Development of multilayer-based x-ray optics for FEL and synchrotron applications

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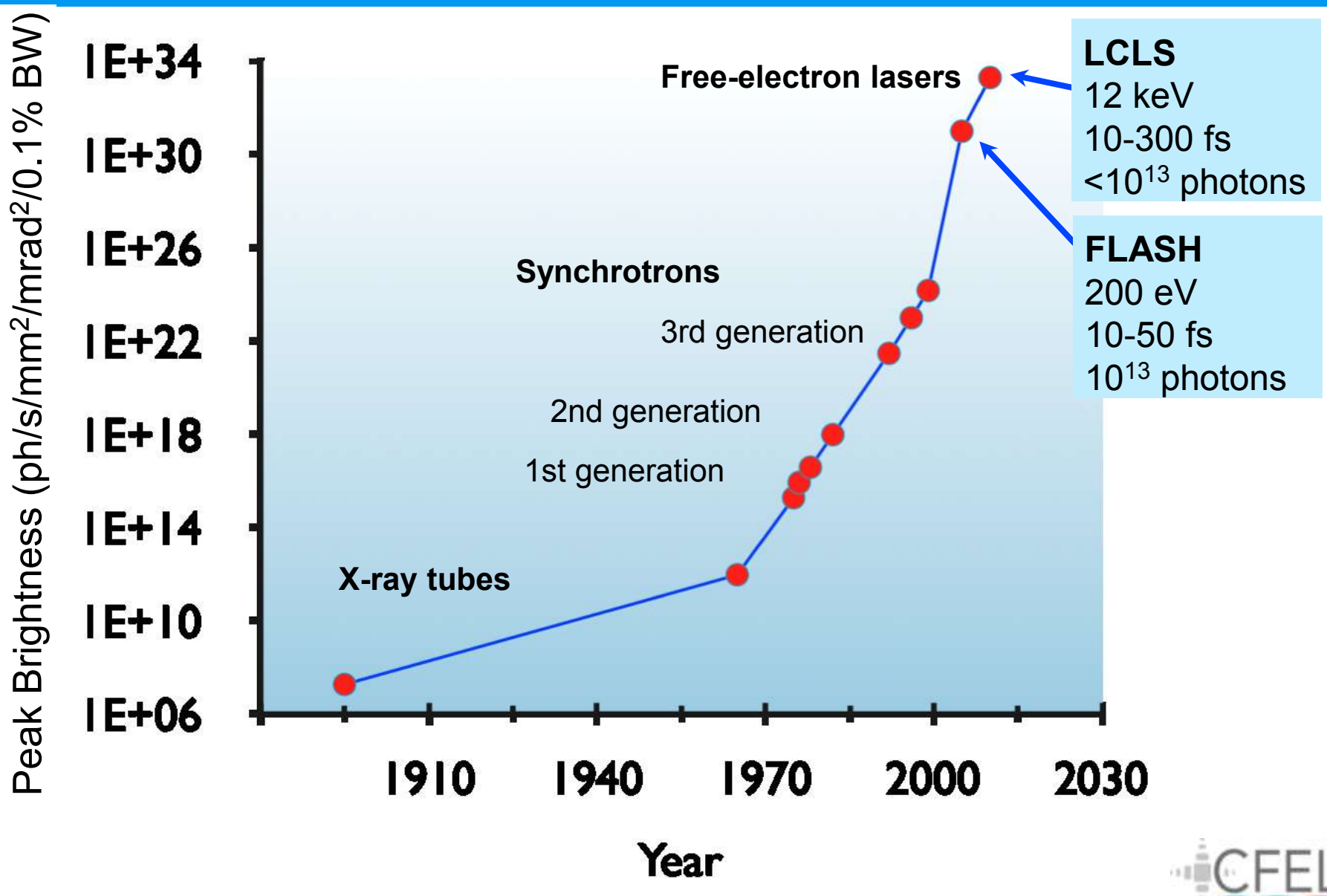
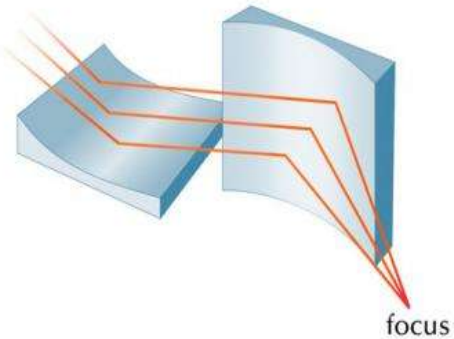
Photon Sciences, DESY, Hamburg

Instrumentation seminar, March 2, 2012

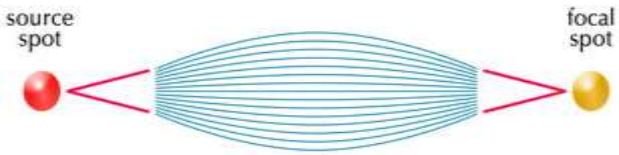
X-ray sources have developed at a staggering pace since their discovery in 1895

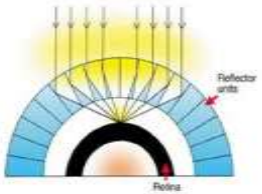


Different types of X-ray optics



Kirkpatrick-Baez mirrors





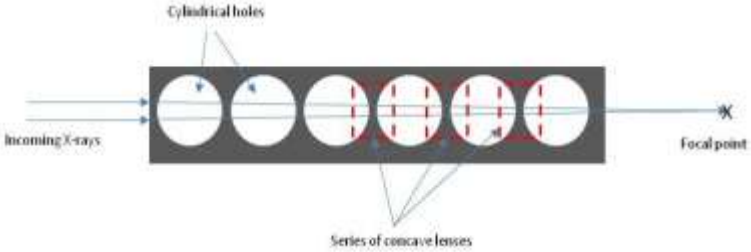
Polycapillary optics

Schwarzschild optics

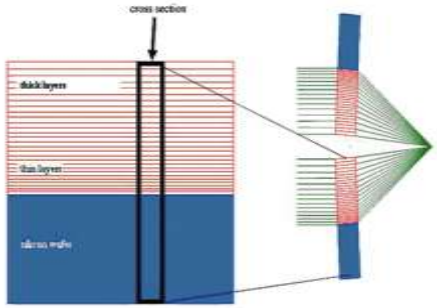
Wolter optics (nested mirrors)

Figure 4: Fresnel zone plate

Fresnel zone plate



Compound refractive lenses



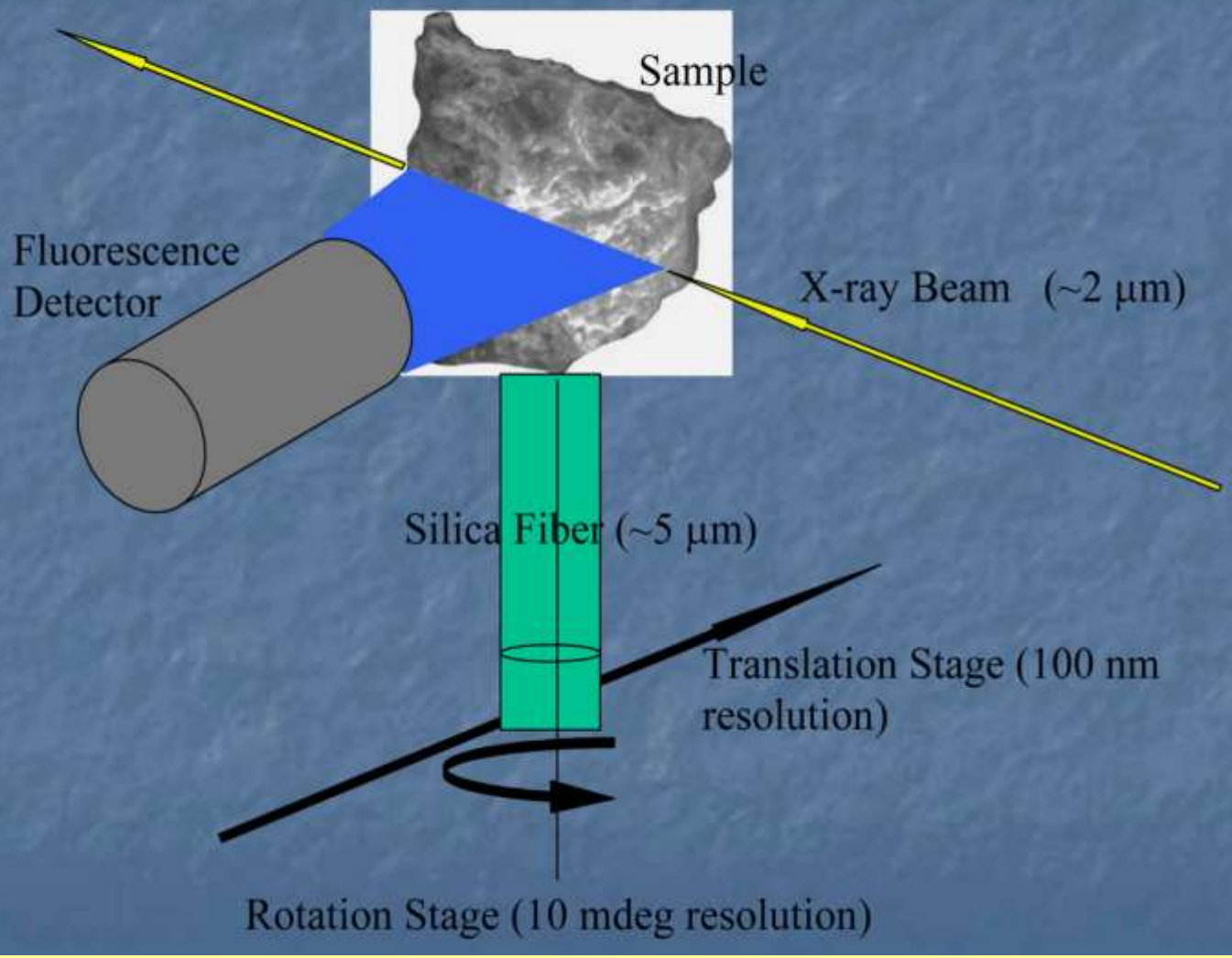
Multilayer Laue lens

Image from Argonne National Laboratory

Images from Xradia.com

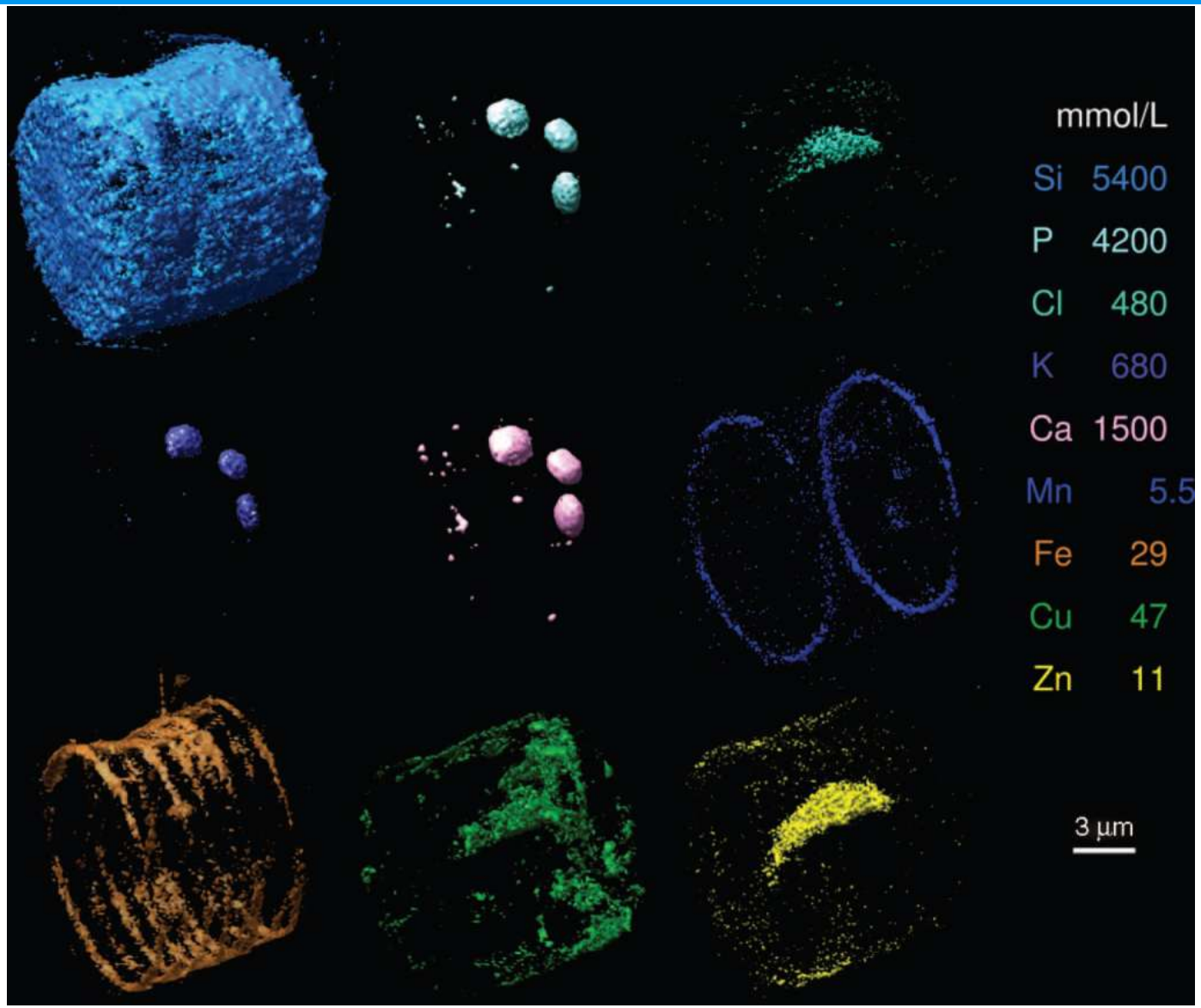
Images from wikipedia.org

Fluorescence Microtomography Apparatus



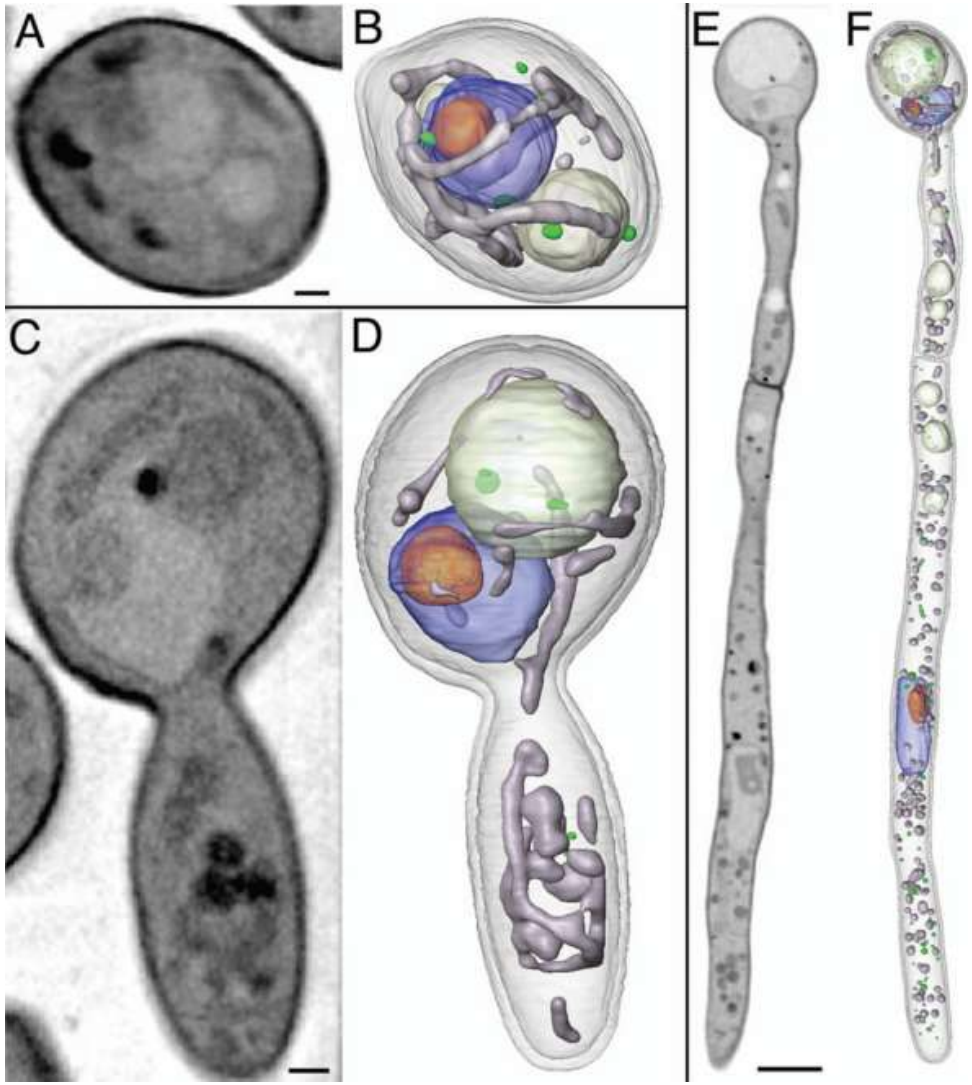
A. Lanzirotti and S. Sutton, The Univ. of Chicago, GSECARS microprobe at APS

3D elemental distributions in the marine protist *Cyclotella meneghiniana* - X-ray fluorescence tomography



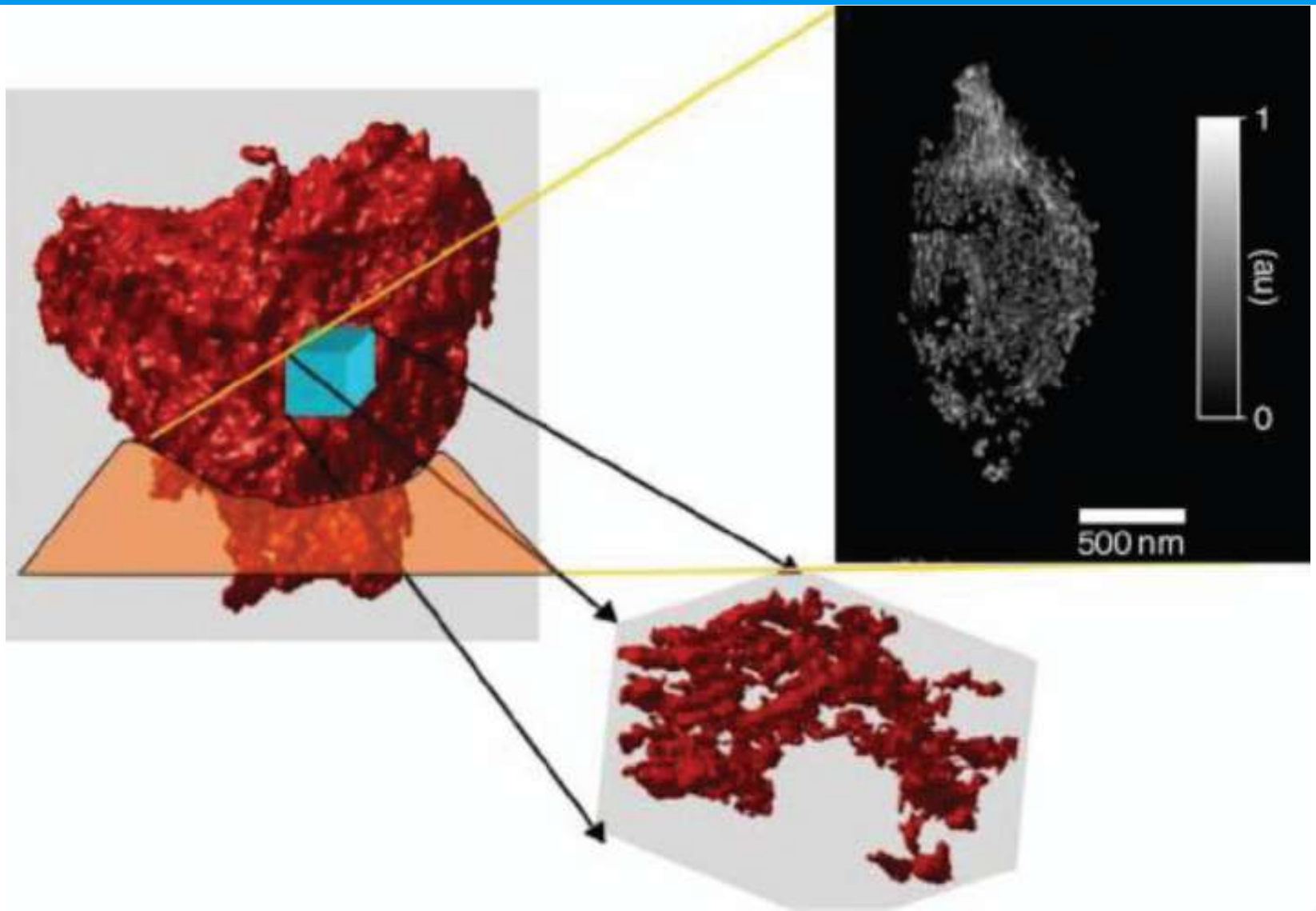
M.D. de Jonge, et al., Proc. Natl. Acad. Sci. USA 107(36) (2010).

Soft X-ray tomographic reconstruction of phenotypical distinct *C. albicans* cells



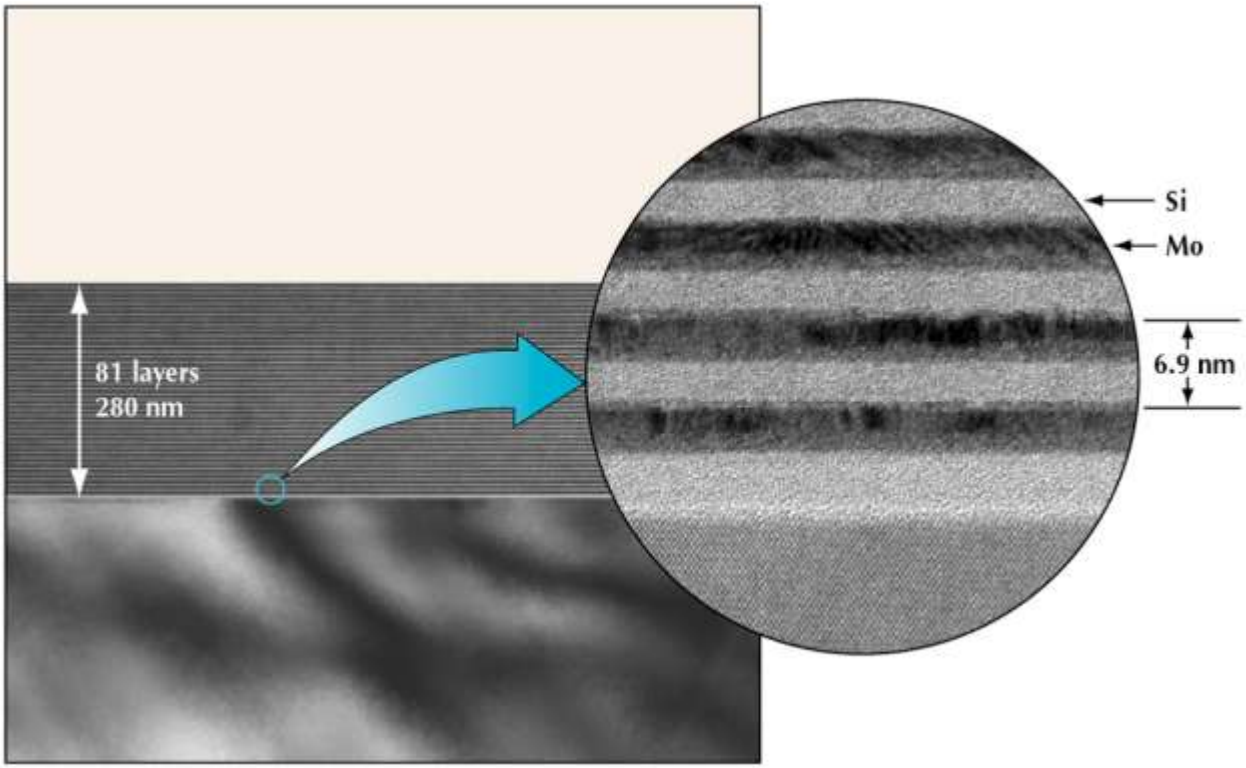
Uchida et al. Proc. Natl. Acad. Sci. USA 106 (2009)

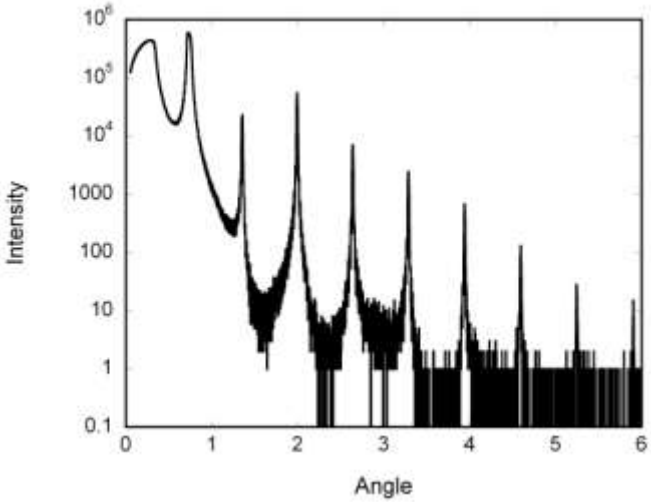
Diffraction microscope image of a Ta_2O_5 aerogel foam

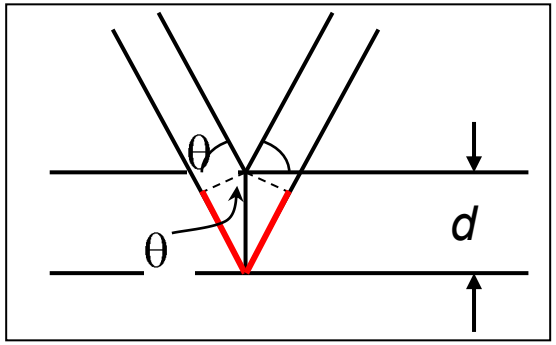


Barty et al. Phys. Rev. Lett. 101 (2008)

Multilayer coatings consist of alternating layers of (usually) two materials of differing refractive index



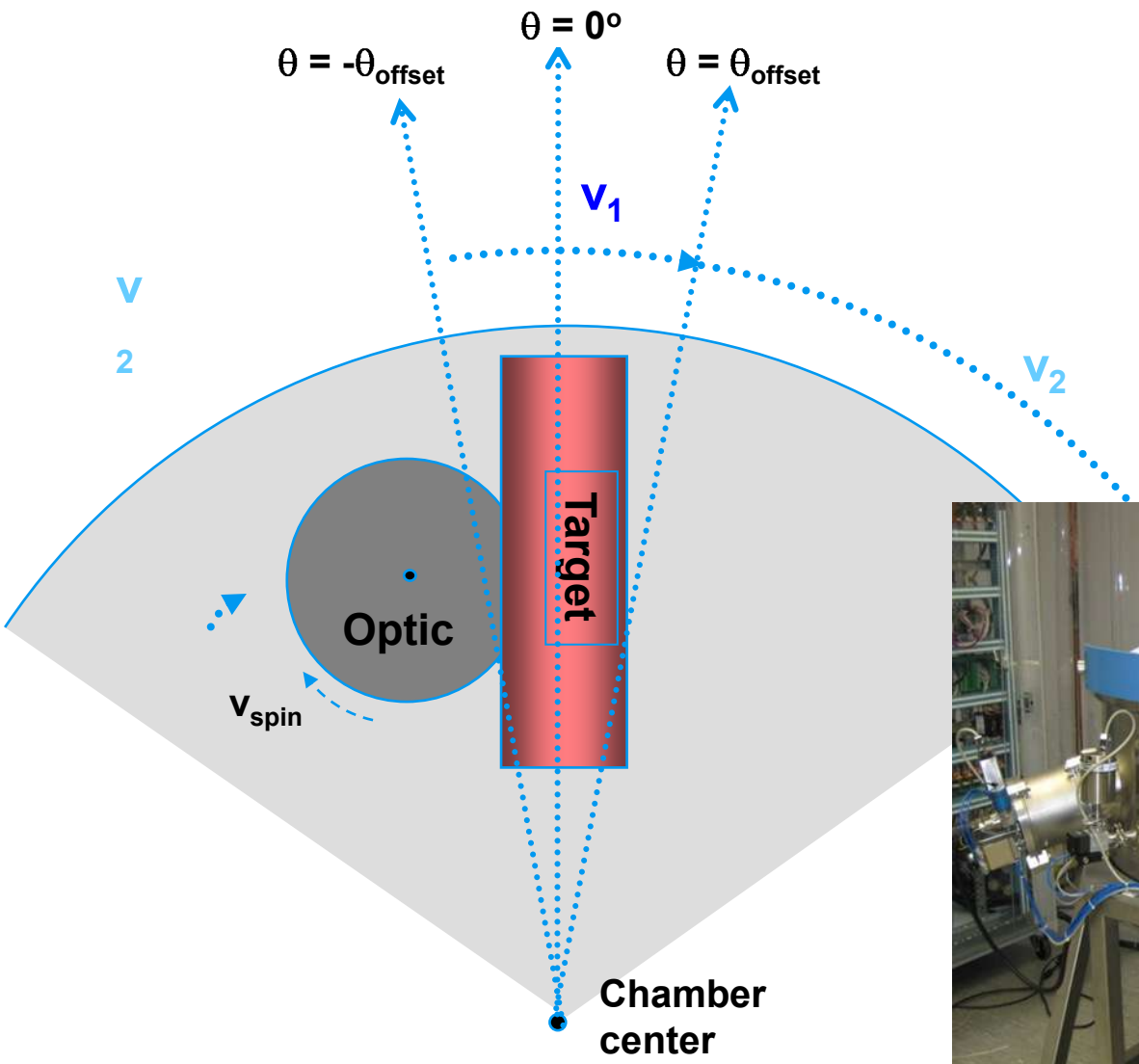


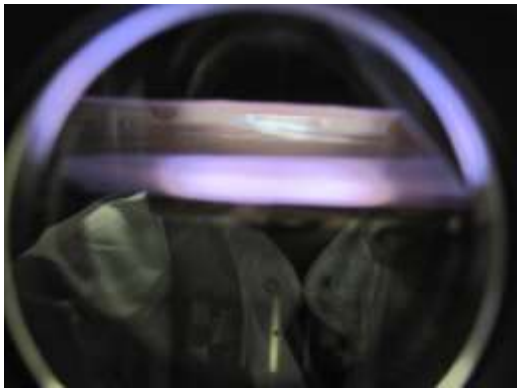


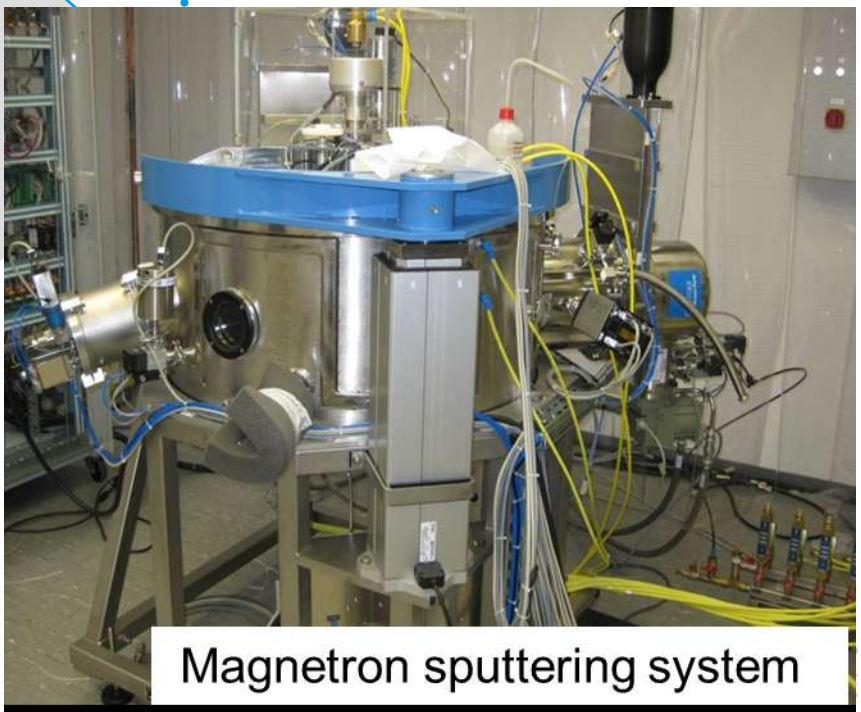
Bragg's Law

$2d \sin\theta = m\lambda$

Velocity modulation and masking are rapidly converging methods used for multilayer thickness control

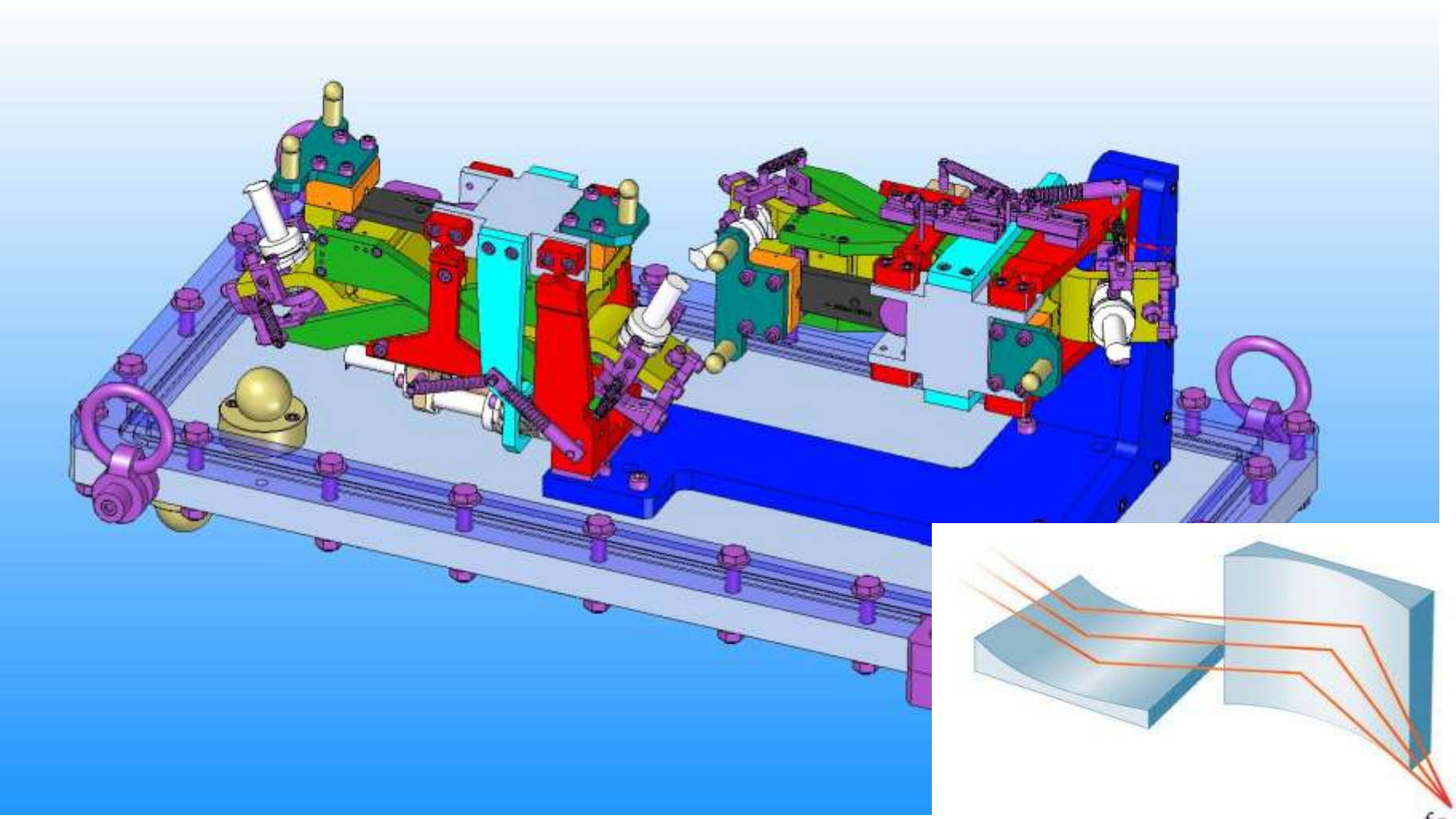






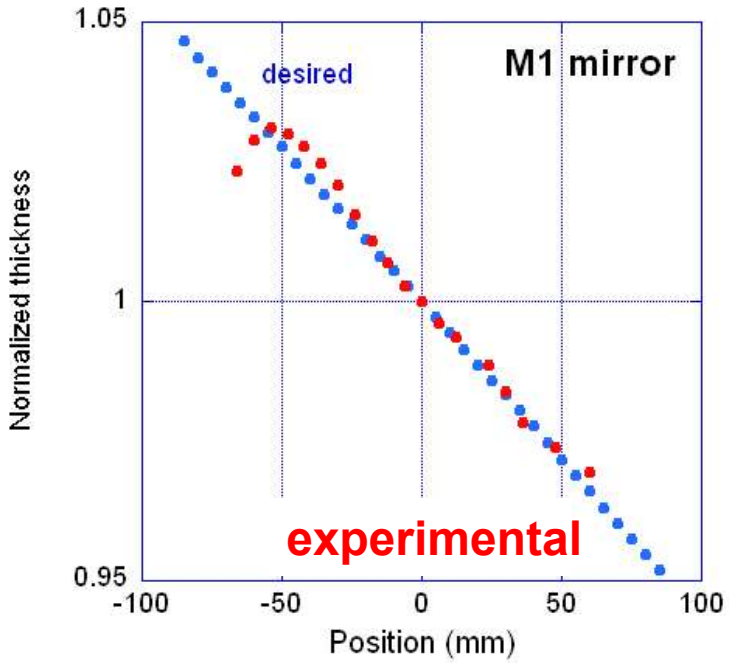
Magnetron sputtering system

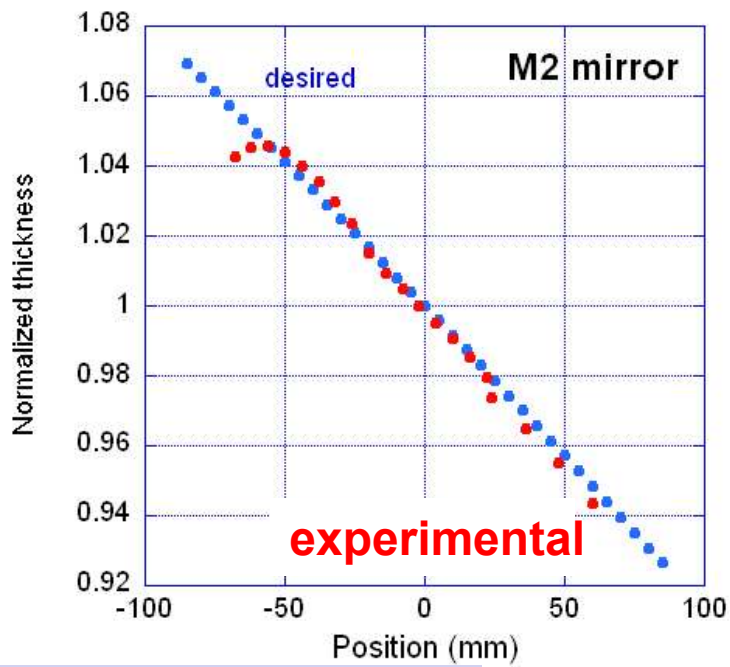
Multilayer coatings for Kirkpatrick-Baez mirrors



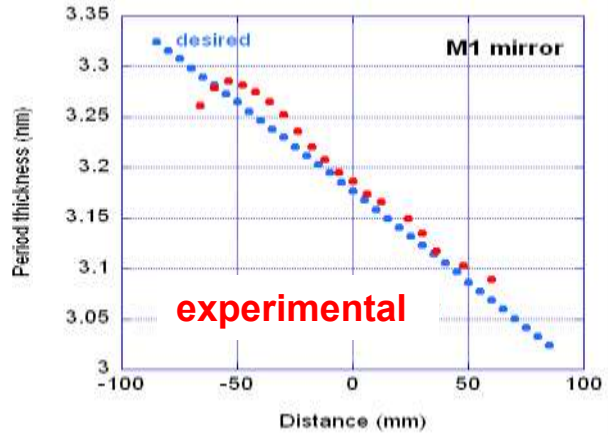
P01 beamline at PETRA III (Collaboration with Rolf Rohlsberger)

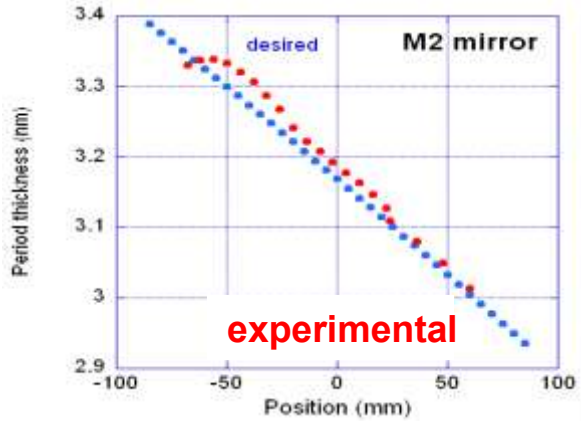
Achieved lateral d-spacing gradients match desired gradients within specifications





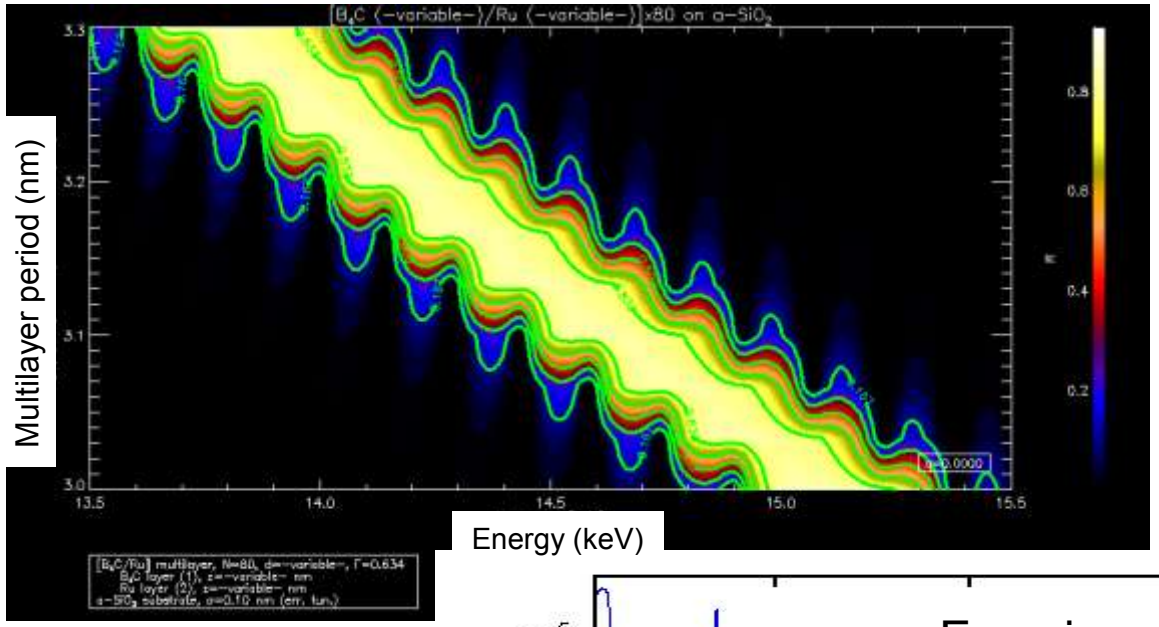
Individual layer thickness ~1.2-1.7 nm



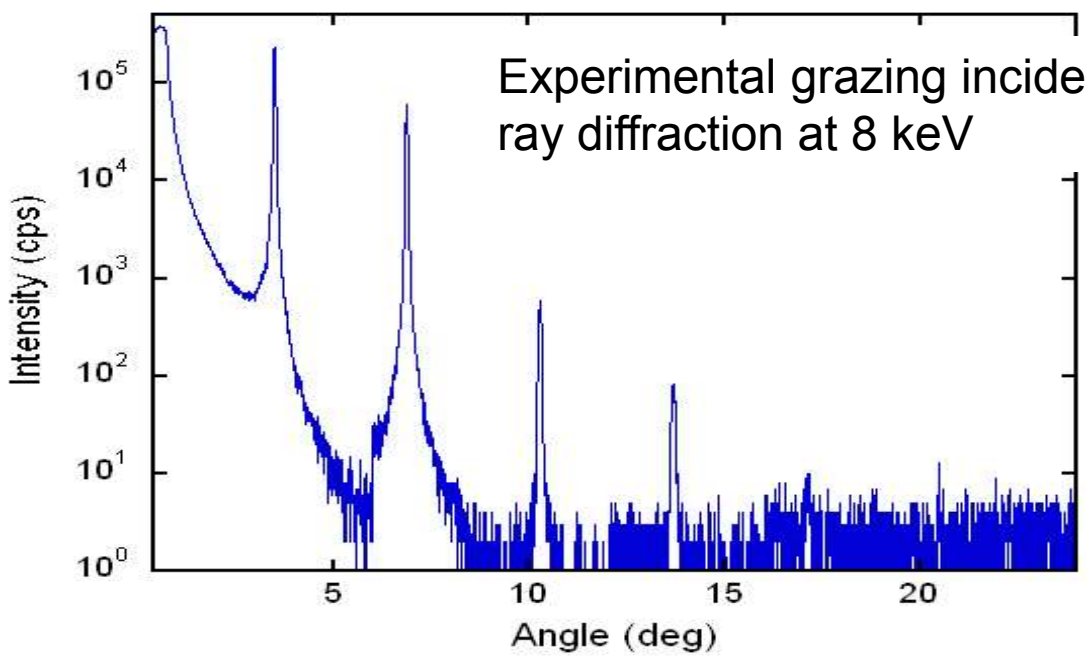


Velocity modulation calculated with software developed by A. Aquila

Absolute reflectivity depends on substrate surface roughness, interface roughness and interdiffusion

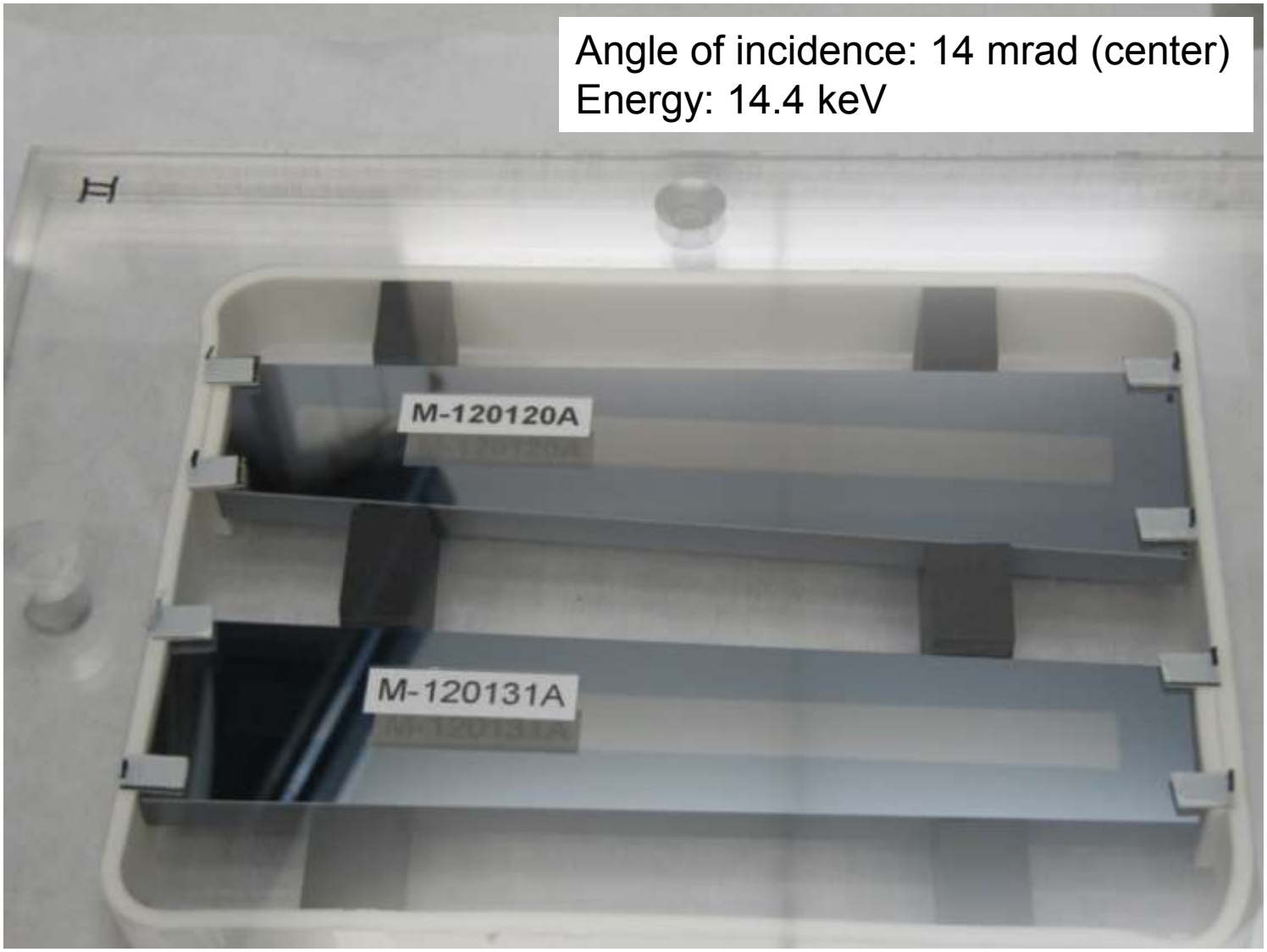


Simulated reflectivity as a function of energy and multilayer period of Ru/B_4C multilayer coated mirror

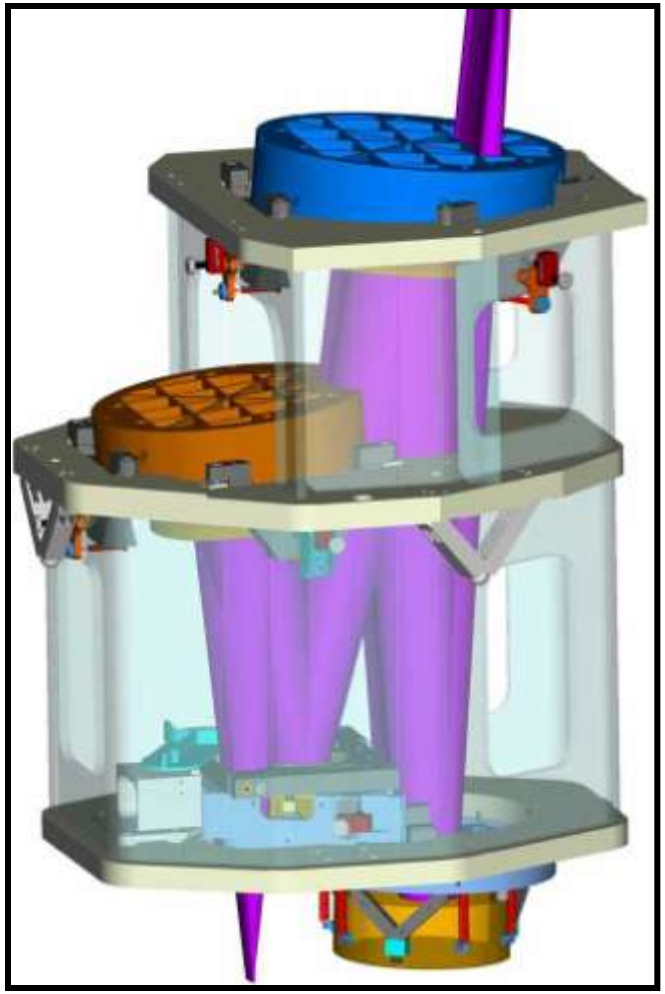


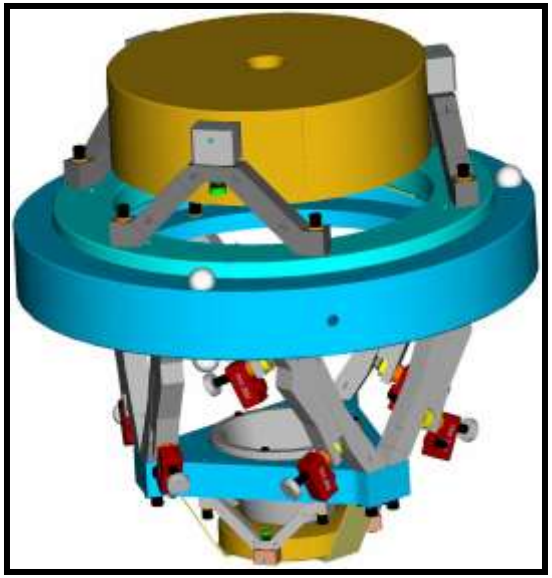
Experimental grazing incidence x-ray diffraction at 8 keV

Two 17 cm long KB mirrors have been successfully coated with high reflectivity Ru/B_4C multilayer



Diffraction-limited performance with normal incidence mirrors was achieved for EUV imaging systems



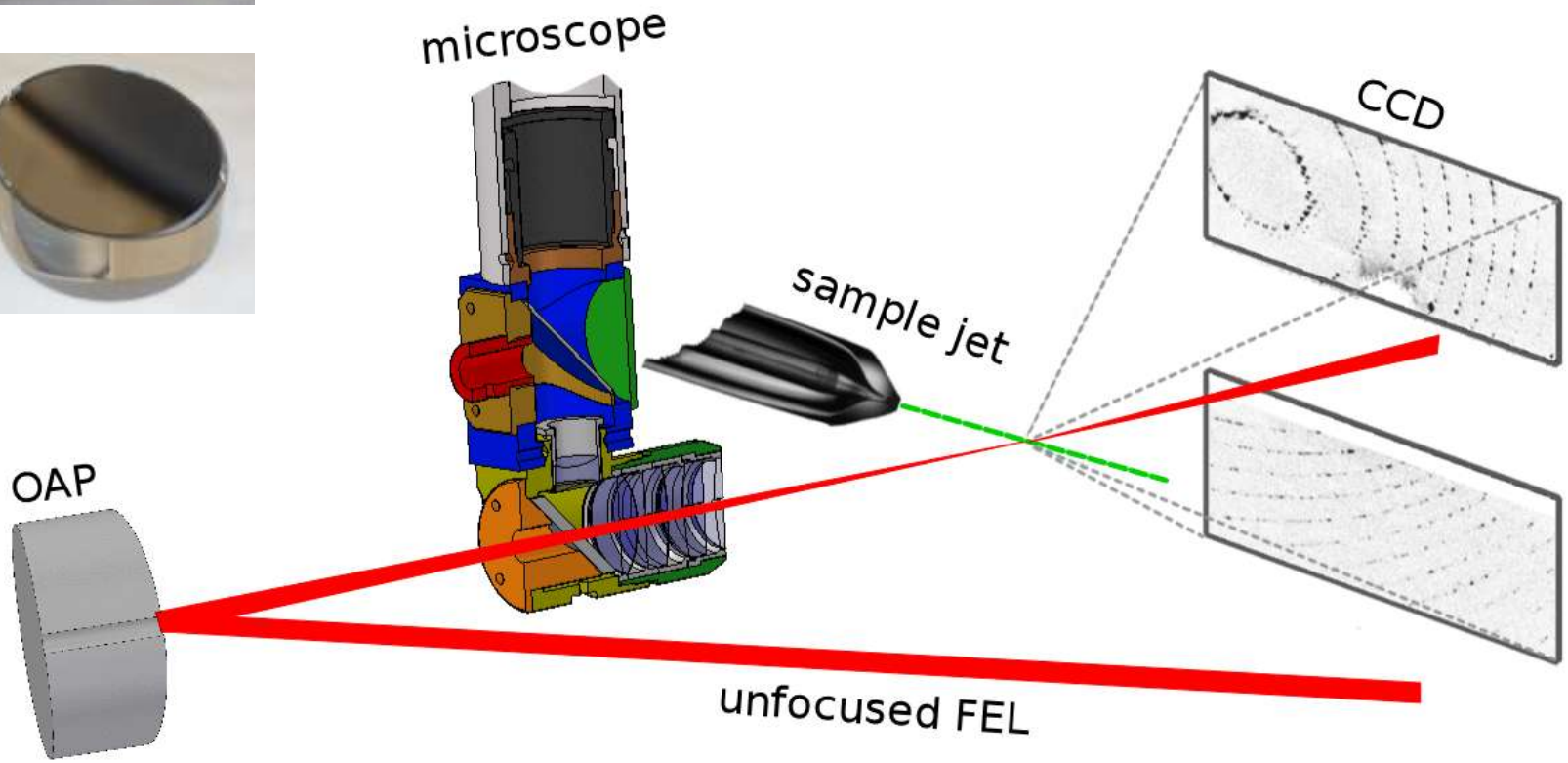


0.3 NA "MET PO Box 2"
2 Aspheric Mirrors

0.1 NA "ETS PO Box 2"
3 Aspheric Mirrors + 1 Sphere

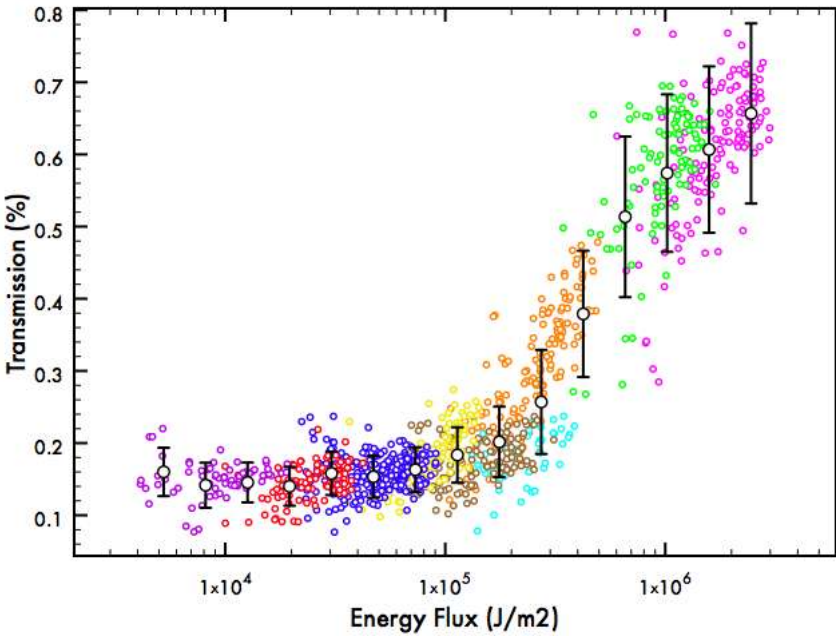
Optics developed, coated and aligned at LLNL as part of EUVL project

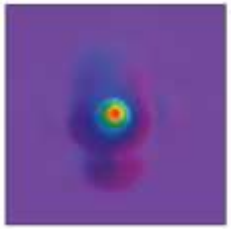
This technology was transferred to normal incidence mirrors for focusing high intensity x-rays from FLASH



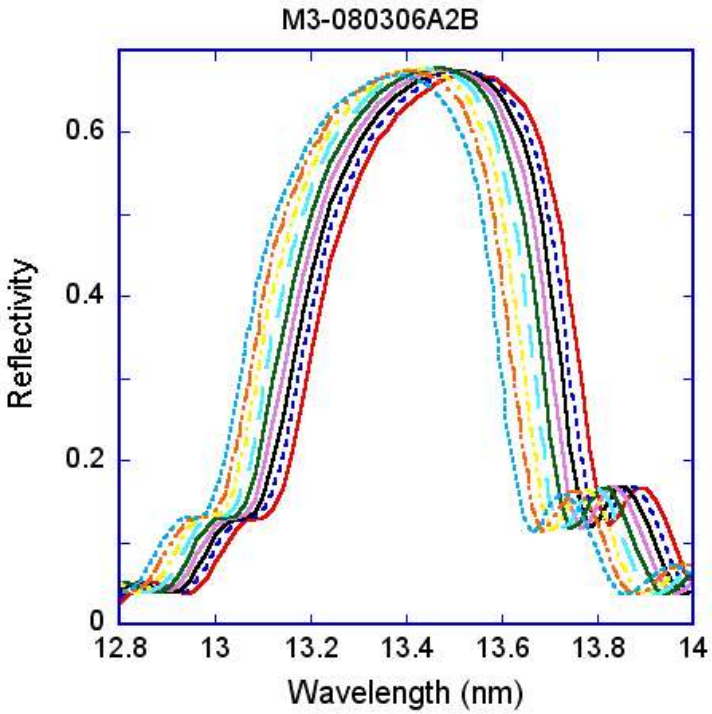
Recent experimental setup in our chamber at FLASH

Our multilayer coated off-axis parabolic mirror focused 13.5 nm FLASH beam to sub-[redacted]n spot





0.35 μm focal spot
(as predicted by Jacek Krzywinski)



Nagler et al., Nature phys. 5, 693 (2009)
Vinko et al., PRL 104, 225001 (2010)

A. Nelson et al., Opt. Exp. 17, 18271 (2009)
S. Bajt et al., SPIE 7361 (2009)

For the first time intensities of 40 mJ / (40 fs (10^{-4} cm)^2), corresponding to power of ~ 10^{17} W/cm^2, were achieved and interesting experiments in warm dense matter could be performed.

Multilayer development for 6.8 nm wavelength

Considerations:

>Reflectivity, temporal and thermal stability, reactivity, intrinsic stress, availability, price

Candidates:

Normal incidence: 0 to 5 deg off normal;

Wavelength: 6 to 7 nm (Source: http://henke.lbl.gov/optical_constants)

Ru/B4C (20% at 6.8 nm, N= 150, J. Korthright)

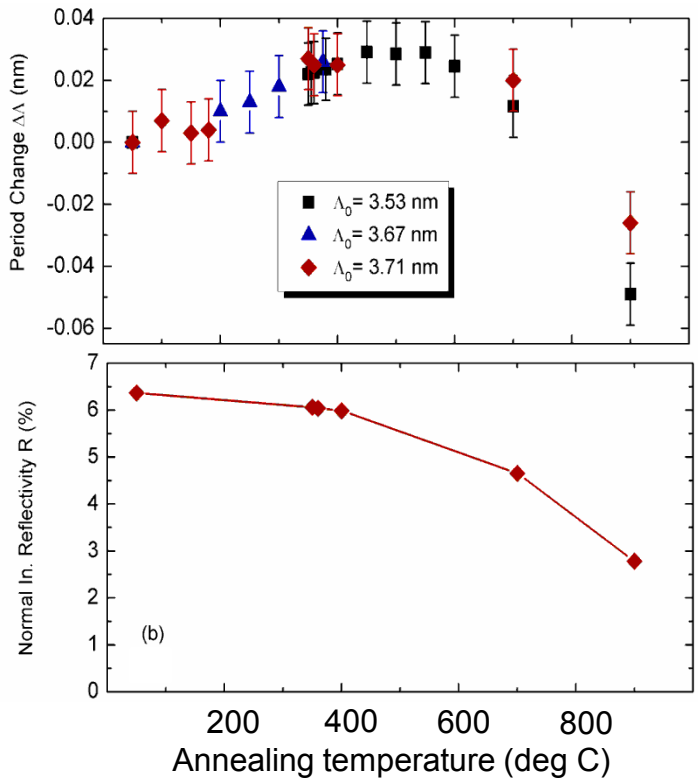
Cr/C (18.9% at 6.42 nm, N = 150, H. Takenaka)

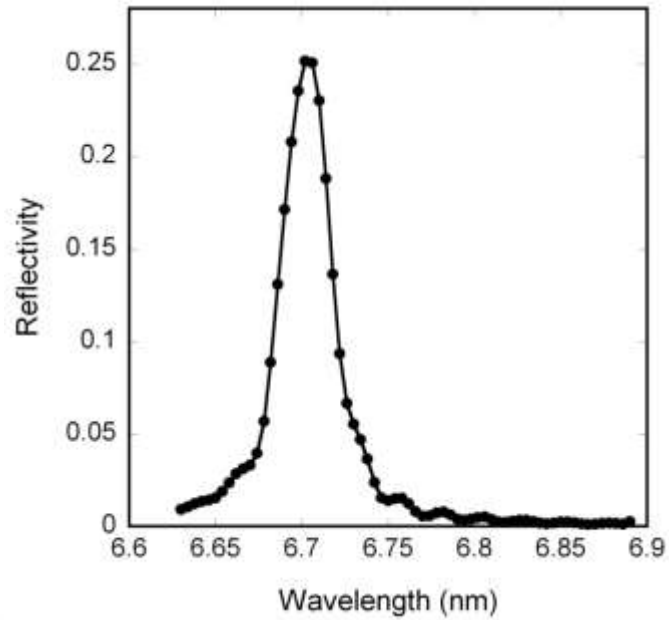
FeCrNi/B4C (16% at 6.8 nm, N = 100, D. Stearns and S. Vernon)

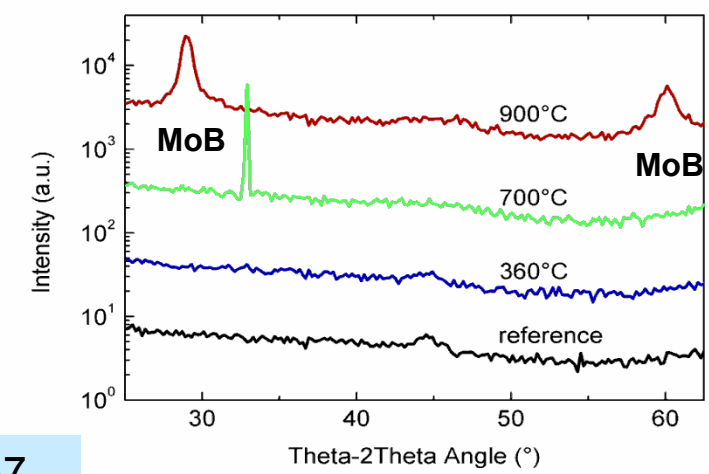
>La/B_4C, LaN/B_4C, LaN/B, La_2O_3/B_4C

>Mo/B, Mo/B_4C

Mo/B_4C MLs for 6.8 nm have decent reflectivity and are thermally stable – a good choice for FEL application

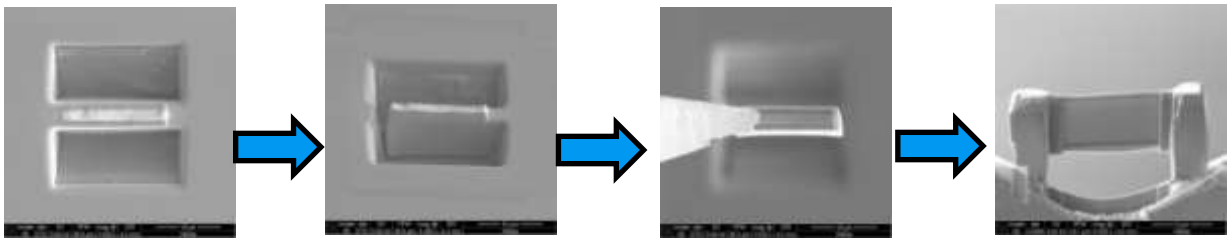




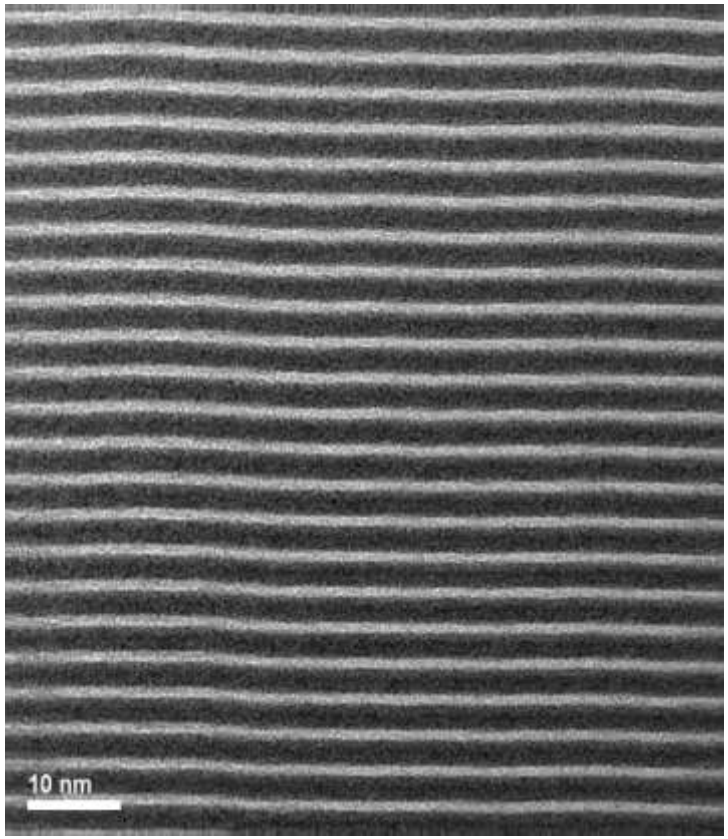


M. Barthelmess and S. Bajt, SPIE 8077-37 (2011)

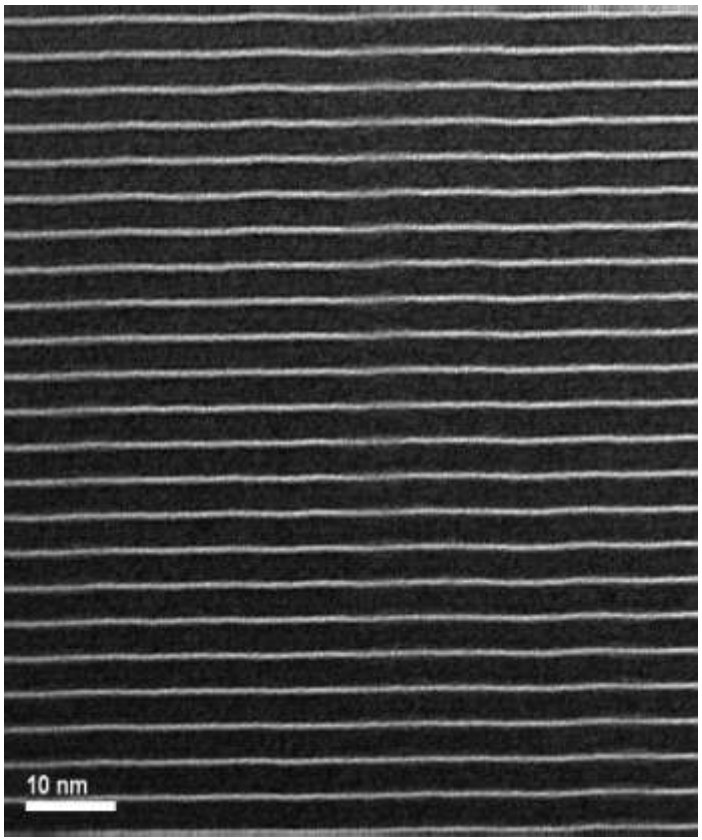
Mo/B_4C ML is thermally stable up to 600 deg C



TEM sample prepared by FIB



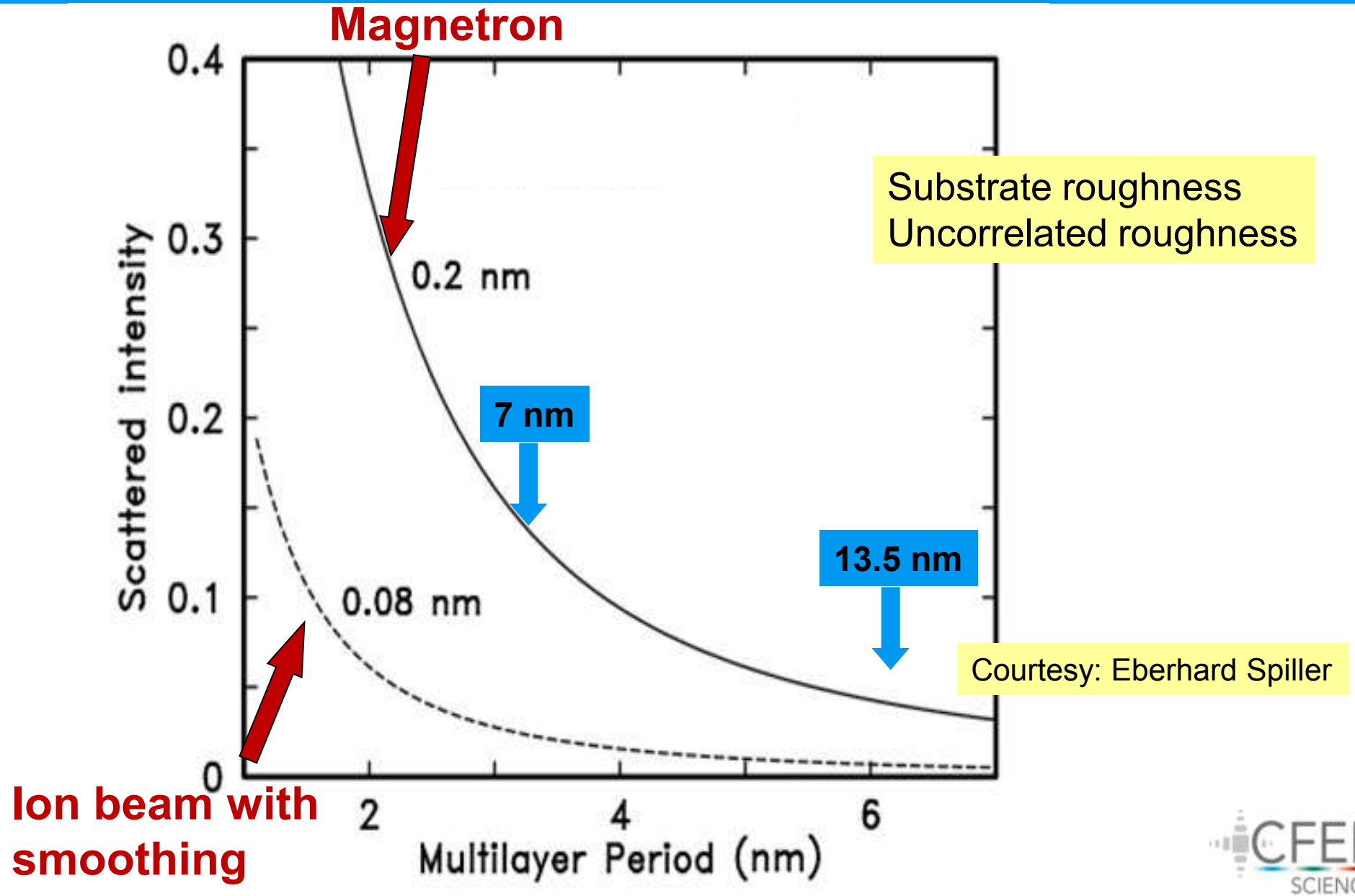
as-deposited state



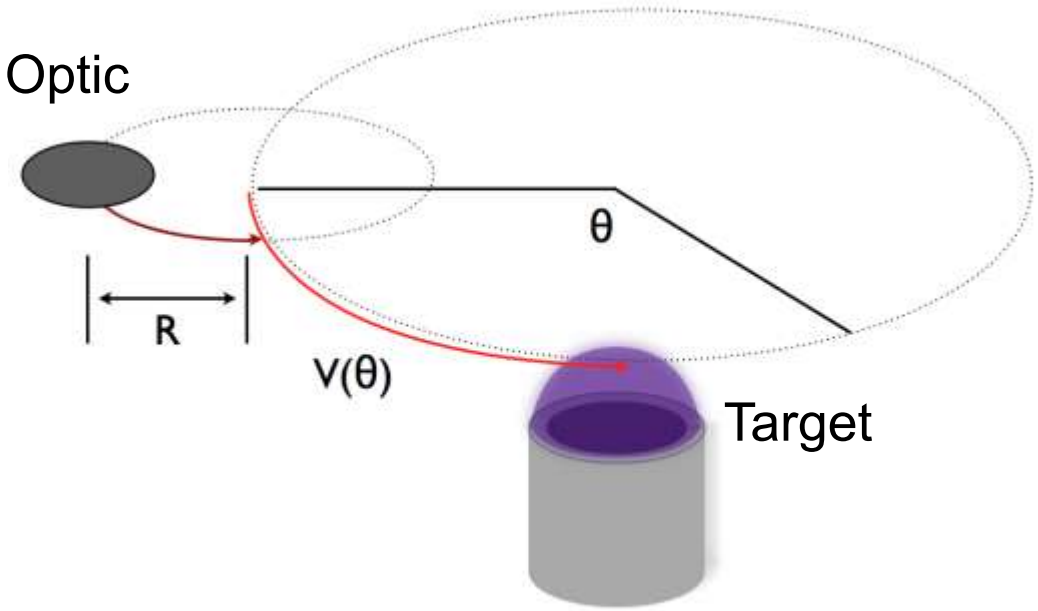
after 1h at 600 deg C

M. Barthelmess and S. Bajt, SPIE 8077-37 (2011)

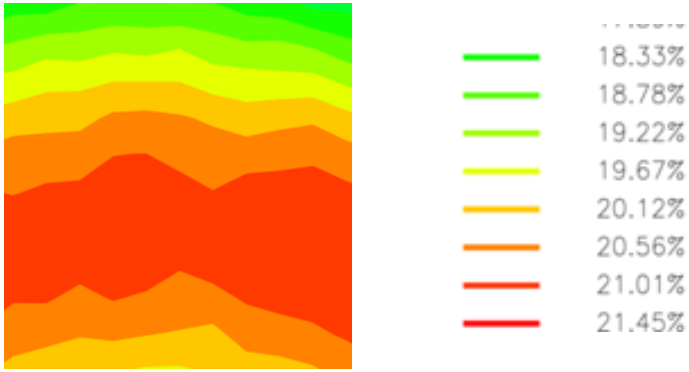
The shorter the wavelength the smaller the period and the higher the impact from interfaces



Achieved wavelength uniformity of 0.1% across clear aperture

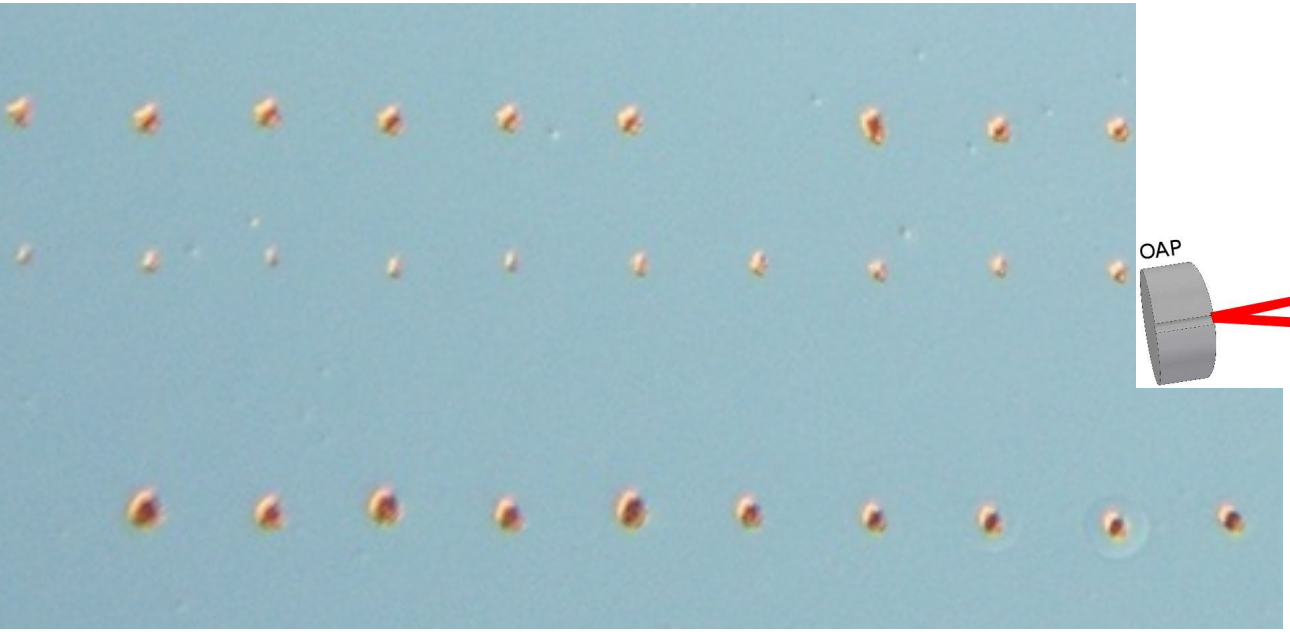


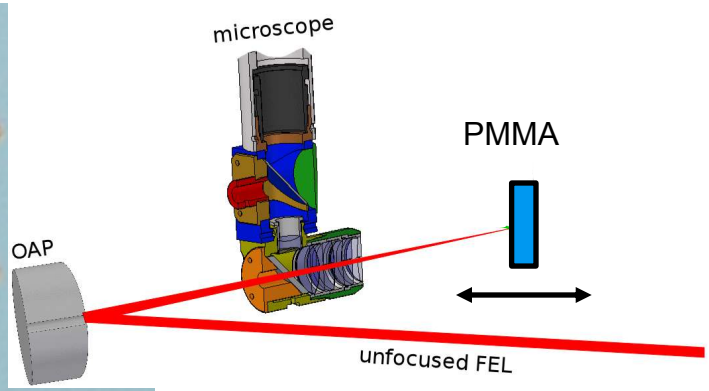
Reflectivity map at a constant wavelength of 6.7980 nm across clear aperture

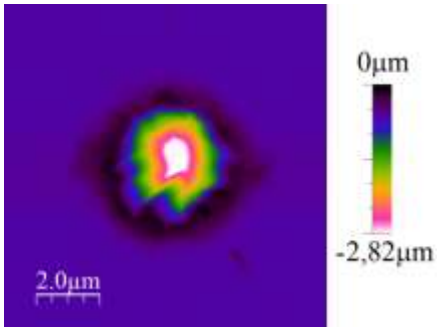


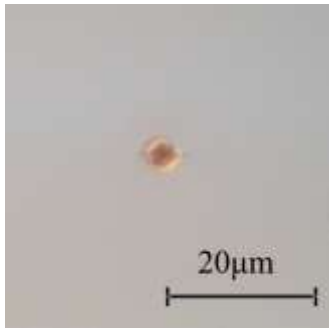
Super-polished substrate with <0.2 nm HSFR and MSFR and figure error of 0.2-0.3 nm

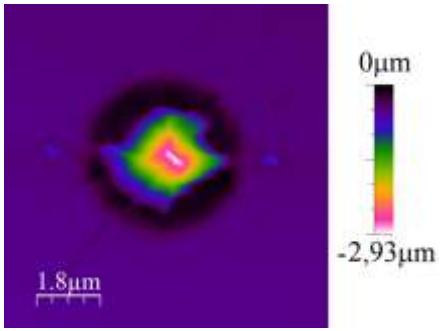
Finding the best focal spot using PMMA





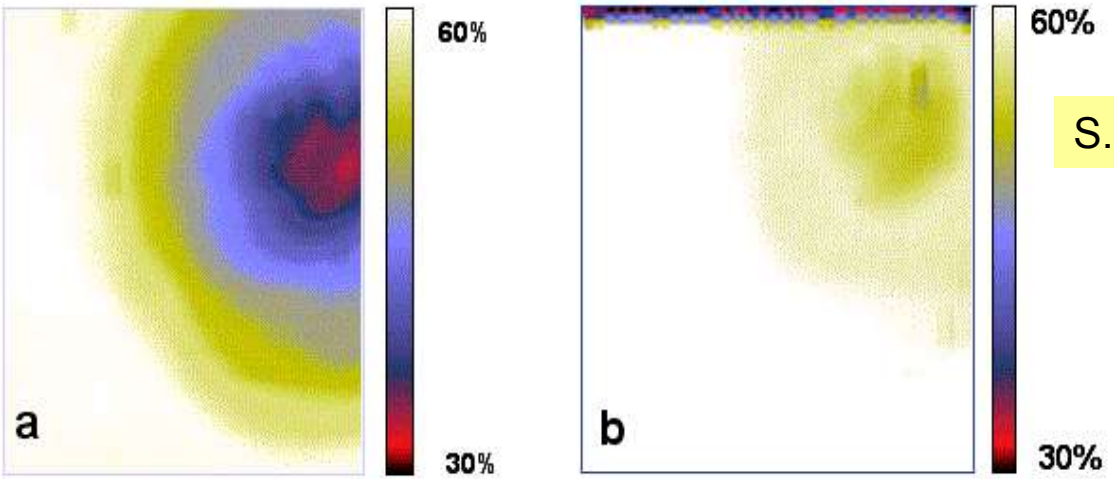






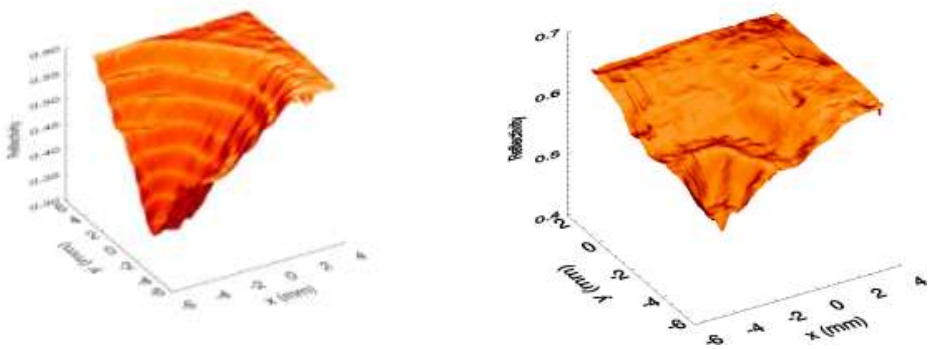
Collaboration with T. Burian, V. Hájková, J. Chalupský, L. Juha (IOP, Prague)

Carbon contamination is also a well known problem in synchrotron and EUVL community



S. Bajt et al., SPIE 7361 (2009)

Reflectivity map shows modulations due to the overlayer thickness variation



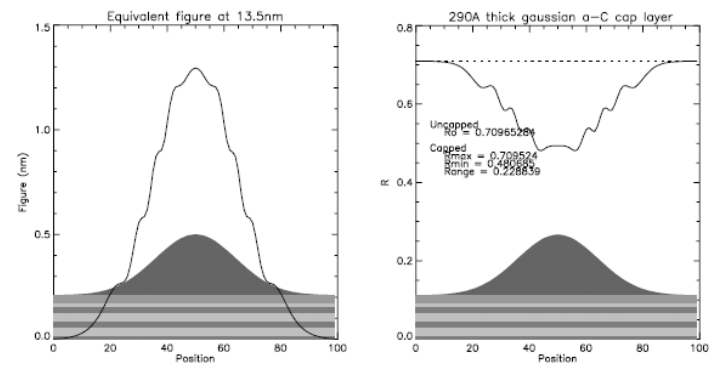
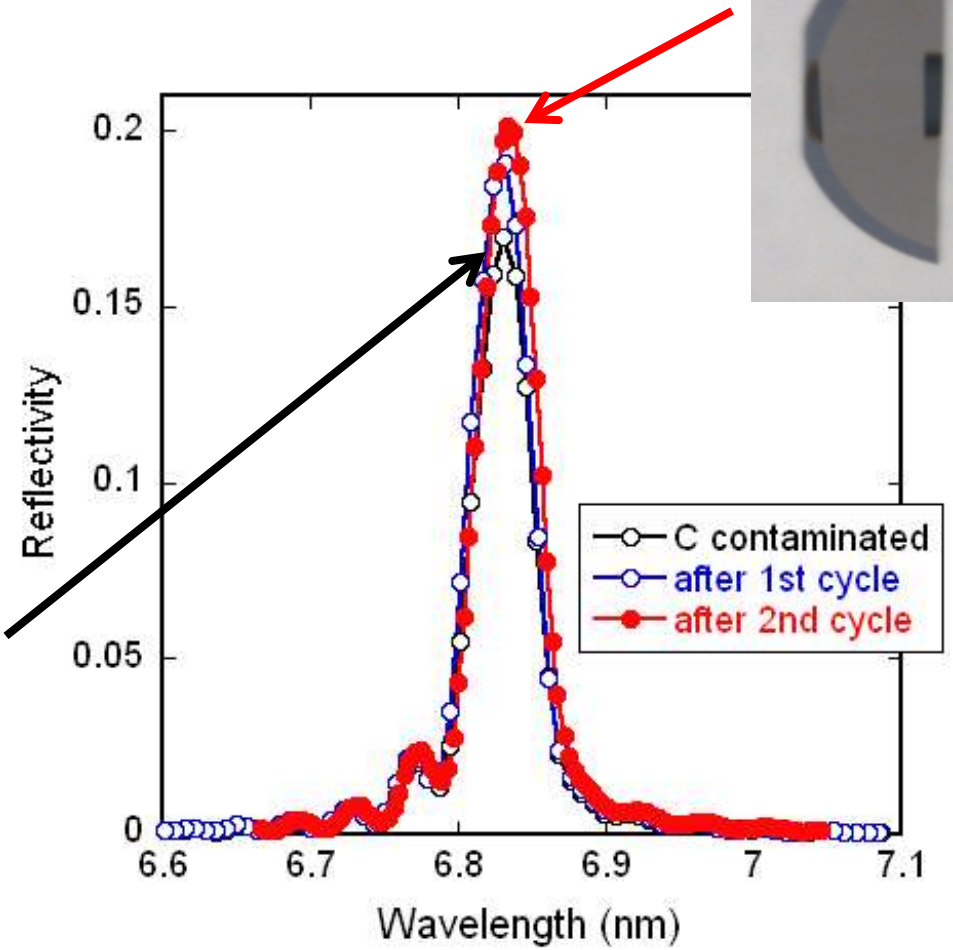


Figure 6

A. Barty and K. Goldberg, SPIE 5037 (2003)

Oxygen plasma cleaning is effective but does not completely recover the initial reflectivity

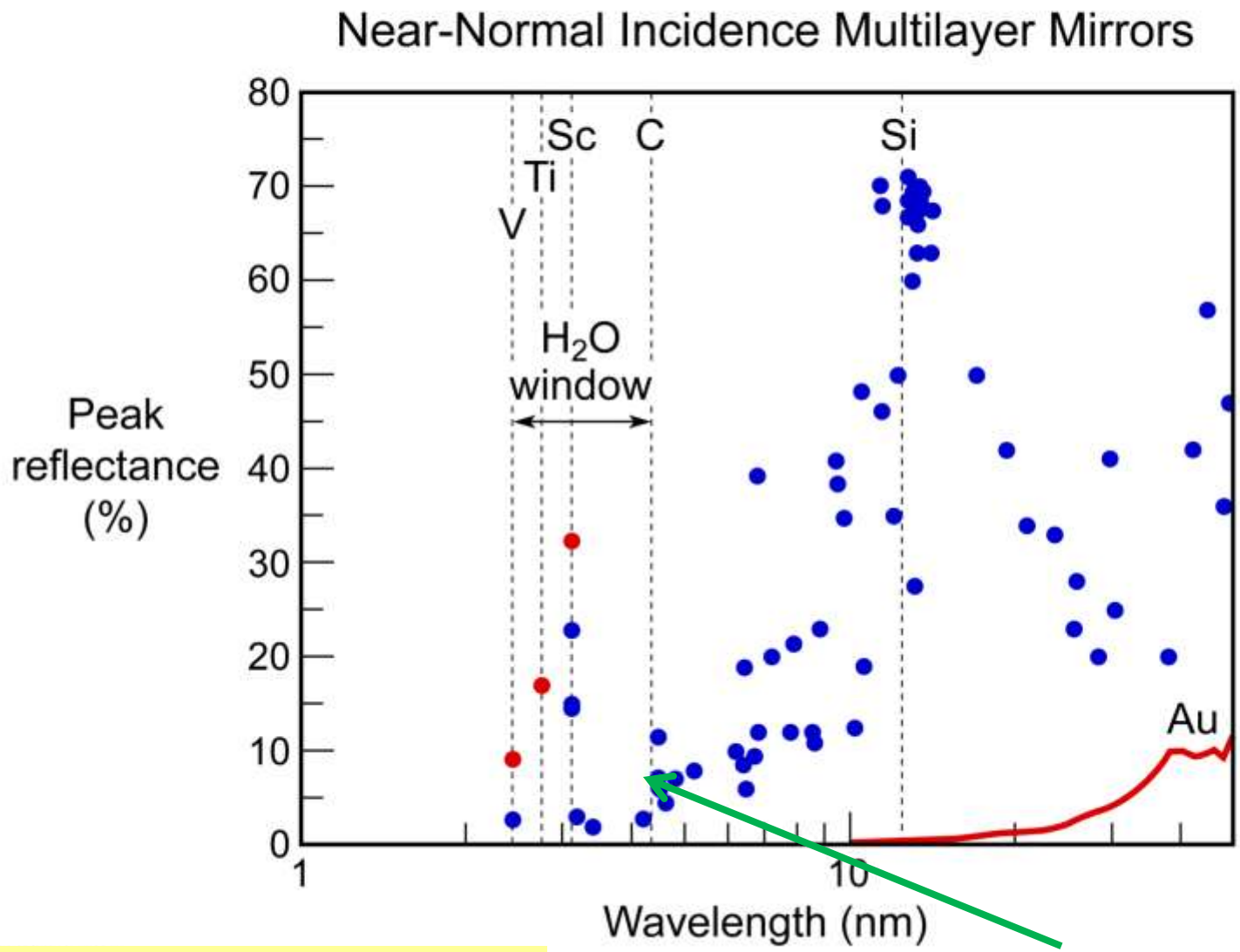
We are developing processes to remove surface contamination from carbon containing MLs



and preliminary results are very encouraging

Miriam Barthelmeß

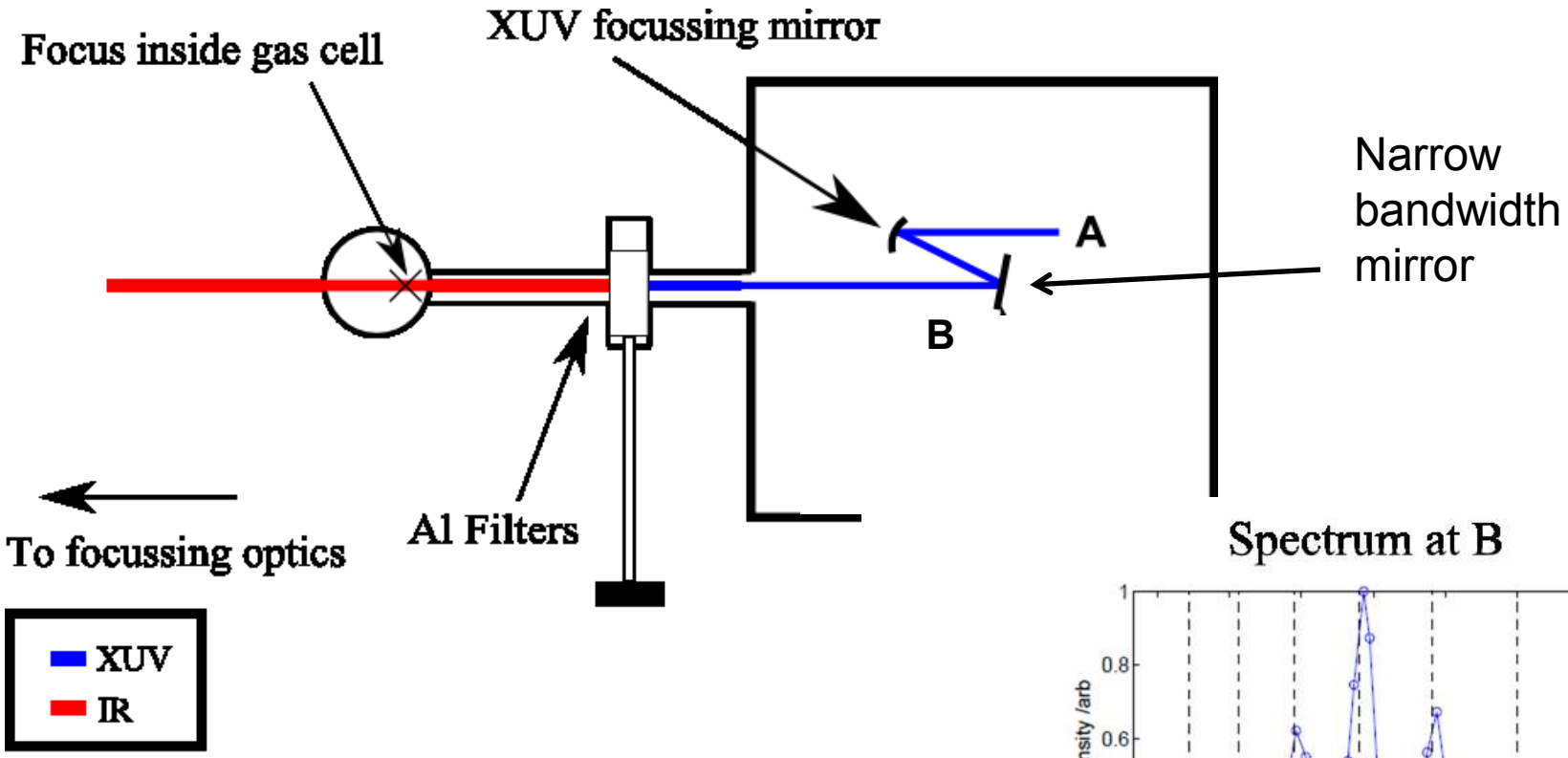
Recent Progress in Multilayer Mirrors

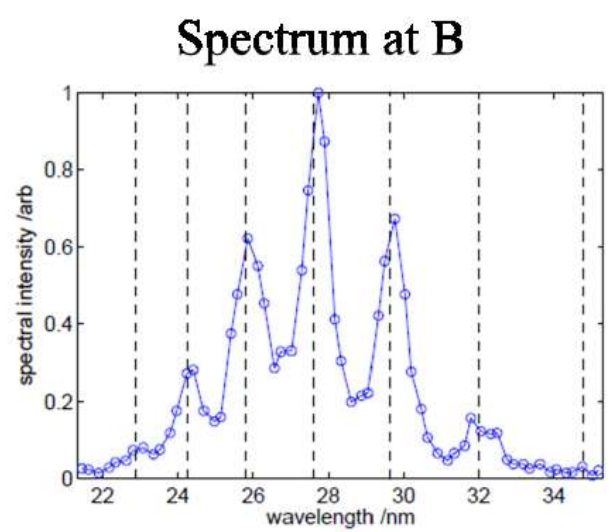


From: Prof. D. Attwood's lecture

$4.2\ \text{nm} < \lambda < 4.4\ \text{nm}$

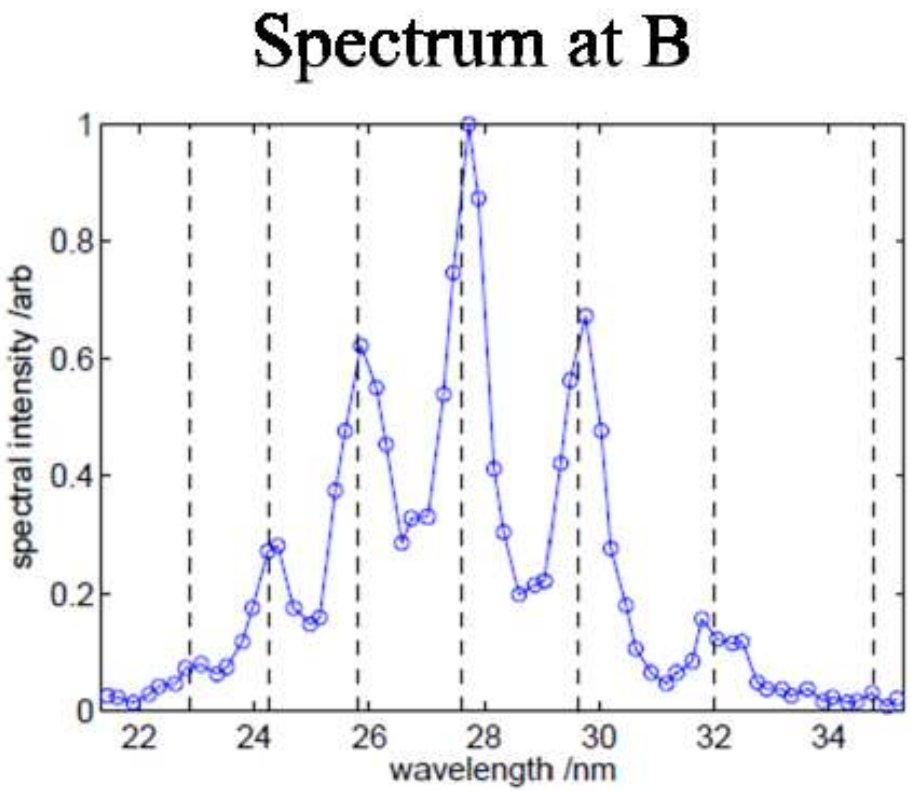
HHG sources produce short and intense pulses

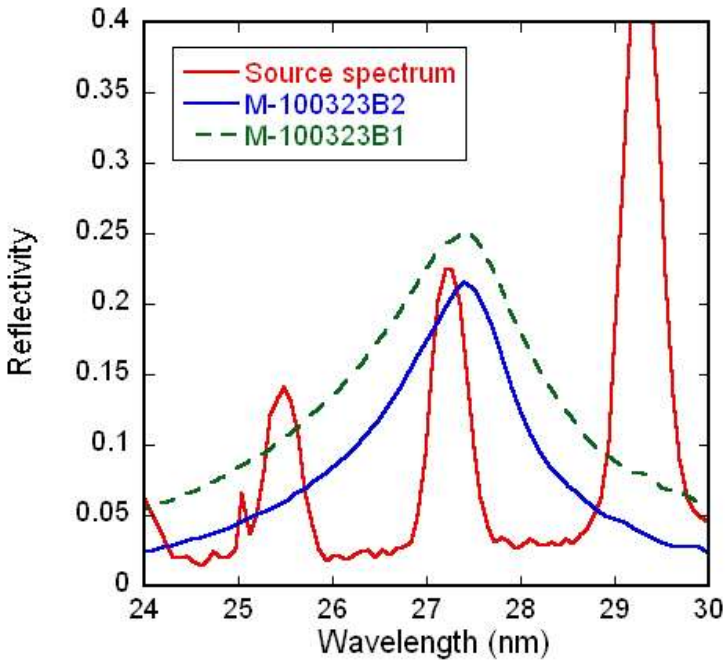




Collaboration with A. Parsons, Univ. of Southampton, UK

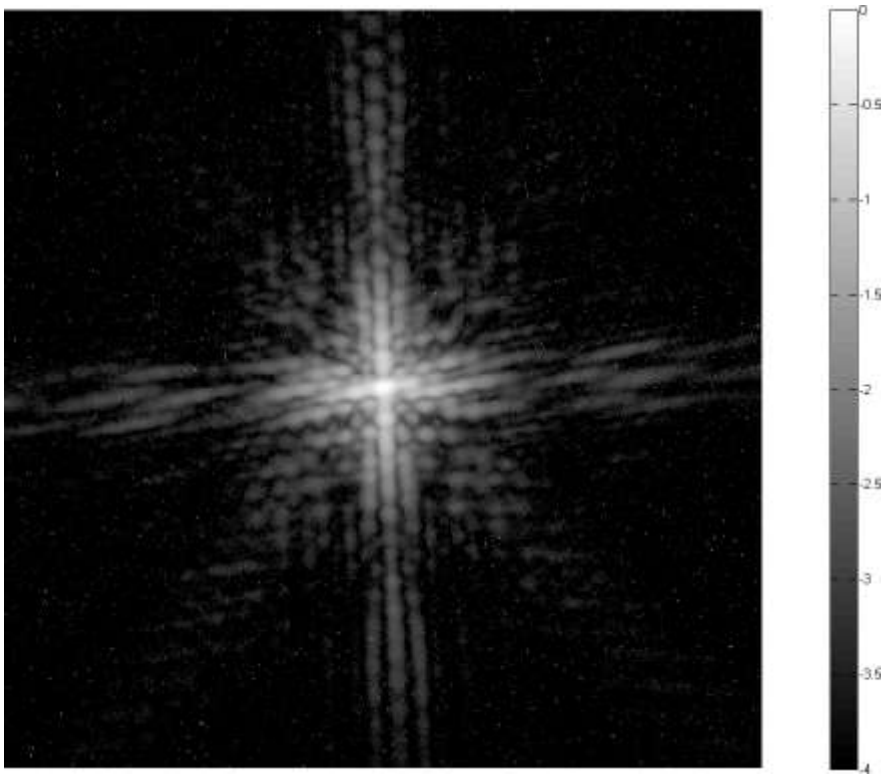
Narrow bandwidth multilayers used with HHG source

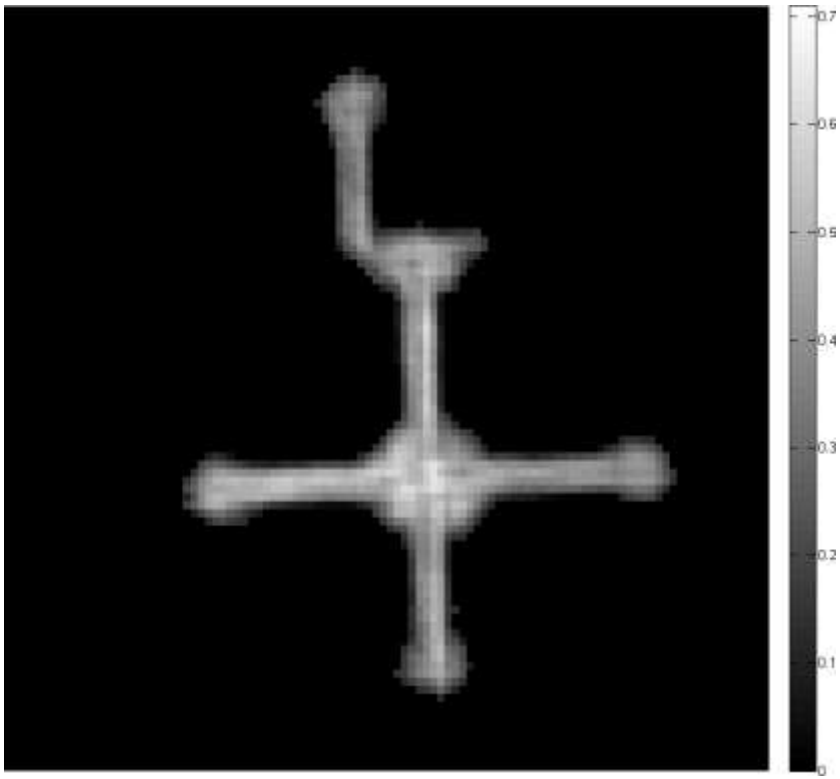




Collaboration with A. Parsons, Univ. of Southampton, UK

Coherent diffractive imaging and reconstruction done using narrow bandwidth multilayers





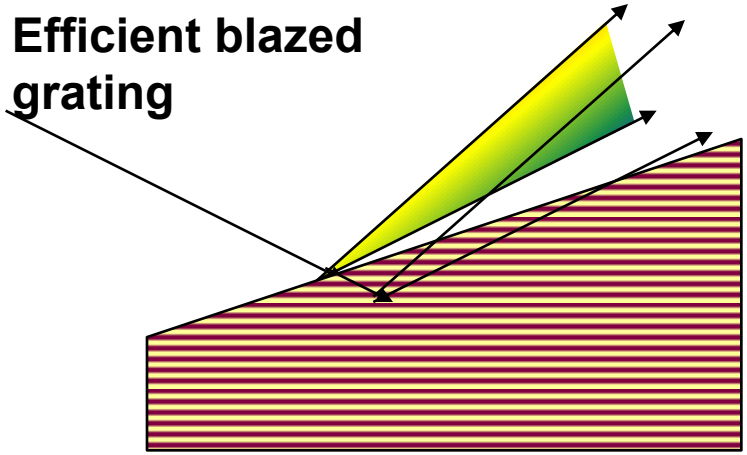
X-ray diffraction obtained with narrowband multilayer

Reconstructed image

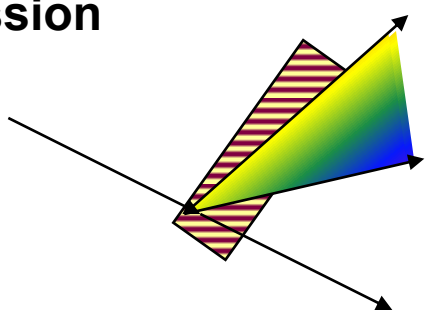
Collaboration with A. Parsons, Univ. of Southampton, UK

Novel X-ray optics are based on thick multilayers

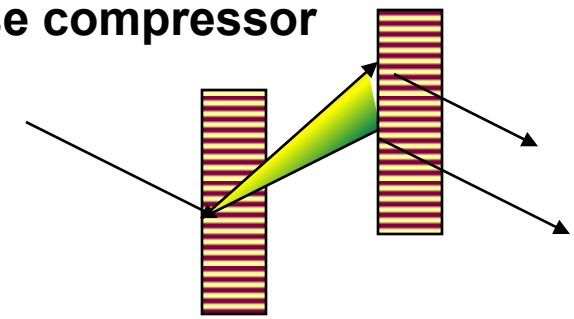
Efficient blazed grating



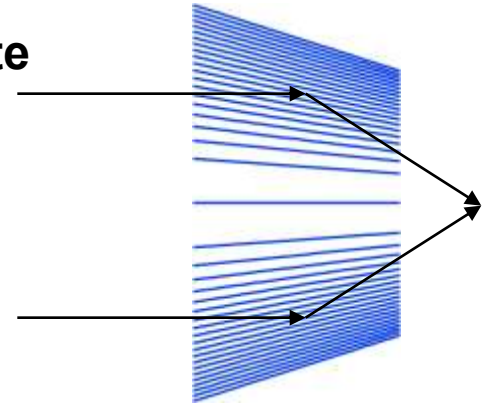
Highly-dispersive transmission grating



Pulse compressor



Volume zone plate



Challenges:

-Deposition of very thick (>50μm) multilayers

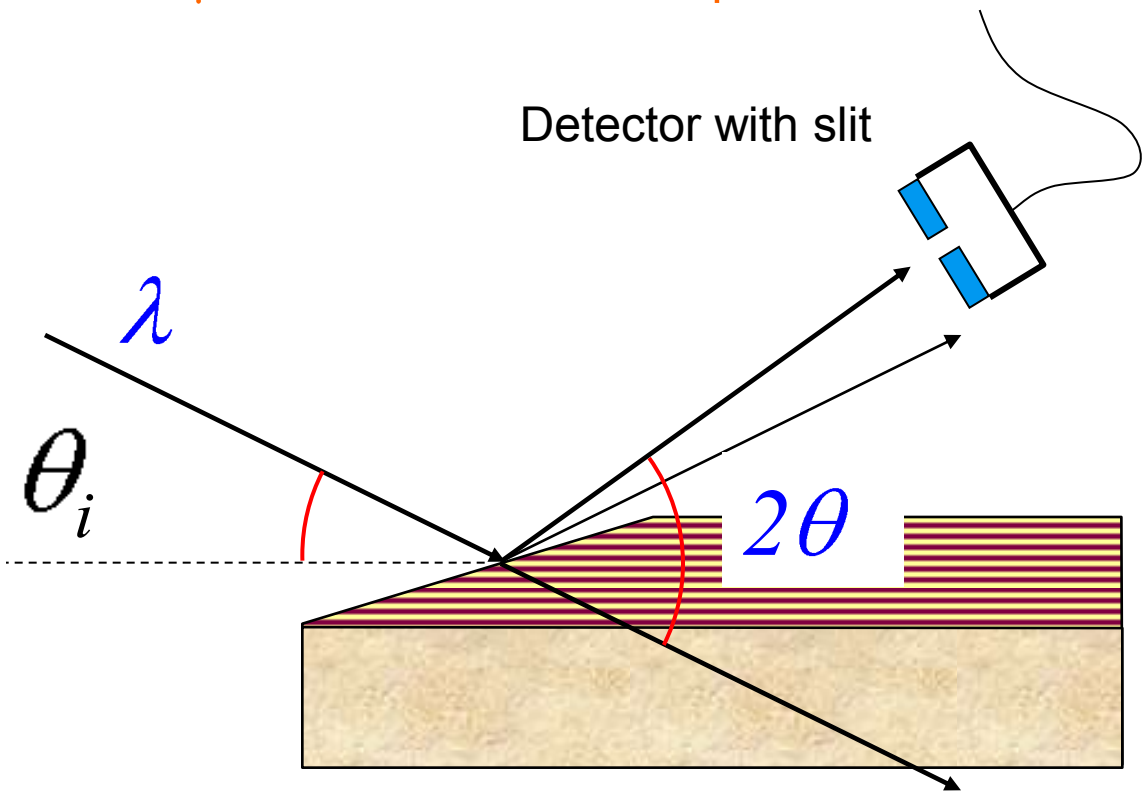
-Characterization, sectioning, mounting, alignment

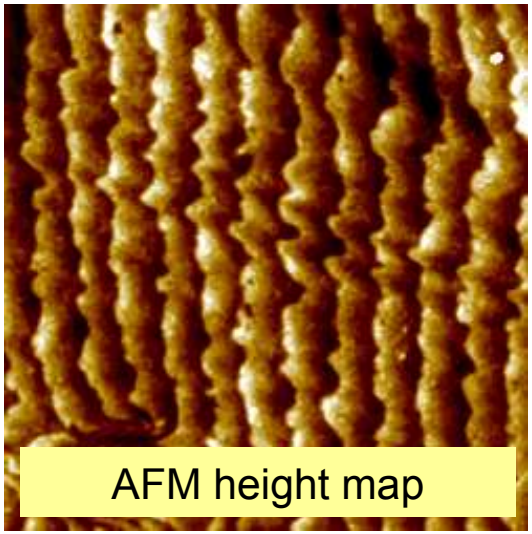
-Theoretical understanding

S. Bajt, H. N. Chapman, A. Aquila, and E. Gullikson, High-efficiency x-ray gratings with asymmetric-cut multilayers, JOSA 29, March 2012.

Our first thick multilayer consisted of 5000 layers and was tested at 13.5 nm at ALS

~17.5 μm thick ML with 7 nm period

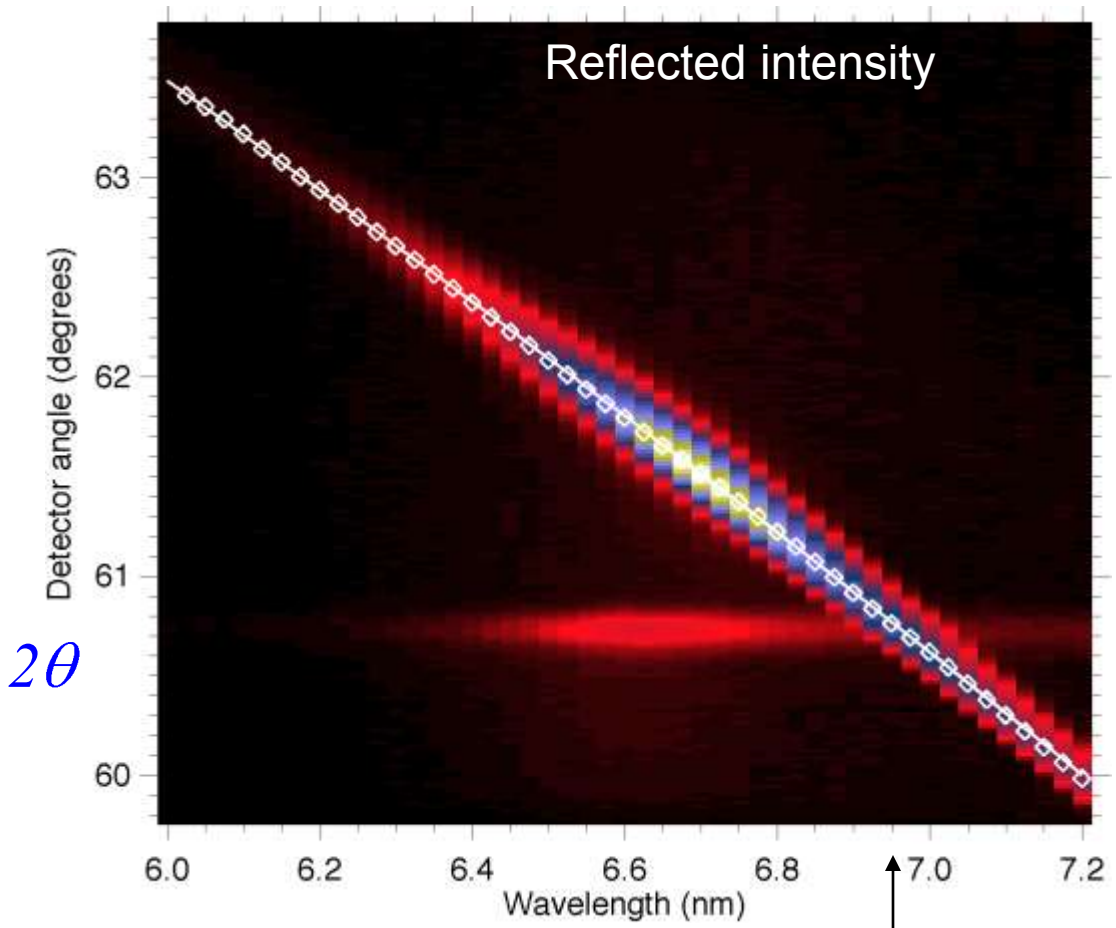




The incidence angle θ_i was determined relative to multilayer planes, not the surface normal of the grating.
We measured dependence of intensity on λ and θ

S. Bajt, H. N. Chapman, A. Aquila, and E. Gullikson, High-efficiency x-ray gratings with asymmetric-cut multilayers, JOSA 29, March 2012.

The dispersion of highly efficient grating matches theoretical prediction



measured peaks

Fit of grating equation, for asymmetric cut of 7.8º

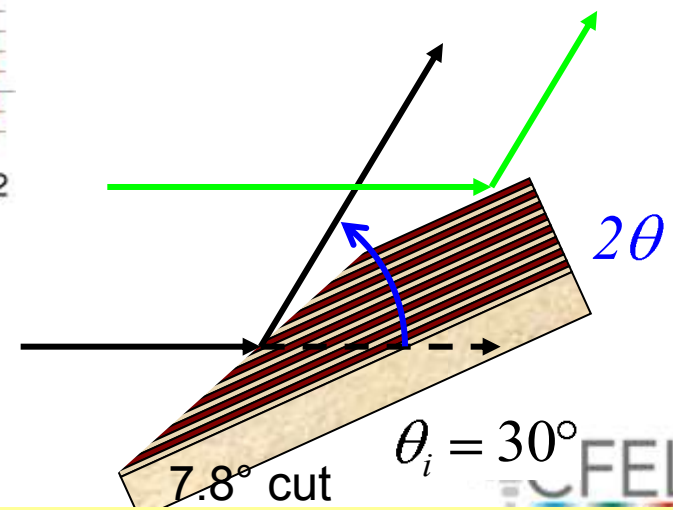
$$(\Delta\theta = 0)$$

$$2\theta = 2\theta_B$$

d = 6.9 nm
Cut angle = 7.8°
Equivalent to 20,000 lp/mm

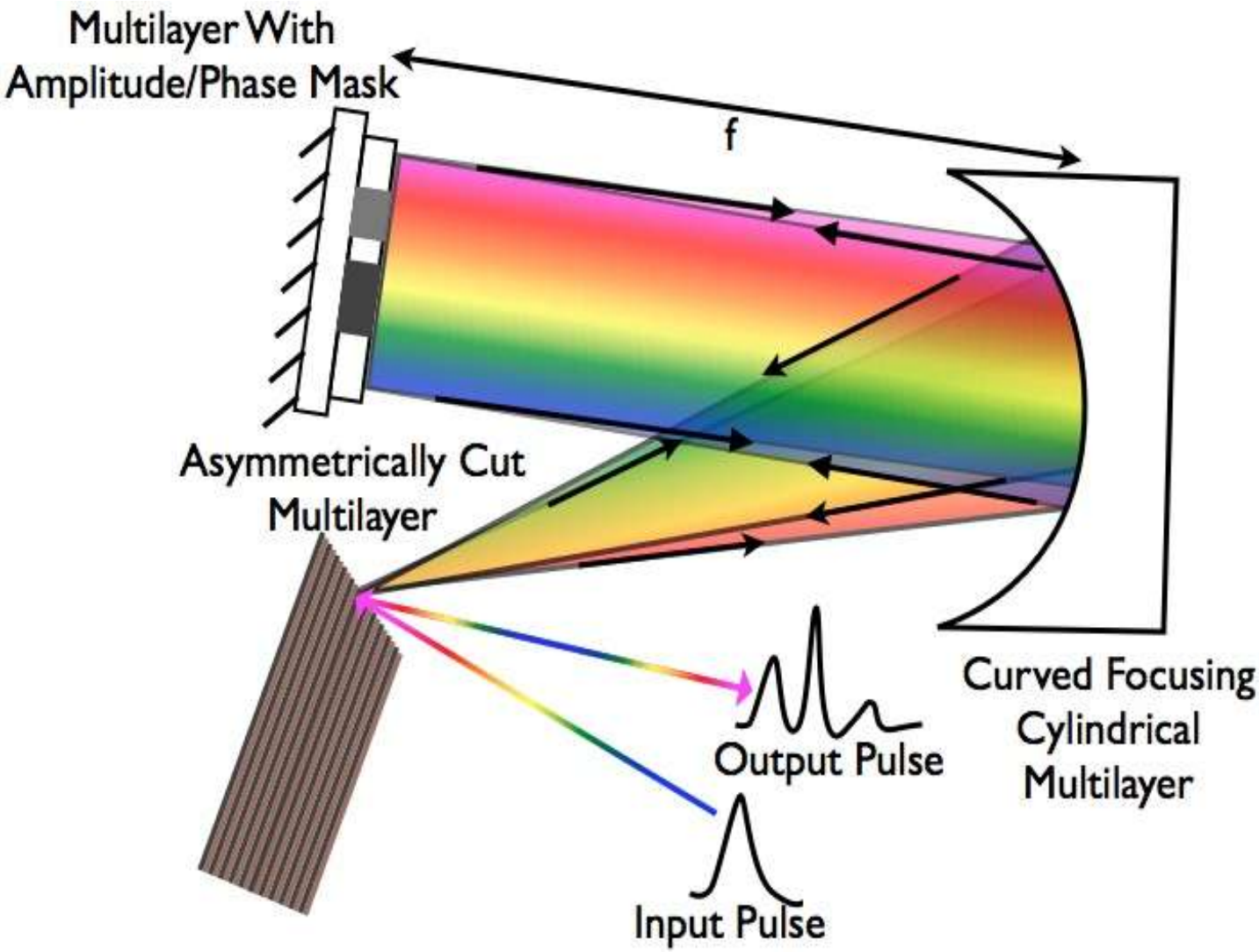
$$\lambda = 2d\sin\theta_B$$

$$(\Delta\lambda = 0)$$



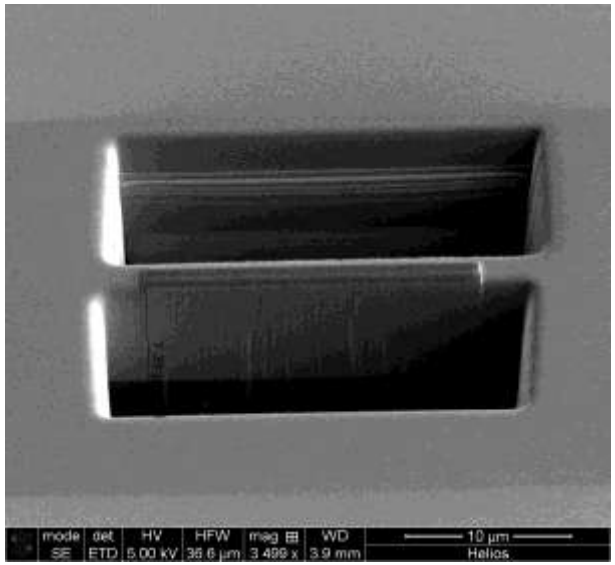
S. Bajt, H. N. Chapman, A. Aquila, and E. Gullikson, High-efficiency x-ray gratings with asymmetric-cut multilayers, JOSA 29, March 2012.

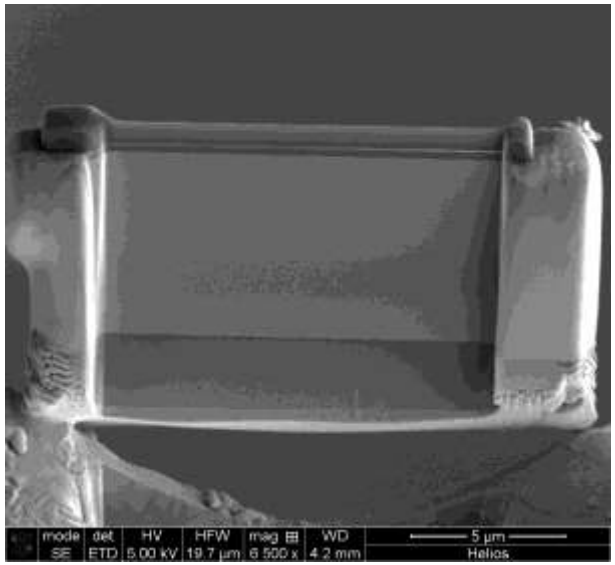
We will pulse shape FEL (FLASH) beam using multilayer coated optics



A. Aquila, M. Drescher, T. Laamann. M. Barthelmess, H. N. Chapman, and S. Bajt, International Journal of Optics, Vol. 2011, Article ID 417075

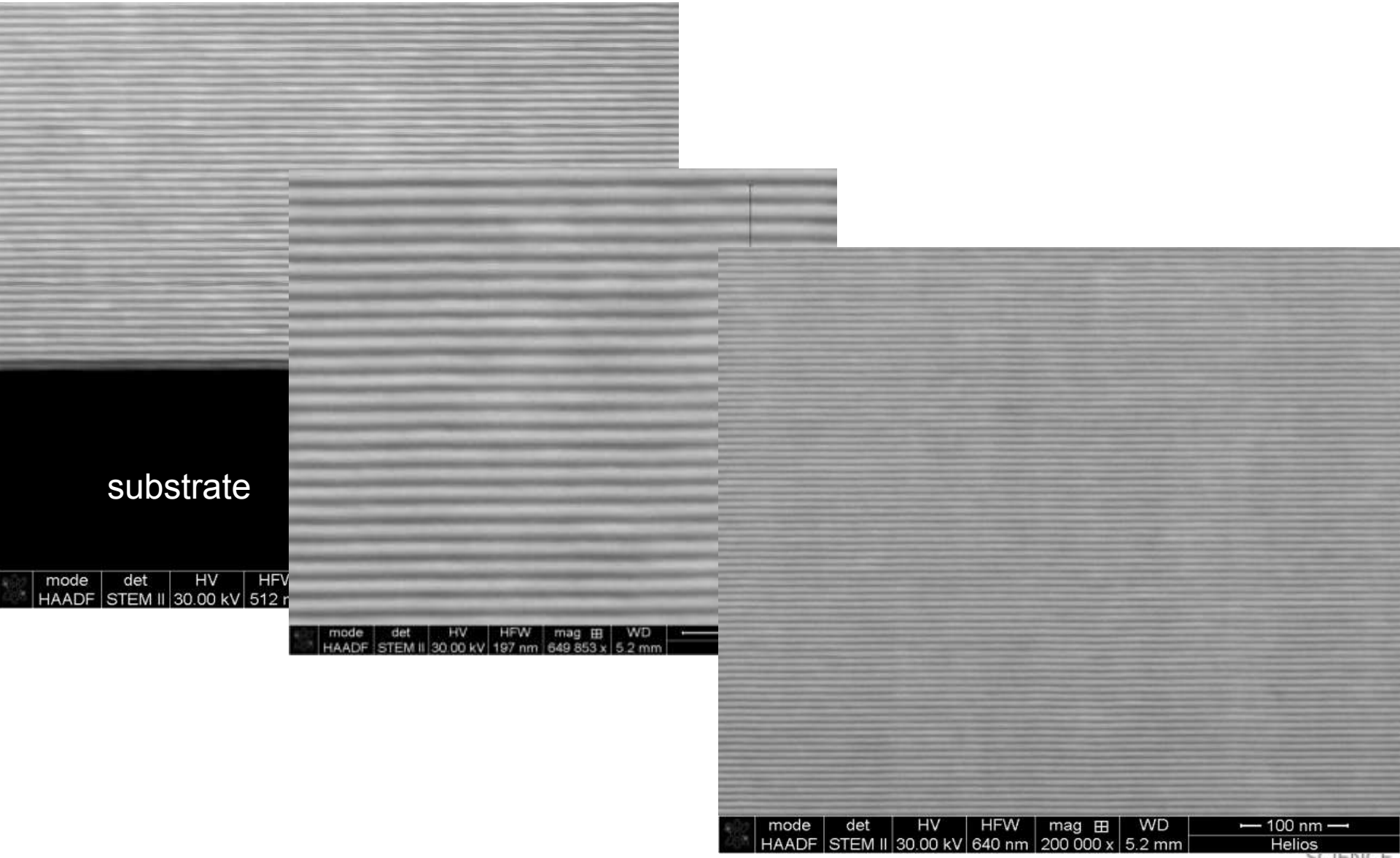
We use dual beam FIB for imaging, patterning and etching nanostructures including multilayers





Lamellas prepared and imaged by Miriam Barthelmeß

Cross section images of a 2000 layer thick multilayer show uniform thick layers and smooth interfaces



Summary

- State-of-the art sputtering deposition tools for “conventional” and thick multilayer optics
- Other equipment for characterizing and manipulating nano-layered and nanostructures
- Normal incidence optic for soft x-ray regime
- Narrow bandwidth optics
- Development of volume optics based on thick multilayers (gratings, pulse compressors, volume zone plates)
- Novel X-ray optics can be used to manipulate the phase space of X-rays, especially for PETRA III and XFEL beams

This type of optics will have impact in:

- Bio-imaging
- Materials and environmental sciences
- X-ray astronomy

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** Now at European XFEL*