SOFT X-RAY IMAGING OF LOW DENSITY TARGET MATERIALS IN THE “CARBON WINDOW” SPECTRAL REGION

Igor A. Artyukov

X-ray Optics Laboratory
Lebedev Physical Institute, Moscow, Russia

iart@sci.lebedev.ru

Co-authors

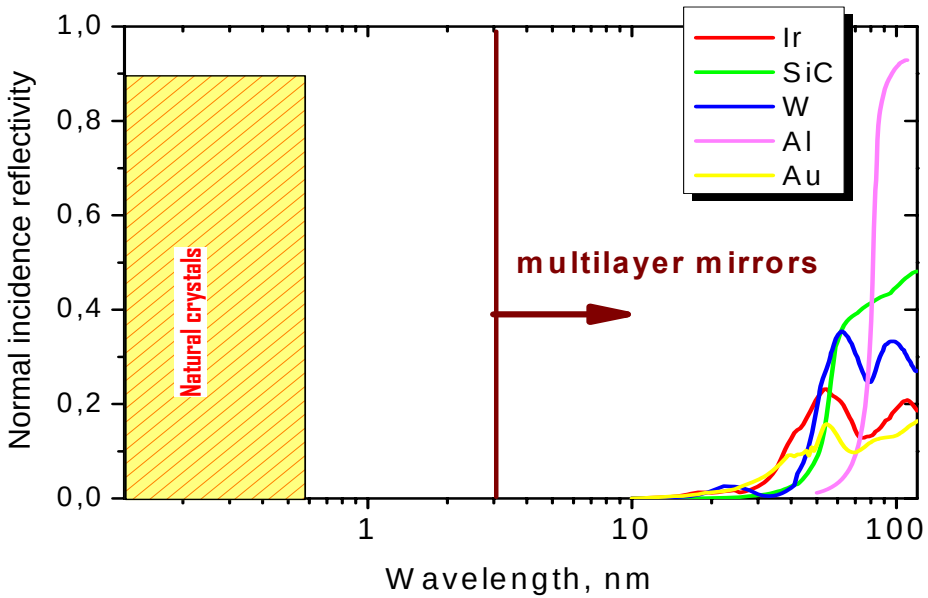
- N.G.Borisenko, A.M.Khalenkov, R.M.Feshchenko, A.V.Vinogradov
  Lebedev Physical Institute RAS, Moscow, Russia
- Yu.S.Kasyanov
  Prokhorov General Physics Institute RAS, Moscow, Russia
- Ye.A.Bugaev, O.Yu.Devizenko, V.V.Kondratenko
  National Technical University "Kharkiv Polytechnic Institute", Kharkov, Ukraine
- V.G.Pimenov
  Institute of Organic Chemistry RAS, Moscow, Russia

Outline

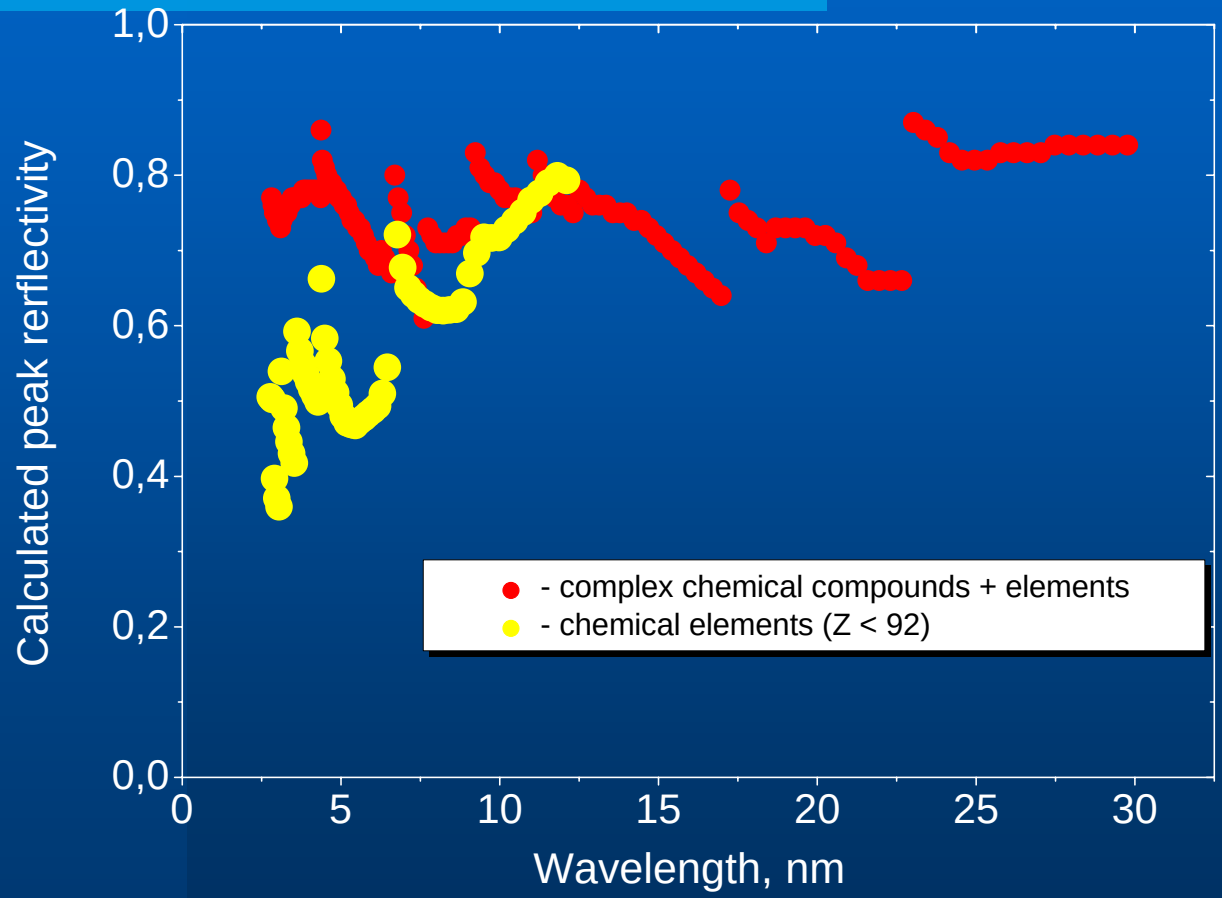
1. Soft X-ray/EUV multilayer optics
2. Transmission and reflected mode microscopy at the soft X-ray/EUV rays
3. “Carbon window” in soft X-ray imaging
4. 3D soft X-ray imaging of thick low-density materials
5. Conclusions

Soft X-rays/EUV as working spectral range for the NI multilayer mirrors

$$2d\cos\varphi \cong m\lambda \quad \Rightarrow \quad d \geq \lambda / 2$$



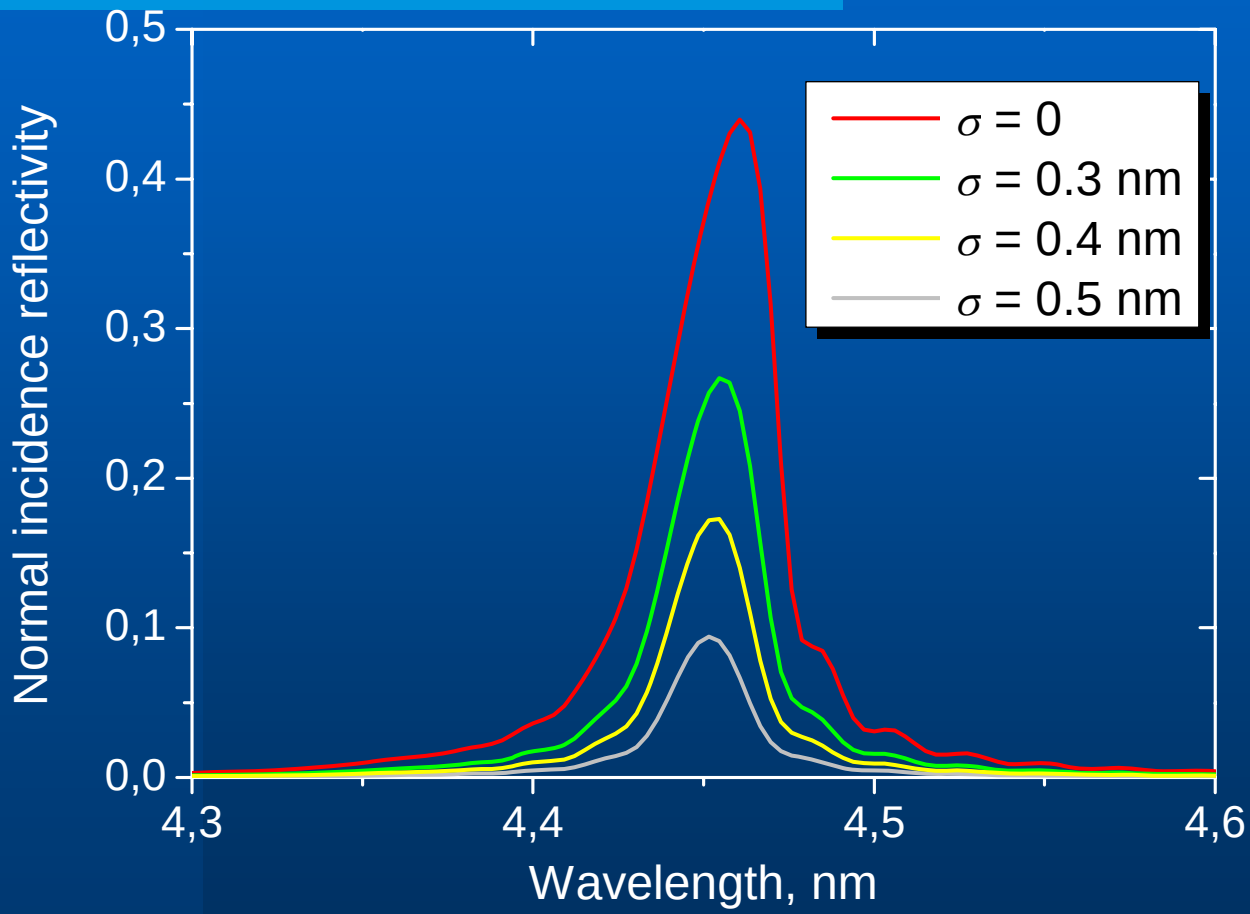
Calculated peak reflectivity of X-ray multilayers mirrors



> 1500 inorganic compounds and chemical elements

I.A.Artyukov, K.M.Krymski, Preprint FIAN # 92, 1994

Interface roughness/diffusion affects the Co/C mirror performance

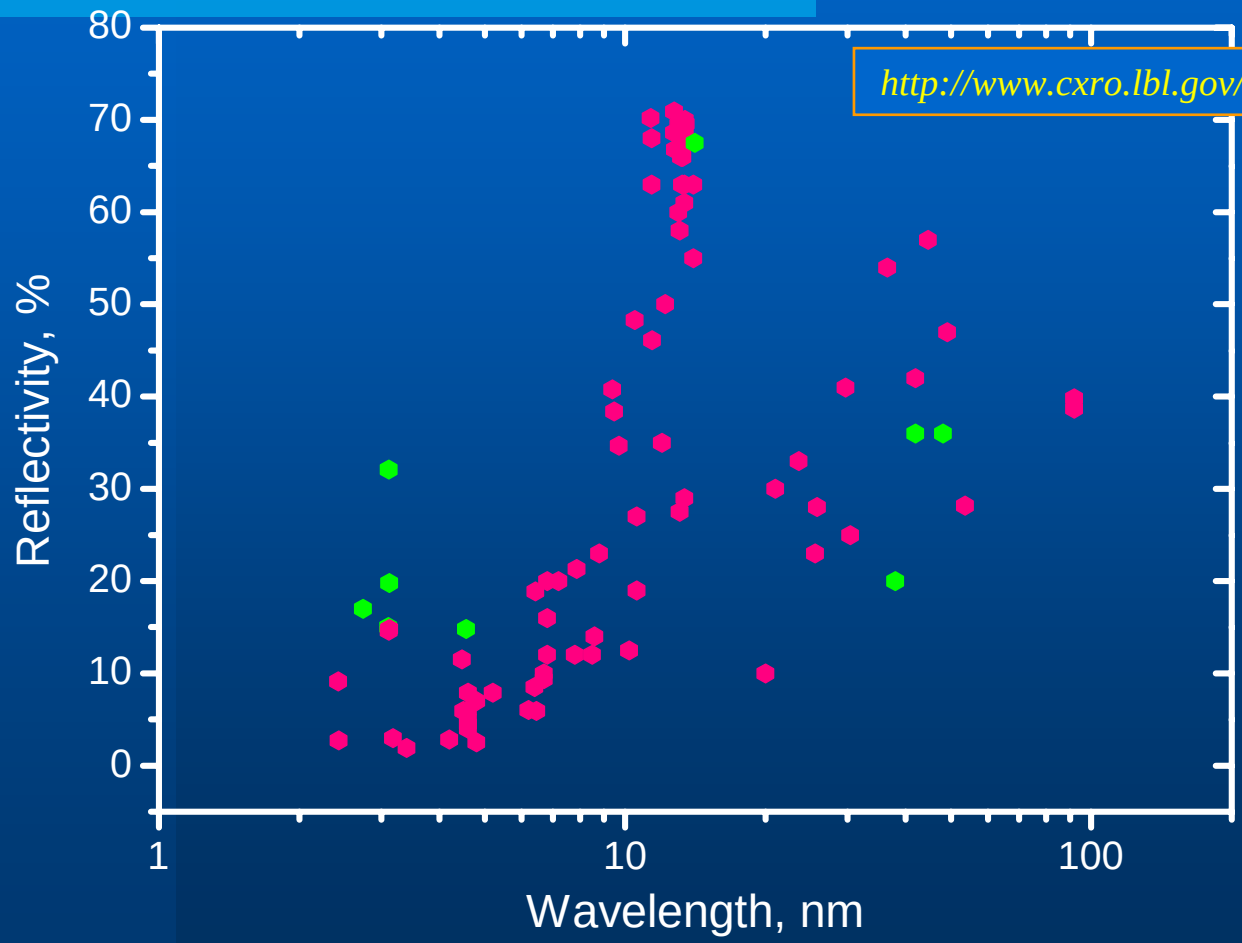


N =200

β= 0.45

Error function profile of the interfaces

Measured reflectivity of MLM

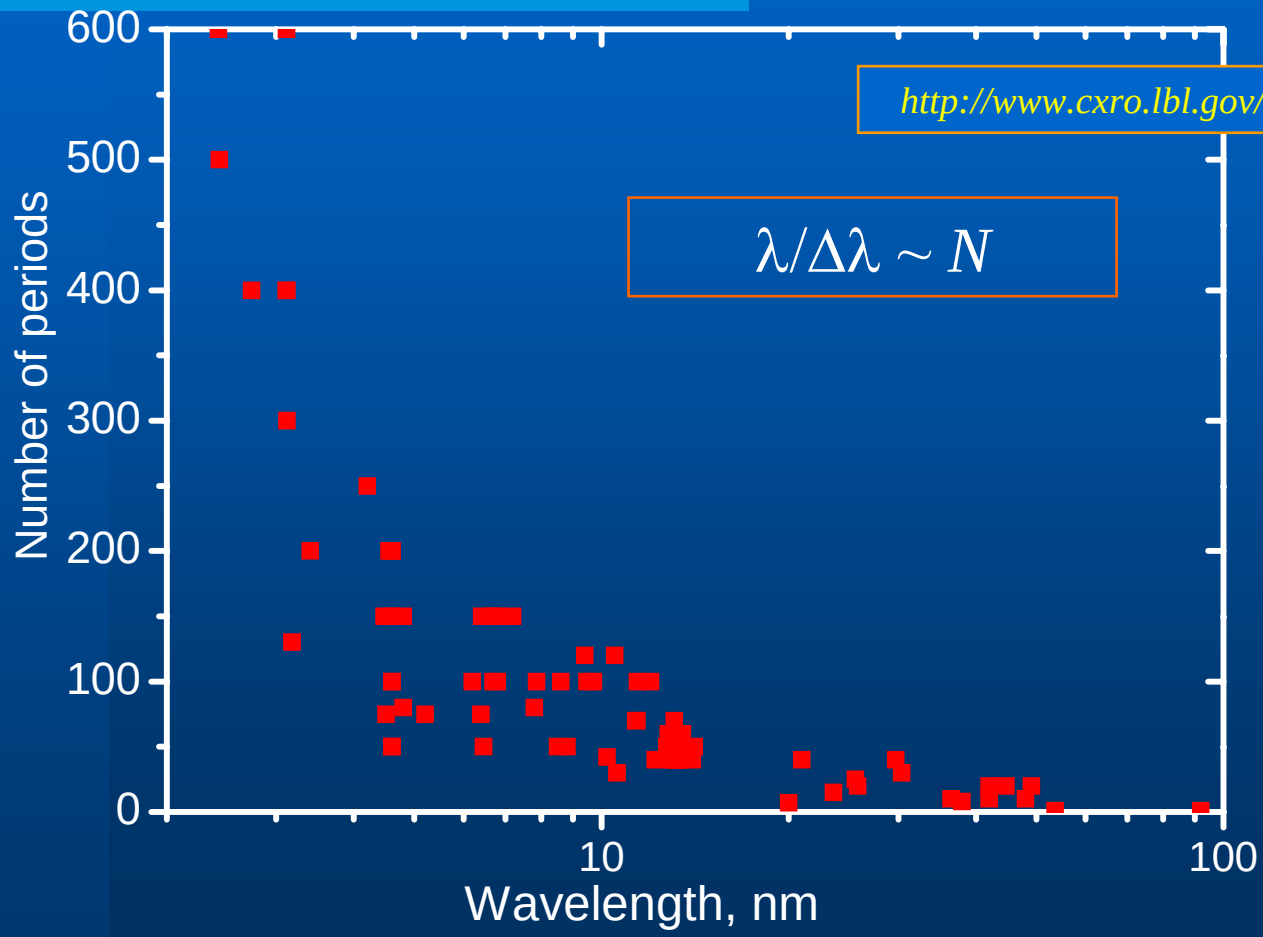


http://www.cxro.lbl.gov/multilayer/survey.html

● - New results for the last 5 years

Number of periods for the measured multilayer mirrors

Физический институт имени П.Н.Лебедева F I A N



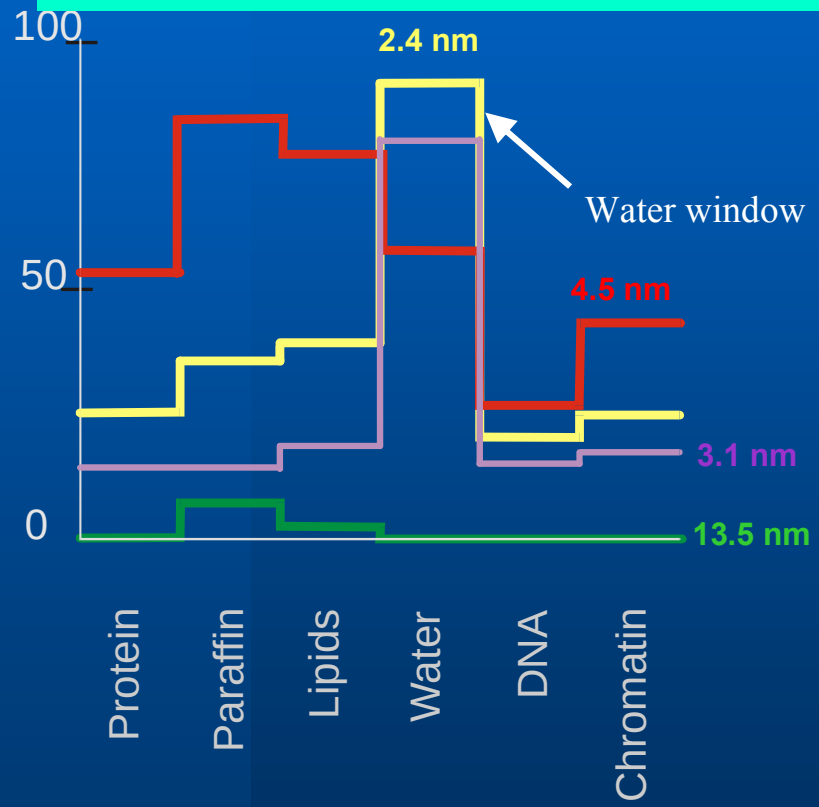
http://www.cxro.lbl.gov/multilayer/survey.html

$\lambda/\Delta\lambda \sim N$

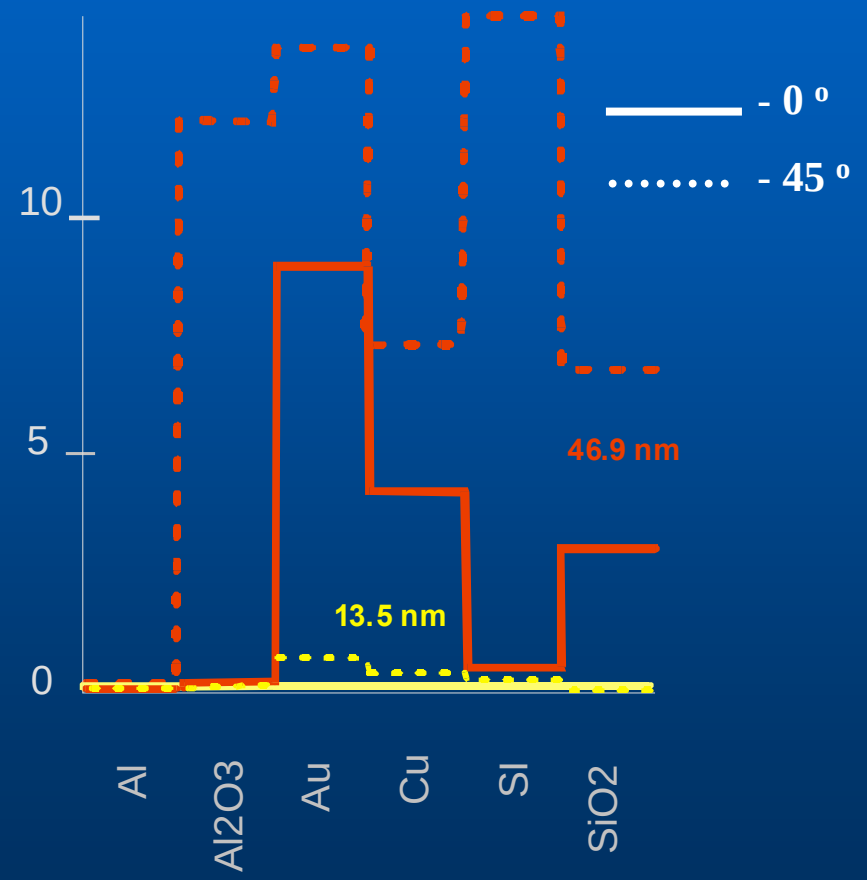
Calculated X-ray contrast patterns

Физический институт имени П.Н.Лебедева F I A N

TRANSMISSION of 1-μm thick samples (%)

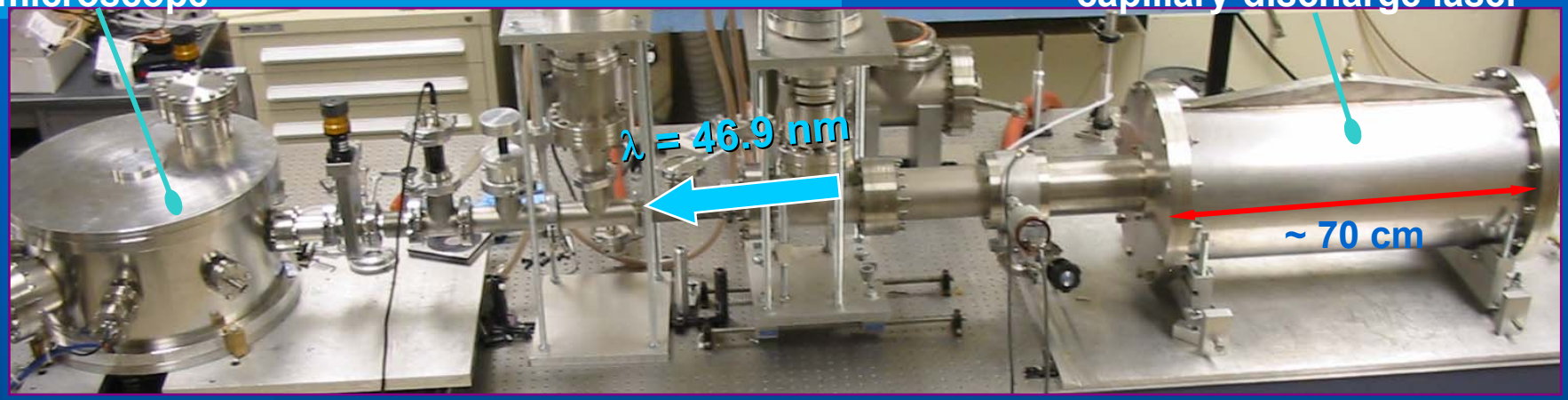


REFLECTIVITY (%)

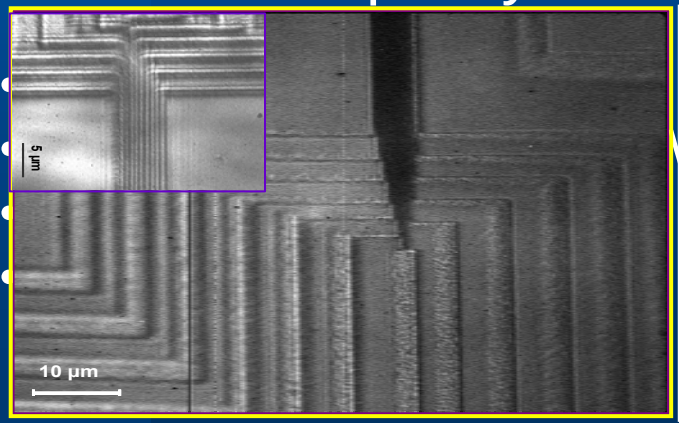


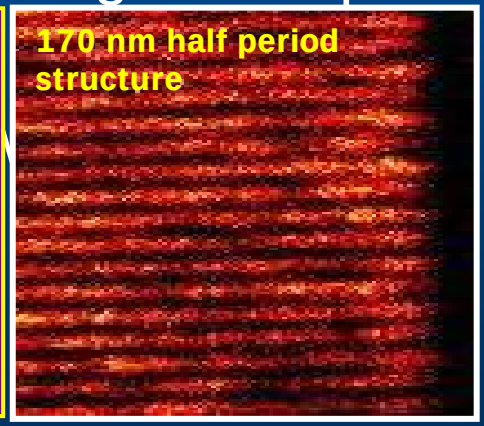
Reflective EUV microscopy with a capillary discharge EUV laser (Colorado State University)

Физический институт имени П.Н.Лебедева F I A N



Ne-like *Ar* capillary-discharge laser parameters:

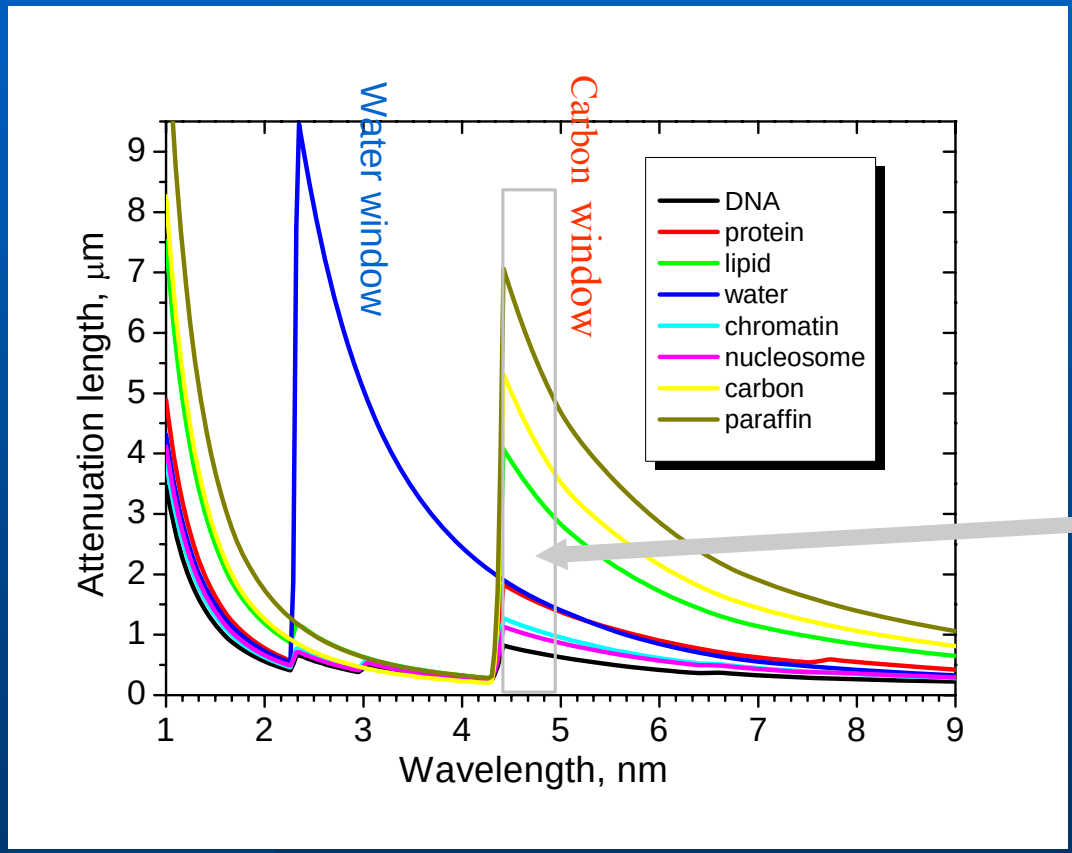


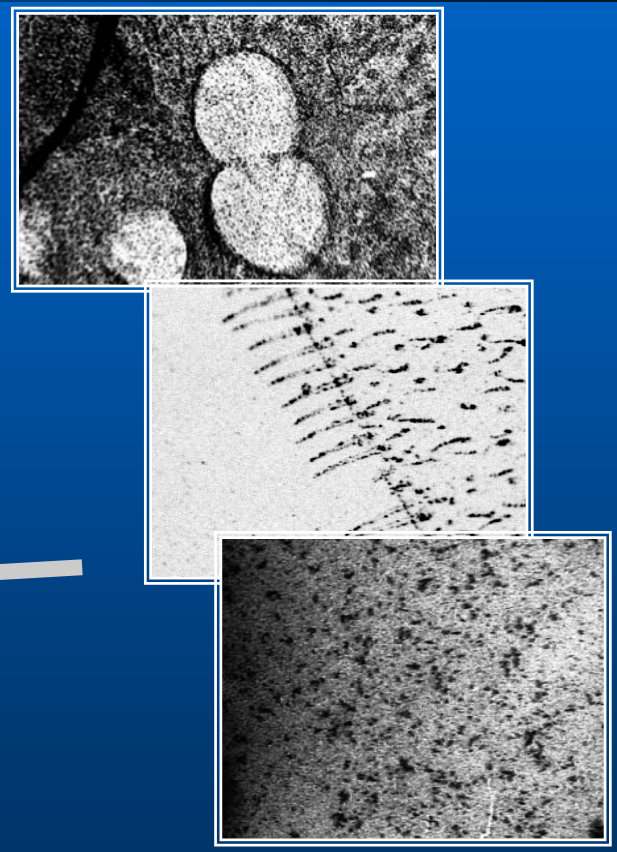


Courtesy of C.Menoni

F. Brizuela, et al., Optics Express, 13, 3983, (2005).

“Carbon window” soft X-ray region



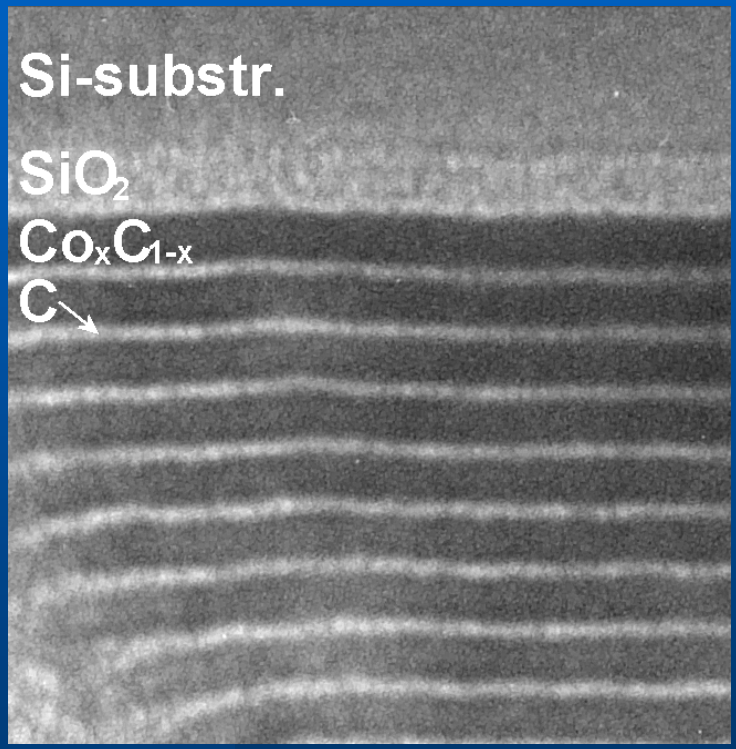


I.A. Artyukov et al., *Proc. SPIE*, Vol. 5919, pp. 94-103, 2005.

“Carbon window” soft X-rays:

- Decreased absorption dose to samples due to better transmission of organic materials. Water is still not opaque.
- Differential contrast of various organic materials
- Ability to study a “thick” (>> 10 μm) sample of carbon-containing materials with sub-micron resolution. 3D imaging
- How power X-ray tubes can be used as an X-ray source

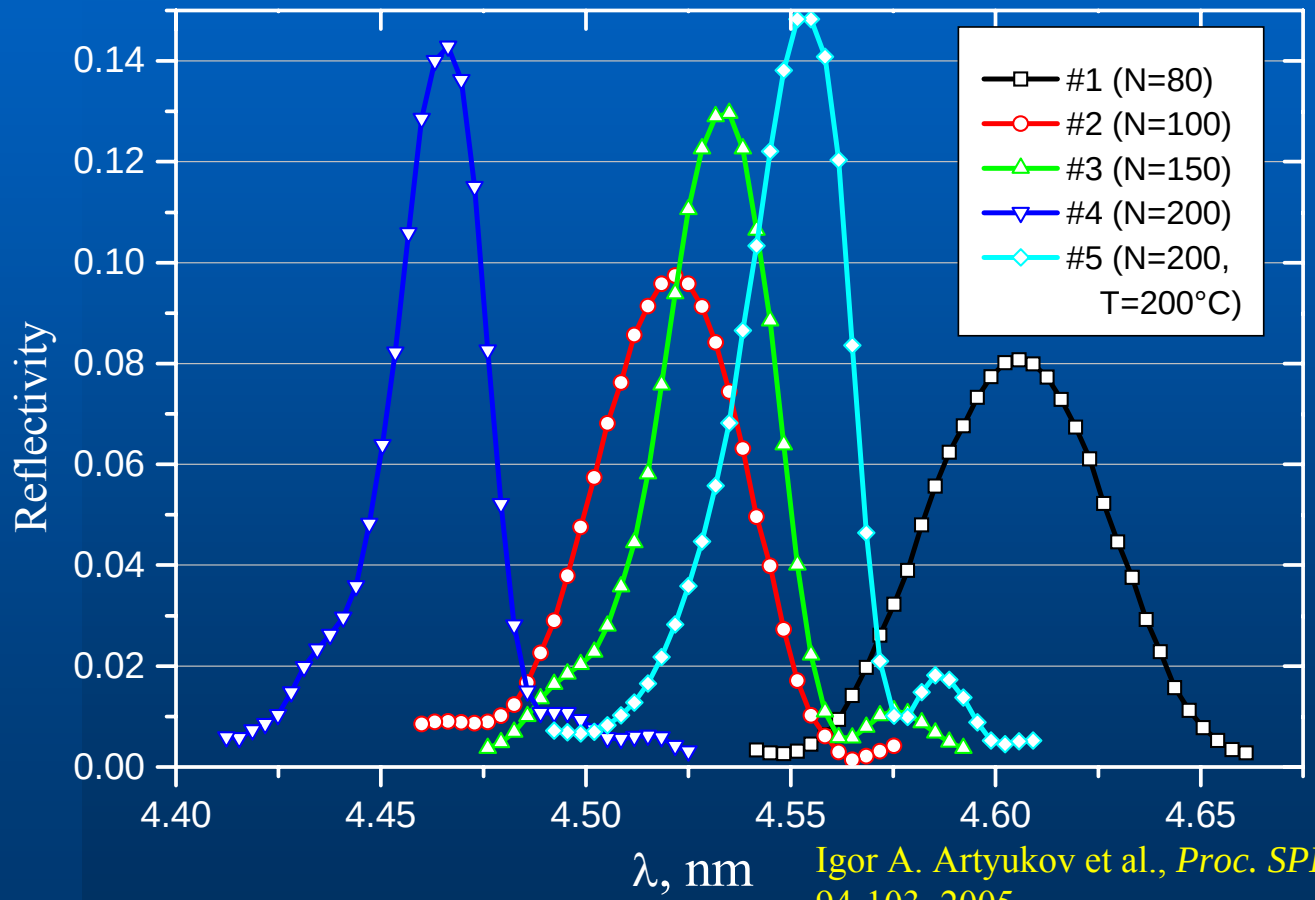
CoC/C multilayer coating for 4.5 nm



- DC-magnetron sputtering
- Number of periods $N = 200$
- Period d=2.25-2.29 nm
- Interface roughness σ = 0.3-0.32 nm (RMS)

Igor A. Artyukov et al., *Proc. SPIE*, Vol. 5919, pp. 94-103, 2005.

Measured reflectivity of Co/C mirrors at the wavelength $\lambda \approx 4.5$ nm



Igor A. Artyukov et al., *Proc. SPIE*, Vol. 5919, pp. 94-103, 2005.

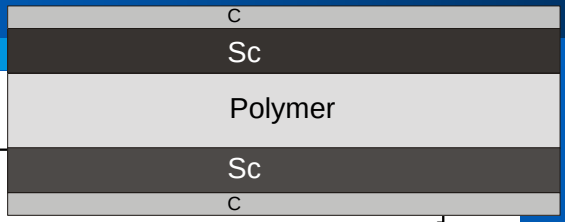
Measured reflectivity of Co/C multilayer mirrors at the wavelength $\lambda \approx 4.5$ nm

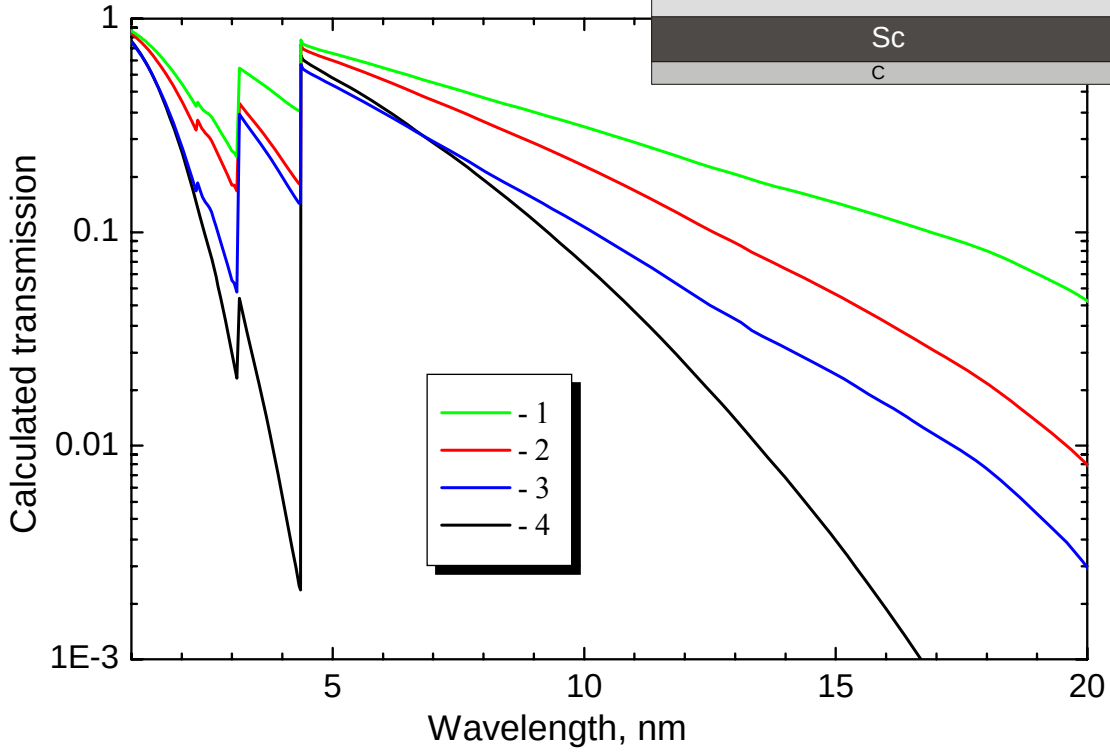
#	Period number	$\Delta\lambda/\lambda$, %	λ_{peak}, nm	R, %
1	80	1.1	4.61	8.1
2	100	0.95	4.52	9.7
3	150	0.66	4.53	13.0
4	200	0.57	4.47	14.3

Near normal-incidence measurements at BESSY II

(incidence angle $\alpha = 5^{o}$)

Scandium coated polymer X-ray filters





1 - Sc: 100 nm, polyimide: 150 nm, C: 4 nm

2 - Sc: 100 nm, polyimide : 300 nm, C: 4 nm

3 - Sc: 200 nm, polyimide : 300 nm, C: 4 nm

4 - Sc: 100 nm, polypropylene: 1.5 μm, C: 4 nm

I.A.Artioukov et al., *Rev. Sci. Instr.*, Vol.74, No.11, pp.4964–4966, 2003.

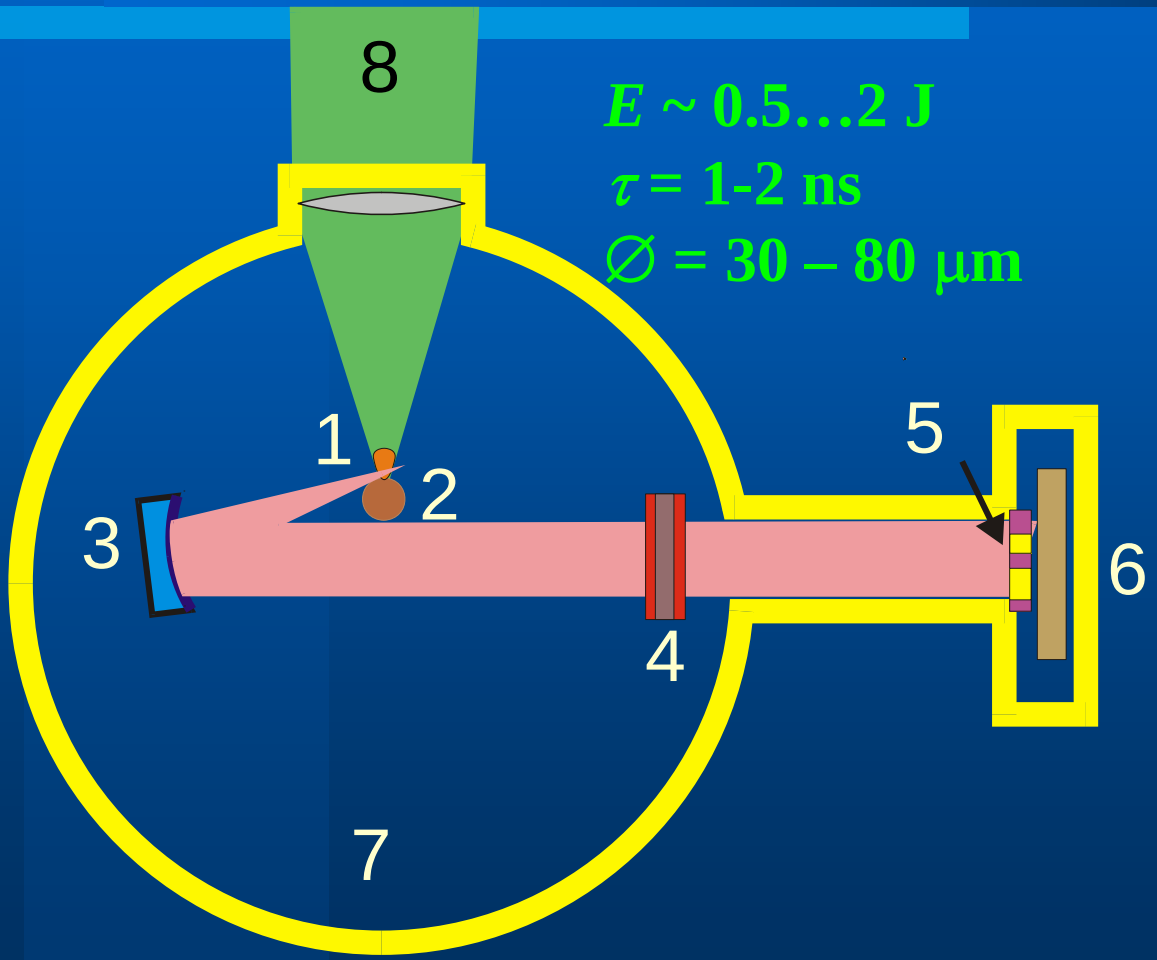
Calculated and measured transmission of Sc/C X-ray filters (T_c and T_{exp})

Физический институт имени П.Н.Лебедева F I A N

Polymer base	Polymer thickness, μm	Scandium thickness, μm	Transmission, %			
			λ=4.47 nm		λ=632.9 nm	
			T_c	T_{exp}	T_c	T_{exp}
Polypropylene	1.5	0.1	62	60.1± 0.4	$7.1 \cdot 10^{-4}$	$(1.0 \pm 0.3) \cdot 10^{-3}$
Polyimide	0.15	0.1	74	60.7±0.7	$7.2 \cdot 10^{-4}$	$(5.5 \pm 0.5) \cdot 10^{-4}$
	0.3	0.1	70	57.0 ±0.7	$7.2 \cdot 10^{-4}$	$(1.7 \pm 0.3) \cdot 10^{-4}$
	0.3	0.2	55	--	$5 \cdot 10^{-7}$	--

All the filters had 4 nm-thick carbon layer (2 sides x 2 nm)

LPP-based soft X-ray micro-radiography at $\lambda = 4.5$ nm



$E \sim 0.5\ldots2$ J

$\tau = 1\text{-}2$ ns

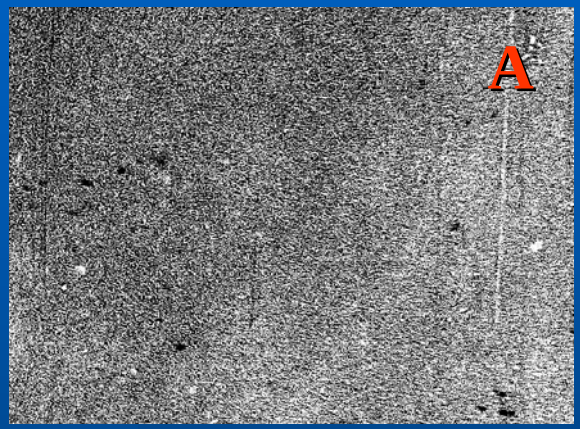
$\varnothing = 30 - 80$ μm

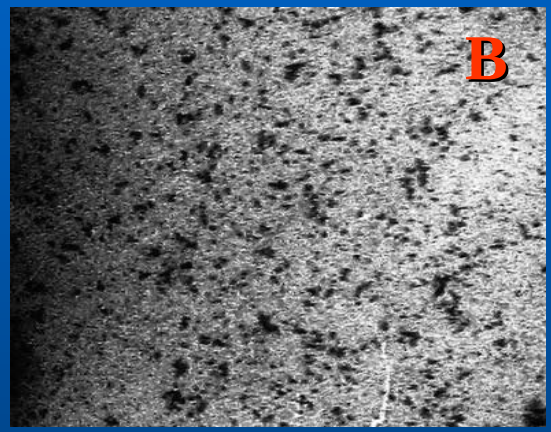
1 – laser-produced plasma
2 – rhenium target
3 – Co/C multilayer mirror
4 – a set of Sc/polyimide filters
5 – sample
6 – X-ray film UF-4
7 – vacuum chamber ($P \sim 10^{-2}$ Torr)
8 – 2nd harmonics of Nd-laser ($\lambda = 0.53$ μm)

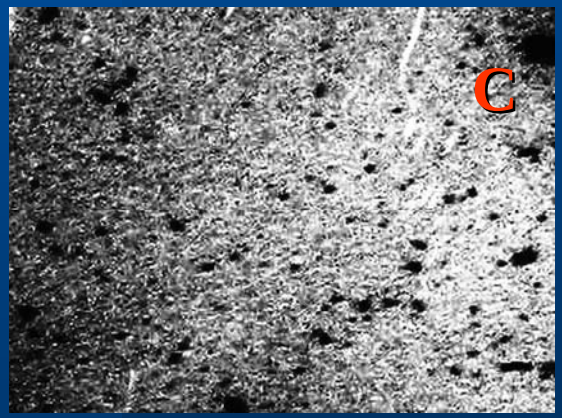
Triple “1” principle

- 1 Joule of laser pulse energy
- 1 nanosecond exposure
- 1 shot per image

Soft X-ray images of the l.d. materials at λ = 4.5 nm (ρ = 1.7-10 mg/cm^3)





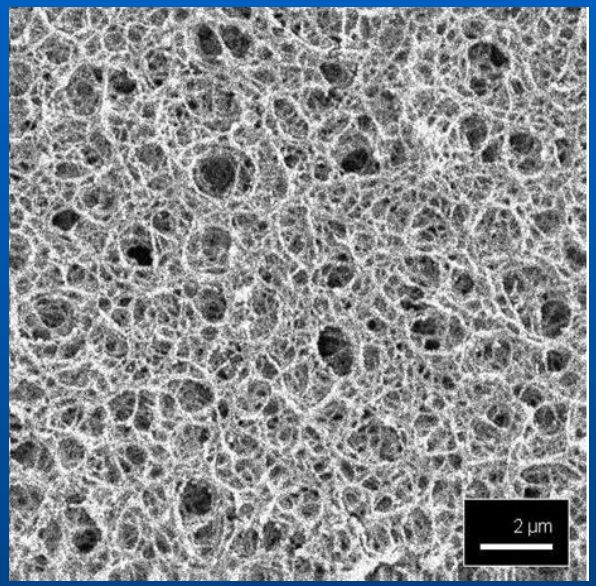


A – TAC film, thickness t = 200 μm, no *Cu*, ρ = 4.5 mg/cm^3

B – TAC film + 20 % *Cu*, t = 200 μm, ρ = 10 mg/cm^3

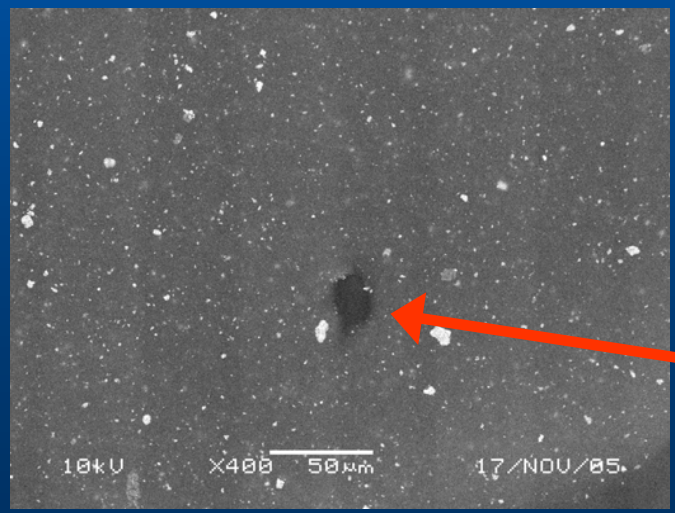
C – TAC film + 10 % *Cu*, t = 300 μm, ρ = 10 mg/cm^3

SEM images
of low density target materials



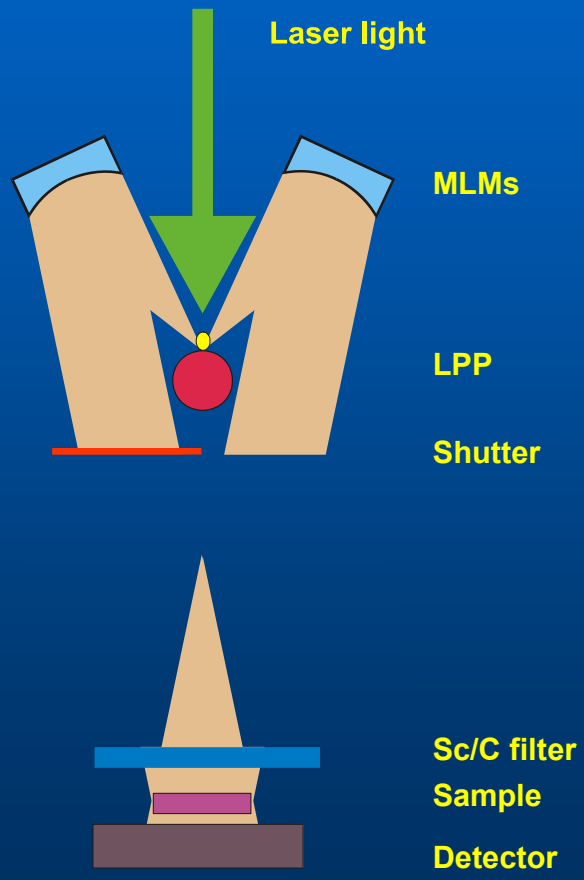
triacetate of cellulose (TAC)

$\rho \sim 10$ mg/cm^3



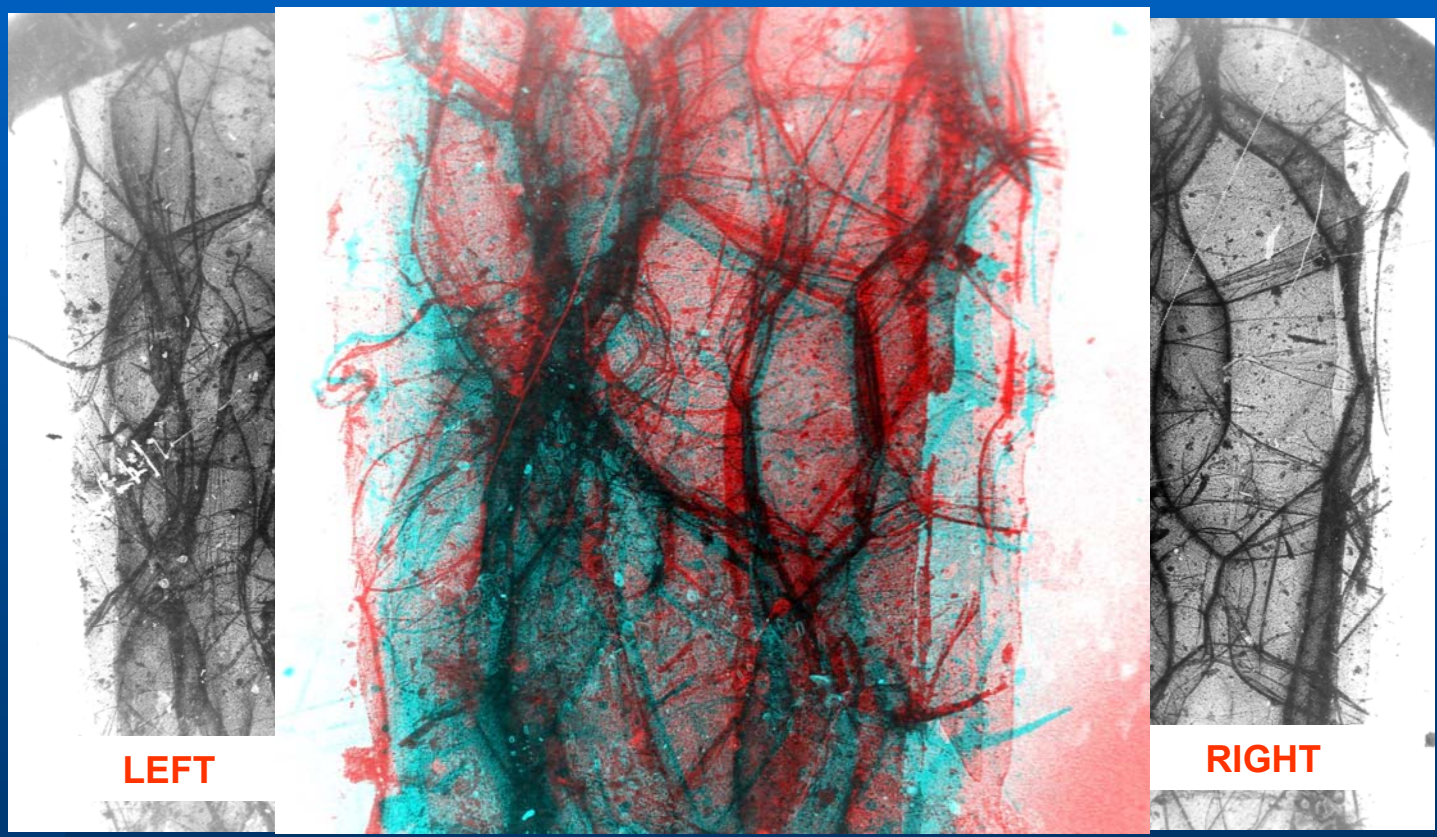
Damage by TEM

Stereo-imaging of thick organic samples

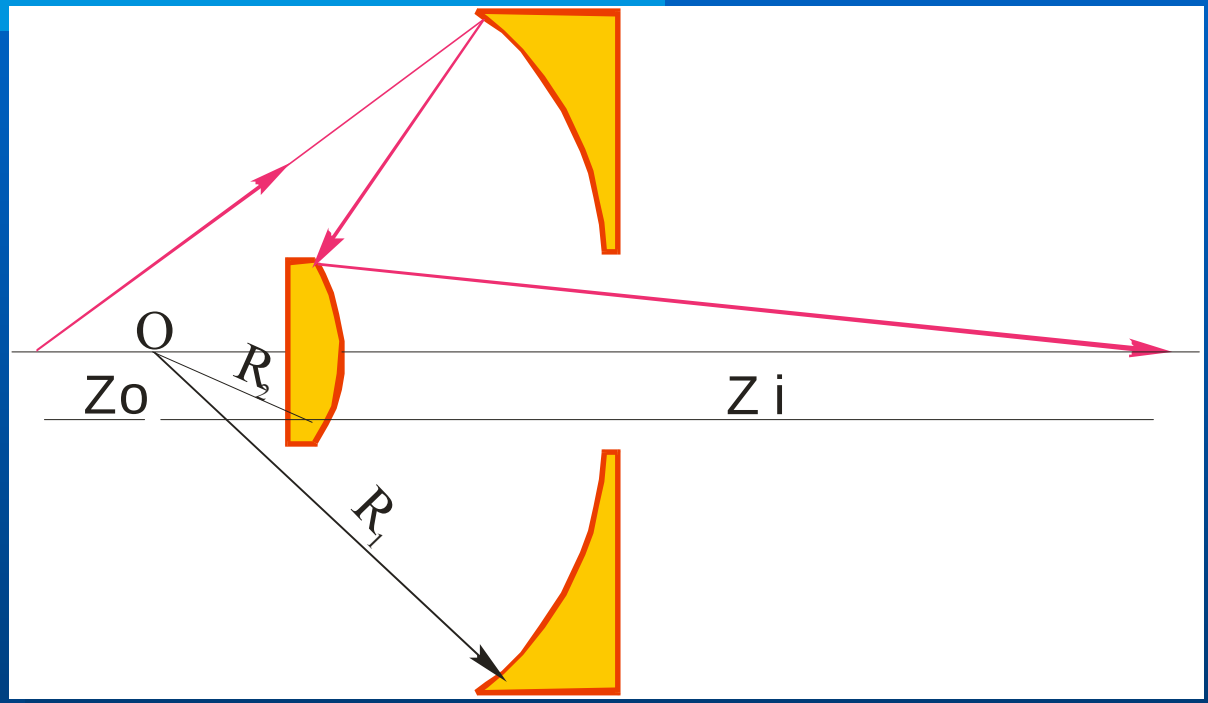


- Thickness t = 0.2…1 mm
- Spatial resolution δ = 1...5 μm
- $N = t/\delta$ = 100…400
- 3D visualization of density (inhomogenities) distribution

Stereo SX imaging of low density foam of the thickness 300-800 micron



Towards better resolution: Schwarzschild objective



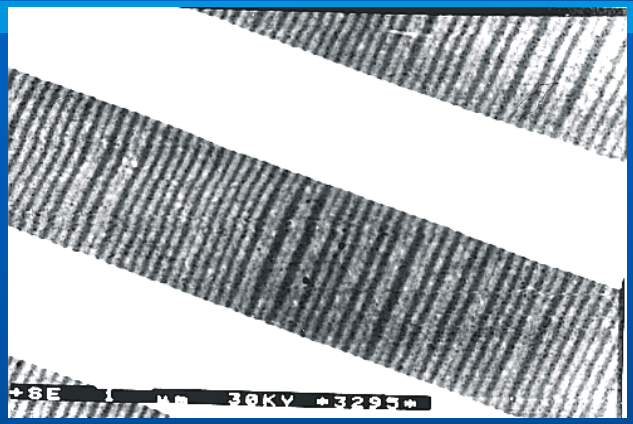
$$Z_0 = \frac{R_1 R_2}{R_1 - R_2 + \sqrt{R_1 R_2}}$$

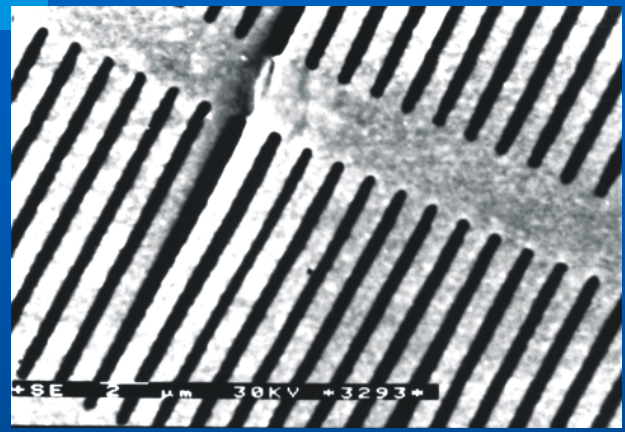
$$M_{Z_0} = \frac{R_1 - R_2 + \sqrt{R_1 R_2}}{R_1 - R_2 - \sqrt{R_1 R_2}}$$

High resolution X-ray imaging using SO at λ=18-20 nm (1994)

Физический институт имени П.Н.Лебедева F I A N

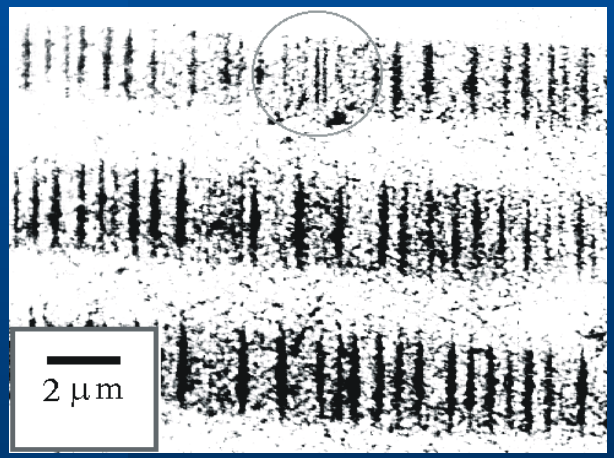
SEM



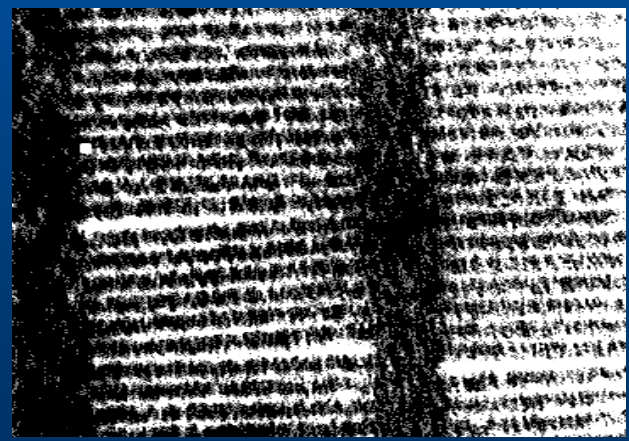


SEM

SXM



0.2 μm-period gold grating



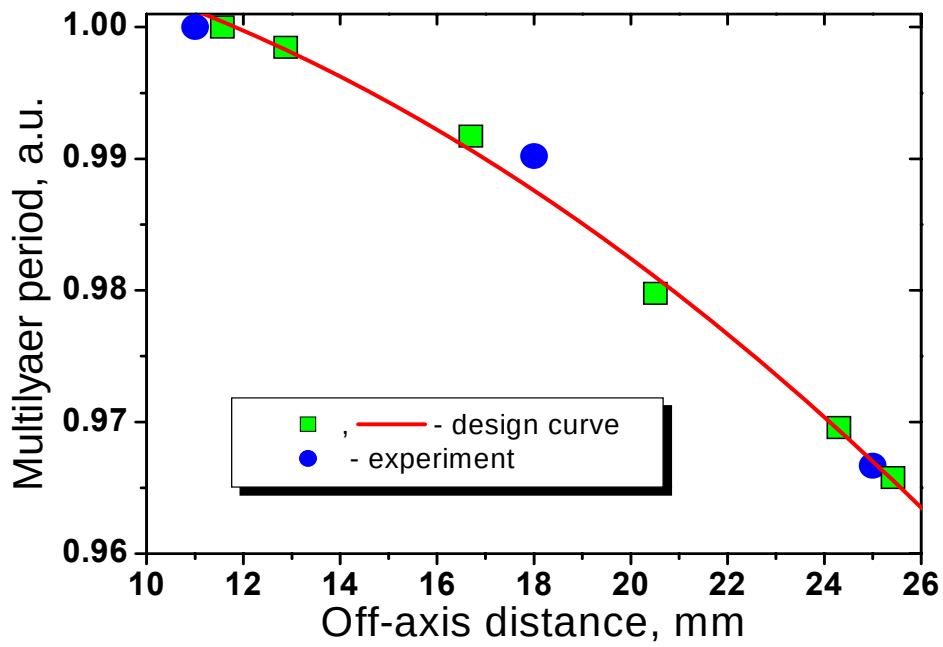
1.4 μm-period grating

SXM

MWTA'07, Moscow, October 15, 2007

I.A.Artioukov et al., Opt. Lett., 20 (24), 2451 (1995)

Fabrication of the SO mirrors



Multilayer coating gradient accuracy is measured to be better than 0.25 % (< 0.06 nm)

I.A.Artyukov et al., Proc.SPIE, San Diego, August 2007.

Conclusions

1. Soft X-ray multilayer mirrors are capable providing 10-15 % of the normal incidence reflectivity at the wavelength ~ 4.5 nm with the spectral resolution $\lambda/\Delta\lambda \sim 200$.
2. “Carbon window” (CW) X-ray absorption microscopy proves to be an effective tool for high contrast imaging of thick carbon-containing samples (thickness up to 1 mm).
3. Combination of large depth of view, high spatial resolution and low absorption has demonstrated to be a basis for the 3D imaging of low density target materials.
4. The improvement of the spatial resolution can be achieved with the help of multi-mirror optical systems. The correspondent work on the soft X-ray Schwarzschild microscope working in CW region is undergoing.

Igor A. Artyukov