Surface characterization of GaAs photocathodes and high current operation experience at the JLab FEL

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Photocathode Workshop, Cornell University, Ithaca NY

October 8-10, 2012

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Motivation

- We had 2 GaAs wafers (each with visible damage spots) removed from FEL gun that had delivered thousands of Coulombs between 2003 and 2007.

- And also one more GaAs wafer that was just heat cleaned but never installed in the gun.

- We were curious about surface characterization, crystal dislocations, implanted ion species, etc., but did not have the chance or the facilities to do this until...
- …we were introduced to Wayne Hess and his team at PNNL who did a thorough analysis.

The PNNL team analyzed 4 bulk GaAs samples#

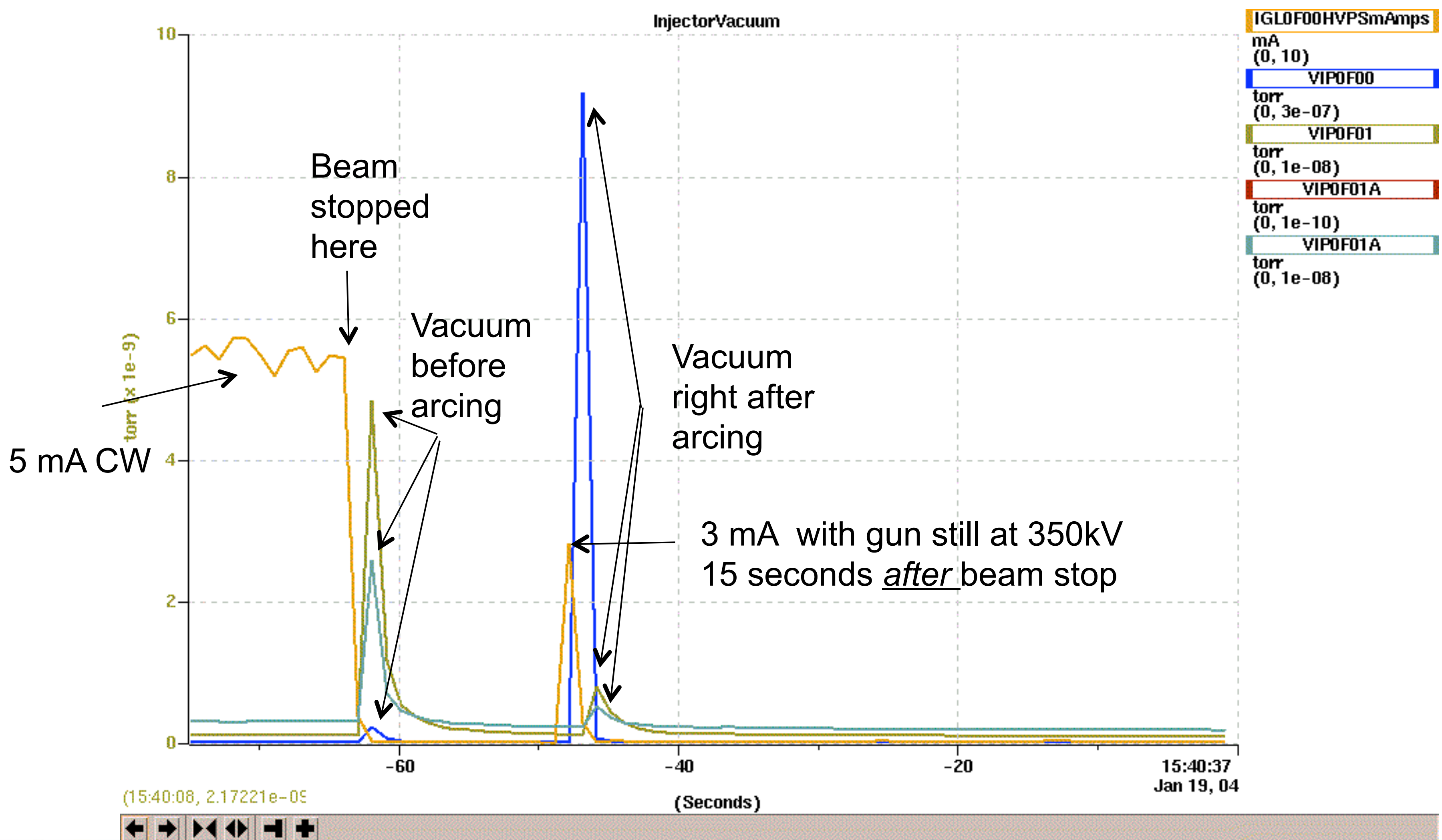
Sample	Coulombs delivered	Heat cycles*	Operating current (mA)	Charge lifetime+ (C)	CW beam time (hrs)	Time in gun (months)	Precondition
Control	0	0	N/A	N/A	0	0	None
Heated	0	1	N/A	N/A	0	0	None
A	1000	12	Up to 9	130	130	12	Isopropanol, acetone, DI, H-cleaned
B	7000	9	1-8	550	900	36	Anodized, Isopropanol, acetone, DI, H-cleaned

Each sample is 30 mm diameter, 0.6 mm thick and Zn-doped
* Each heat cycle is 1 hour ramp to 550°C and 3 hour soak
+ 1/e lifetime between re-Cs (QE replenishing) at 5mA CW

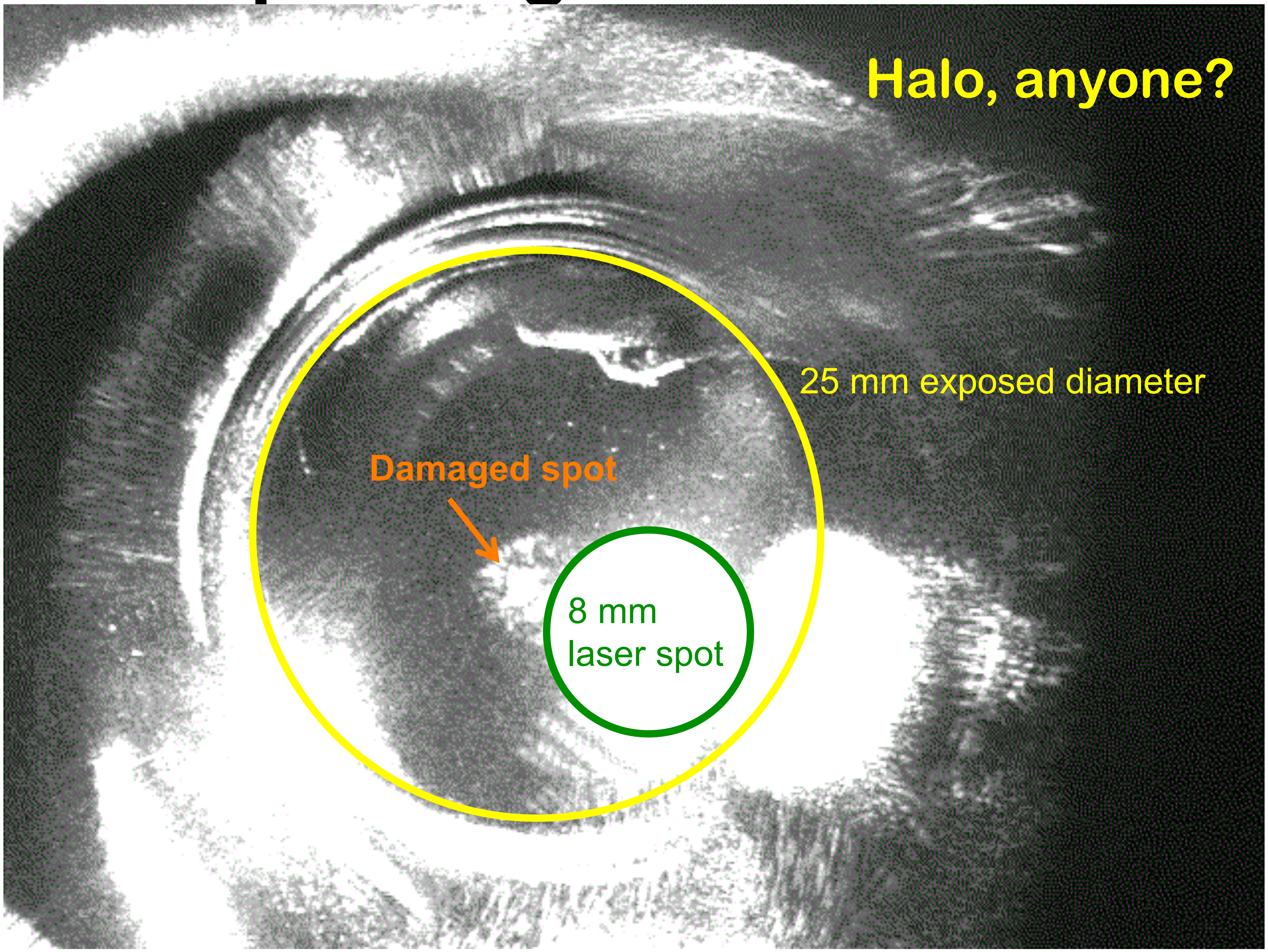
Sample “A” operational history

- Installed in FEL gun in 2003
- Operational at 350kV
- Operated reliably at 5 mA CW
- Achieved 9 mA CW for a few minutes
- Stable FEL operation >5 mA CW limited by halo
- In particular FEL operation > 8 mA CW often led to sudden beam stop
  - resulted in total loss of QE and produced damage spot
  - QE fully recovered by heat clean and subsequent NEA re-activation
  - observed increased beam halo after each event
- Removed from gun in 2004 b/c of excessive halo

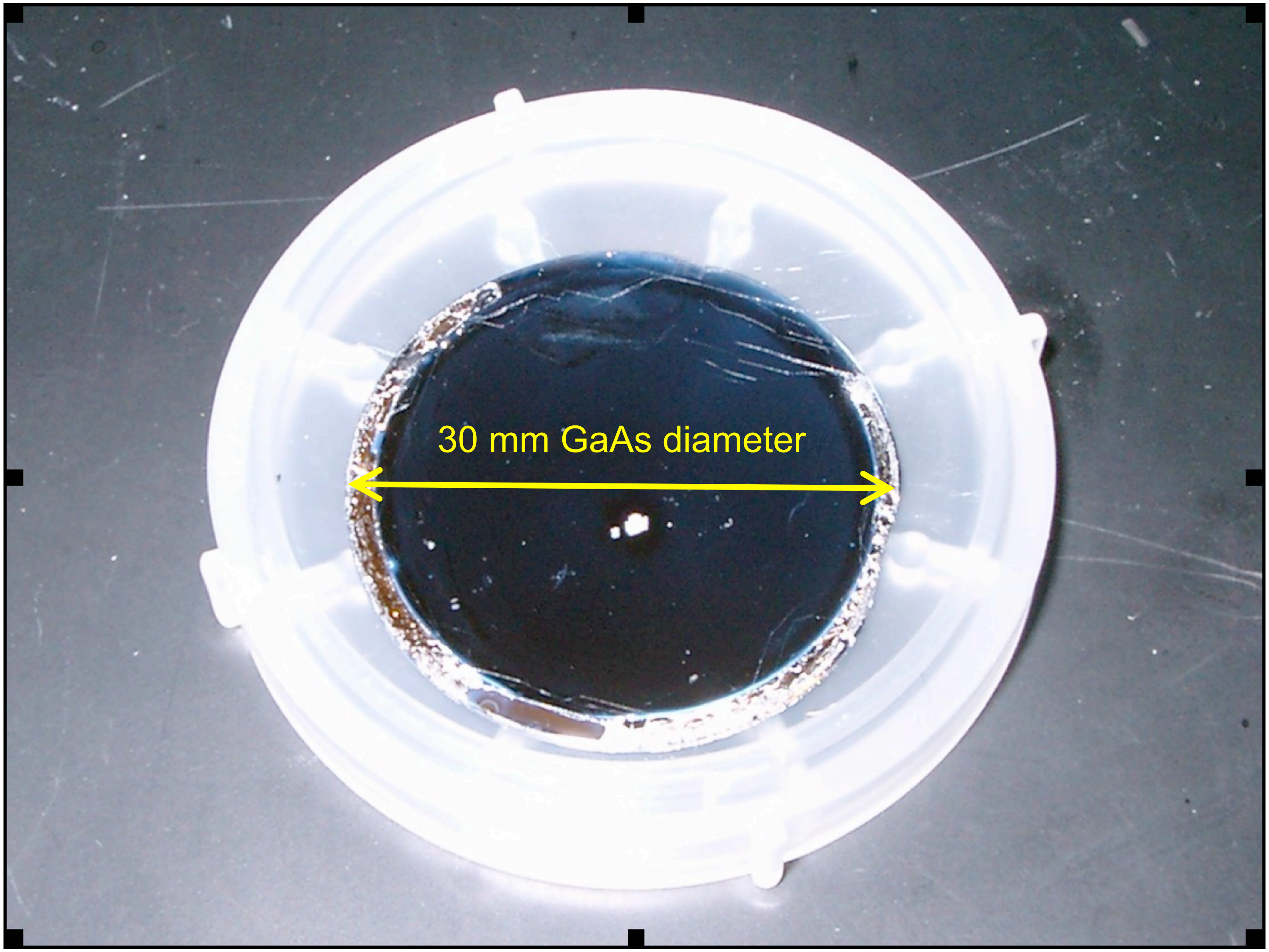
At least 3 mA of current at 350kV during the cathode 'arcing'



Picture of sample "A" while operating at 7 mA CW



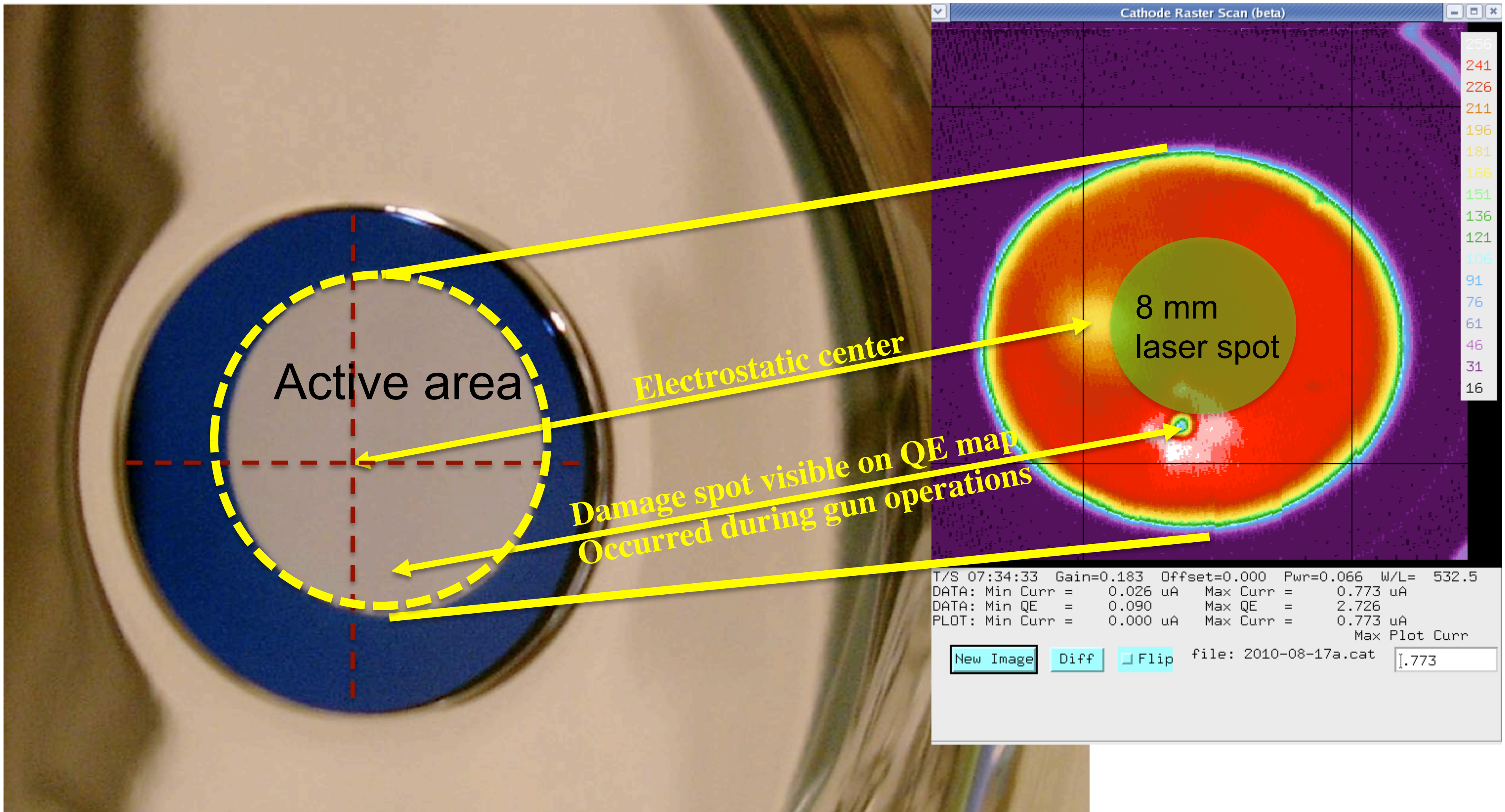
Sample "A" removed from gun in 2004



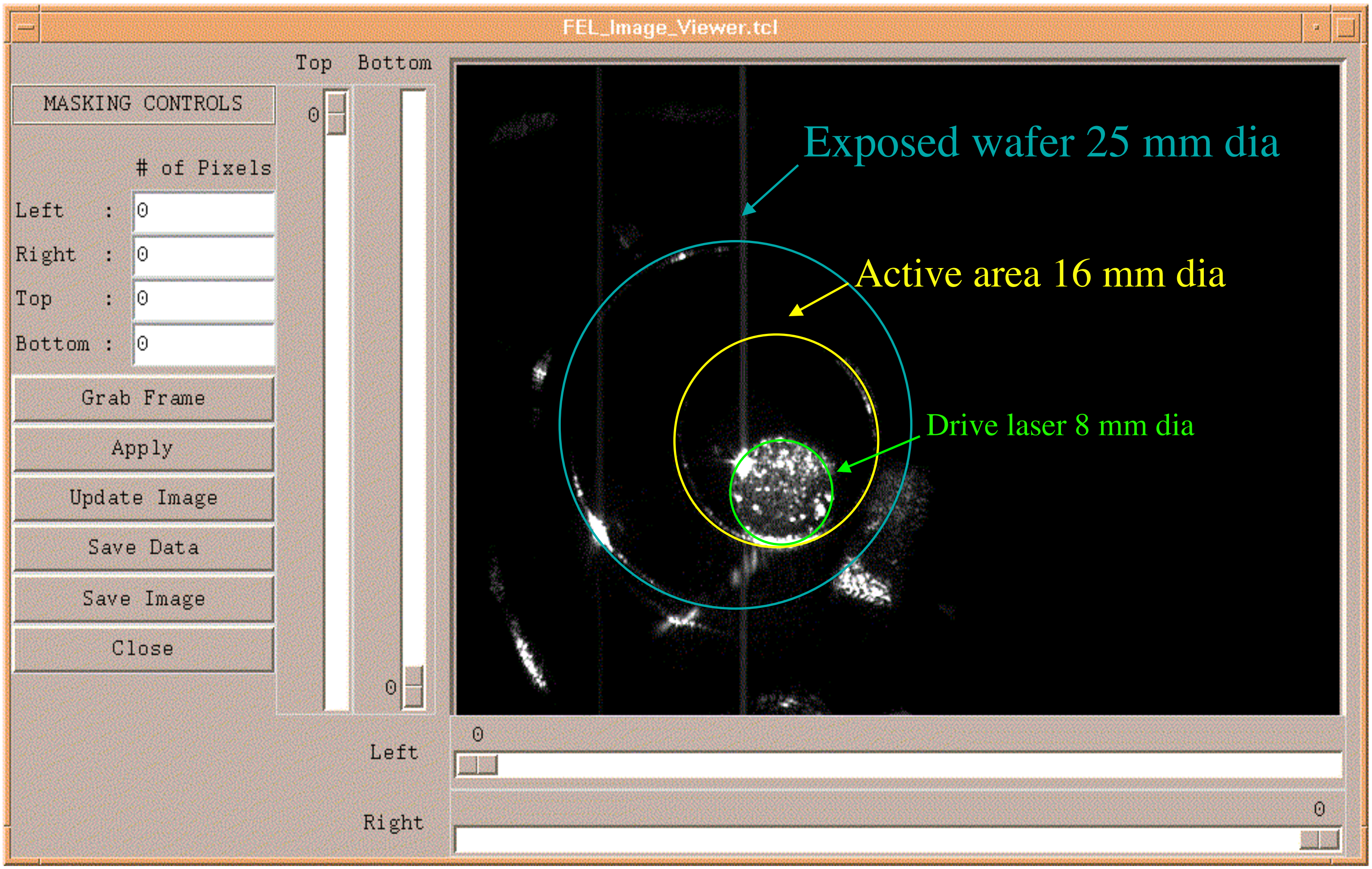
Sample “B” operational history

- Sample was anodized to reduce beam halo
- Installed in FEL gun in 2004
- Operational at 350kV for 3 years
- Operated reliably at 5-8 mA CW
- Stable FEL operation >8 mA CW limited by halo
- Similar as with sample “A”, FEL operation > 8 mA CW often led to sudden beam stop
  - resulted in total loss of QE and produced damage spot
  - QE fully recovered by heat clean and subsequent NEA re-activation
  - observed increased beam halo after each event
- Removed from gun in 2007 during gun rebuilt after insulator puncture during HV conditioning

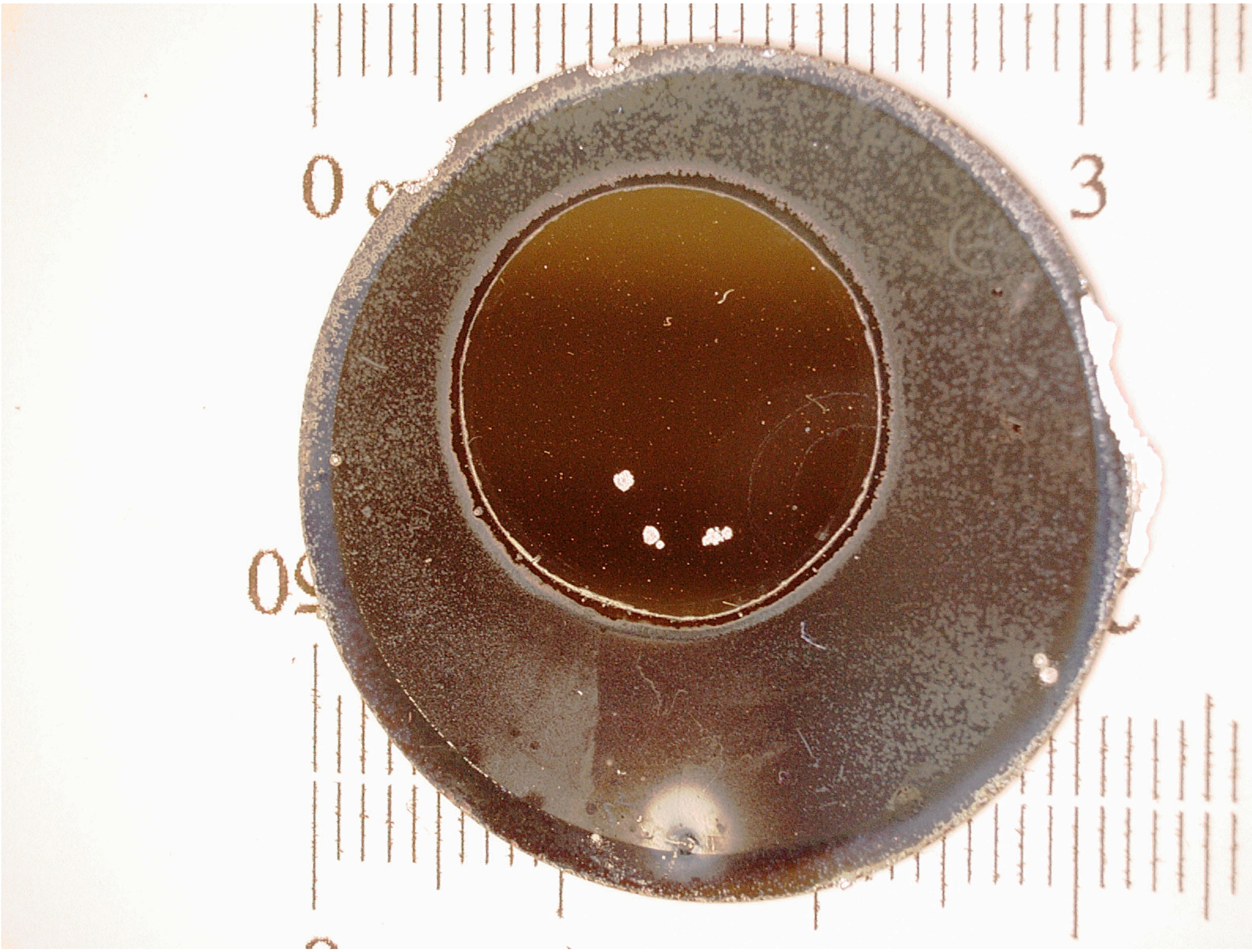
Picture of sample “B” mounted to the gun electrode and corresponding QE map



Picture of sample "B" taken while delivering 5 mA CW



Sample "B" removed from gun in 2007



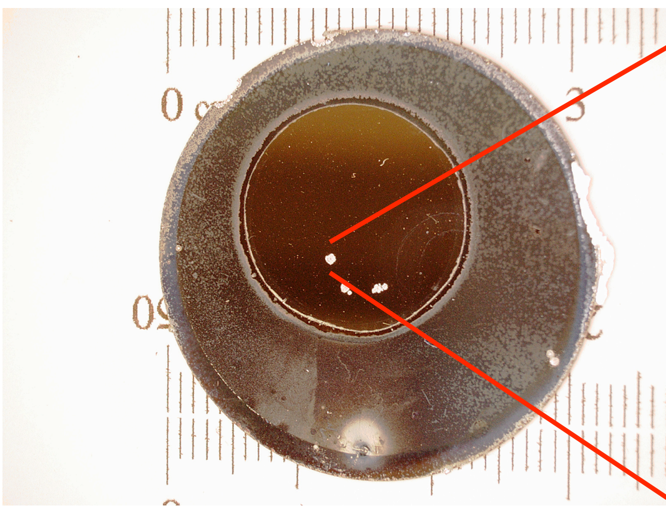
Analyzing techniques utilized…

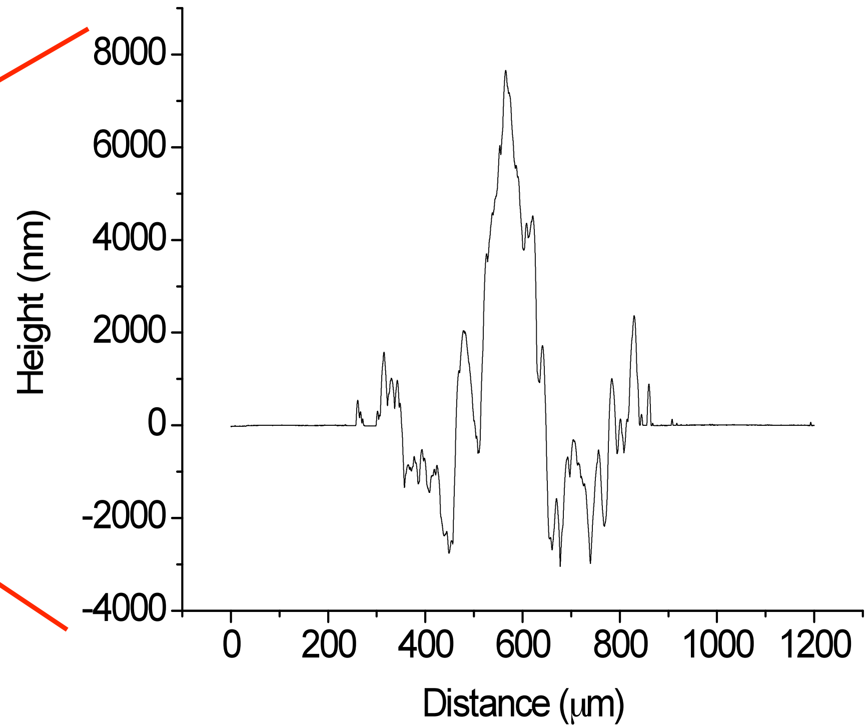
- Profilometry
- Atomic Force Microscopy (AFM)
- Helium Ion Microscopy (HIM)
- Rutherford Backscattering Spectrometry (RBS) and
- Time Of Flight Secondary Ion Mass Spectrometry (SIMS)

… to study

- Influence of extended hours of operation on topography
- Chemical composition on damaged and undamaged regions
- Overall crystalline quality, particularly under damage spots
- Effect of ion back bombardment in terms of crystalline quality and implanted species
- Surface Cs and contaminations levels

Profilometry measurements on one of the damage spots shows an 8 micron tall feature





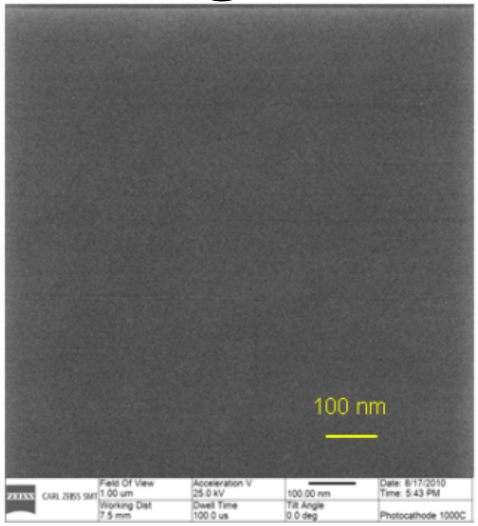
All of the damage spots on both removed samples show similar profiles

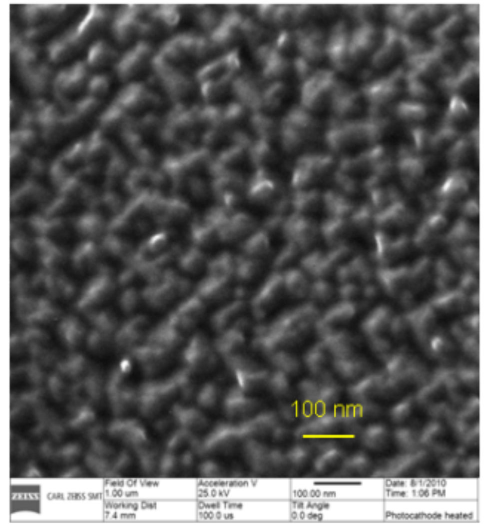
AFM measurements indicate that surface roughness seems to decrease with operational time in the gun, and does not increase with additional heat cycles

Sample	Coulombs delivered	Heat cycles*	Operating current (mA)	Charge lifetime+ (C)	CW beam time (hrs)	Time in gun (months)	AFM roughness (nm)
Control	0	0	N/A	N/A	0	0	0.2
Heated	0	1	N/A	N/A	0	0	5.5
A	1000	12	Up to 9	130	130	12	4.6
B	7000	9	1-8	550	900	36	4.0

Helium Ion Microscopy is consistent with AFM roughness measurements…

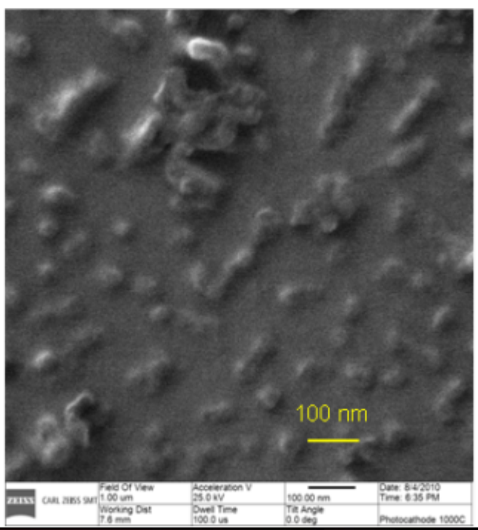
Control
No heat
0.2 nm

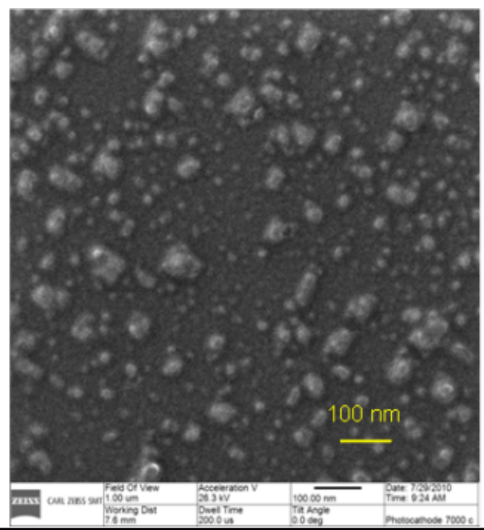




Heated
1 heat cycle
5.5 nm

Sample A
12 heat cycles
4.6 nm

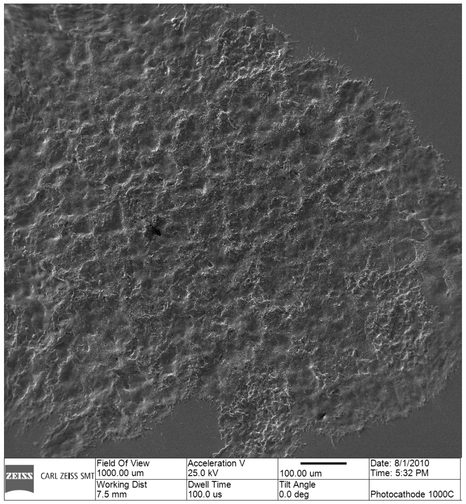


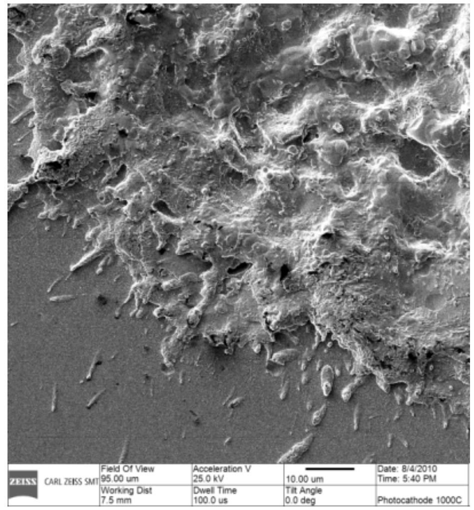


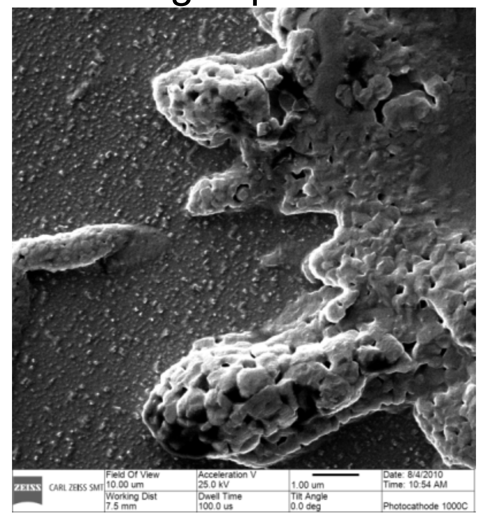
Sample B
9 heat cycles
4.0 nm

…and provides really cool images of damage spots

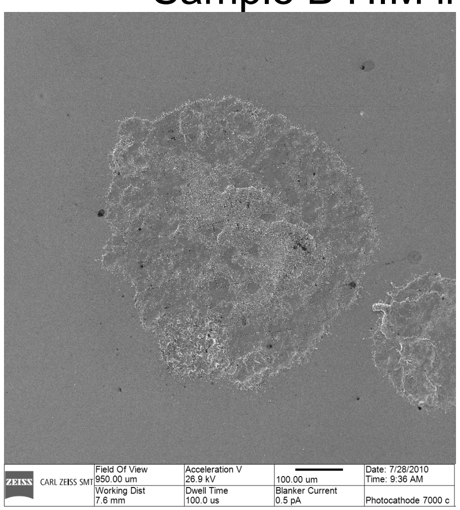
Sample A HIM images at increasing magnification of damage spot

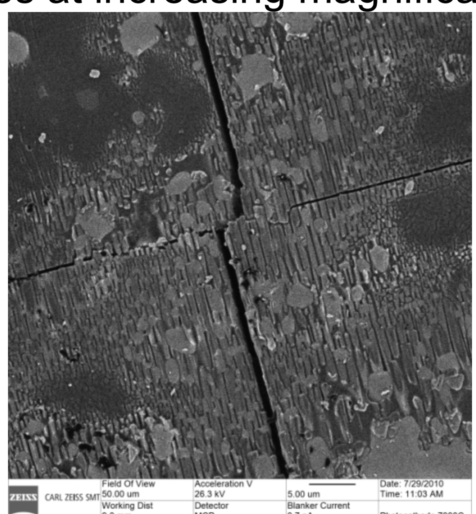


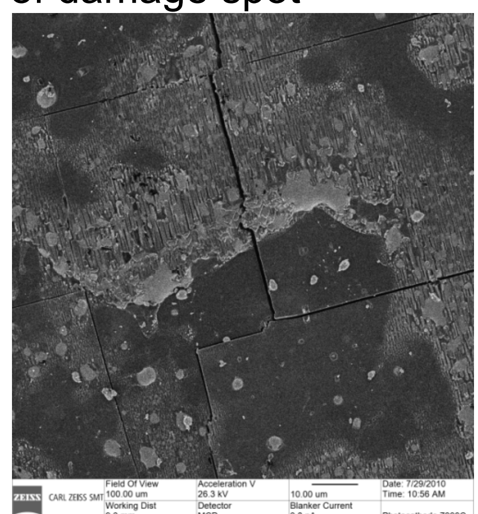




Sample B HIM images at increasing magnification of damage spot







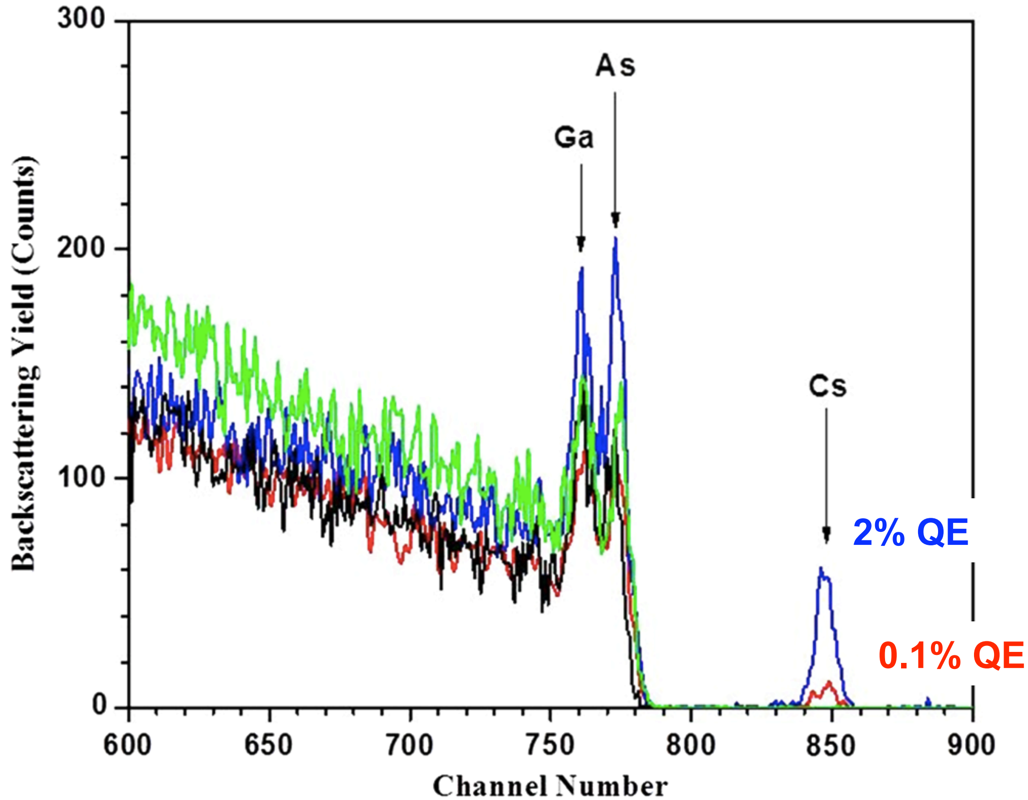
RBS results show evidence of surface Cs sputtering but no significant crystal damage

minimum yield

χ_{min} 3% = well order crystal

Sample	χ_{min}	AFM roughness
Control	5.0%	0.2 nm
Heated	4.5%	5.5 nm
Sample A	7.4%	4.6 nm
Sample B	4.8%	4.0 nm

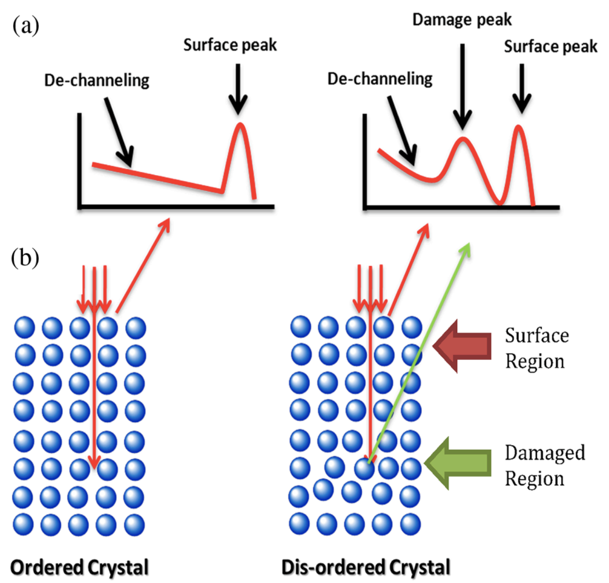
These values indicate considerable crystal order, with respect to the bulk of the crystal, even though these surfaces display well-defined nanostructures.

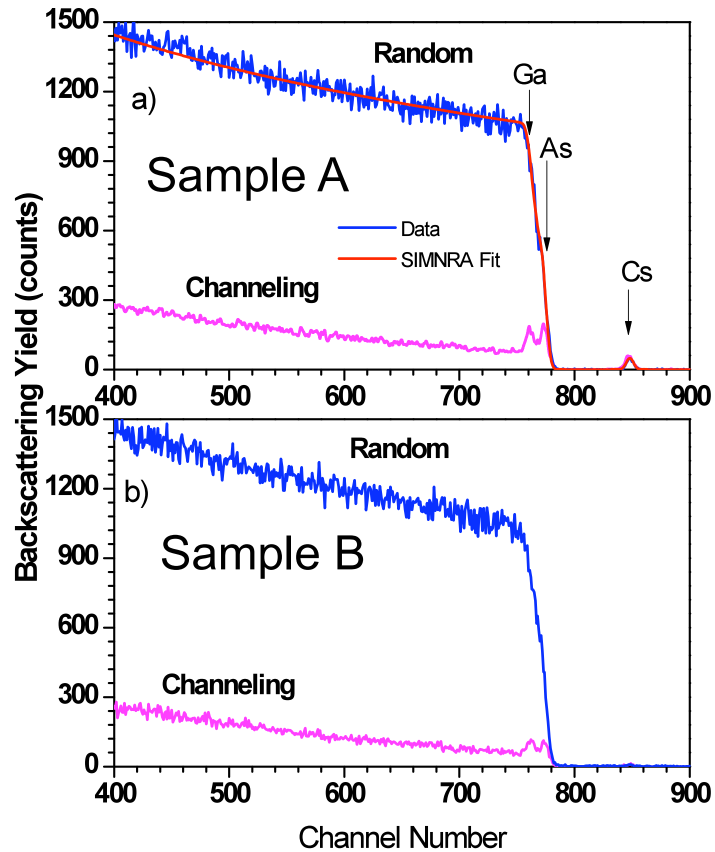


RBS taken in the laser-illuminated region

RBS shows no indication of crystal damage

If loss of QE is due to bulk wafer damage induced by ion back bombardment, then we would expect to observe damage peaks in the channeling spectrum.

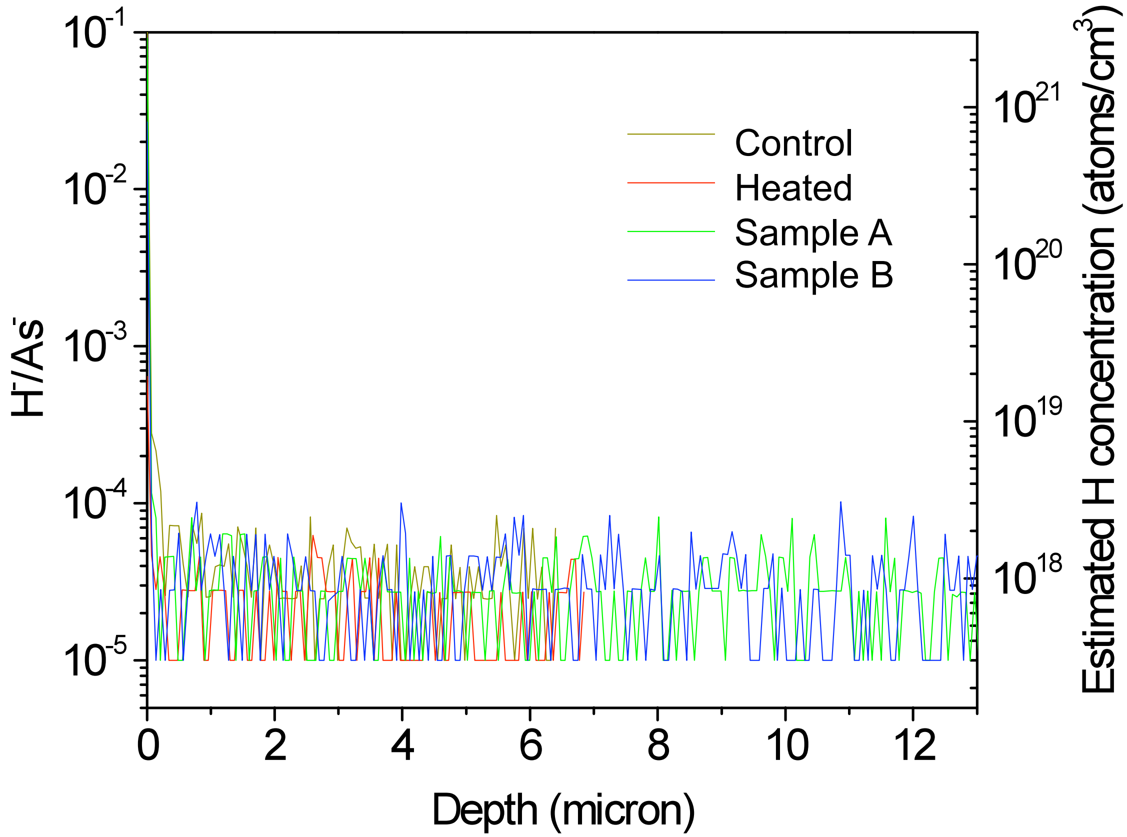




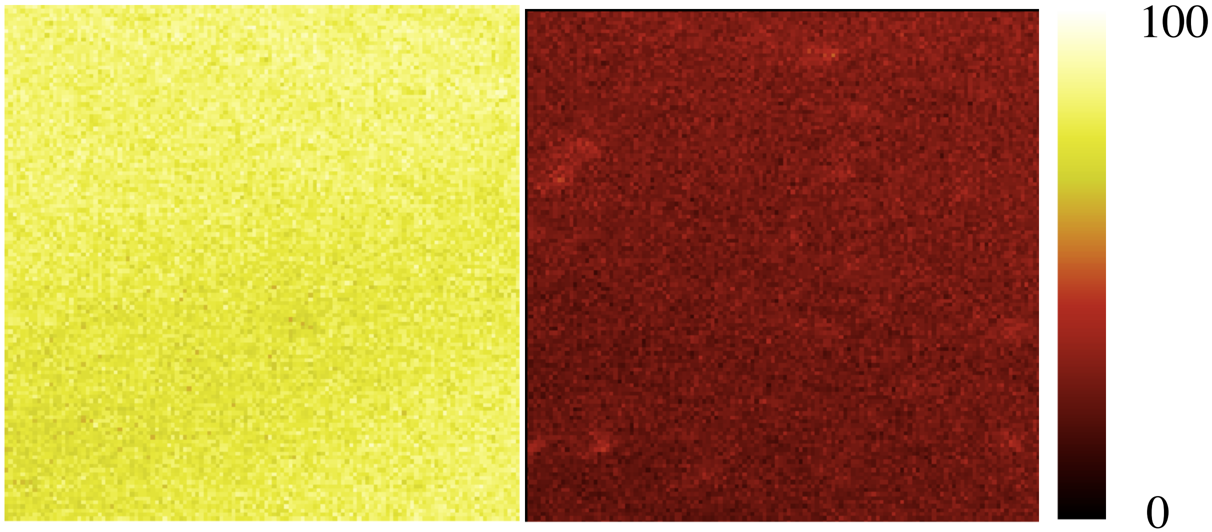
Calculations indicate that hydrogen implantation should peak at a depth of 1.5 μm which, in turn, should lead to a damage feature near channel 450.

The channeling spectra do not show any evidence of damage peaks.

The SIMS depth profiles show no evidence of hydrogen implantation. Hydrogen concentrations in all the samples are lower than our detection limit of 1×10^{18} atoms/cm^3



SIMS-measured Cs surface concentrations are consistent with those determined by RBS



Sample A, 2% QE prior to removal from gun

Sample B, 0.1% QE prior to removal from gun

Positive ion SIMS images obtained from sample A (1000 coulomb) and from sample B (7000 coulomb) showing relative Cs concentrations. The field of view in both is 150 μm 150 μm.

Conclusions

- It is clear that surface underwent roughening due to heating, as is well known by preferential As evaporation below the congruent temperature 625°C.
- It is NOT clear, though, why the surface roughness decreased with operational time in the gun and not with additional heat cycles.
- The quality of the crystal in the laser-illuminated region is not affected strongly by topography changes

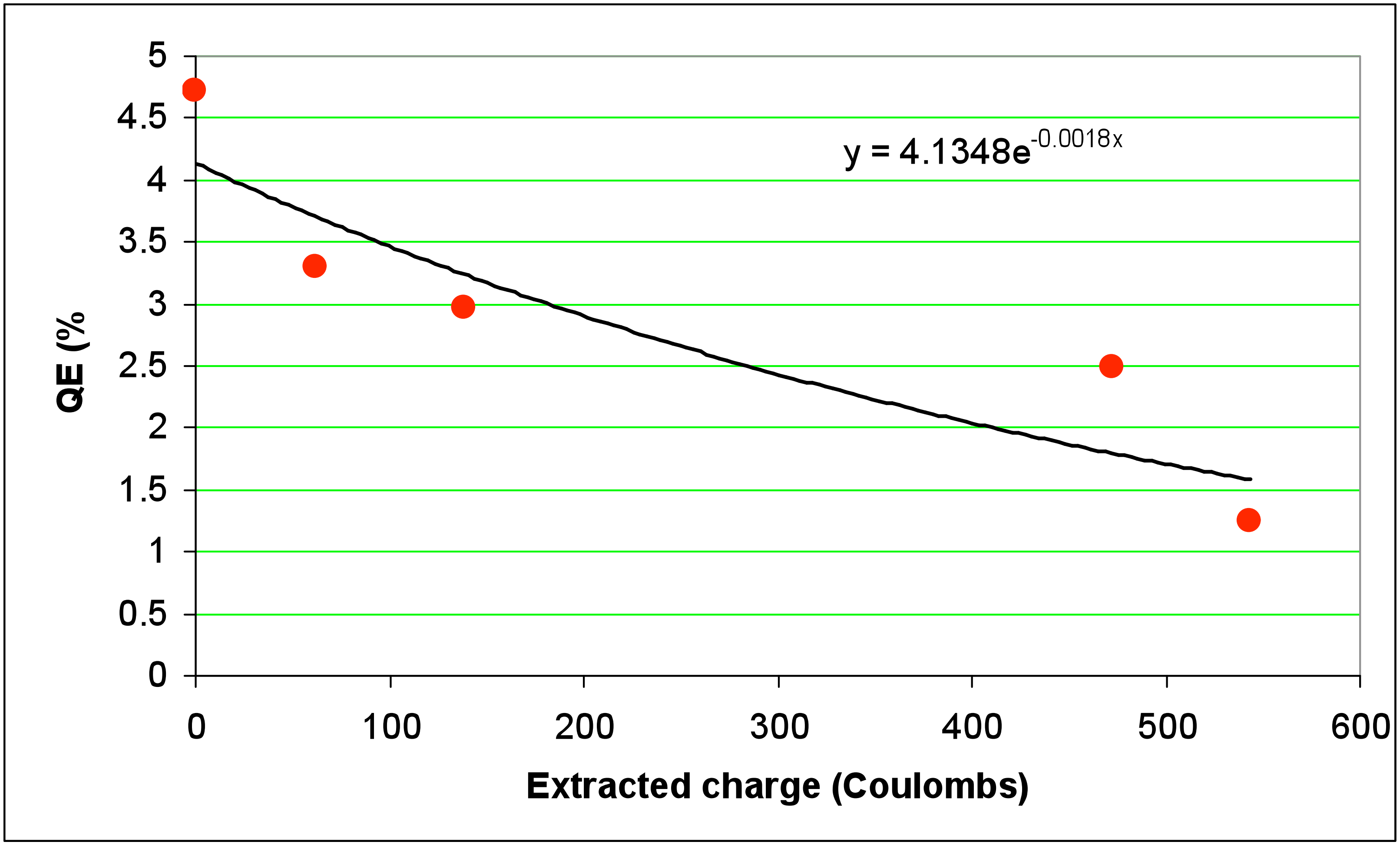
Final remarks

What is interesting about our findings is that the FEL photocathodes in the 350 keV gun showed ***evidence of Cs sputtering, but not of ion-induced crystal damage***, at least within the resolution of the measurements. The correlation found by the RBS measurements between Cs concentration and QE of each sample prior to removal from the gun supports the Cs sputtering by ion back bombardment as a QE degradation mechanism. The combination of SIMS and RBS measurements should have indicated crystal dislocations or hydrogen implantation due to back bombardment if present, but the data showed no evidence of this.

- The work presented is based on a few number of samples (very limited availability) and more statistics would be required to confirm or revoke the results

Backup slides

Photocathode lifetime* operating at 1 to 5 mA CW is about 550 Coulombs or 50 hours



Injector vacuum during 5 mA CW run