EUV/SXR Optics and Metrology Development at RITE

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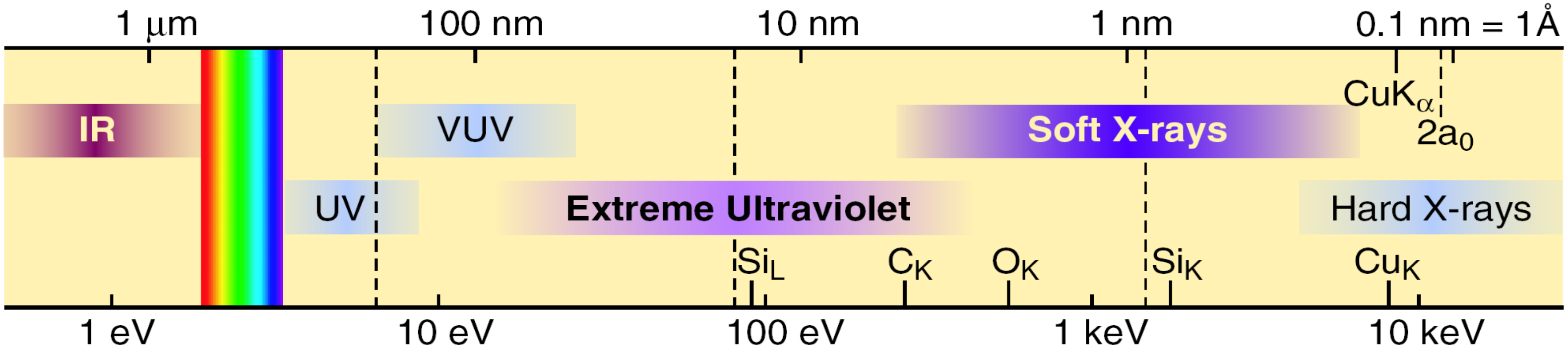
Rigaku Innovative Technologies Europe Ltd. (RITE), Prague,
Czech Republic

2017 International Workshop on EUV Lithography, CXRO, LBNL,
Berkeley, CA, June 12–15, 2017

Electromagnetic radiation spectrum

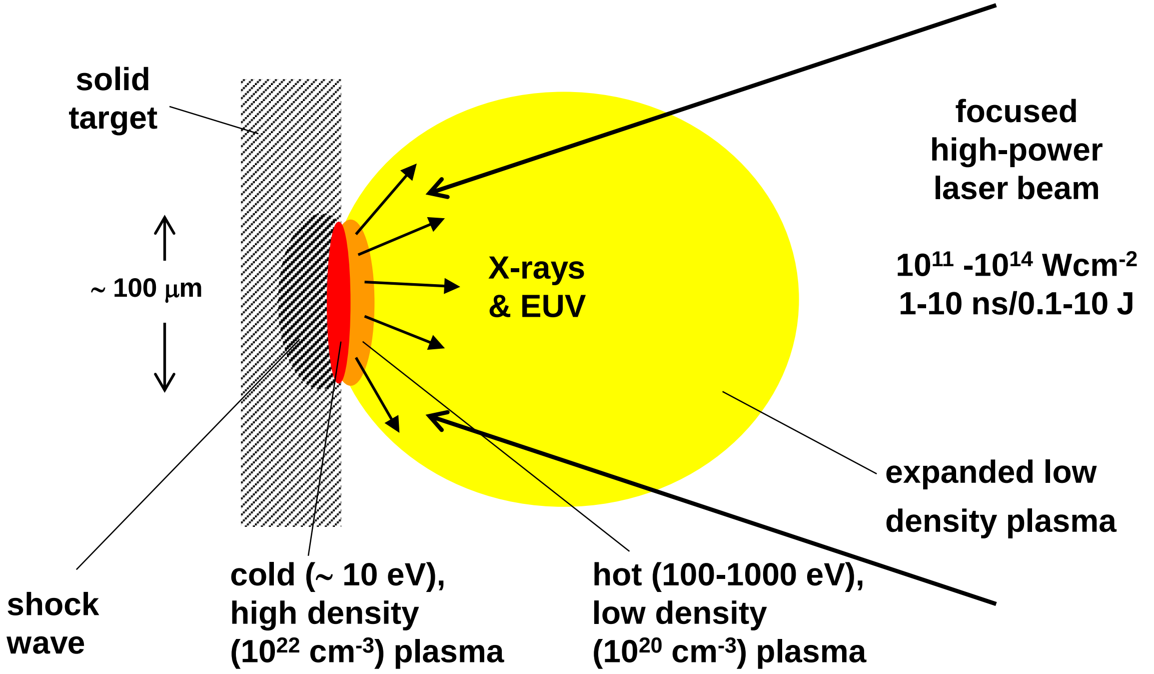


D. T. Attwood *Soft X-rays and Extreme Ultraviolet Radiation: Principles and Applications* (Cambridge University Press, Cambridge, 1999)

13.5 nm / 92 eV	**EUV Lithography**
6.2 nm / 200 eV	**BEUV Lithography**
2.34 – 4.39 nm / 283 – 531 eV	**Water Window Microscopy**
5 – 17 keV	**X-ray Microscopy**

Microscopy ⟶ Tomography

Laser Produced Plasma – solid (liquid) target



solid target

~ 100 µm

shock wave

X-rays & EUV

cold (~ 10 eV), high density (10^{22} cm^{-3}) plasma

hot (100-1000 eV), low density (10^{20} cm^{-3}) plasma

expanded low density plasma

focused high-power laser beam

10^{11} -10^{14} Wcm^{-2}
1-10 ns/0.1-10 J

Nd:glass

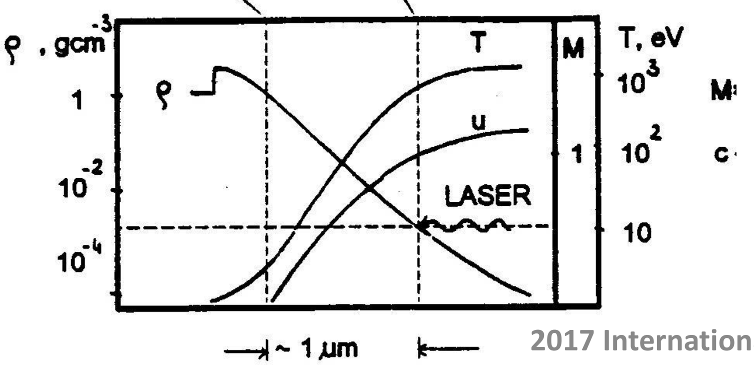
Nd:YAG

KrF

CO_2

Ablation surface

Critical surface

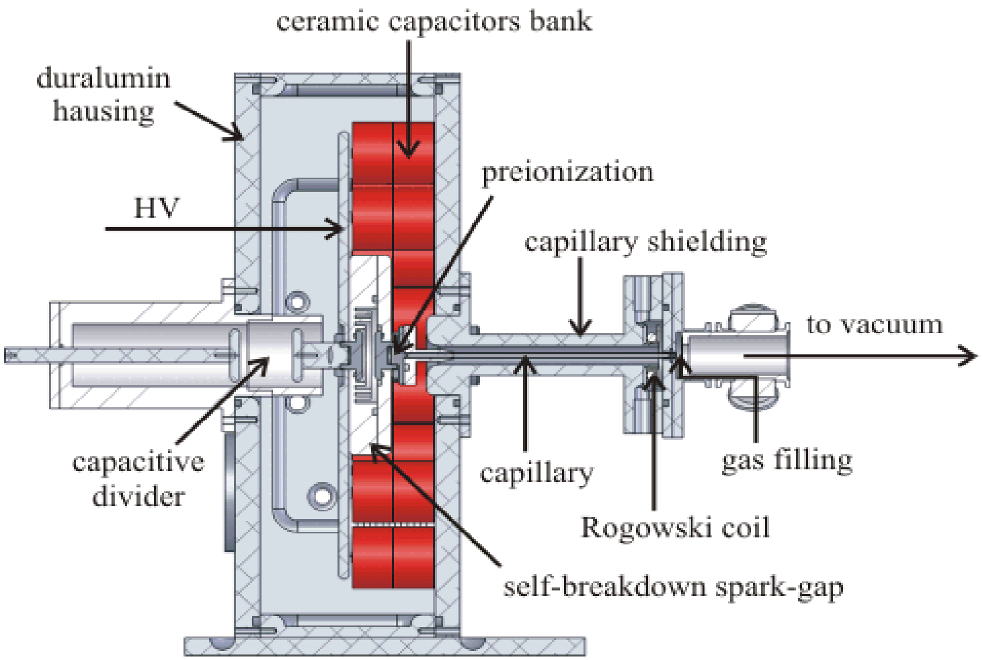


Laser plasma parameters for maximum EUV emission (e.g.)

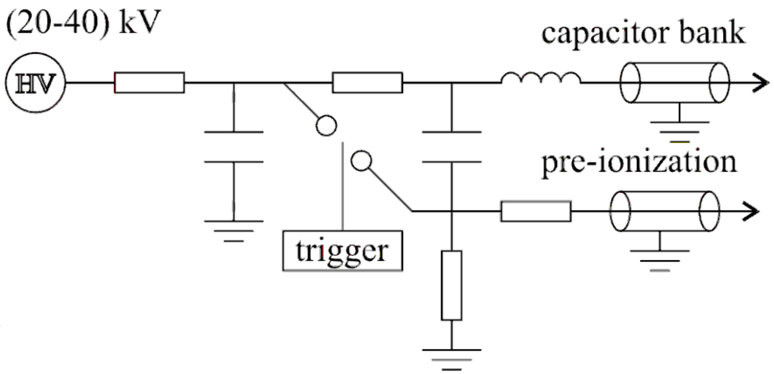
~ 40 eV, ~ 10^{19} cm^{-3}

Pinching Plasmas

Capillary Discharge Plasma



Main discharge unit

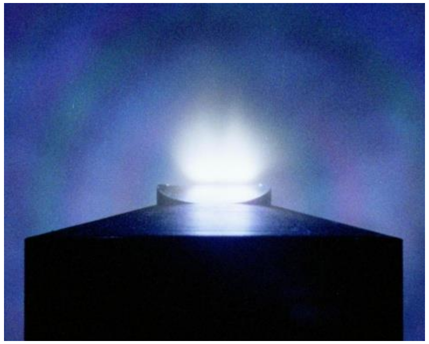


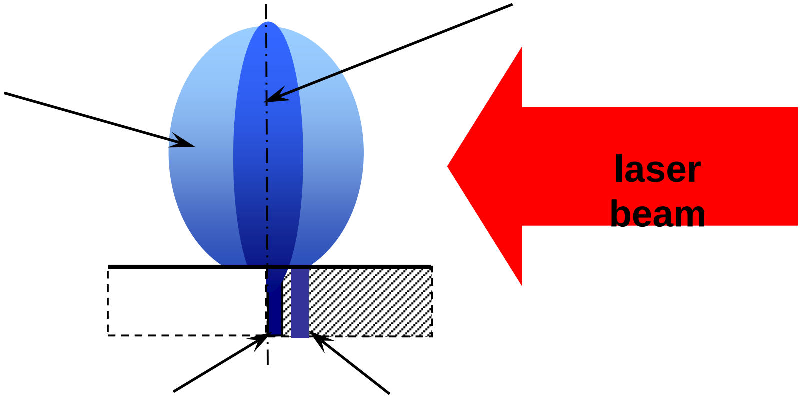
Charging circuit

- Ceramic Capacitors (1.25 ÷ 31 nF).
- Al_2O_3 capillary, 3.2mm dia., 20cm long.
- Low inductance -> high dI/dt.
- Pulse-charged: 1x Marx + coil.
- RL Rogowski coil.

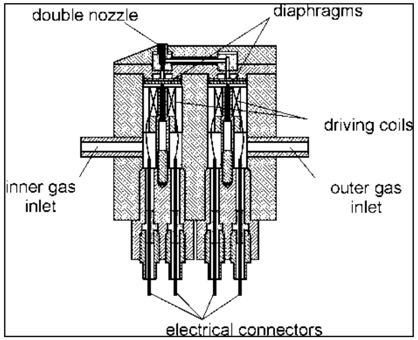
Design and construction of new experimental capillary discharge apparatus (A. Jancarek, M. Nevrkla)
CTU Prague, Faculty of Nuclear Sciences

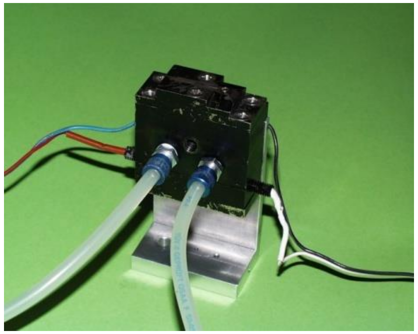
Laser Produced Plasma – gas puff target



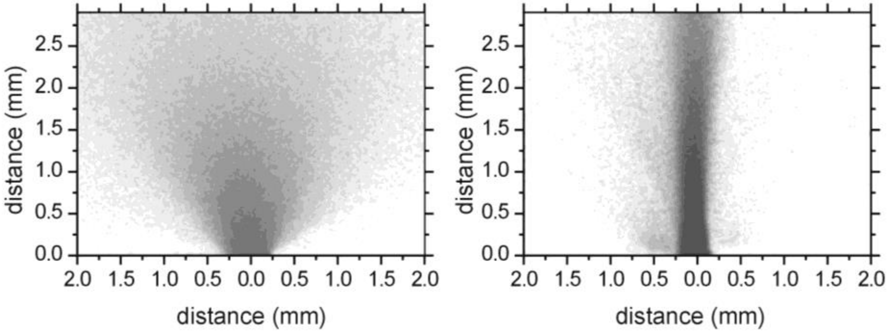


- **electromagnetic valve system**



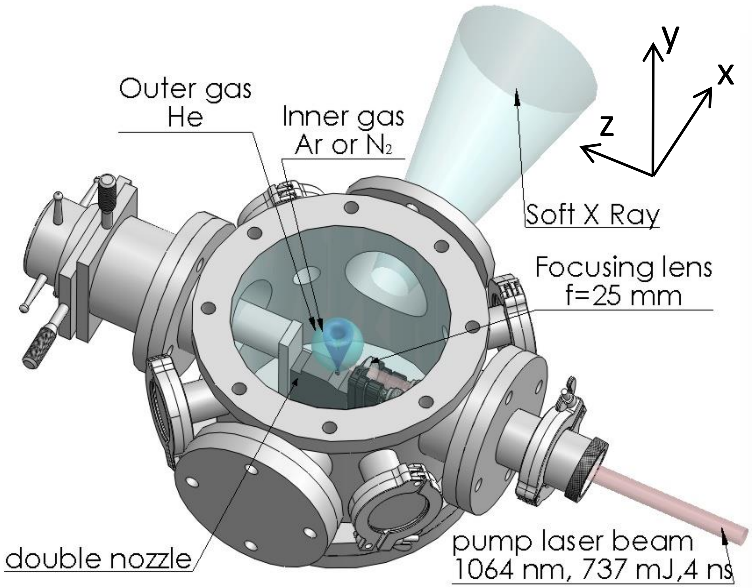


- **X-ray backlighting images**



H. Fiedorowicz *et al. Appl.Phys. B 70 (2000) 305; Patent No.: US 6,469,310 B1*
WAT , Warszaw

LPP - Gas puff target EUV laser-plasma short wavelength source



Scheme of the gas-puff target source

Photograph of the setup

Pumping laser	Nd:YAG laser (EKSPLA), 4 ns/500mJ pulses, repetition rate **10Hz**
Nozzle	Inner: circular 0.4mm in diameter Outer: ring 0.7mm/1.5mm diameters
Gasses	Working gasses: Ar, Kr, Xe, O_2, N_2, outer gas : He

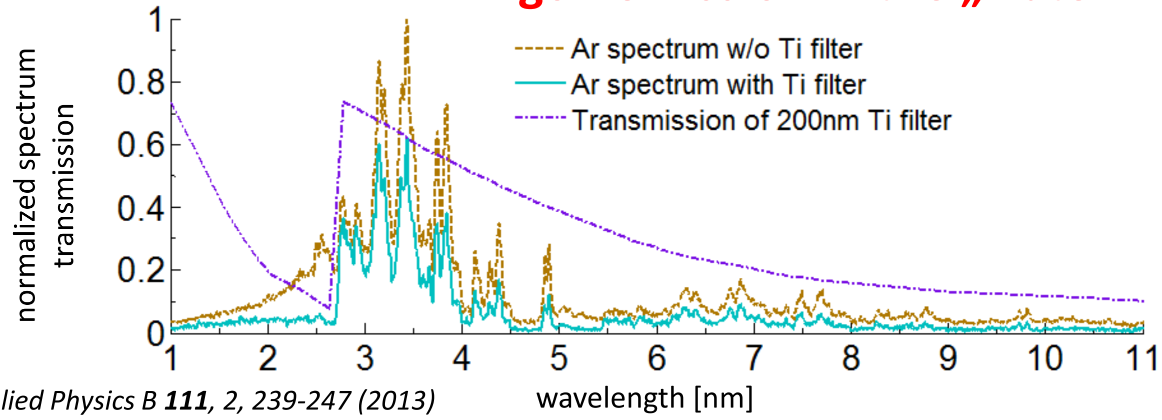
54
Xe
131.29

Advantages:

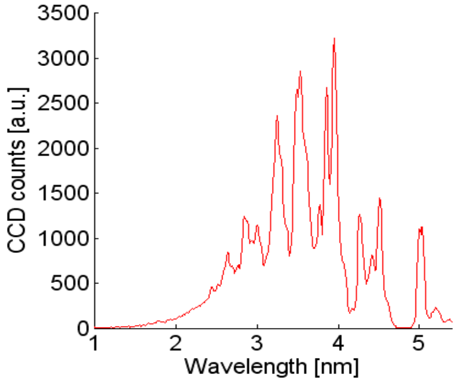
- ✓ no debris from gaseous targets
- ✓ compact construction, high repeatability
- ✓ high conversion efficiency, very robust – thousands of shots/day

LPP - Gas puff target EUV laser-plasma short wavelength source spectra

Argon emission in the „water window”

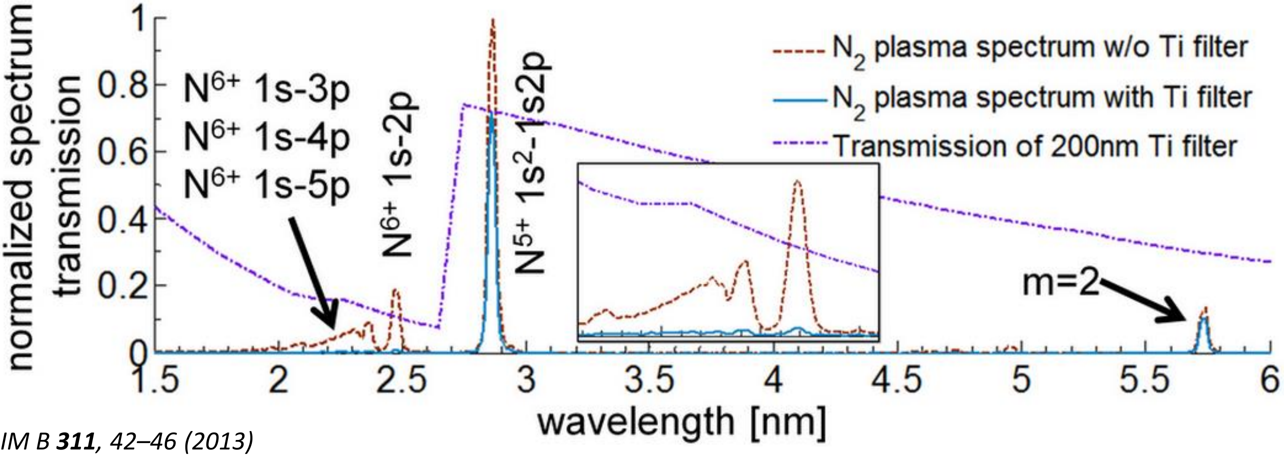


Applied Physics B ***111****, 2, 239-247 (2013)*

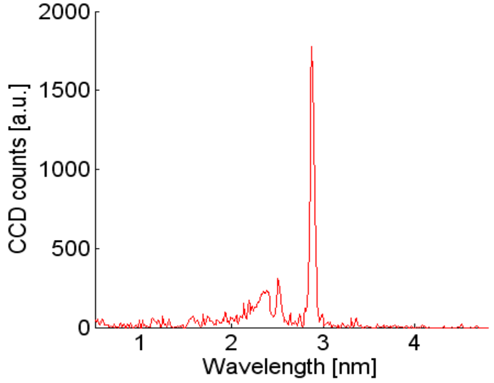


NIM B ***268****, 10, 1692-1700 (2010)*

Nitrogen emission in the „water window”



NIM B ***311****, 42–46 (2013)*



NIM B ***268****, 10, 1692-1700 (2010)*

EUV/XUV/XR sources

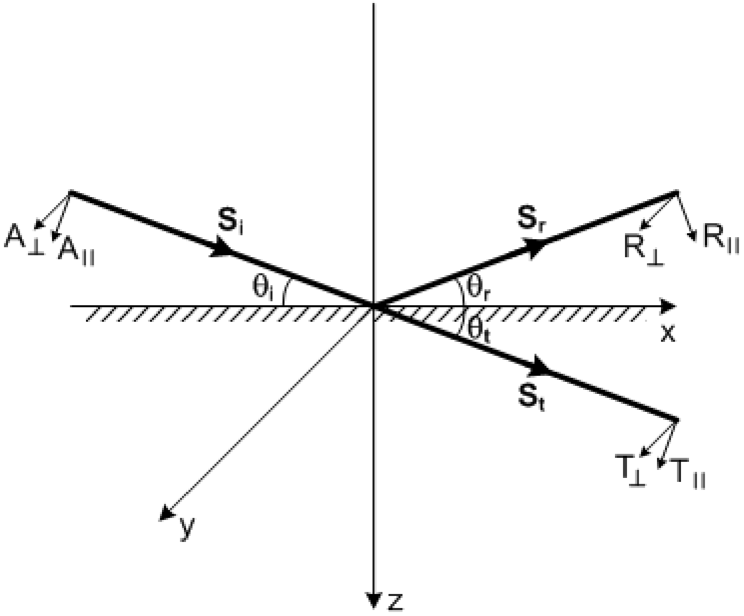
Synchrotron and FEL radiation

Reflection of X-rays

Complex refractive index

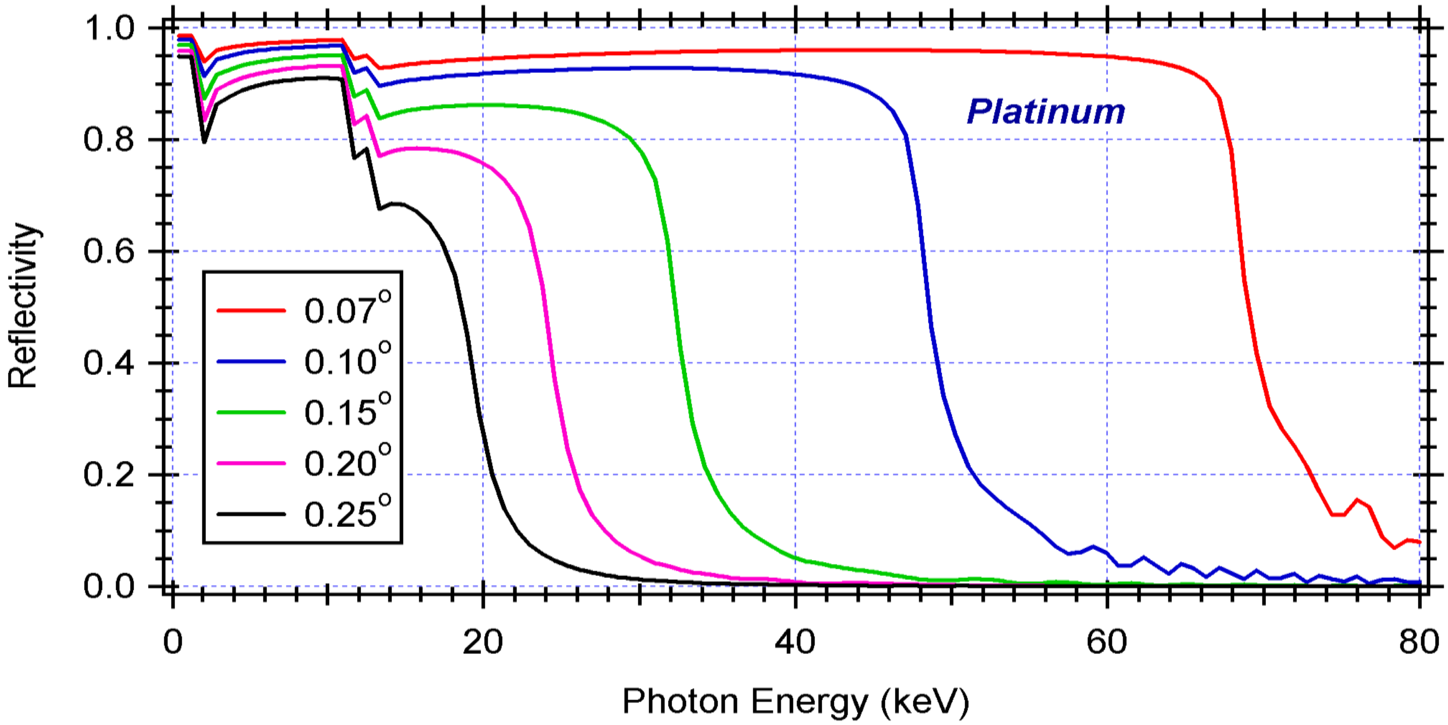
$$\mathbf{n} = 1 - \delta - i\beta$$

Refraction and Reflection of X-rays

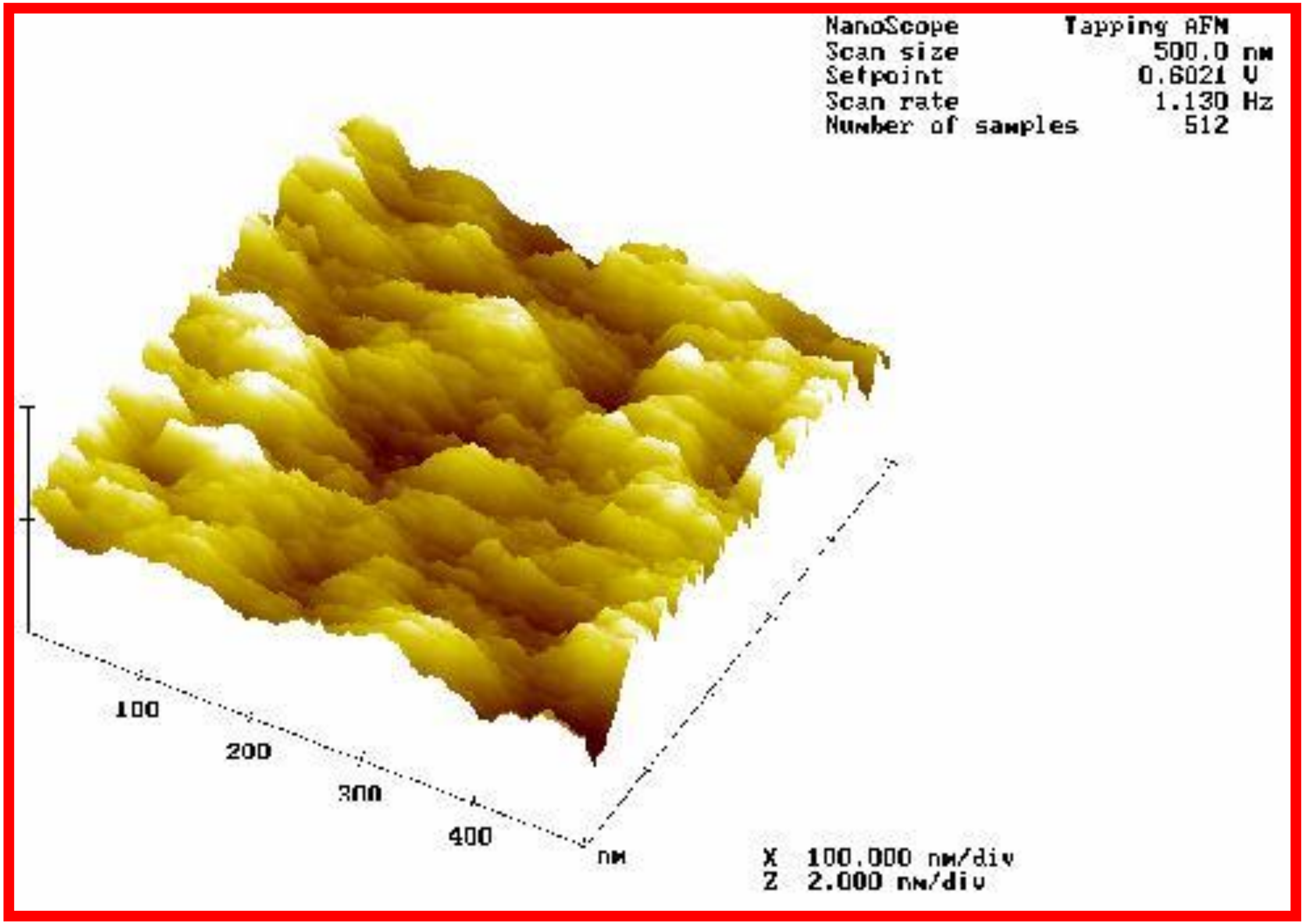


Total external reflection

Reflection of X-rays – photon energy and grazing angle



Reflection of X-rays – microroughness



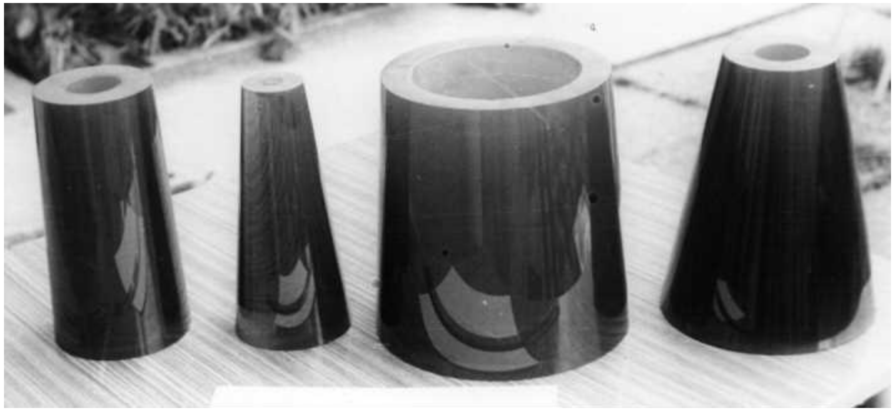
NanoScope Tapping AFM
Scan size 500.0 nm
Setpoint 0.6021 V
Scan rate 1.130 Hz
Number of samples 512

X 100.000 nm/div
Z 2.000 nm/div

Tapping AFM images of the surface of the double - sided flats developed for Schmidt lobster-eye telescopes. The resulting microroughness RMS is 0.3 nm.

Grazing Incidence (GI) replicated X-Ray Optics
48 years of research and development in Prague

Replication Technology for X-ray Optics Manufacturing



Mandrels used for manufacturing of X-ray mirrors (Glass ceramics Sital, Acad of Sci, Prague, 1969)

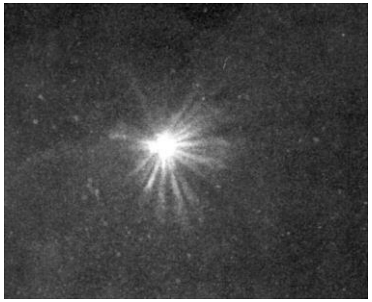
Replicated X-ray mirrors (hyperbolas, Ni surfaces, Acad of Sci, Prague)

History – milestones and examples of projects

(Academy of Science, Czech Technical University, Reflex, Rigaku)

- **1969 First considerations started**
- **1970 First X-ray mirror produced (Wolter 1, 50 mm)**
- **1971 Wolter 1, 80 mm**
- **1976 Wolter 1, 115 mm**
- **1979 First mirrors flown in space (two Wolter 50 mm, Vertikal 9 rocket)**
- **1980 Vertikal 11 rocket (two Wolter 50 mm)**
- **1981 First large Wolter mirror (240 mm)**
- **1981 Salyut 7 orbital station (Wolter 240 mm nested)**
- **1985 Applications for plasma physics, EH 17 mm, PP 20 mm**
- **1987 First high quality X-ray foils for foil mirror X-ray telescope (SODART)**
- **1988 Fobos 1 Mars probe, TEREK X-Ray Telescope**
- **1989 KORONAS I X-ray mirror, Wolter 80 mm**
- **1990 First Micromirror (aperture less than 1 mm, Bede Ltd.)**
- **1993 Collaboration with SAO, USA, WF X-ray optics started**
- **1996 First Lobster Eye test module produced, Schmidt geometry**
- **1997 Double-sided X-ray reflecting flats (SAO MA USA, CTU Prague)**
- **1997 Lobster Eye Angel geometry project started**
- **1999 First Lobster Eye test module produced, Angel geometry**
- **2001 Thin segmented X-ray mirrors**
- **2005 Replicated Image Slicers for LEO, EU FP6 projects, Cambridge**
- **2006 MFO Kirkpatrick-Baez optic, University of Boulder, CO, NASA, USA**
- **2007 Innovative technologies for X-ray telescopes, PECS, ESA XEUS projects**
- **2008 – 2017 EUV/BEUV/WW/SXR/XR Grazing Incidence mirrors …**

Examples of Imaging GI X-ray optics

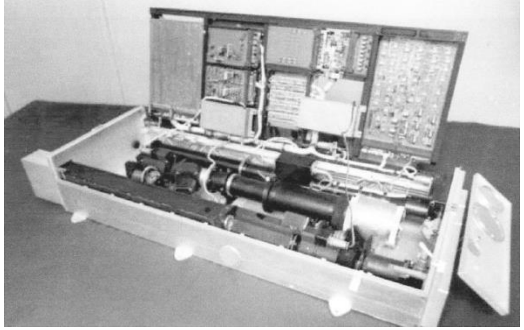


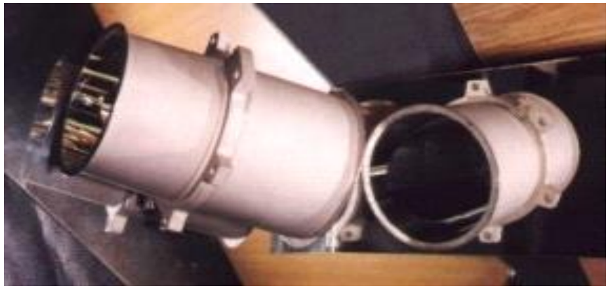
X-ray image of the
laser plasma by the
17 mm EH microscope
(IPPLM Warsaw)

1985 Applications for plasma physics
(EH 17 mm, PP 20 mm)

1988 FOBOS 1 Mars probe,
TEREK X-ray telescope

1989 KORONAS I
(Wolter 80 mm)





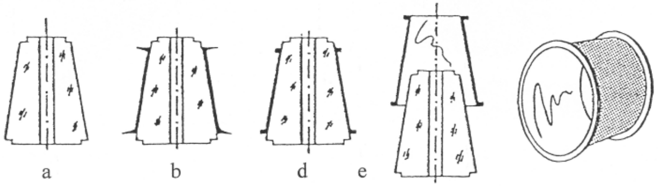
Replication technology

MANDREL
with Au surface
layer

Ellipsoidal mirror for
spectral region
10 – 15 nm

Replication technology

- Replication technology developments in the Czechoslovak Acad. of Sci., National Research Institute for Materials (1969*)*
  - 2-3 mirrors from one master

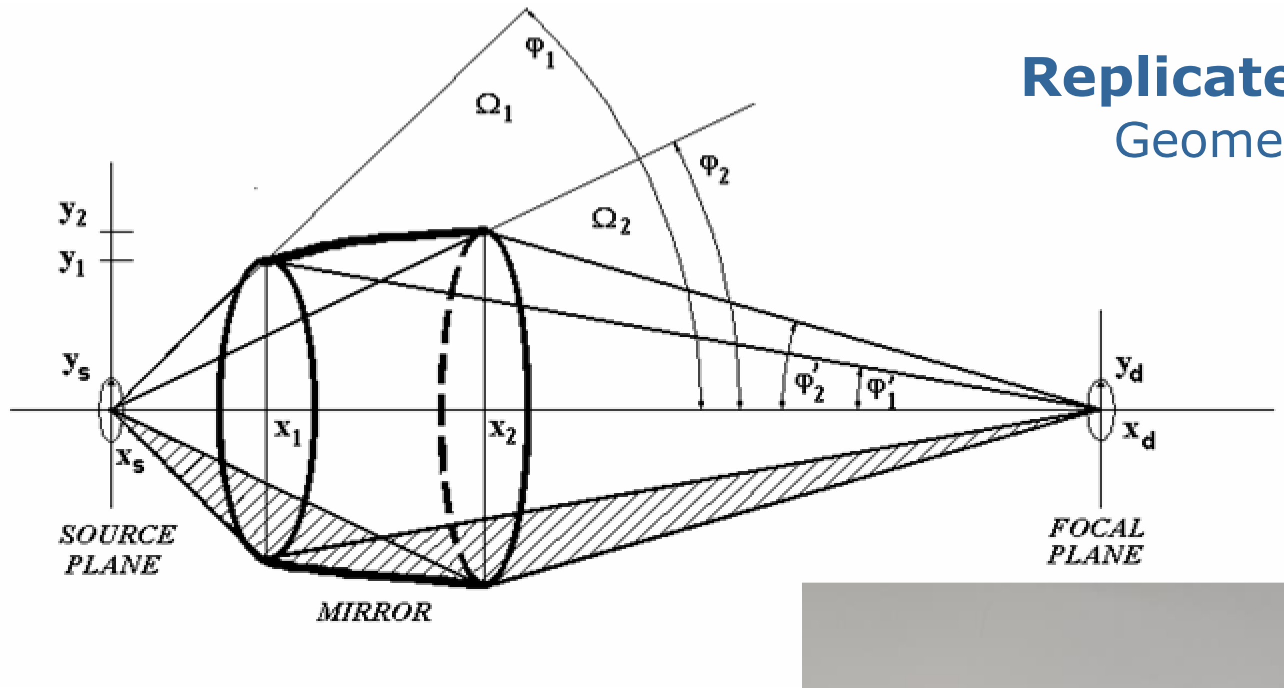


a - master,
b - master with electroformed nickel layer
d - cutting/finishing of the edges
e - removing the Ni mirror shell

- Improvement of replication technology:
  - less damage of mandrel
  - reduced weight
- Laboratory and space applications
  - Wolter objectives 17 mm and 20 mm dia
  - EH Wolter used (1985) for taking photographs of laser plasma in Institute of Plasma Physics and Laser Microfusion in Warsaw

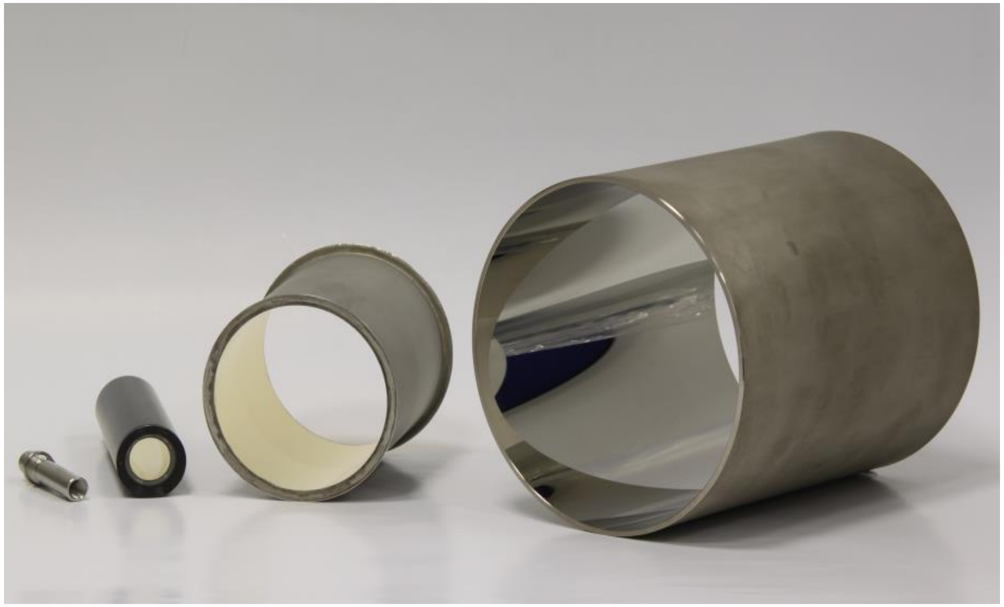
Replicated GI Mirrors

Geometry and size



Example: Elliptical mirror

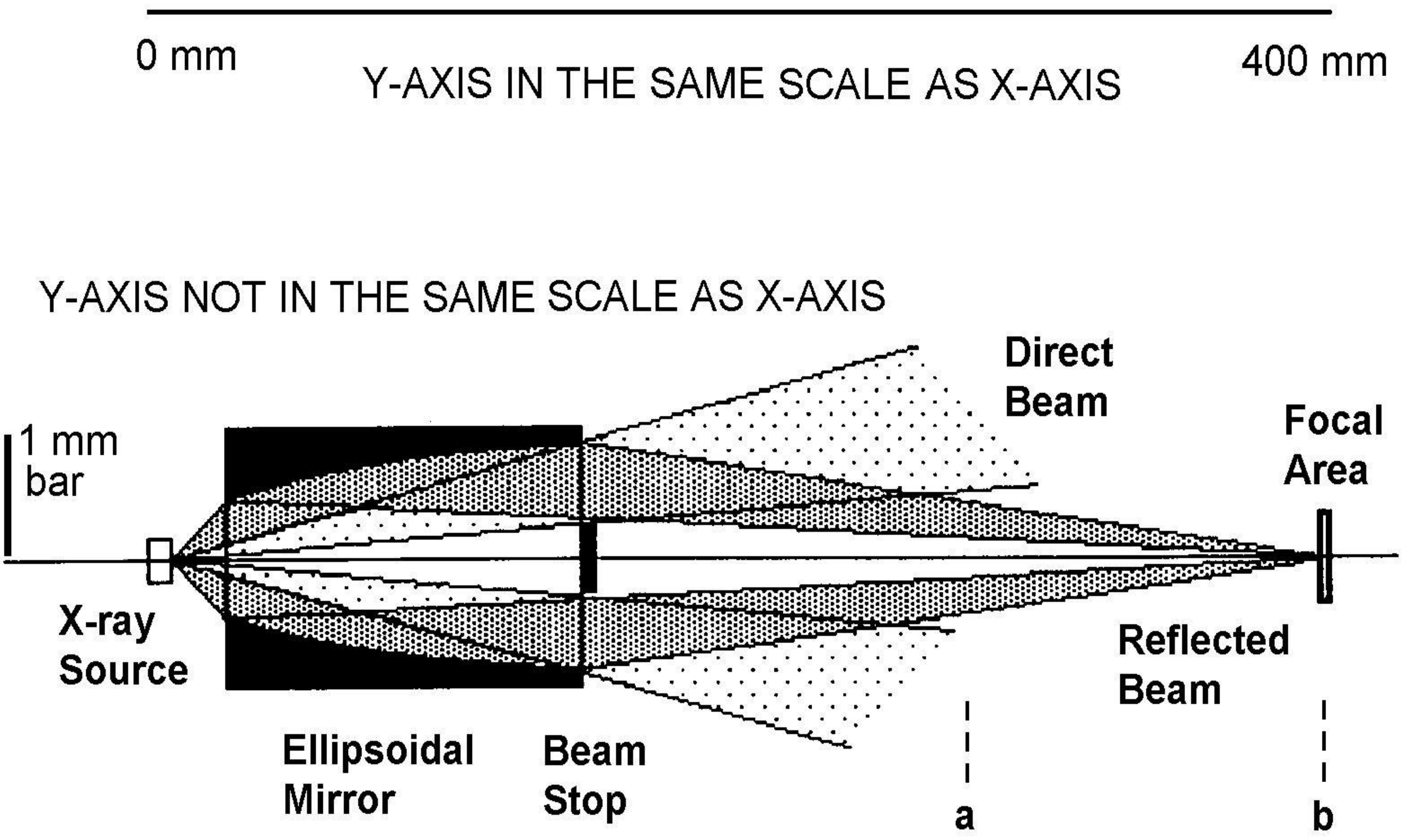
- Mirror surface has shape of rotational ellipsoid
- Source is placed in left focus
- Detector or sample is placed in right focus
- Radiation strikes mirror surface at grazing angles 0,5° ÷ 20°
- Mirror is focusing radiation from left focus on right focus



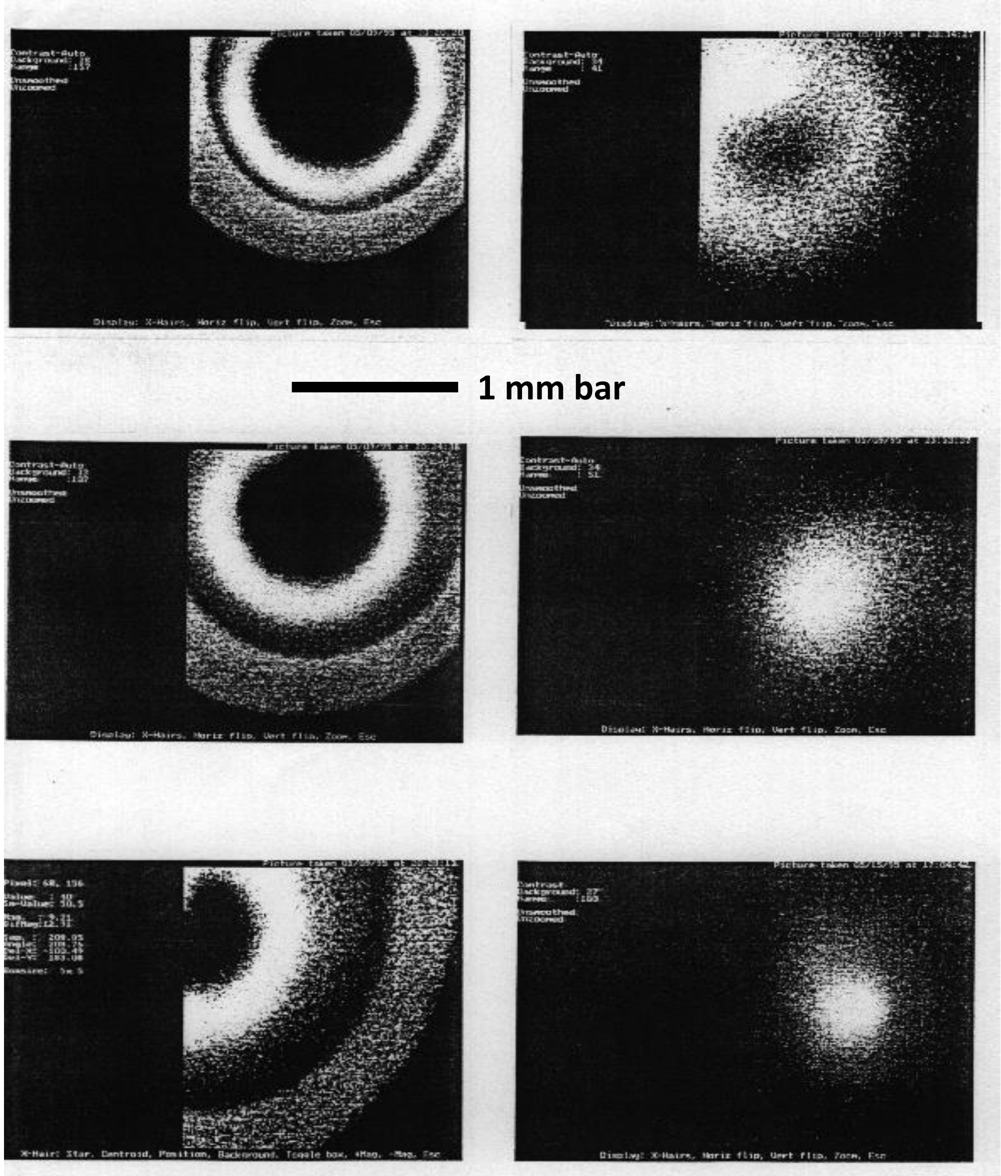
GI Mirrors – Spectral Range

- Metallic surface (Au, Ni, Mo, Ru...)
- $R \geq 50\%$
- Grazing angles: 0.5° - 20°
- Surface roughness: $R_a \approx 0.2 – 2$ nm
- Dimensions: D = 5 – 300 mm
  L = 10 – 250 mm
- Optical shapes: elliptical, parabolic, aspherical shapes upon request
- Spectral range: EUV (60 – 200 eV)
  Soft X-ray (200 – 2000 eV)
  X-ray (2 - 20 keV)

Ellipsoidal mirror for 8 keV microfocus source



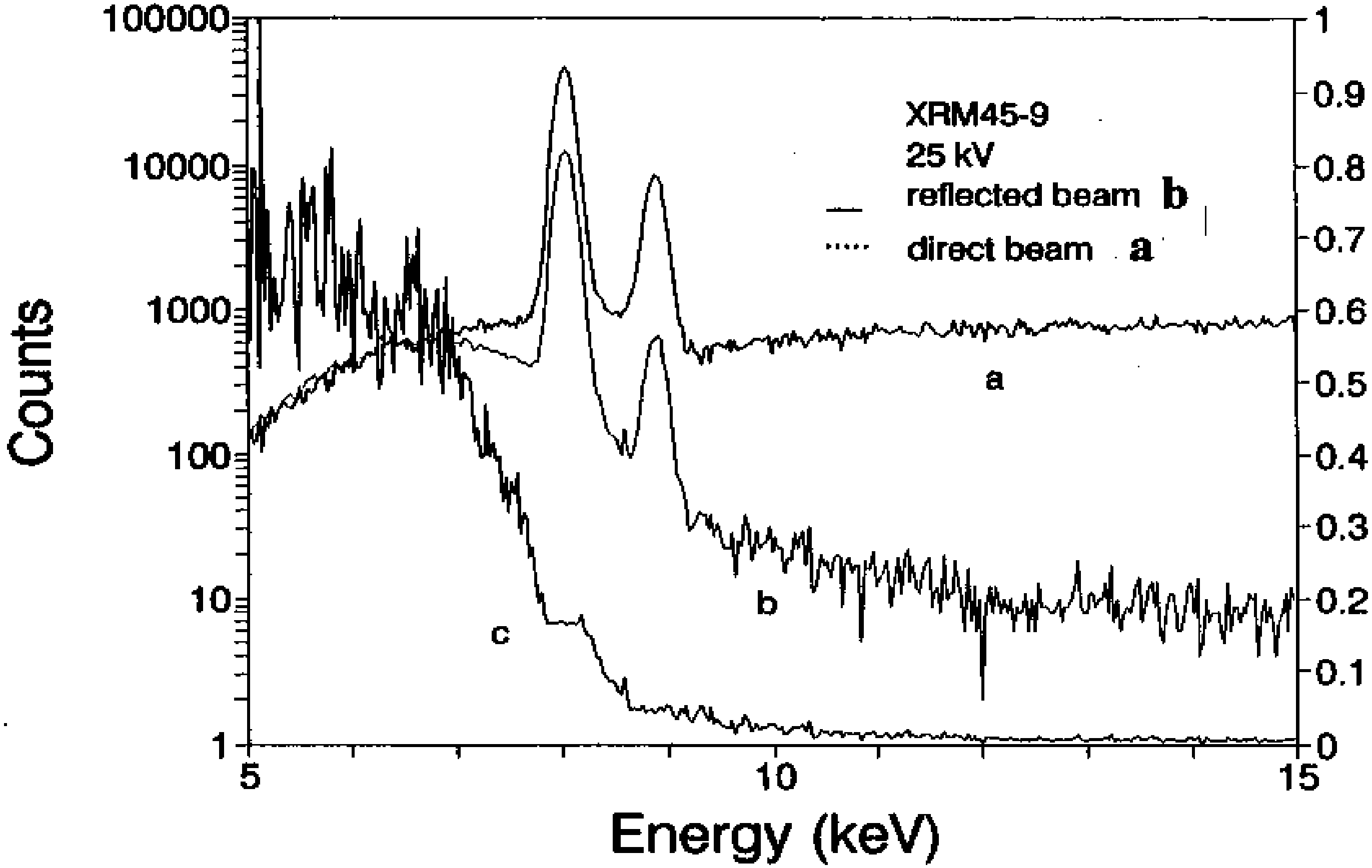
Ellipsoidal optic for 8 keV microfocus source



A series of X-ray beam images behind the output of ellipsoidal mirror with beam stop on the axis.

Converging reflected beam and diverging direct beam are clearly distinguishable.

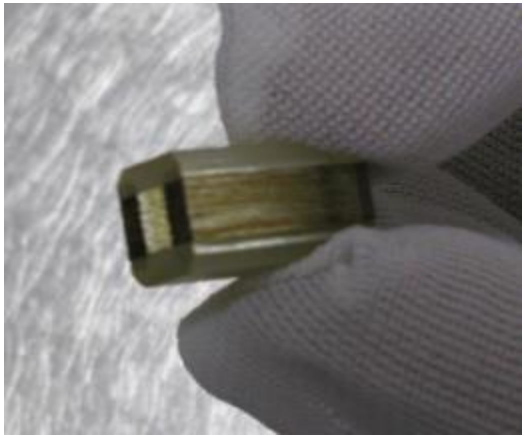
Ellipsoidal X-ray Mirror as a Spectral Filter



XGI Mirrors Manufactured by Rigaku Innovative Technologies Europe (RITE)

- RITE is the Czech company owned by the Rigaku Corporation (Tokyo, Japan)
- Established in 2008 as European center for the design, development and manufacturing of **X-ray optics**, **X-ray detectors** and **X-ray sources**
- Colaboration with Czech academic institutions and high-tech companies
- Ellipsoidal and parabolic optics for EUV/BEUV/WW/SXR/XR

  (laser plasma research, EUVL, WW and X-ray microscopy, space, …)
- Slope error < 10 arcsec (5“), microroughness < 2 nm (0.5 nm)

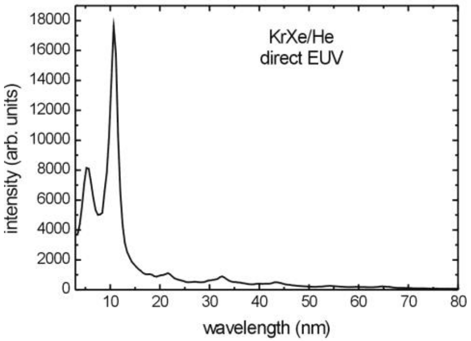


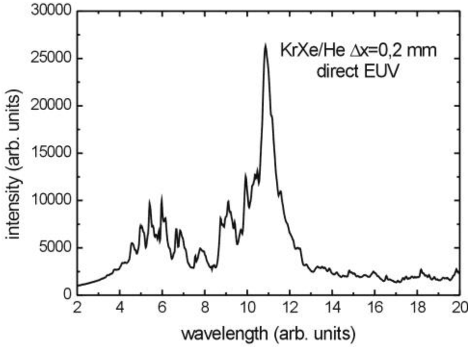
Replicated GI Mirrors Applications

Ellipsoidal GI mirror
for WW
(2.3 – 4.4 nm)

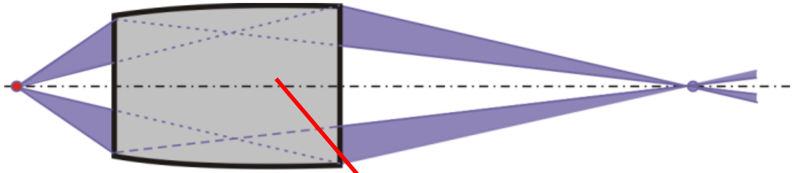
Ellipsoidal GI mirror
For EUVL
(10-15 nm)

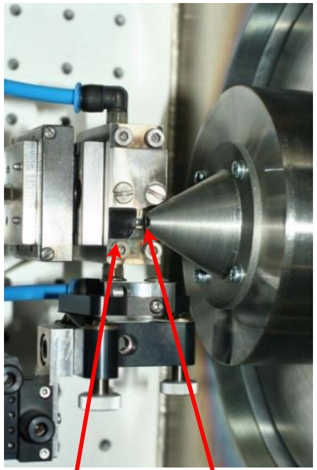
Laser-plasma produced EUV source: laser 0.8 J / 4 ns

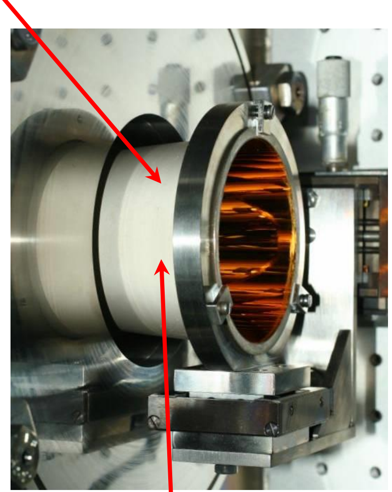




Low and high resolution EUV spectra of plasma radiation



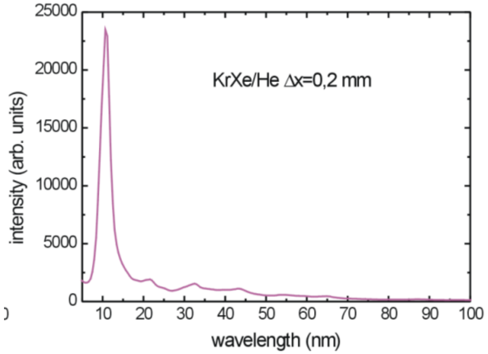


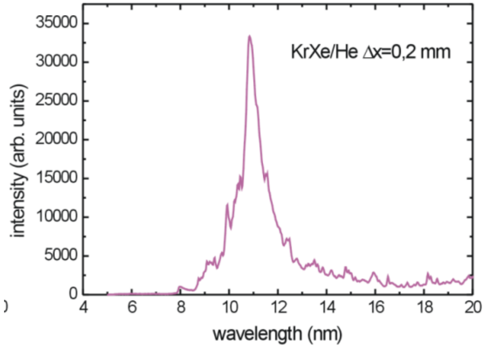


Gas puff valve

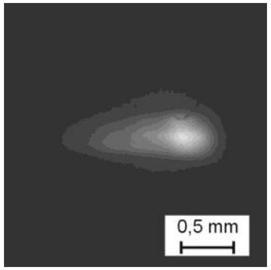
Orifice for differential pumping

Ellipsoidal EUV collector



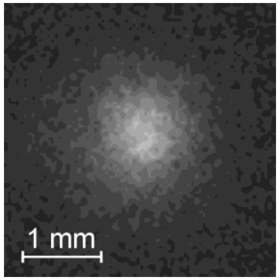


Low and high resolution EUV spectra of reflected radiation



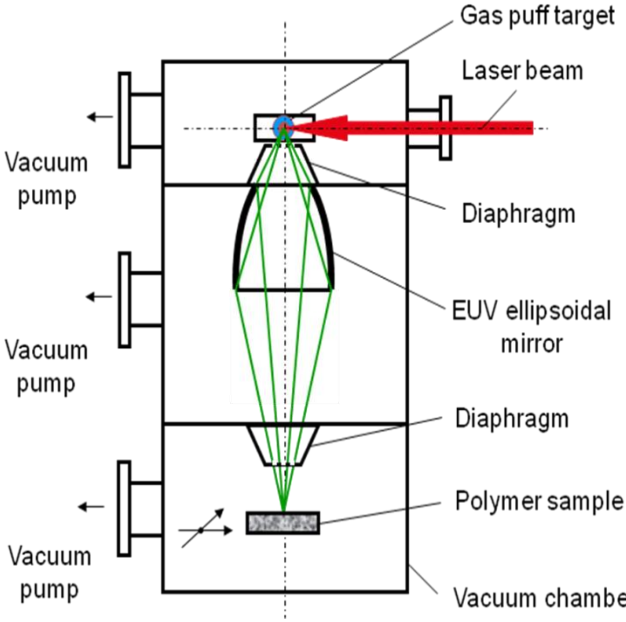
Plasma image

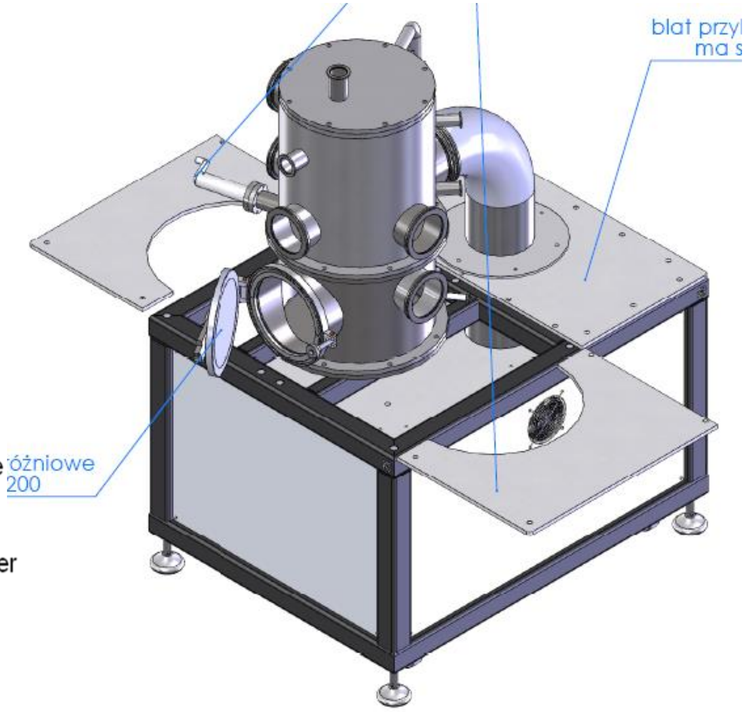
Focal spot image

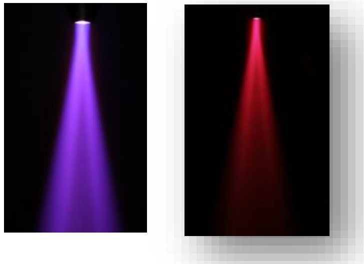


Laser plasma EUV source for processing polymers

Laser plasma EUV source dedicated for processing polymers has been designed at IOE and was built in co-operation with EKSPLA, RIGAKU and PREVAC high-tech companies







EKSPLA

Rigaku

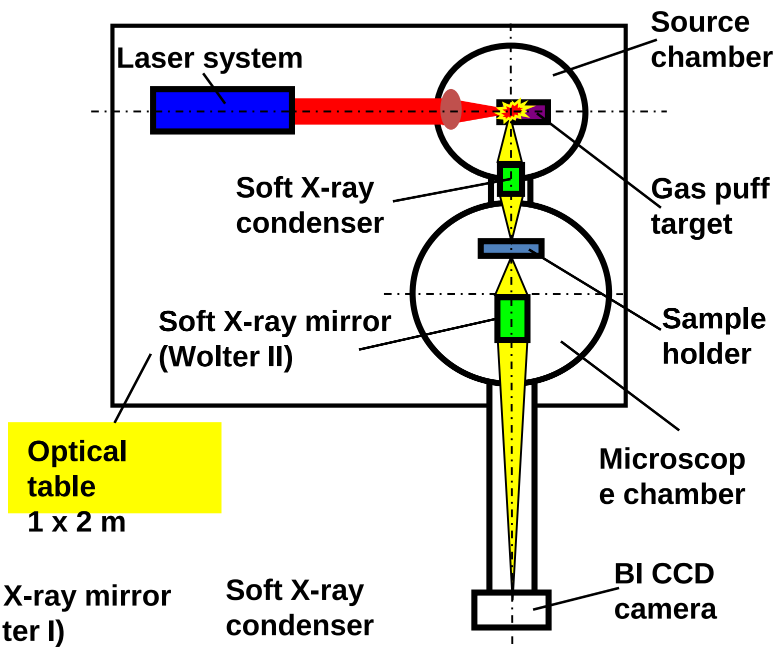
EUREKA

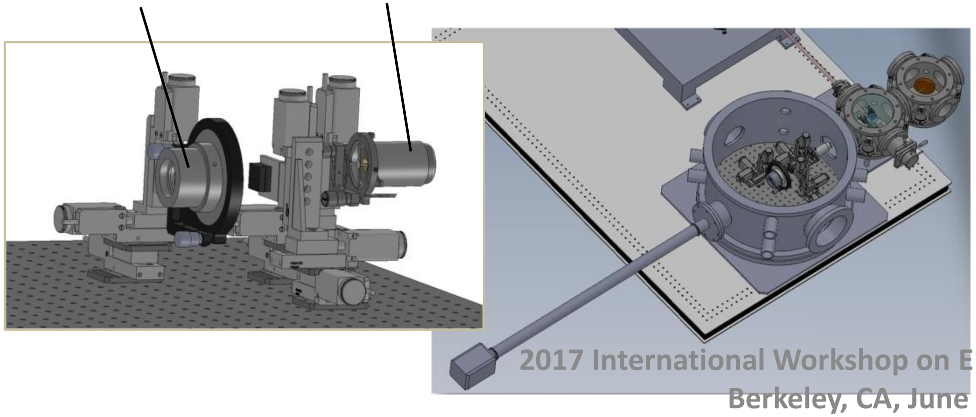
PREVAC

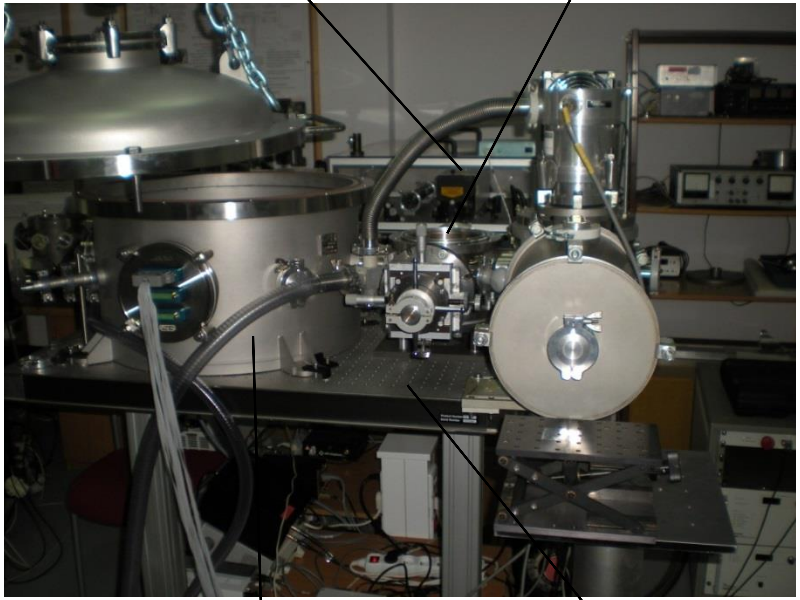
Bartnik et al. *Nucl. Instr. Methods A* 647 (2011) 125

NANOIMAGING USING SOFT X-RAYS

Desk-top soft X-ray microscope with a laser plasma source

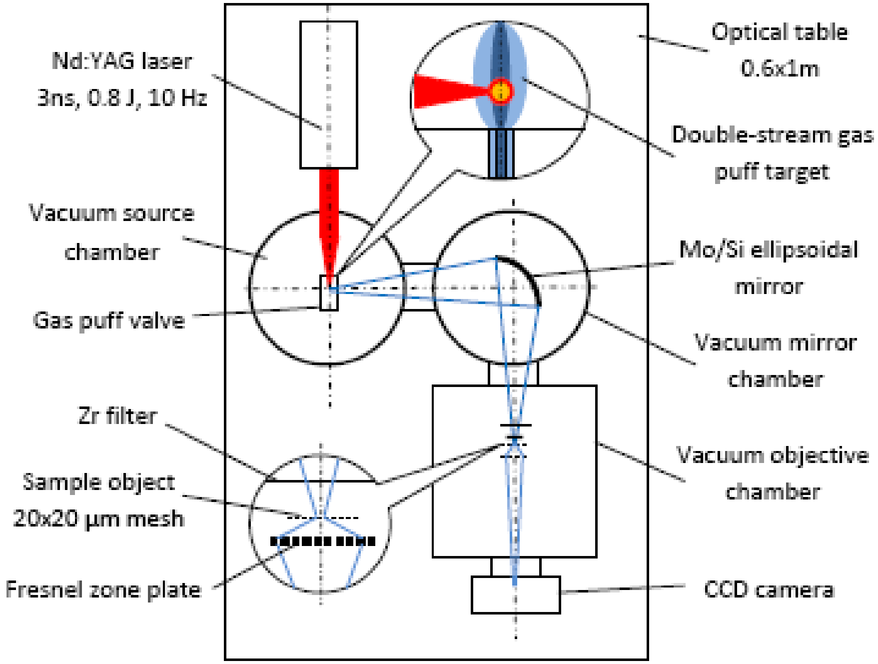

Laser system
Source chamber
Soft X-ray condenser
Gas puff target
Soft X-ray mirror (Wolter II)
Sample holder
Optical table 1 x 2 m
Microscope chamber
BI CCD camera


Soft X-ray mirror (Wolter I)
Soft X-ray condenser

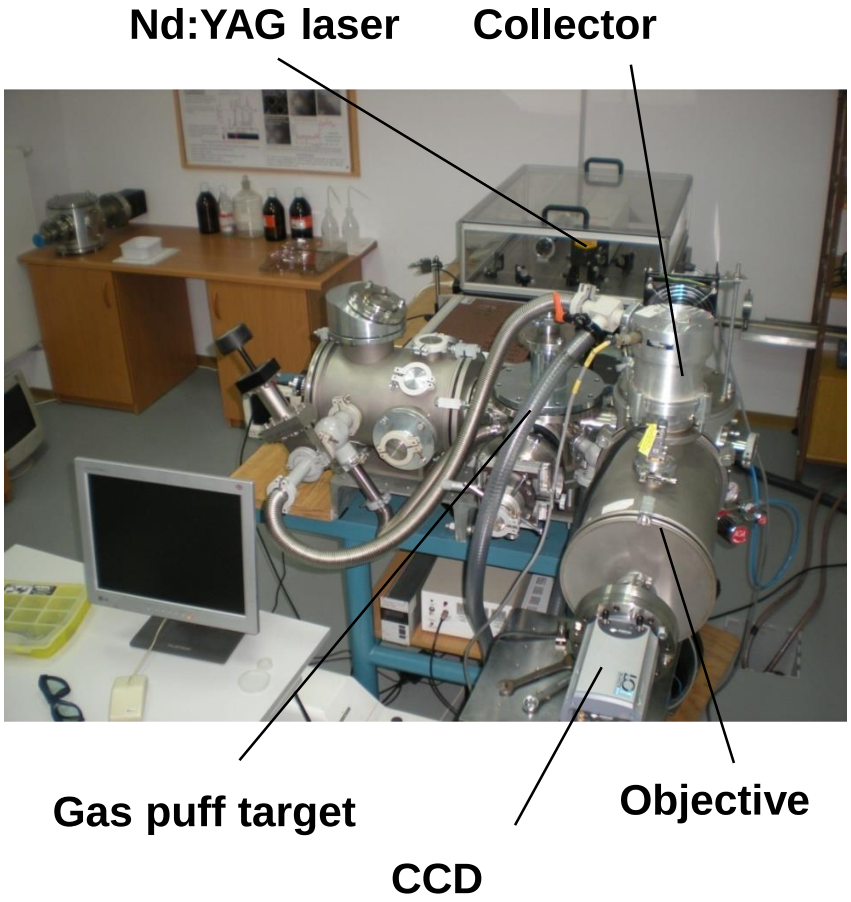

Nd:YAG laser
Source chamber
Microscope chamber
Optical table

EUV IMAGING IN A NANOSCALE

Desk-top soft X-ray microscope with a laser plasma source

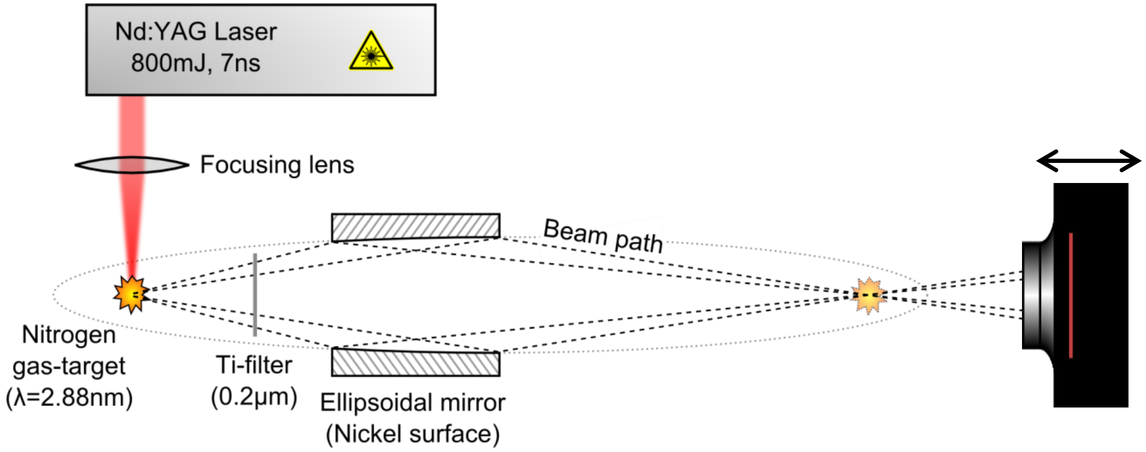


Optical table
0.6x1m



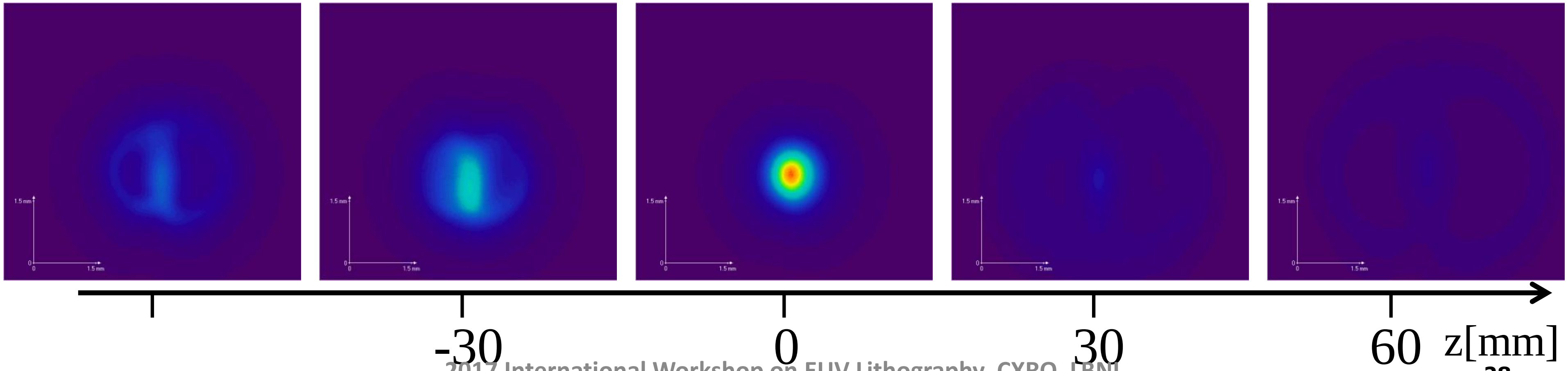
Focusing of soft X-ray radiation

Setup at LLG with Rigaku ellipsoid

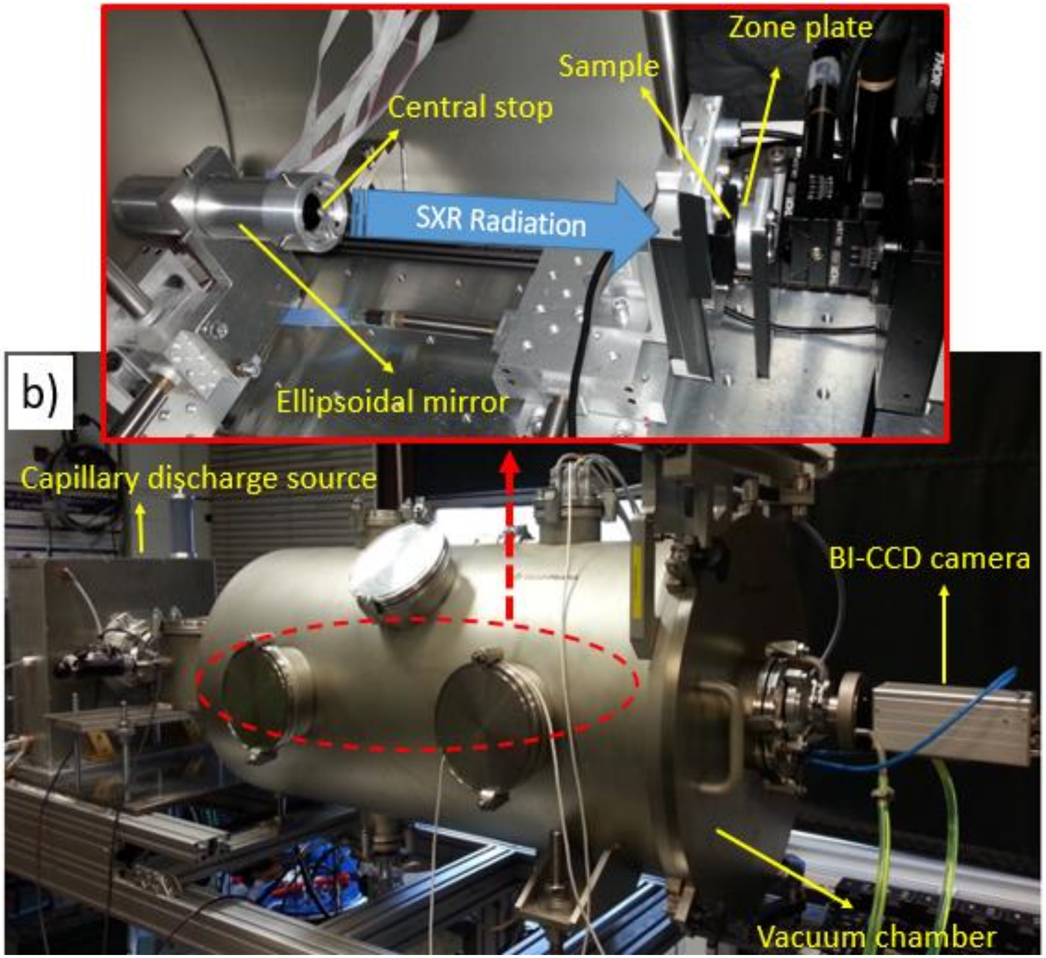


- 200 nm Ti filter
  → T = 72%
- (before: 1200 nm, T=14%
  = 1/5 · 72%)
- phosphor coated CCD
  → exposure level ~ 80%
  in focal plane

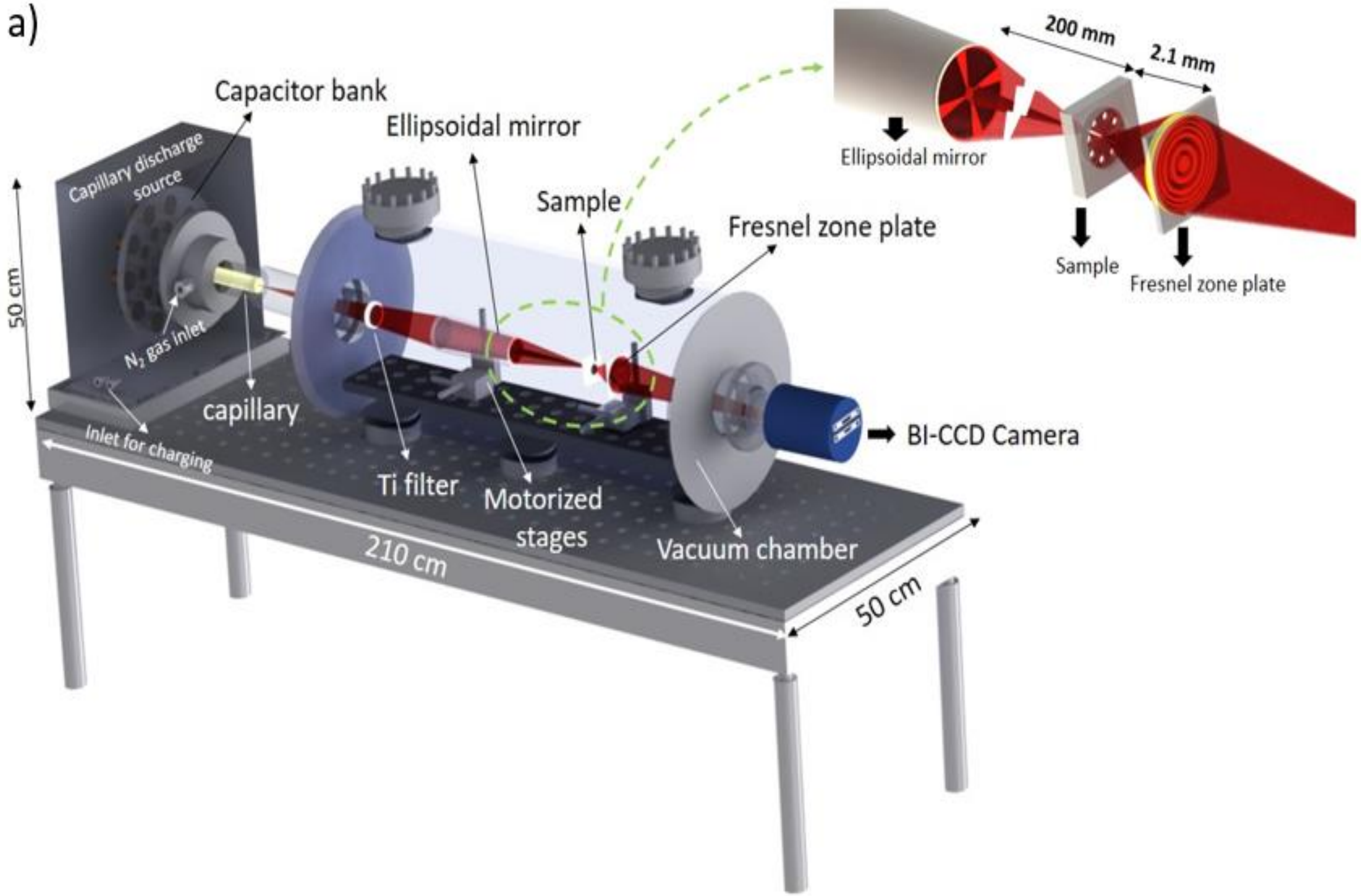
Dr. Klaus Mann, LLG Gottingen



EUV microscope with capillary discharge plasma source (Nitrogen, λ = 2.88 nm), ellipsoidal grazing incidence condenser and Fresnel Zone objective (Czech Technical University in Prague)

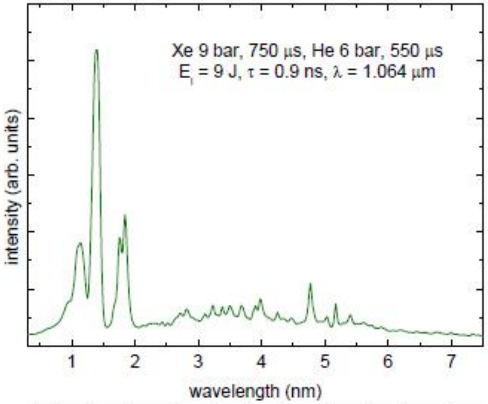


EUV microscope with capillary discharge plasma source (Nitrogen, $\lambda = 2.88$ nm), ellipsoidal grazing incidence condenser and Fresnel Zone objective (Czech Technical University in Prague)



Replicated GI Mirrors Spectral and Focusing Analysis

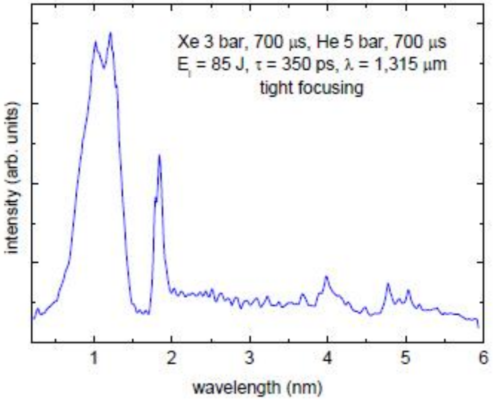
Focusing system prepared for a soft X-ray plasma source based on Xe gas target, driven by a 10 J/ 1ns/ 10 Hz Nd:YAG laser system



10J laser system

IOE, Warsaw

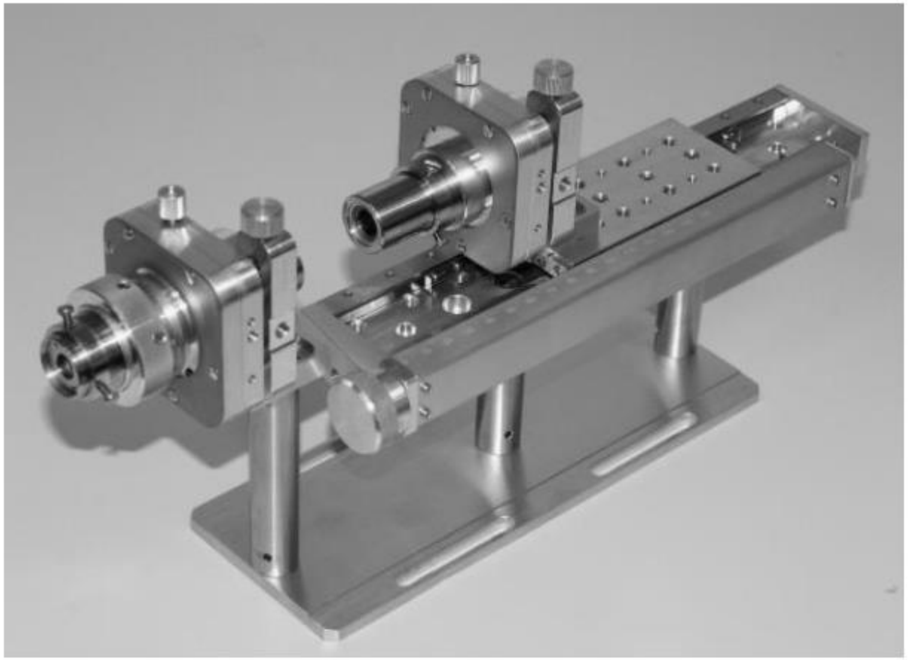
Spectrum for 9J



600J laser system

PALS , Prague

Spectrum for 85J

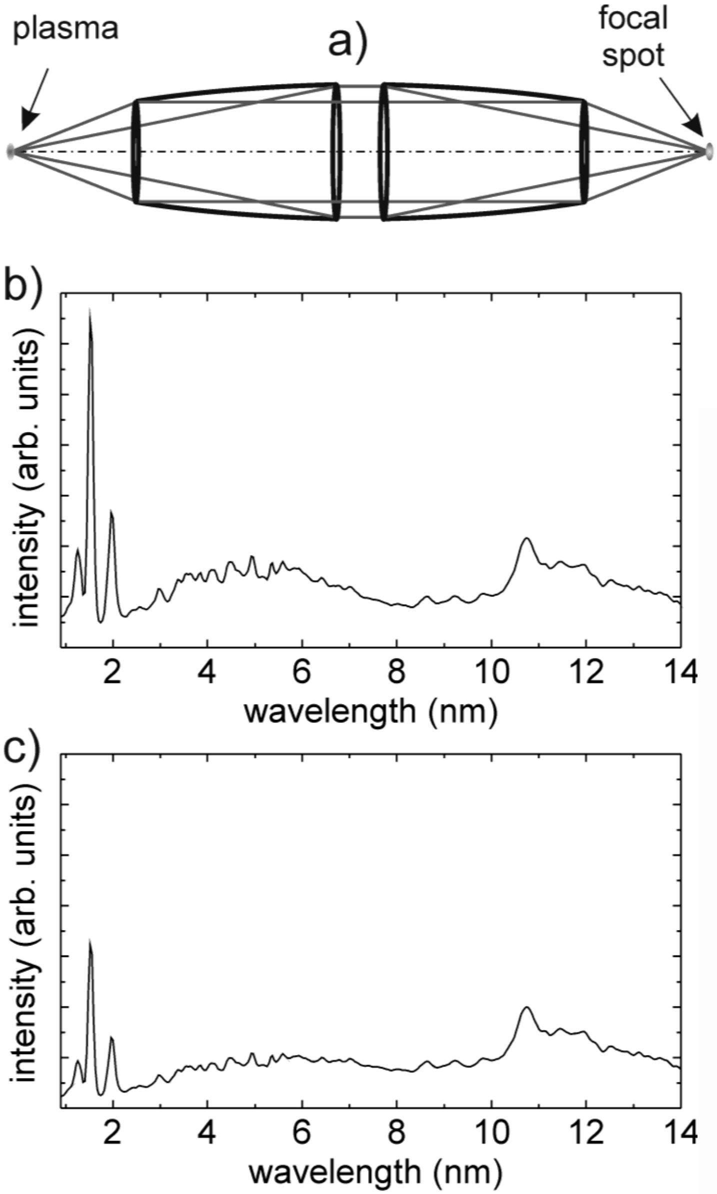


Set of 2 coaxial paraboloidal mirrors optimized for the wavelength 1.5 nm

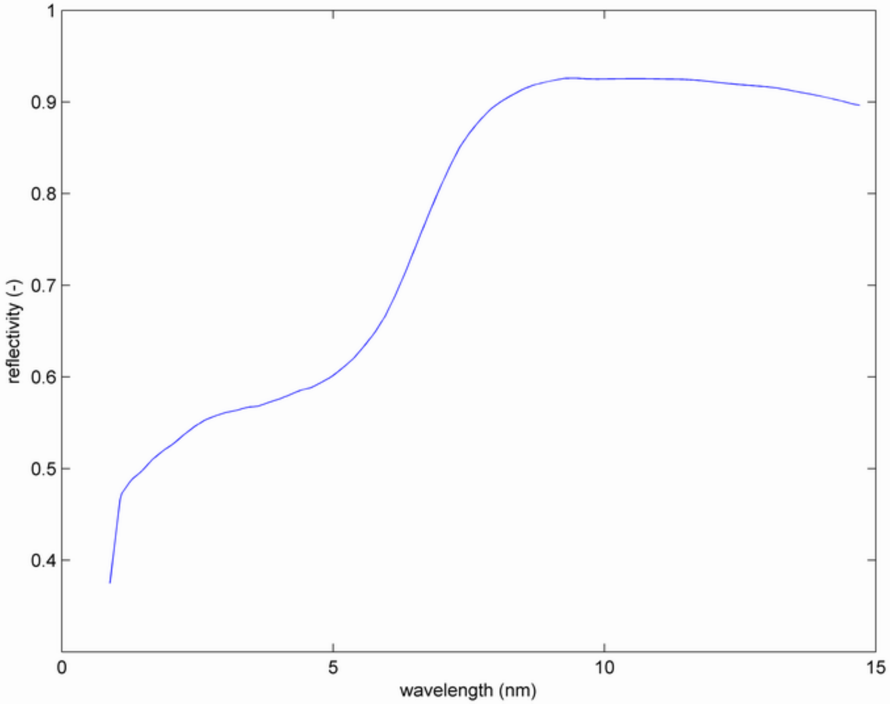
Plasma

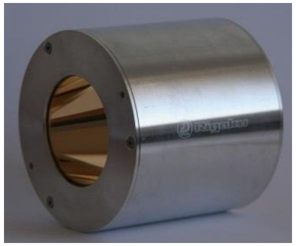
Focal spot

Measurement of GI SXR mirror spectral reflectivity

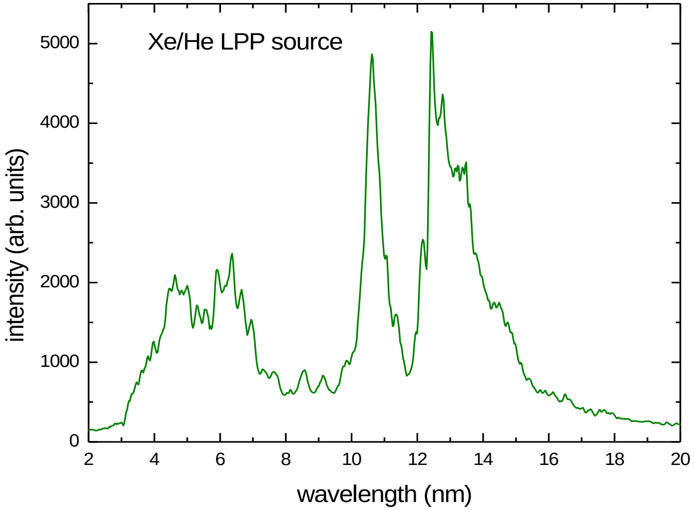


- (a) Schematic view of the paraboloidal collector
- (b) Spectrum of the unaltered Xe plasma radiation
- (c) Spectrum of Xe plasma radiation focused using the paraboloidal collector
- (d) Calculated spectral reflectivity in 1-15 nm range



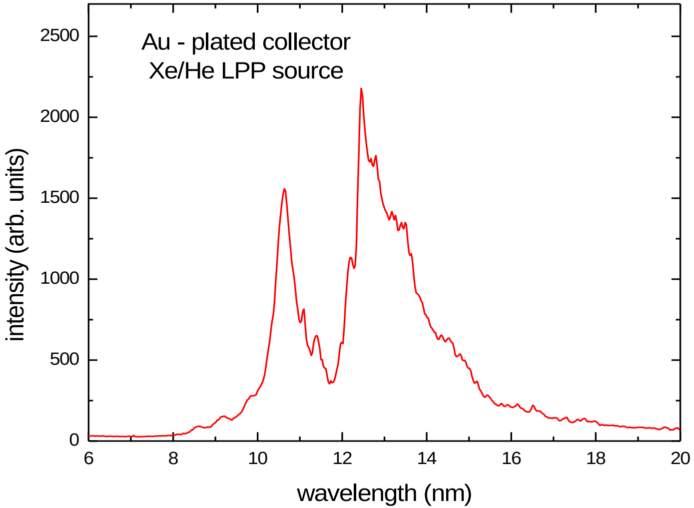


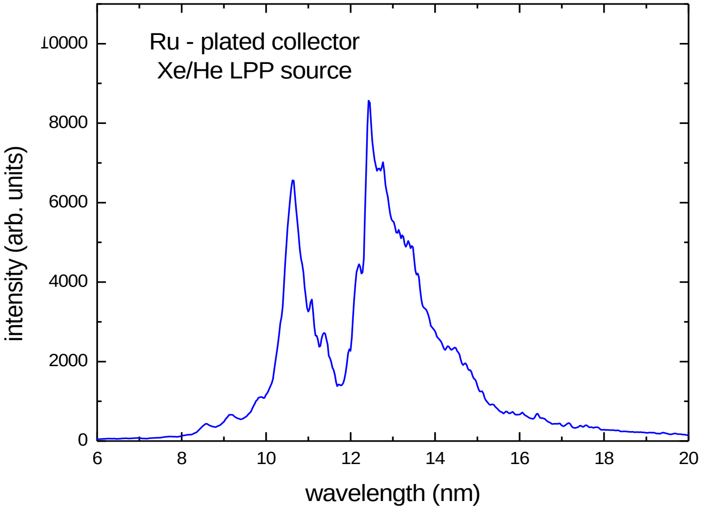
Comparison of Au and Ru coated EUV collector reflectivity



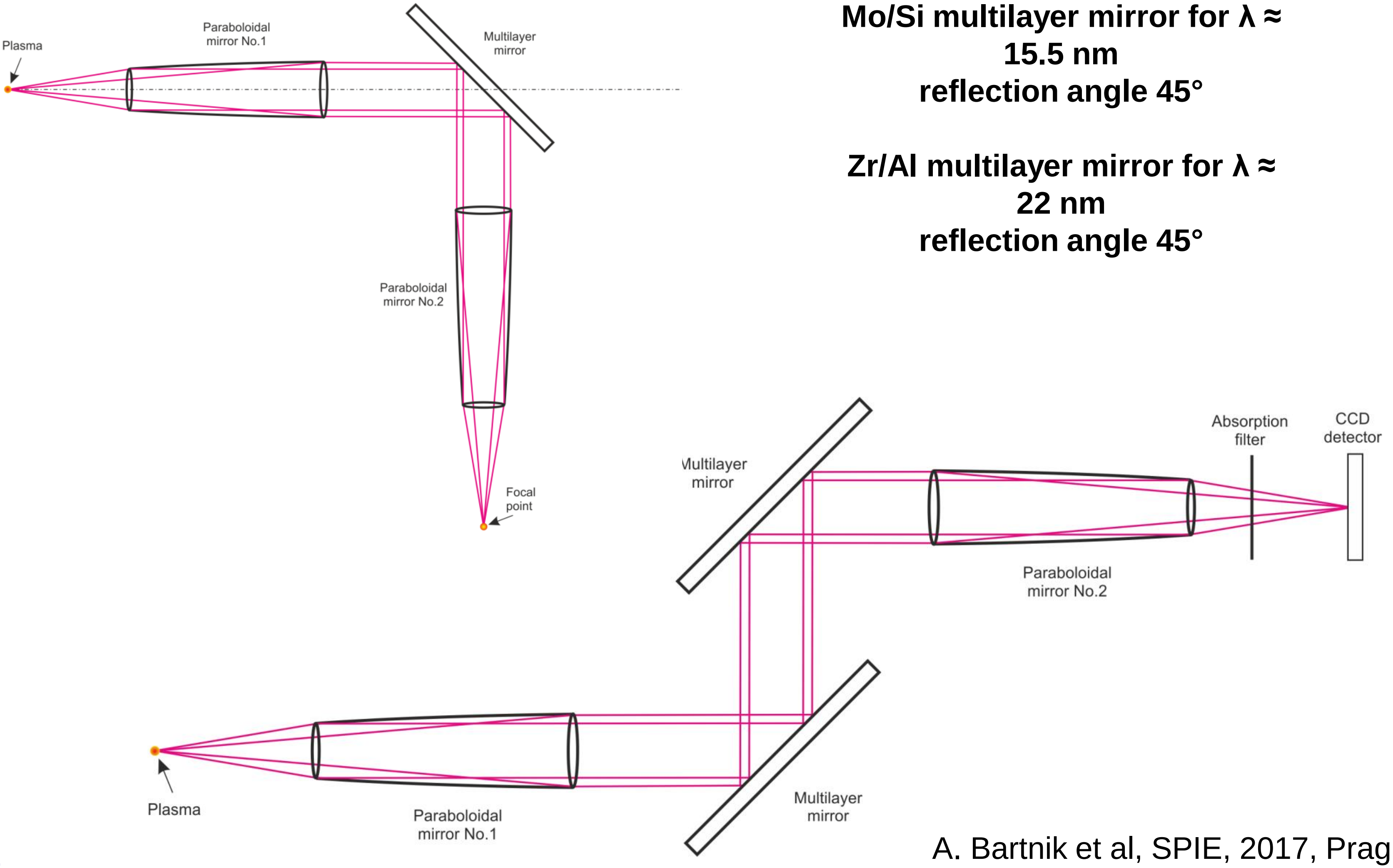
Spectra of Xe/He plasma radiation:

- **a) Xe plasma emission**
- **b) Radiation reflected from the Au coated collector surface**
- **c) Radiation reflected from the Ru coated collector surface**





Detection systems based on paraboloidal moirrors



Mo/Si multilayer mirror for λ ≈ 15.5 nm
reflection angle 45°

Zr/Al multilayer mirror for λ ≈ 22 nm
reflection angle 45°

A. Bartnik et al, SPIE, 2017, Prague

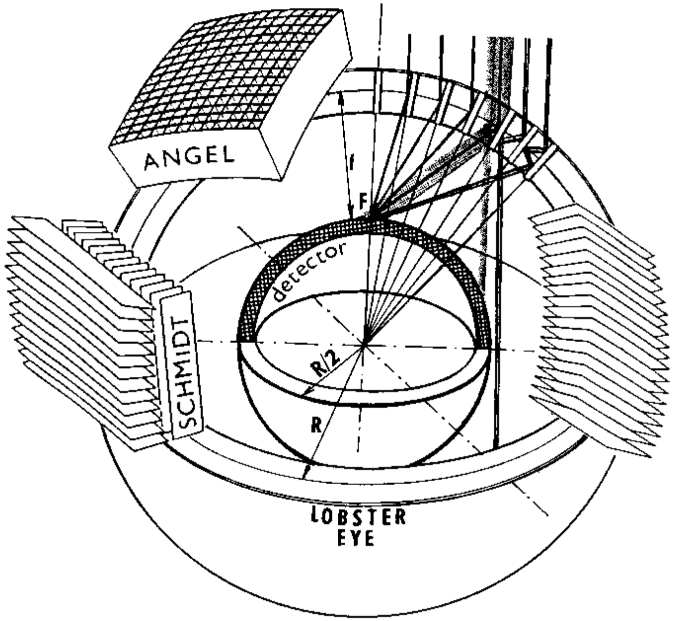
GI EUV Mirrors

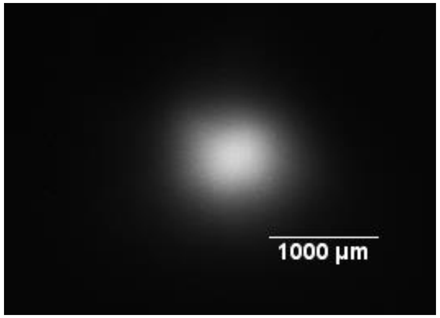
Ellipsoidal GI EUV mirror for 13.5 nm

Ellipsoidal GI EUV mirror for 13.5 nm

EBL2: EUV exposure and surface analysis system

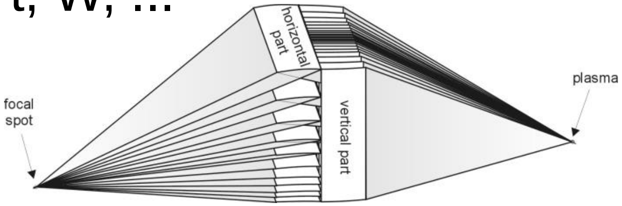
Multi-foil optics





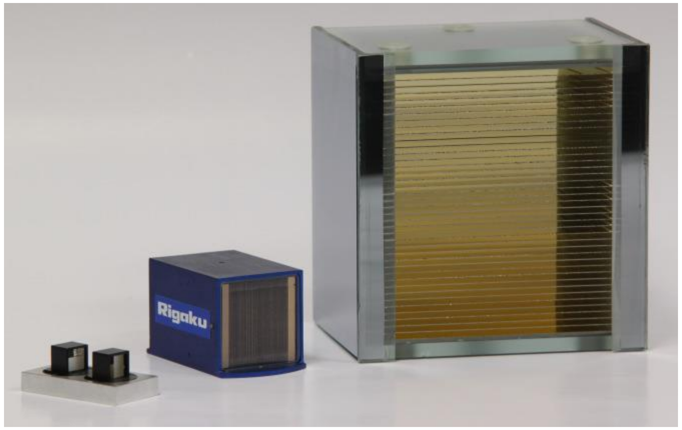
Wide FOV

- Glass or silicon substrates
- Planar or ellipsoidal mirrors
- Foils 3×3 mm to 300×300 mm
- Thickness from 30 µm – 1 mm
- Wavelength: EUV – soft X-ray
- Surface: Au, Ni, Mo, Pt, W, ...



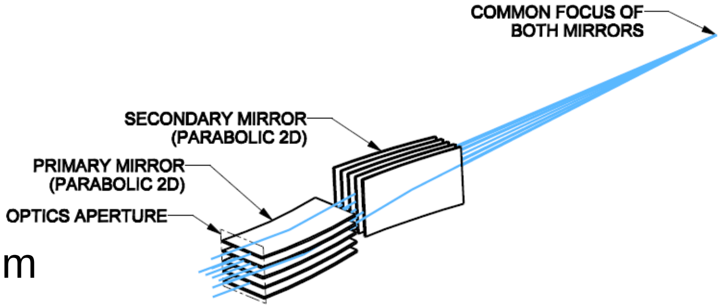
<u>Lobster Eye</u>

- 5 – 10 keV
- Focal length: 1000 – 1200 mm
- Imaging: 1:1
- Spot size: 0.5 mm
- FOV: 2°

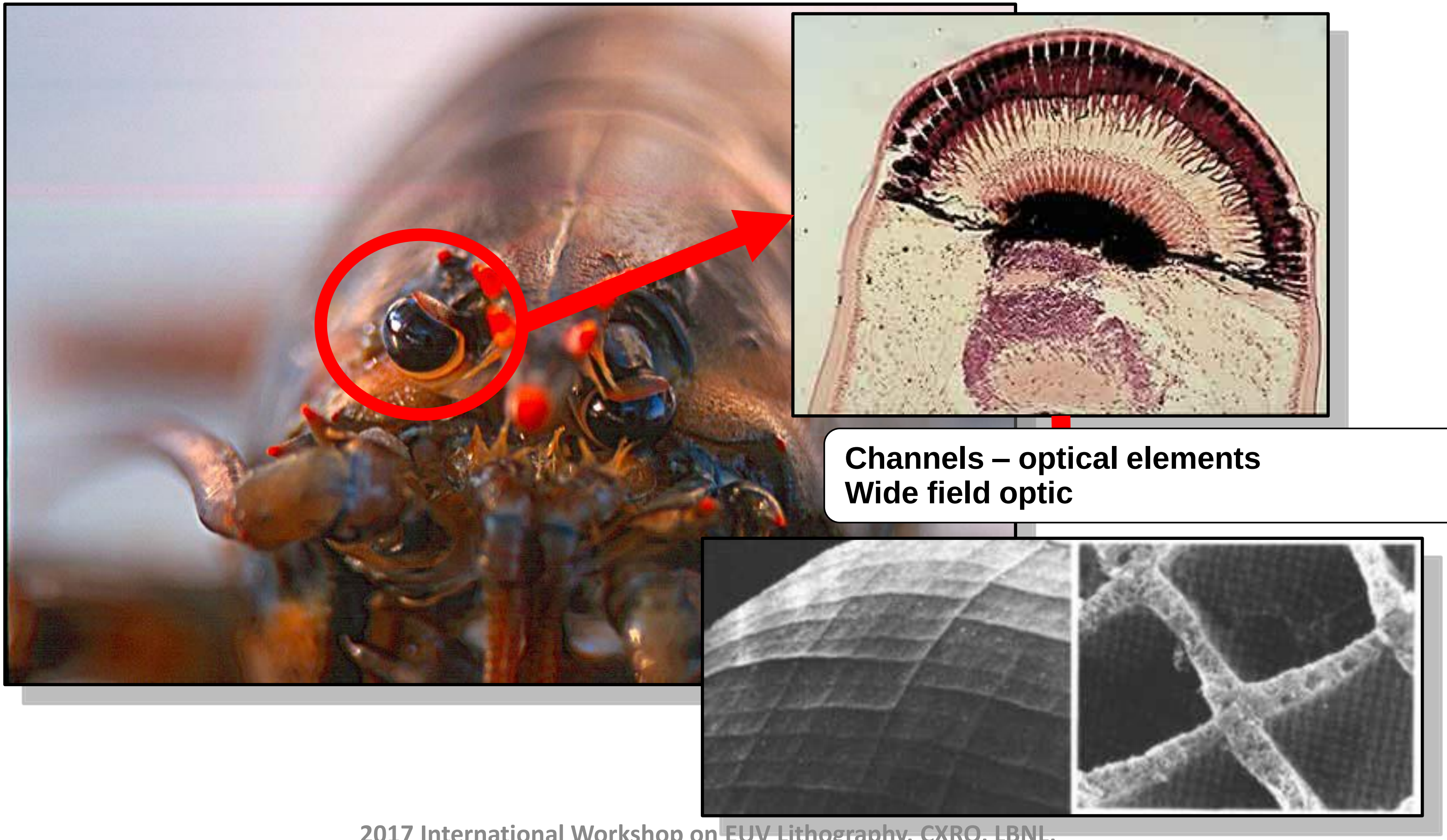


<u>MFO KB system</u>

- 80 – 120 eV
- FOV: 20°
- Spot size: 0.5 – 1.0 mm



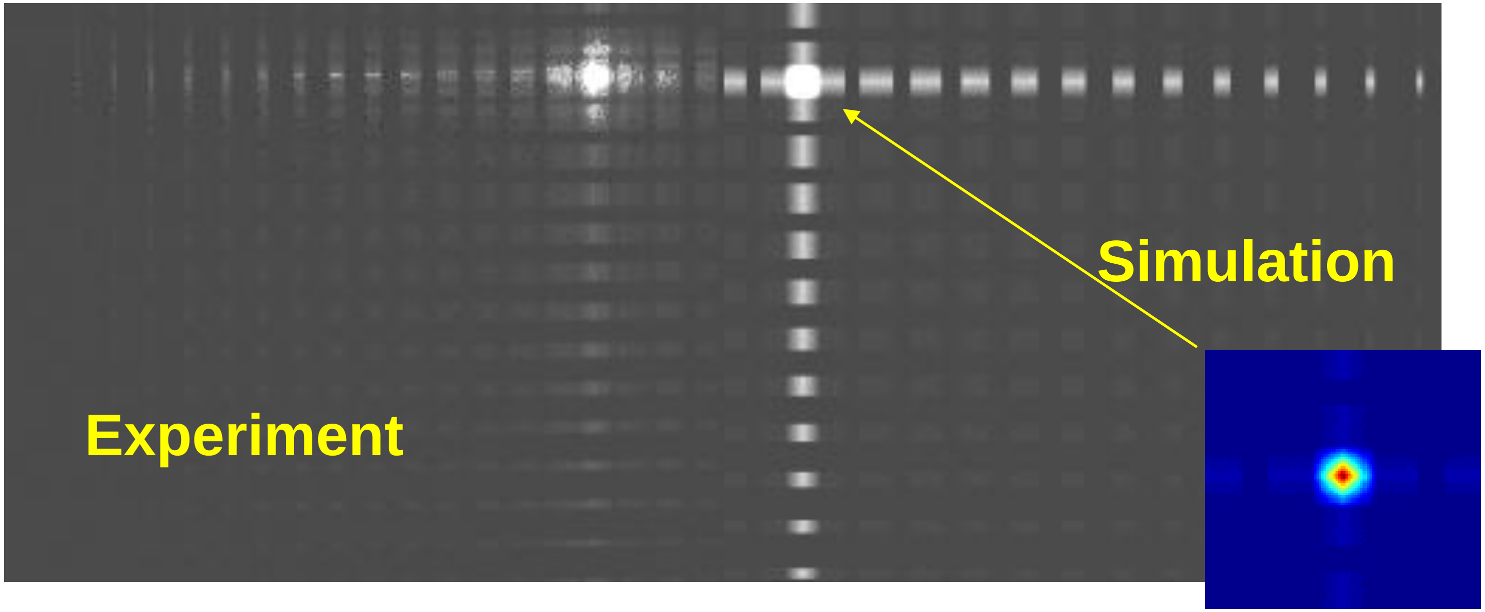
Lobster Eye



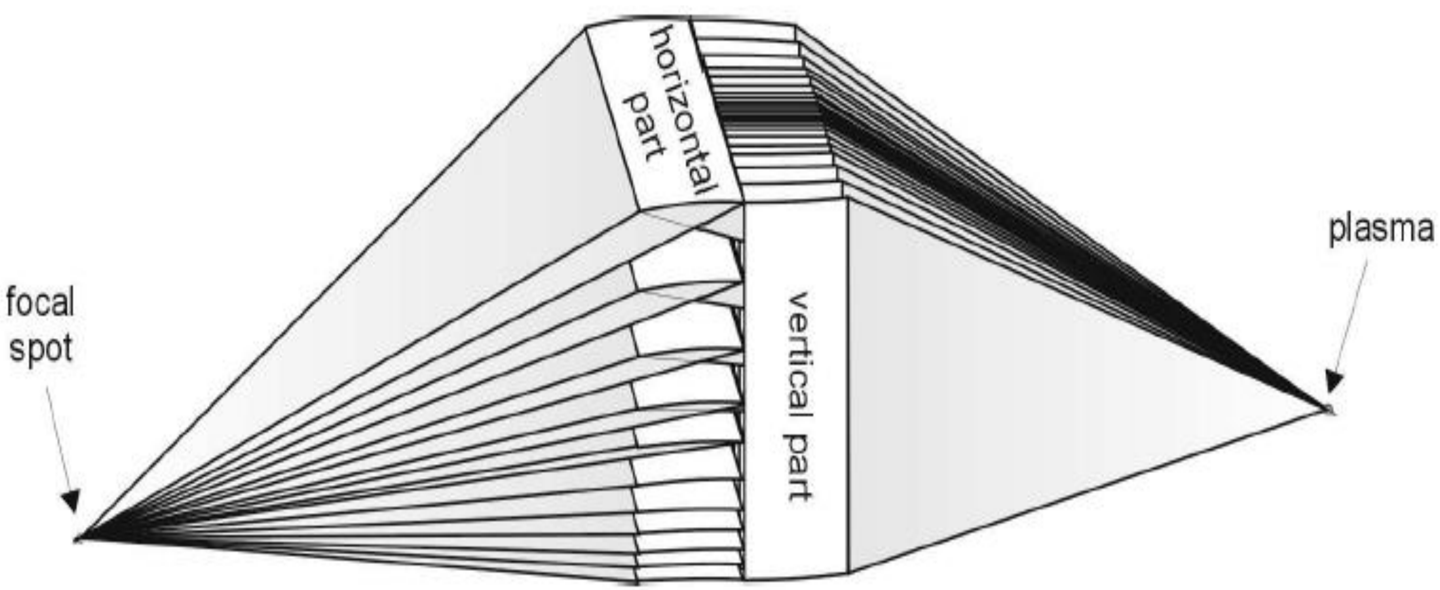
Channels – optical elements
Wide field optic

X-ray LE - experiment vs theory

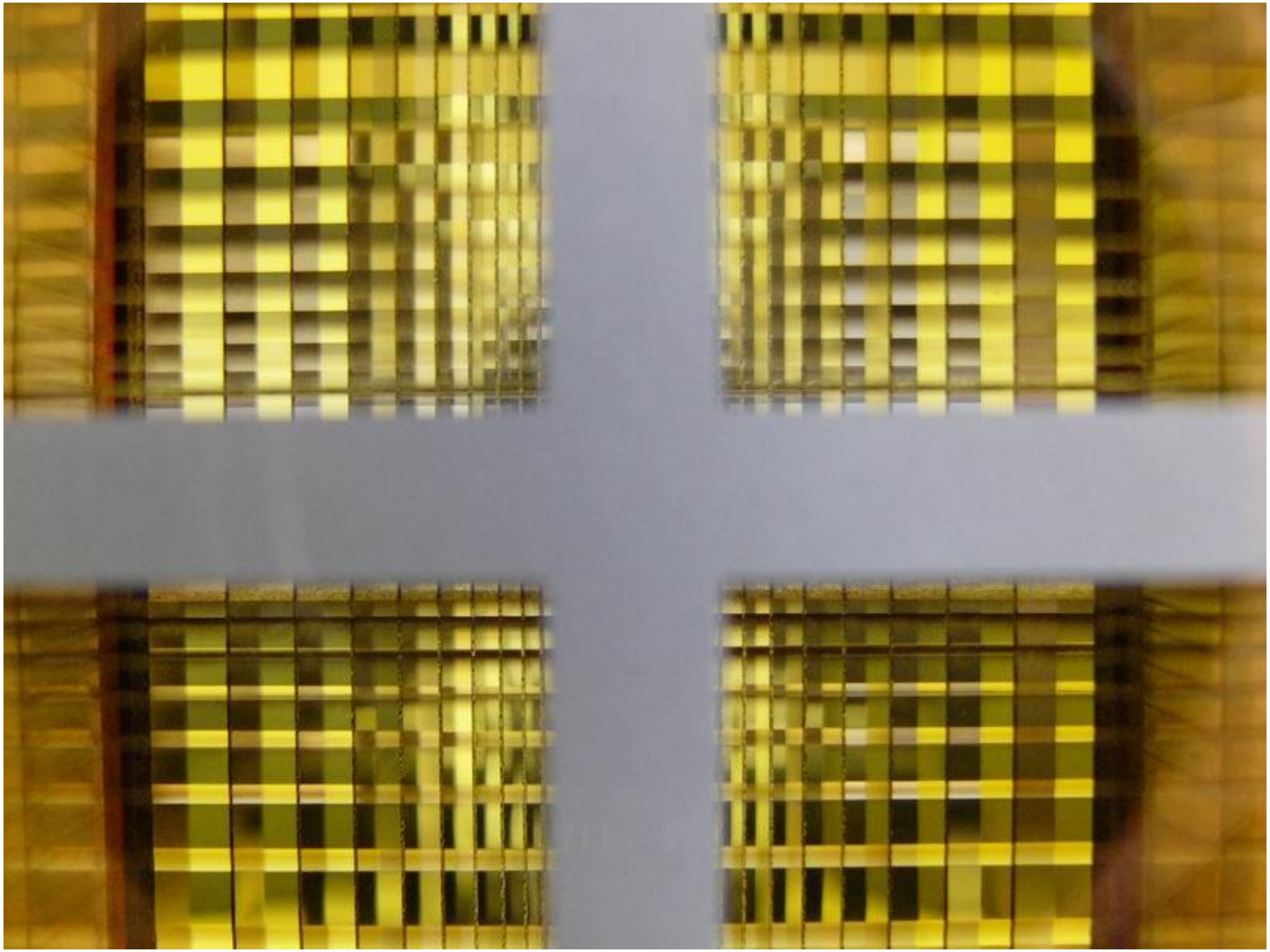
- Point-to-point focusing system
- Source: 20 μm size, 8 keV photons
- Source-detector distance: 1.2 m, 8 keV photons
- Detector: 512x512 pixels, 24x24 μm pixel size
- Intensity Gain: G=570 (experiment) vs. G=584 (comp. simulation)



Focusing of XUV radiation and XUV modification of materials (experiments at CTU, PALS and WAT)



Schematic view of one half of the multi–foil (MFO) XUV bifacial Kirkpatrick-Baez condenser – experiments at WAT, Warsaw.

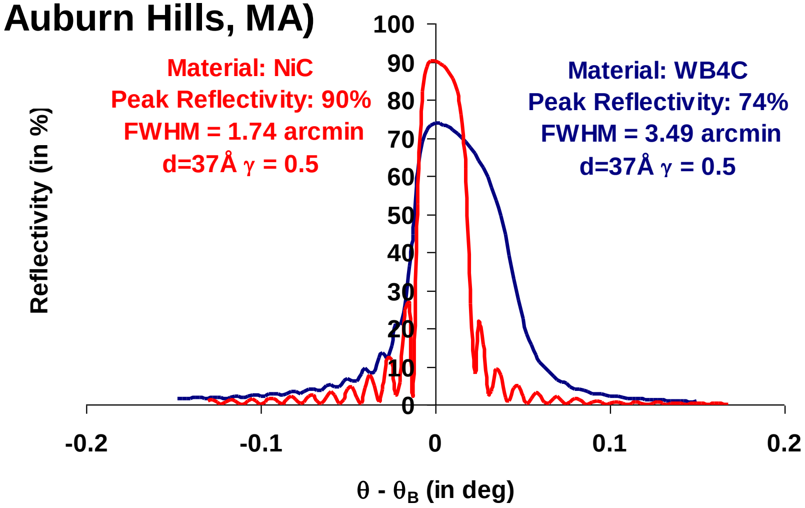


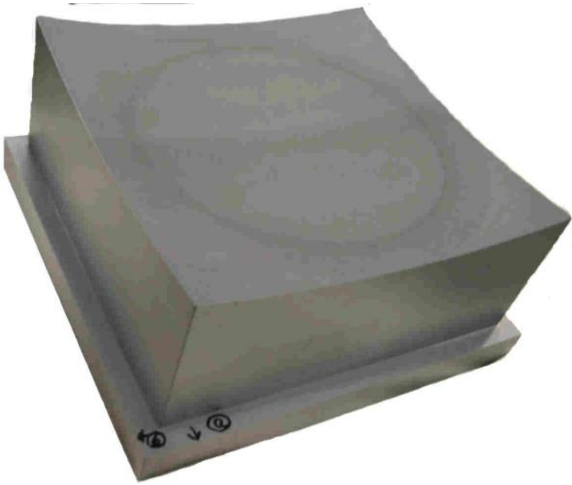
MF K-B system for EUV lithography

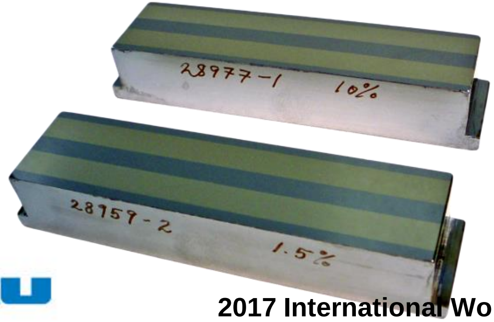
Multilayer optics

(Rigaku Innovative Technologies, Auburn Hills, MA)

- > 20 years of experience (Osmic)
- Design: uniform or graded (lateral, radial, bilateral 2D), depth graded, flat, curved, glancing ($< 1°$) to normal incidence
- Wavelength range: 40 eV – 40 keV
- Number of period: N_{max} = 1000
- Size: from 3 – 1500 mm
- ML period: d_{min} = 10 Å
- Spectral resolution: $\Delta\lambda/\lambda$ = 0.3% (high selective) – 20% (depth graded)
- Materials: W/Si, W/C, Ni/Ti, Ni/B_4C, Ni/C, Cr/C, Cr/Sc, Mo/Si, Mo/B_4C, V/C, Ru/B_4C, Al_2O_3/B_4C, SiC/Si, Si/C, SiC/C, Fe/Si, …

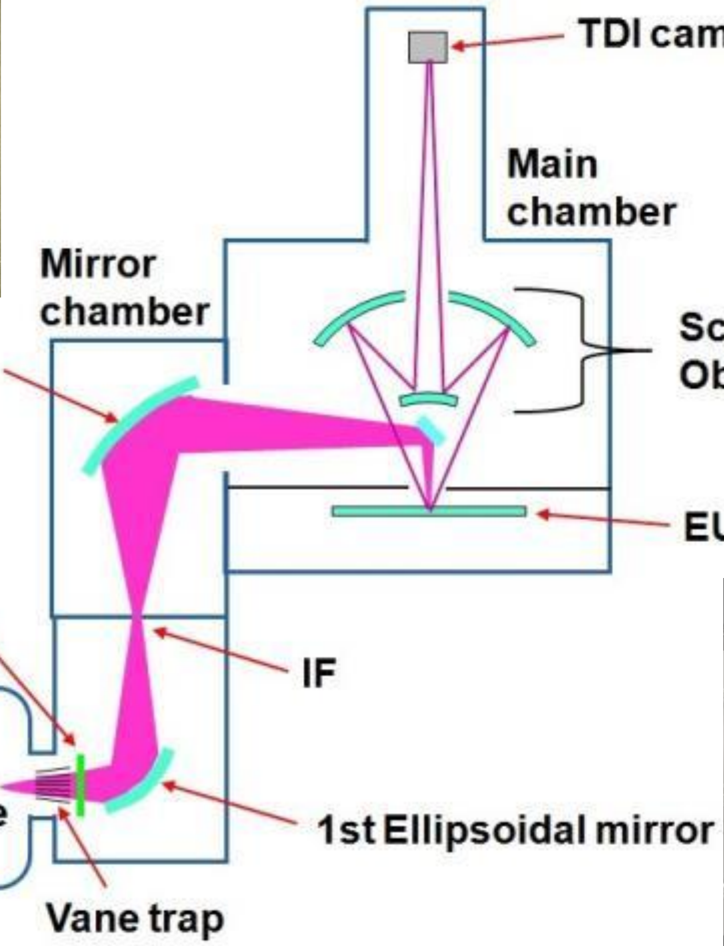






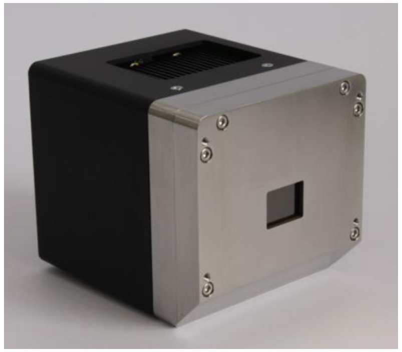
Multilayer optics

(Rigaku Innovative Technologies, Auburn Hills, MA)



Detectors

- High resolution X-ray detectors (small FOV)
- Medium resolution X-ray detectors (bigger FOV)
- X-ray diode detectors
- pA - meters



QUANTUM EFFICIENCY MEASUREMENTS (photon number)

PARAMETER	Ar data	N_2 data
SXR flux (photons/pulse) @ 1.1 m from source	(4.64±0.71)E+8 QE=106.83	(3.01±0.34)E+06 QE=119.5
SXR flux (photons/pulse) @ Ce:YAG plane (N_{inc})	(1.48±0.23)E+11 QE=106.83	(9.60±1.08)E+8 QE=119.5
Scintillated light flux (N_{sc}) (photons/pulse), QE=0.6	(1.03±0.15)E+10	(1.86±0.2)E+08
Nd:YAG scattered photon flux, QE=0.22	(1.29±0.04)E+9	(1.29±0.04)E+9
Photon efficiency $=N_{sc} / N_{inc}$	6.9%	19.4%

THANK YOU FOR ATTENTION

Prague