FLASH-induced damage to various optical materials

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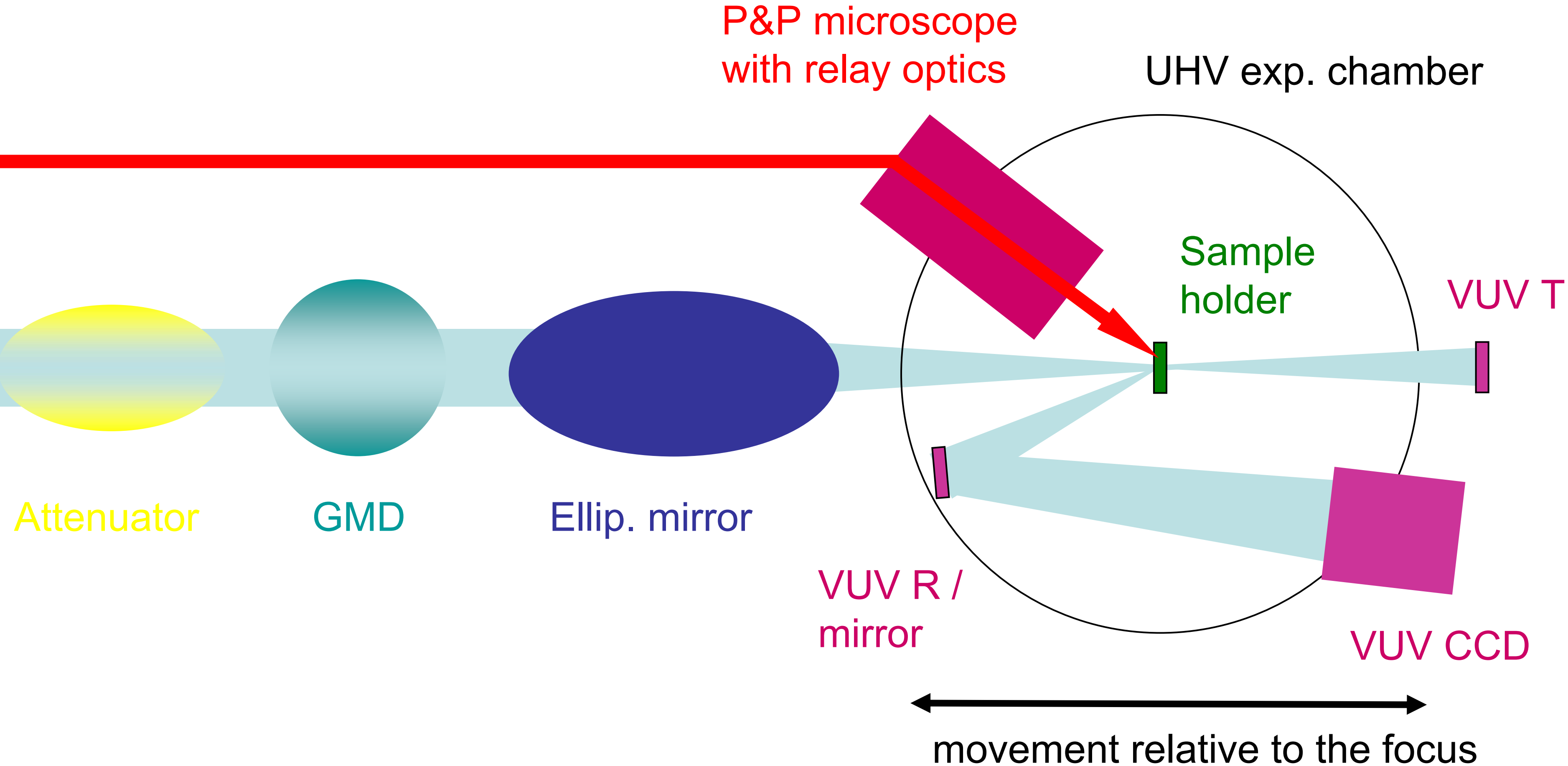
Layout

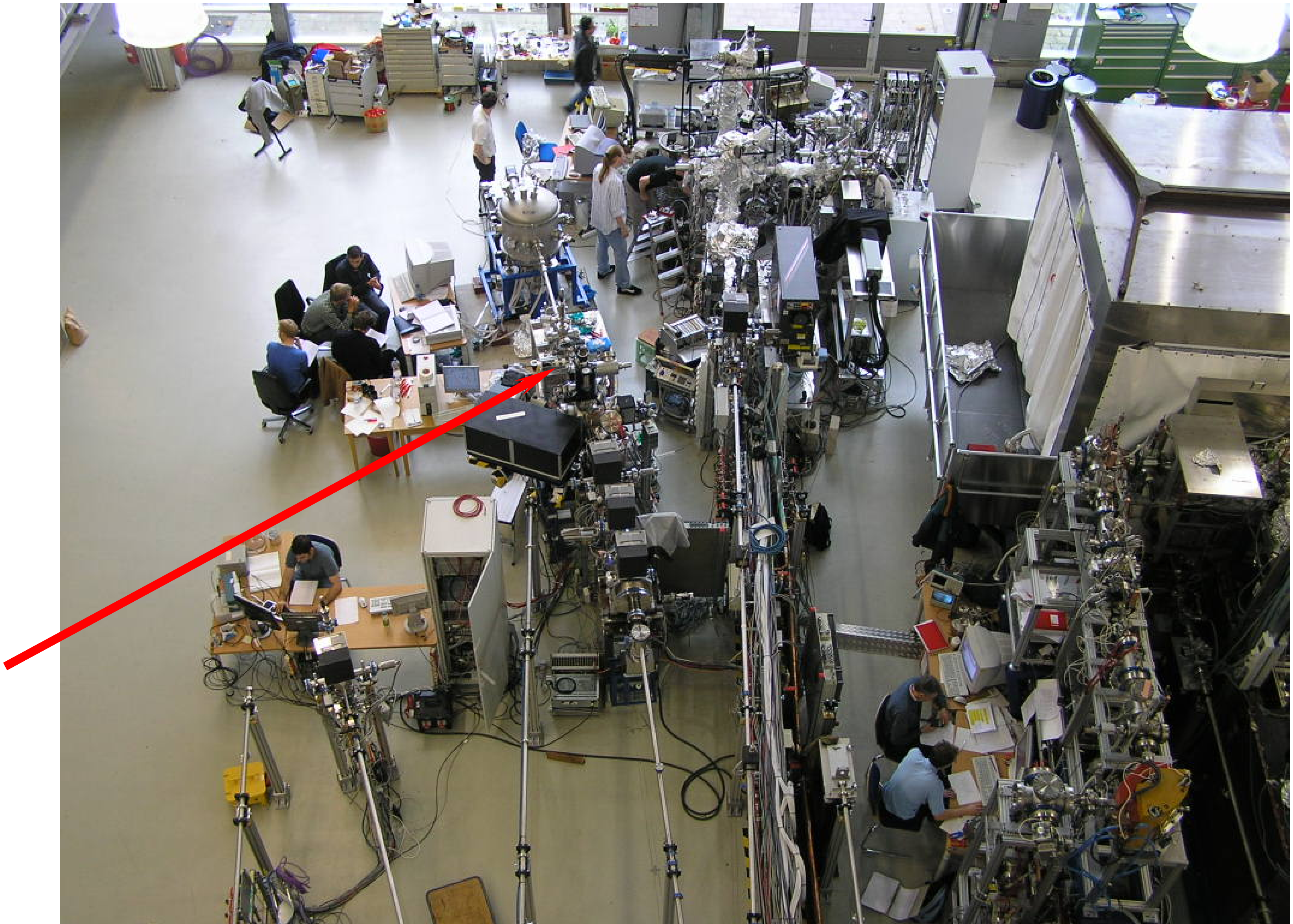
- Damage experiment @ FLASH
  - experimental setup
  - irradiation conditions
- Damage (*post-mortem analysis*)
  - Si bulk
  - a-C thin layer
  - SiC and B4C bulk
  - SiC multilayer
  - ScSi mulitlayer
- Damage (*pump-probe microscopy*)
- Transmission/Reflectivity
  - during the pulse
  - 1 color pump-probe
- Conclusions

Damage experiment @ FLASH
Experimental setup



Damage experiment @ FLASH

Experimental setup



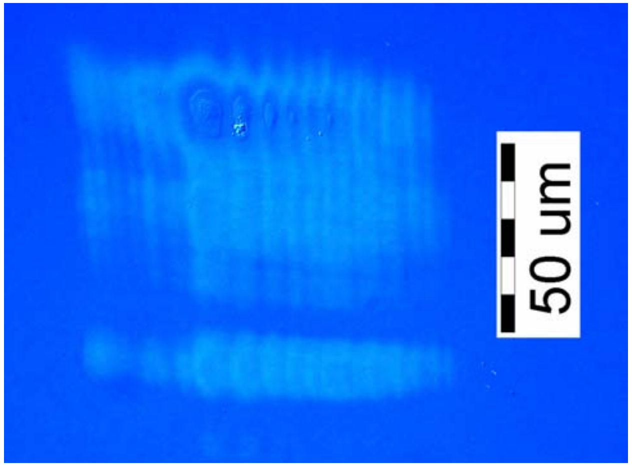
Damage experiment @ FLASH

Irradiation conditions

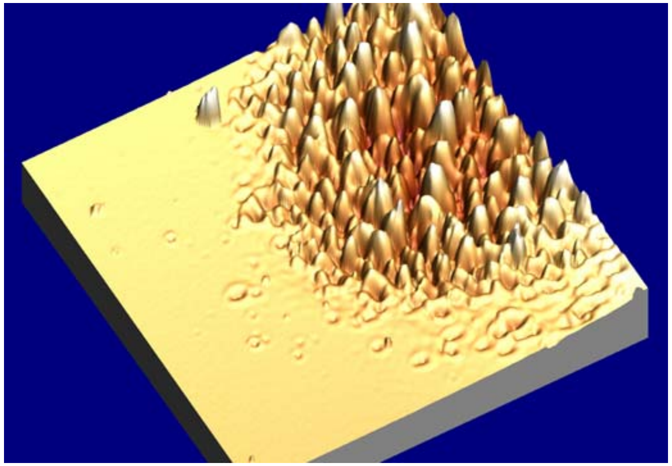
Wavelength [nm]	**13.4 – 32.5** **89 – 98**
Pulse duration [fs]	**10 – 50** **30 – 100**
Pulse energy [μJ]	**0.1 - 20**
Spot diameter [μm]	**20 – 30** **15 – 100**
Fluence [mJ/cm^2]	**1 - 5000**
Pulse number	**1** **10-100**

Damage

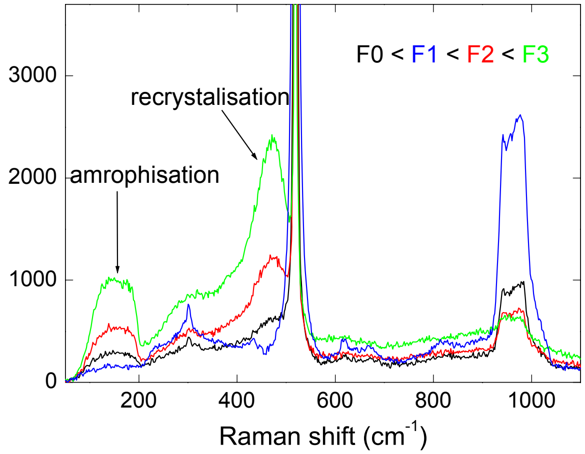
„*Post-mortem*” analysis



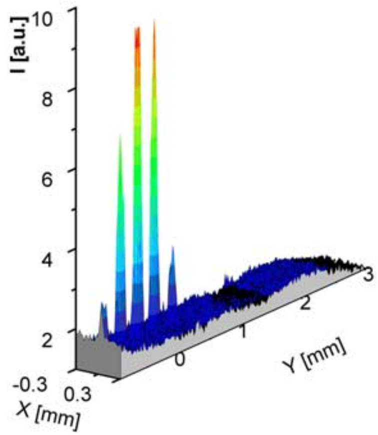
Optical microscopy



AFM



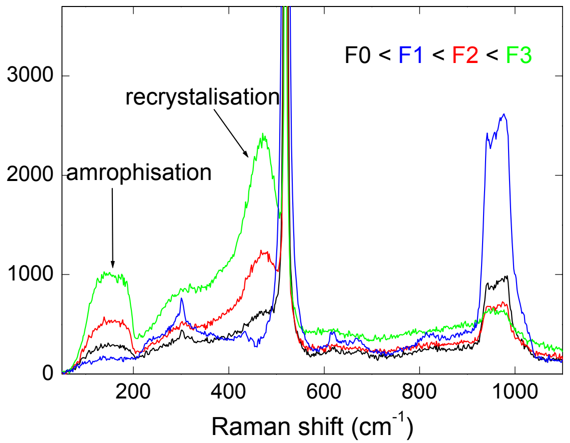
Raman spectroscopy

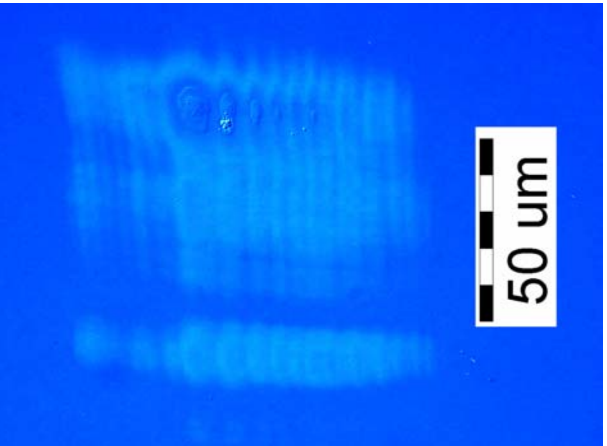


X-Ray Diffraction

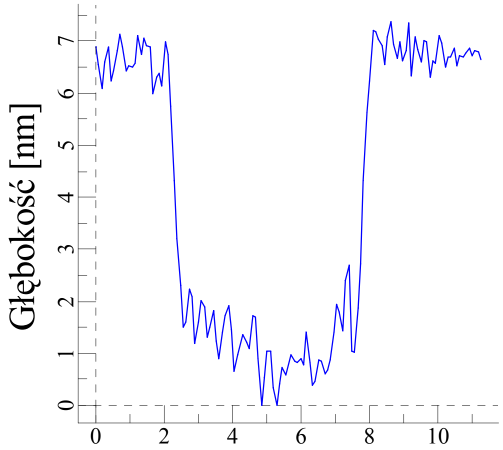
Si – bulk (11 pulses@89 nm)

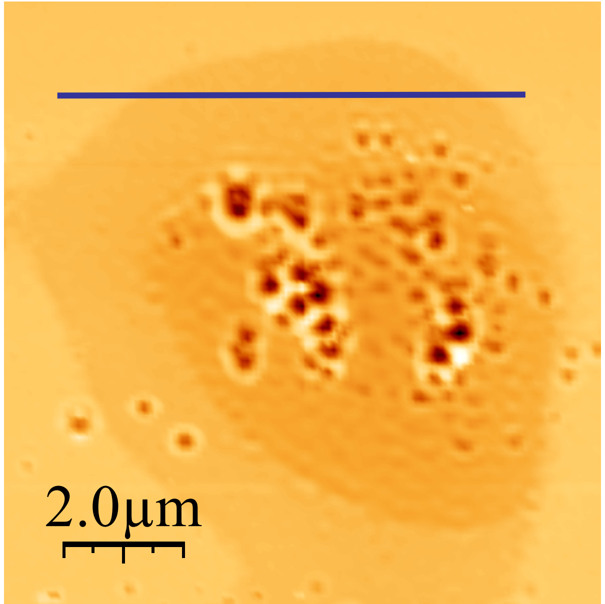
F<4 mJ/cm²



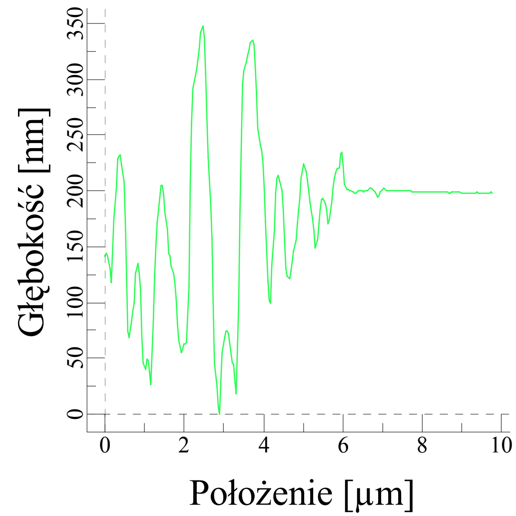


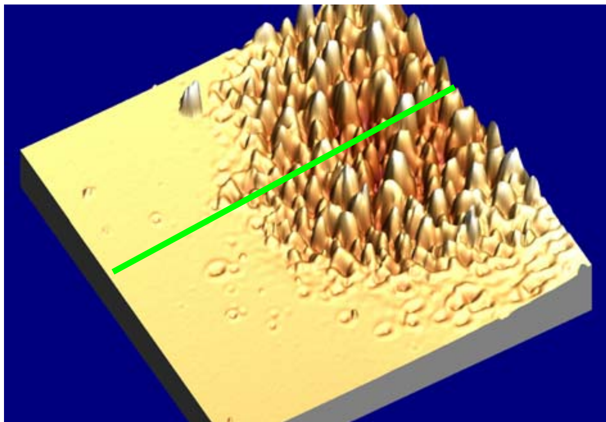
F~40 mJ/cm²





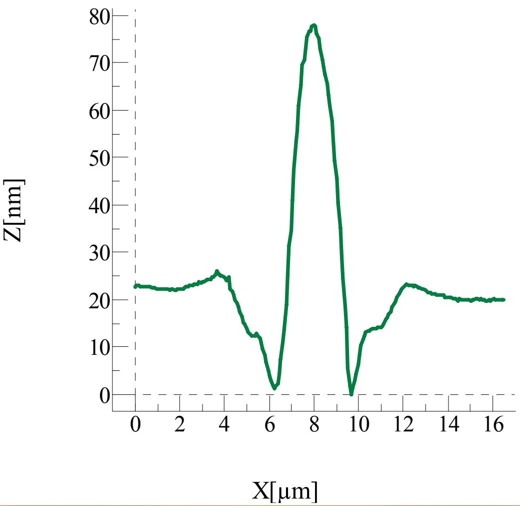
F~70 mJ/cm²

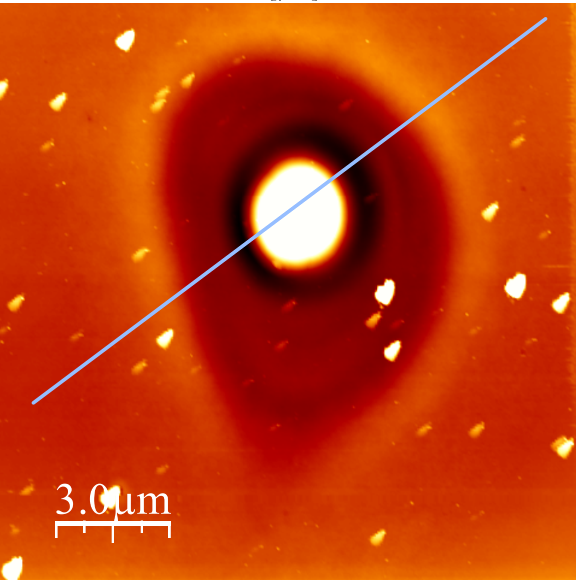




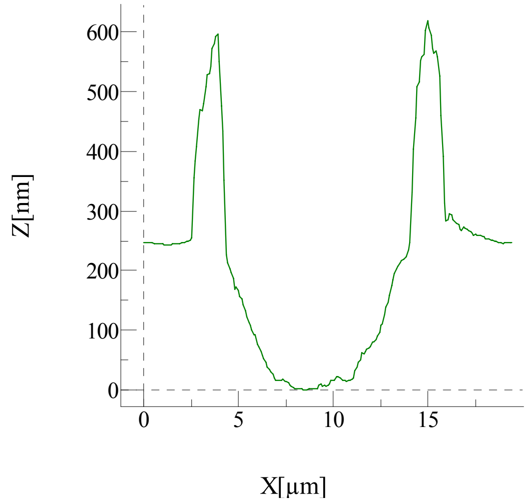
Si – bulk (1pulse@32.5 nm)

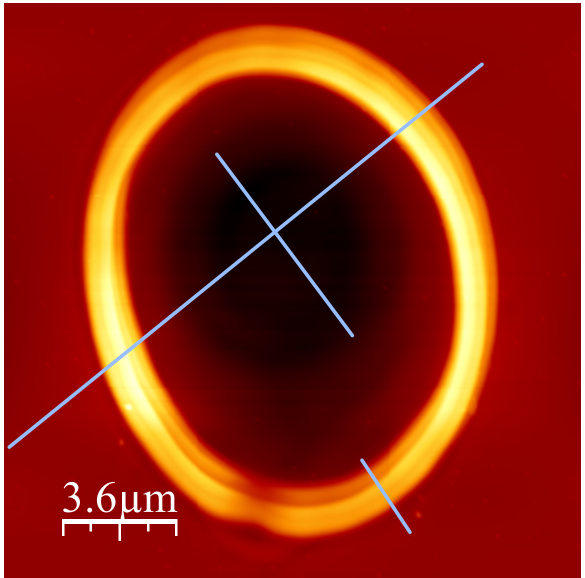
F~325 mJ/cm^2

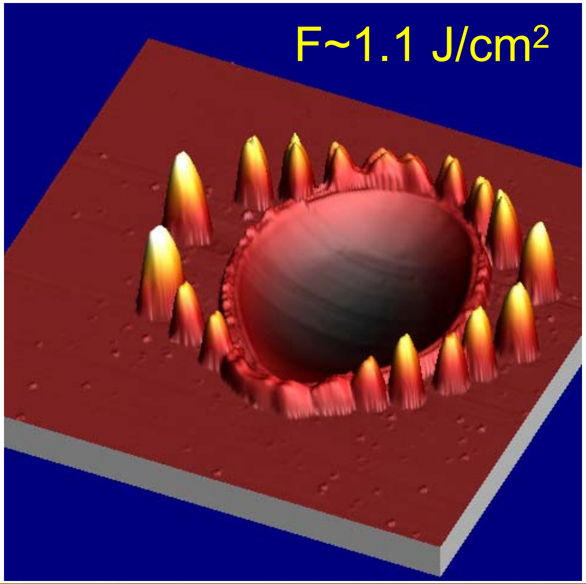


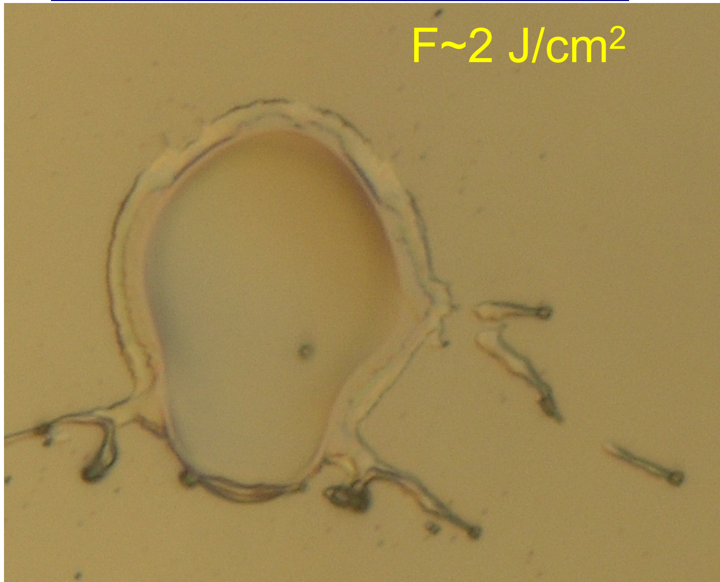


F~640 mJ/cm^2



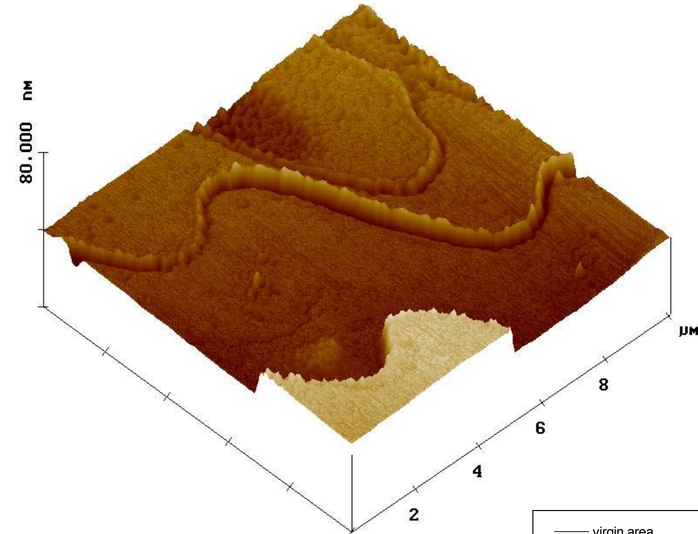


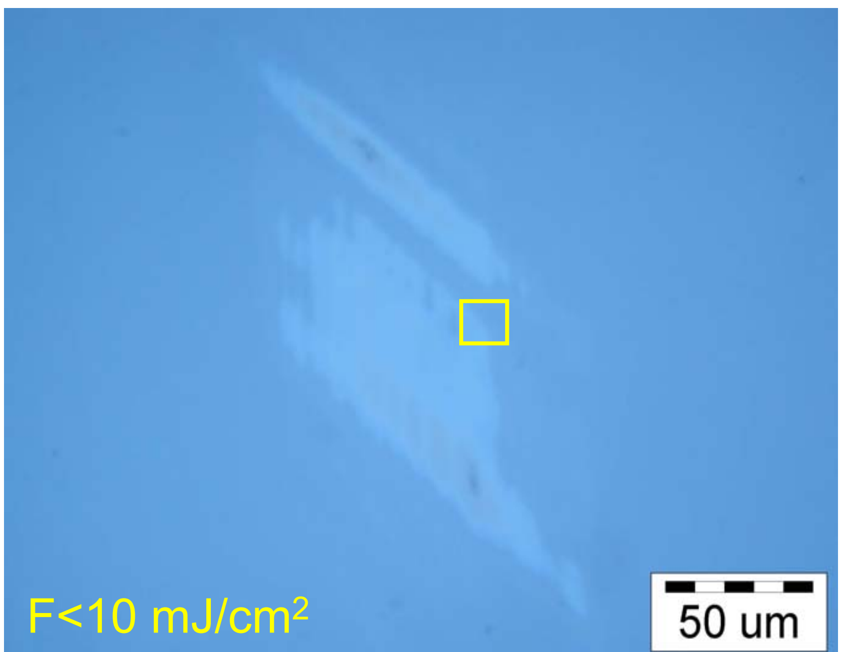


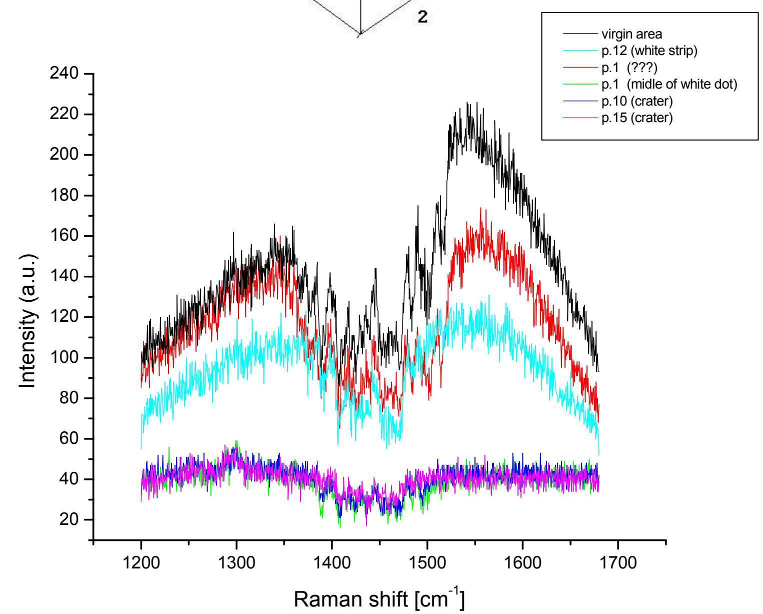


a-C – thin layer on Si @89 nm

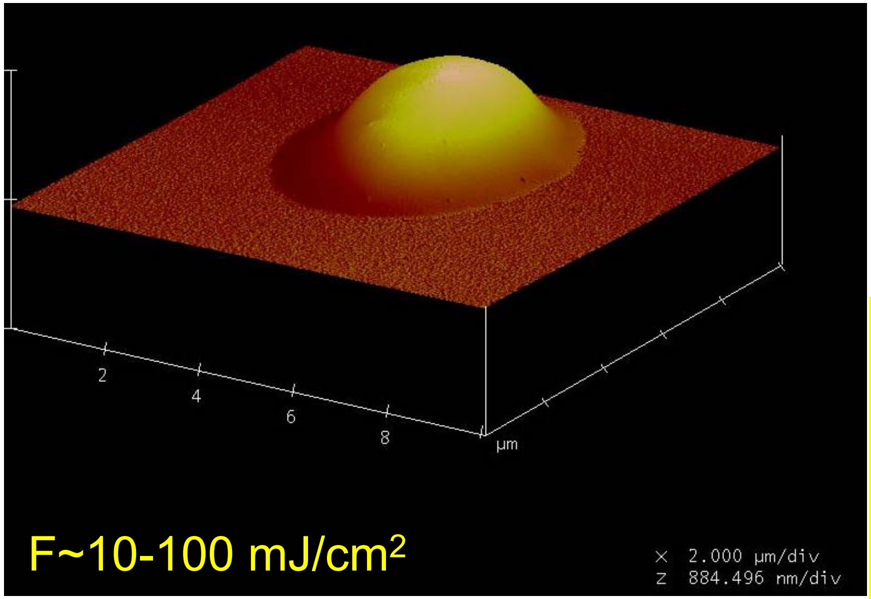
- Amorphous-carbon samples (a-C) consisted of 46 nm-thick a-C layers magnetron-sputter-deposited on a silicon wafer. The surface roughness of the a-C layers were less than 3 Å.

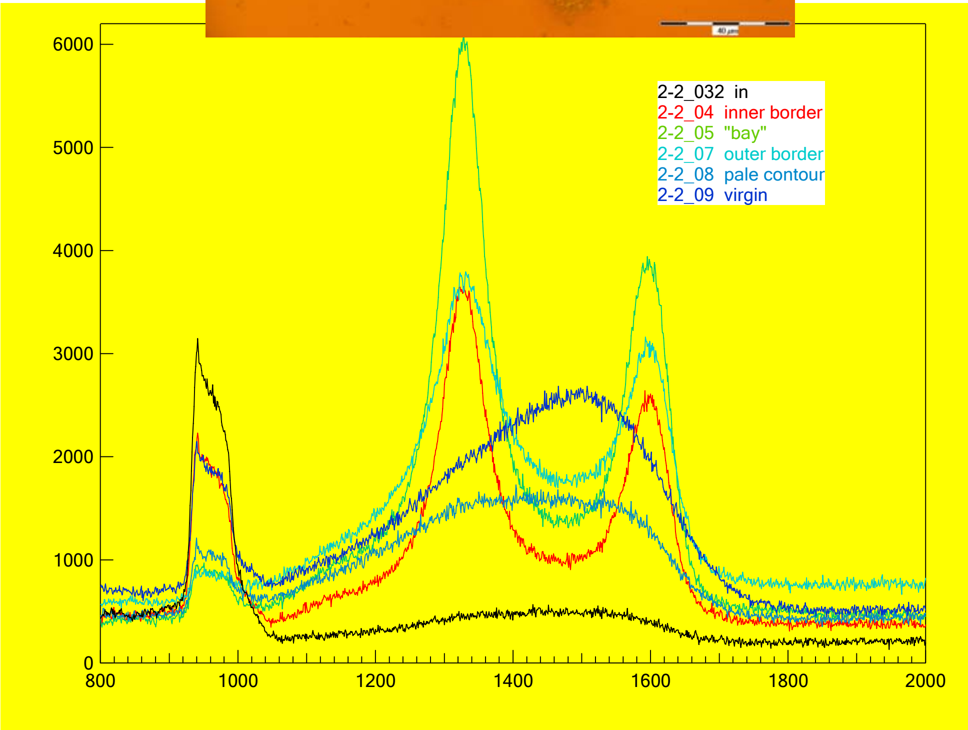






a-C – thin layer on Si @32.5 nm

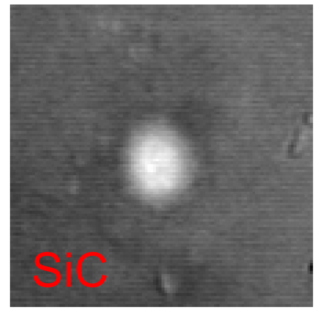




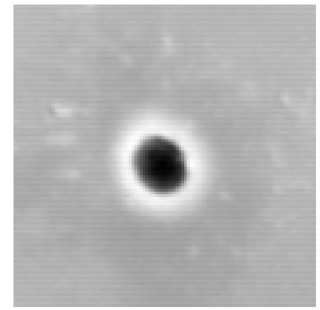
SiC & B4C

- SiC slabs were fabricated using chemical-vapor deposition and had an average grain size of 7.5 mm. After polishing and prior to exposure, the surface roughness of the samples was analyzed using atomic-force microscopy (AFM). The root-means-square (RMS) roughness of the sample surface was 1.8 Å.
- B4C slabs were fabricated by hot-pressing of B4C powder and had an average grain size of 5 mm. The polishing of the hot-pressed B4C produced numerous rip outs of B4C grains. A smooth surface was achieved in between the rip outs, with an RMS surface roughness of 5 Å.

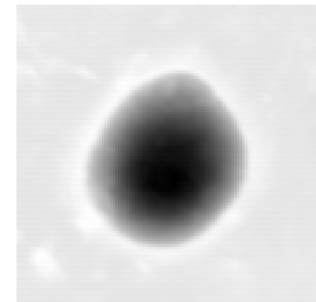
<0.3 J/cm^2

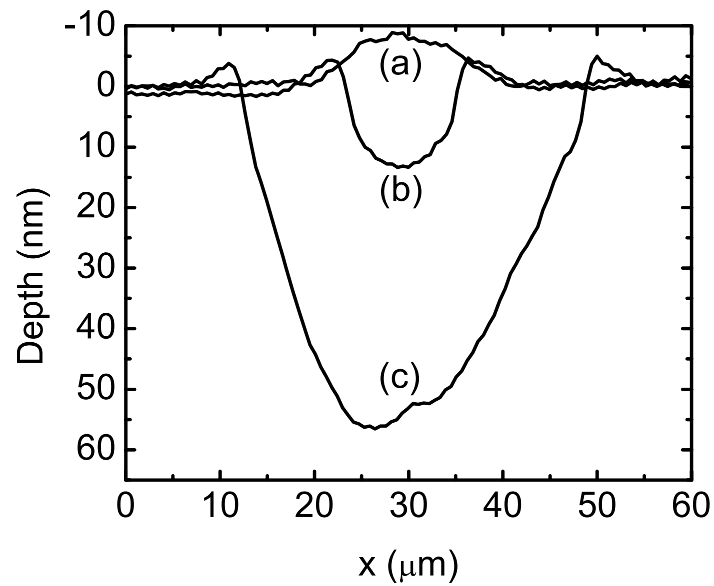


<0.3 J/cm^2



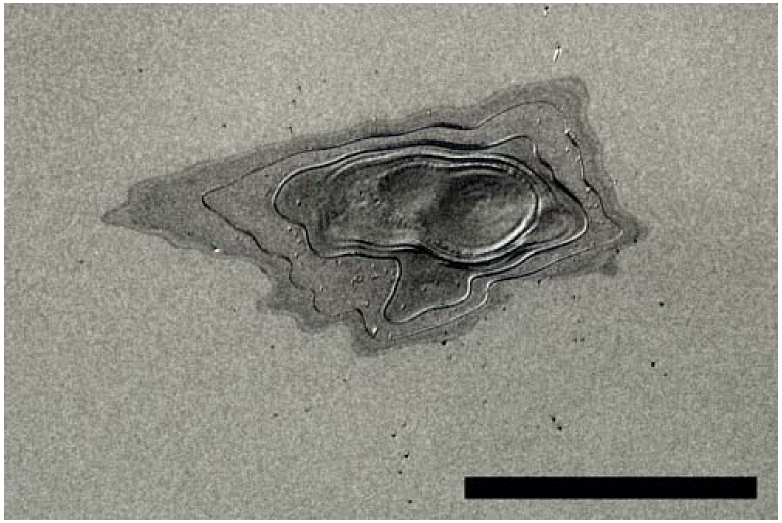
~0.5 J/cm^2

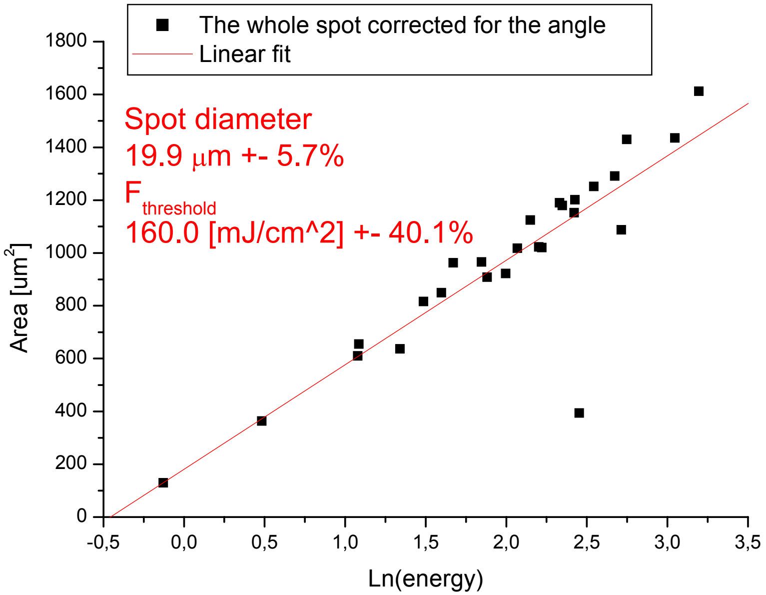




SiC multilayer

- The multilayer films consisted of ten Si/C bilayers, sputter-deposited on a Si (100) wafer. In order to detect radiation-induced changes of the multilayer, we chose multilayer design that provided a narrow angular reflectivity peak at a reflection angle of 45º and a wavelength of 32 nm. This narrow bandwidth makes the multilayer very sensitive to any changes in the multilayer structure or the optical constants of its constituents



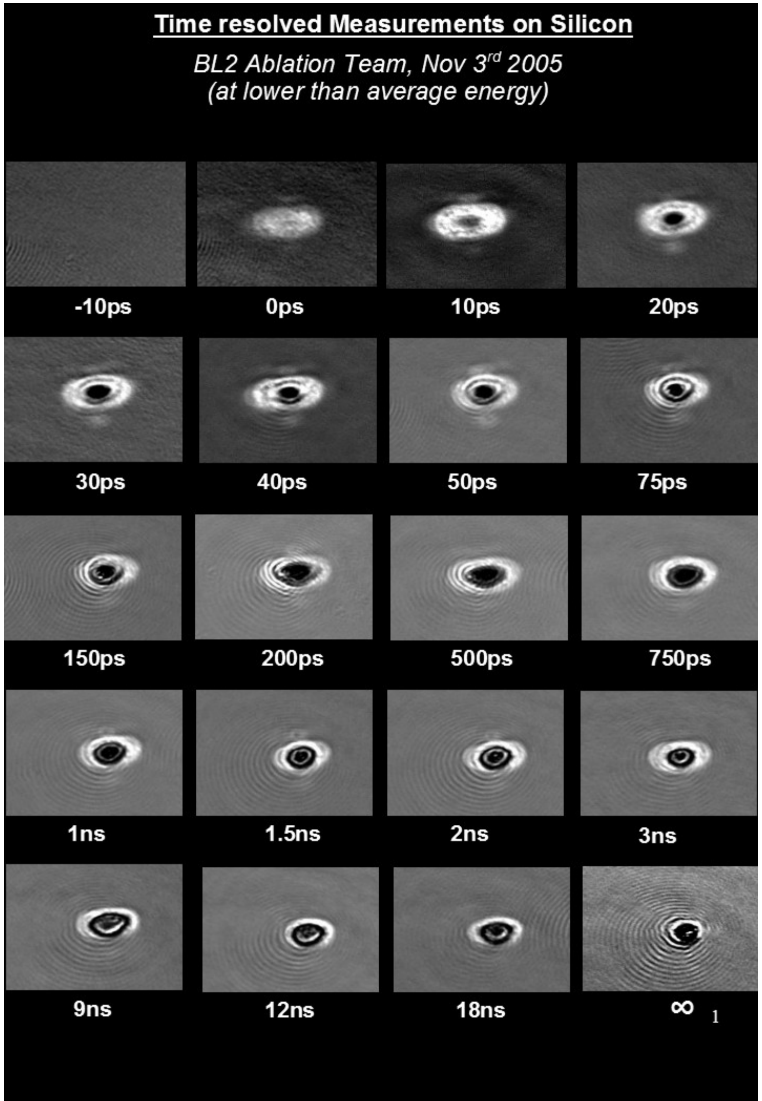


Damage thresholds [mJ/cm²]

λ = 89 nm		λ = 32.5 nm	
Si	< 4	Si	87 ± 45
a-C	<10	a-C	65 ± 30
		SiC	141 ± 70
		B_4C	197 ± 100
		CVD diamond	156 ± 75

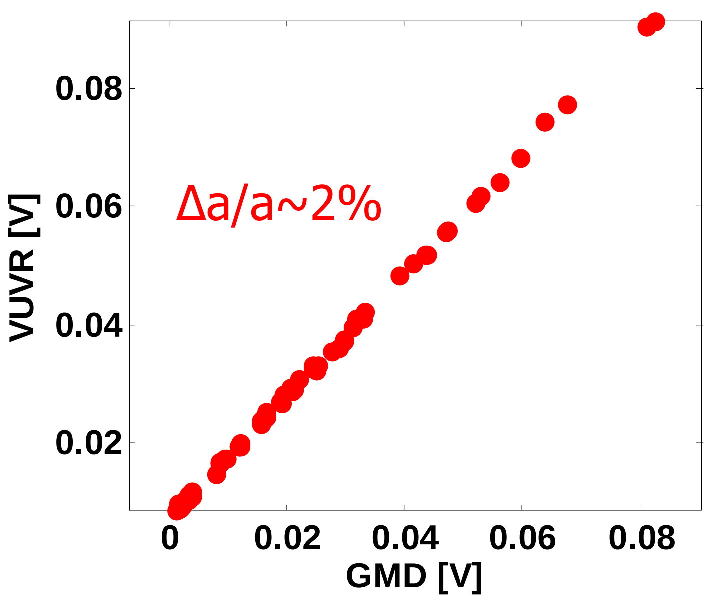
Dynamic of damage processes

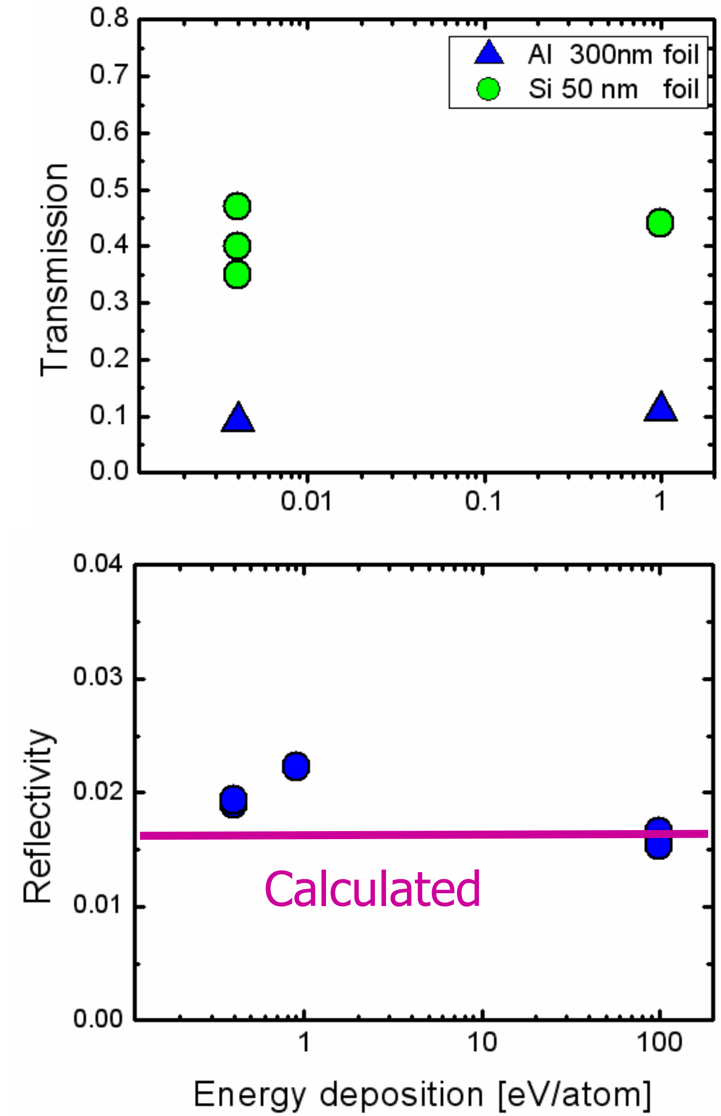
2 color pump & probe



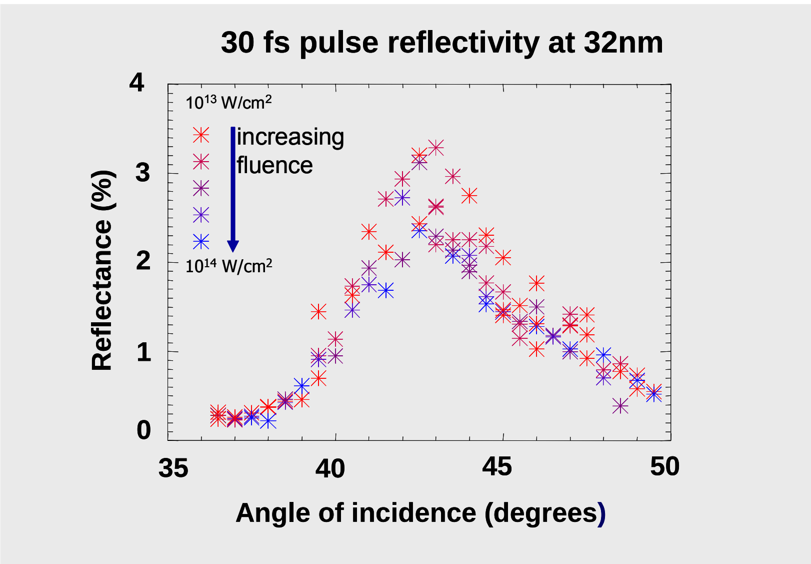
Transmission/Reflectivity during the pulse

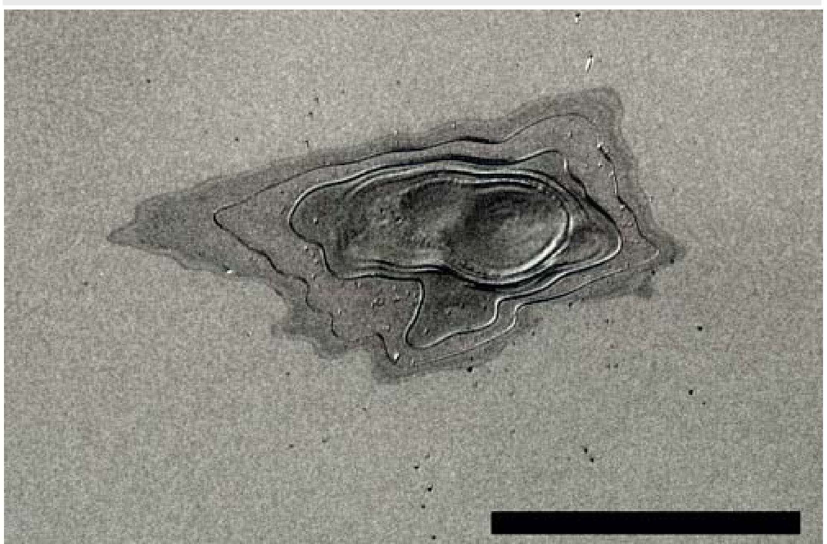
- 50 nm Si film
- 300 nm Al film
- SiO_2 monocrystal



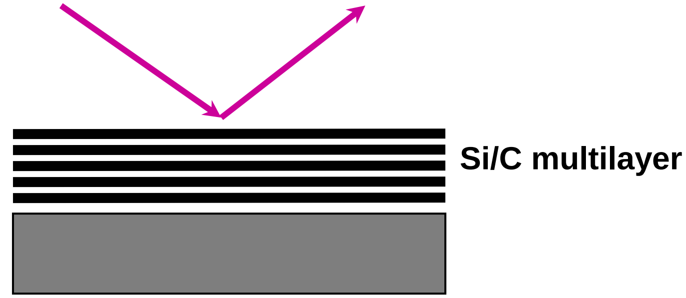


Transmission/Reflectivity during the pulse





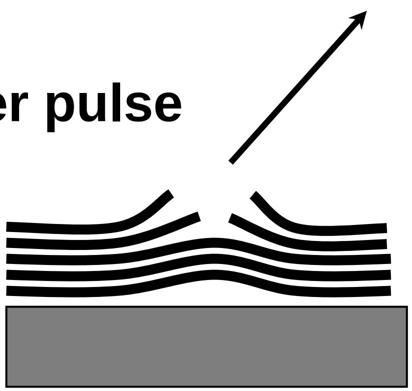
During the pulse



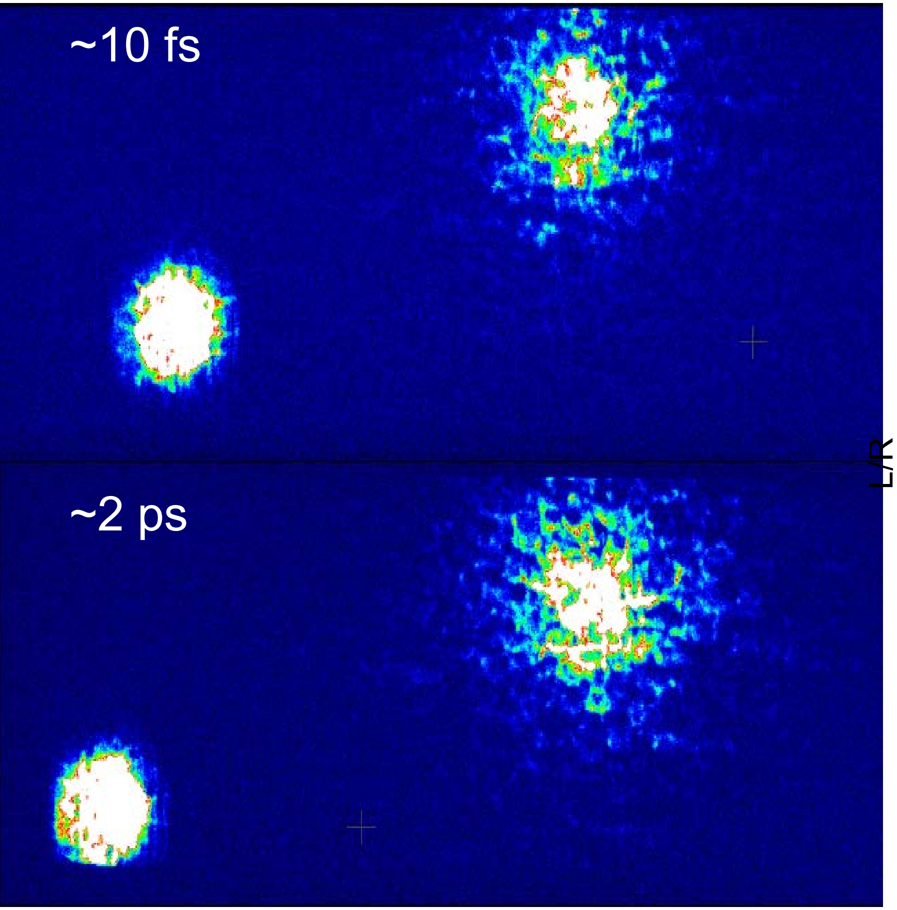
Reflectivity, optical constants unchanged
Multilayer *d* spacing not changed by more than 0.3 nm

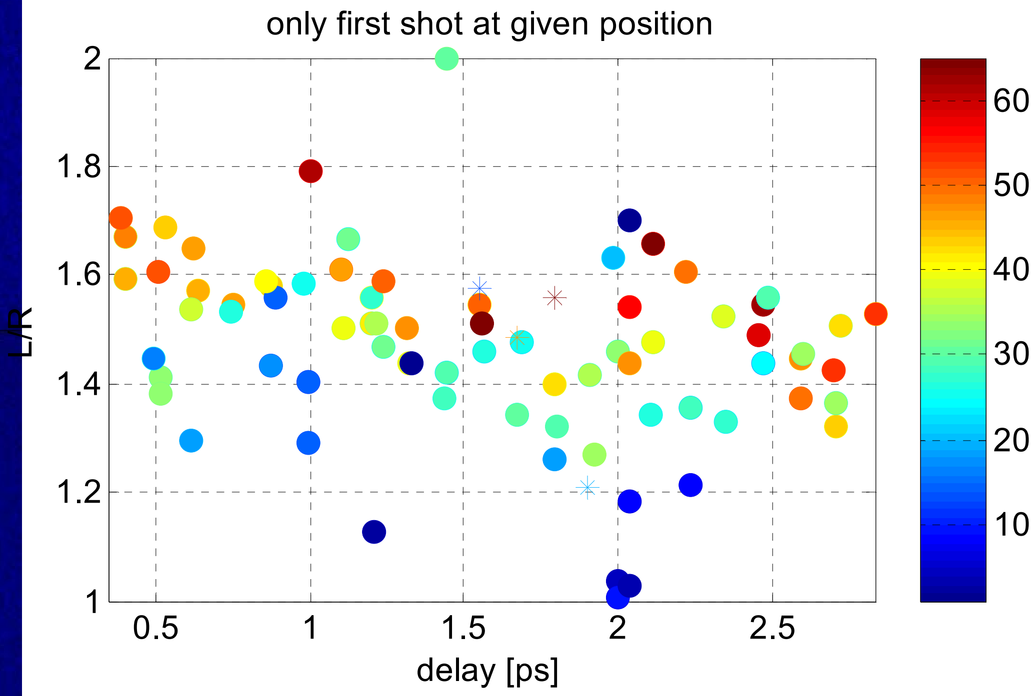
Plasma forms, layers ablate

After pulse



Transmission/Reflectivity
pump-probe





Conclusions

- The optical response at 32.5 nm wavelength of the investigated materials (Si, SiO2 – bulk and Si, Al – thin foils) appears to be linear up to the maximum attainable intensities (≈ 1014 W/cm2) and deposited energy densities in excess of 100 eV per atom [publication in preparation].

- The multilayer performance does not degrade during the damaging pulse Initial results from one-colour pump-probe experiments in 2006 suggest that the optical properties of the multilayer do not change significantly from 10 fs up to 2 ps after excitation.

- First time-resolved reflectivity measurements in the visible range of solid surfaces (Si, GaAs) irradiated with FLASH have been investigated using picosecond optical imaging. Distinct differences in the material response are found in comparison to fs optical excitation. These differences are attributed to the increased penetration depth of the XUV-radiation and the absence of any absorption nonlinearities.

- Damage thresholds were obtained for a variety of inorganic materials in the wavelength range 13.5 nm - 100 nm The threshold fluence for surface-damage is comparable to the fluence required for thermal melting. For larger fluences, the crater depths and morphology suggest that the craters are formed by ejection of (2-phase) molten material. For optical lasers such behavior is only known in the case of cw- and long-pulse irradiation.

Literature

1) S.P. Hau-Riege et al.: Sub-nanometer scale measurements of the interaction of ultrafast soft x-ray free-electron-laser pulses with matter (submitted 2006).
2) N. Stojanovic et al.: Ablation of solids using a femtosecond XUV free electron laser (accepted for publication *Appl. Phys. Lett.,* 2006).
3) S.P. Hau-Riege et al., “Damage threshold of solids under free-electron-laser irradiation at 32nm wavelength” (submitted 2006).
4) J. Krzywinski et al.: Conductors, semiconductors and insulators irradiated with a short-wavelength free-electron laser (accepted for publication in *J. App. Phys*., 2006).
5) FLASH beamtime report - 2005
6) 16) L. Juha et al.: Radiation damage to amorphous-carbon optical coatings, *Proc. SPIE* **5917**, 91 (2005).
7) 17) J. Chalupský et al.: Ablation of organic molecular solids by focused soft X-ray free-electron laser radiation presented at the *10th International Conference on X-ray Lasers – ICXRL 2006*, Berlin, August 21-26 2006; submitted to the Proceedings.