266nm)

20 μm

Laser Cleaning on Niobium

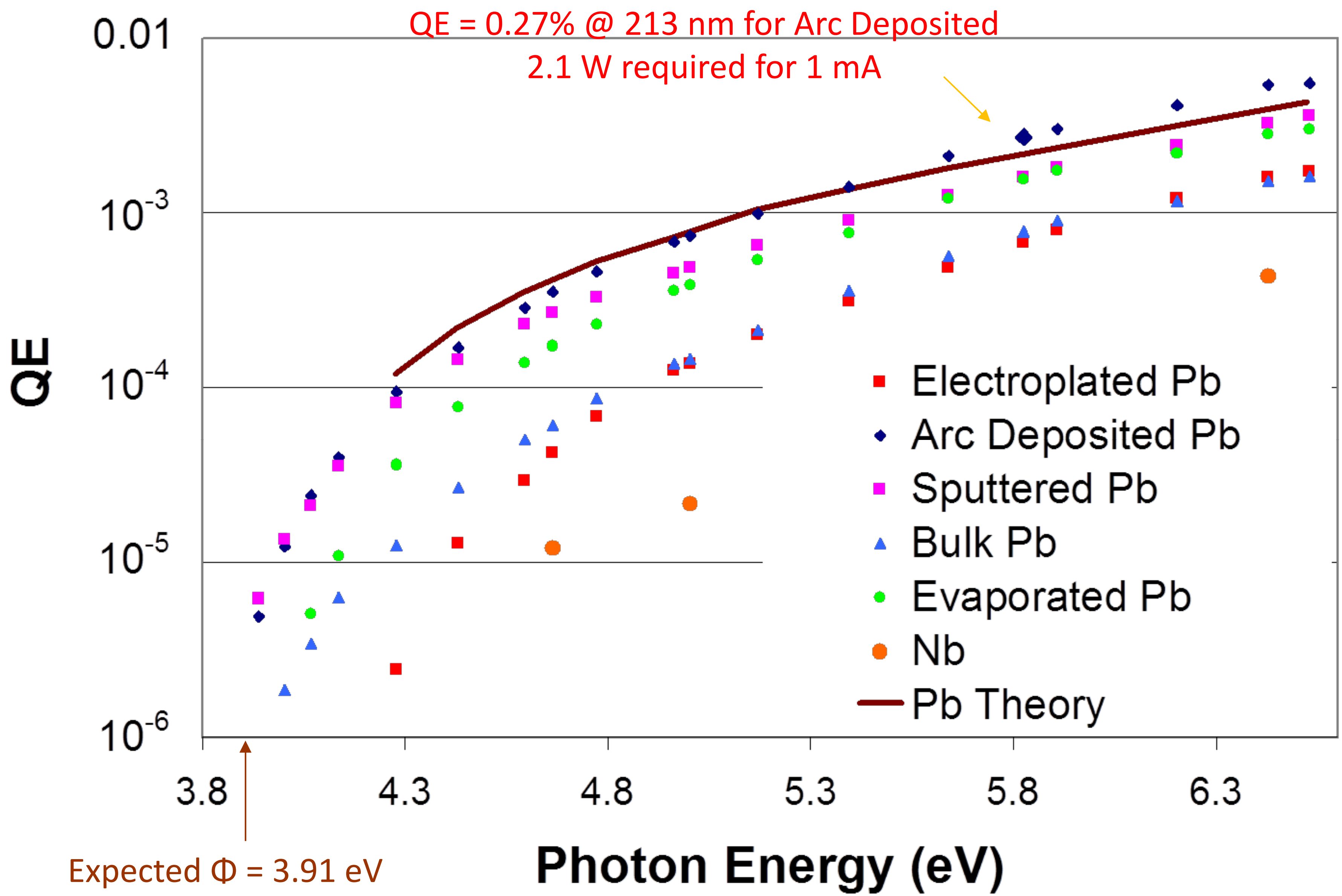
Cleaning with 12ps Nd: YAG (266 nm)



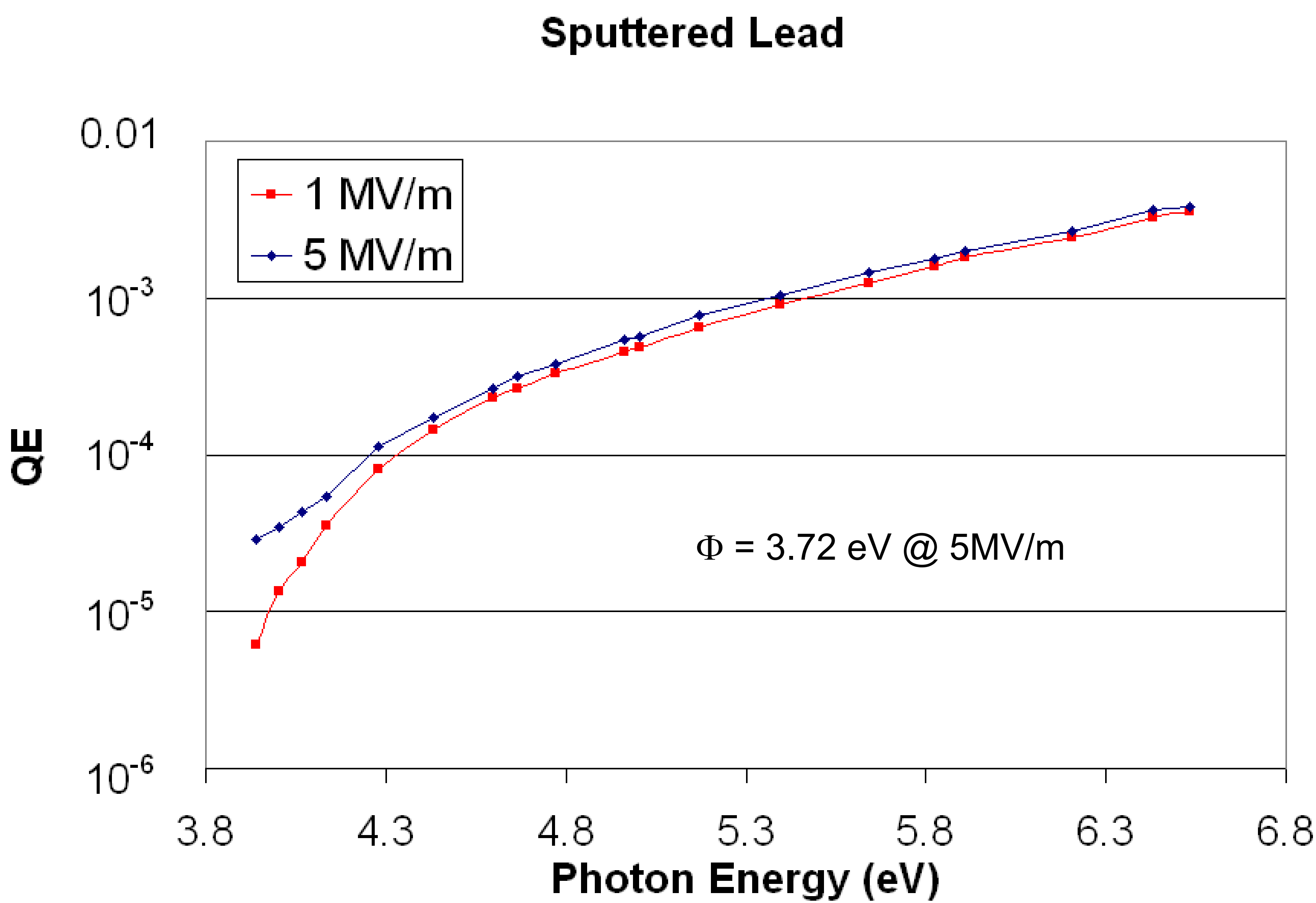
Cathode Preparation - Lead

- Nb Cathodes used as substrate
- Four deposition methods:
  - Electroplating
  - Vacuum deposition (evaporation)
  - Sputtering
  - Vacuum Arc deposition
- Solid lead, mechanically polished
- In situ laser cleaning
  - KrF Excimer (248 nm), 12 ns pulse, ~0.2 mJ/mm^2

DC Room Temperature Photoemission Results



J. Smedley, T. Rao , J. Sekutowicz Phys. Rev. ST Accel. Beams **11**, 013502 (2008)

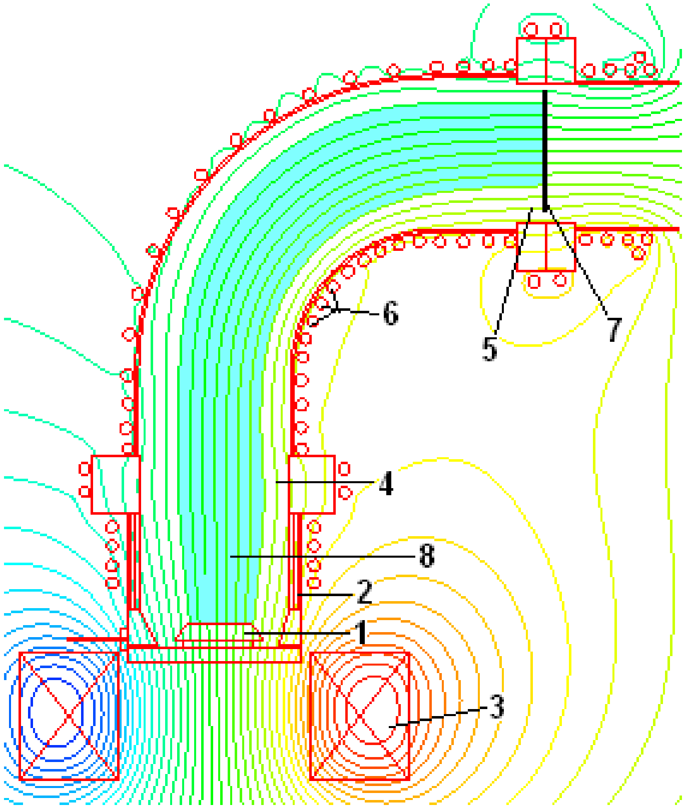


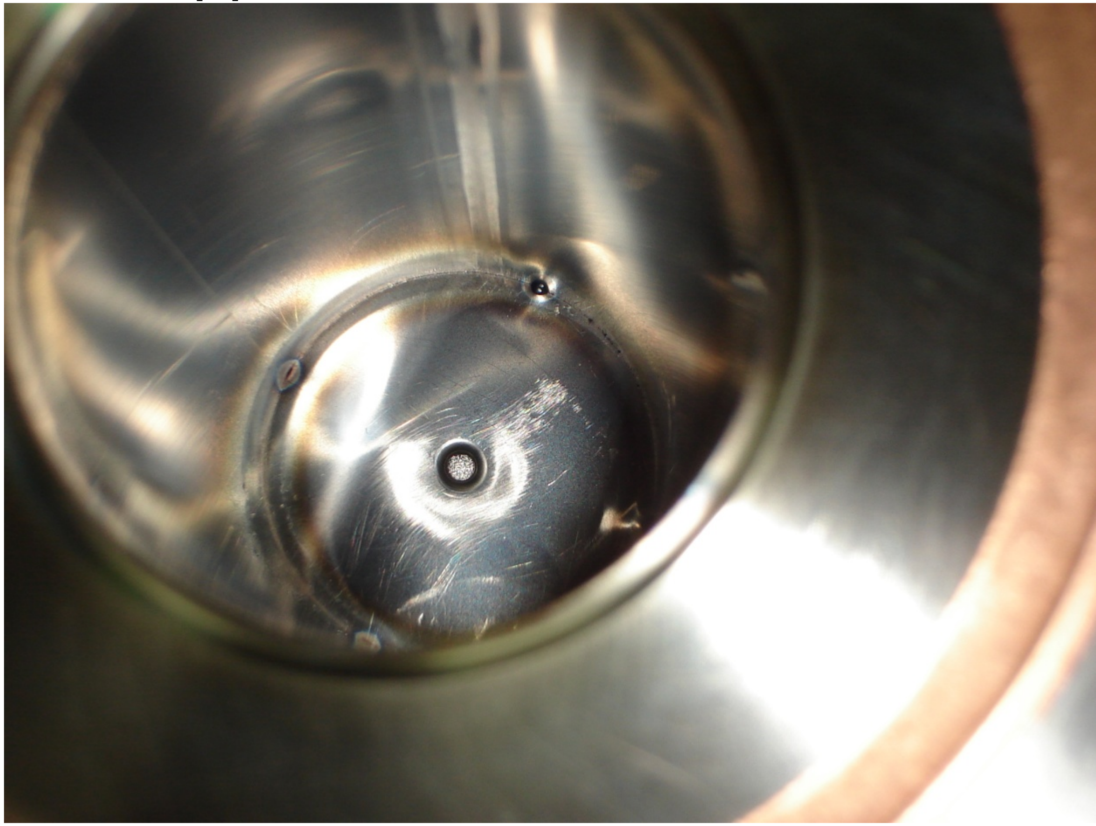
Sputtered Lead
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
QE
1 MV/m
5 MV/m
Φ = 3.72 eV @ 5MV/m
3.8
4.3
4.8
5.3
5.8
6.3
6.8
Photon Energy (eV)

Arc Plating of DESY Cavity Cathode Area

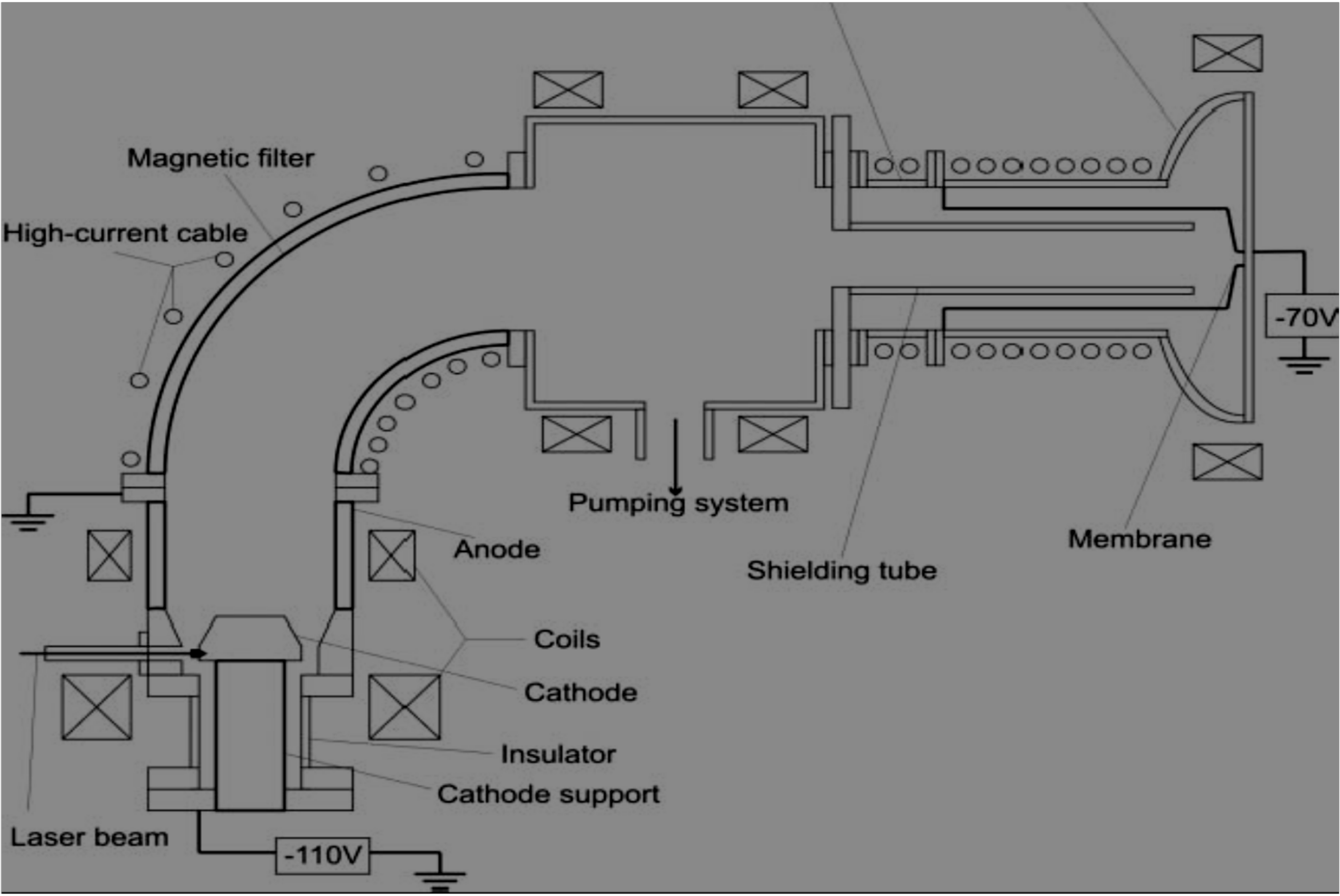
Coating technique and apparatus built at INS

Courtesy P. Strzyzewski, A. Soltan INS, Swierk.

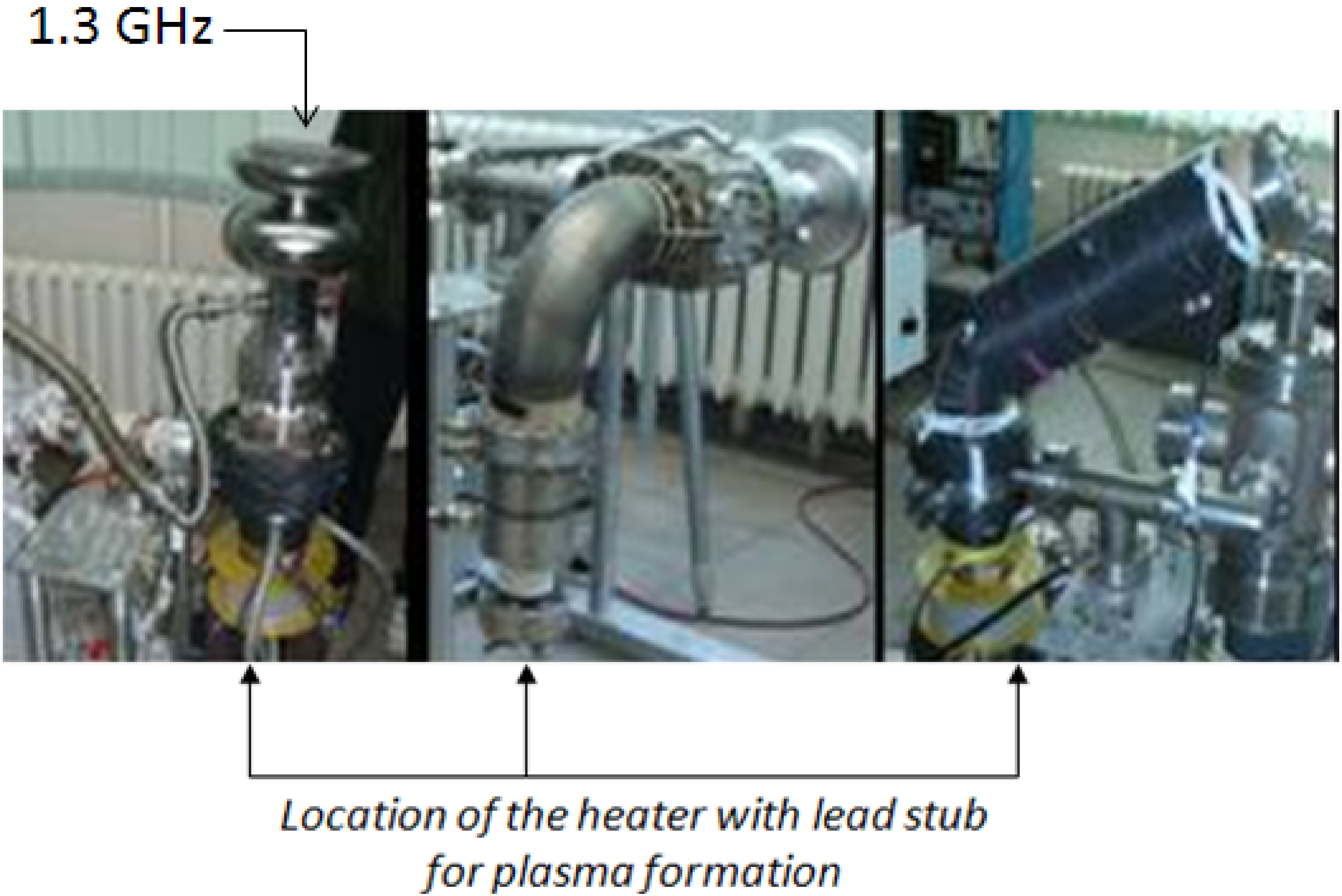




1 – cathode, 2 – anode, 3 – focusing coil, 4 – filter inlet, 5 – filter exit, 6 – high-current cable, 7 – ion collector position, 8 – plasma stream.

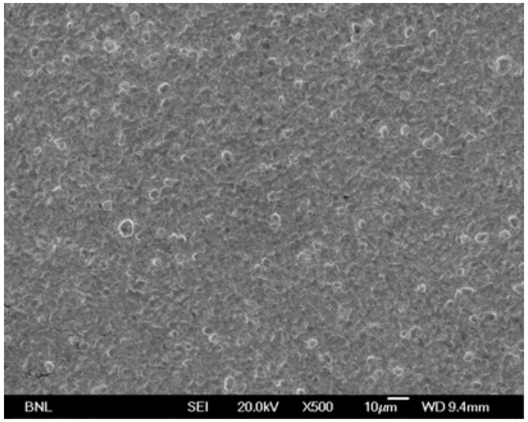


Magnetic filter
High-current cable
Pumping system
-70V
Anode
Membrane
Shielding tube
Coils
Cathode
Insulator
Cathode support
Laser beam
-110V

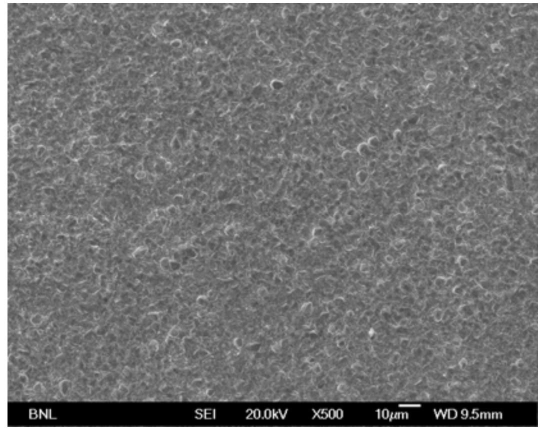

1.3 GHz
Location of the heater with lead stub
for plasma formation

Lead Surface Finish and Damage Threshold

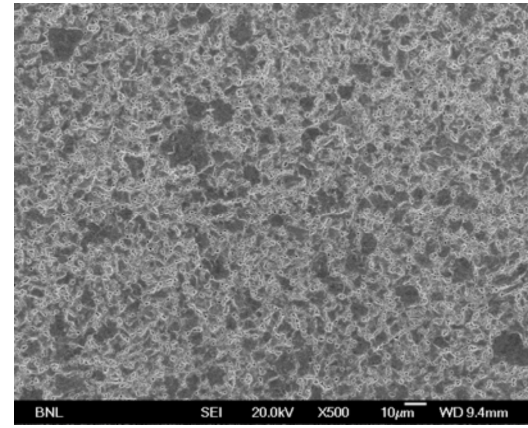
Electroplated Lead



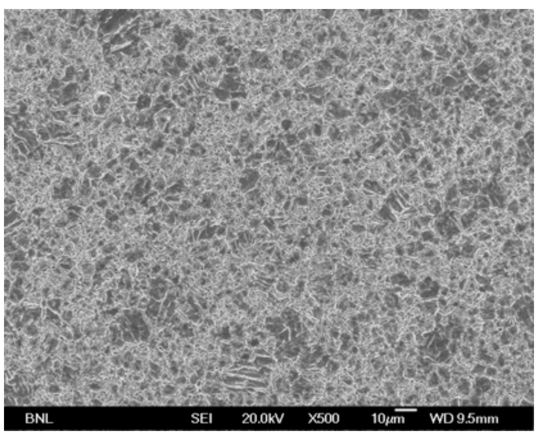
Prior to Laser Cleaning



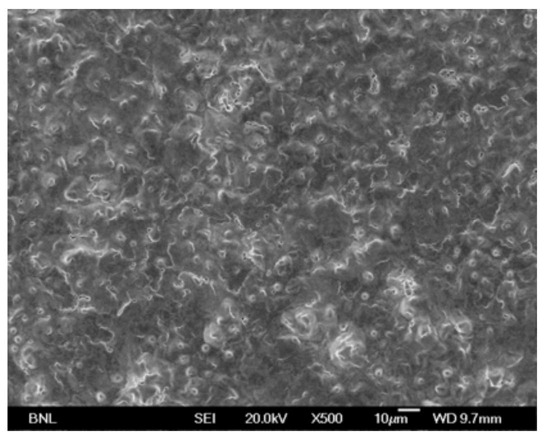
0.11 mJ/mm^2



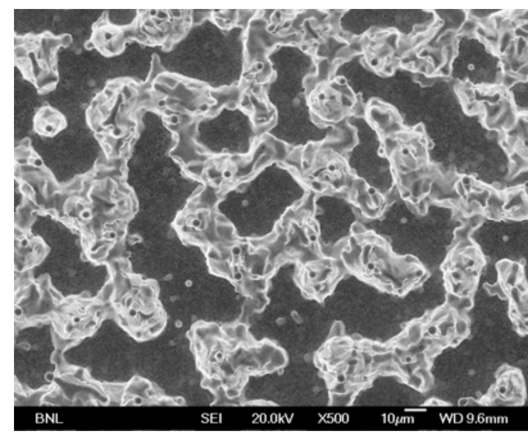
0.26 mJ/mm^2



0.52 mJ/mm^2



1.1 mJ/mm^2

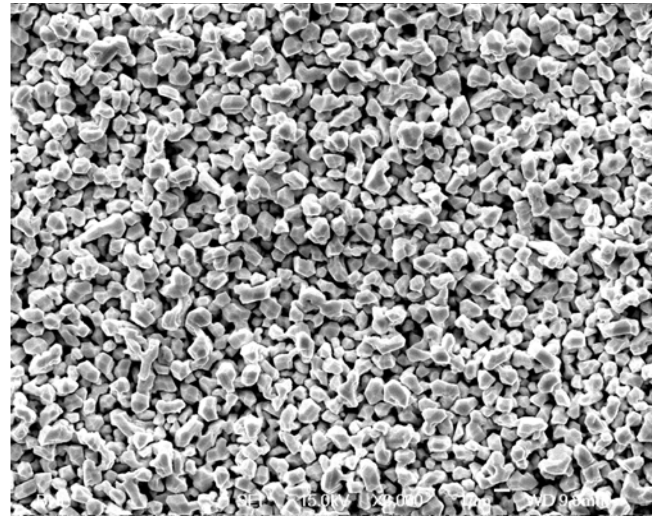


1.8 mJ/mm^2

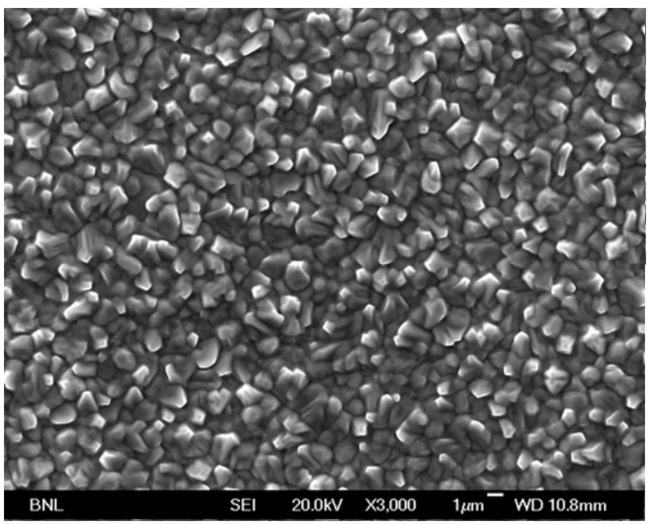
Surface Uniformity

Arc Deposited

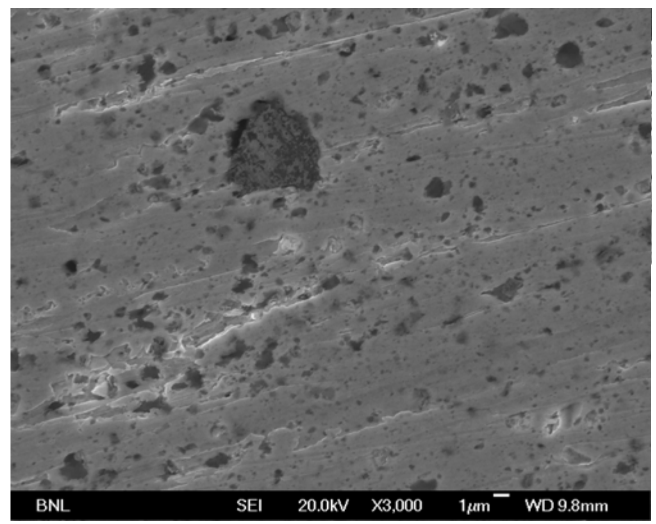
Sputtered



Vacuum Deposited



Solid



10 μm

All cathodes laser cleaned with 0.2 mJ/mm^2 of 248nm light

Cold Temperature QE

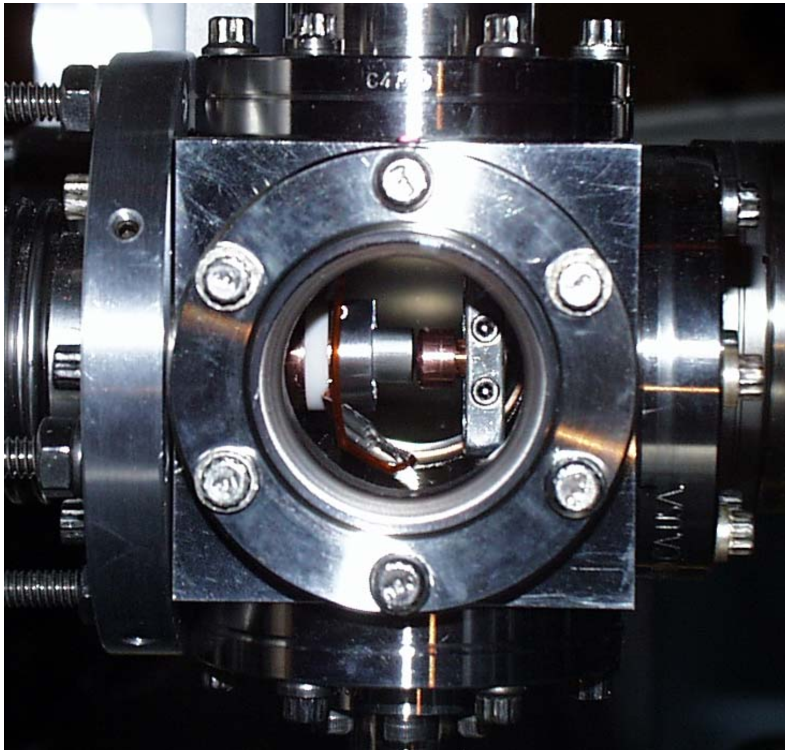
Previous measurements made at room temperature

How will lead behave at cryogenic temperatures?

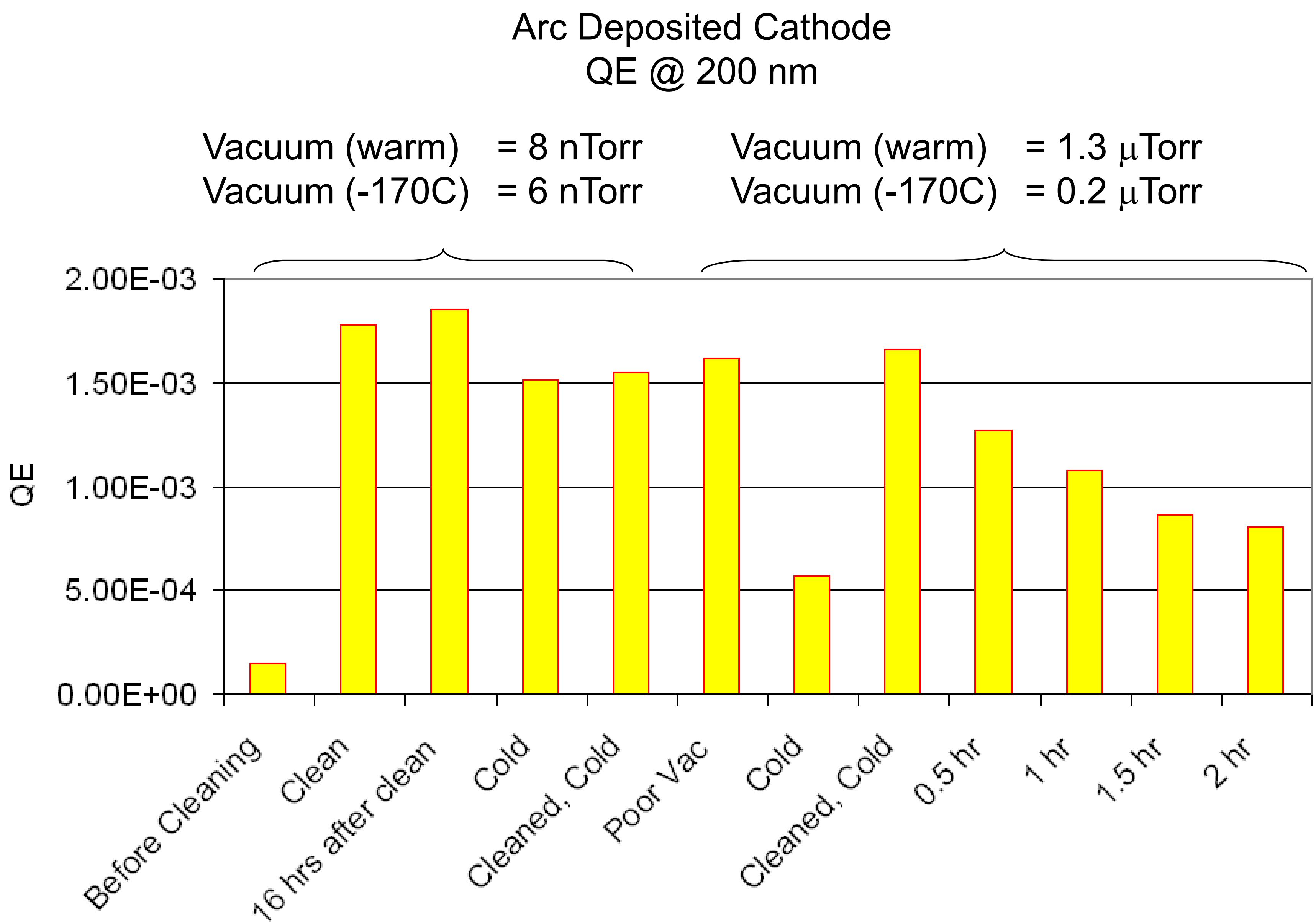
To find out, we mounted the cathode on a LN_2 cooled vacuum cold finger, capable of reaching -170 C

Electroplated and Arc Deposited

Structurally, the lead coatings were unaffected by multiple warm/cold cycles



Effect of Temperature and Vacuum on QE

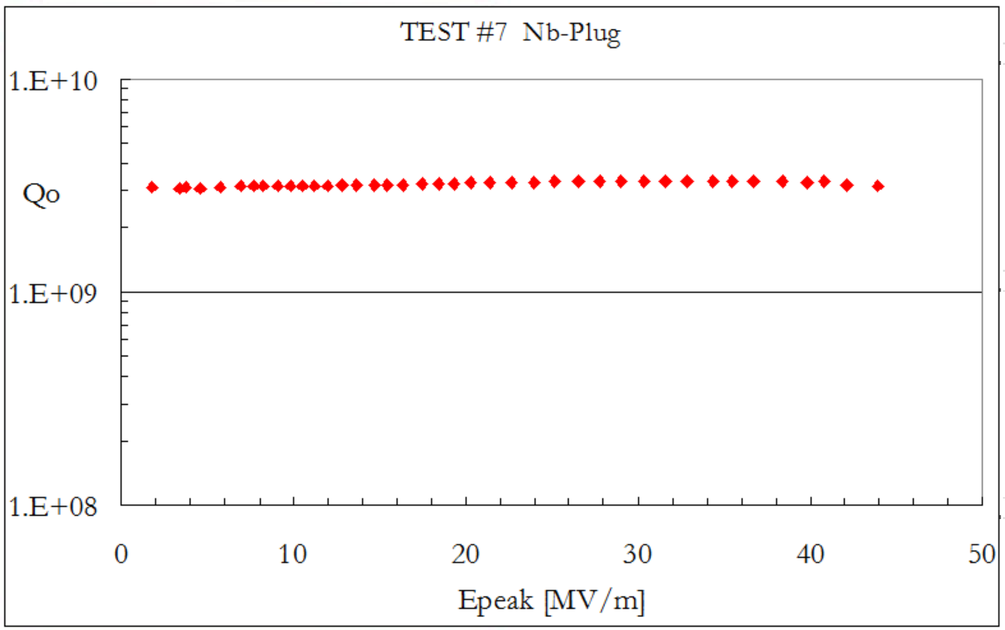


Hybrid Cavity Options

Plug Gun (Jlab)

1.42 GHz niobium cavity w/ removable plug

$Q_0=3x10^9$ w/ Nb Plug

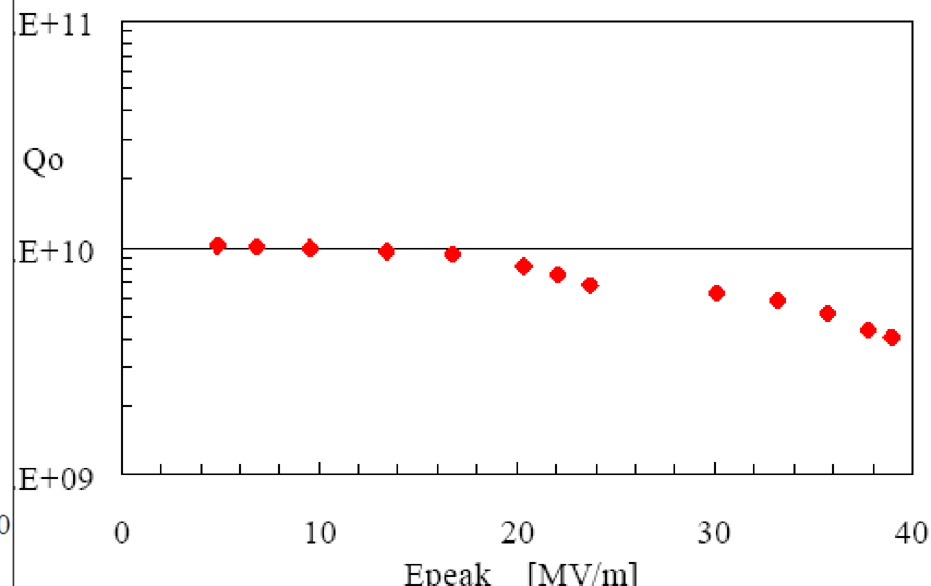


P. Kneisel, et al., PAC 05

DESY Gun

1.3 GHz niobium cavity

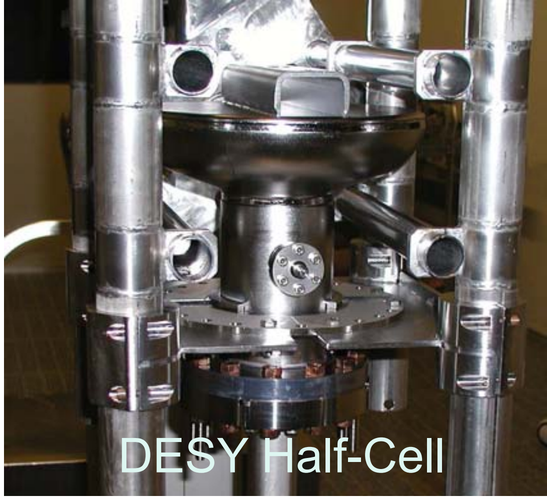
$Q_0=1x10^{10}$ w/o Lead Plating

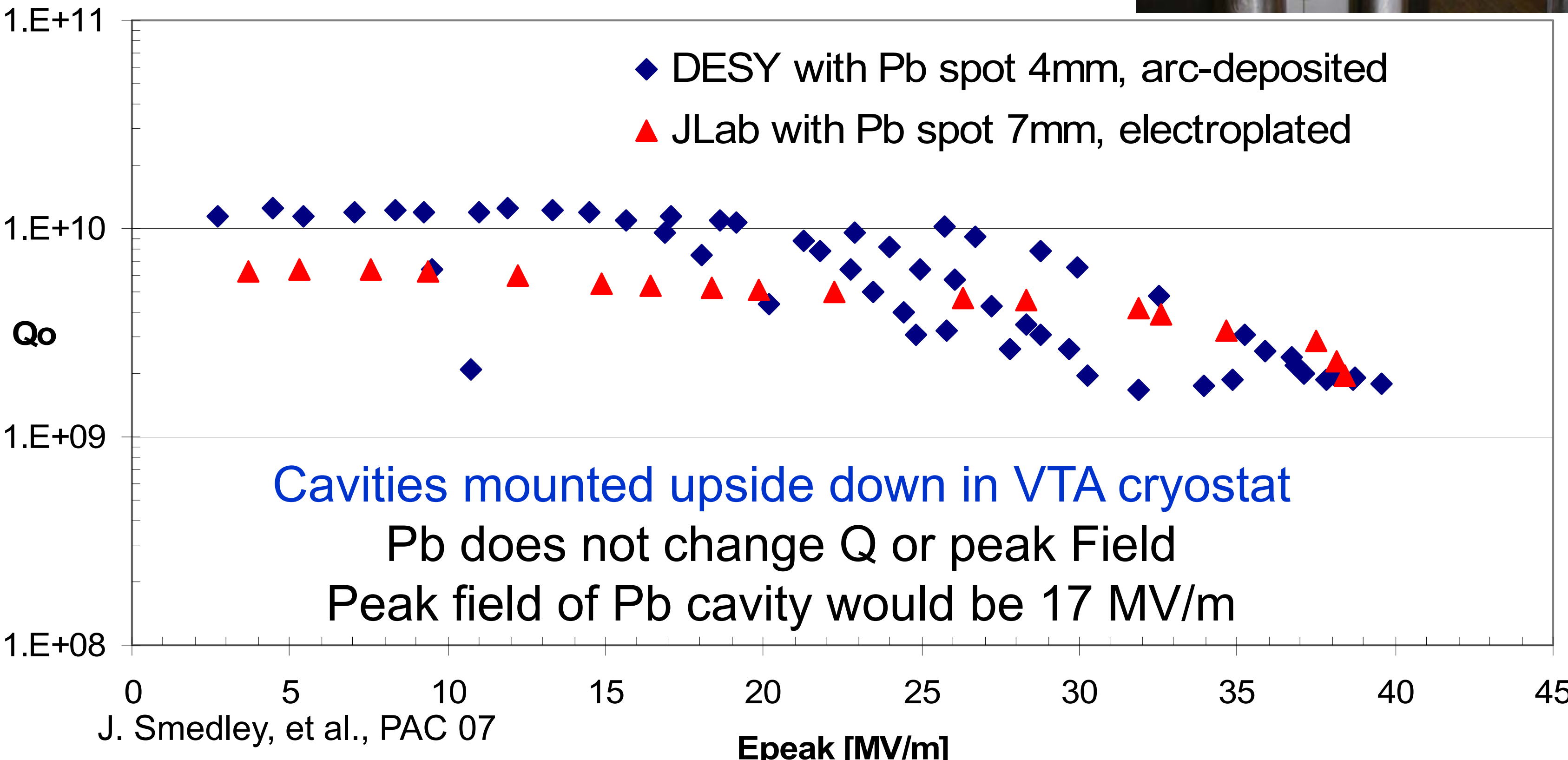


Cavity Tests

Nb-Pb Half-cells

Status March 07



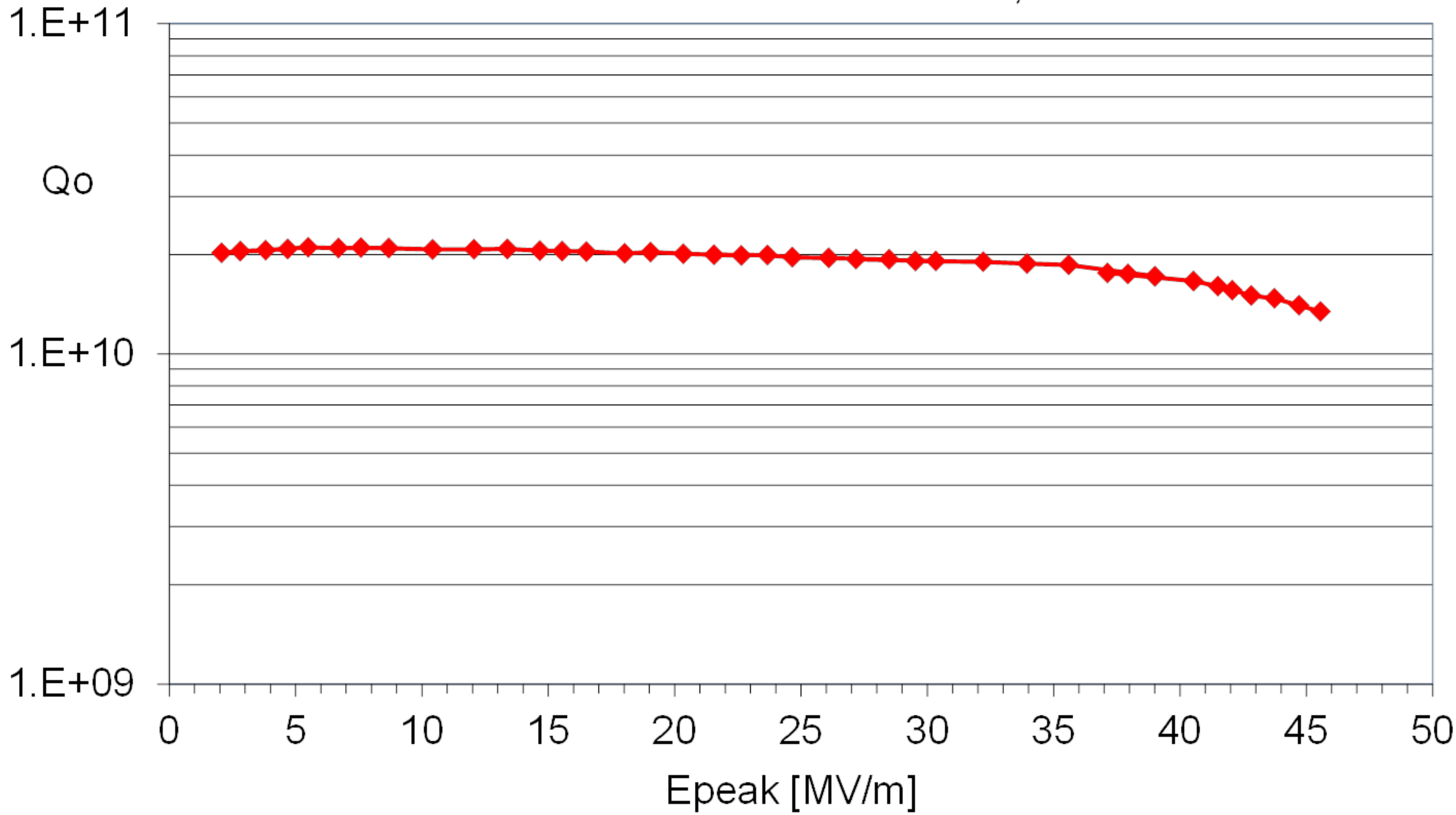


J. Smedley, et al., PAC 07

J. Smedley, et al., ERL 07

J. Sekutowicz, et al., PAC 07

1.6-Cell DESY Gun Cavity with Pb
Test No 8 on December 8th, 2008



Vertical Test Area at Jlab

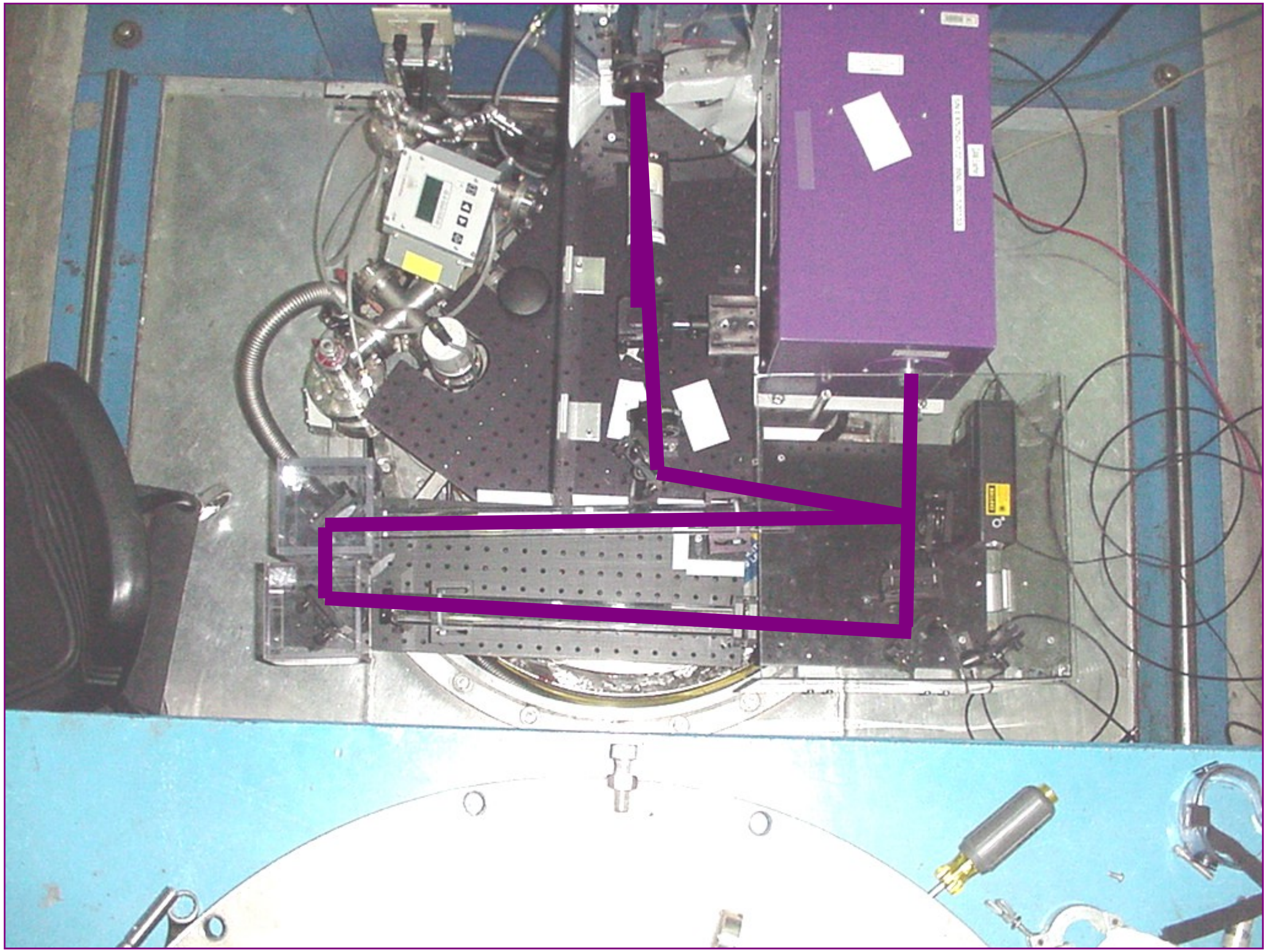
RF Sources for
0.7-2 GHz

Cool to 2K in 8 hrs

Cavity cleaning
and preparation

Space in radiation
shield *extremely*
limited

Optical Layout in Shield



Laser Parameters

248 nm (5 eV)

6 mJ/pulse

5.3 ns FWHM

150 Hz (20-250)

Not synchronized

Layout

6 m transport

2.7 m in cryostat

1.5 m lens

1:1 imaging of iris

3 mJ/pulse on cathode w/iris open

DC QE Measurements in VTA

Previous measurements made at room temperature

How will lead behave at cryogenic temperatures?

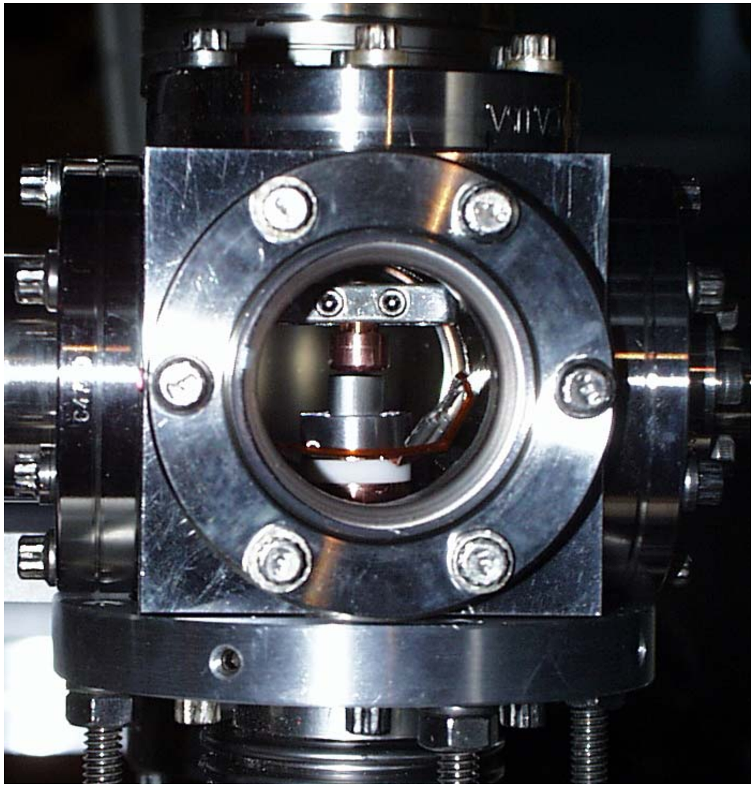
1 kV bias on anode, 1 mm spacing

Arc-deposited Lead on Niobium, deposited at same time as cavity

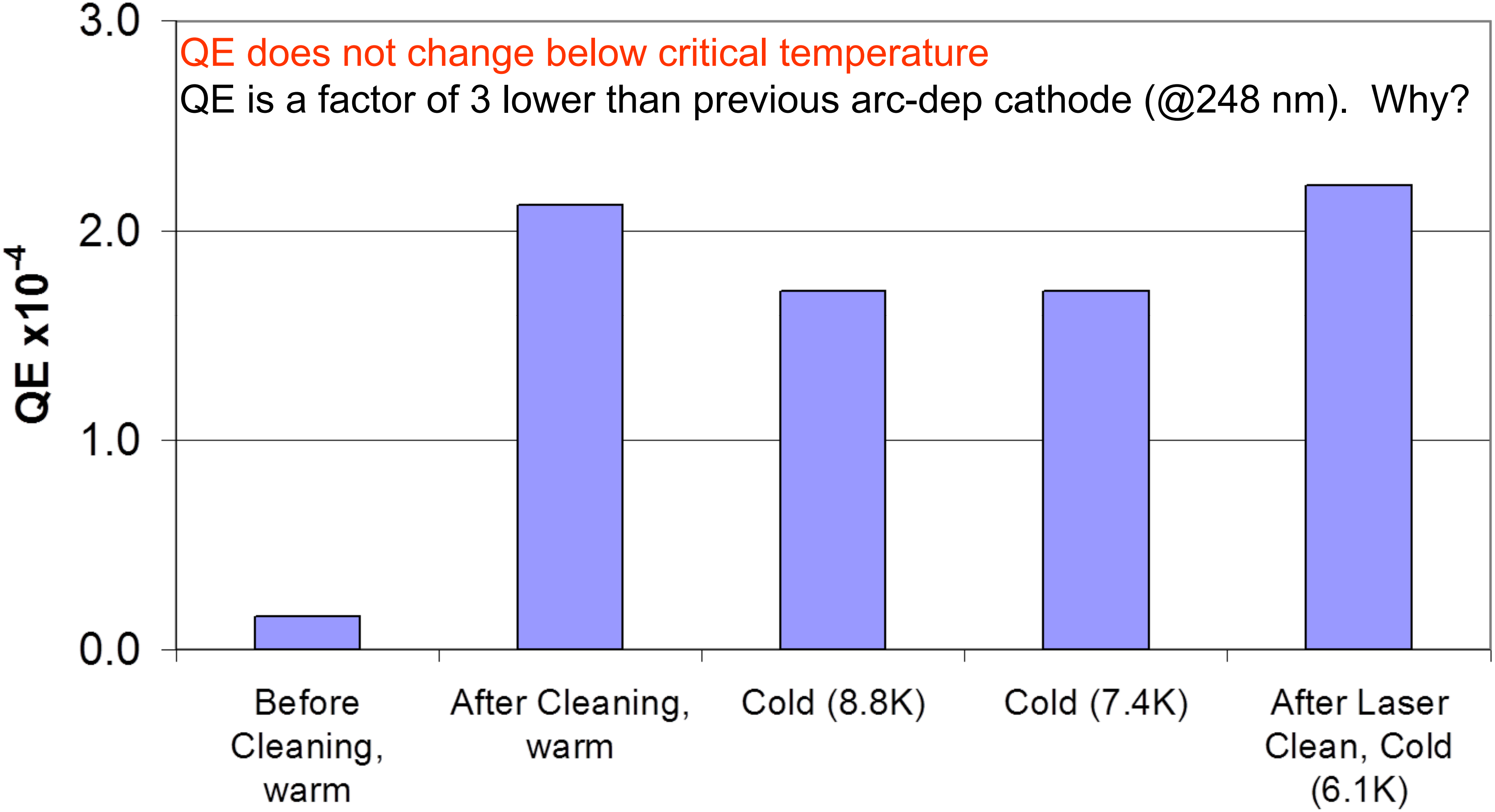
Current measured leaving cathode

Cathode laser cleaned in situ

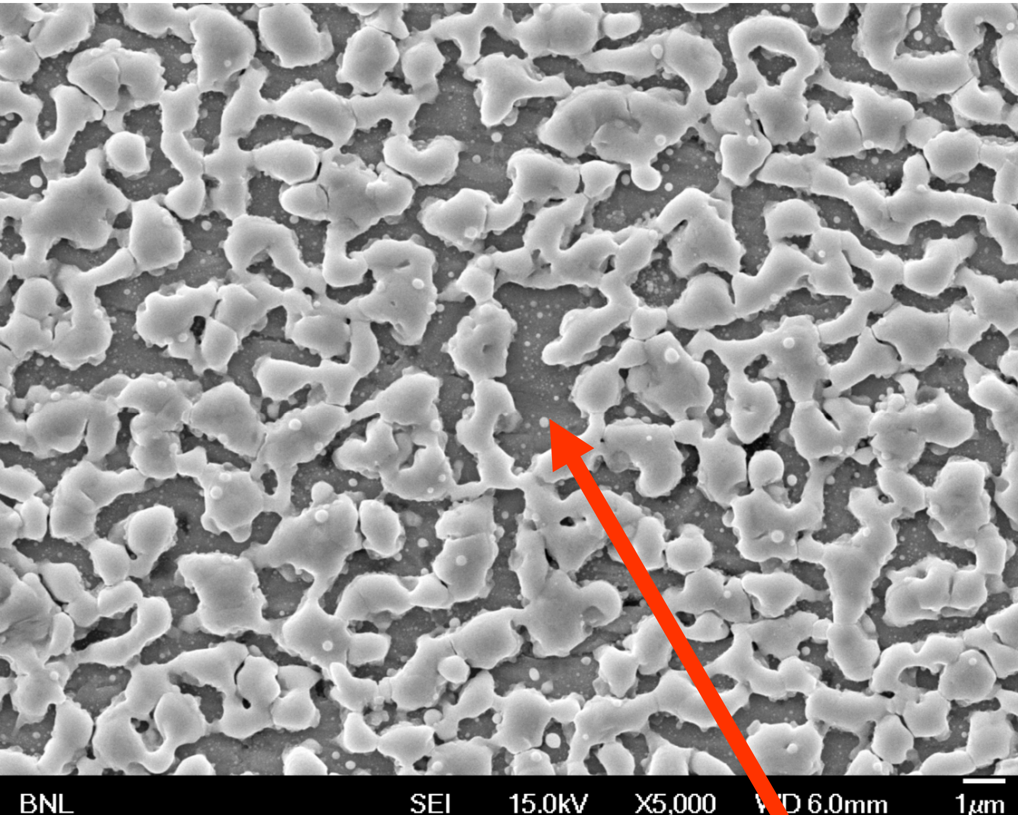
Laser transport same as for RF test



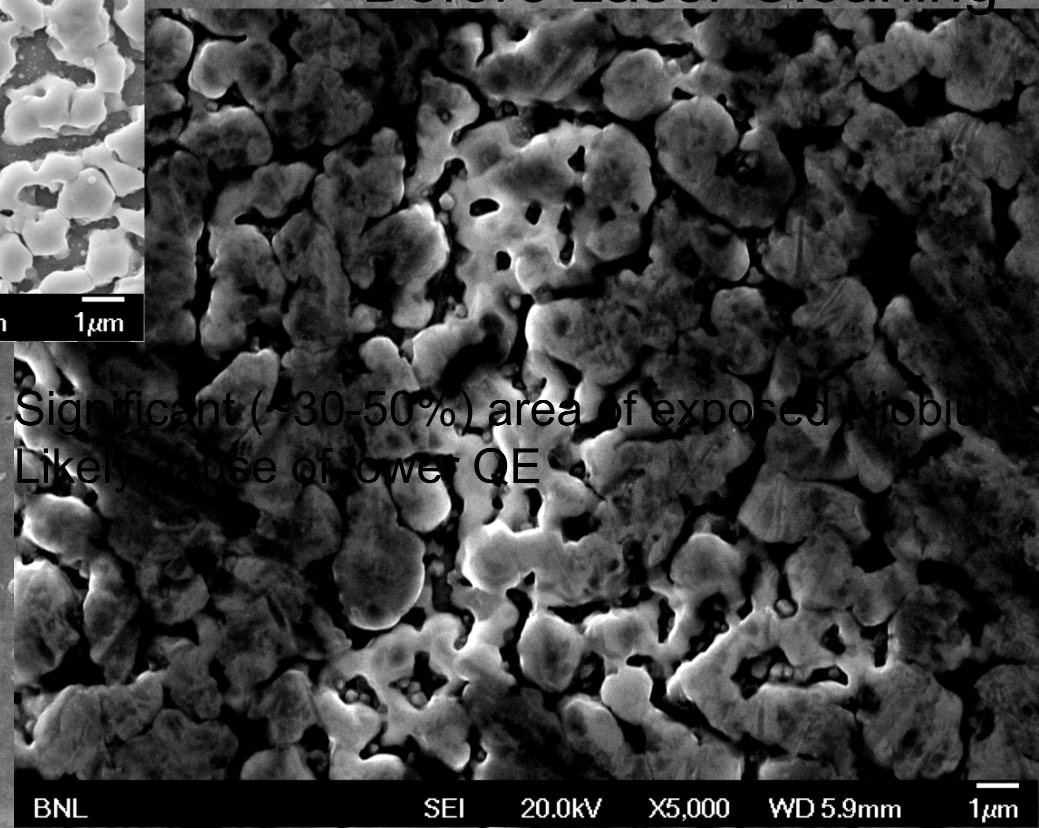
DC Quantum Efficiency of Arc Deposited Lead Cathode (1 MV/m field)



DC Lead Cathode



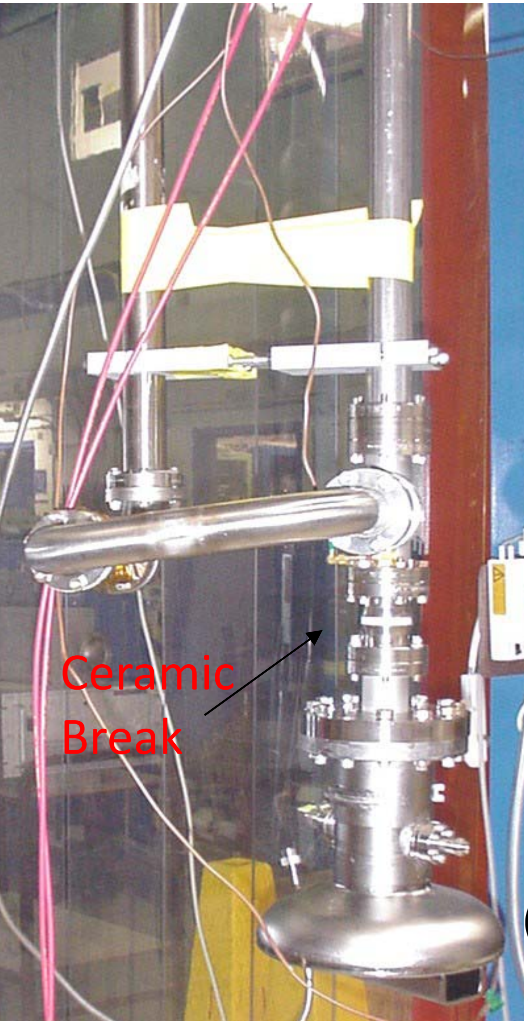
Arc Deposited Lead
Before Laser Cleaning

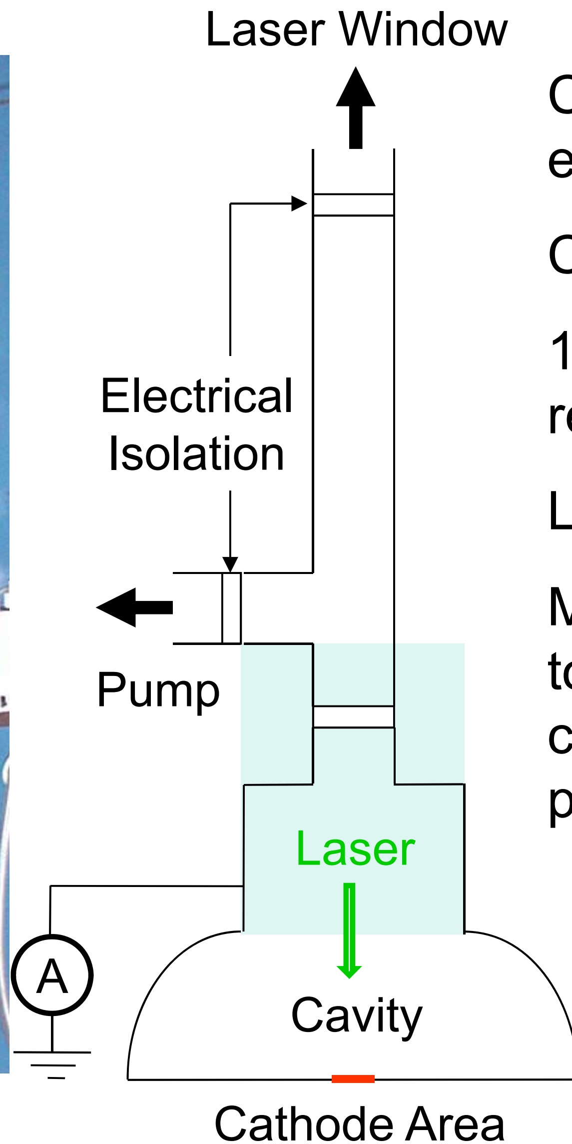


Arc Deposited Lead
After Laser Cleaning

Significant (~30-50%) area of exposed Niobium
Likely cause of lower QE

Charge Measurement





Cavity and beam pipe are electrically isolated

Current measured leaving cavity

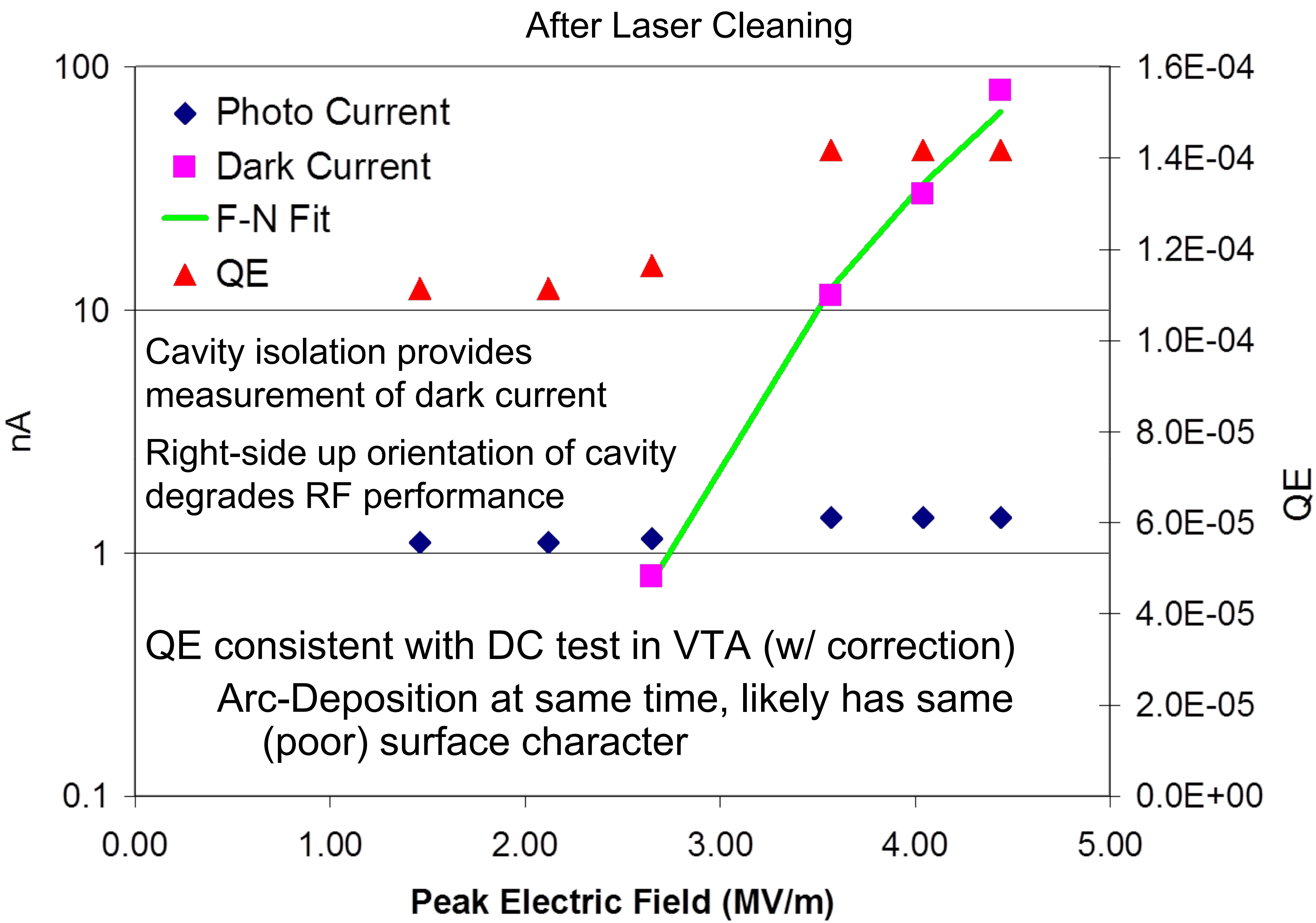
1 kV DC bias on beam tube to retard secondary emission

Laser pulse duration = 5.3 ns

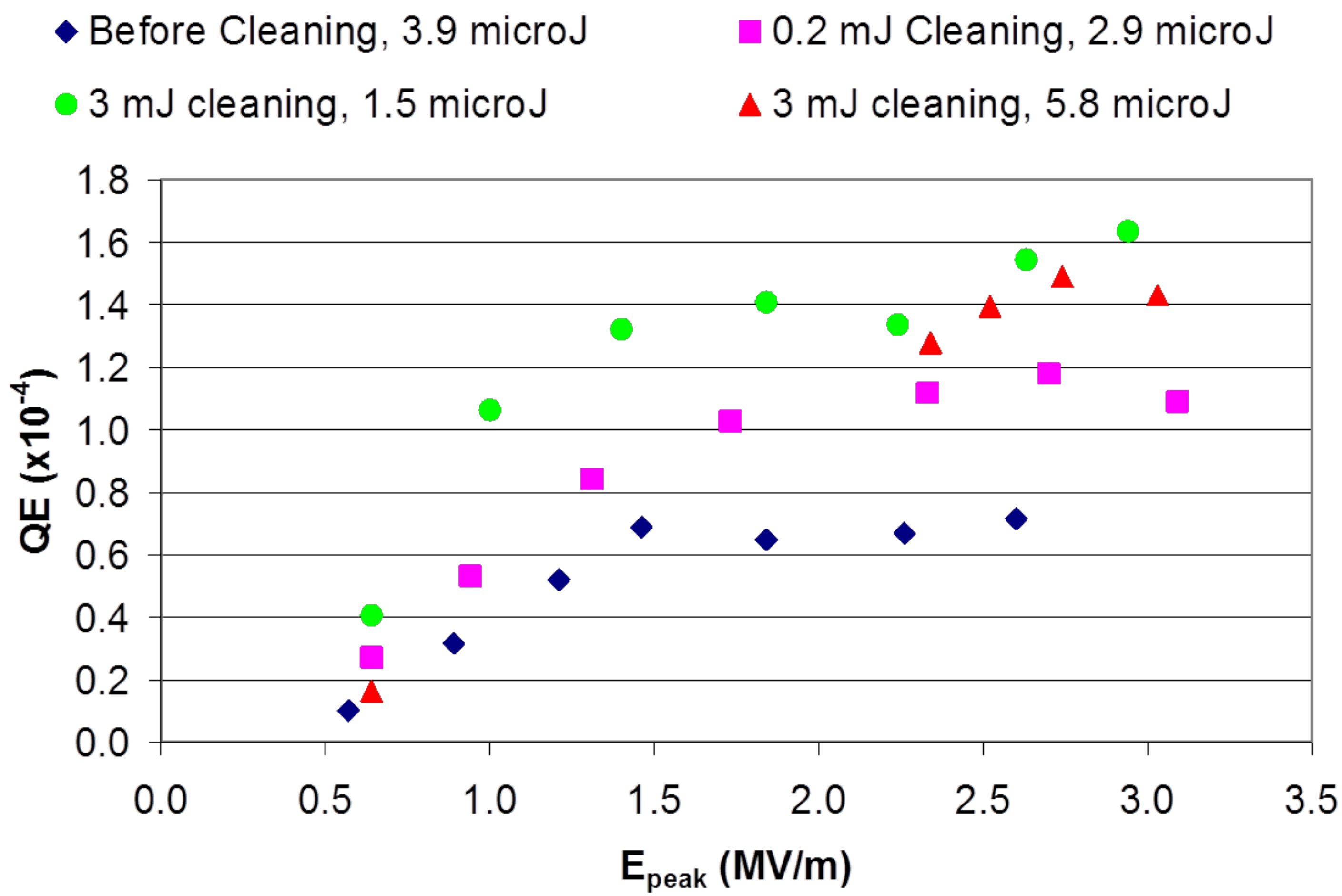
Many RF cycles illuminated – need to model electron escape from cavity as a function of launch phase

ASTRA simulation finds this factor to be 3.7 for DESY cavity and 3.9 for Plug cavity for fields >0.5 MV/m

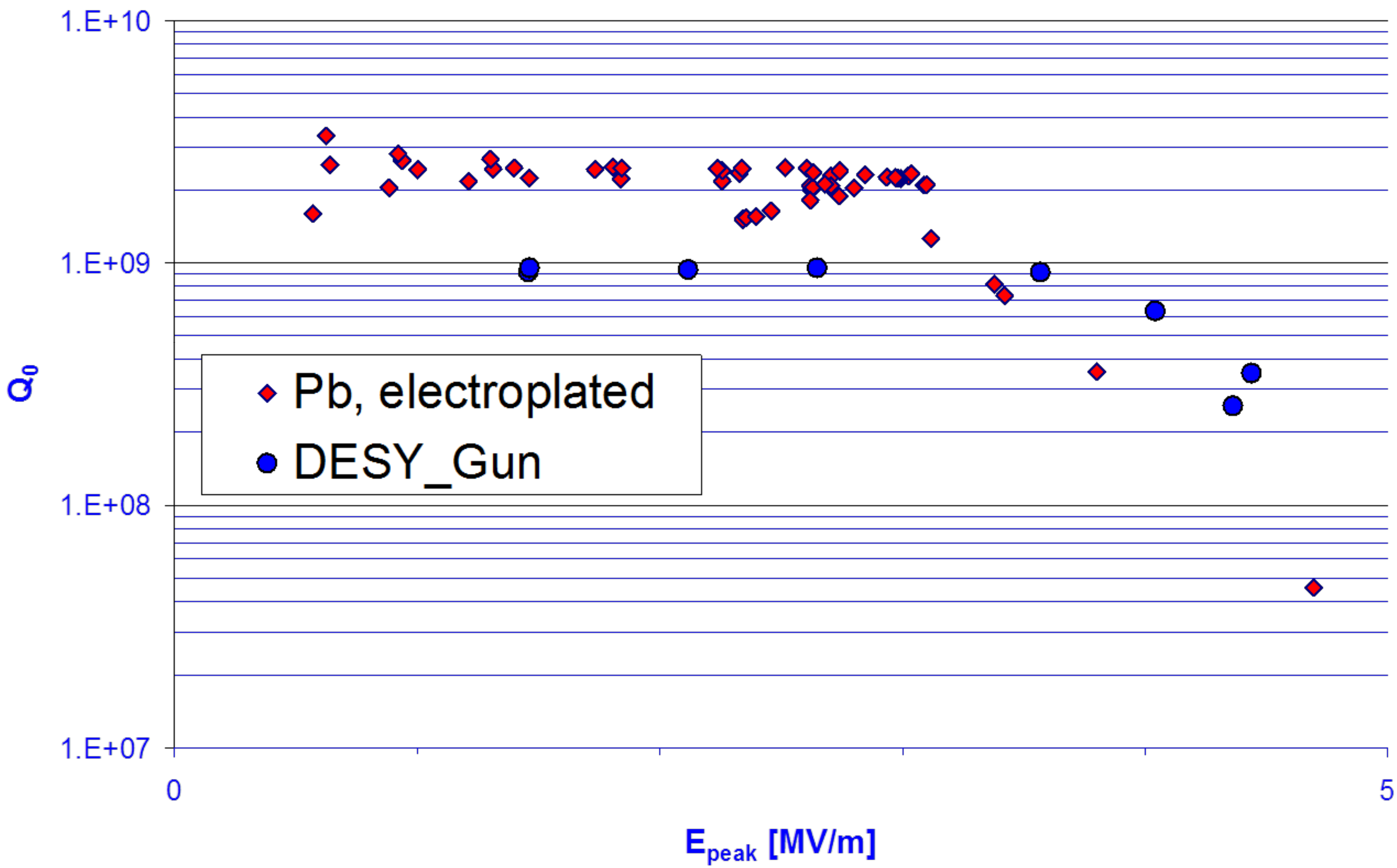
DESY Cavity, Arc-Dep Cathode

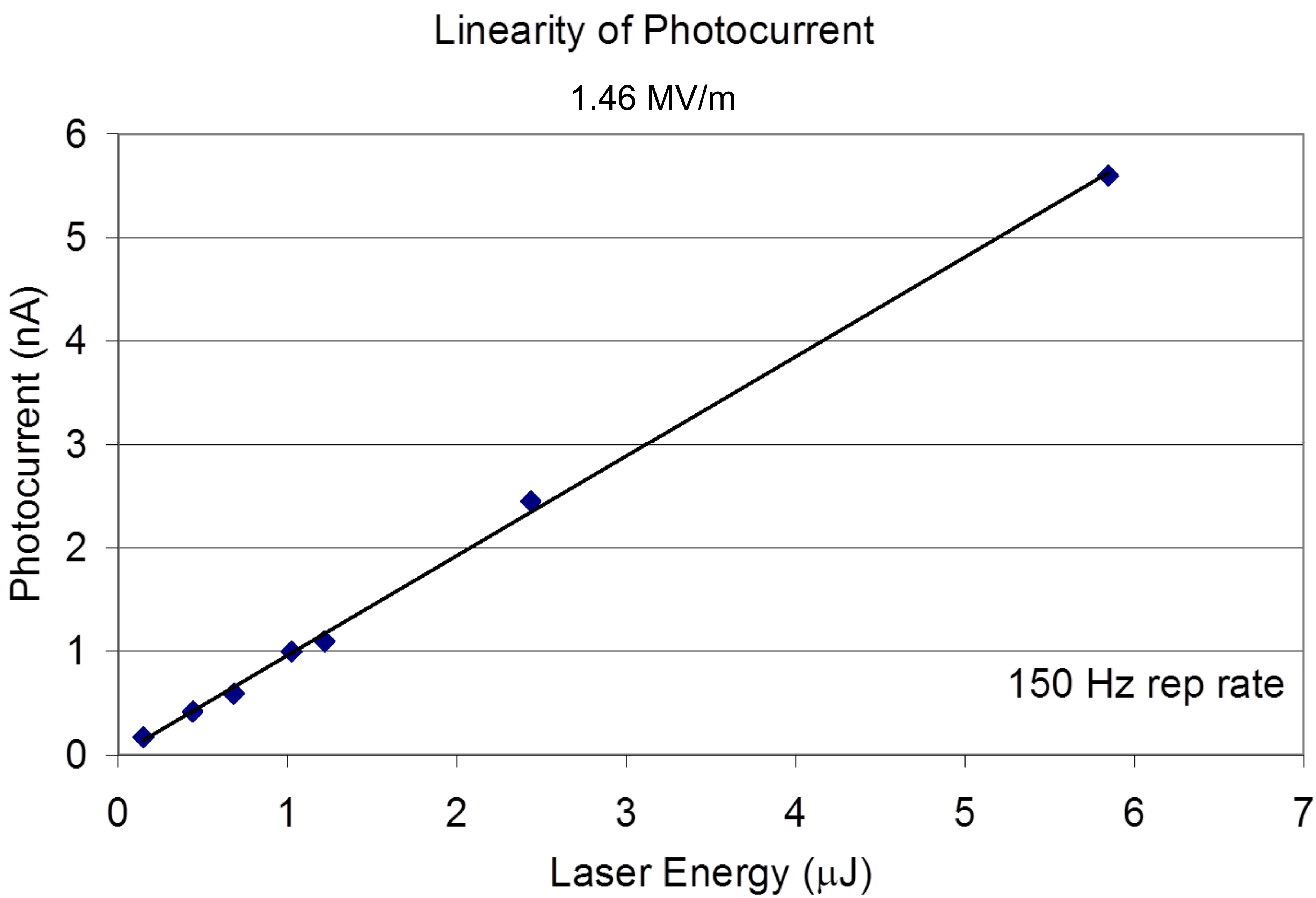


Jlab Plug Cavity QE

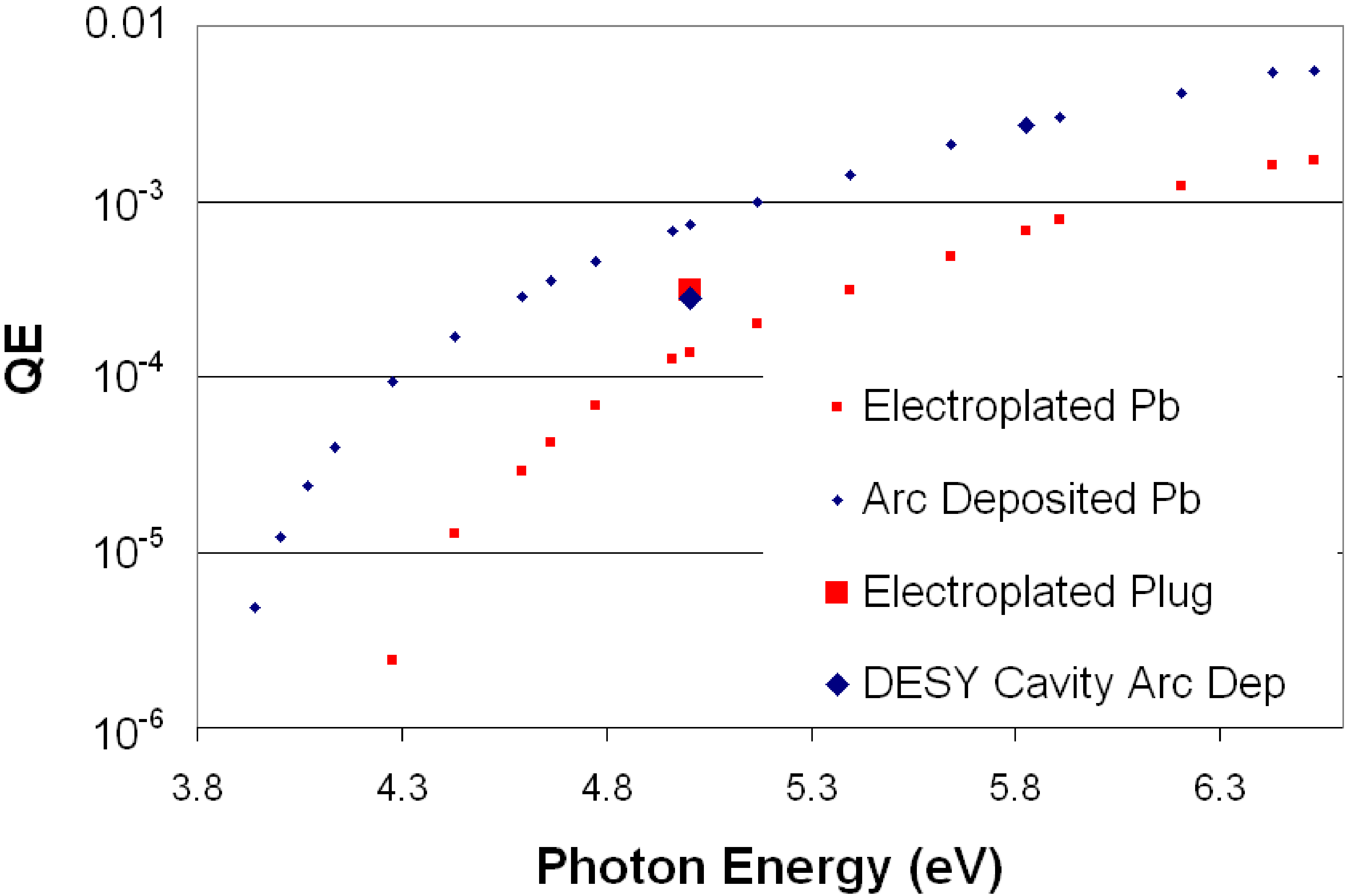


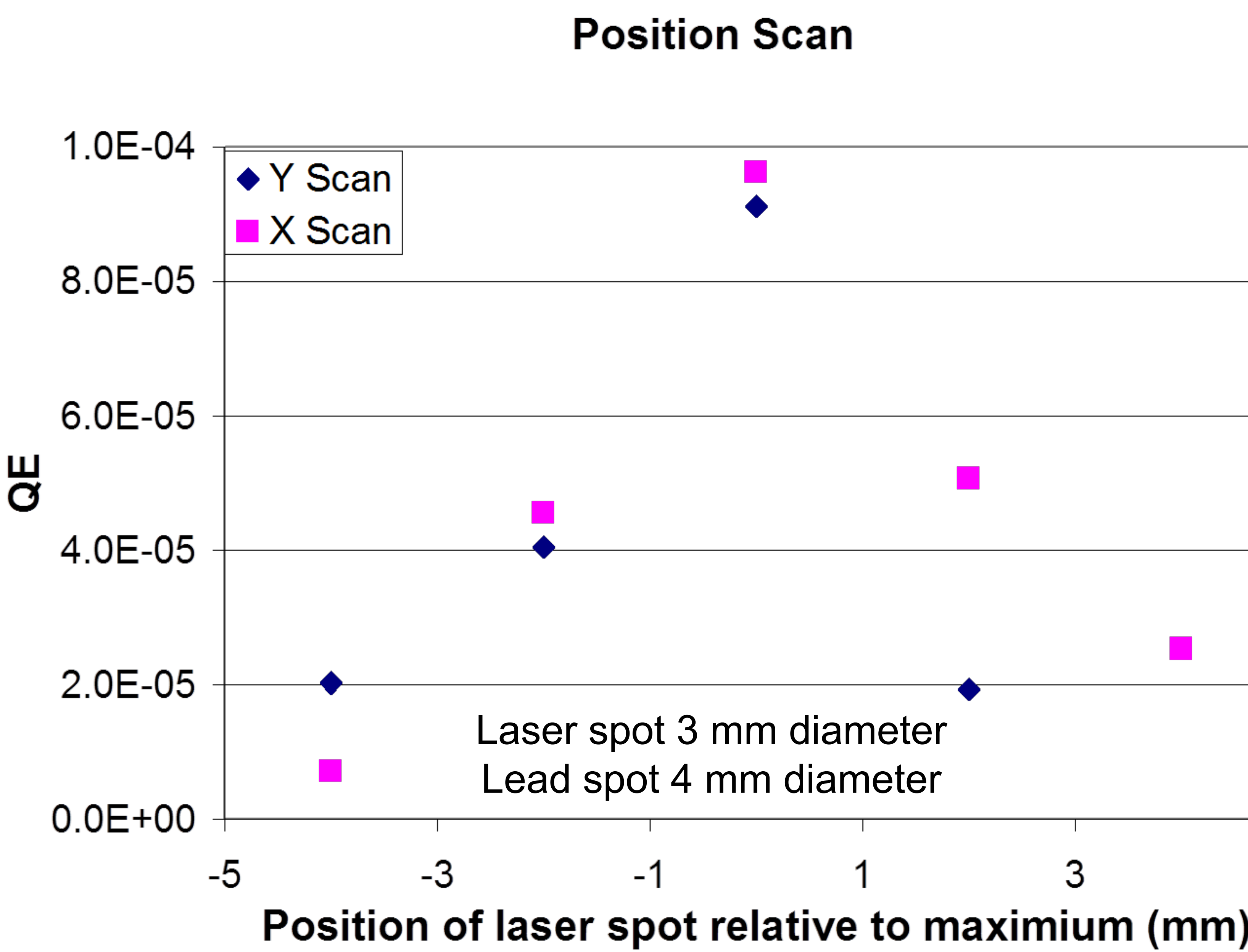
Exit-up cavity orientation




Linearity of Photocurrent
1.46 MV/m
Photocurrent (nA)
0
1
2
3
4
5
6
150 Hz rep rate
0
1
2
3
4
5
6
7
Laser Energy (μJ)

Comparison to Room Temp DC




Position Scan
Y Scan
X Scan
1.0E-04
8.0E-05
6.0E-05
4.0E-05
2.0E-05
0.0E+00
QE
Laser spot 3 mm diameter
Lead spot 4 mm diameter
-5
-3
-1
1
3
5
Position of laser spot relative to maximium (mm)

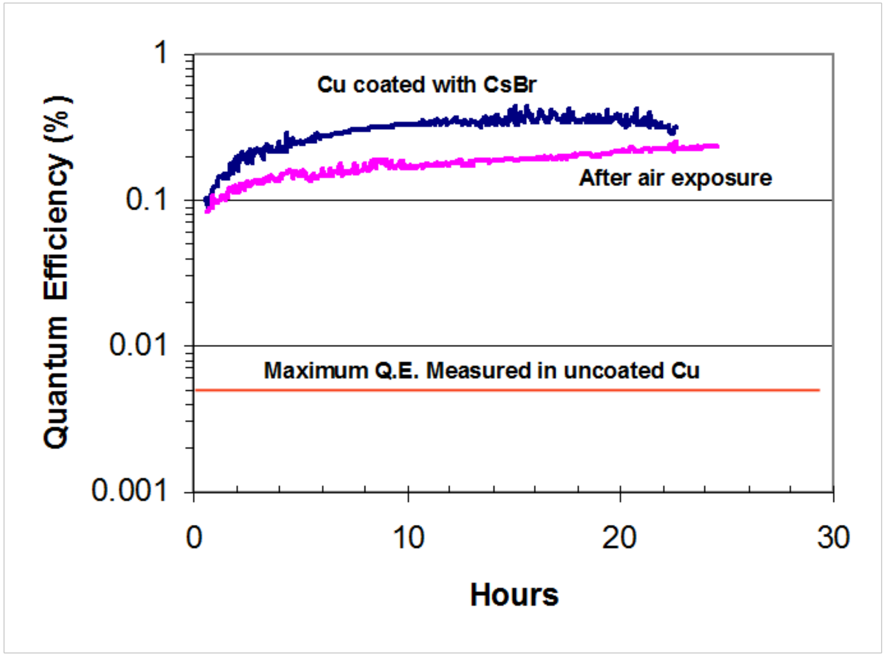
Electroplated Plug Quench Test

- Irradiate Nb wall with full laser energy
  - Nb, because this energy might evaporate Pb w/ field on
- 1 mJ (2.9x3 mm^2) & 2.9 mJ (4x5 mm^2) per pulse

  0.7 W on cathode
- Vary repetition rate, observe Q change
- Q drops ~20-30%, no evidence of quench
- No strong dependence on repetition rate
- Cooper pairs recovering between shots
- From theory, we expect this recovery time to be ~1 μs
- Good news for 1 MHz operation at ~3μJ/pulse

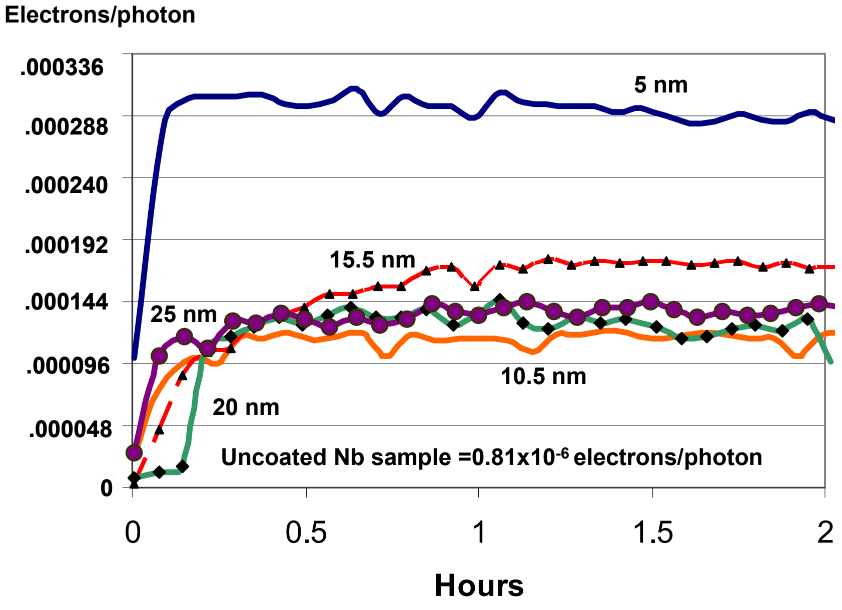
Coated Metal Cathodes

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.



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

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.

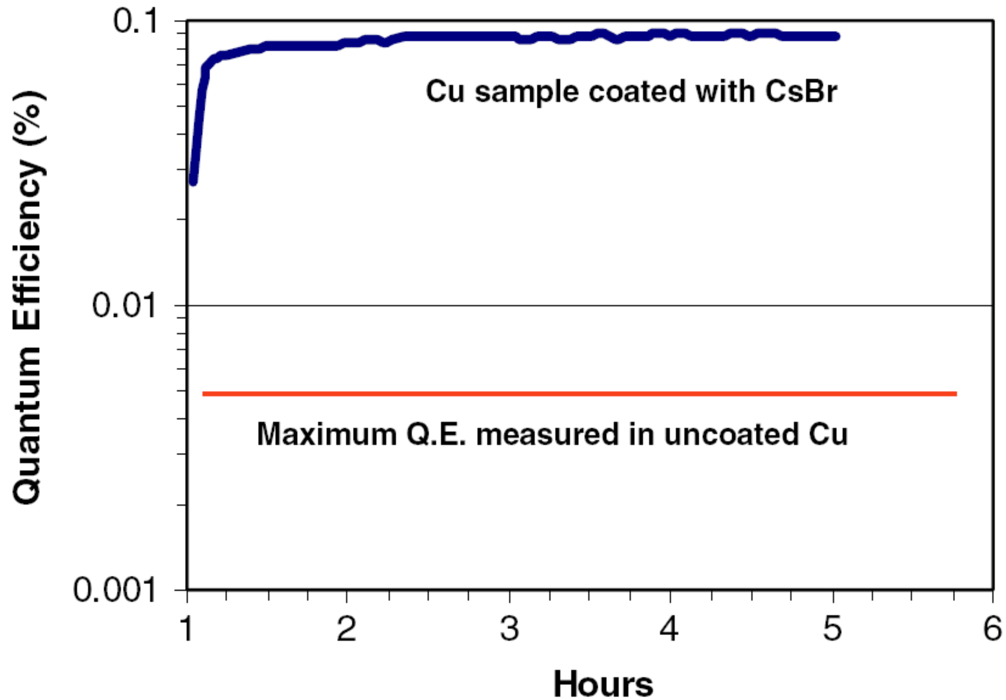


J. Maldonado et al., "Performance of a CsBr coated Nb photocathode at room temperature", JAP 107, 013106 (2010).

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS
11, 060702 (2008)

Robust CsBr/Cu photocathodes for the linac coherent light source

Juan R. Maldonado,[1] Zhi Liu,[2] D. H. Dowell,[2] Robert E. Kirby,[2] Yun Sun,[2]
Piero Pianetta,[2] and Fabian Pease[1]



- 20 nm coating of CsBr increases cathode QE by x50
- Brief atmospheric exposure OK!
- 4.8 eV photon – less than CsBr band gap of 7.3 eV
- Two excitation mechanisms –
  - Electron injection from Cu into CsBr conduction band
  - Exciation of intraband states

Semiconductor Photocathodes

The primary path to high average current in photoinjectors

The good points:

- QE can be >10%
- Many use visible light
- Polarized cathodes possible

However:

- Require UHV (<0.1 nTorr)
- Limited Lifetime
- Response time
- Complicated

Common types:

Cs_2Te – QE ~7% @ 262 nm, Lifetime 100's of hrs

K_2CsSb – QE >4% @ 532 nm, Lifetime <10 hrs

Cs:GaAs – QE ~0.5% @ 800 nm (polarized), 6% @ 527 nm

W.E. Spicer & A. Herrera-Gomez, Modern Theory and Applications of Photocathodes, SLAC-PUB-6306 (1993)

K_2CsSb (Alkali Antimonides)

Work function 1.9eV, E_g= 1.2 eV

Very high QE for visible light (4% -12% @ 532 nm, >30% @ 355nm)

- Band Gap eliminates e-e scattering for hv<$2E_g$
- Narrow antimony valence band limits unproductive absorption

Deposited in 10^{-11} Torr vacuum

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

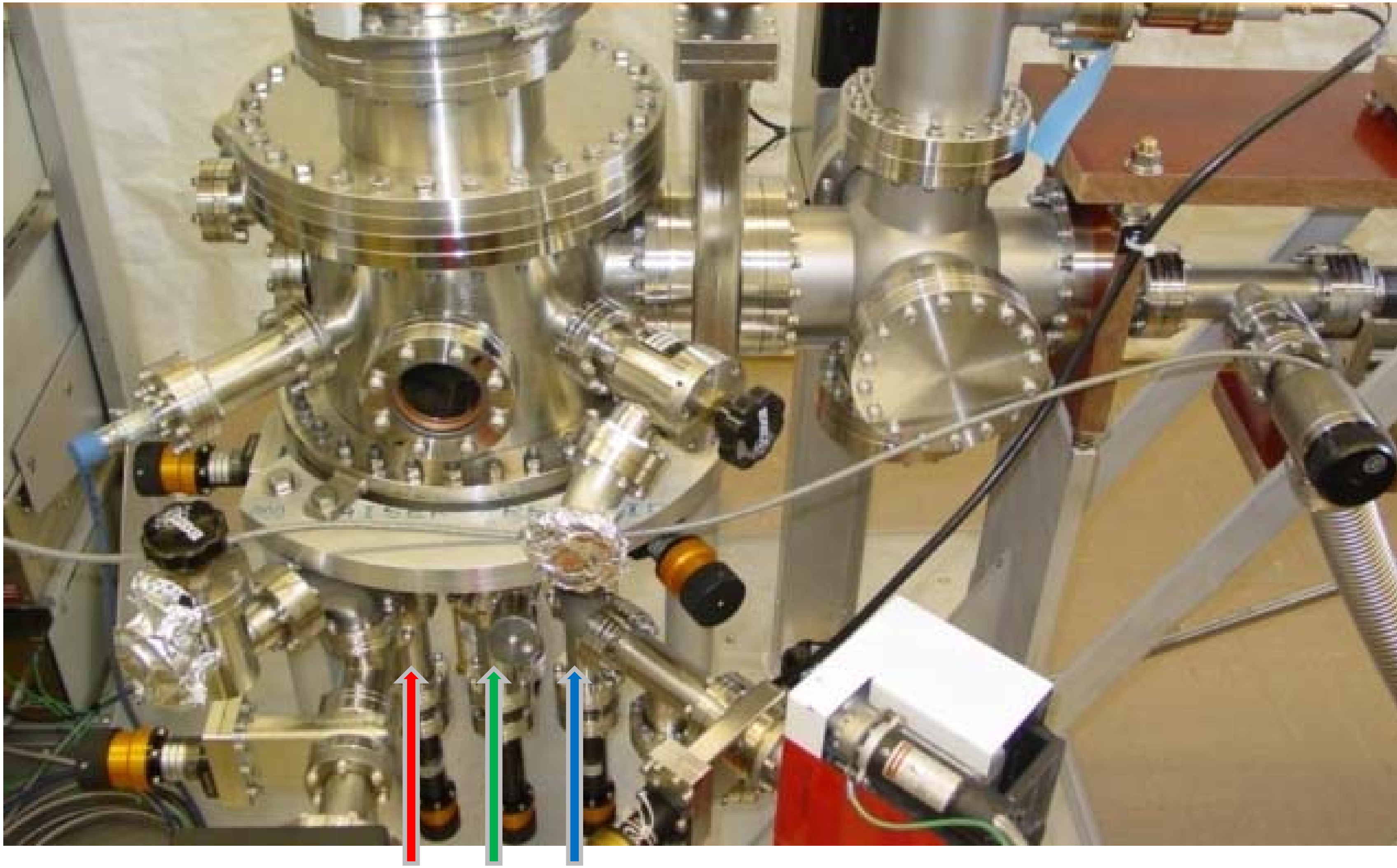
Cathodes stable in deposition systems (after initial cooldown)

Typical lifetime in an RF injector is measured in hours

- Chemical poisoning is major cause of QE loss
- Improved vacuum should help (DC/Superconducting injectors)

D. H. Dowell *et al*., *Appl. Phys. Lett.*, **63**, 2035 (1993)
C. Ghosh and B.P. Varma, *J. Appl. Phys.*, **49**, 4549 (1978)

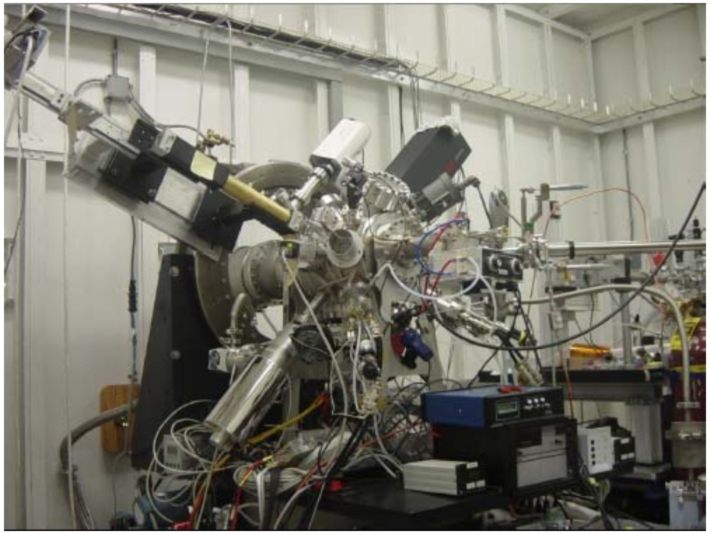
Deposition System

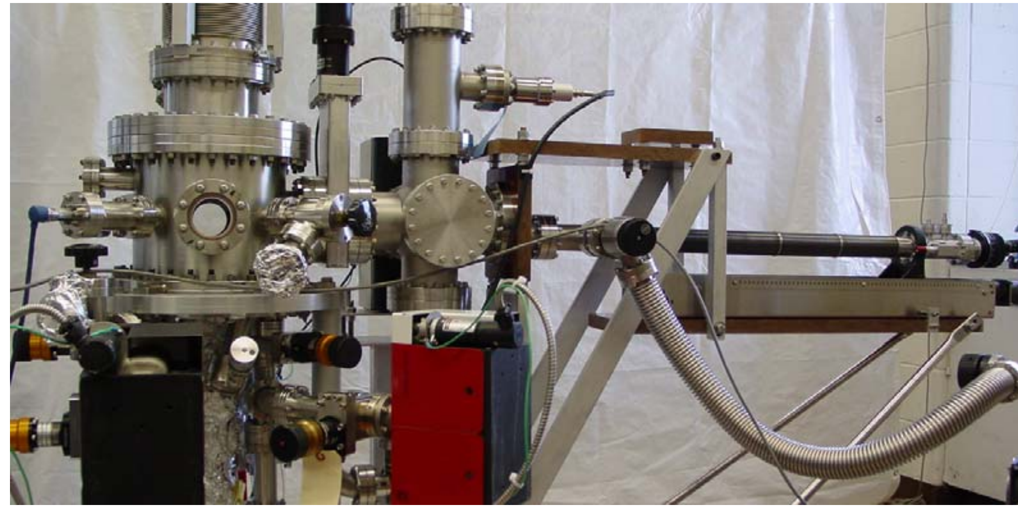


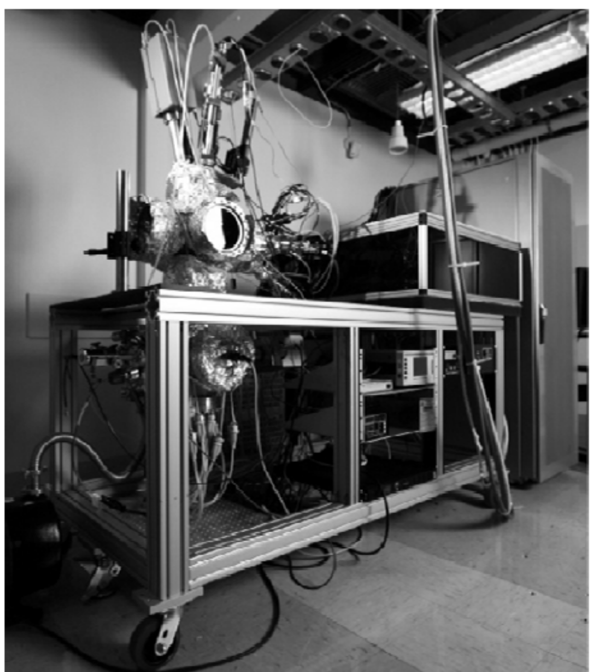
Sb K Cs

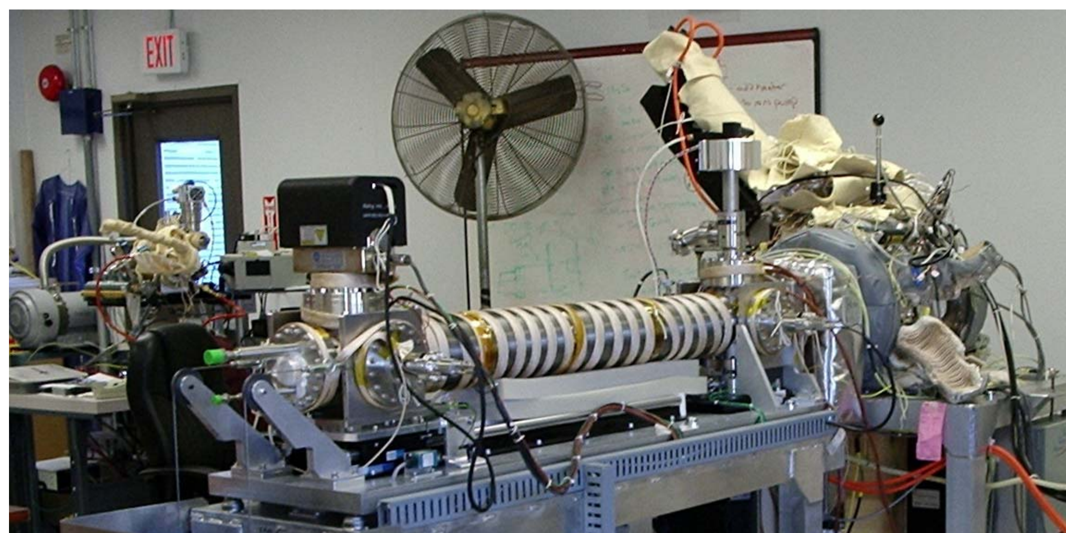
Sequential deposition with retractable sources (prevents cross-contamination)
Cathode mounted on rotatable linear-motion arm
Typical vacuum 0.02 nTorr (0.1 nTorr during Sb deposition)

Alkali Antominide Growth









Basic Recipe for Photocathode Production

1.) Optically polished Mo substrate heat cleansed at 600° C for 30 min

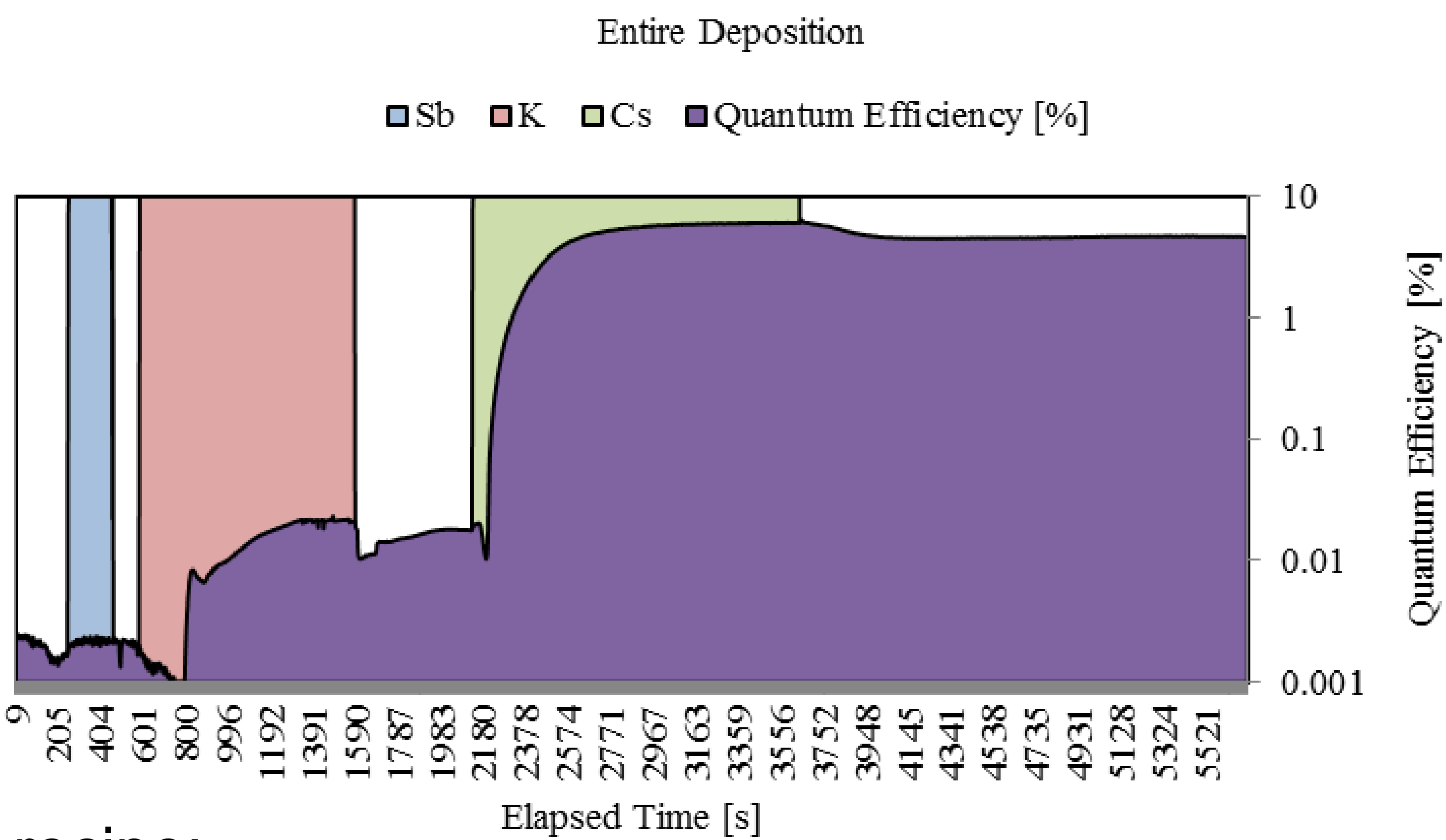
2.) 50 Å Sb evaporated from effusion cell while substrate is at 160° C

3.) K and Cs evaporated sequentially from de-alloying sources (Bi-Cs and Bi-K) while substrate is at temperatures lower then 160° C. Evaporation continues as needed until maximum QE is achieved in each case.

Different recipes (temps, order) are observed produce similar results

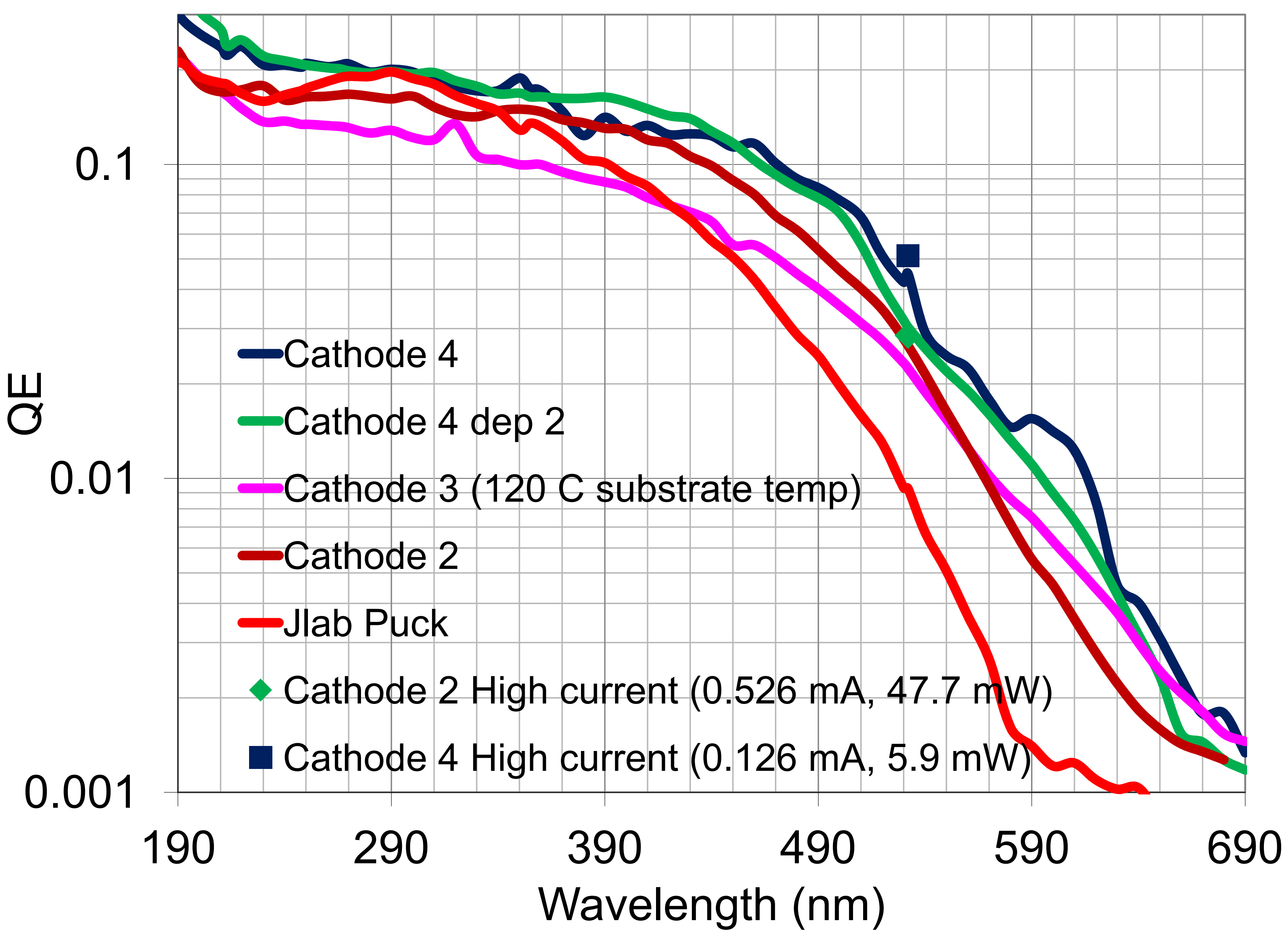
Substrate

Cathode



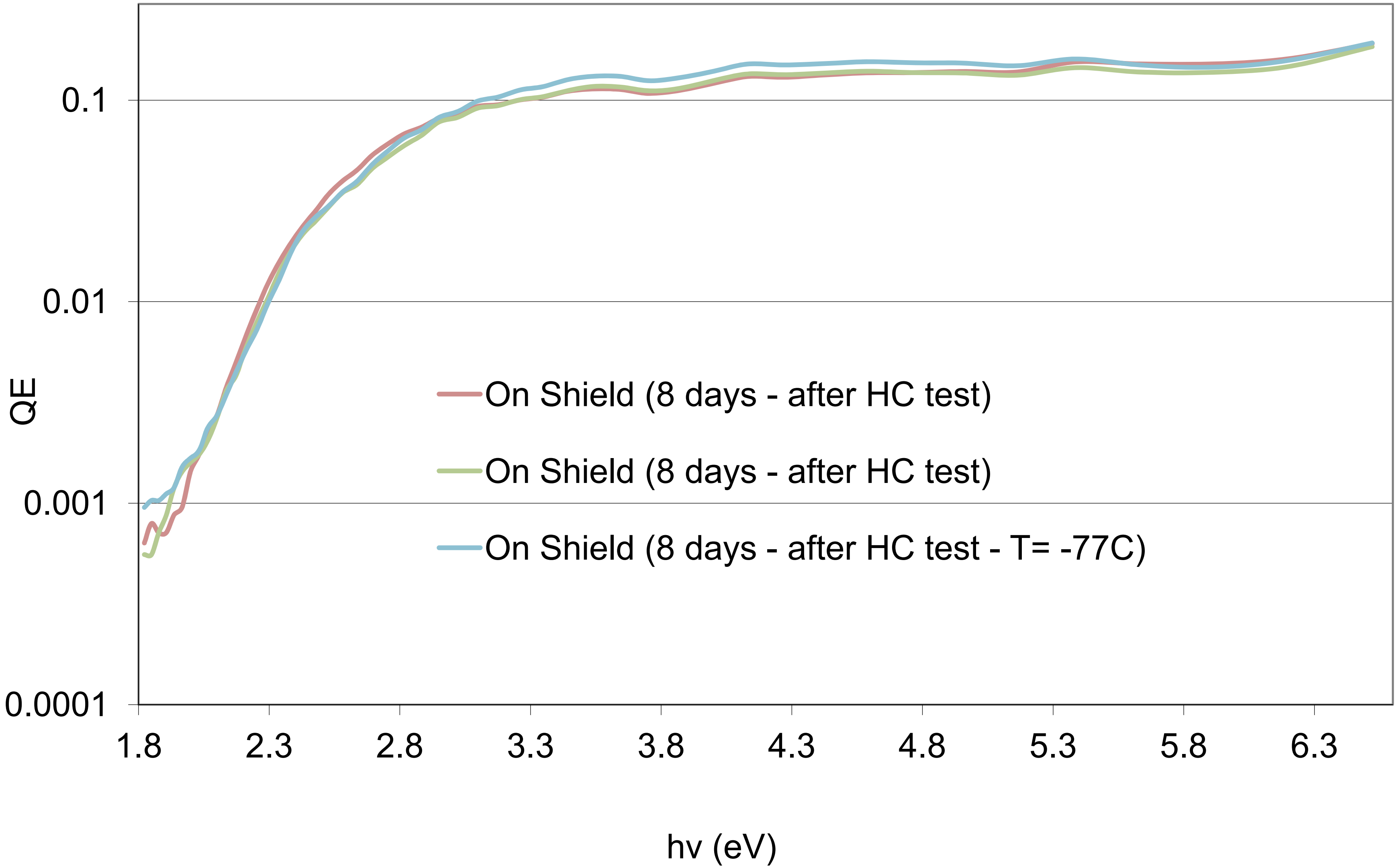
Typical recipe:

- Molybdenum or Stainless Steel Substrate
- Evaporate 200 Å layer of Sb with substrate 150-190 C
- Evaporate K at 140 C
- Evaporate Cs at 120-135 C, while monitoring QE at 532 nm
- Cathode QE at 532 nm is 6%, but falls to 4.5% during cool
- Total time is ~1hr

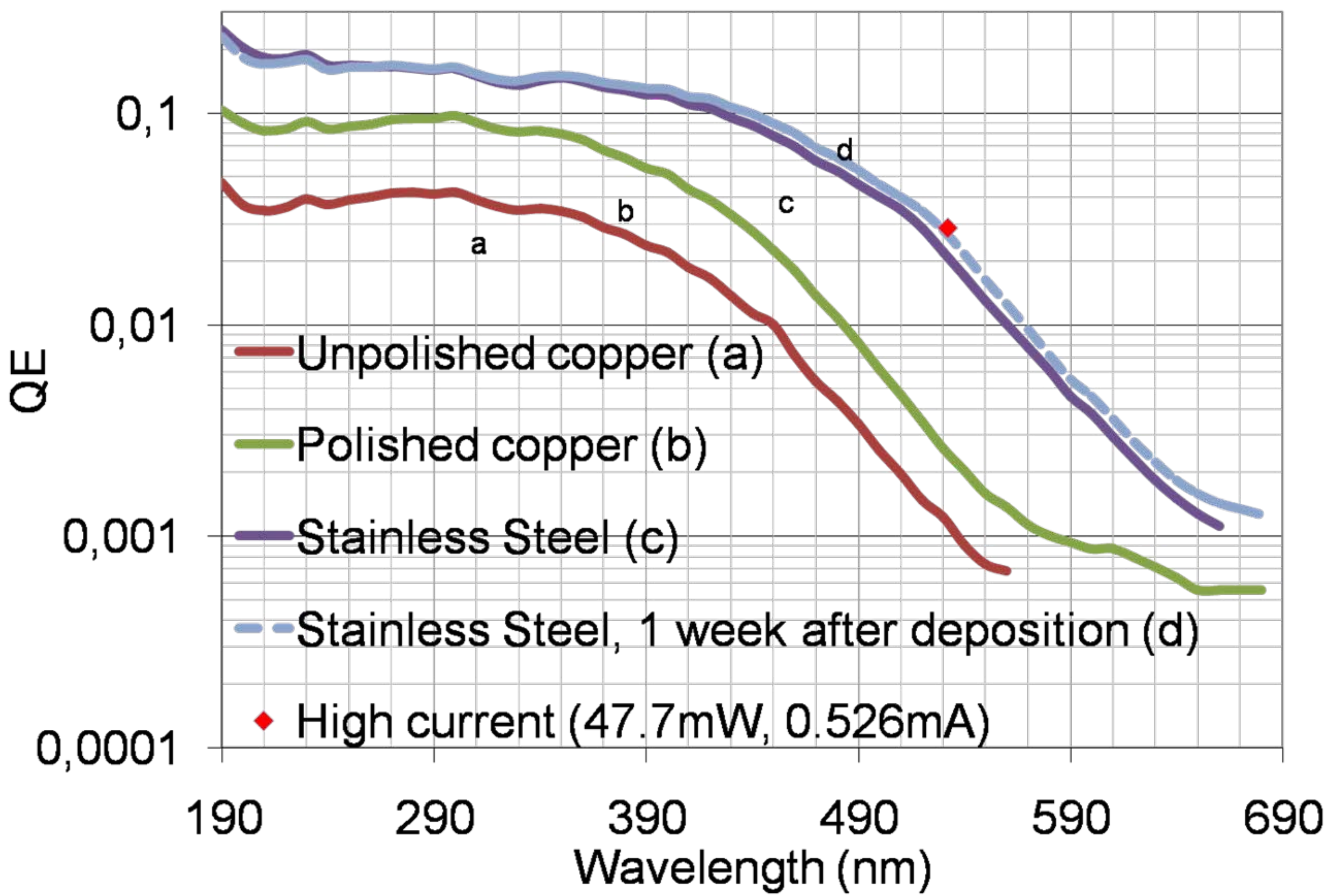


QE
0.1
0.01
0.001
190
290
390
490
590
690
Wavelength (nm)
Cathode 4
Cathode 4 dep 2
Cathode 3 (120 C substrate temp)
Cathode 2
Jlab Puck
Cathode 2 High current (0.526 mA, 47.7 mW)
Cathode 4 High current (0.126 mA, 5.9 mW)

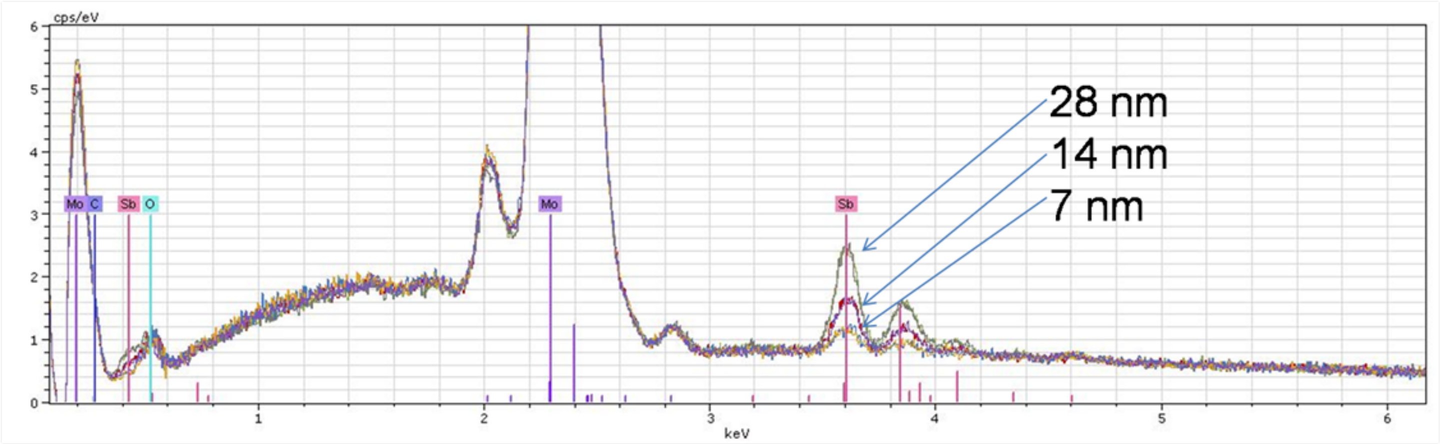
Temperature Dependence



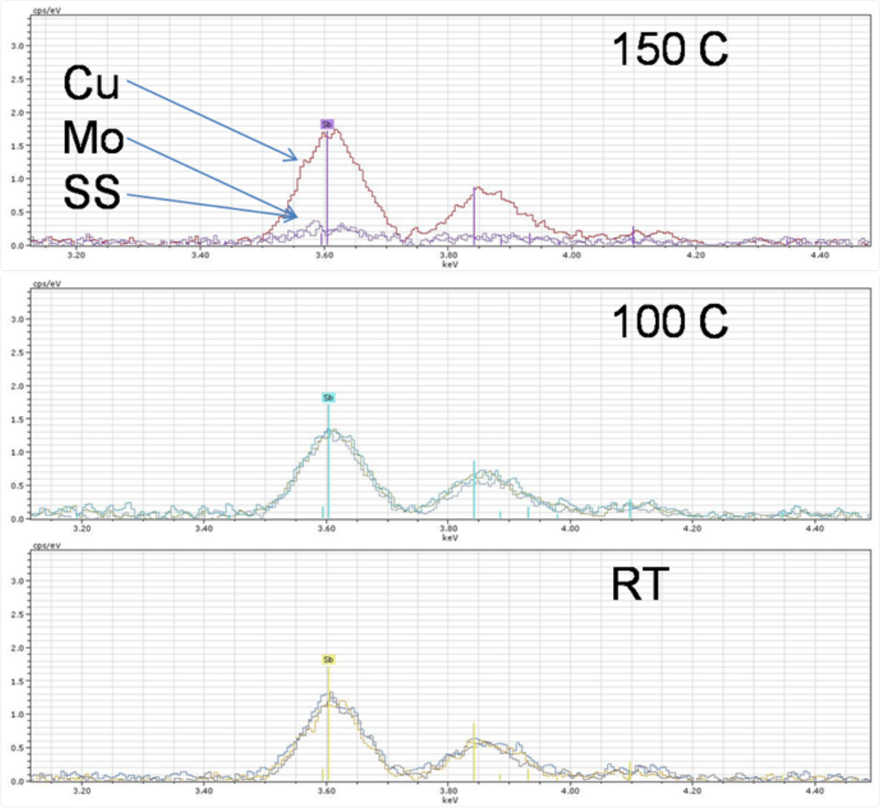
Substrate Dependence



X-ray Fluorescence on Sb films

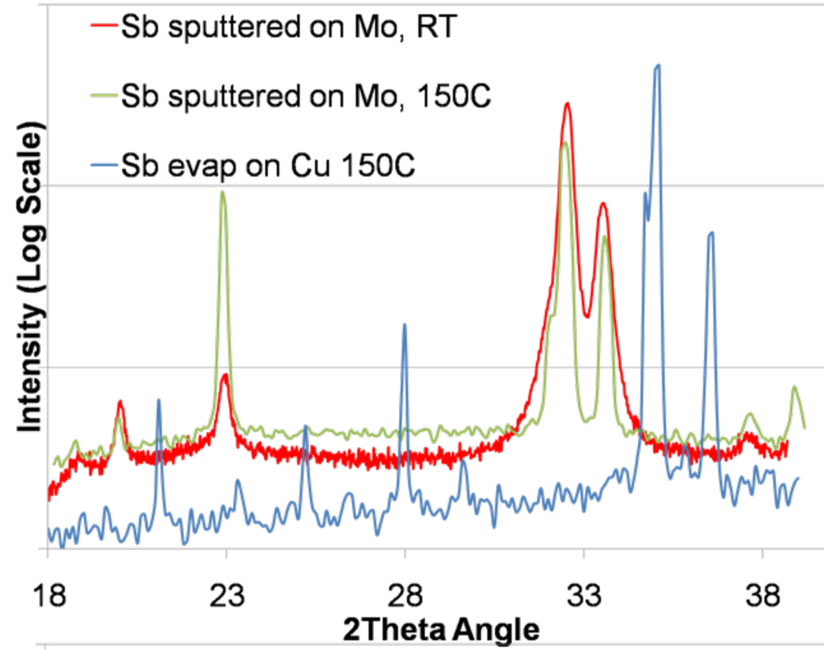


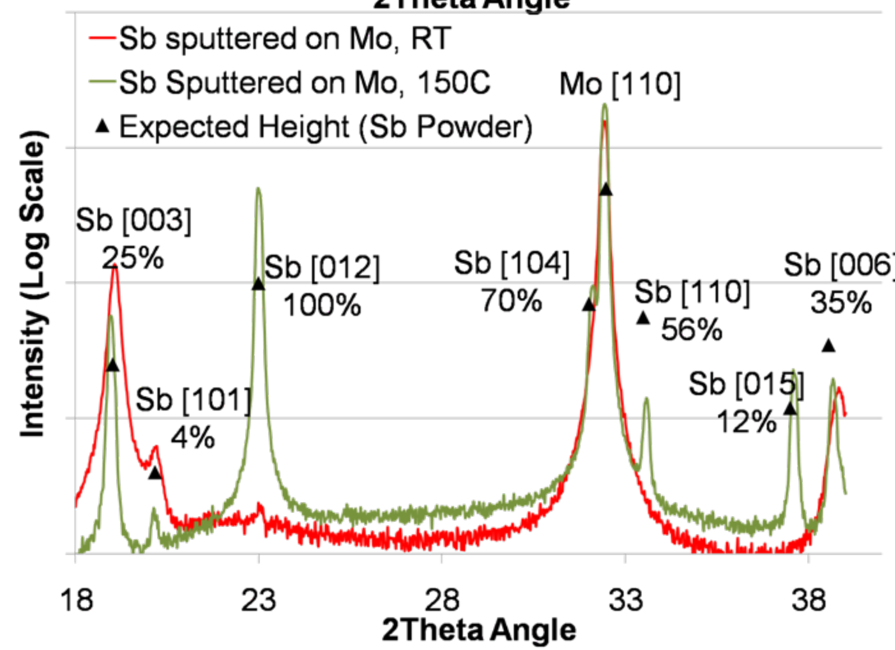
- Use EDX spectroscopy in SEM
  - Measure Sb thickness
  - Spatial uniformity
- For room temperature evaporation, Sb sticks to all 3
- At 150 C, Sb film on Mo and SS very non-uniform, and not as thick as the FTM would suggest



X-ray Diffraction – Sb on Mo and Cu

- Sb on Mo at 150 C shows powder texture
- At RT, there is a pronounced [003] surface normal
- For Copper substrate at 150 C – no Sb or Cu peaks -> forming an alloy!
- Perhaps this is why the QE is always low on Copper substrates…





K_2CsSb: A cathode with excellent characteristics for accelerator applications

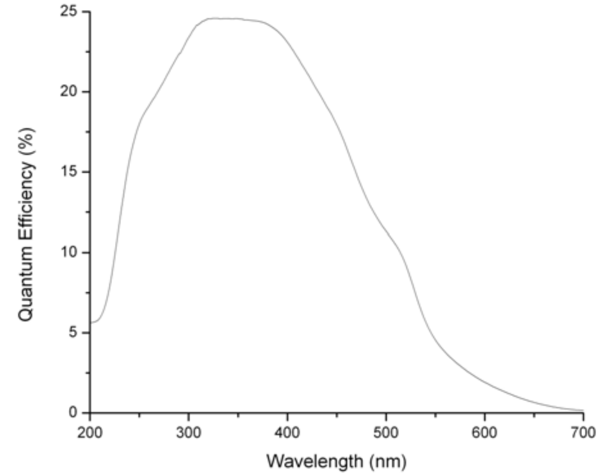
APPLIED PHYSICS LETTERS **99**, 034103 (2011)

A low emittance and high efficiency visible light photocathode for high brightness accelerator-based X-ray light sources

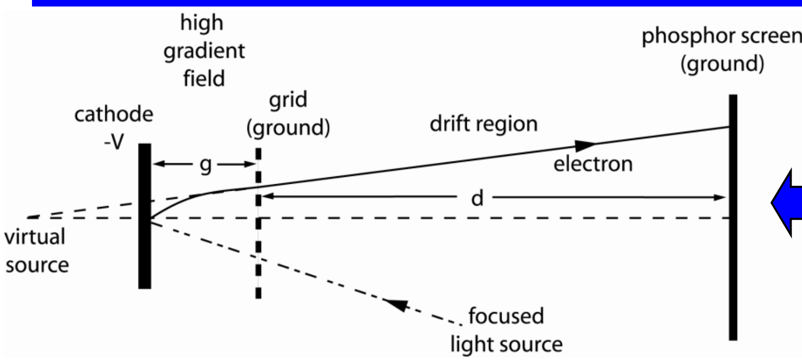
T. Vecchione,[1] I. Ben-Zvi,[2,3] D. H. Dowell,[1,4] J. Feng,[1] T. Rao,[2] J. Smedley,[2] W. Wan,[1] and H. A. Padmore[1,a)]
[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[2]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[3]*Stony Brook University, Stony Brook, New York 11794, USA*
[4]*SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*

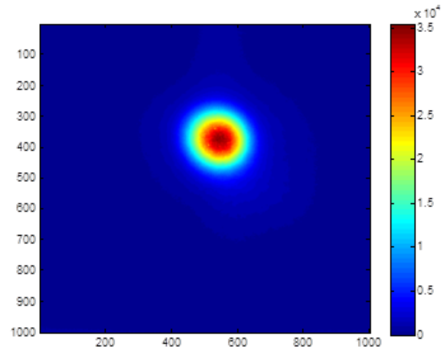
(Received 19 May 2011; accepted 27 June 2011; published online 21 July 2011)

Free-electron lasers and energy recovery linacs represent a new generation of ultra-high brightness electron accelerator based x-ray sources. Photocathodes are a critical performance-limiting component of these systems. Here, we describe the development of photocathodes based on potassium-cesium-antimonide that satisfy many of the key requirements of future light sources, such as robustness, high quantum efficiency when excited with visible light, and low transverse emittance. © *2011 American Institute of Physics*. [doi:10.1063/1.3612916]



Fast (msec), high field (4 MV/m; can be > 10 MV/m) measurement of transverse momentum

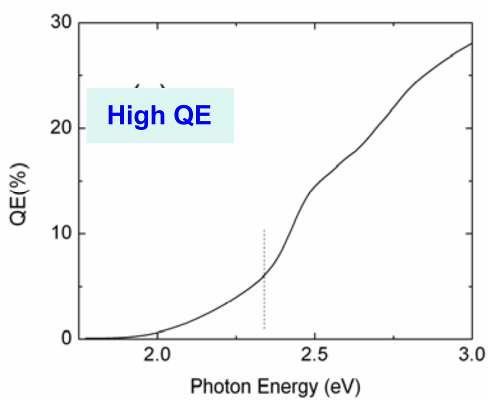


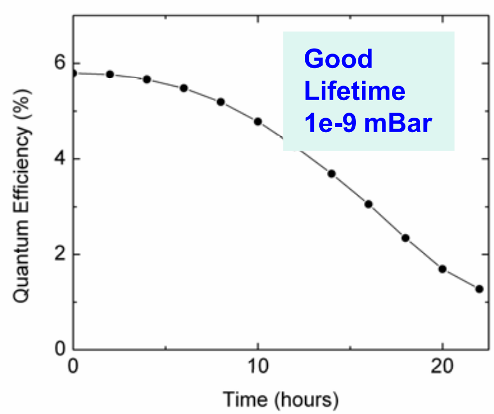


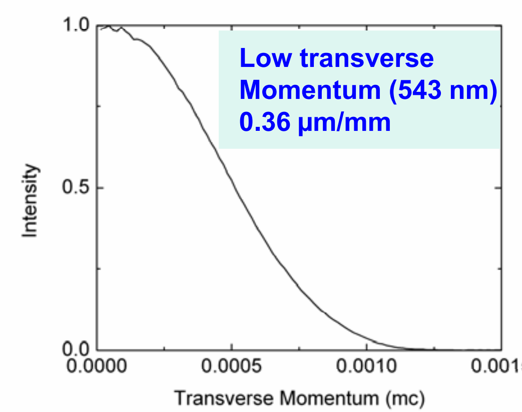
$$r = \sqrt{\frac{mc^2}{2eV}}(2g+d)\left[\frac{p_x}{mc}\right]$$

r = radial coord on detector
g – cathode to grid distance
d = drift distance

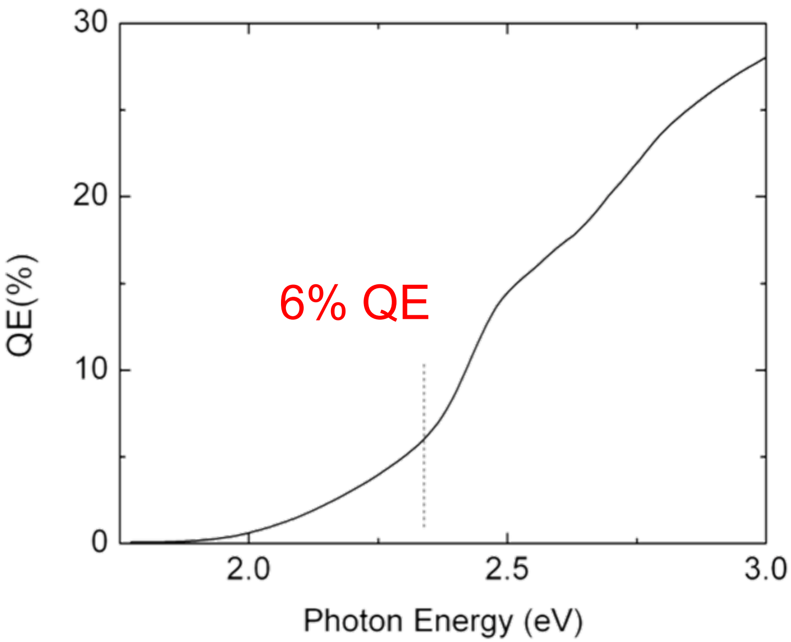
Instrumental resolution less than for kT

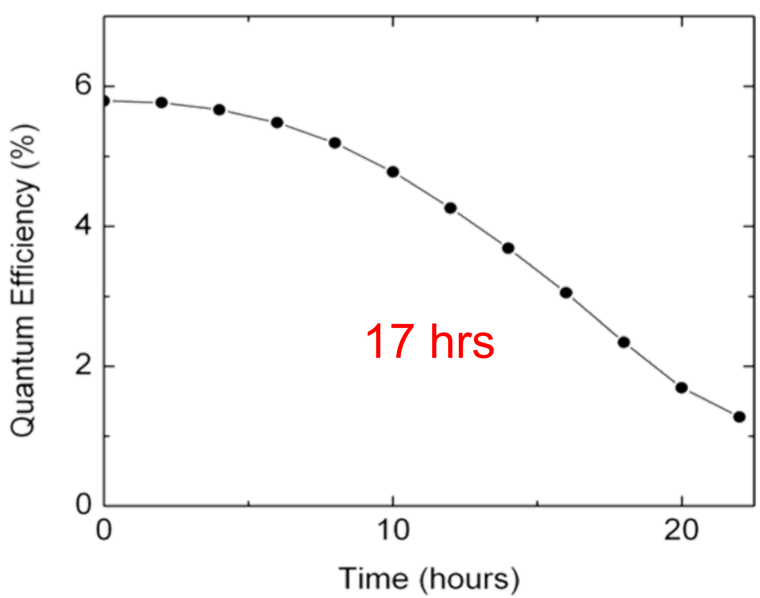






Performance and Robustness of K_2CsSb at 532 nm





Performance:
When illuminated with a 100 μm focused laser, a current density of 100 mA/cm^2 was maintained over several days

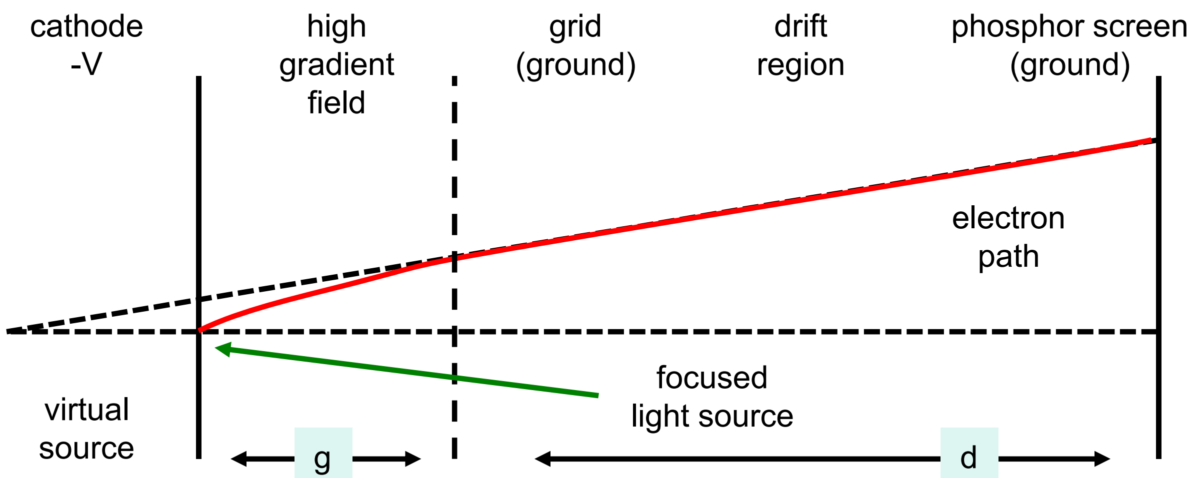
Damage to cathode has been observed from UV radiation however none seen so far at 532

Robustness:
QE vs time at 5e-9 torr pp H20
- 50% decay time of around 17 h
- Stable to relatively high partial pressures of water
- pp in DC, RF and SRF photo-guns is better than this

Known to be stable over months when stored in UHV. However, robustness may be dependent on the details of the deposition

Setup for Measurement of Transverse Momentum

Electrons accelerated in a high gradient field, 0.4 - 3 MV/m
Anode is a mesh grid, 25 µm mesh pitch
Laser focused onto cathode at 30° through grid, 543 nm typical
Laser spot size is ~ 200 µm FWHM
Imaging done on a phosphor screen
Imaged by a lens coupled CCD camera using msec exposure times
Instrumental resolution is less than kT
System tested and calibrated on metals, Sb and Mo

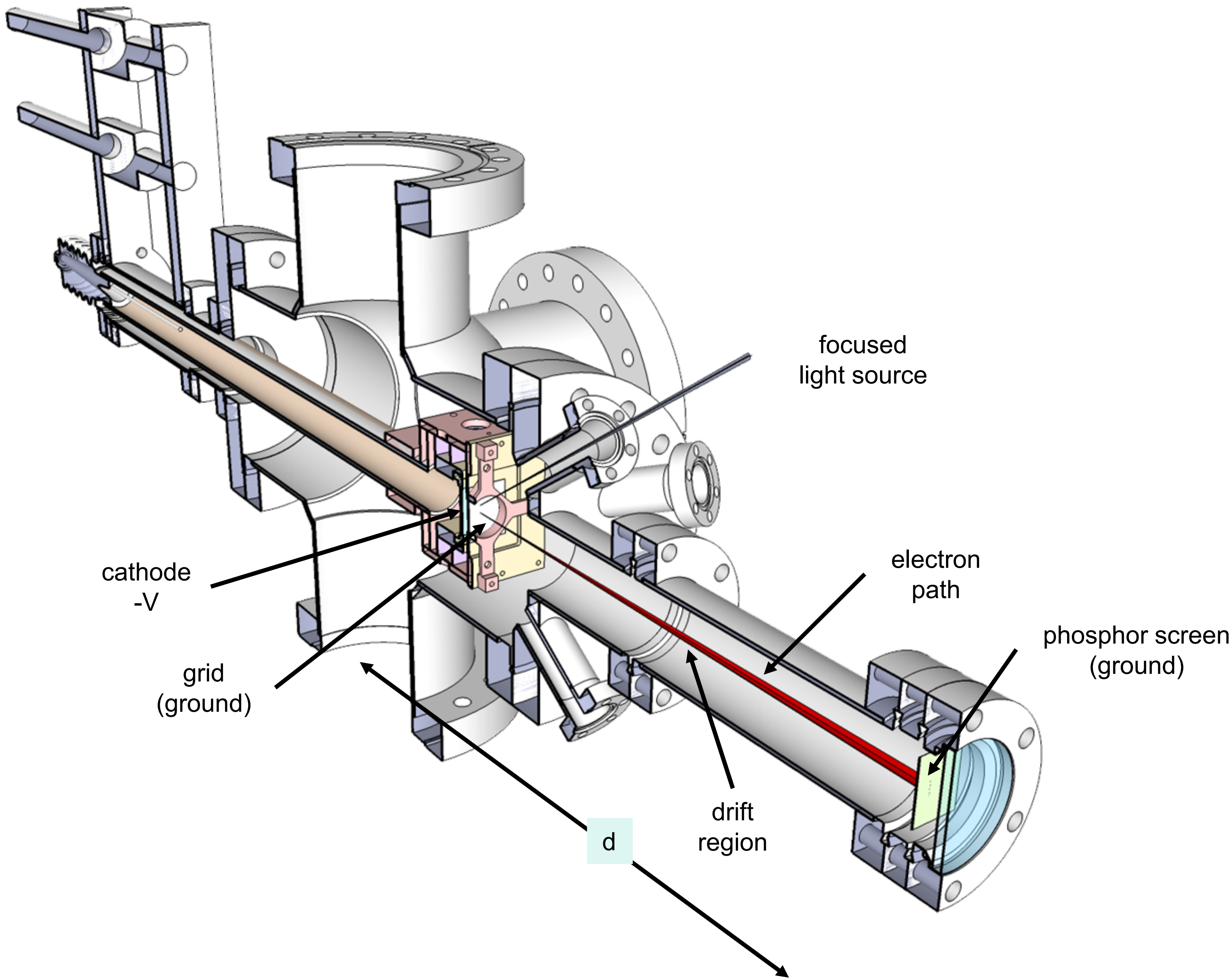


$$r = \sqrt{\frac{mc^2}{2eV}}\,(2g+d)\left(\frac{p_x}{mc}\right)$$

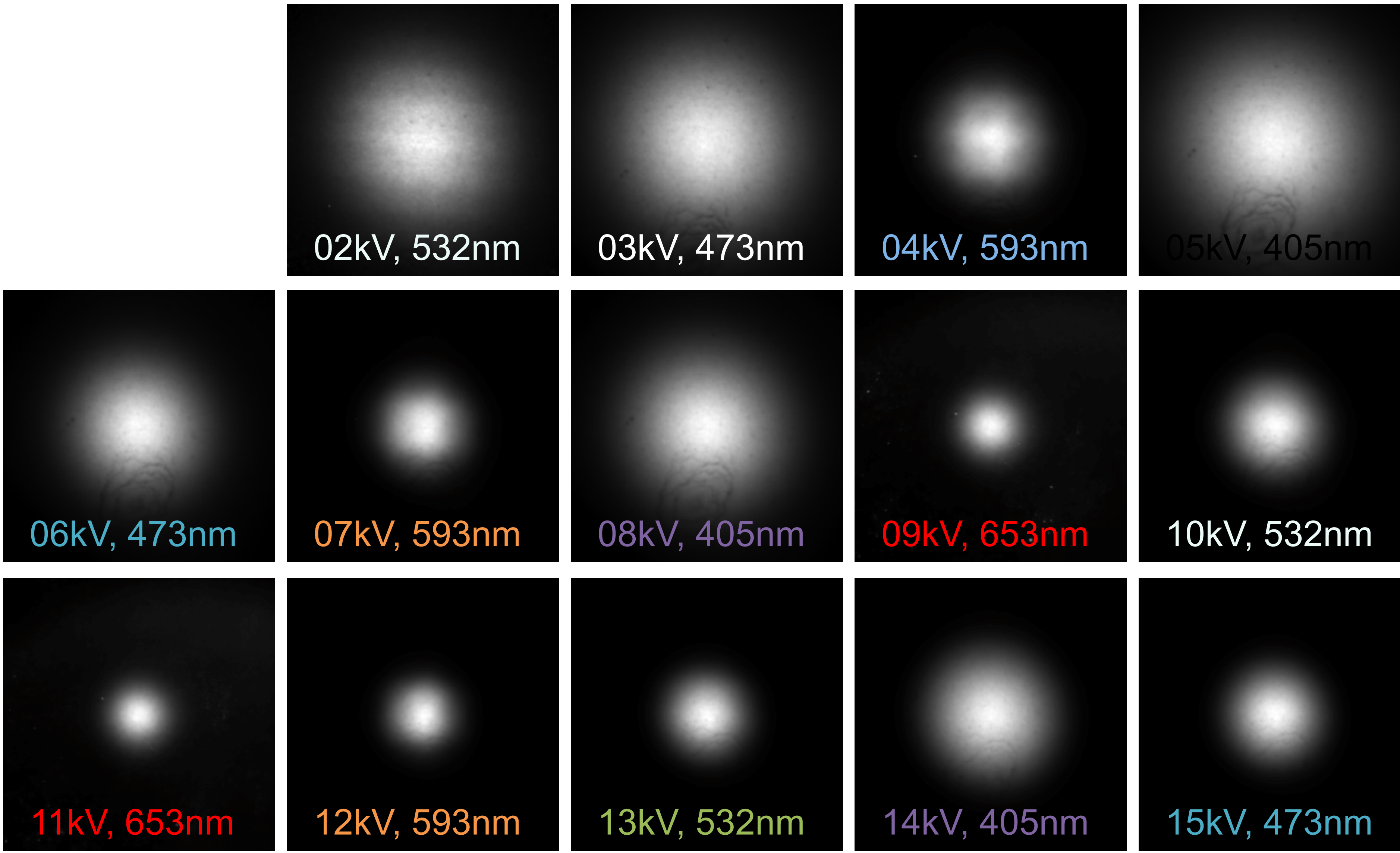
$$\frac{\varepsilon}{\sigma_x} = \frac{\langle p_x^2 \rangle^{1/2}}{mc}$$

r = radial coordinate on detector
g = cathode to grid (anode) gap, 5 mm
d = drift distance, 252 mm
V = applied voltage, varied from 2 kV - 15 kV

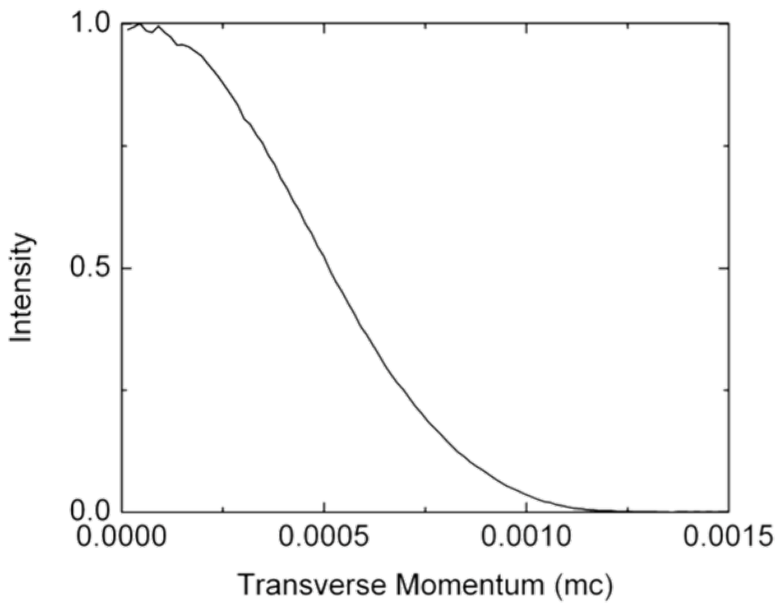
Diagram of the "Momentatron"

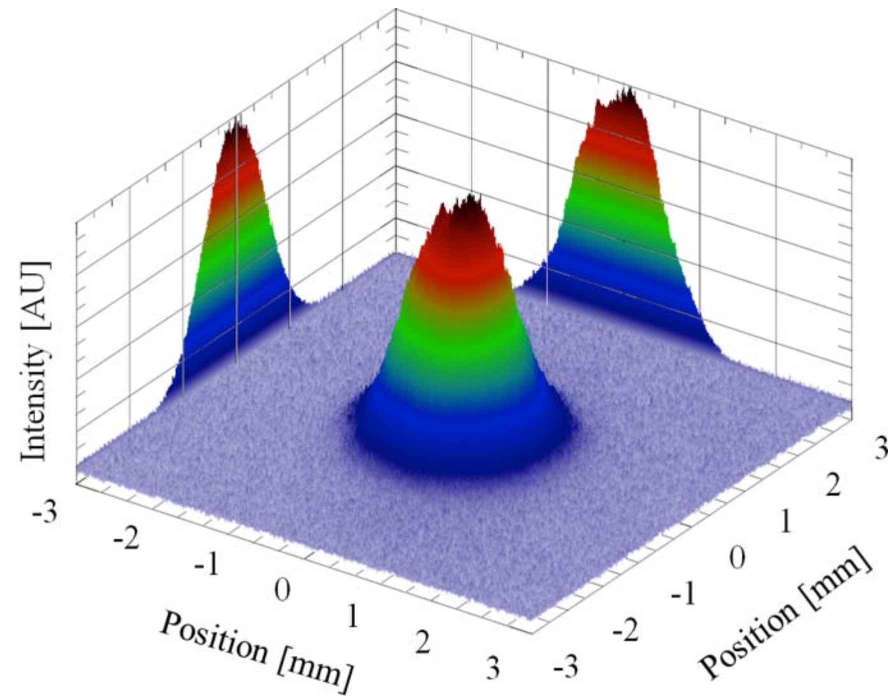


Various Transverse Momentum Measurements on K_2CsSb



Transverse Momentum Measurement on K_2CsSb at 543 nm

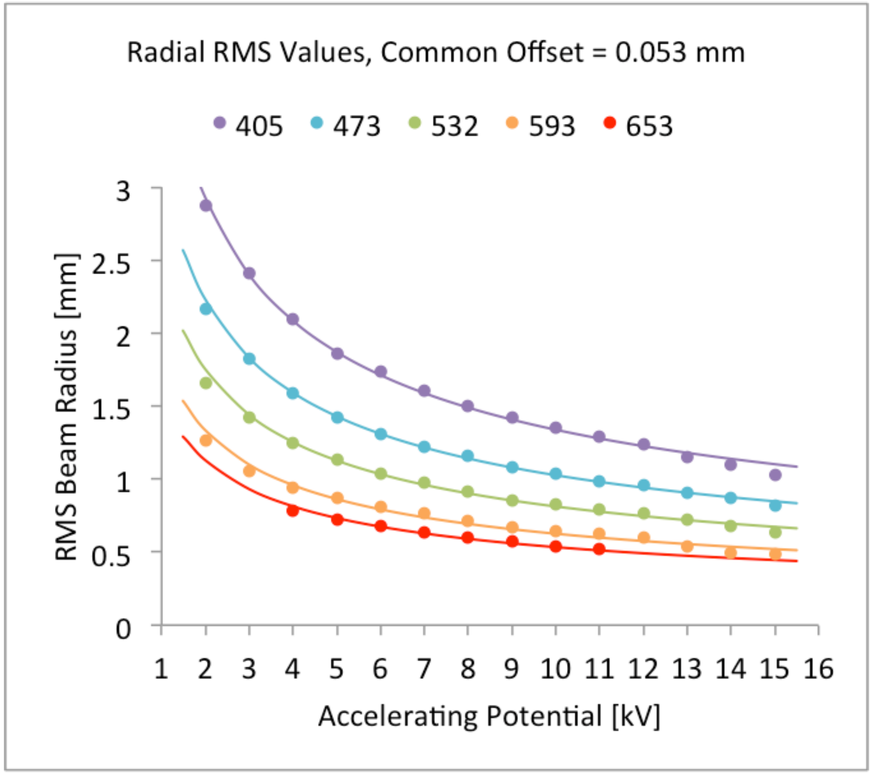




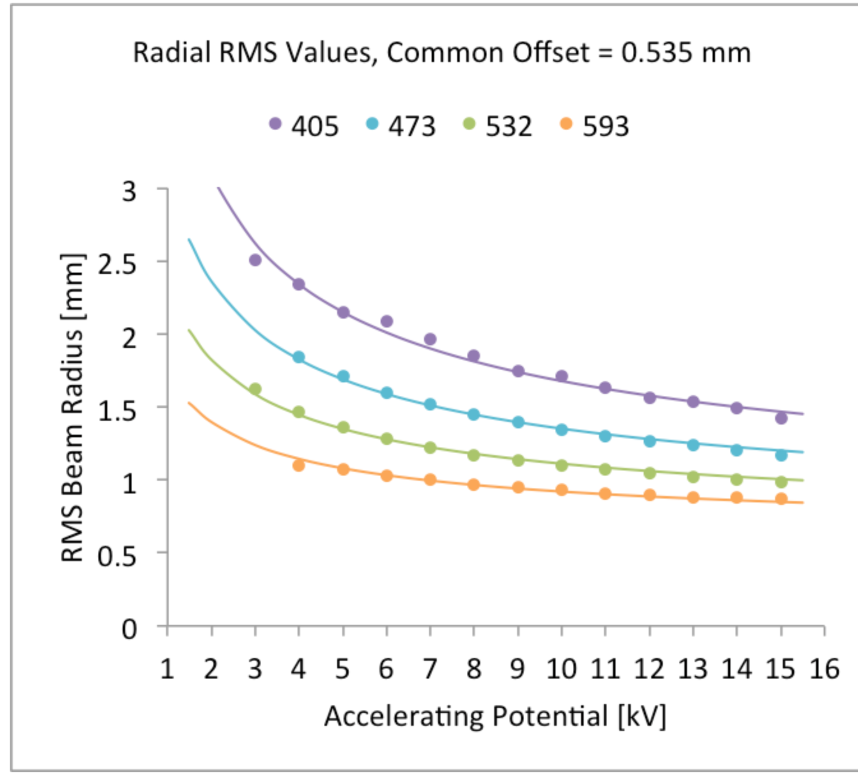
ε = 0.36 micron / mm rms beam size

Emittance Growth due to Cathode Thickness

Thin Cathode (smooth)



Thick Cathode (rough)



ε_{405} = 0.70 μm / mm

ε_{532} = 0.43 μm / mm

ε_{593} = 0.33 μm / mm

ε_{653} = 0.28 μm / mm

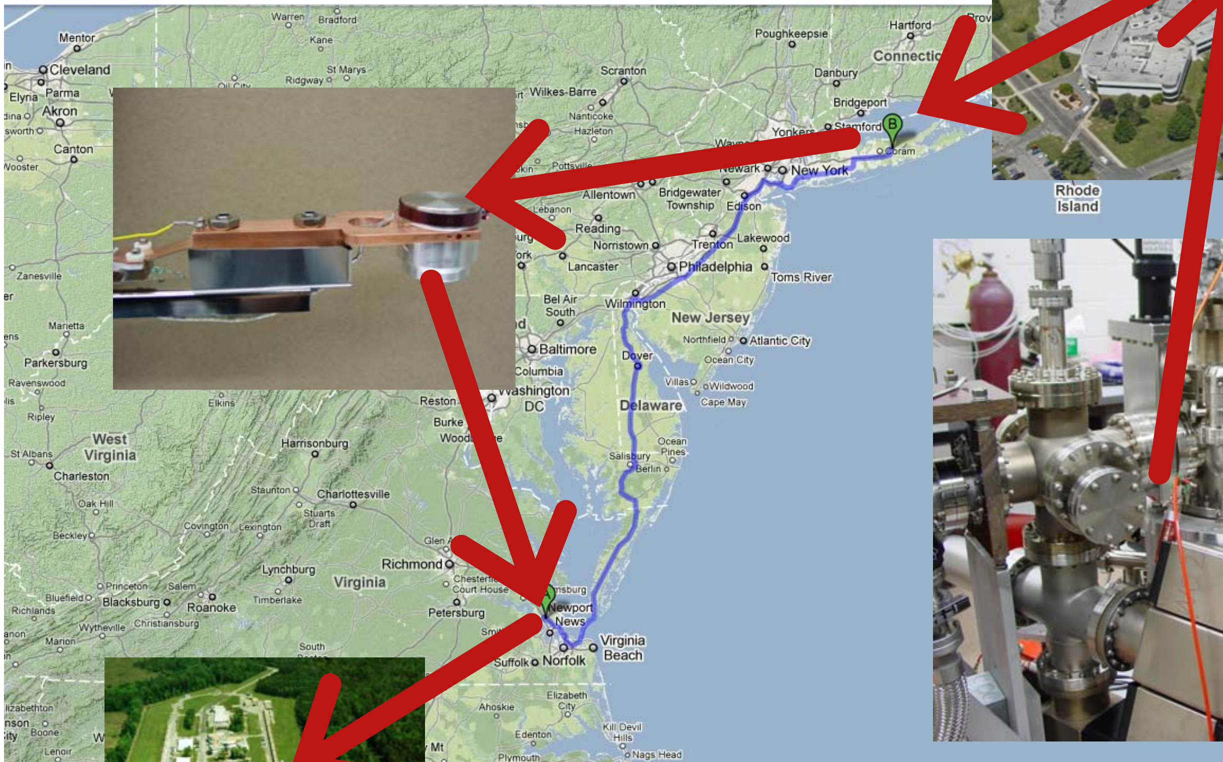
E_{405} = 0.89 μm / mm

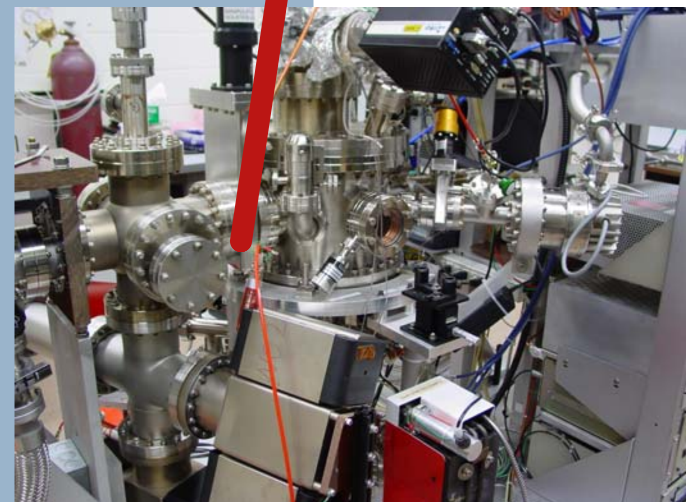
E_{532} = 0.57 μm / mm

E_{593} = 0.48 μm / mm

Note: the unit "/ mm" implies per mm RMS beam size

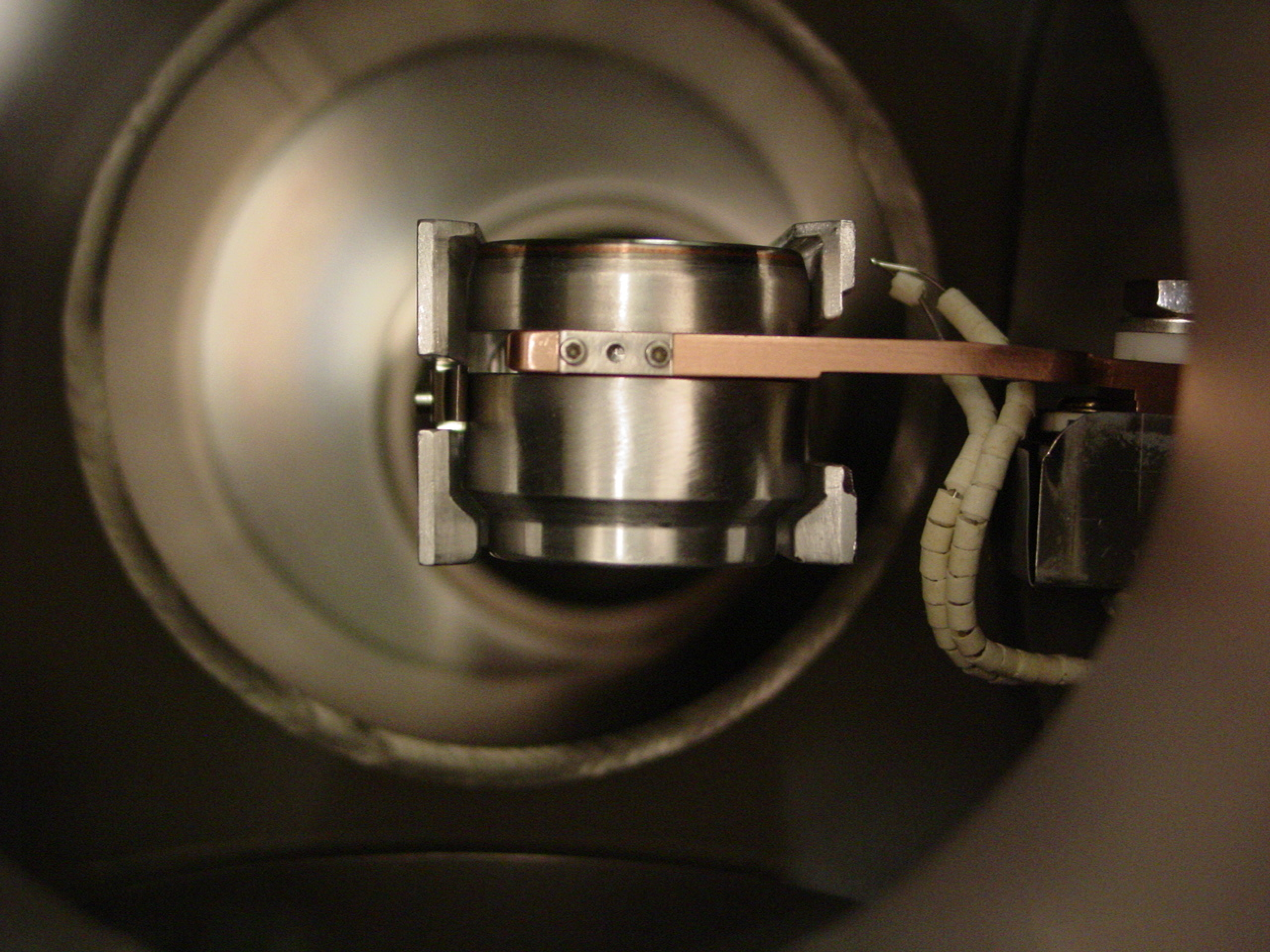
Photocathode was made at BNL...

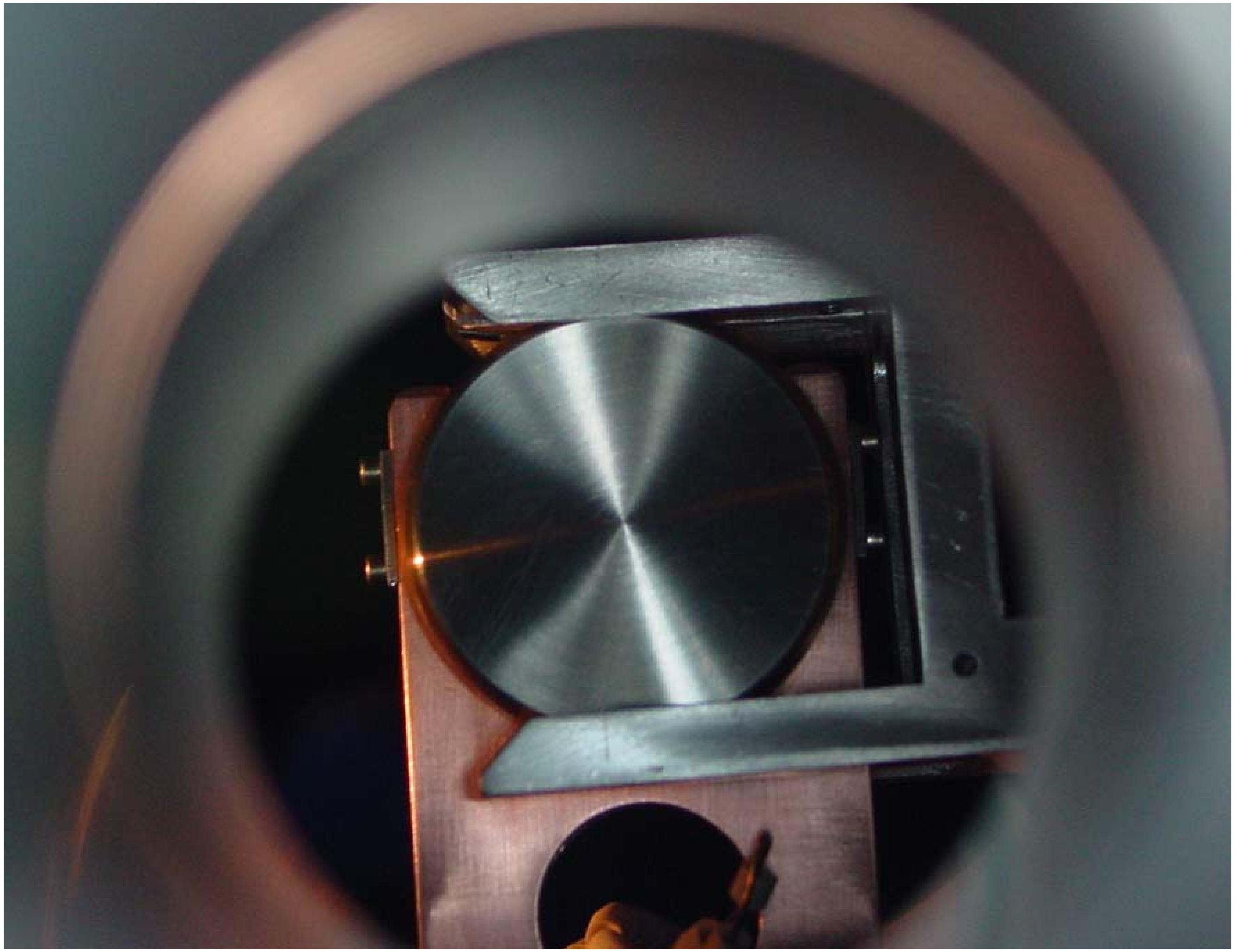




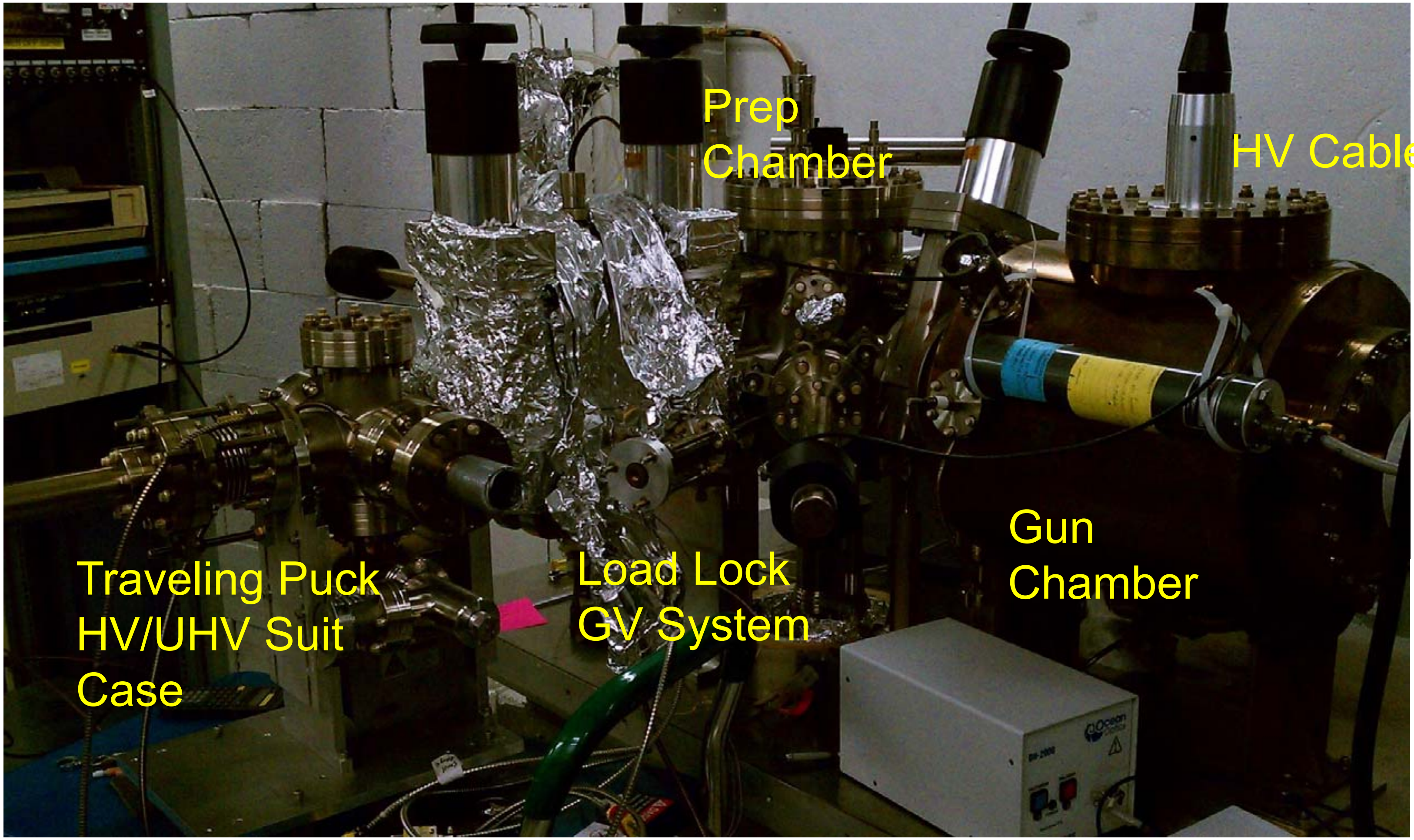
…and brought to JLab for testing.

Long Dark Lifetime!

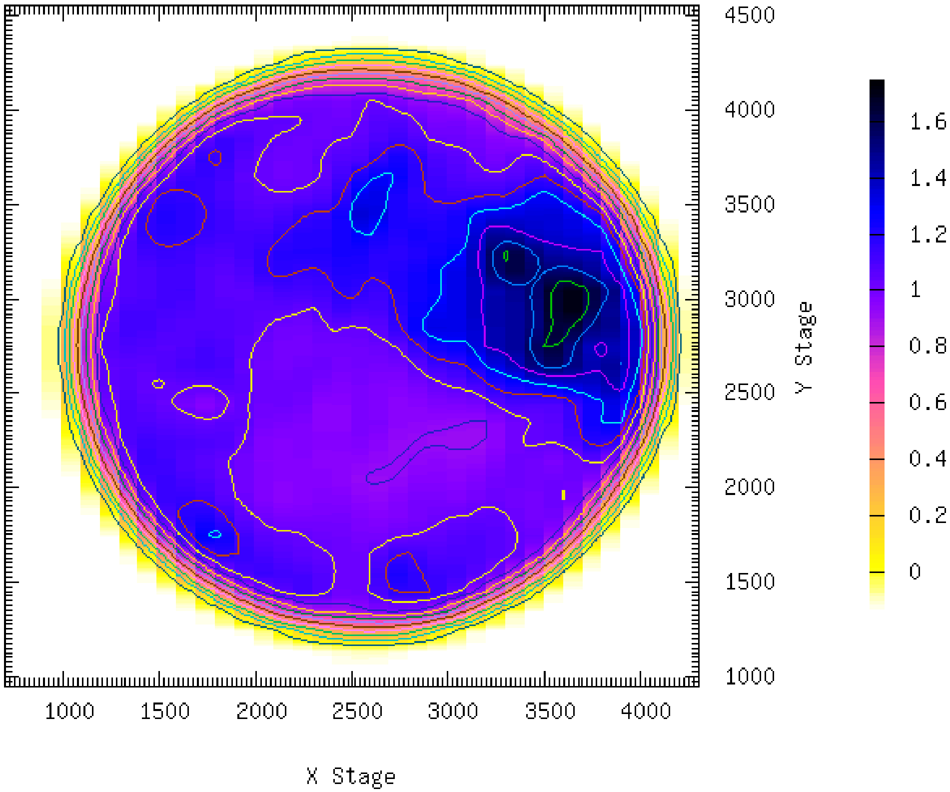




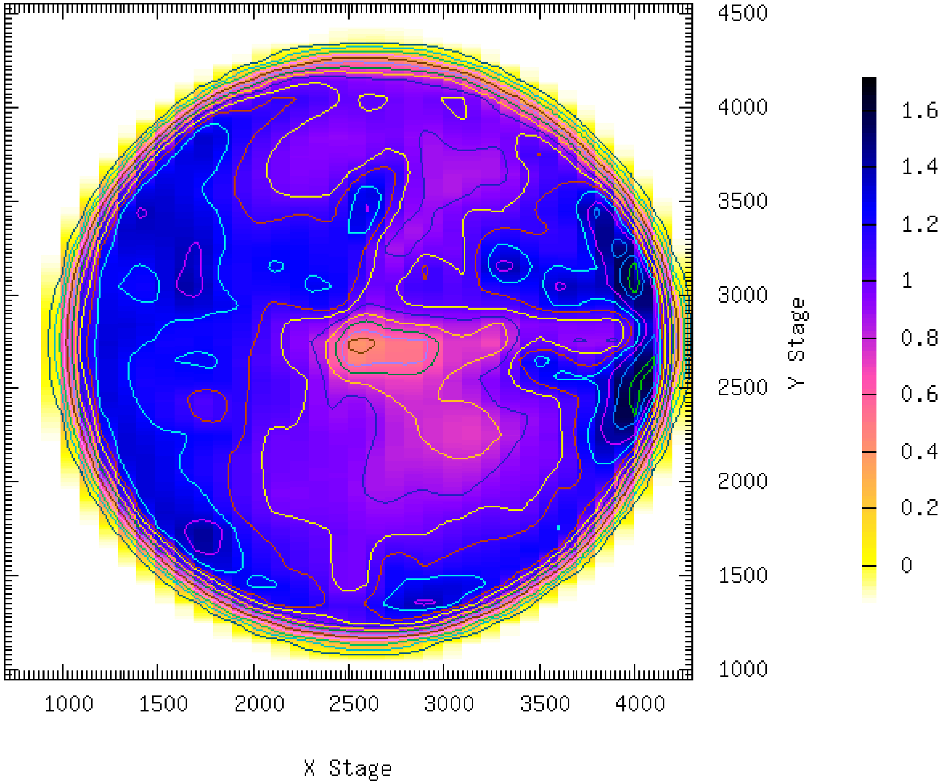
Jlab 200 kV DC Gun



QE map at 532 nm



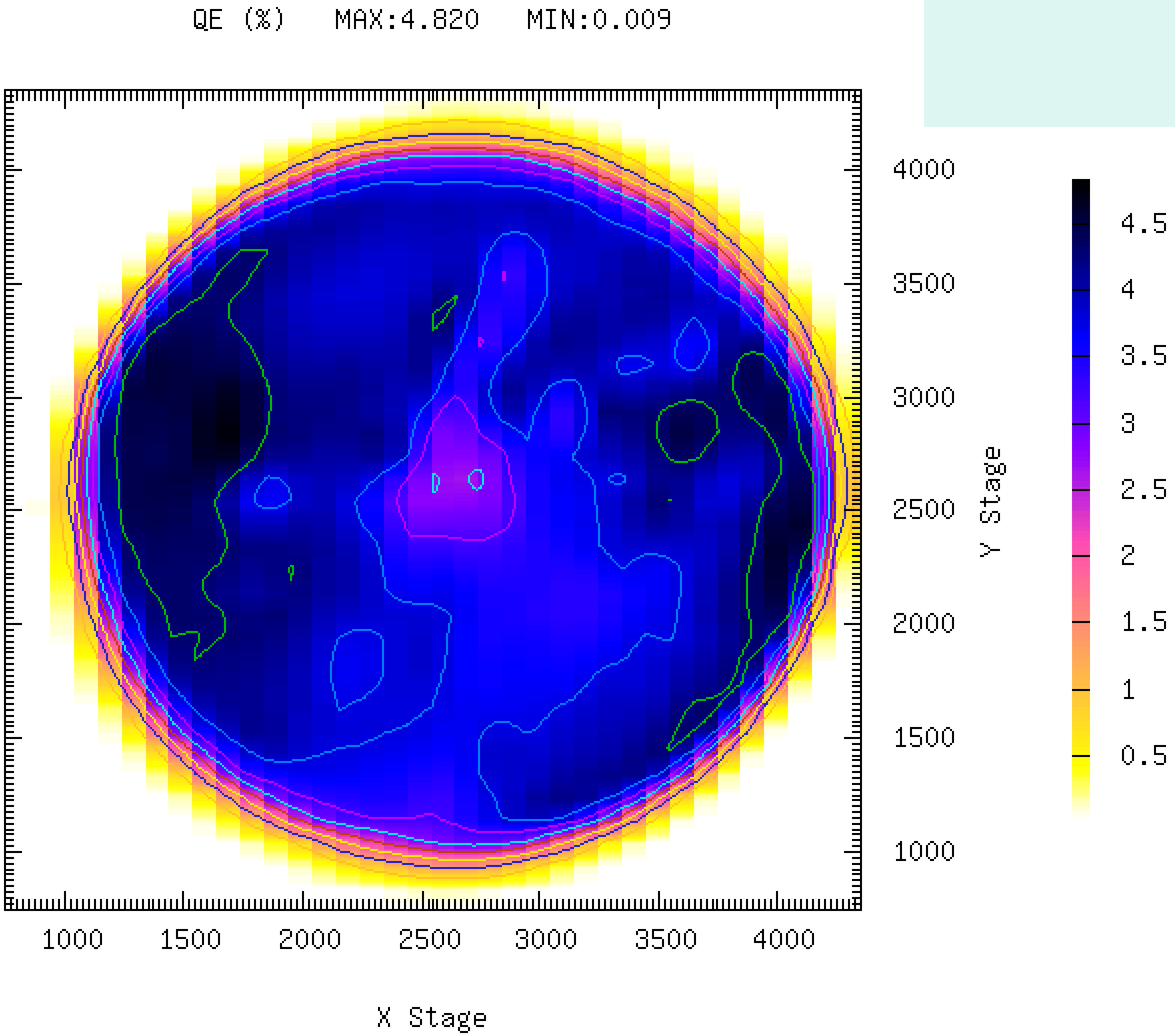
Initial



After 50C extracted from Electrostatic Center

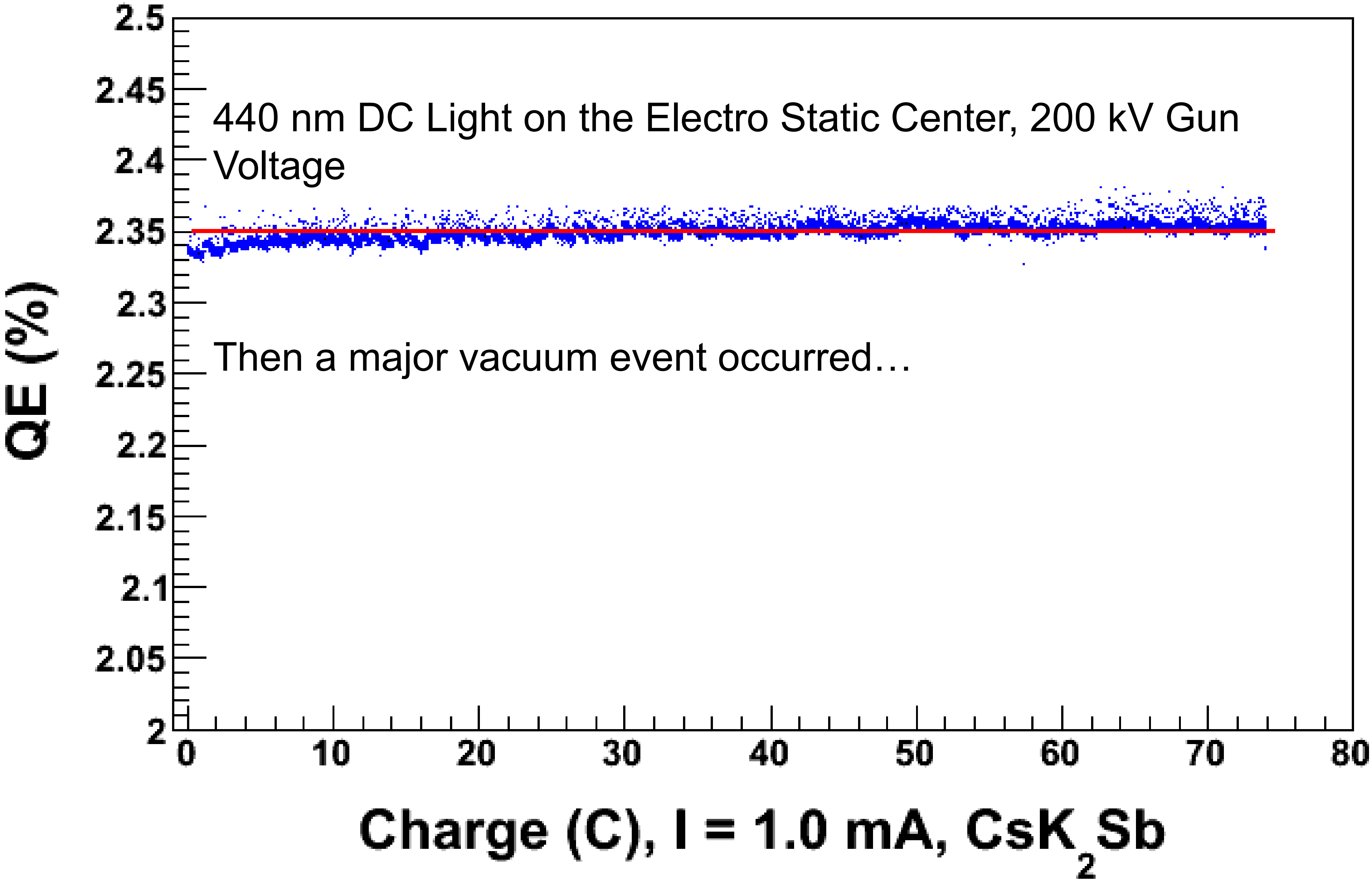
- Ran 1 mA beam using 532nm light with 350 μm laser spot size

QE map at 440 nm

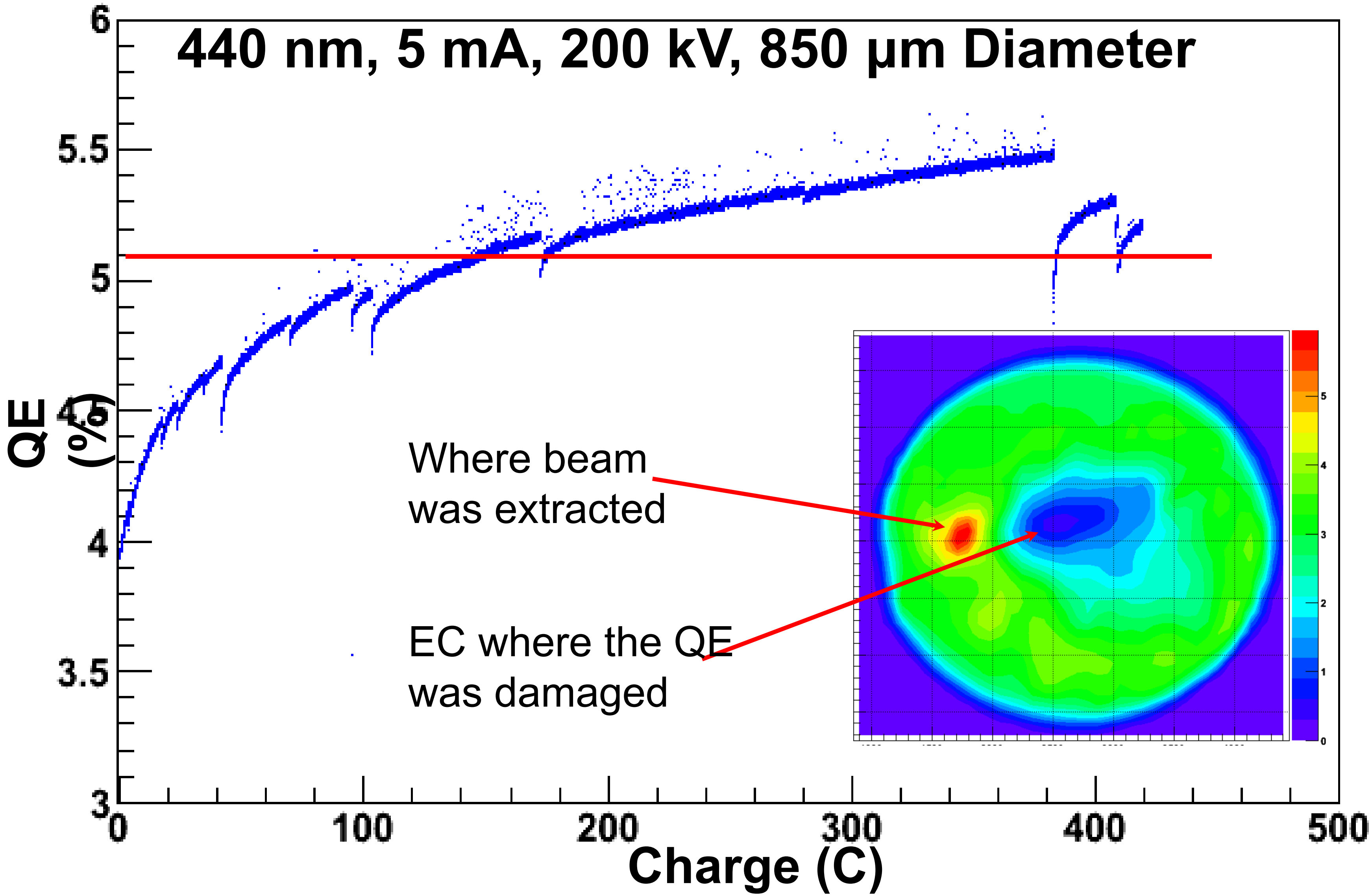


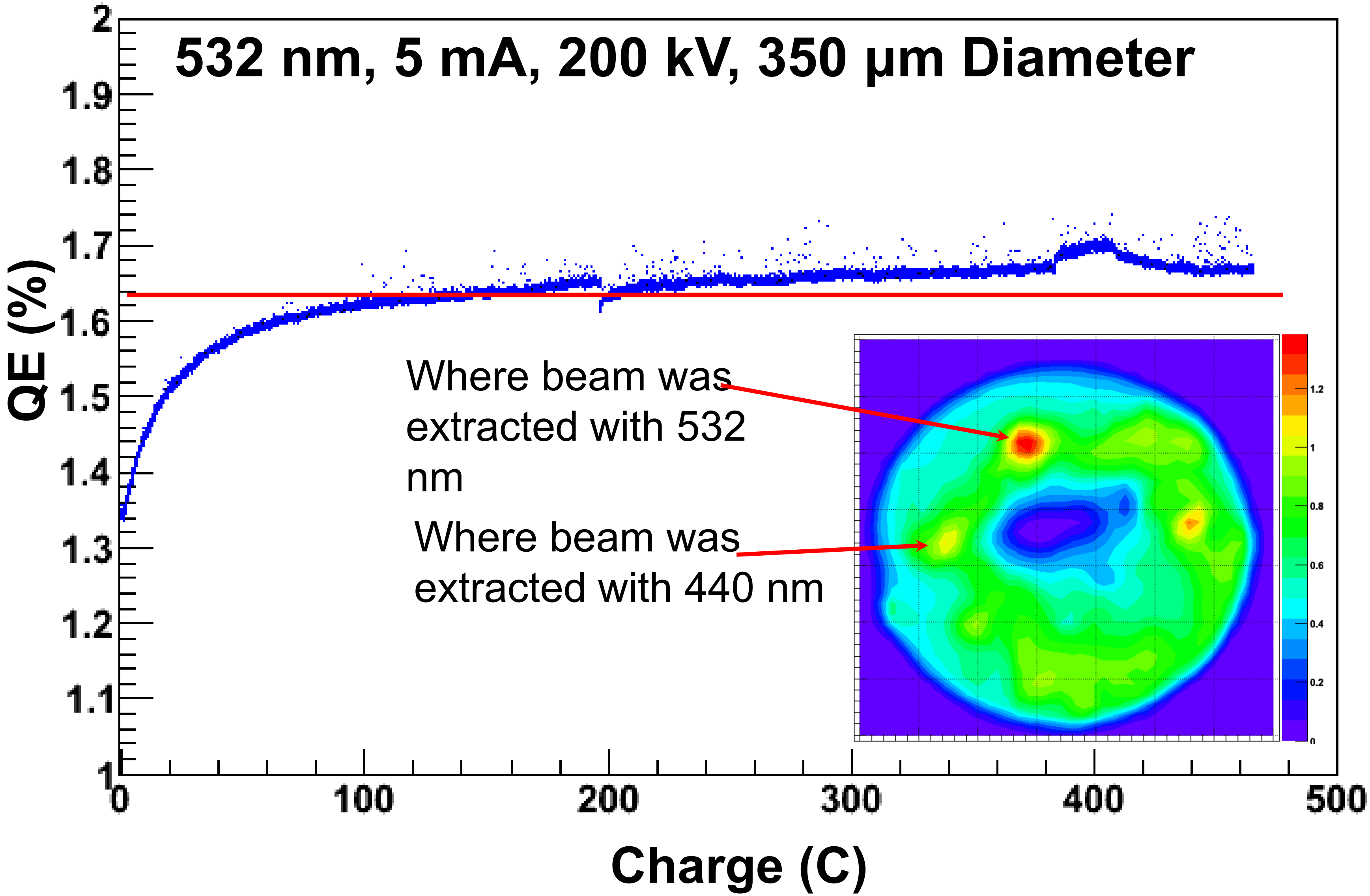
440 nm (~850micron spot size)

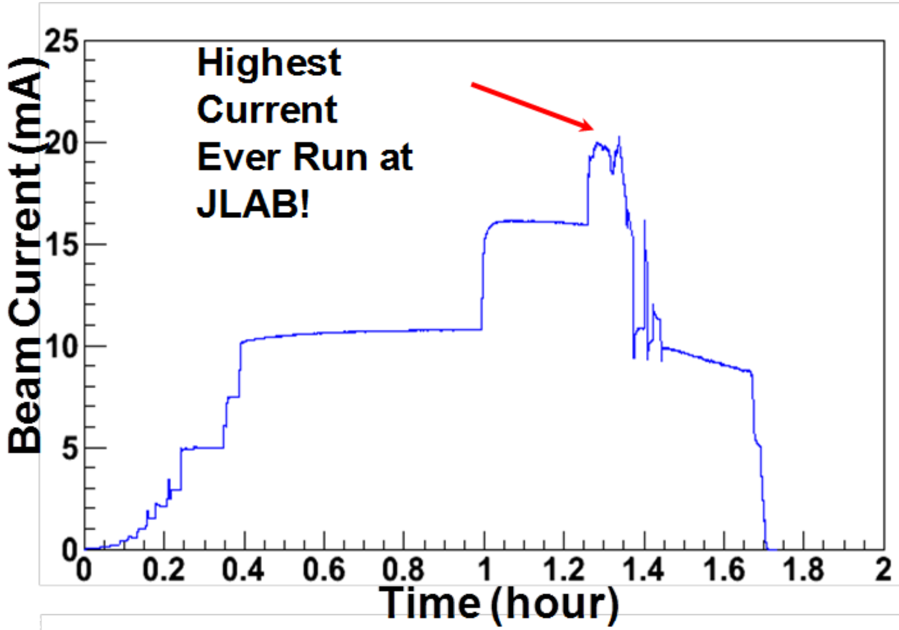
(Lack of) QE decay at 440 nm

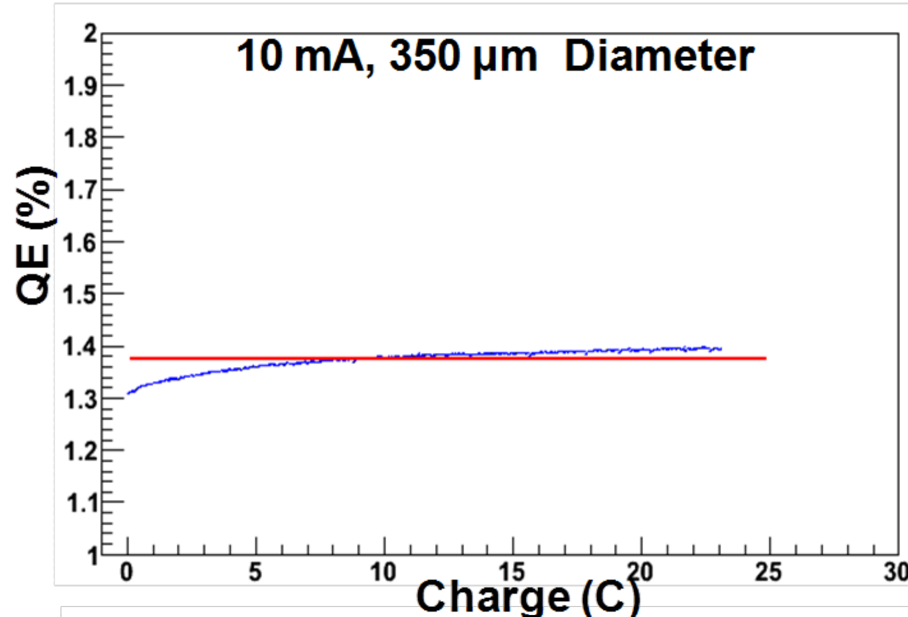


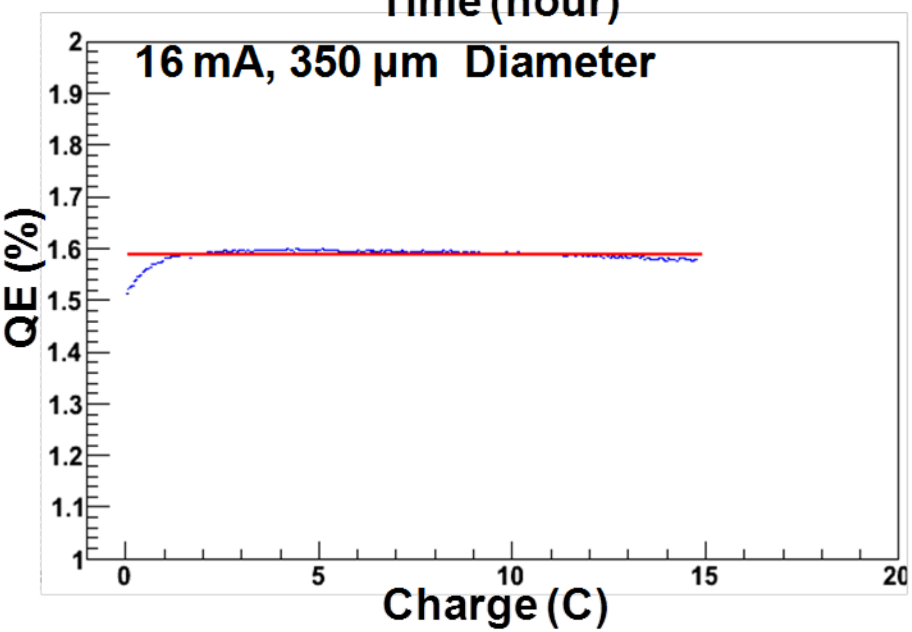
…and the QE improved!

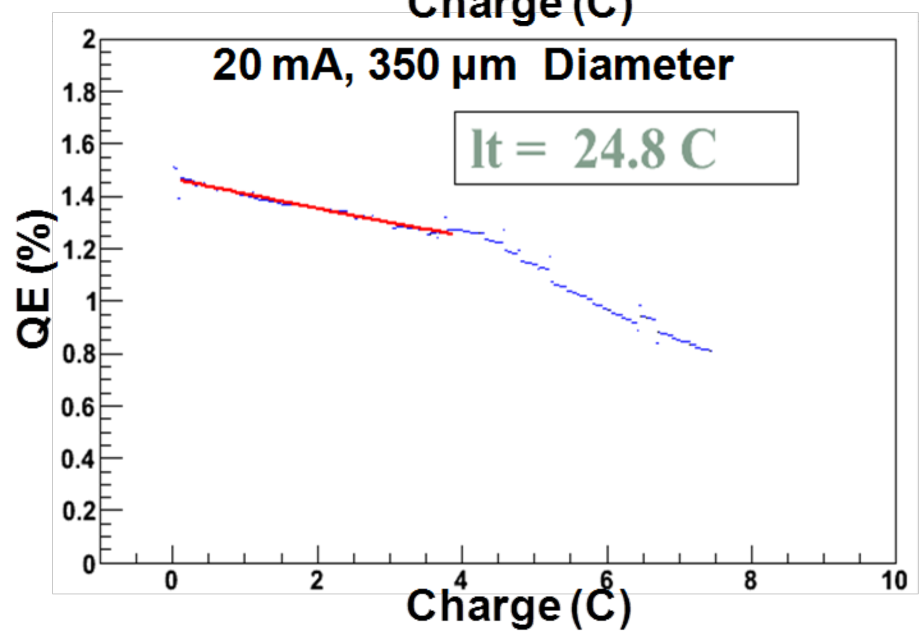



532 nm, 5 mA, 200 kV, 350 µm Diameter
QE (%)
Charge (C)
Where beam was extracted with 532 nm
Where beam was extracted with 440 nm
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0
100
200
300
400
500


Highest
Current
Ever Run at
JLAB!
Beam Current (mA)
Time (hour)

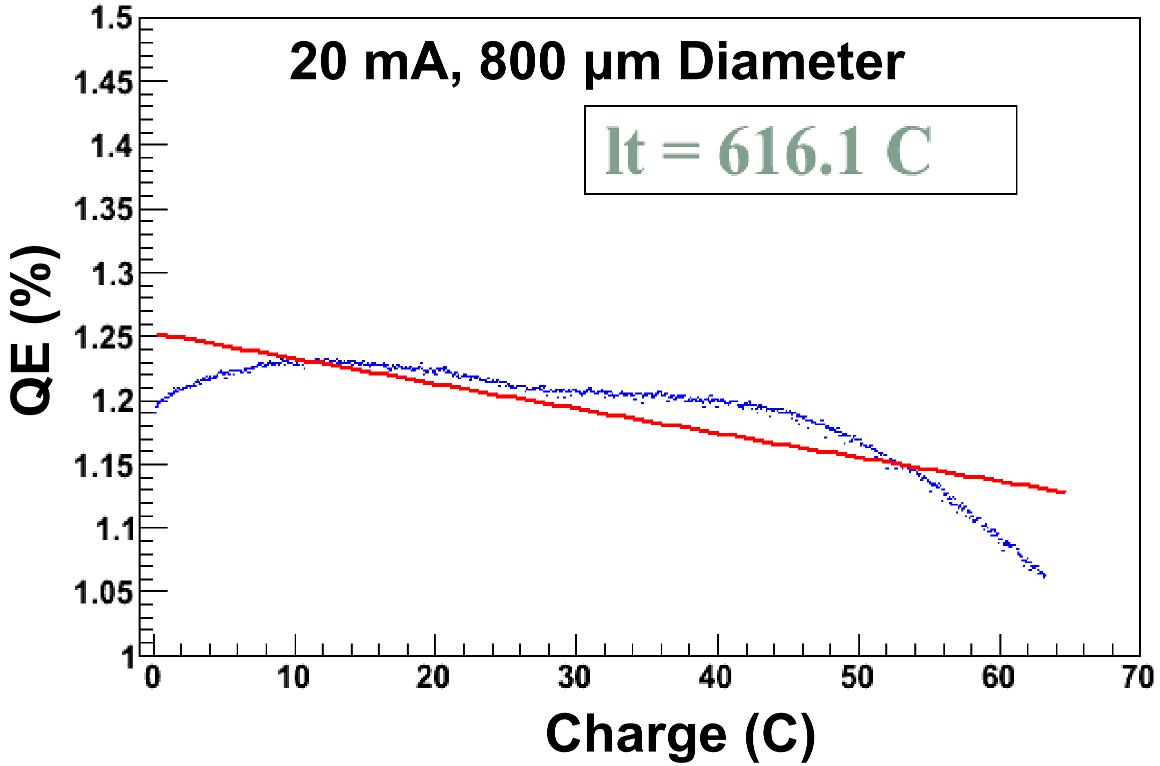

10 mA, 350 μm Diameter
QE (%)
Charge (C)


16 mA, 350 μm Diameter
QE (%)
Charge (C)

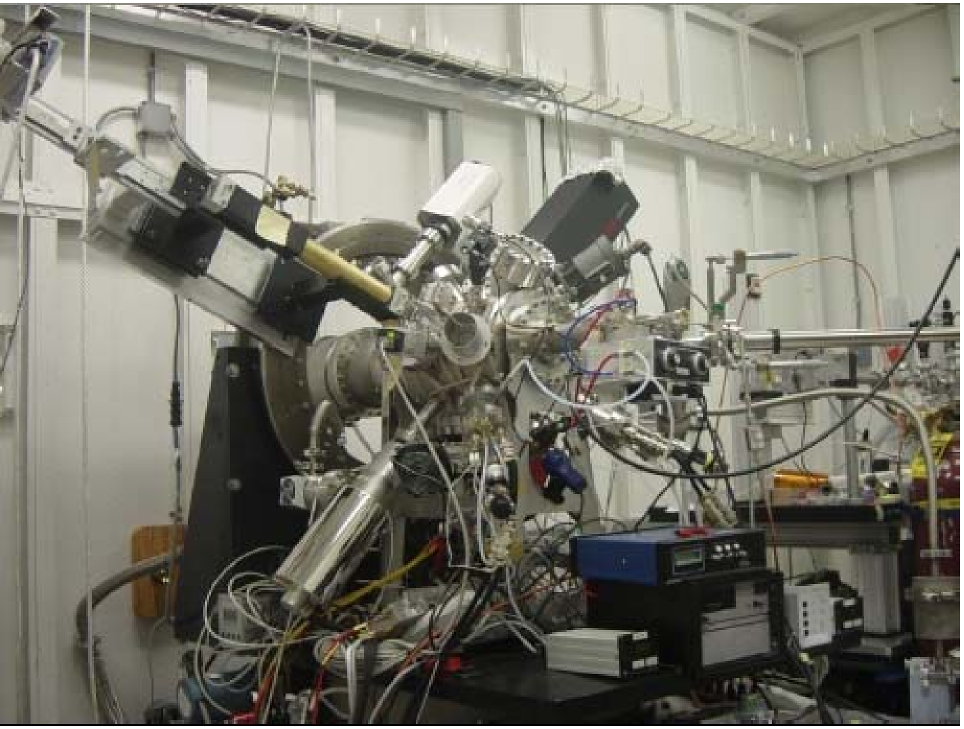

20 mA, 350 μm Diameter
It = 24.8 C
QE (%)
Charge (C)

- Lifetime at 20 mA increases with larger laser spot – probably a heating effect

- Test ongoing with a new cathode

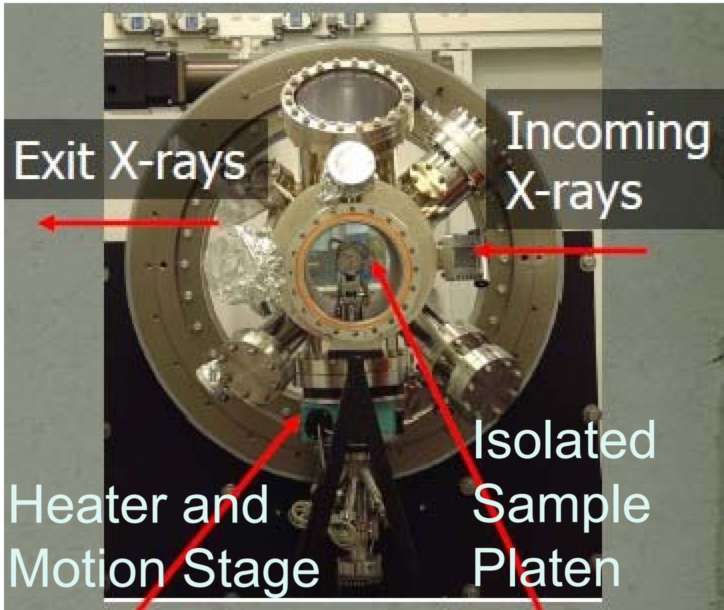


Deposition with *In Situ* Analysis

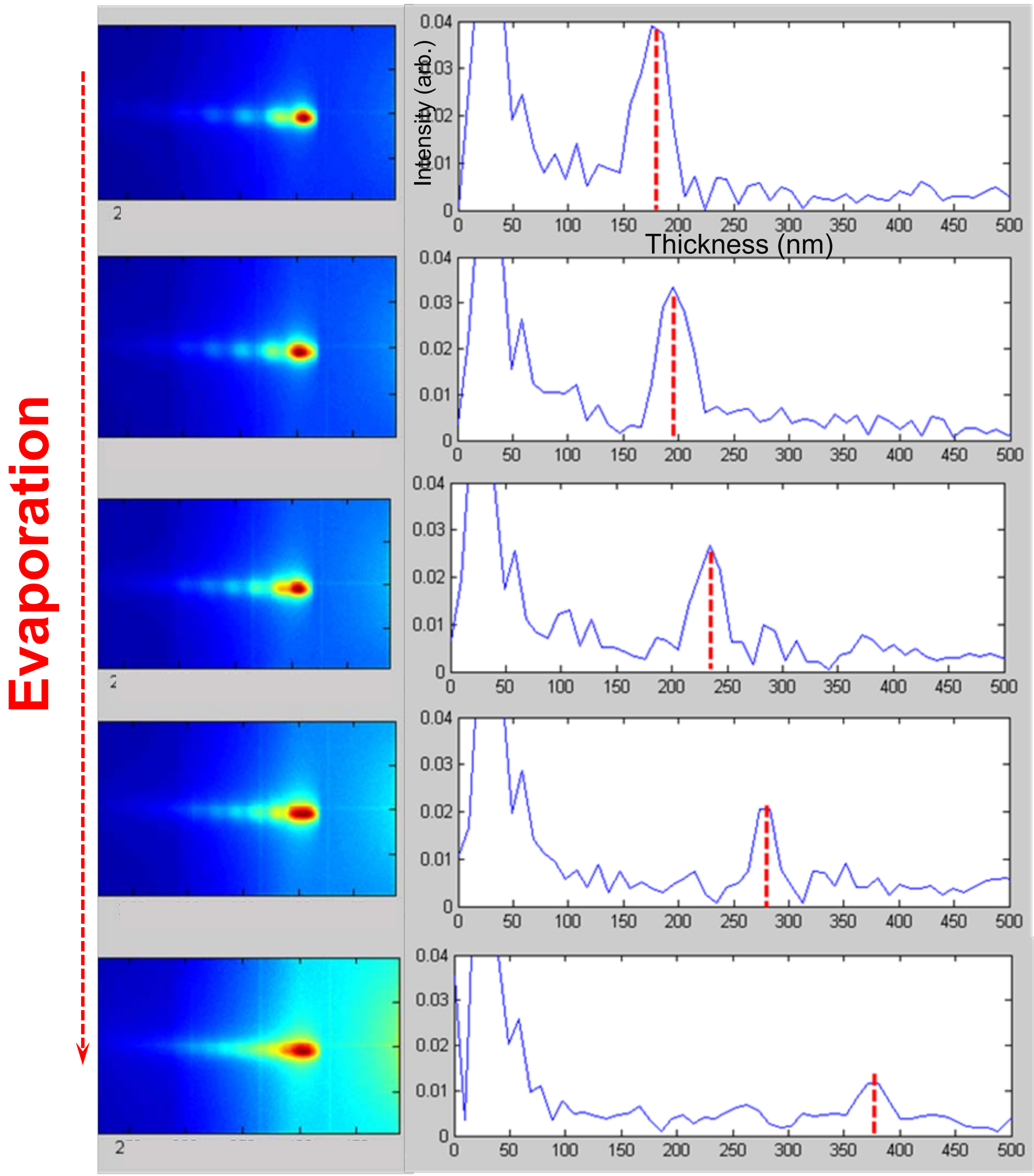


UHV system w/ Load Lock
Sb Line Source (evaporation)
Sb Sputtering
K and Cs Alvasources
SAES Getter Sources
Heat Cathode to 800C
Gas cooling
QE Measurement with 532 nm
Residual Gas Analyzer, Quartz FTM

In-Situ Diagnostics (during growth):
- Pilatus 100k X-ray camera
- XRD for grain size and orientation in plane and reflection geometry
- X-ray fluorescence for stoichiometry and contamination
- Reflection high energy electron diffraction



Raw X-ray Image FT giving film thickness (nm)

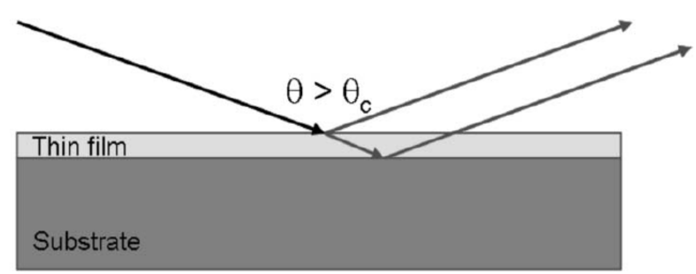


Pilatus 100k detector
4 degrees from normal
Grazing incidence X-rays

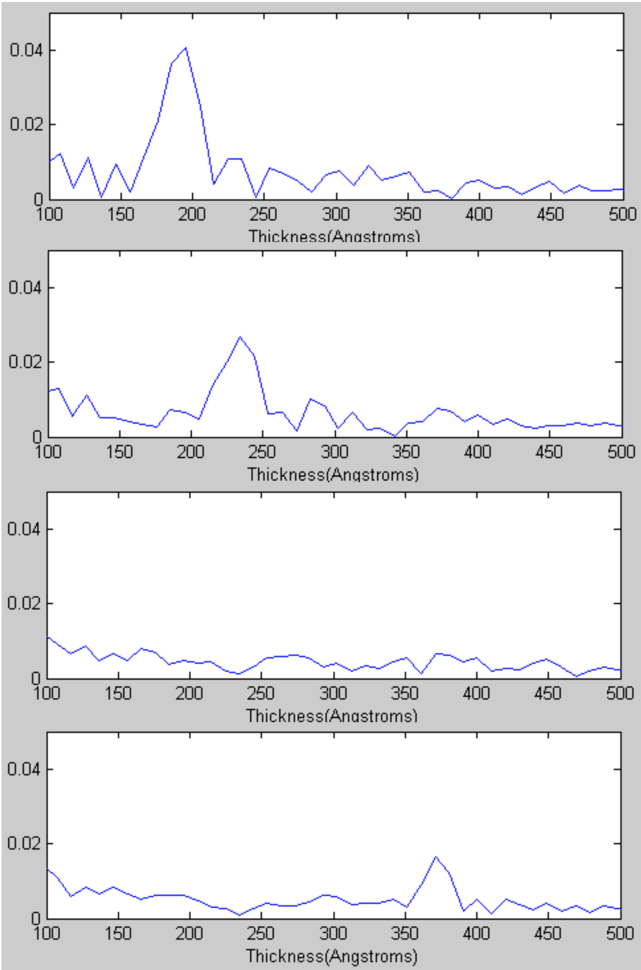
Interference between the top surface and bottom surface reflection

Fourier transform provides film thickness during deposition

SEM measurements gave a final film thickness of 39 nm (compared to 37 nm from XRR)



K-growth on Sb: One Example



Sb-film (18nm)

K-evaporation started

K-evaporation goes on

Final film

Sb film starts with about 3 nm (consistent with AFM measurements)

K-evaporation starts:

- Roughness is increasing
- Single peak shows that K instantaneously (1s) reacts and intermixes

Ongoing evaporation of K:

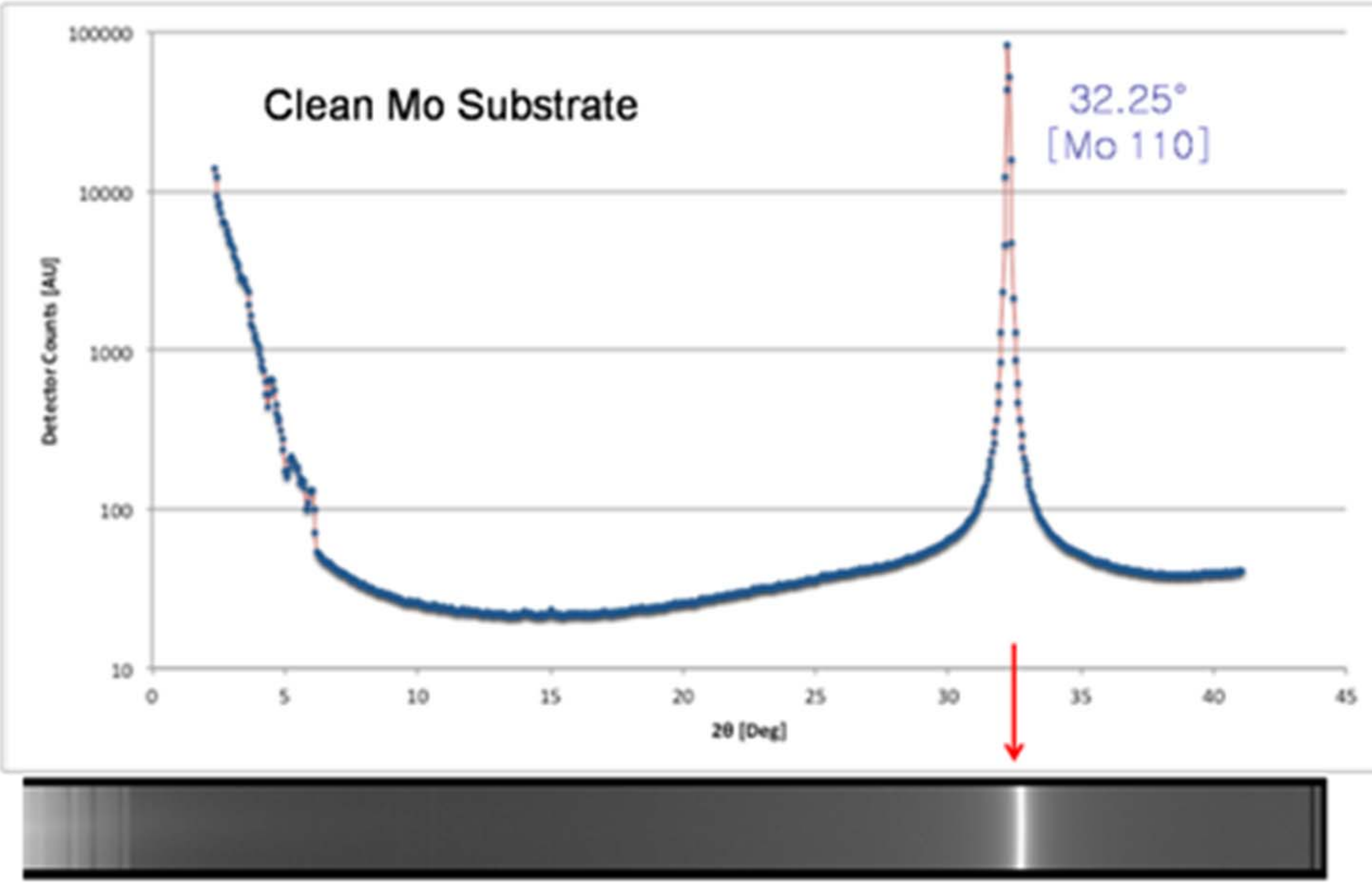
- Film shows large roughness (no peak)

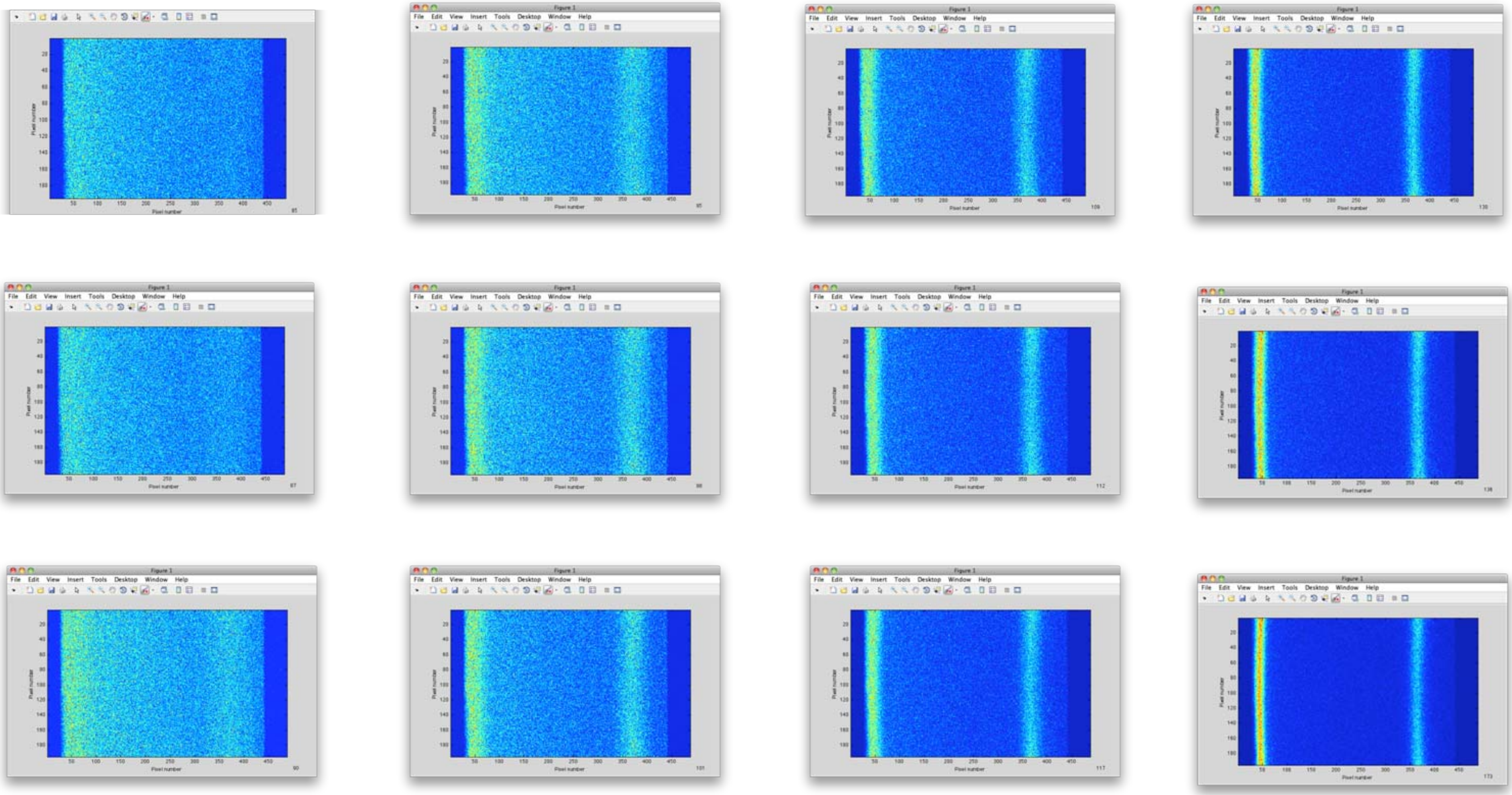
Final Film:

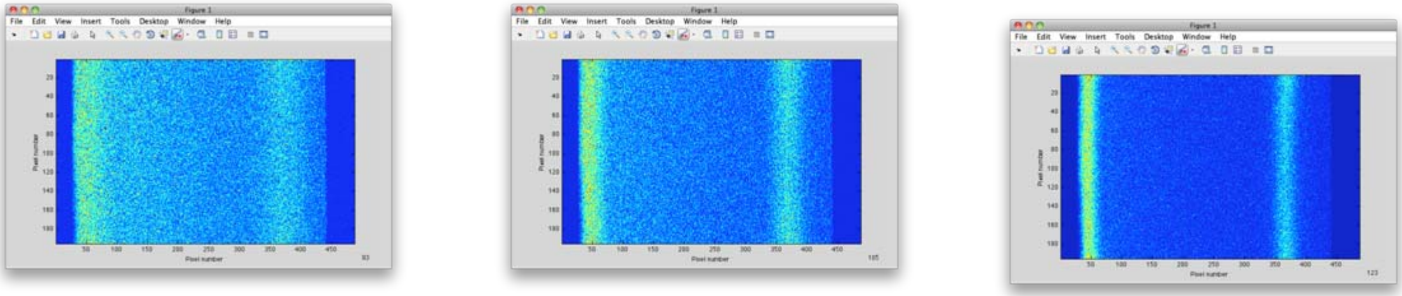
- At 37 nm, roughness has decreased and peak reappears
- Crystalline phase transition?

Currently in progress: More quantitative analysis and systematic recipe variations

In Situ X-ray Diffraction (XRD) - Substrate

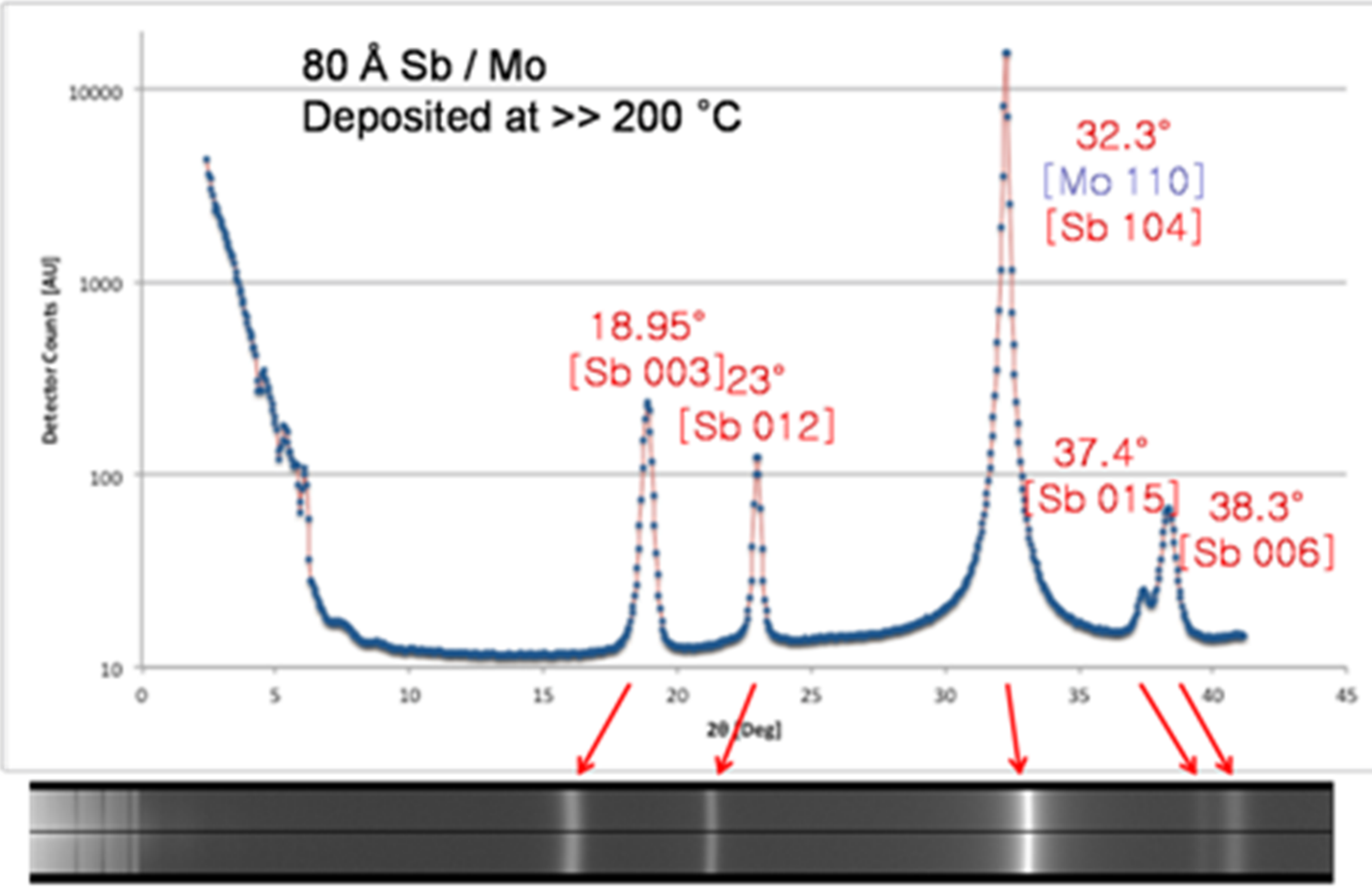




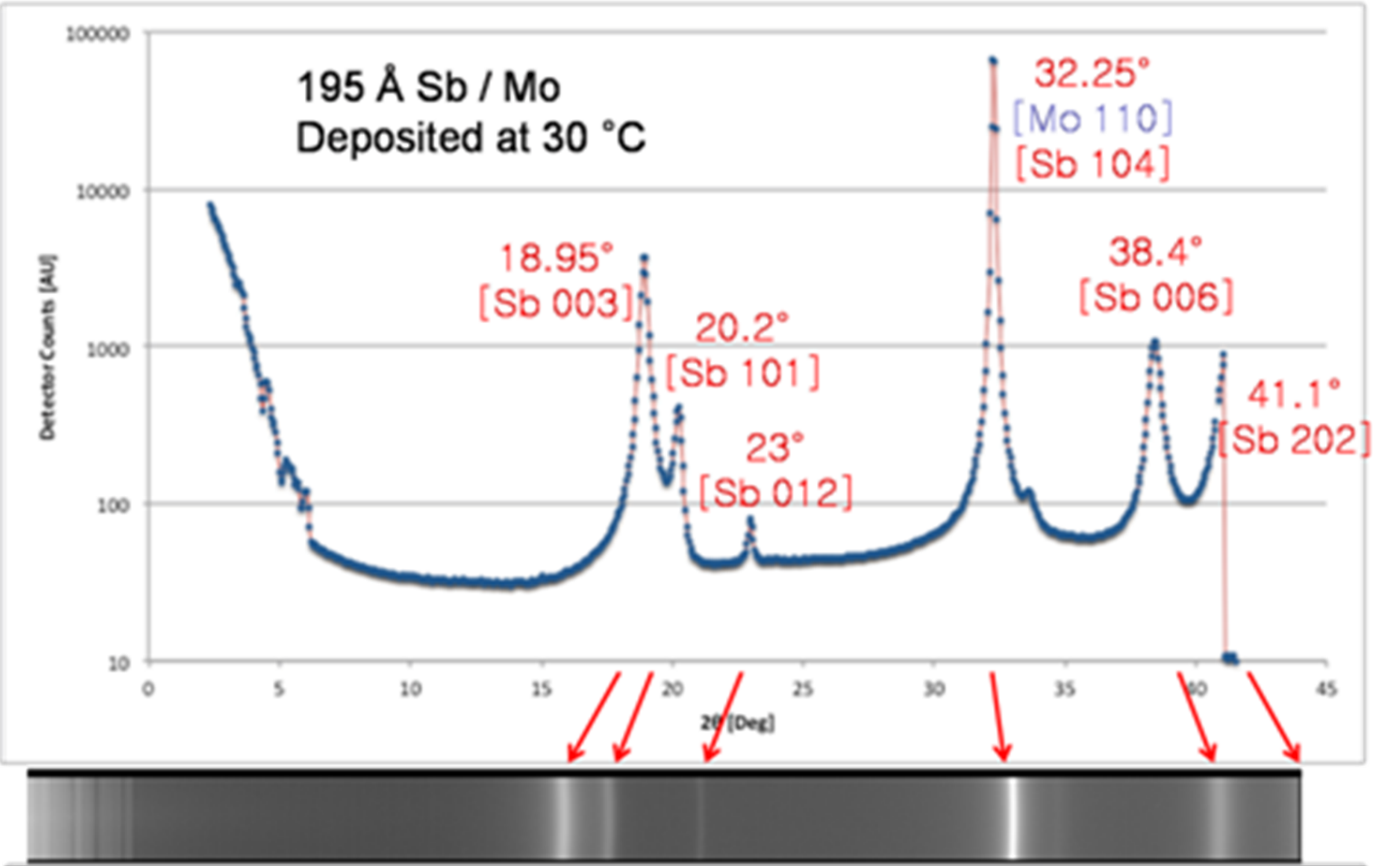


42 nm final film thickness
Onset of crystalline structure ~8nm

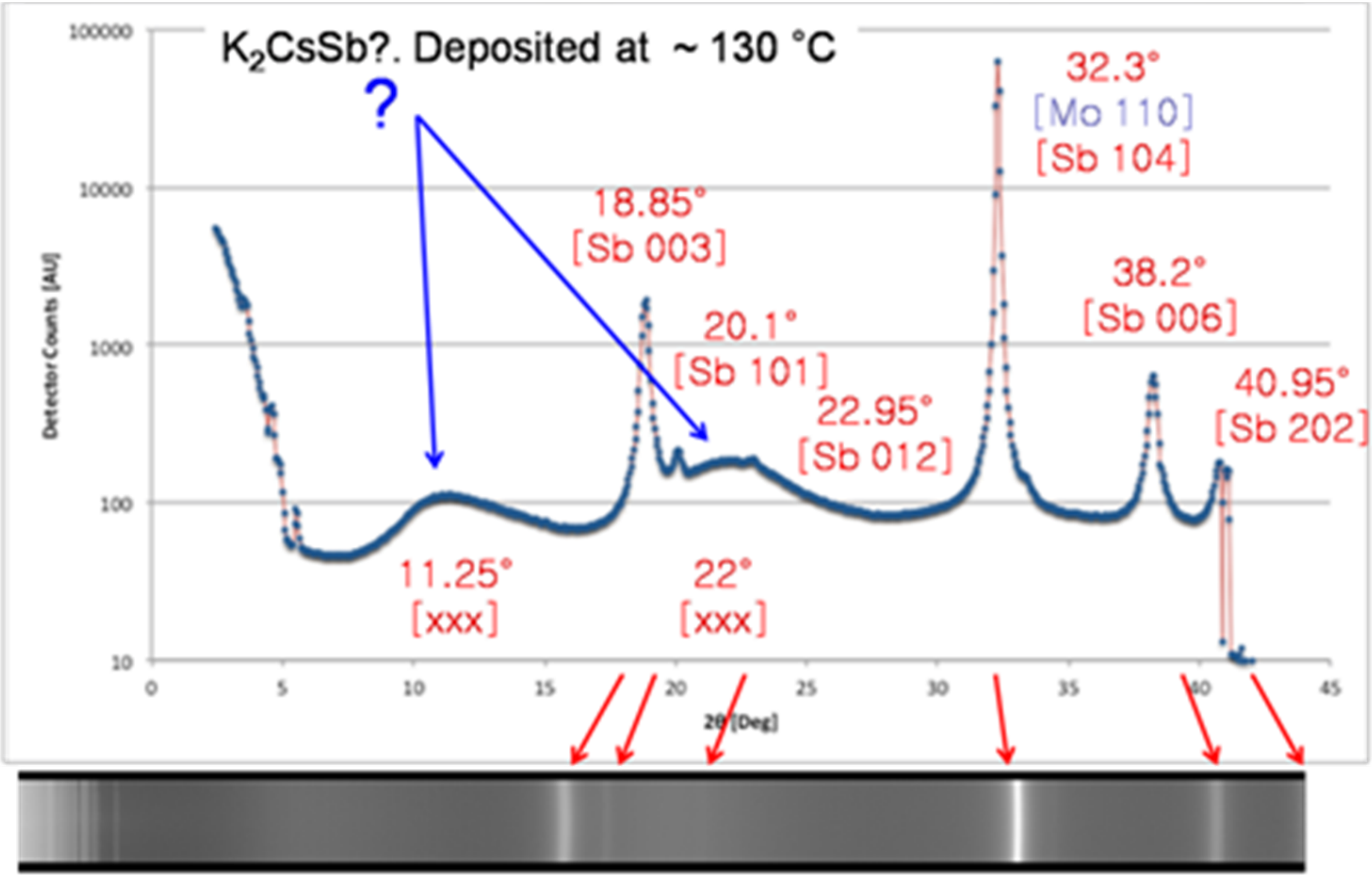
In Situ XRD – High Temperature Sb Sputter



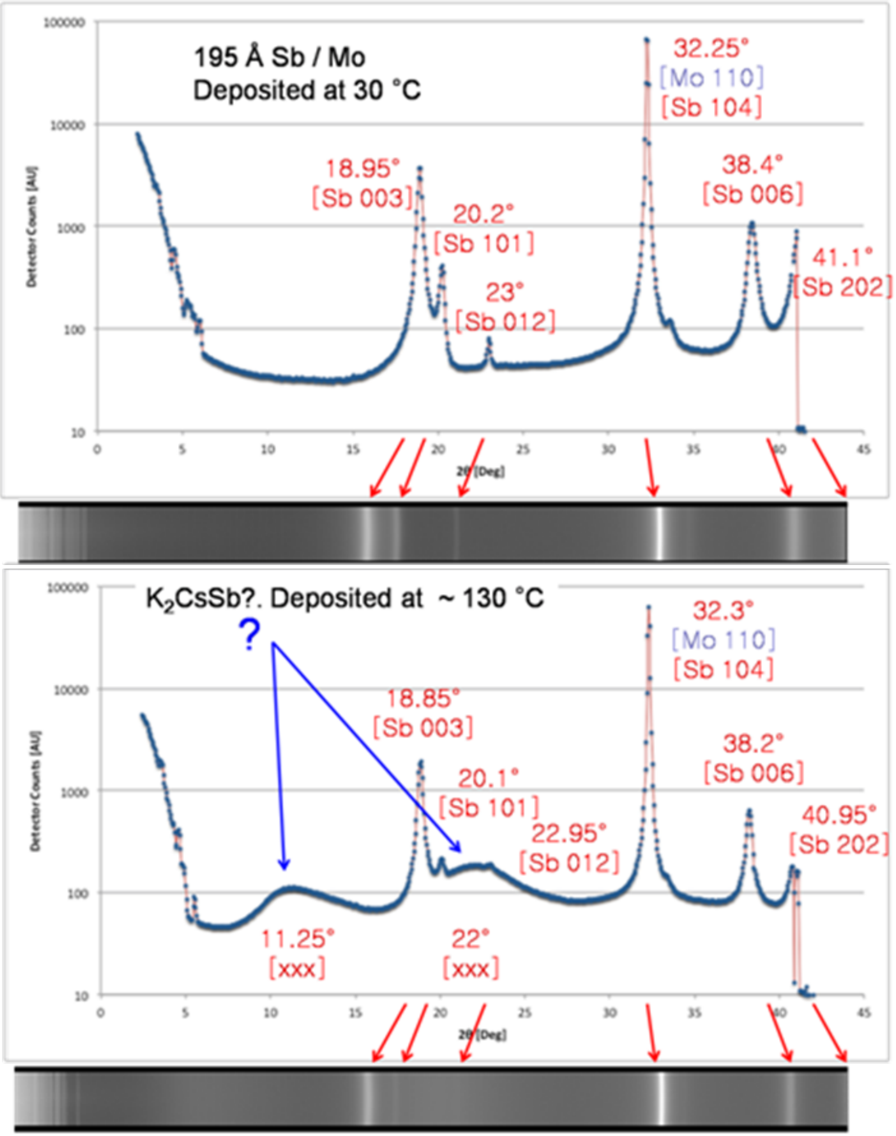
In Situ XRD – Room Temperature Sb Sputter



In Situ XRD – Alkali Evaporation

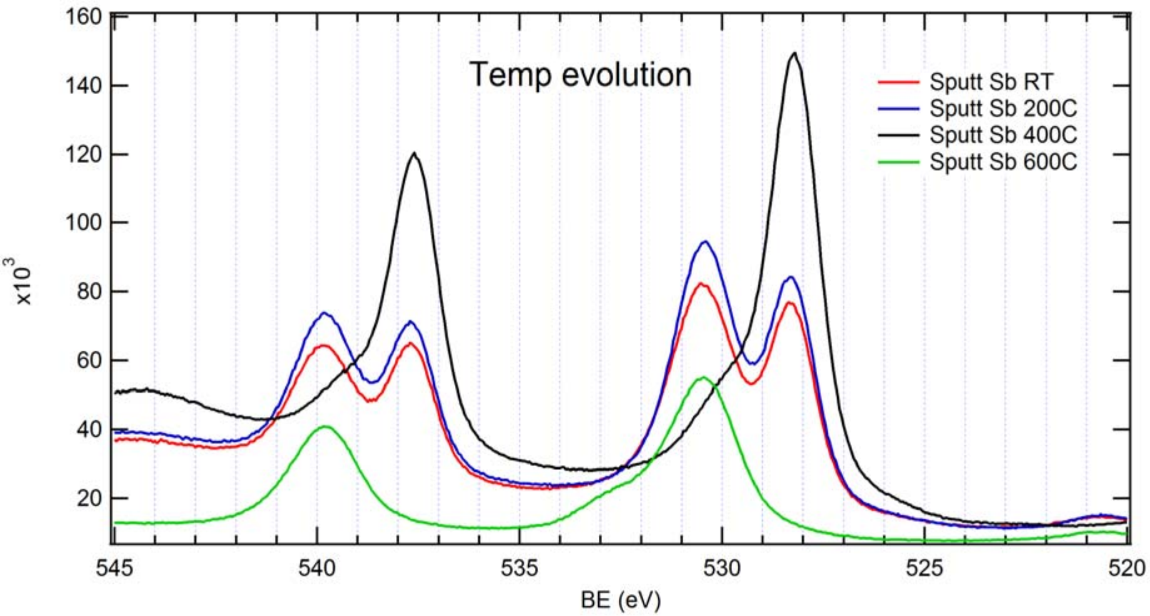


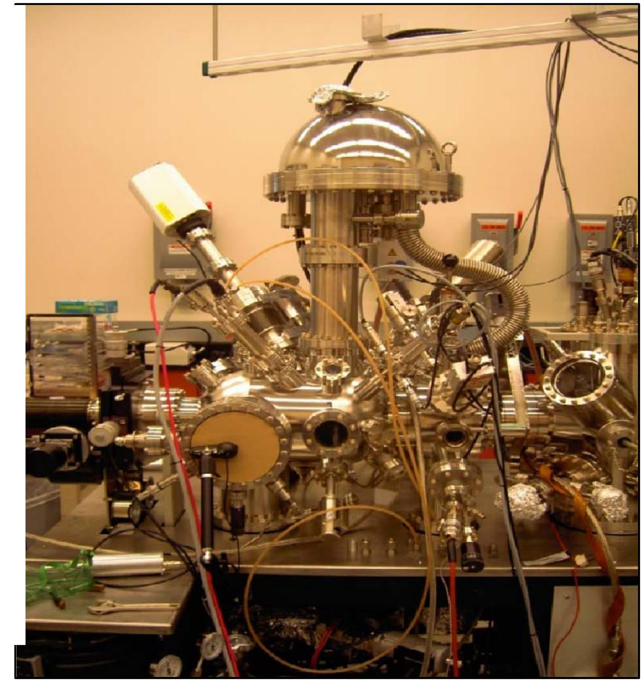
In Situ X-ray Diffraction (XRD)



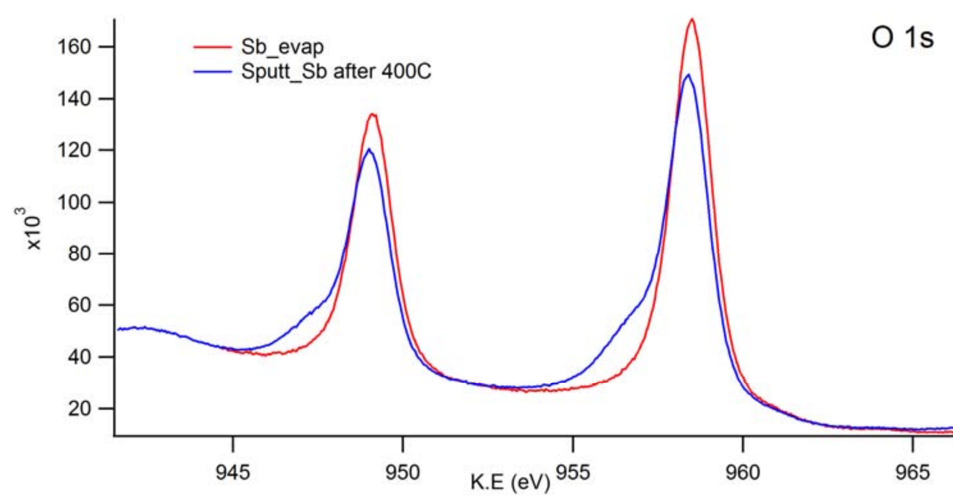
- High indexed reflections disappear:
  - Indication that crystallite gets smaller or very strained
- Main reflections show reduced intensity
  - Smaller crystals but still Sb-phase present
- Strong background observable:
  - Not clear which $Cs_xK_ySb_n$-phases are produced
  - Is active cathode material in amorphous phase?

XPS *in-situ* on cathode growth at CFN

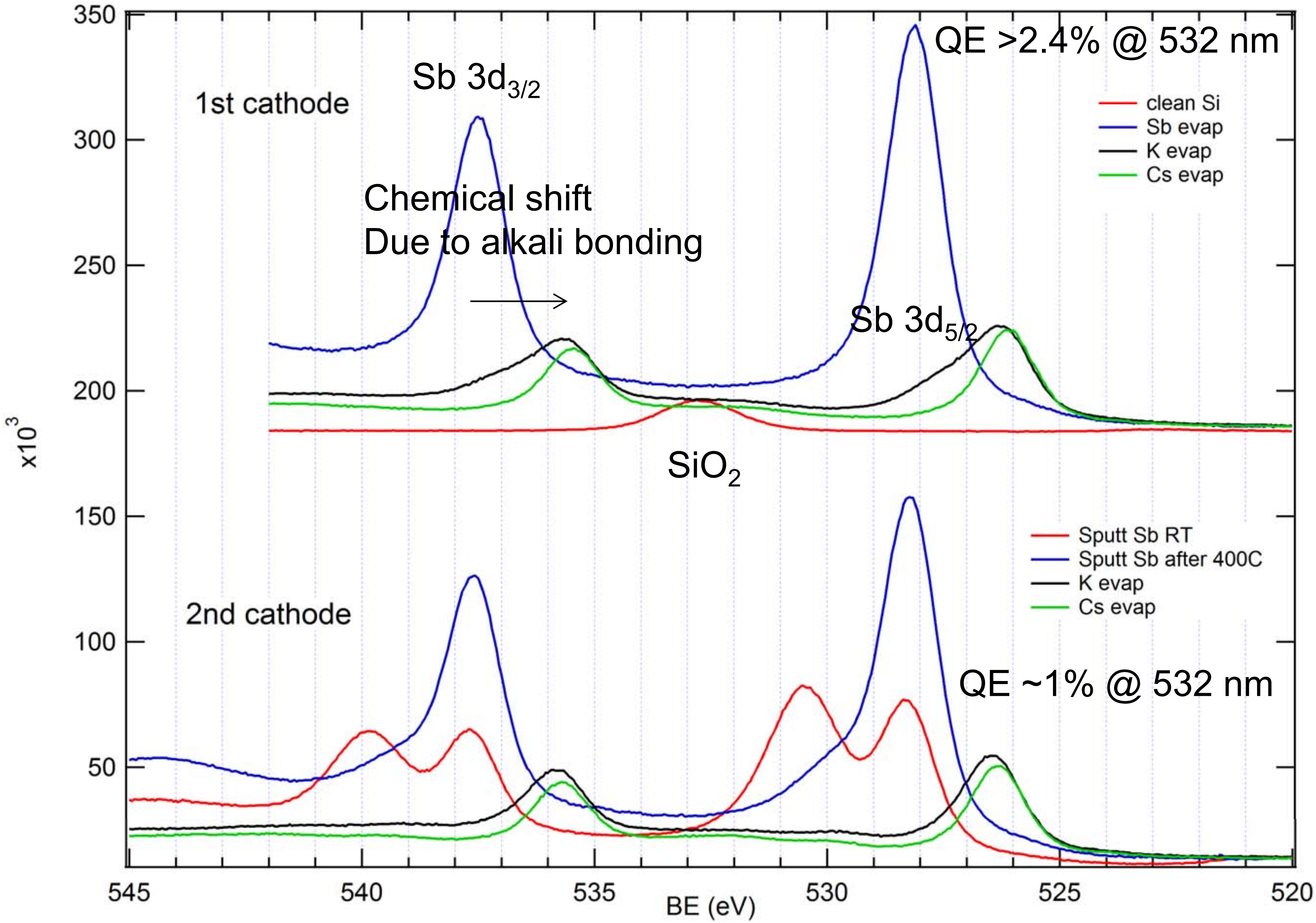




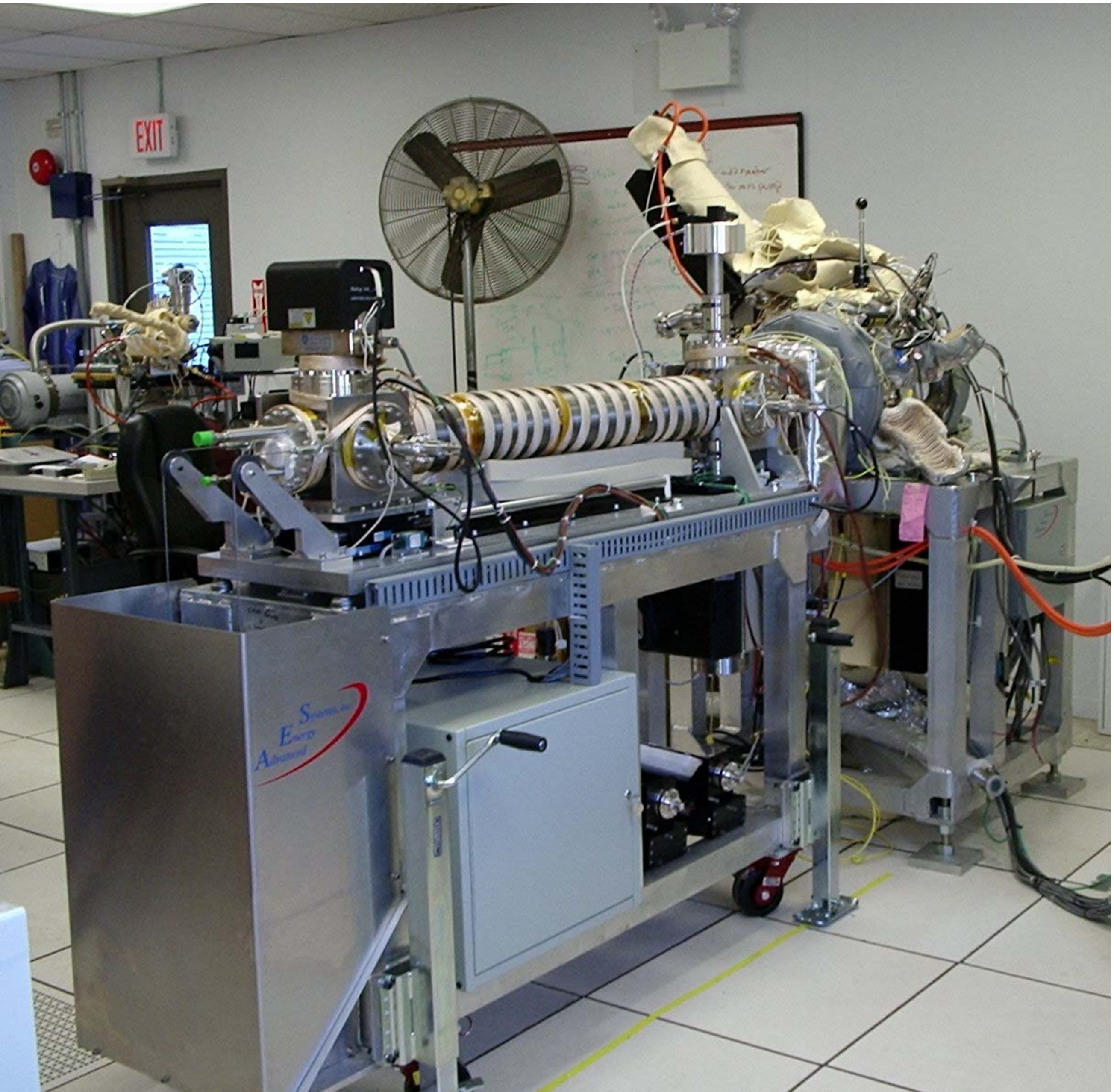
- Used to optimize heat treatment of air-exposed Sb film
- Initially Sb and Sb-O
  - 200C does nothing
  - 400C removes most of oxide
  - 600C desorbs Sb, exposes Si Substrate



XPS *in-situ* on cathode growth at CFN



Deposition System for 704 MHz gun

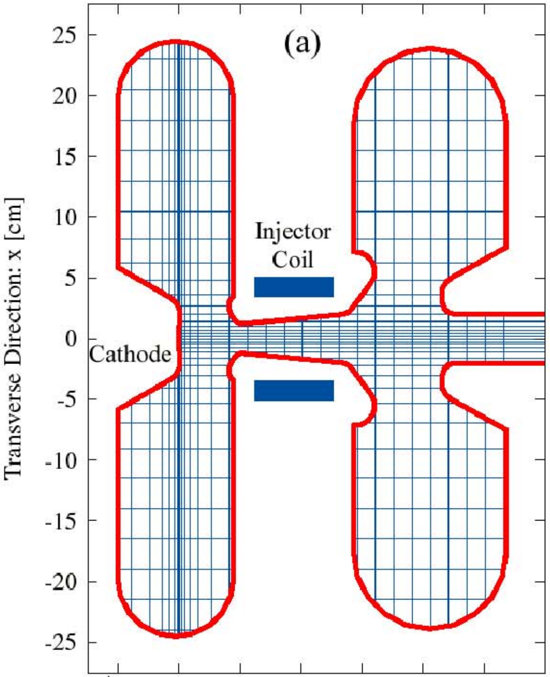


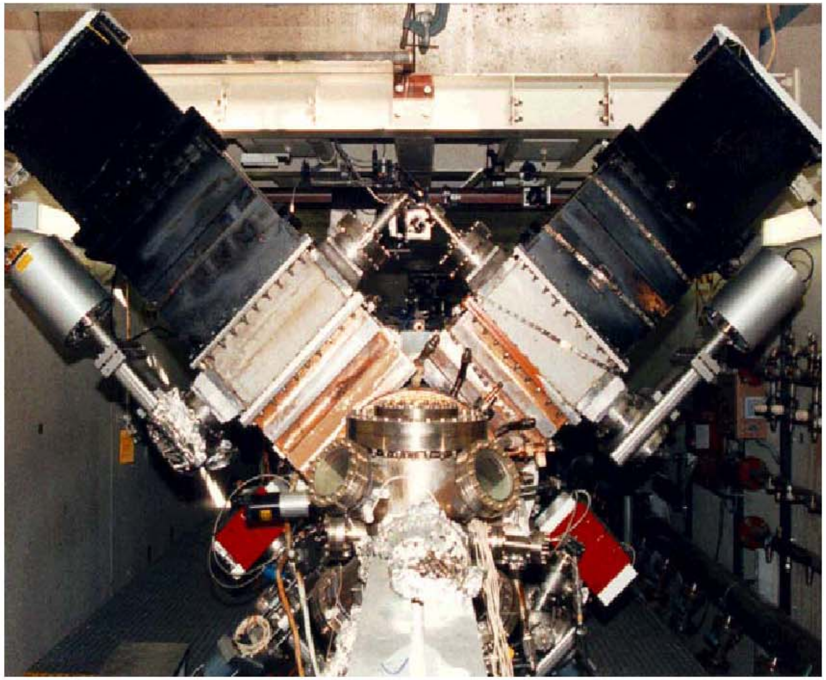
Sb films deposited

Alkali sources mounted

Cathodes coming soon!

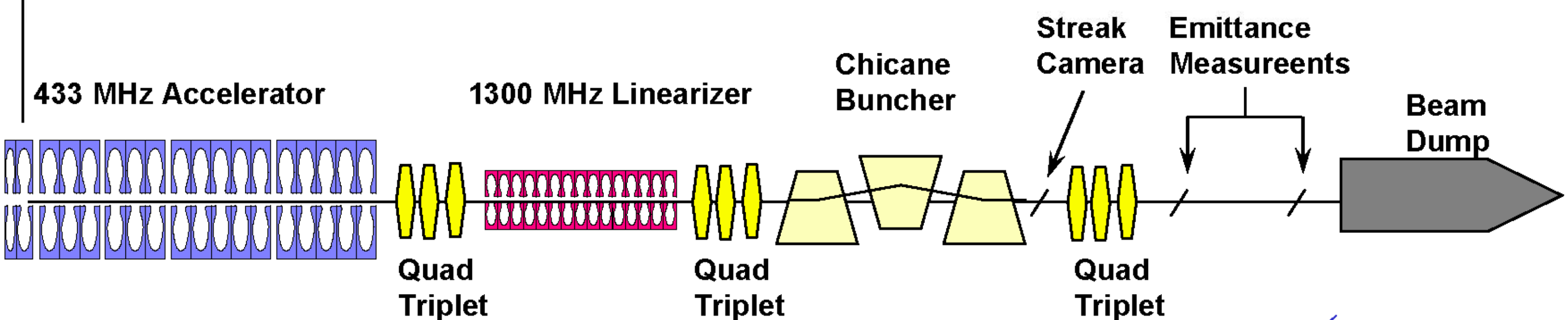
The Boeing Gun: Still the Demonstrated State-of-the Art





Cathode Parameters
K_2CsSb
5%-12% QE @ 527nm
Peak Current 45-132A
Average Current 35 mA
(140 mA @ 25% DC)
Lifetime 1-10 hrs

Gun Parameters
433 MHz
26 MV/m peak field
0.6 MW RF Power



Material Courtesy David Dowell and John Adamski

D. H. Dowell *et al*., *Appl. Phys. Lett.*, **63**, 2035 (1993)

Bialkali Photocathodes in Boeing Gun

D. Dowell et al. Nucl. Inst. Meth. **356** (2-3), 167-176 (1995).

433 MHz RF Gun

26 MV/m E Field

53 psec pulse length (long pulses)

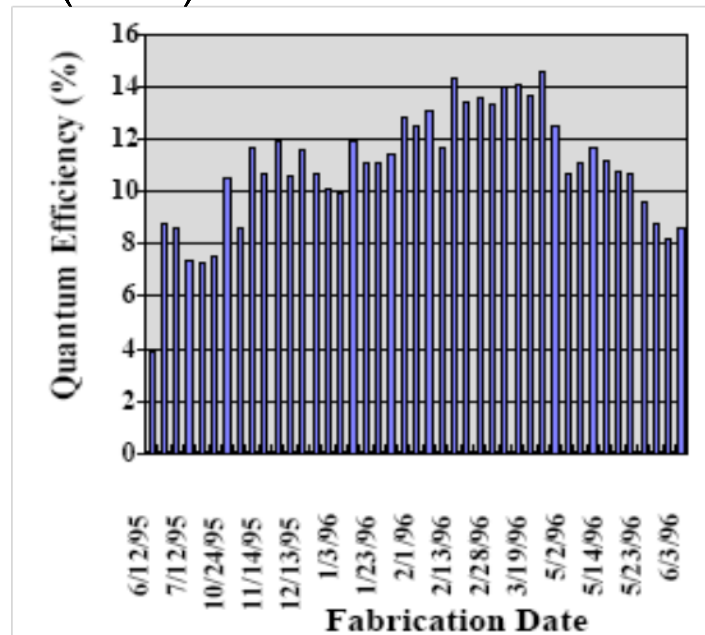
132 A peak current (high current density)

3-5 mm FWHM cathode spot size

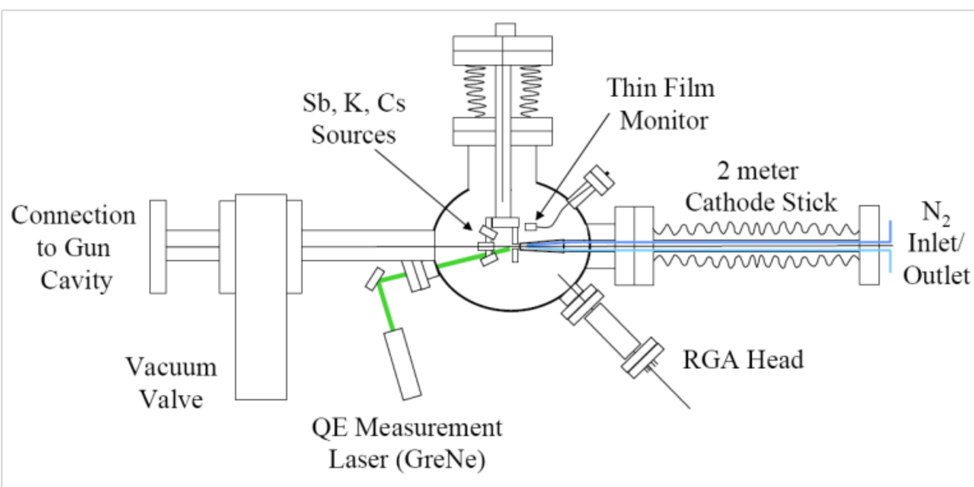
up to 7 nC / pulse

macro rate 30 Hz / micro rate 27 MHz

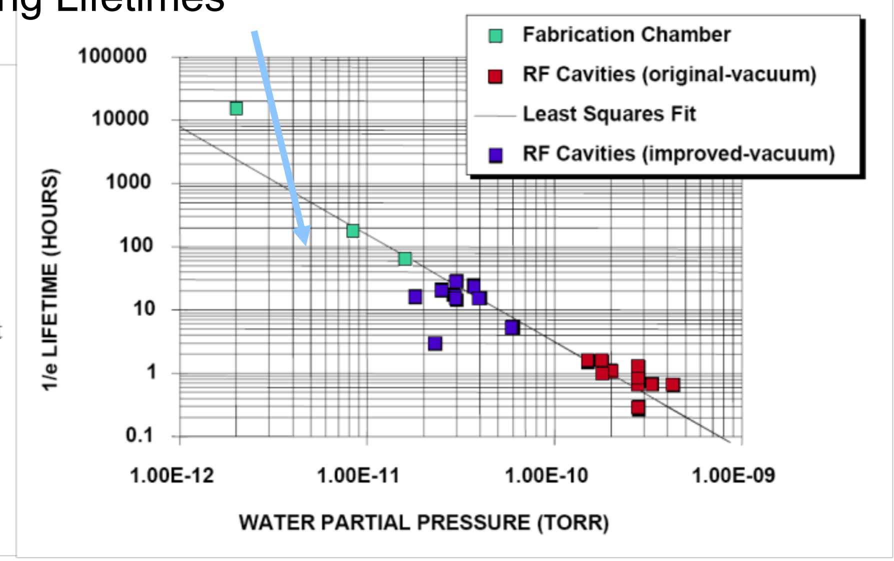
25% duty factor



Current record holder?
– 14% QE w/ green laser



Long Lifetimes



Cs_2Te

Most common cathode for ~1mA injectors

Work function 3.6eV, E_g= 3.2 eV

Good QE for UV light (Max >20%, Average ~7% @ 262 nm)

Deposited in 10^{-11} Torr vacuum

- Typically sequential (Te->Cs); Cs deposition used to optimize QE
- Co-deposition increases performance

Typical lifetime in an RF injector is measured in weeks-months

- Chemical poisoning (and Cs loss?) is major cause of QE loss
- Improve vacuum should help (DC/Superconducting injectors)

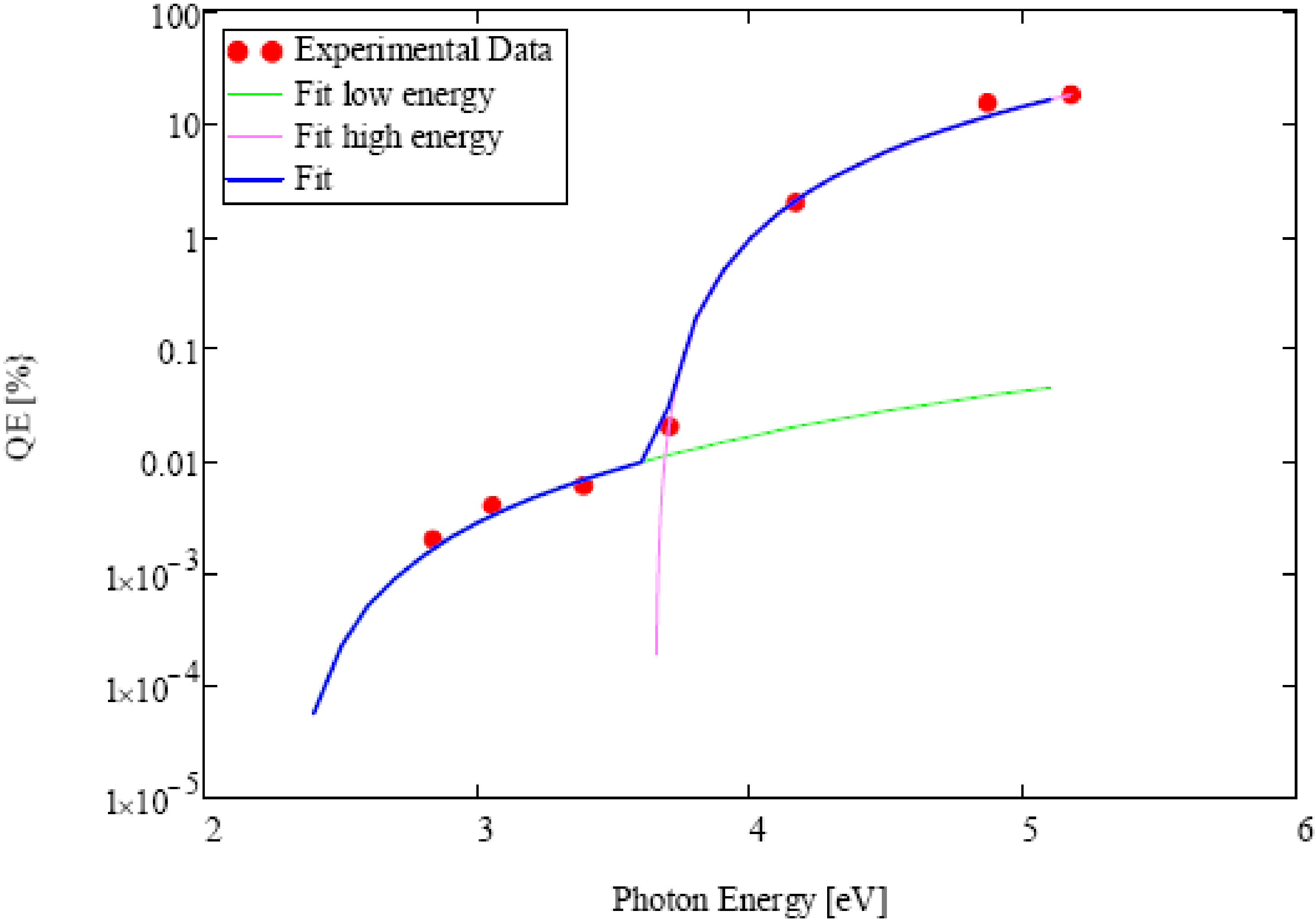
Can be shipped in vacuum suitcase

D. Sertore *et al.*, PAC07, 2760

G. Suberlucq, EPAC04, 64

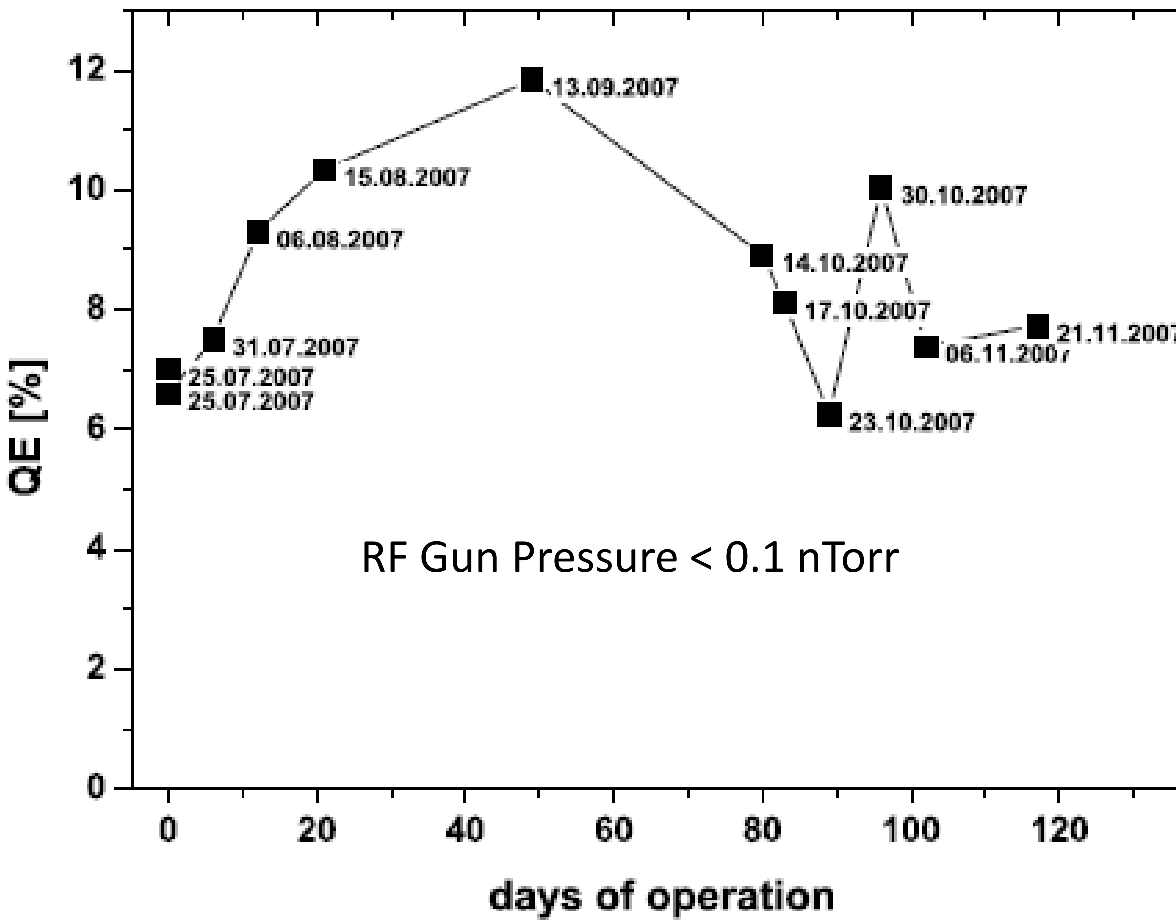
F. Banfi *et al.*, FEL07, 572

Spectral Response



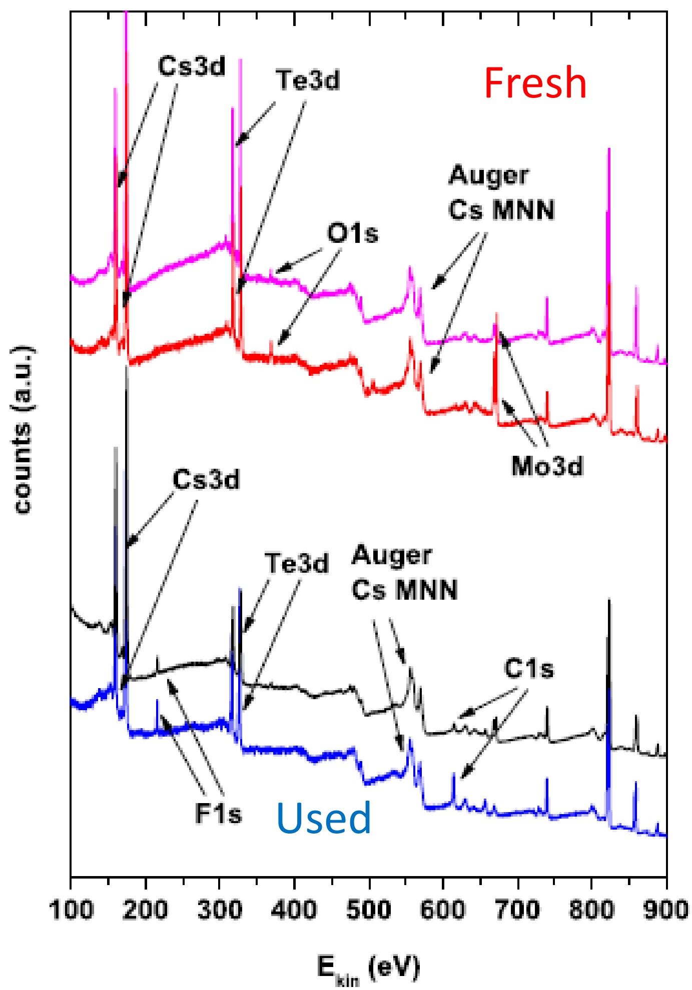
D. Sertore *et al.*, PAC07, 2760

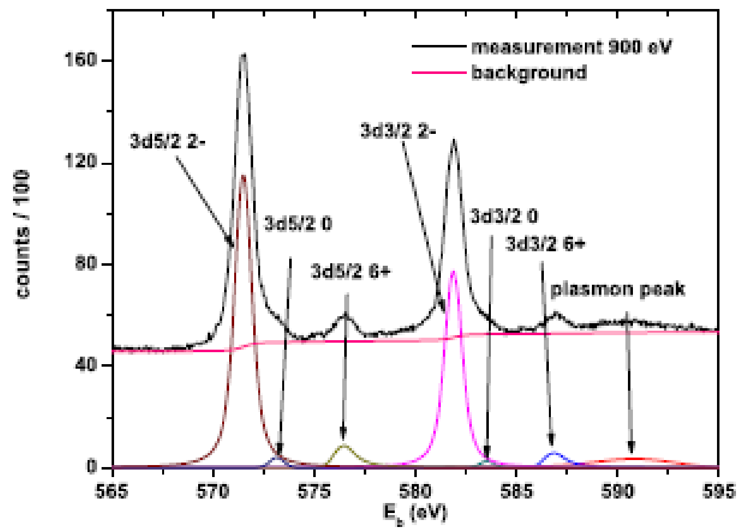
Lifetime in RF gun
FLASH/INFN-LASA



S. Lederer *et al.*, EPAC08, 232

XPS of Cs_2Te





Fresh Cathode

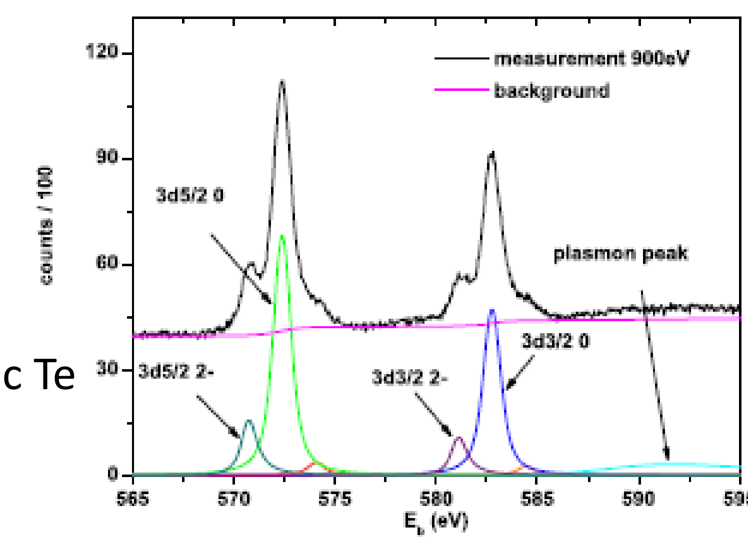
Te 3d has oxidation state of -2

=> Cs_2Te

Used Cathode

Te 3d has oxidation state of 0

=> Metallic Te



Used cathode shows C & F peaks from Teflon components in injector!

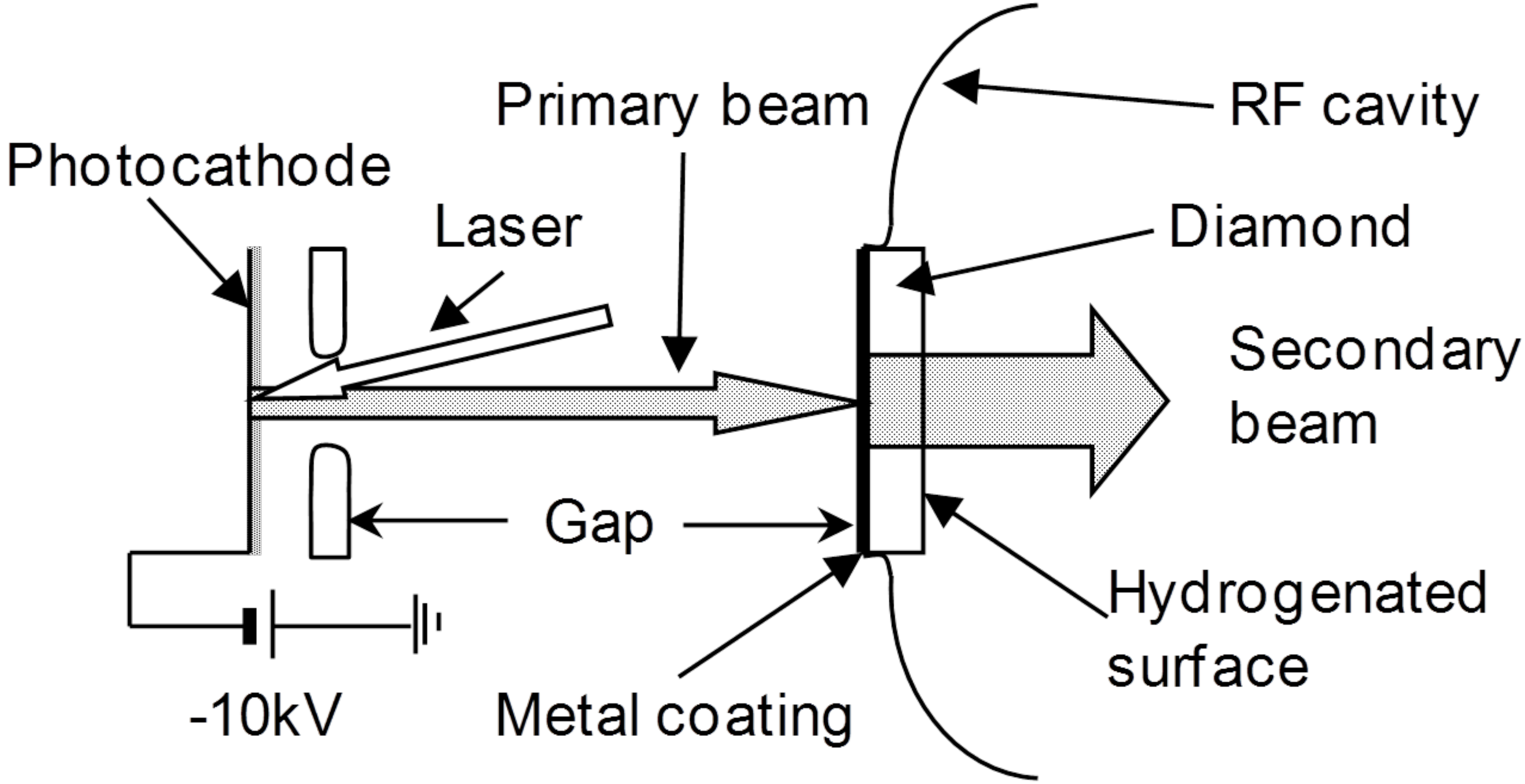
S. Lederer *et al.*, FEL07, 457

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	?

Diamond Amplifier



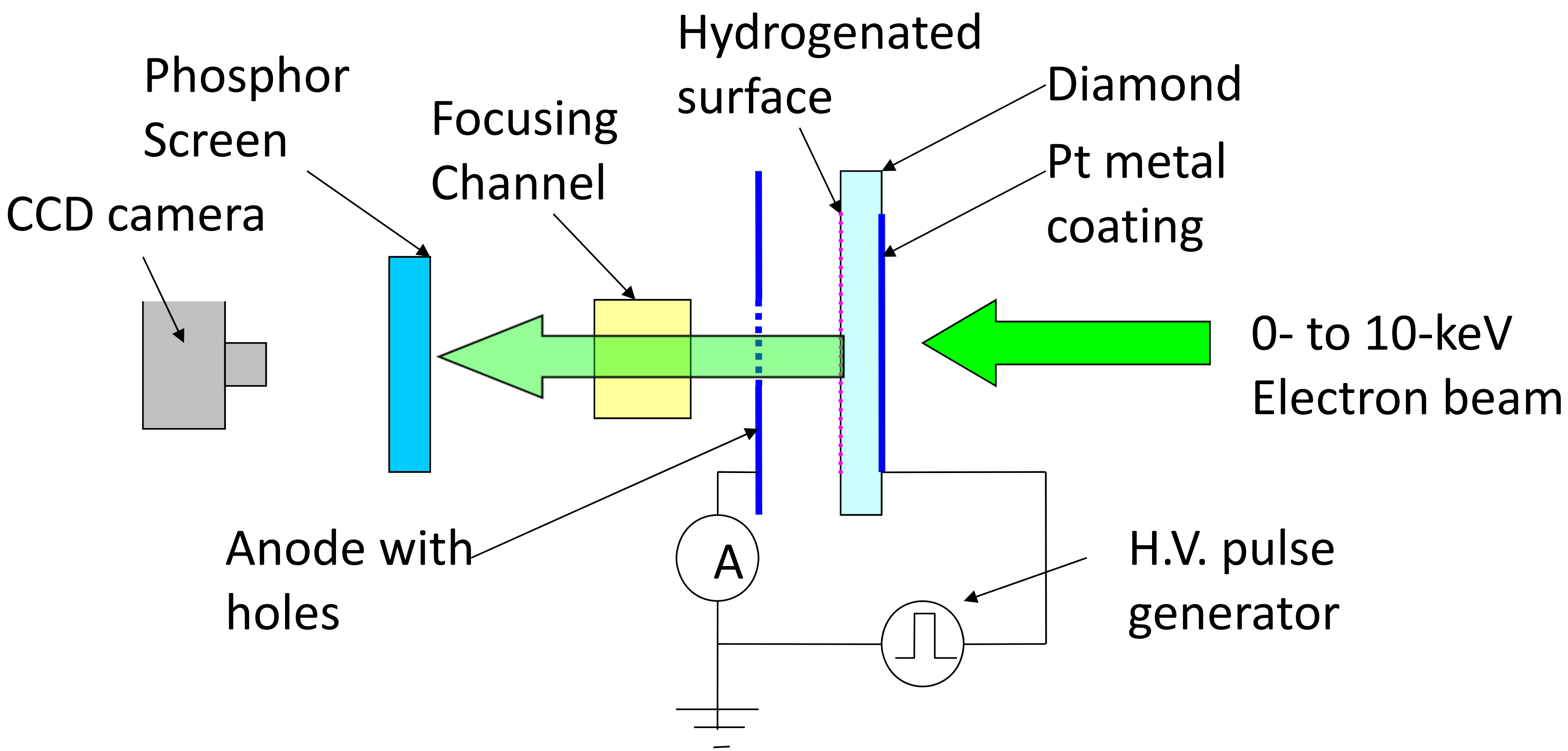
Advantages

Secondary current can be >300x primary current

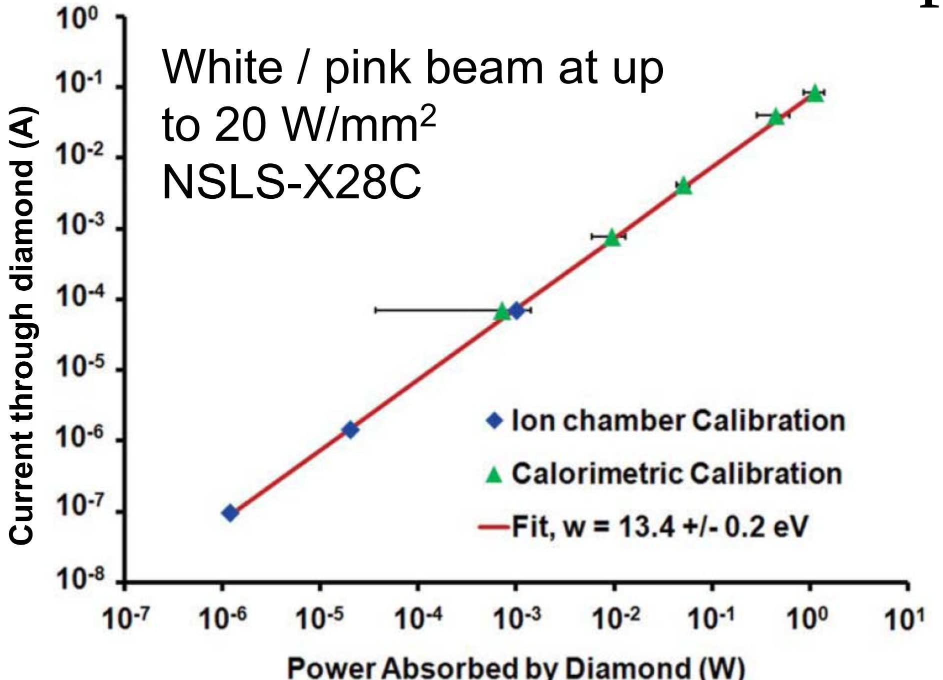
Diamond acts as vacuum barrier

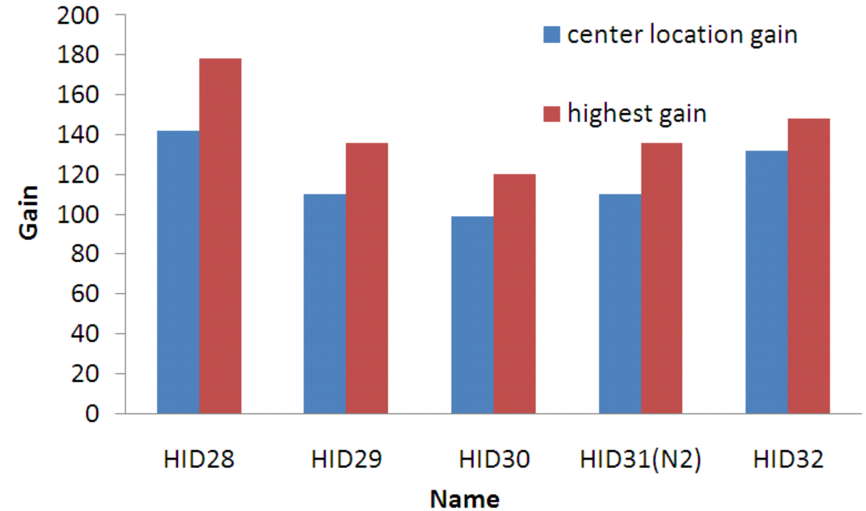
e^- thermalize to near conduction-band minimum

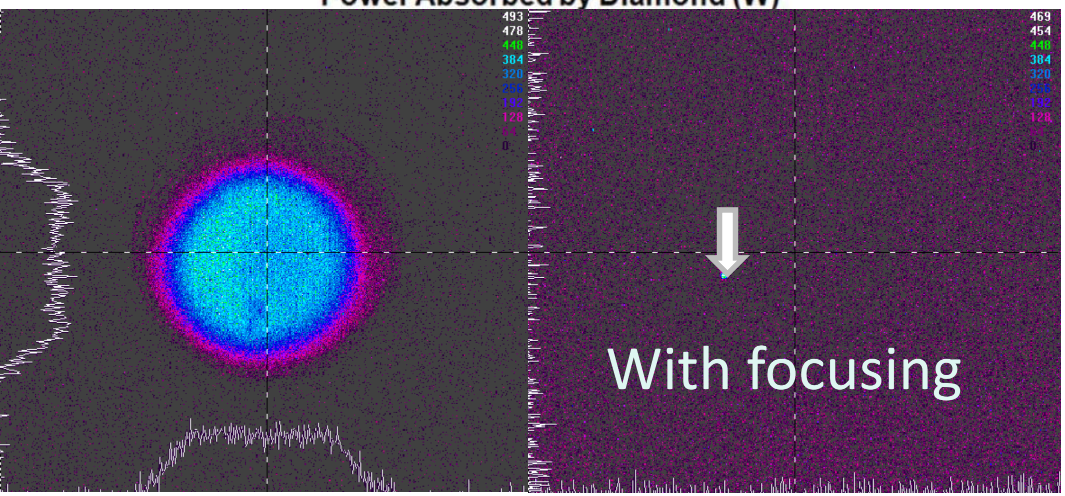
Diamond Amplifier Setup



Diamond Amplifier Results







Demonstrated emission and gain of >100 for 7 keV primaries

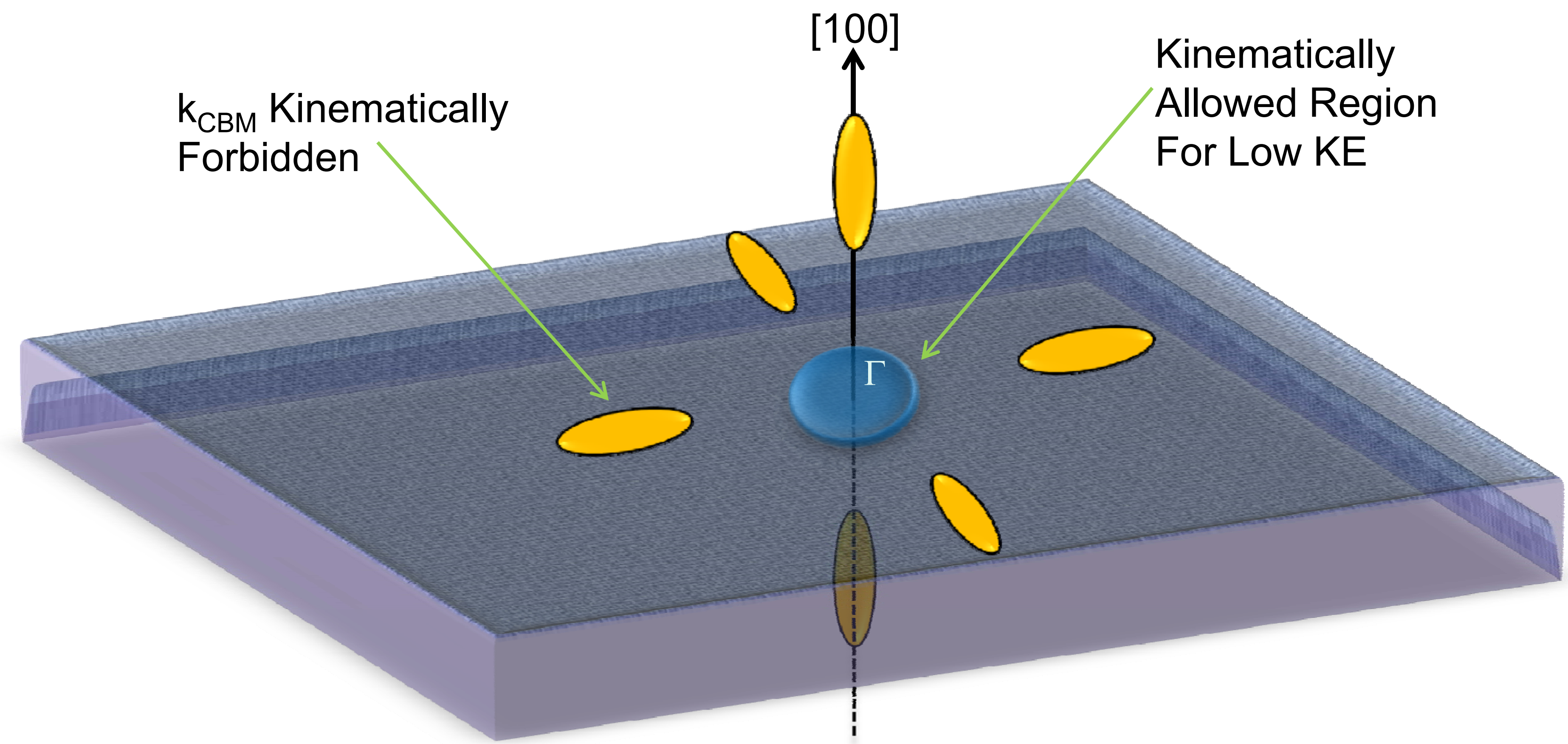
Emitting ~60% of secondaries

X-ray photons have been used to generate current densities in excess of 20A/cm^2 with no deviation from response linearity

X. Chang et al., Phys. Rev. Lett. **105**, 164801 (2010)
J. Bohon, E. Muller and J. Smedley, J. Synchrotron Rad. **17**, 711-718 (2010)

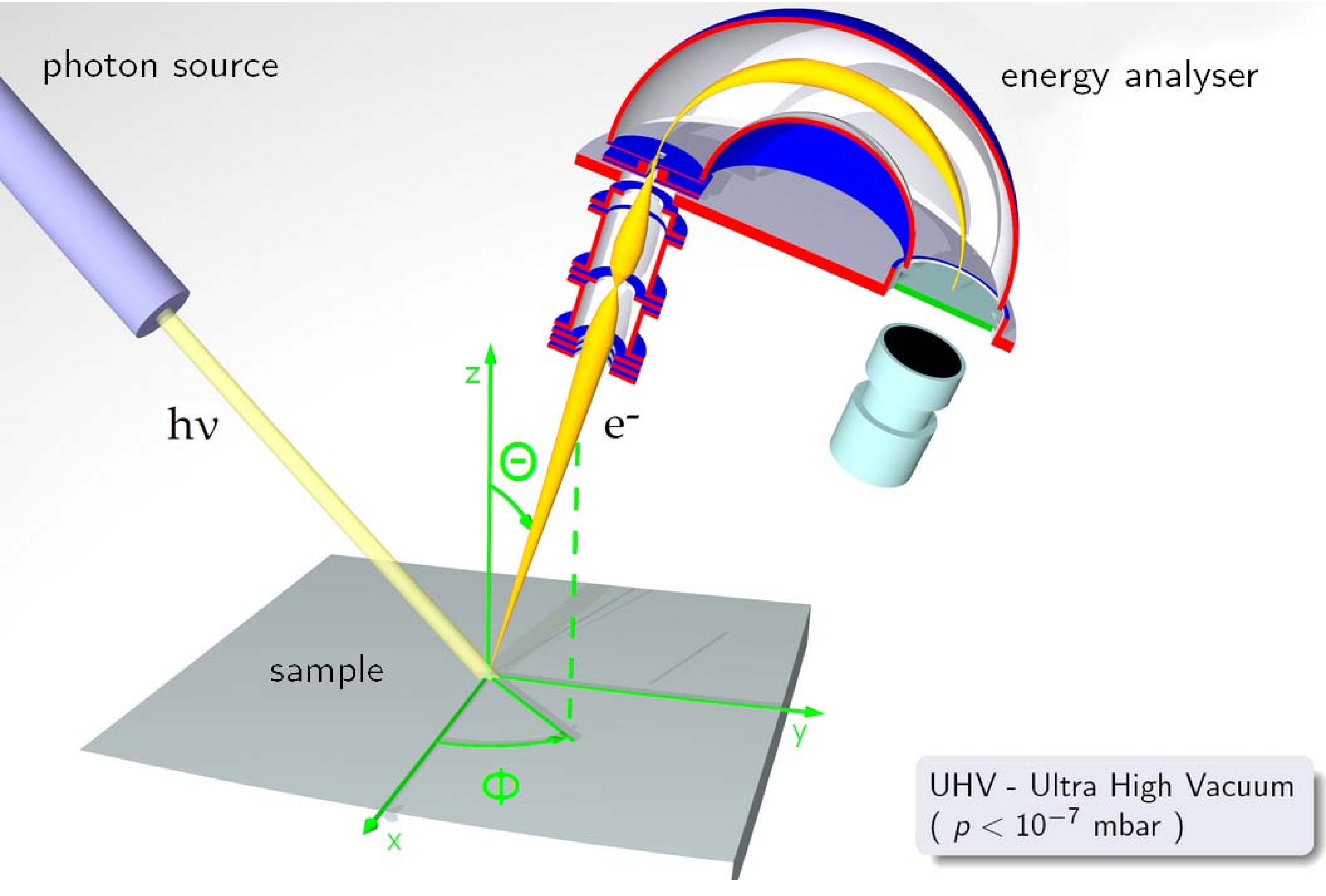
Why Does Diamond Emit?

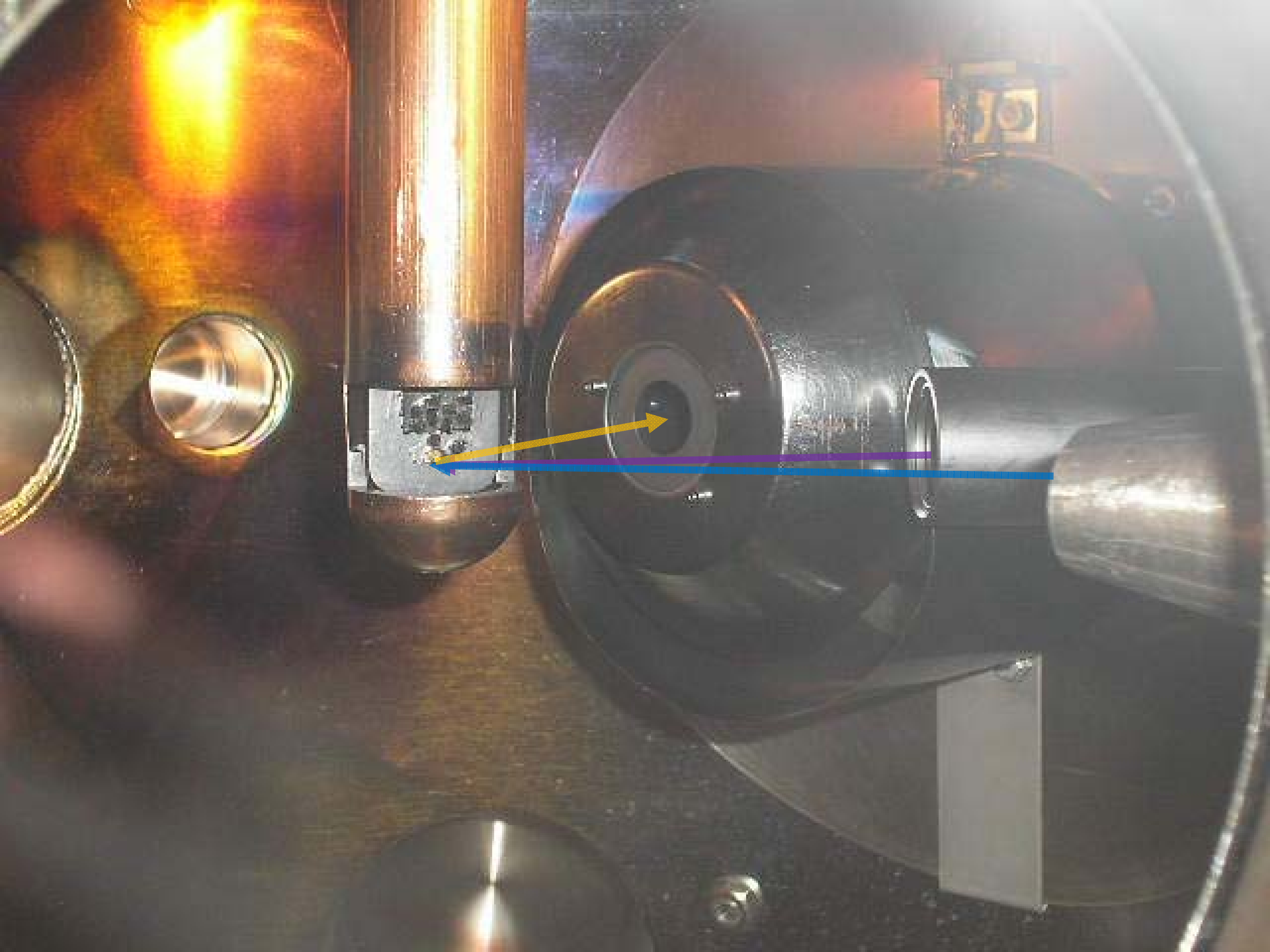
Projection of k-space onto [100] Surface



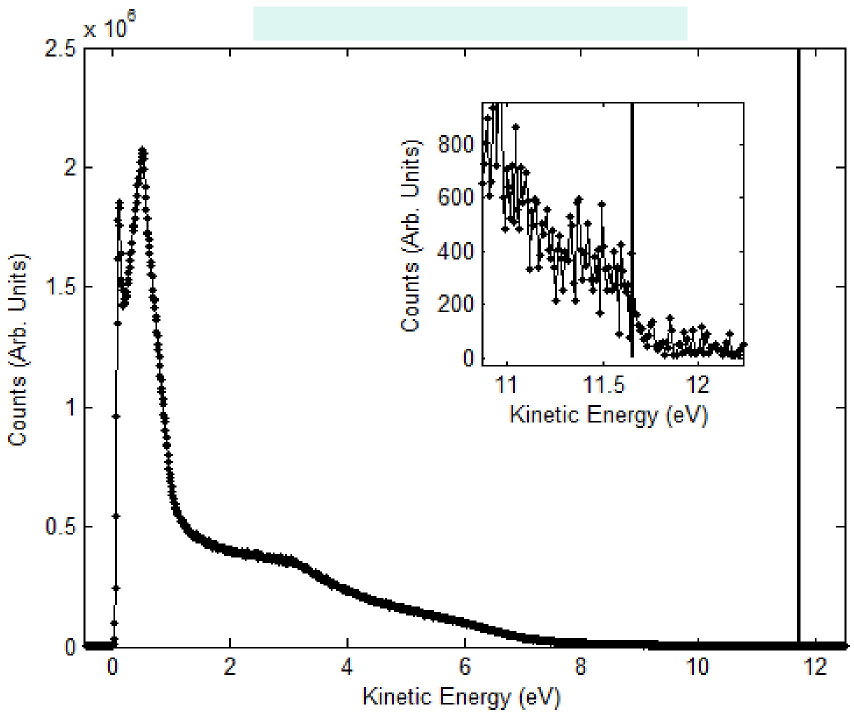
This is the crux of the problem for NEA Diamond

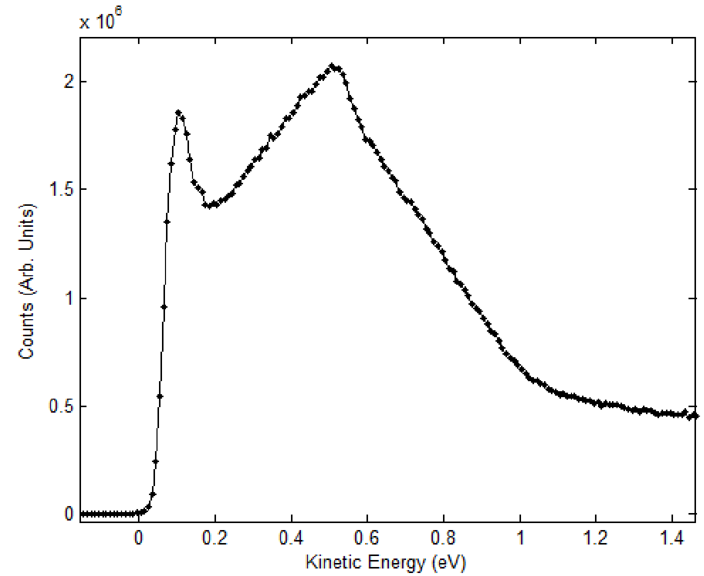
Angle-Resolved Photoemission Spectroscopy





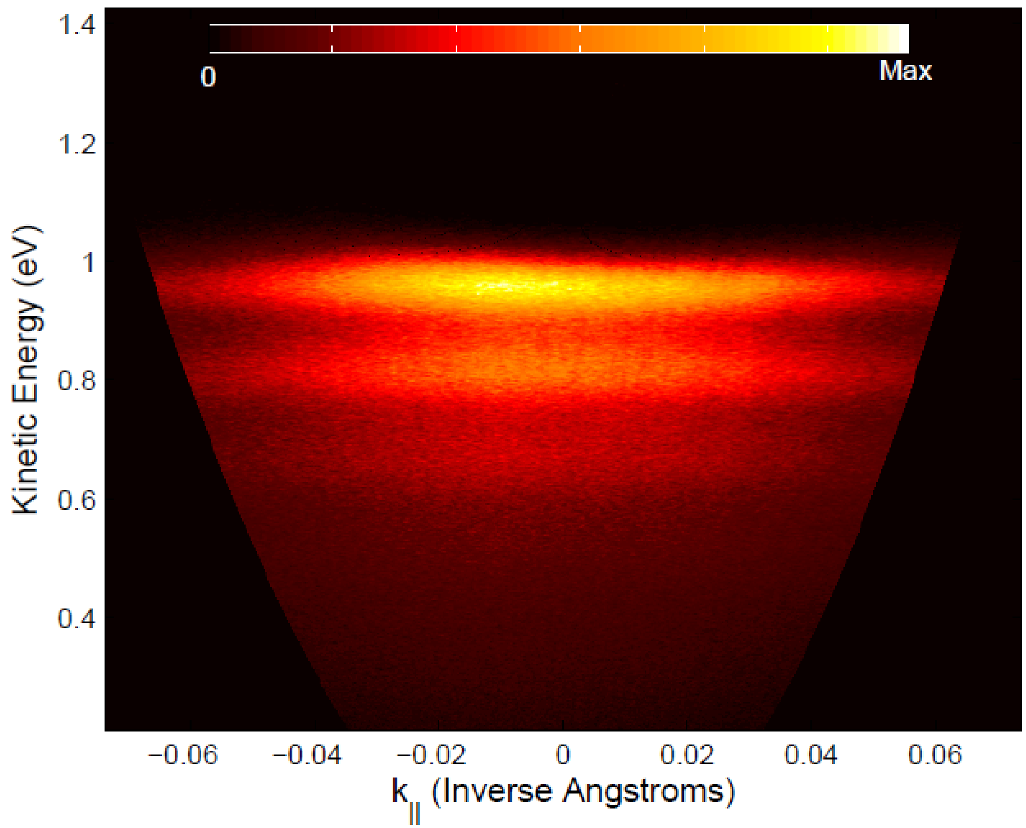
Synchrotron Measurement of B-Doped Diamond





- Photon Energy 16 eV (p-polarized)
- -10 V Bias between sample and ground
- Fermi Edge Detected (Au referenced) – Past Metal-Insulator Transition (barely)
- Typical features associated with NEA (LE peak…)

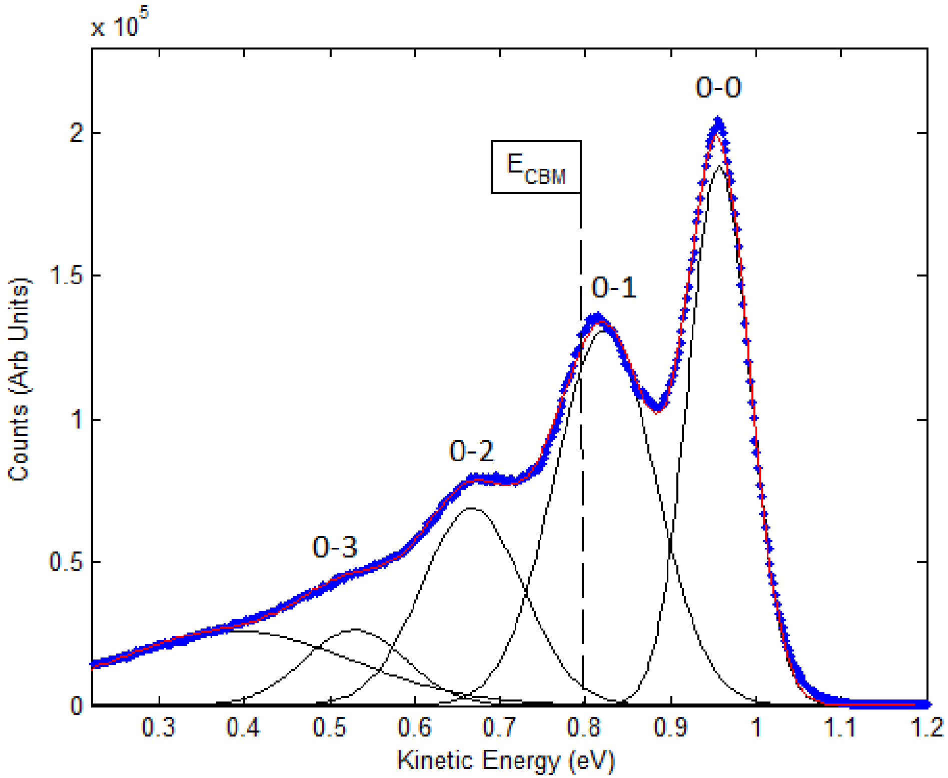
6 eV Laser ARPES



- E_F located at 1.662 eV according to Au reference!
- Very efficient process (scan is short, slits are SMALL)
- KE scale referenced to E_{vac} for NEA material

J. D. Rameau, et al., Phys. Rev. Lett. **106**, 137602 (2011)

EDC at Normal Emission



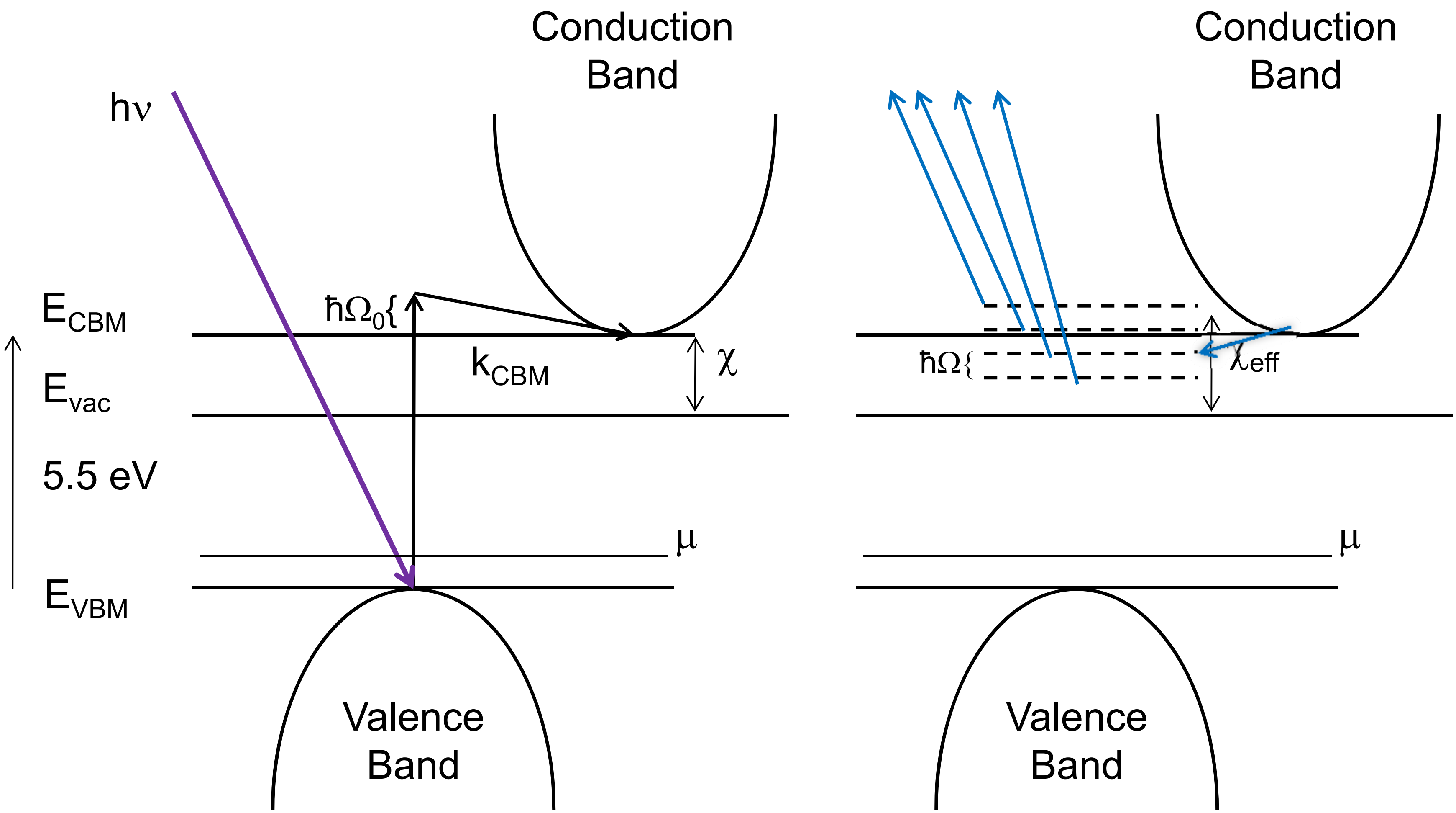
Data Points
Total Fit
Decomposition

χ_{peak} = .955 eV

$\Delta E_{peak} = \hbar\Omega_0 \sim 145$ meV

- Narrow cut around normal emission
- Gaussian fits for all peaks
- *No Background* (e.g. from A_{inc}, “bad” secondaries)
- Angular spread ~15 degrees

Excitation in the Bulk   Emission at the Surface



Optical Phonon Spectrum

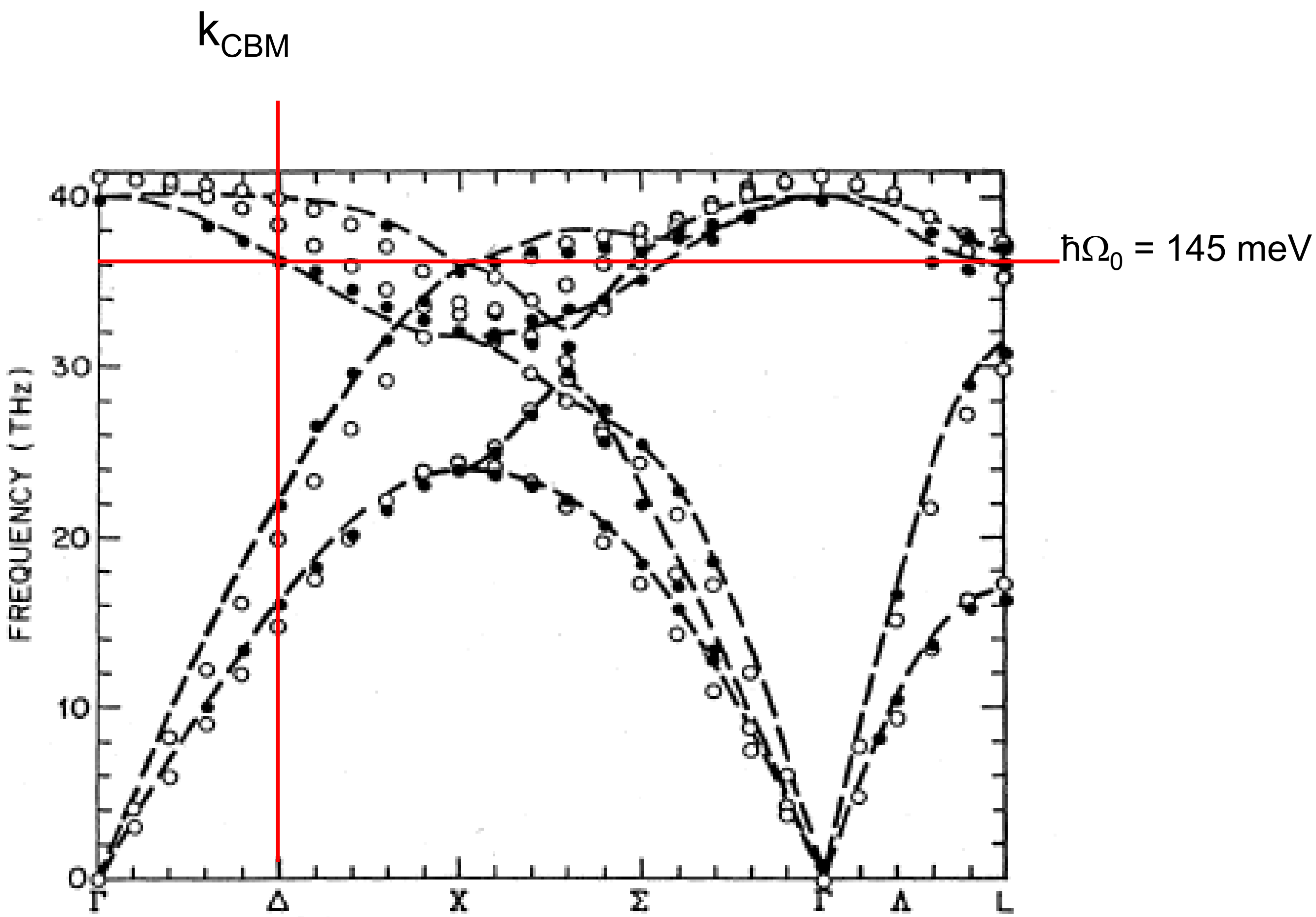


FIG. 2. Phonon dispersion curves for diamond. The open circles and dashes correspond to fits δ_1 and δ_4 in Table I. The solid circles are experimental data from Ref. 14.

E.O. Kane PRB 31, 7865 (1984)

Summary

Lead is an attractive option for medium current injectors with high bunch charge. The deposition of lead can be accomplished without compromising the RF performance of the cavity

Alkali Antimonides represent an interesting and fruitful path toward even higher currents. In-situ characterization will hopefully lead to higher QE, longer lifetime, and ***less cooking!***

The diamond amplifier may provide a path to reaching ampere level average current. Many challenges await.

Thanks!

D. Dowell; P. Knesiel, M. Poelker, J. McCarter, R. Mammai; J. Sekutowicz; R. Nietubyc; H. Padmore, T. Vecchione; K. Attenkofer, S. Lee; I. Ben-Zvi, T. Rao, E. Muller, X. Chang, J. Rameau, J. Bohon and my colleagues at BNL;