Laboratory EUV/SXR
Grazing Incidence Optics and Metrology

Ladislav Pina,

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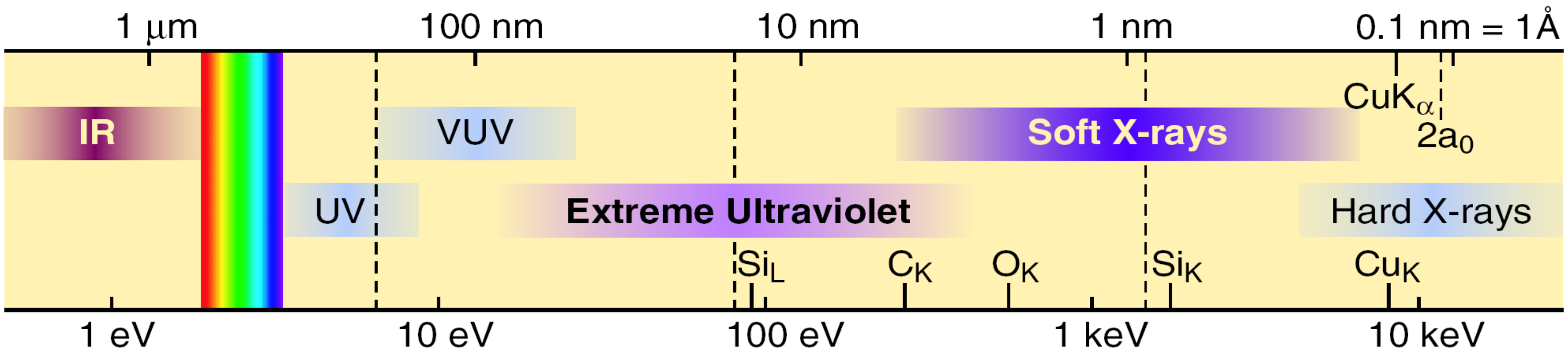
Electromagnetic radiation spectrum



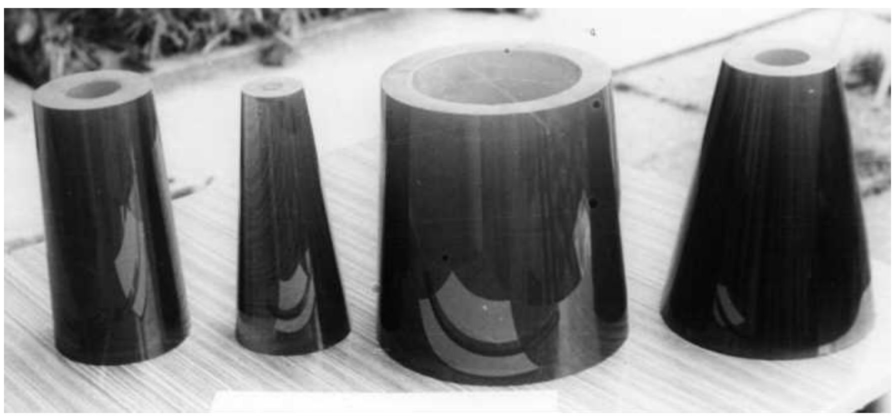
D. T. Attwood *Soft X-rays and Extreme Ultraviolet Radiation: Principles and Applications* (Cambridge University Press, Cambridge, 1999)

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 and Tomography**
5 – 17 keV	**X-ray Microscopy and Tomography**

Grazing Incidence (GI) electroformed X-Ray Optics

50 years of X-ray mirrors research and development in Prague

Electroforming Technology for X-ray Optics Manufacturing



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

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

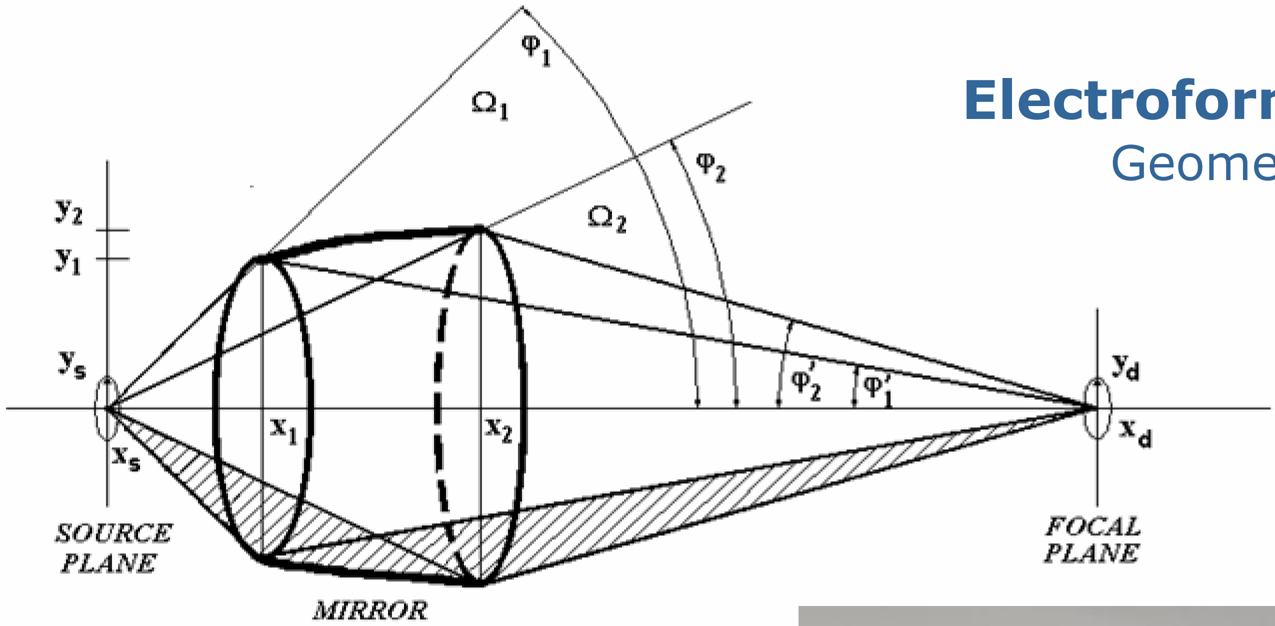
History – milestones and examples of projects

(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 < 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 – 2019 EUV/BEUV/WW/SXR/XR Grazing Incidence mirrors ...**

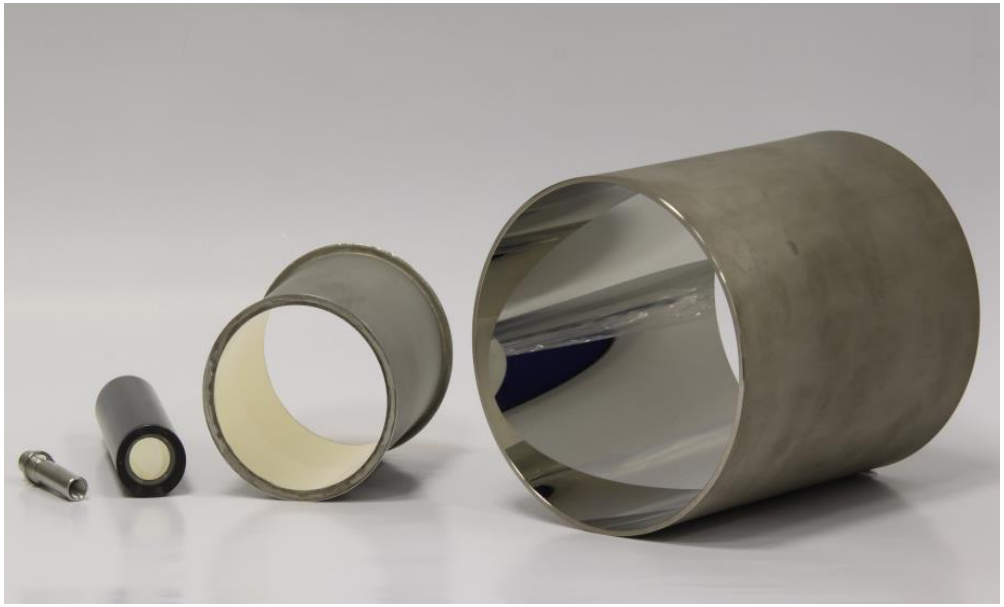
Electroformed GI Mirrors

Geometry and size

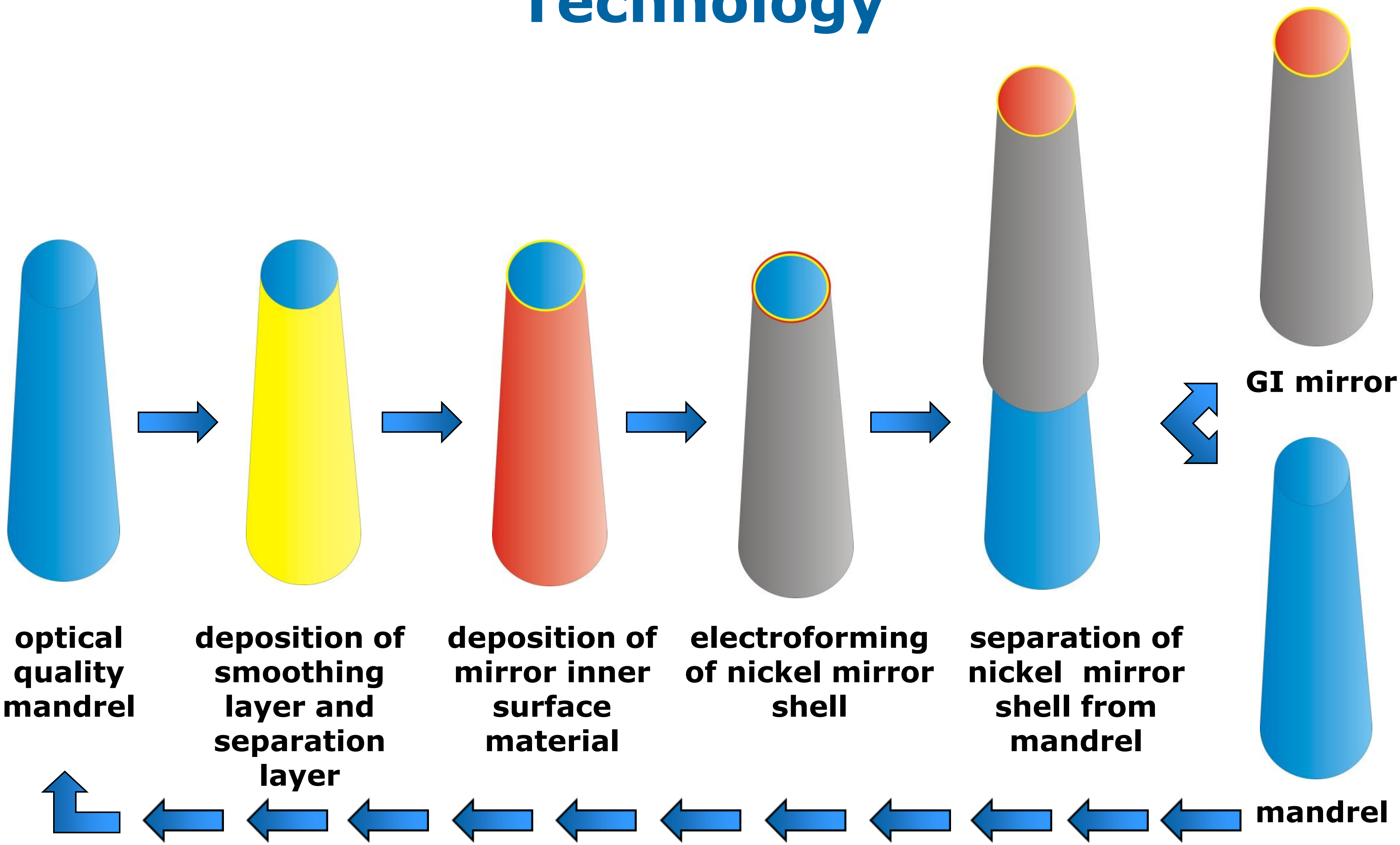


Example: Ellipsoidal mirror

- **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**



Electroforming and Replication Technology



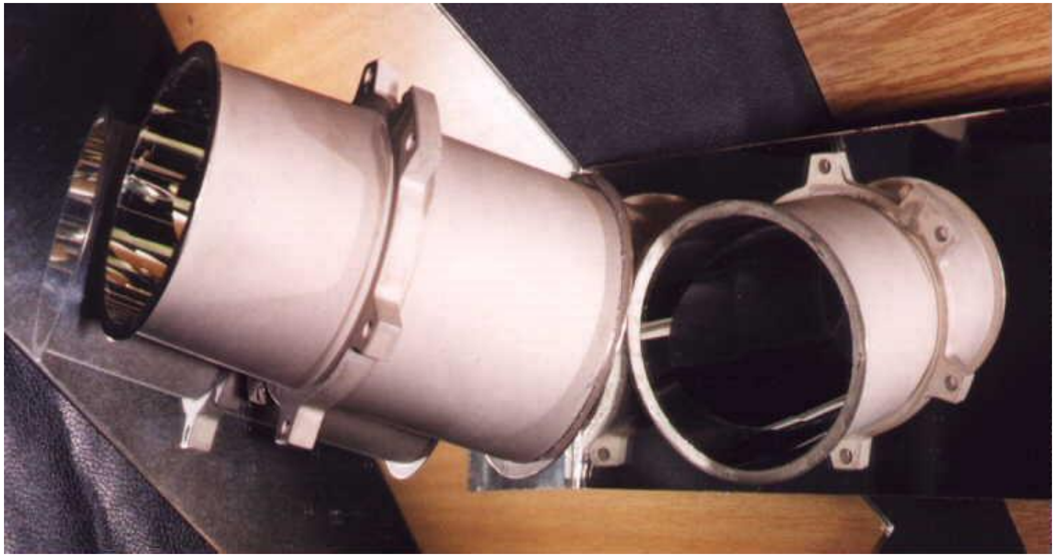
For quality reasons number of mirrors replicated from one mandrel might be limited

Electroforming and Replication Technology

MANDREL
with Au surface layer

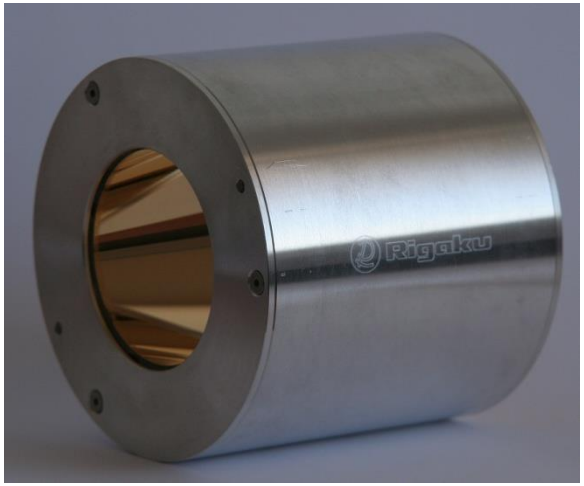
Ellipsoidal mirror for spectral region
10 – 15 nm

Electroforming and Replication Technology



Electroformed Wolter X-ray Mirrors for Space Research (aperture 80 mm)

Electroformed X-ray Mirror for XRD (input aperture 0.4 mm, 8 keV, grazing angle 0,5°)



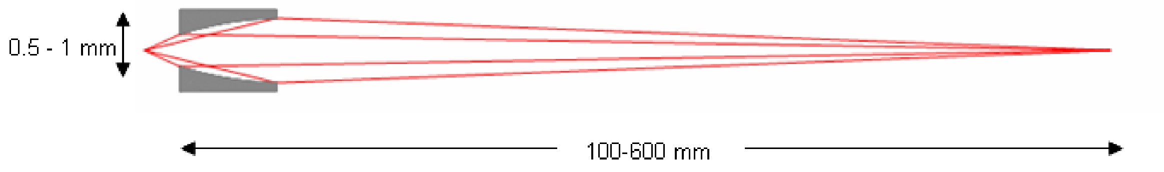
Electroformed EUV Condensor for Laser Plasma Research and EUV Litography

GI mirrors now designed and manufactured by Rigaku Innovative Technologies Europe s.r.o.

- A part of Rigaku Corporation group (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 (LPP and DPP research, EUVL, WW and X-ray microscopy, SXR spectroscopy, space, …)
- Slope error < 10 arcsec (3“), microroughness < 2 nm (0.2 nm)

Ellipsoidal and Parabolic GI Micromirrors

- Apertures as small as 0.4 mm dia
- Mirrors optimised for 8 keV
- Grazing angle 9.5 mrad at the mirror input
  (Au coated reflecting surface)
- Au or Ni surface
- Convergence / Divergence lower than 1.5 mrad (ellipsoidal mirrors)
- Convergence / Divergence lower than 0.1 mrad (parabolic mirrors)



Electroformed GI Mirrors

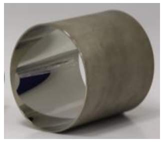
Ellipsoidal GI mirror for WW application (2.3 – 4.4 nm)

Ellipsoidal GI mirror For EUVL applications (10-15 nm)

GI EUV Mirrors

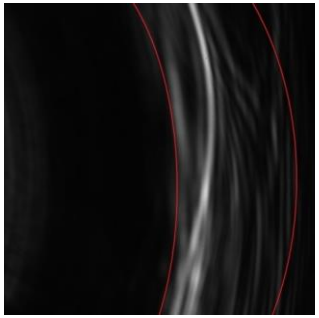
Current design and production requests

- For optics e.g. consisting of several shells:



  i. Length tolerances 0.1 mm or less
  ii. Aligning of the optic shells in regards to each other
  iii. Wall thickness of the individual shells
    - Wall thickness is an issue if you have to stabilize strain and stress in the optics and its inner surface. The thinner the more strain and stress, the less precise the shape and location of the focal spot.
    - For 'older' applications like Wolter telescopes or single shell optics for EUV we traditionally produce thicker-wall optics.
    - For 'modern' applications like for soft X-rays in spectroscopy lab instruments we now produce thin wall optics with about **80 µm wall** thickness. This gives challenges to handle the optics but also additional strain and stress challenges.

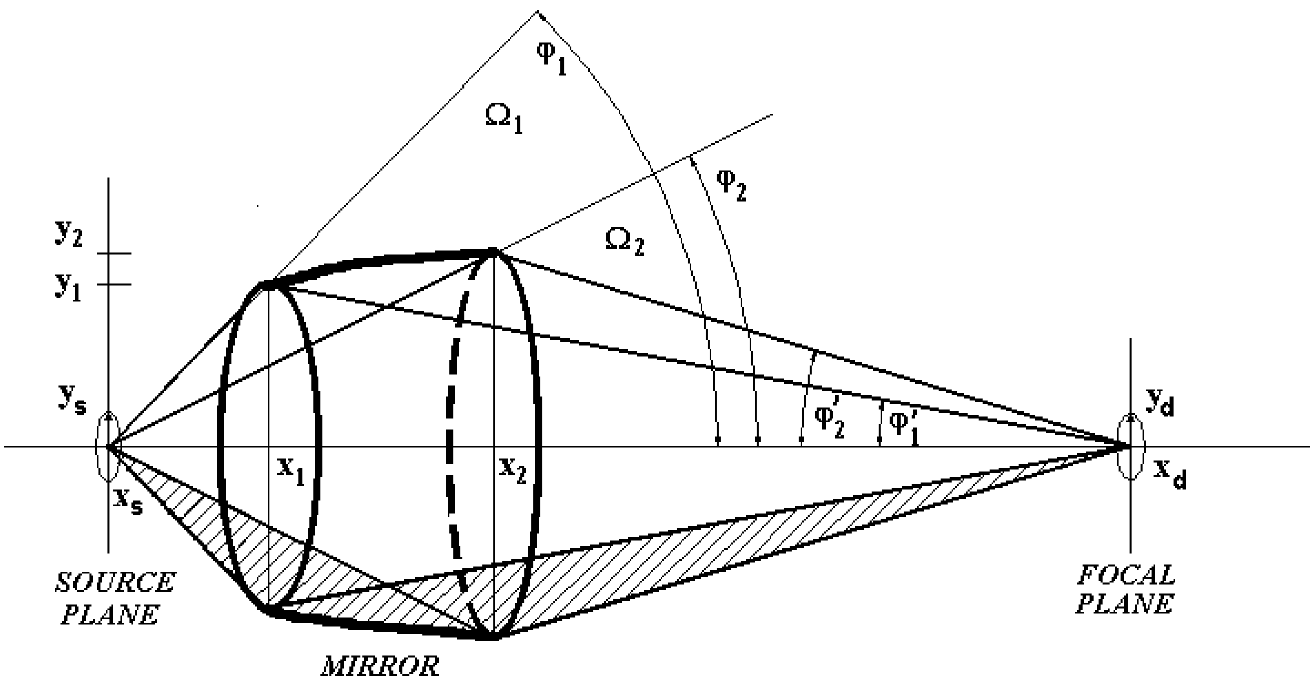
(a) Non stabilized stress in the shells



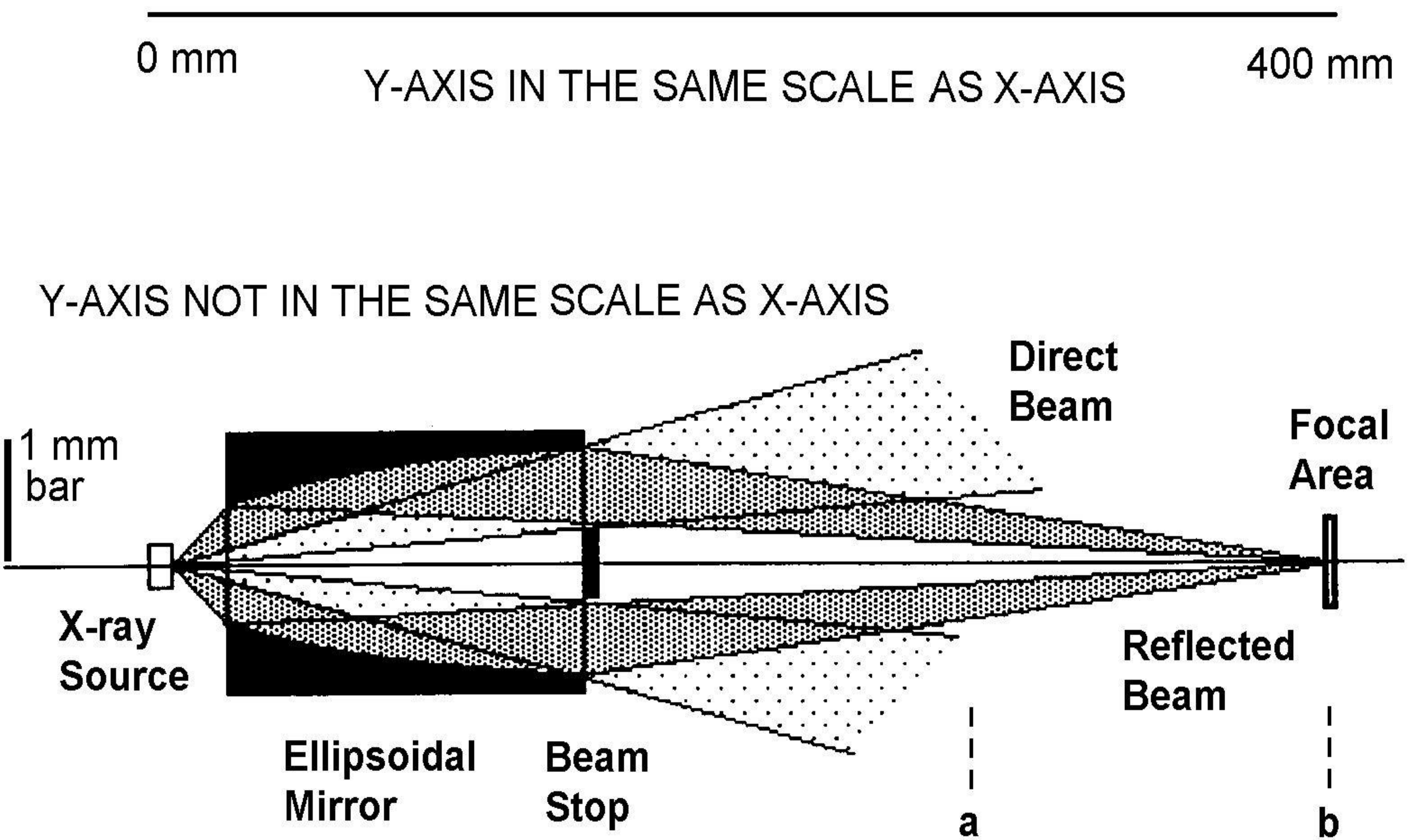
(b) Stabilized stress in the shells

Electroformed GI Mirrors Focusing and Spectral Analysis

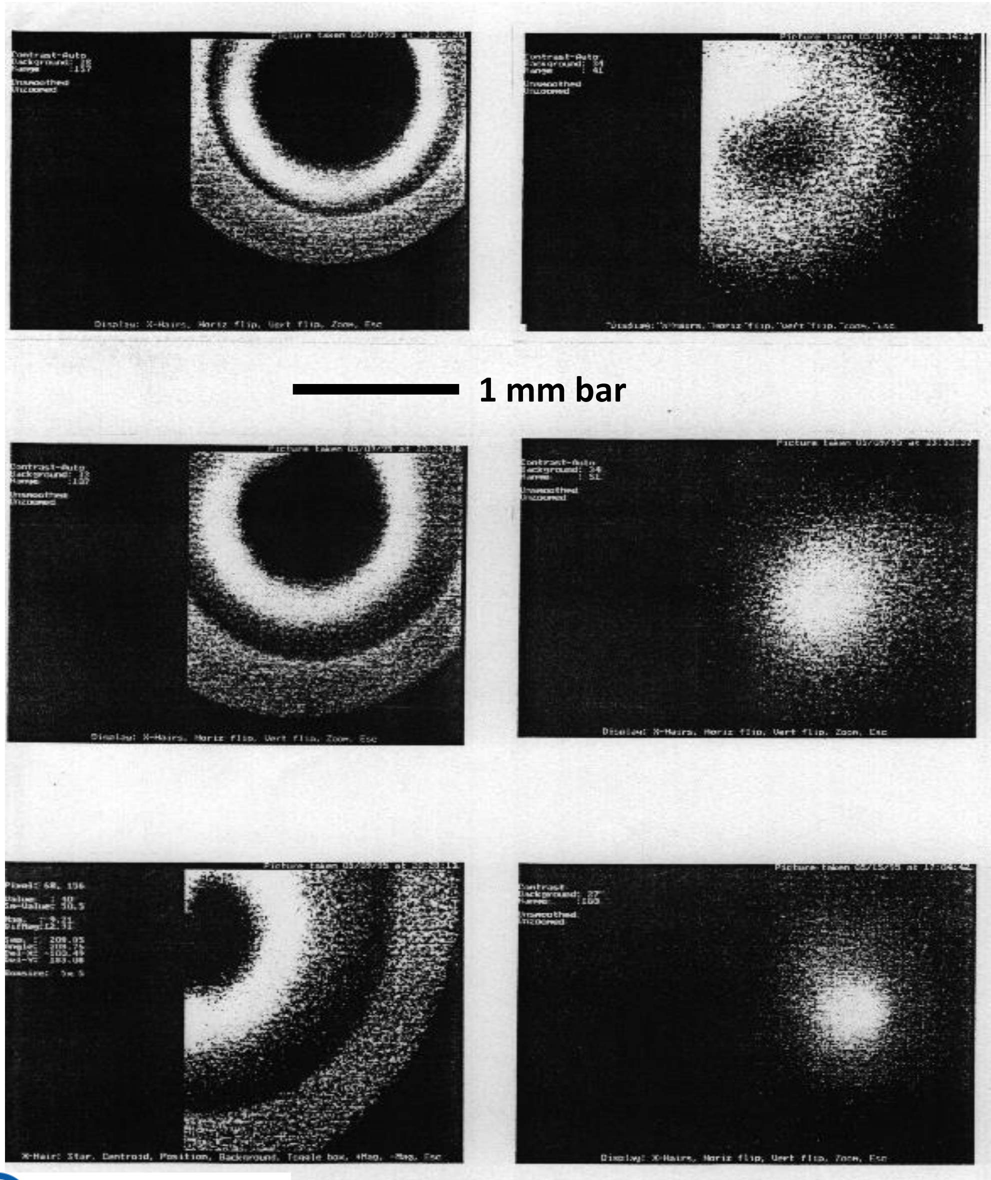
ELLIPSOIDAL MIRROR



Ellipsoidal mirror for 8 keV microfocus source



Ellipsoidal mirror for 8 keV microfocus source

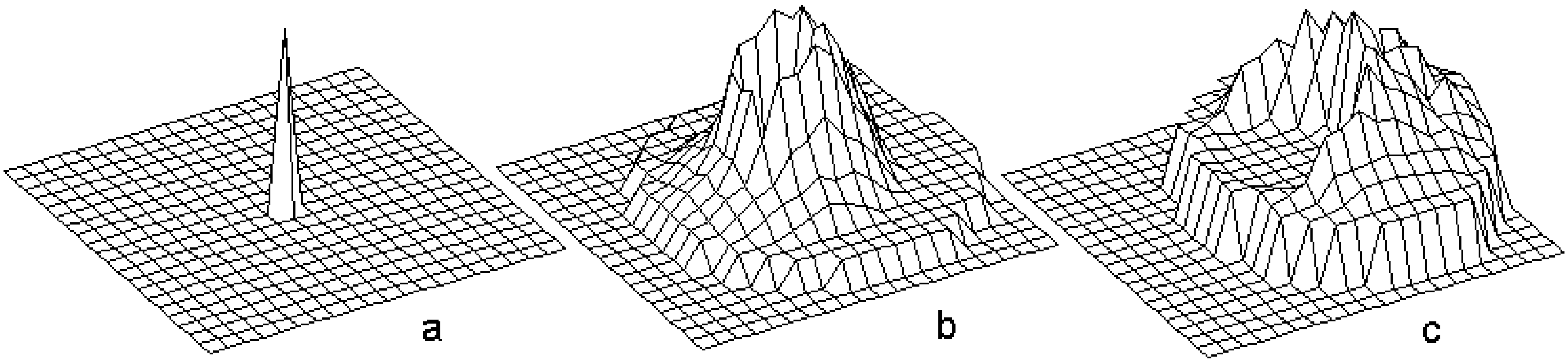


A series of X-ray beam images behind the output of ellipsoidal mirror with beam stop on the axis.

Converging reflected beam and diverging direct beam are clearly distinguishable.

Ellipsoidal mirror for 8 keV microfocus source

Focal spots for off-axis source position (ray-tracing model)

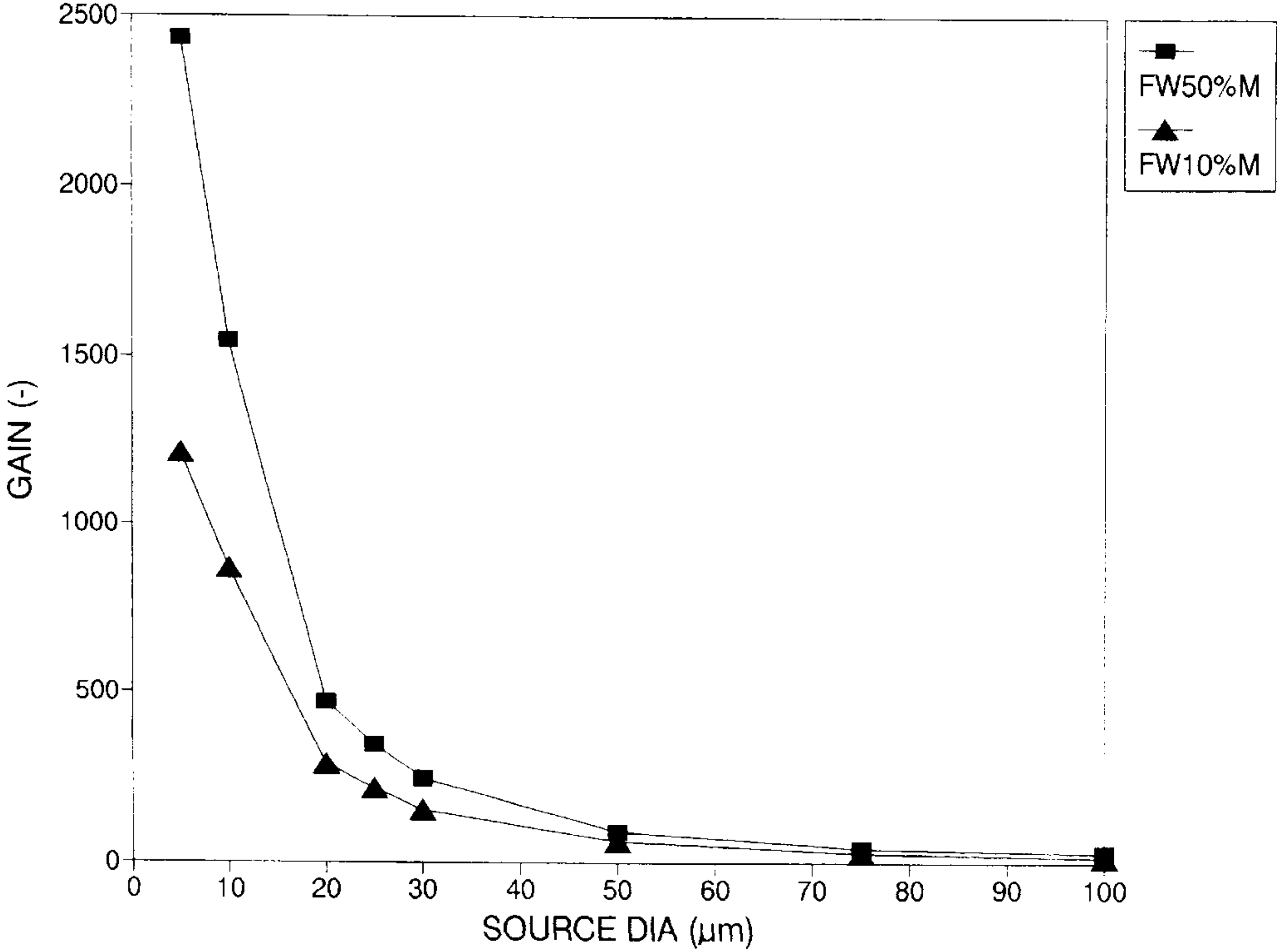


Graphs a to c showing the effect of point-like X-ray source off-axis displacement on the detector intensity distribution for ellipsoidal mirror.

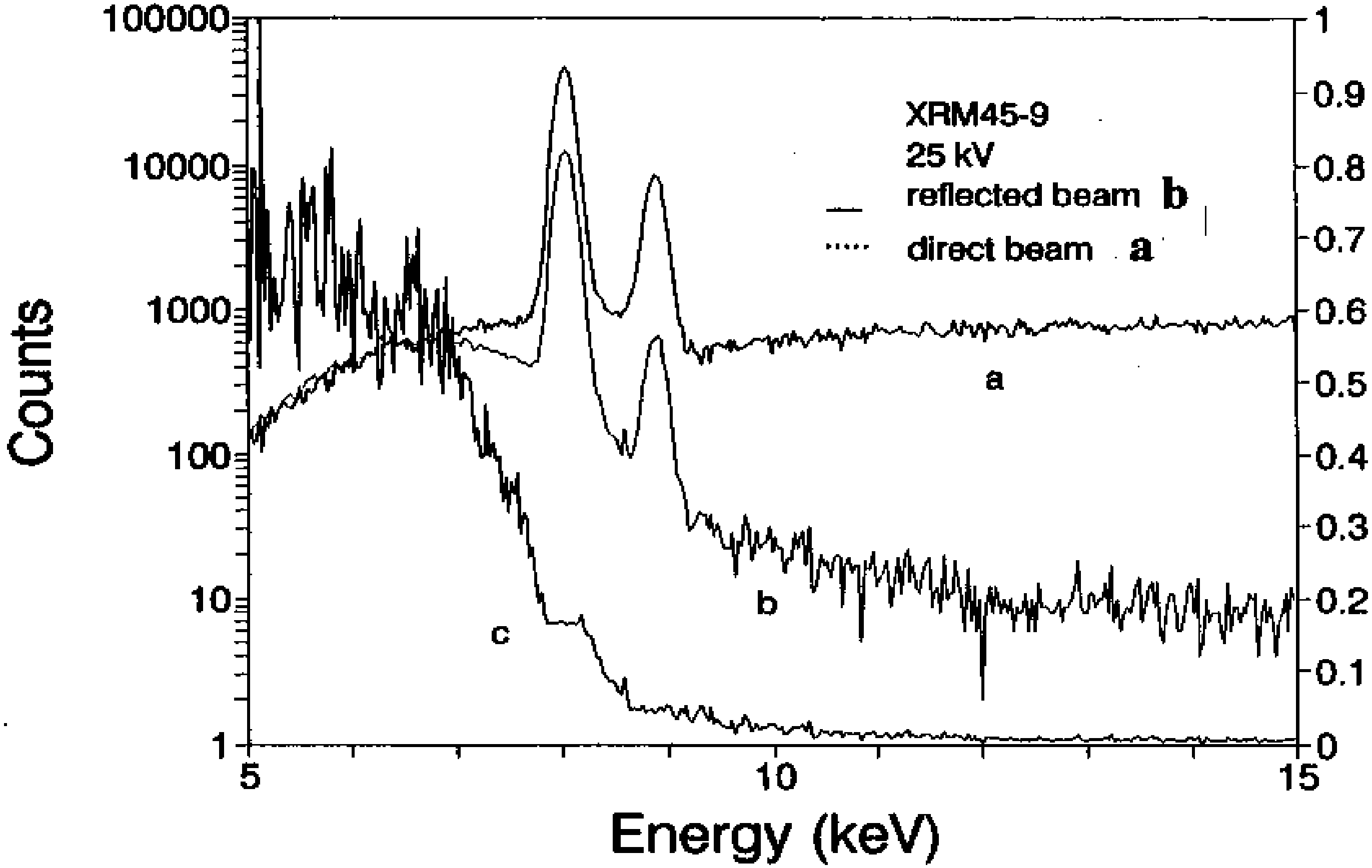
a – 0 um source displacement,
b – 200 um displacement,
c – 400 um displacement.

Ellipsoidal mirror for 8 keV microfocus source

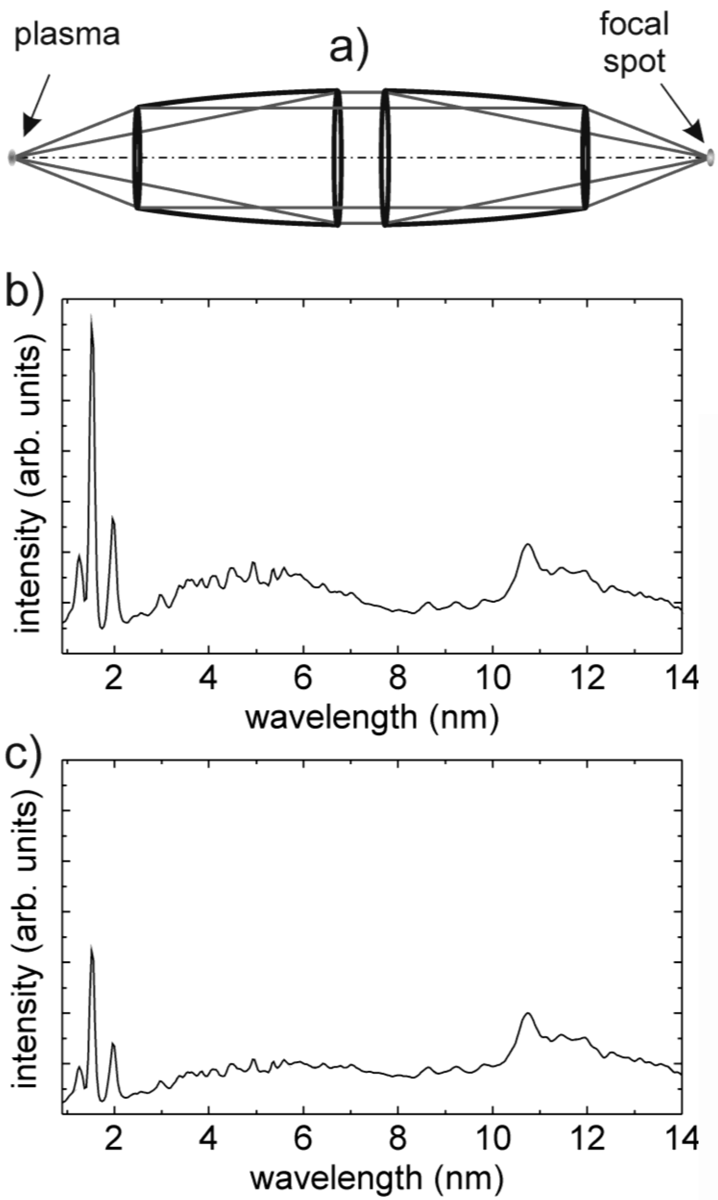
Intensity gain as an X-ray source size function (ray-tracing model)



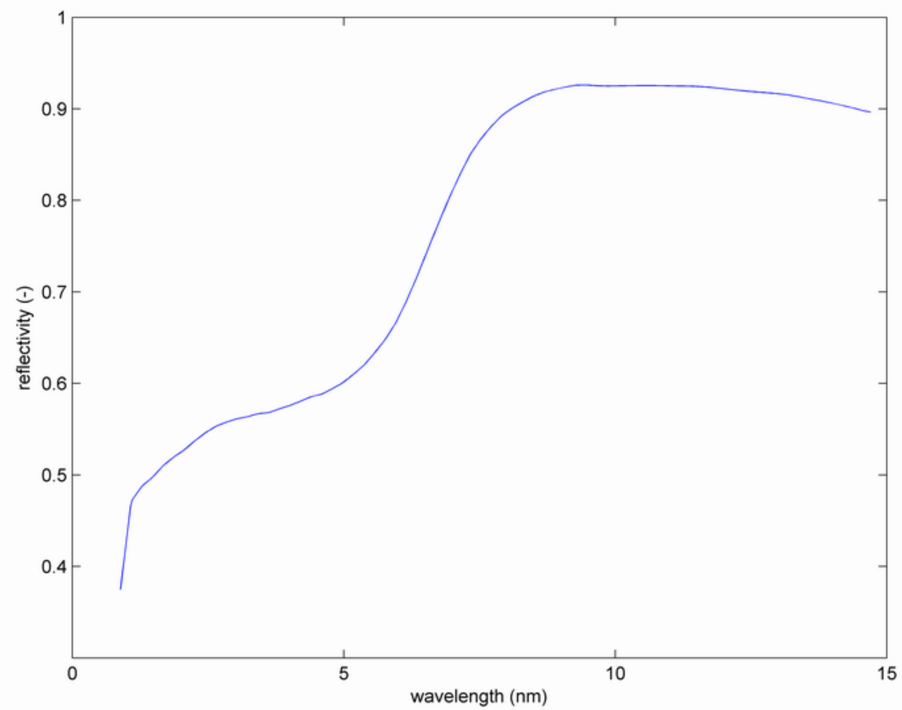
Measurement of XR GI mirror spectral reflectivity



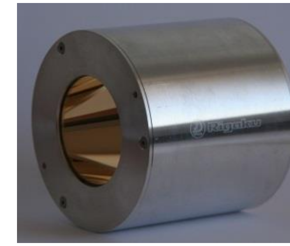
Measurement of SXR GI mirror spectral reflectivity

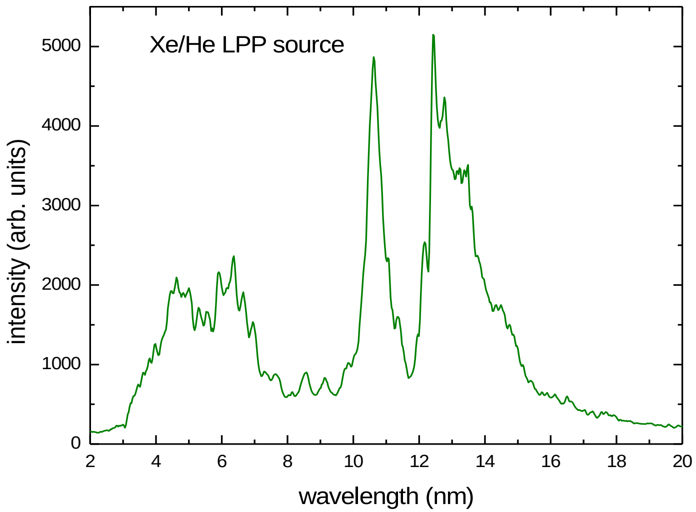


(a) Schematic view of the paraboloidal collector
(b) Spectrum of the unaltered Xe plasma radiation
(c) Spectrum of Xe plasma radiation focused using the paraboloidal collector
(d) Calculated spectral reflectivity in 1-15 nm range



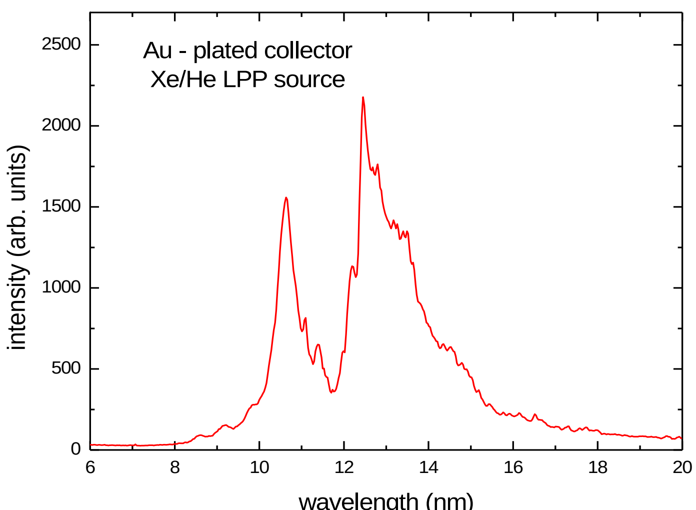
Comparison of Au and Ru coated EUV collector reflectivity

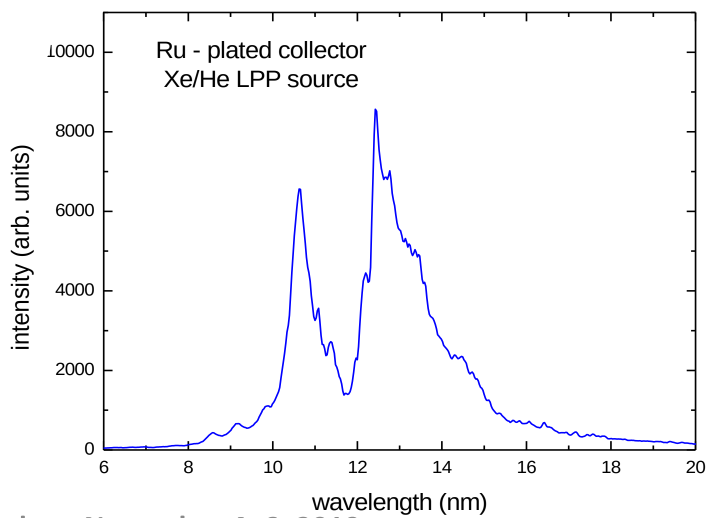




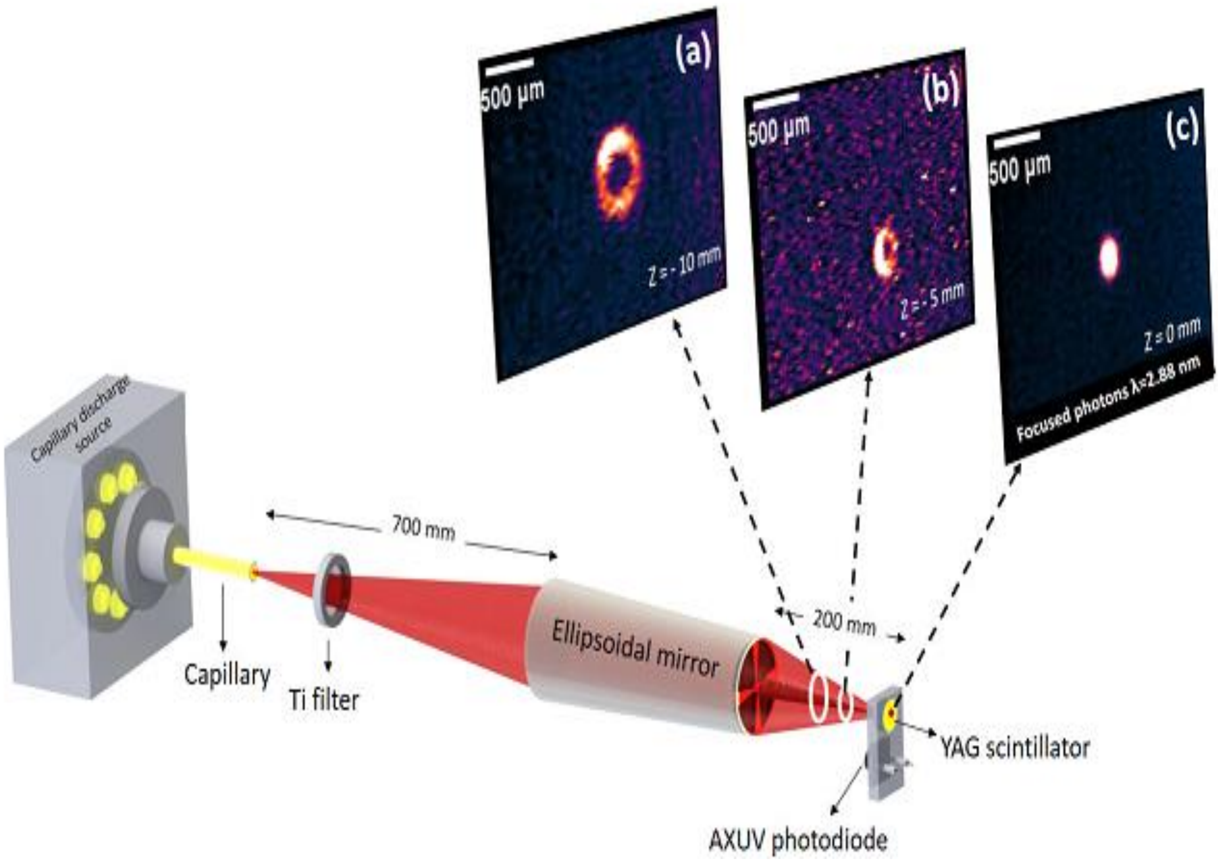
Spectra of Xe/He plasma radiation:

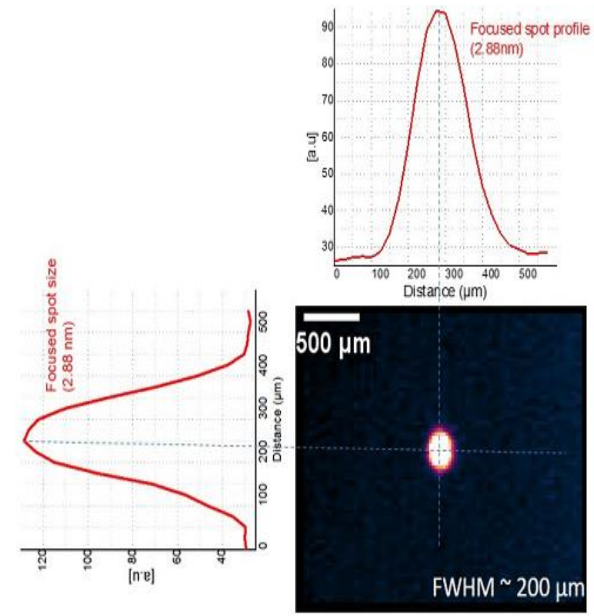
- **a) Xe plasma emission**
- **b) Radiation reflected from the Au coated collector surface**
- **c) Radiation reflected from the Ru coated collector surface**





DPP source and condensor metrology
(images of focused beam)





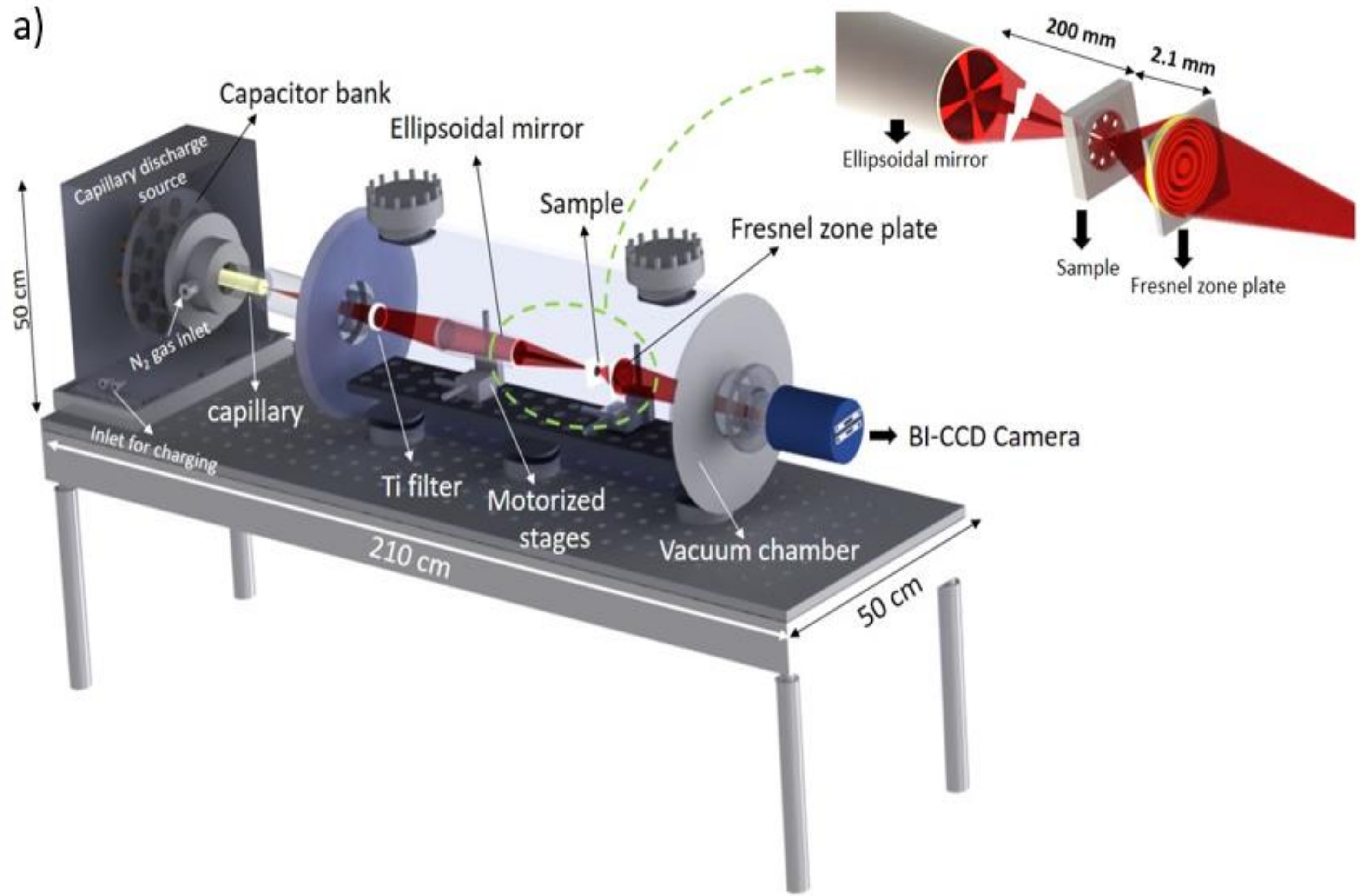
Focal spot image
(λ=2.88 nm)

M. Fahad Nawaz, A. Jancarek, M. Nevrkla, P. Wachulak, J. Limpouch, L. Pina, " Focusing and photon flux measurements of the 2.88 nm radiation at the sample plane of the soft X-ray microscope, based on capillary discharge source", Proc SPIE 2015,p. Art No. 951014.

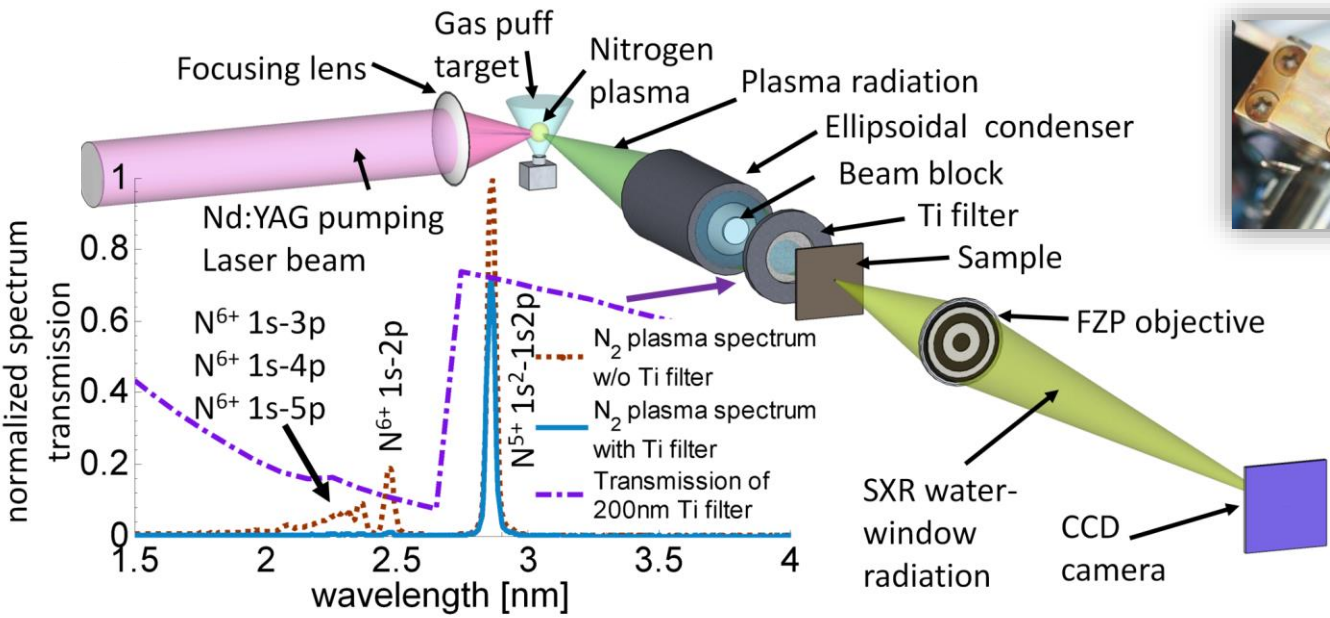
Electroformed SXR GI Mirrors Application Examples

(industrial commercial applications excluded due to NDAs)

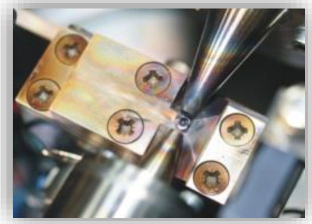
EUV microscope with capillary discharge plasma source (Nitrogen, λ = 2.88 nm), ellipsoidal grazing incidence condenser and Fresnel Zone objective (Czech Technical University in Prague)



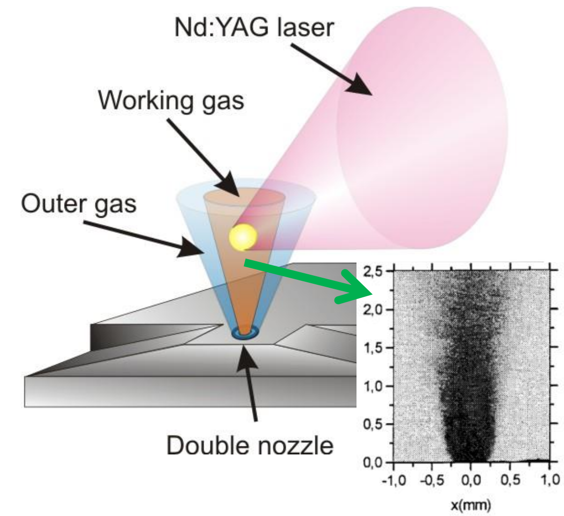
Fresnel Zone plate based SXR microscope experimental setup

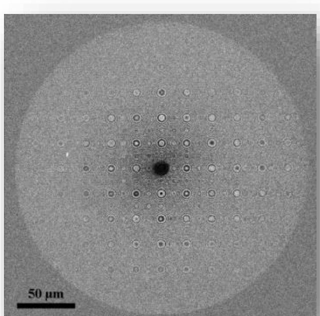


Scheme of the setup and spectrum of the nitrogen plasma source



Double stream N_2/He gas puff target, N_2= **8 bar**, He = **6 bar**



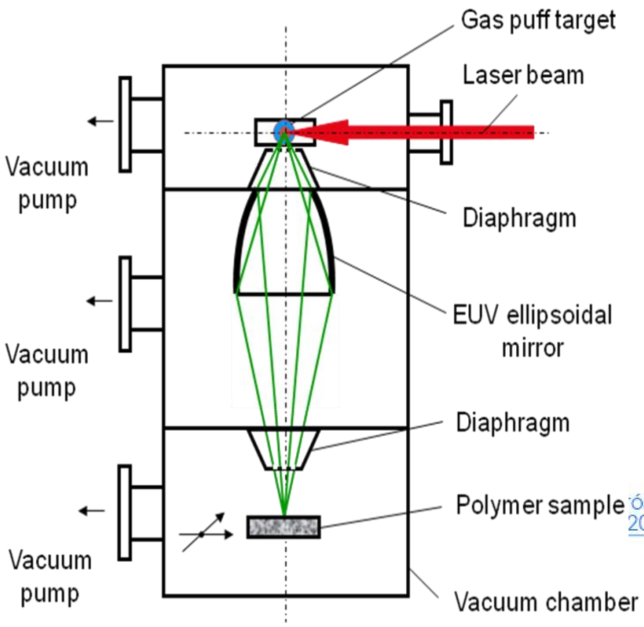


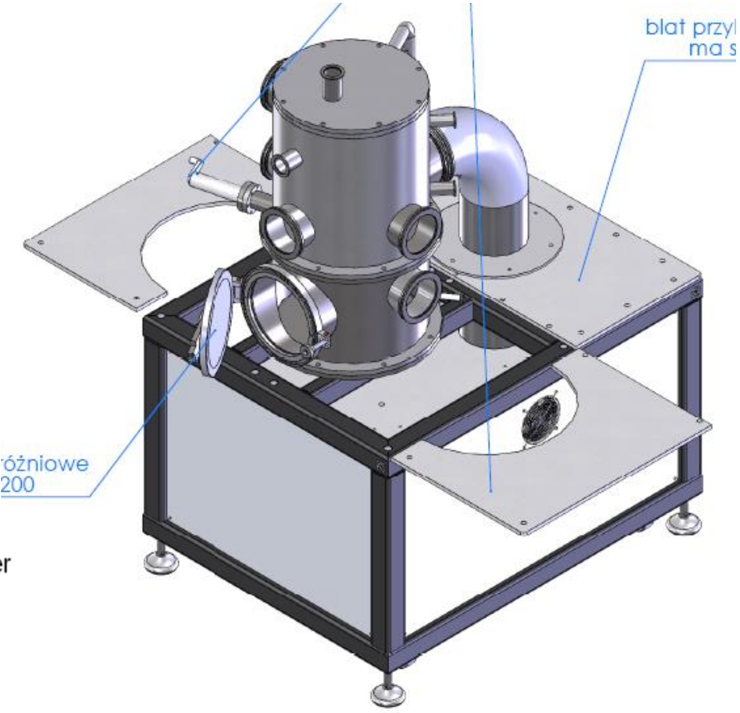
FZP objective **:
Si_3N_4 zoneplate **400 nm** thick
D = **250 um**, dr = **30 nm**,
f = **2.6 mm**, λ = **2.88 nm**, NA_{O_in}= **0.048**
magnification: **220x-600x**

Number of photons: ~(7.9+/-0.2)x10^9 /pulse @ λ=2.88 nm
Energy: (561+/-17) nJ/pulse at 10 Hz repetition rate
Inverse relative bandwidth (FWHM): λ/Δλ ~ 70, (spec. limit)
Plasma size: ~310x470 um^2

Laser plasma EUV source for processing polymers

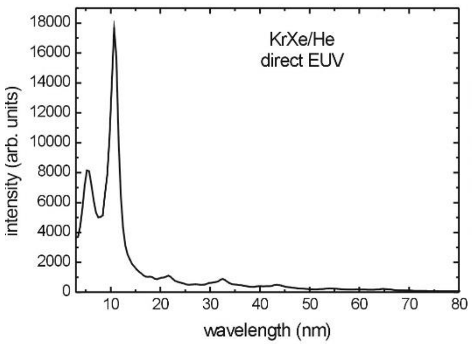
Laser plasma EUV source dedicated for processing polymers has been designed at IOE and was built in co-operation with EKSPLA, RIGAKU and PREVAC high-tech companies

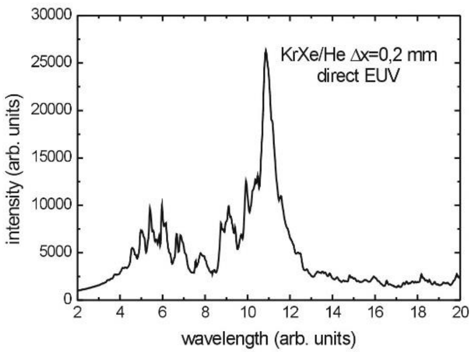




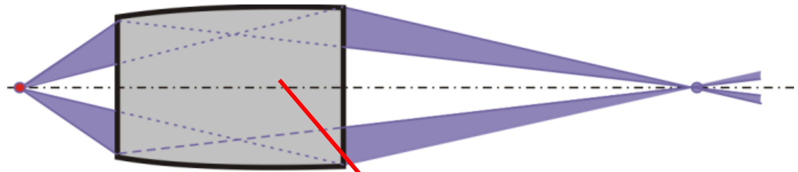
Bartnik et al. *Nucl. Instr. Methods A* 647 (2011) 125

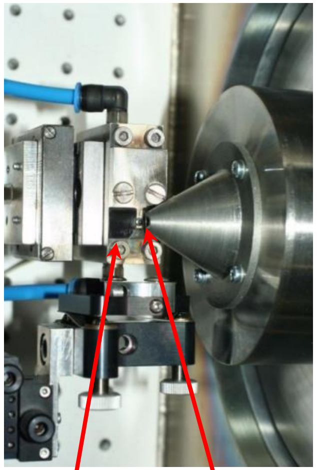
Laser-plasma produced EUV source: laser 0.8 J / 4 ns

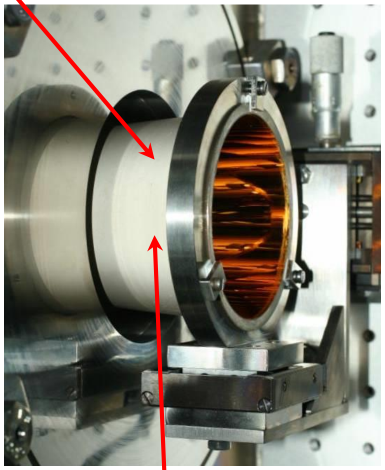




Low and high resolution EUV spectra of plasma radiation



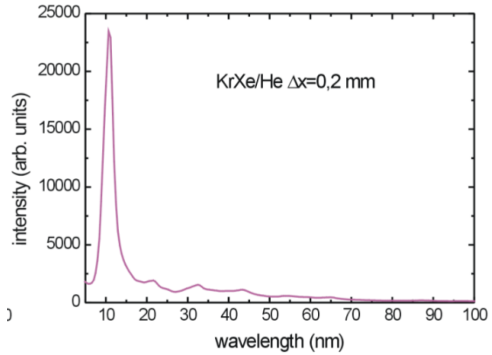


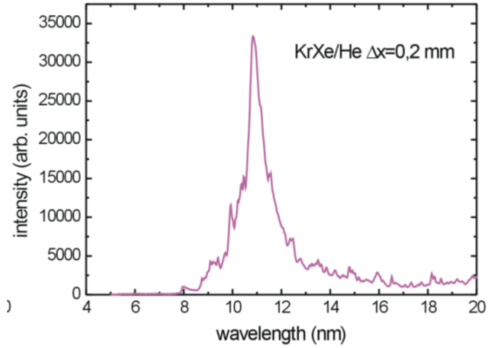


Gas puff valve

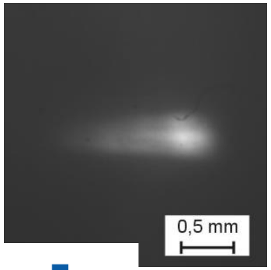
Orifice for differential pumping

Ellipsoidal EUV collect**or**

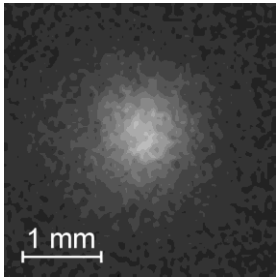




Low and high resolution EUV spectra of reflected radiation

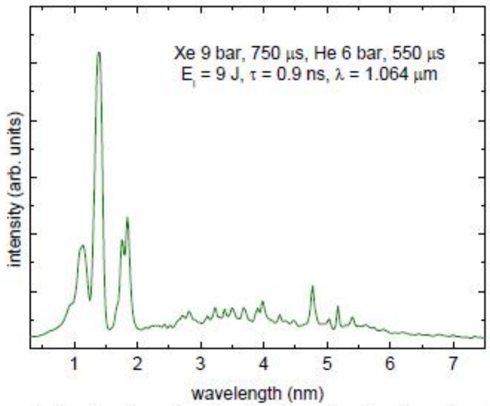


Plasma image



Focal spot image

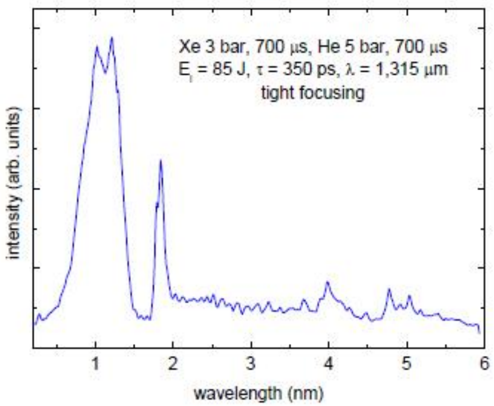
Focusing system prepared for a soft X-ray plasma source based on Xe gas target, driven by a 10 J/ 1ns/ 10 Hz Nd:YAG laser system



10J laser system

IOE, Warsaw

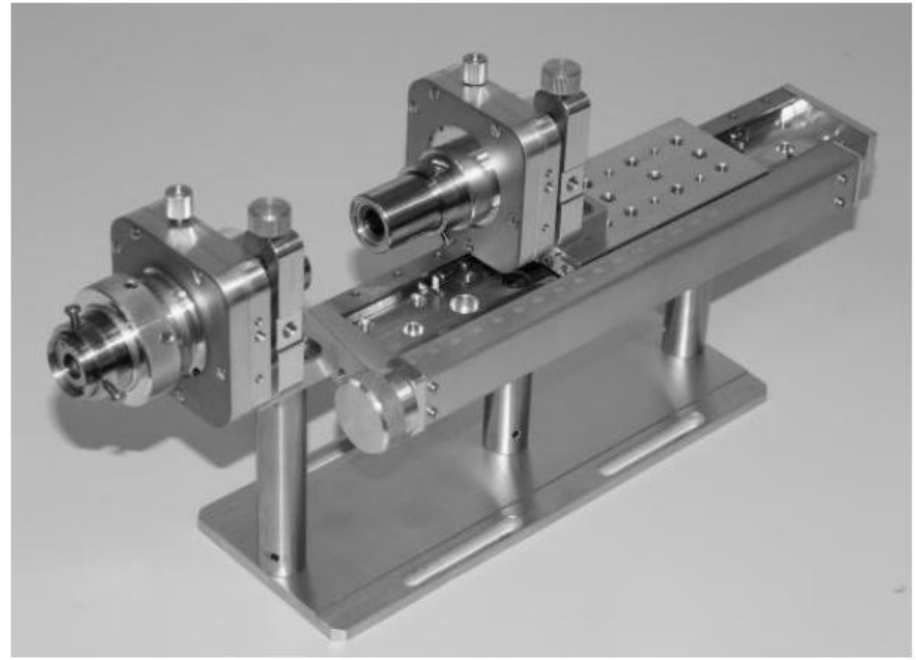
Spectrum for 9J



600J laser system

PALS , Prague

Spectrum for 85J



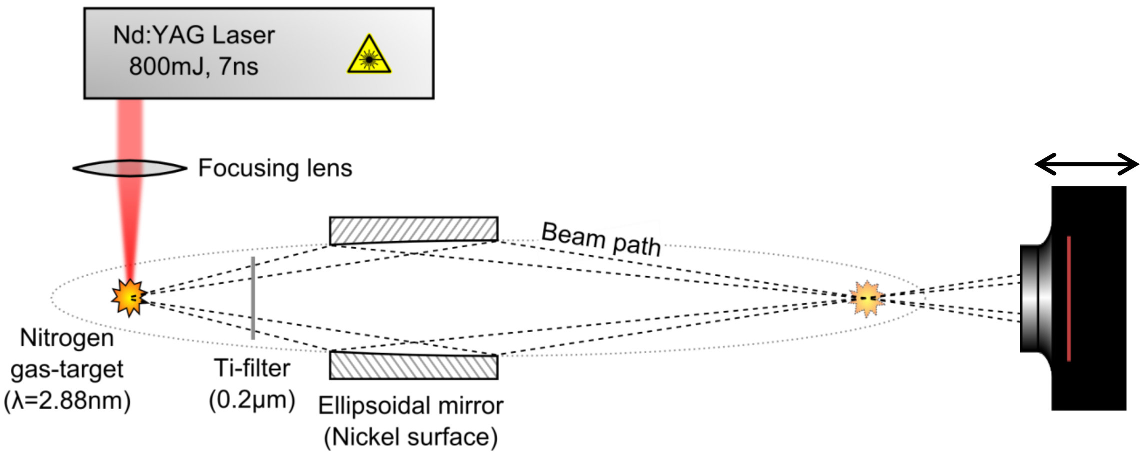
Set of 2 coaxial paraboloidal mirrors optimized for the wavelength 1.5 nm

Plasma

Focal spot

Focusing of soft X-ray radiation

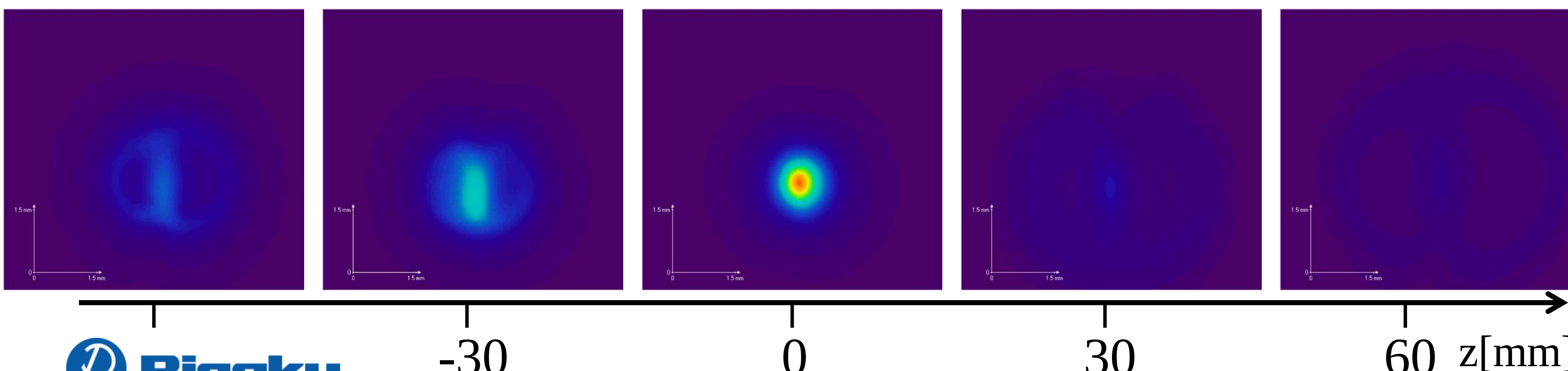
Setup at LLG with Rigaku ellipsoid



- 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



Summary

- **EUV/BEUV/SXR/XR grazing incidence mirrors have been studied and analyzed**
- **Selected applications of EUV/BEUV/SXR/XR mirrors were presented**

THANK YOU FOR ATTENTION

Prague