Damage on Materials of interest for FEL optics

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+

„damage team“

The people

- *Core team:*
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  - M. Störmer – *Helmotz Zentrum Geesthacht, Geesthacht*
- *+ for FLASH experiment*
  - *A. Gleeson – STFC, UK*
- *+ for LCLS experiment*
  - S. Hau-Riege, R.A. London, A. Graf, S. Baker, R. Soufli - *LNBL, Livermore*
  - J. Krzywinski, J. Bozek, C. Bostedt, S. Möller - *SLAC, Stanford*
- *+ for SCSS experiment*
  - C. Svetina, A. Bianco - *Sincrotrone Trieste*
  - M. Nagasono - *XFEL Project, Riken*

Motivations

Why studying damage as up to now no problems occurred?

- extending the FEL parameters / optics :
  - ➔ energy up to 200 mJ / pulse*
  - ➔ photon energy range: water window, hv > x 10 keV
  - ➔ specific structures: multilayer, grating, zp…
- fundamental aspects: interaction of intense X-ray fs pulses with solids
  - ➔ bulk material: PMMA, Si, SiO_2, diamond
    - » needed for beam characterization

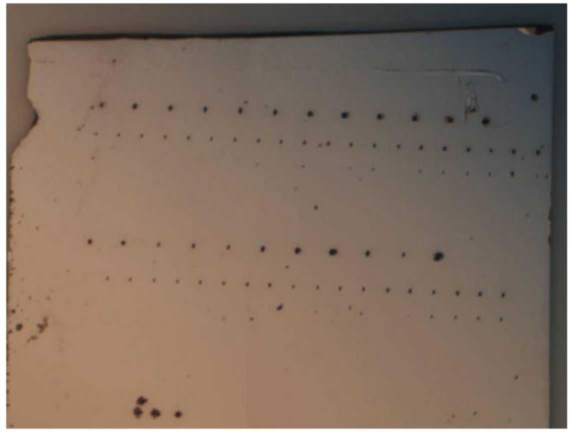
Yurkov et al. DESY Print TESLA-FEL 2011-01

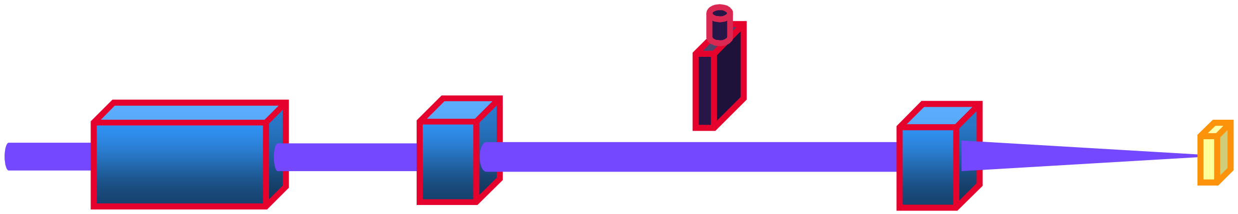
Overview

- Experiment
  - ➔ set-up
  - ➔ normal incidence case
- X-ray mirror specific geometry
  - ➔ FLASH results
  - ➔ Effect of electron transport
  - ➔ Multi-layer case
- Beam characterization by ablation
- Conclusion and developments

Experiment – set-up

- 1st step: beamtime
  - → SCSS : 20, 24 eV
  - → FLASH : 12, 38, 91, 177 eV
  - → LCLS : 830 eV

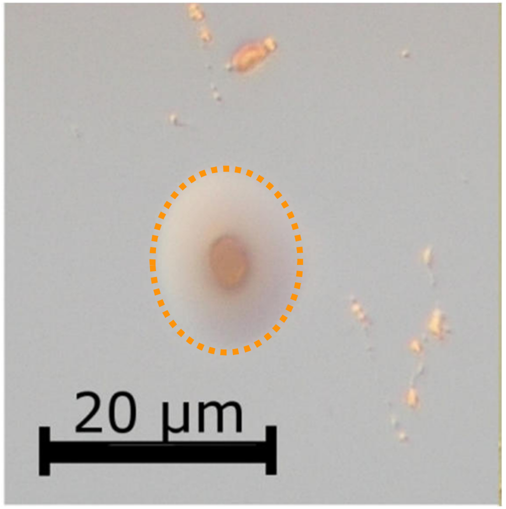


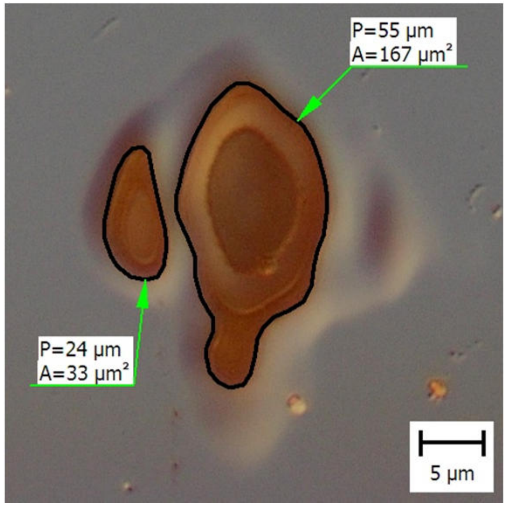


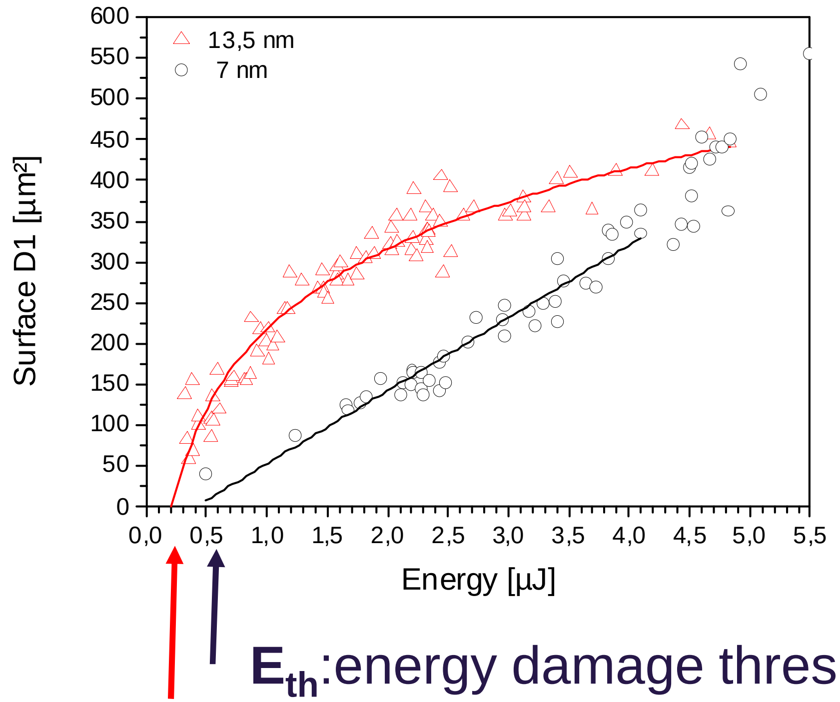
- 2nd step: damage analysis
  - → surface morphology: DIC microscope, AFM, SEM
  - → structure : micro-Raman, x-ray diffraction (XRD), ESCA

Results – damage threshold

Normal incidence







E_{th}:energy damage threshold

Fluence damage theshold

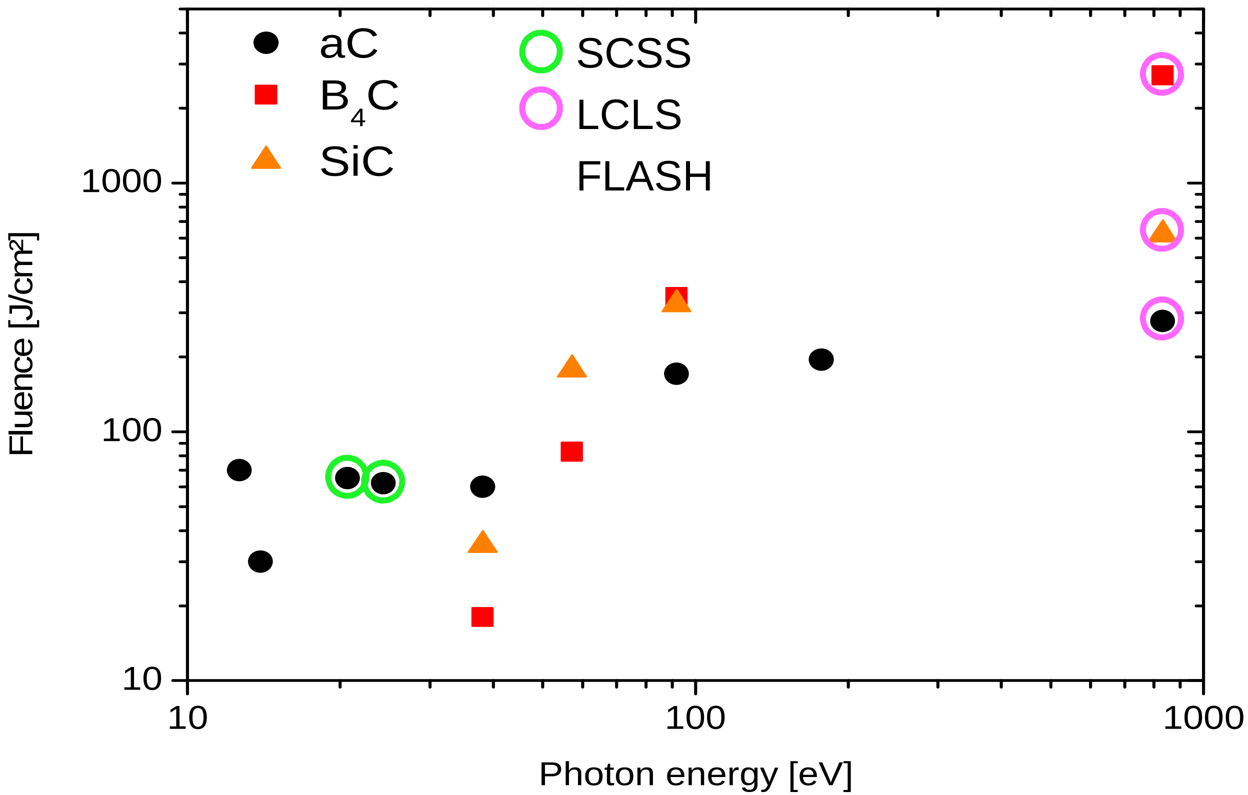
F_{th} (J.cm^{-2}) = E_{th} / A_{eff}

beamsize needed => effective area method+

+ Chalupsky *et al., Opt. Express* **18**, 27836 (2010).

Comparison for materials

Normal incidence, single shot damage threshold for mirror coating materials: aC, SiC and B_4C



Summary of:

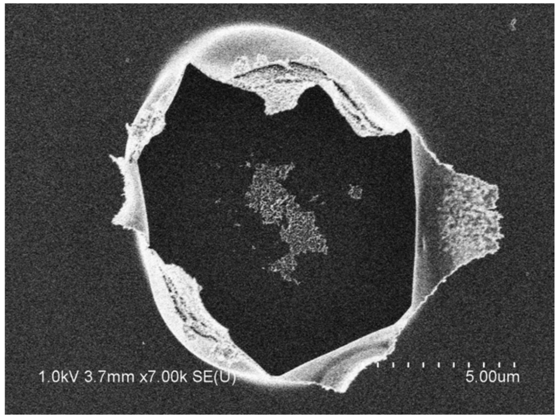
- APL, **84** 657 (2004)
- JAP, **101** 043107(2007)
- APL, **90** 173128 (2007)
- APL, **95** 111104 (2009)
- APL, **95** 031111 (2009)
- Opt.Expr., **28** 23933 (2010)
- to be published

- clear photon energy dependance of the damage threshold: **experiments needed!**

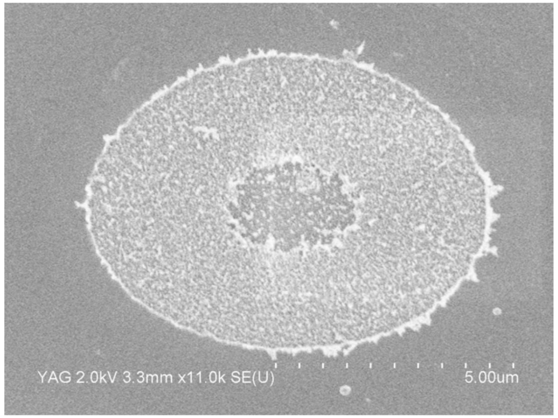
Specific case of X-ray mirror

x-ray mirror : thin layer ~ 40 nm

40 nm



940 nm

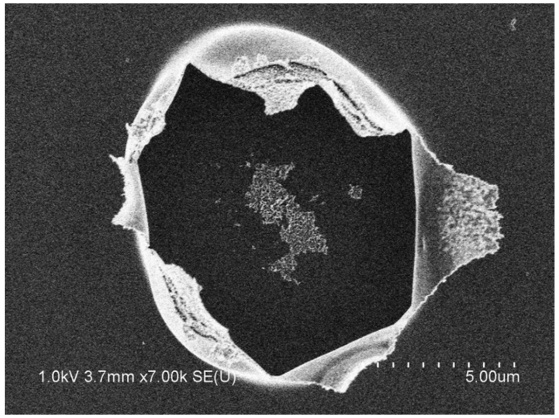


1 µJ – 13.5 nm / 91 eV

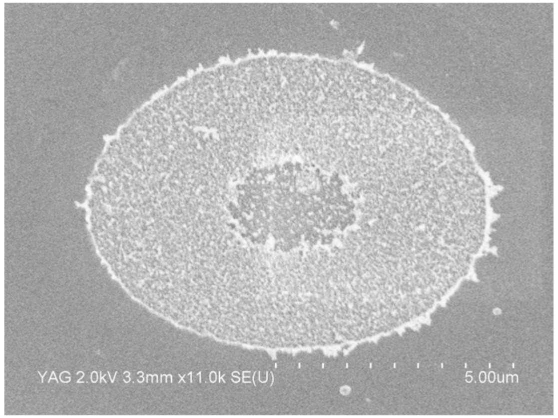
Specific case of X-ray mirror

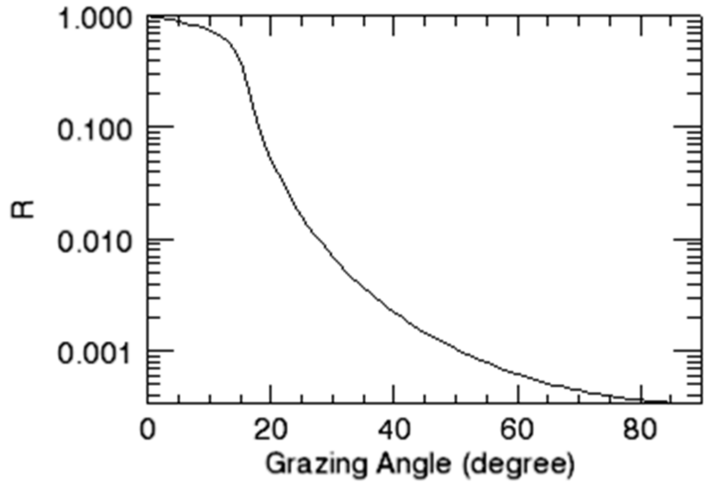
x-ray mirror : thin layer ~ 40 nm, small grazing angle < θc

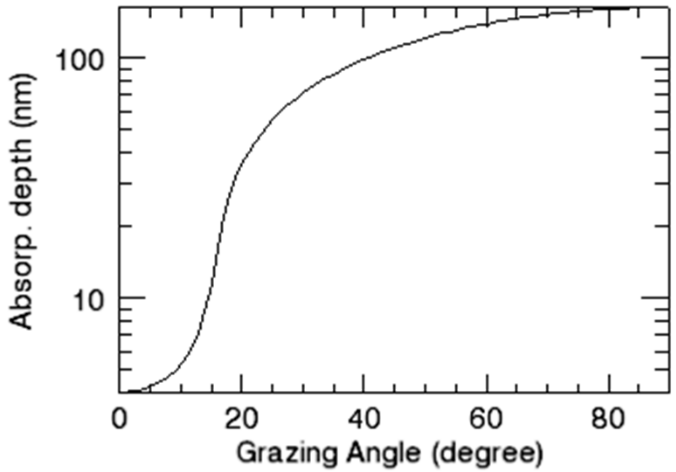
40 nm



940 nm







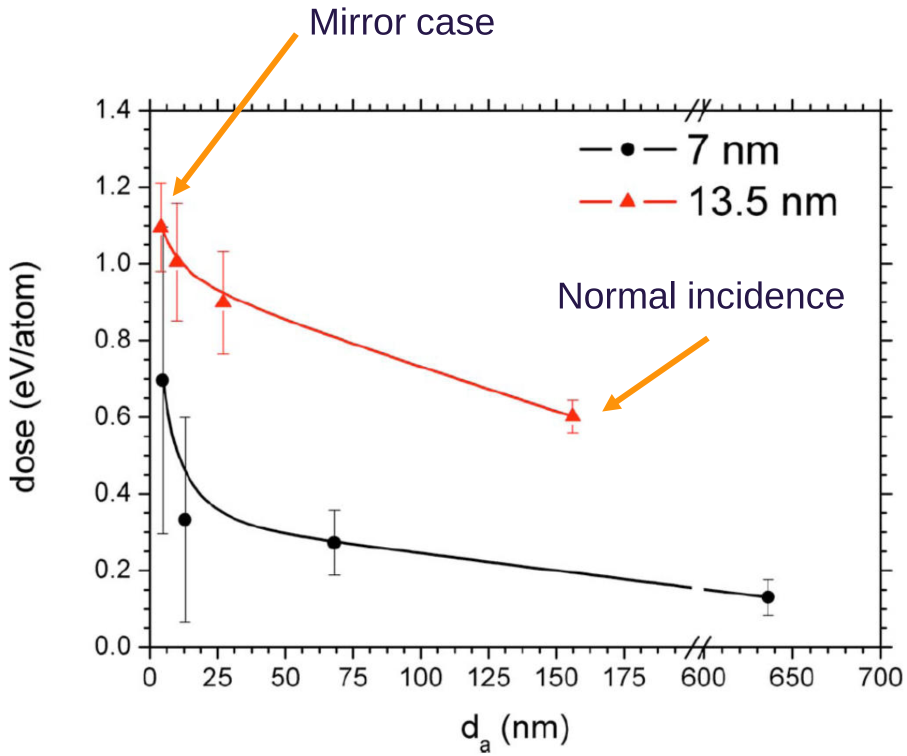
1 µJ – 13.5 nm / 91 eV

Results - damage threshold

- Energy absorbed per atom = dose (eV/atom)

$$D_{th} = F_{th} \cdot \frac{(1-R)}{l_a \cdot n_a}$$

- ➔ l_a : absorption depth
- ➔ R : reflectivity
- ➔ n_a : atomic density



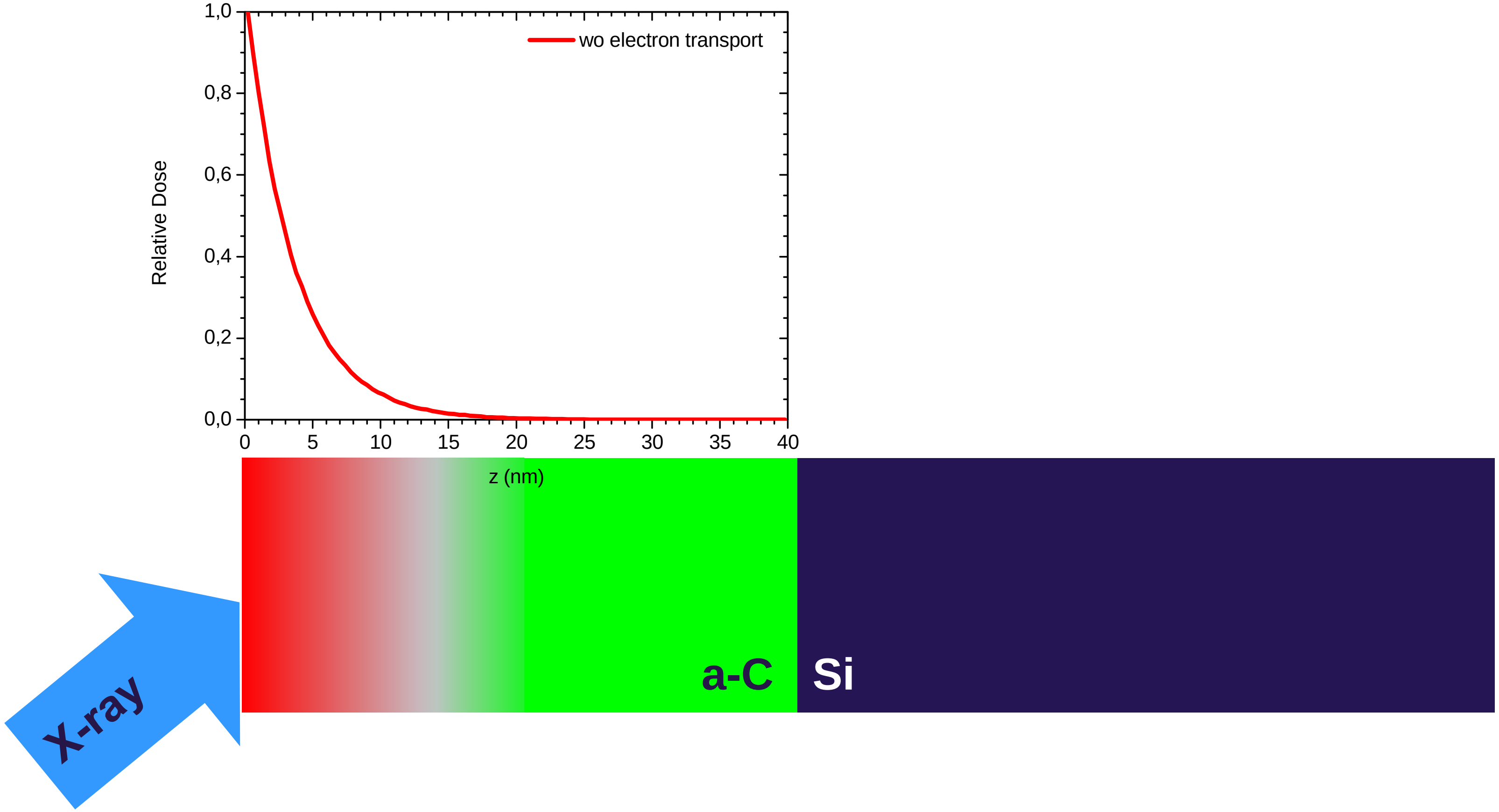
Below θ_c

➔ D_{th} = 2 to 3 x D_{th} (90°)

+ Chalupsky et al. – APL 95, 031111 (2009)

Experiments: damage on a-C

- effect of electron transport: MC simulations – 830 eV



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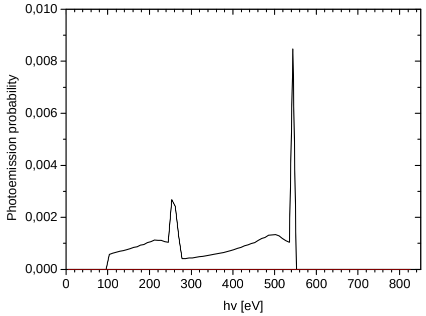
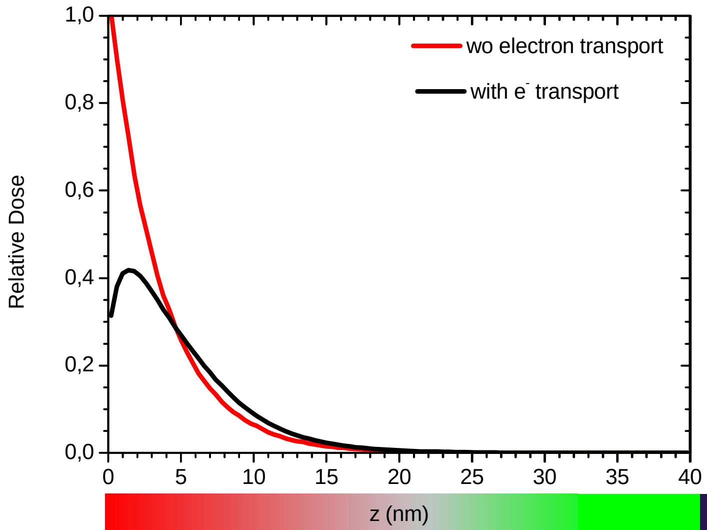
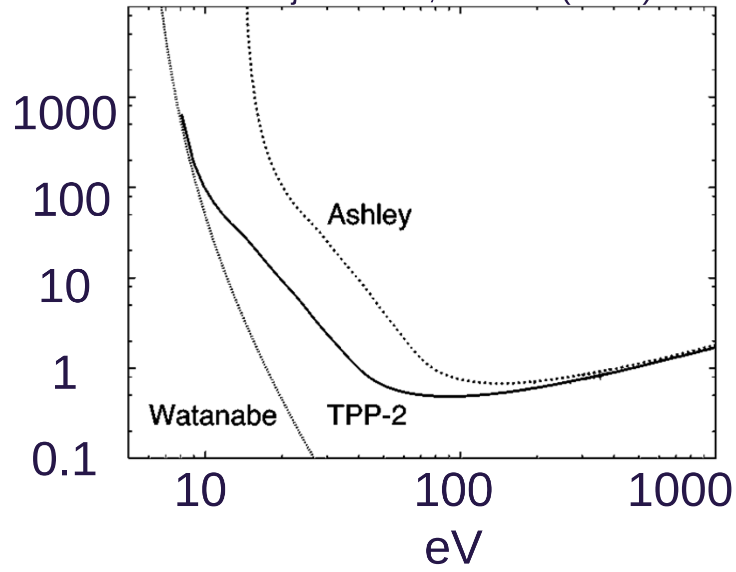
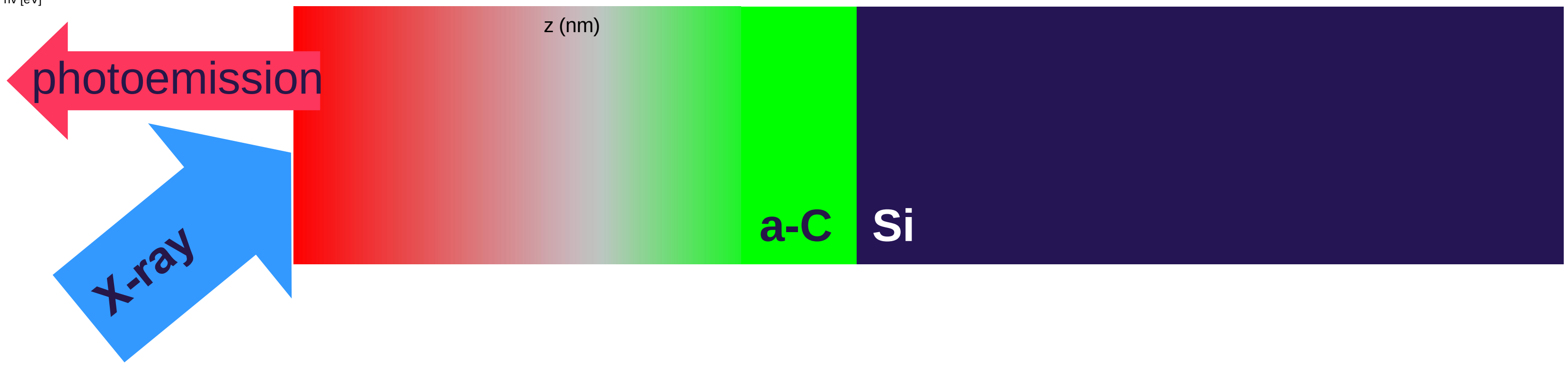




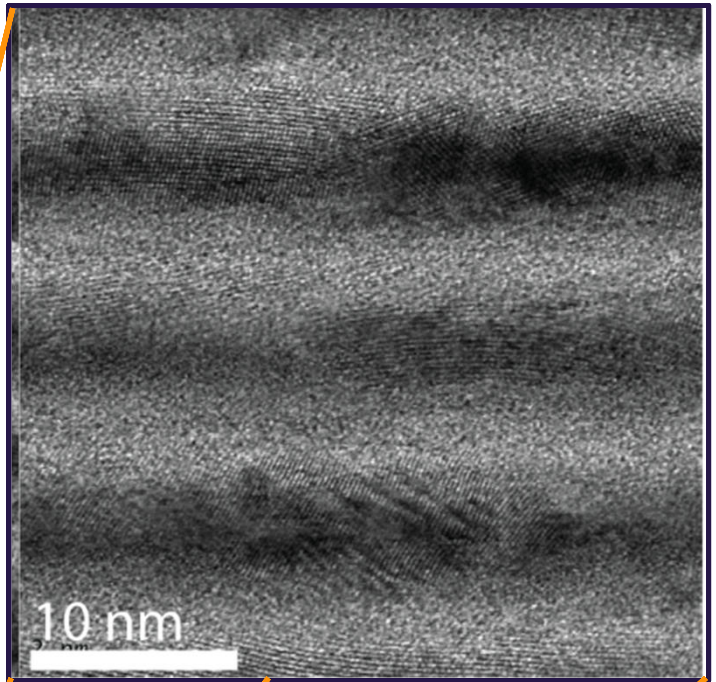
B. Ziaja JAP **97**, 064905 (2005)





Special Case of Multilayers

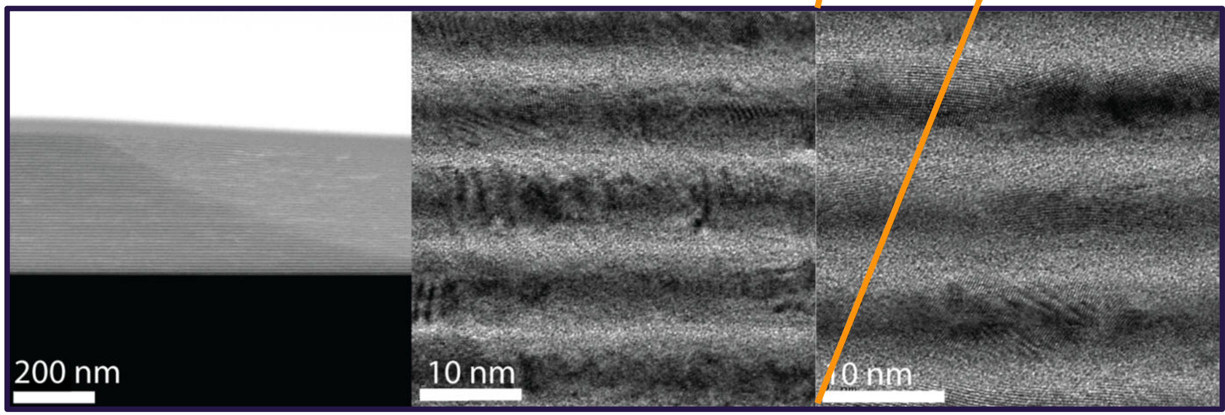
Slide by courtesy of R. Sobierajski



Single shot damage at "resonance – angle" for 2 structures at 13,5 nm FLASH:

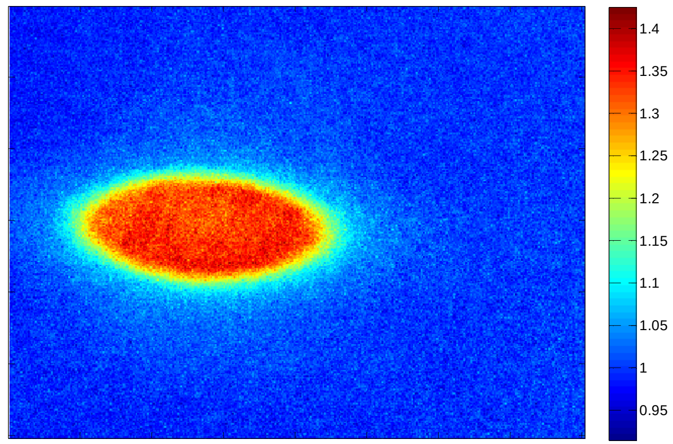
Mo / Si F_{th} = 45 +/- 7 mJ/cm²

MoN /SiN F_{th}= 48 +/- 7 mJ /cm²

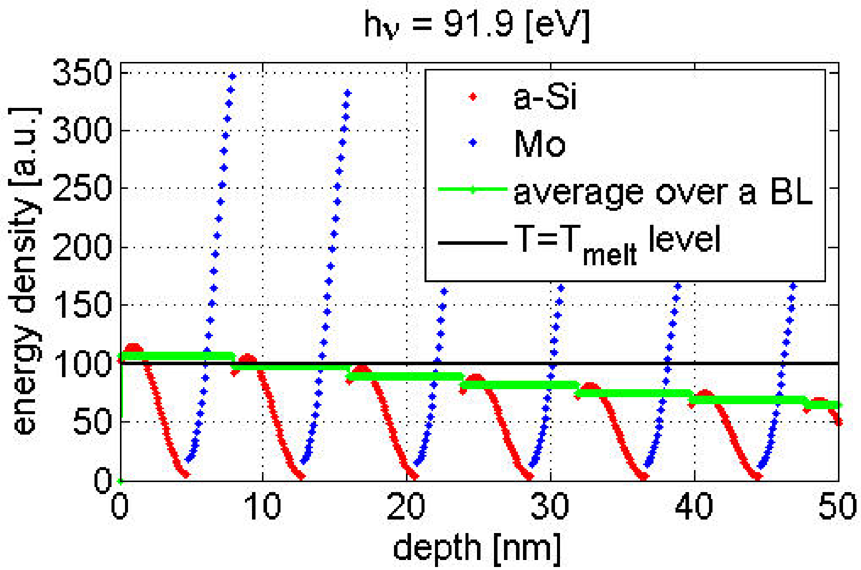


a. Zoomed in on the side of the crater
b. undisturbed Mo/Si ML structure – crystaline Mo and amorphous Si layers
c. inside the crater –instead of a-Si , crystalline silicides formation due to the melting of a-Si and enhenced atomic diffusion

Single shot damage at "resnonance –angle" for 2 structures at 13,5 nm FLASH: Mo / Si and MoN /SiN



XUV pump – optical probe (time resolved microscopy image @ 10 ps delay w/r the XUV pulse) 40% increase of reflectance due to the a-Si layer melting



Calculated energy deposited: 13,5 nm FLASH: Mo / Si

Special Case of Multilayers

Slide by courtesy of R. Sobierajski

Main results:

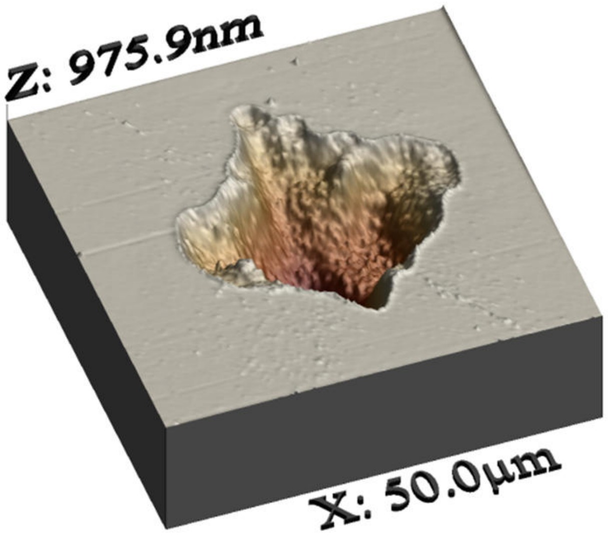
- No changes in the reflectivity during the fs FEL pulse.
- Energy density deposited in the sample's surface via absorption is the highest for the on-resonant conditions (Bragg reflection) in-spite of the higher reflectivity.
- The depth-profile of the radiation energy deposited in the sample is smoothened by fast heat diffusion process by electrons.
- At the damage threshold the (averaged over a bilayer) energy density at the surface corresponds to the energy density required for melting of one of the multilayer materials.

More details: A. R. Khorsand, R. Sobierajski, et al. Opt. Express **18**,700 (2010).
R. Sobierajski, S. Bruijn et al. Opt. Express **19**, 193 (2011)

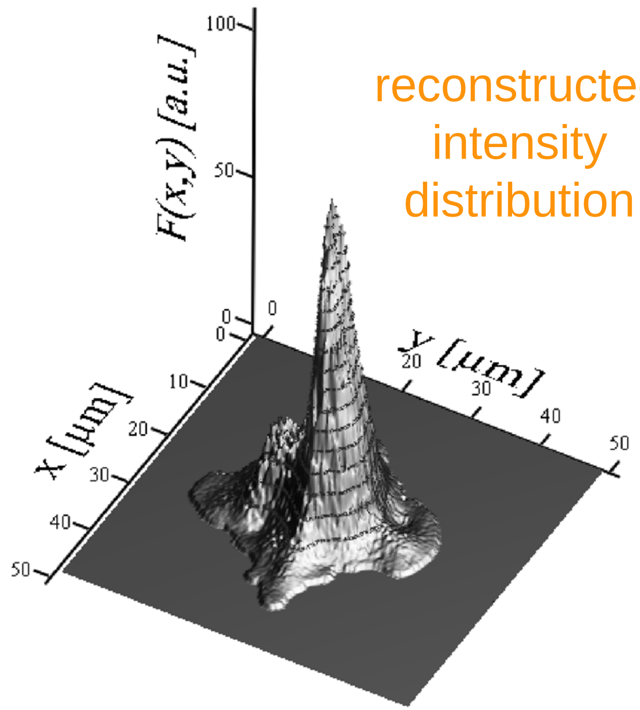
Beam characterization

Slide by courtesy of J. Chalupsky

Initial beam imprint



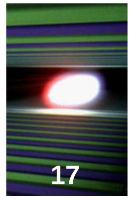
- Application:
  - ➔ Spot size measurments
  - ➔ Optics setting / optimization



reconstructed intensity distribution

A reconstructed beam profile depicting inhomogenities and deviations from an ideal Gaussian beam.

Chalupsky et al., *Opt. Express* **15**, 6036 (2007).
Chalupsky et al., *Opt. Express* **18**, 27836 (2010).



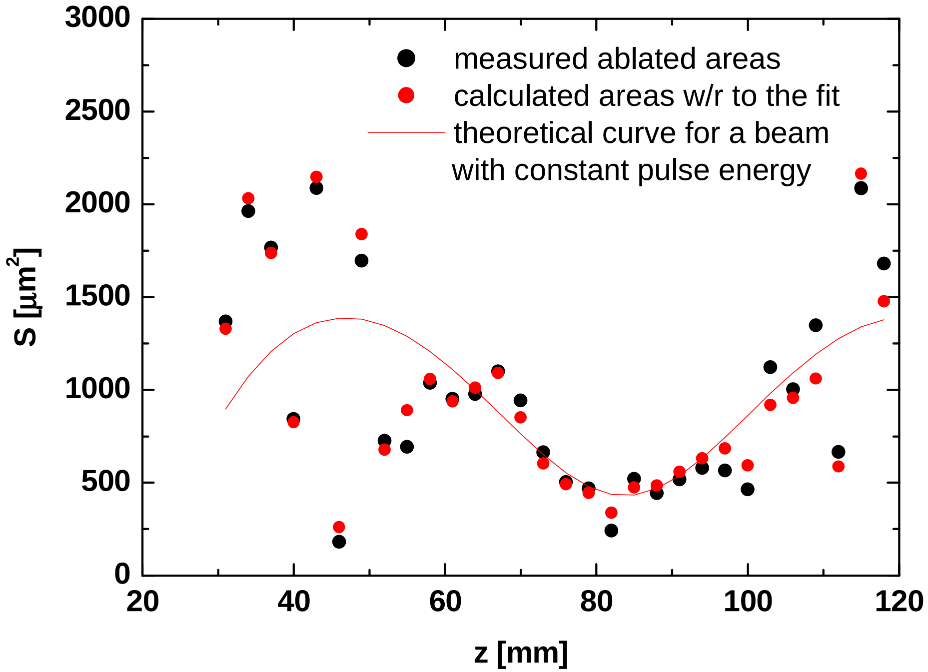
Beam characterization

Slide by courtesy of J. Chalupsky

Caustic curve measurements : FLASH , 7 nm

Assuming a stigmatic beam :

$$S(z,F_0)=S_{foc}\left(1+\frac{(z-z_c)^2}{z_0^2}\right)\left(\ln\frac{F_0}{F_{th}}-\ln\left(1+\frac{(z-z_c)^2}{z_0^2}\right)\right)$$



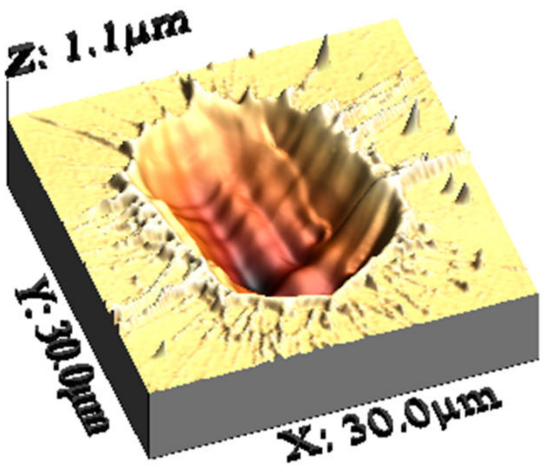
$S_{foc}=(127\pm19)\mu m^2$
$z_c=(83.7\pm0.7)$mm
$z_0=(11.7\pm1.1)$mm
$\ln(E_{th})=(-2.07\pm0.15)\ \ln(\mu J)$

Here, S_{foc} is the focal spot area, z_c the beam waist position, z_0 the Rayleigh range, F_{th} the threshold fluence, and F_0 the peak fluence at the focus.

Beam characterization

Slide by courtesy of J. Chalupsky

$PbWO_4$: a good candidate for short wavelengths

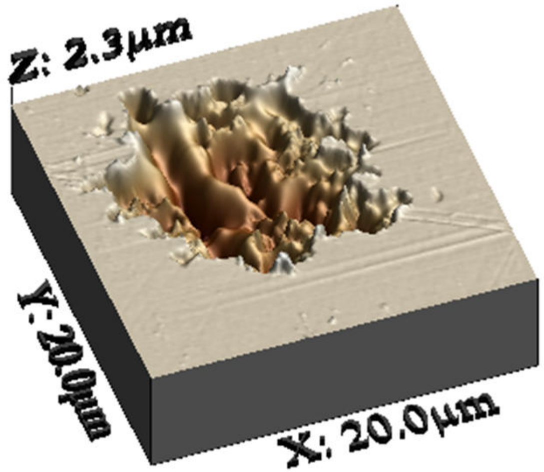


- an ablative imprint in $PbWO_4$ created by 6Å LCLS radiation (2keV) out of the focus (AMO station, Sep 2009)

- the pulse energy adjusted by a gas attenuator (T=1%)

- no Be filters used

- in principle usable for beam profile reconstruction at 2keV



- an ablative imprint in $PbWO_4$ created by 6Å LCLS radiation (2keV) out of the focus

- the pulse energy adjusted by a gas attenuator (T=2%)

- Be filters used (T=20%)

- a micron-sized speckle structures indicate that the wavefront has been shattered by the Be filter

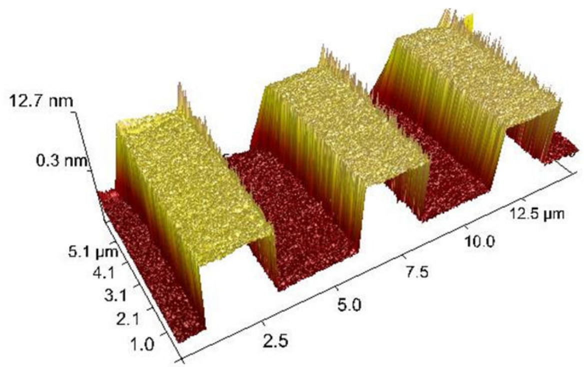
NEXT FLASH BEAMTIME

May 2011: Core team + „3 sites“ collaboration

- new material non C based for H_2O window
  - → current mirror: aC, B_4C, SiC -> Ni, B(?)

91 eV	aC	Ni*	Cr*
F (mJ/cm²)	171±40	54±5	60±10

- damage on grating structure



- Multishot damage process?
- specific targets for in-situ spot characterization

* Non published L. Juha et al.

Conclusion

What DAMAGE STUDIES can do for you:

- design of beamline: single shot damage
  - optical coatings
  - ML / grating
  - crystal x-ray monochromator / beam diagnostic
  - …..everything that goes in the beam
- beam characterization
- optimization of focusing optics device