Optics for EUV/XUV/XR sources and laboratory submicron microscopy

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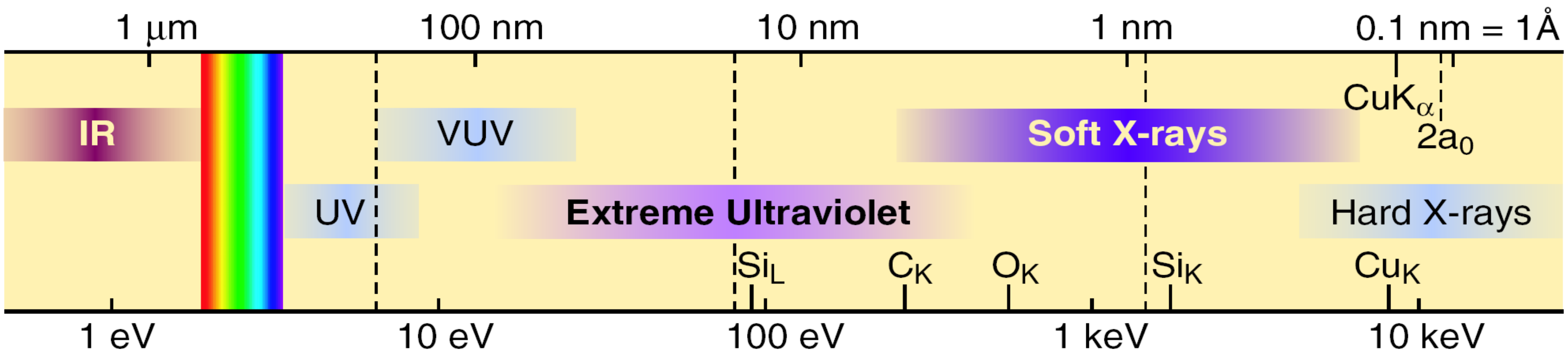
Electromagnetic radiation spectrum



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

Motivation

- Novel optical systems for X-ray astrophysics
- Effective use of current state of the art EUV/XUV/ XR laboratory sources
- Novel optical systems for EUV/XUV/ XR microscopy and tomography
- Effective use of current state of the art EUV/XUV/ XR matrix detectors
- Collector optics and diagnostic tools for EUV/XUV lithography

XR/XUV Micron to Submicron Resolution Matrix Detectors

Applications:

- **X-ray microscopy (industry, life sciences)**
- **X-ray micro tomography (μCT)**
- **X-ray micron size beam alignment**
- **X-ray optics alignment**
- **Synchrotron facilities**
- **Phase contrast X-ray imaging**
- **Diagnostic tools for EUV litography**

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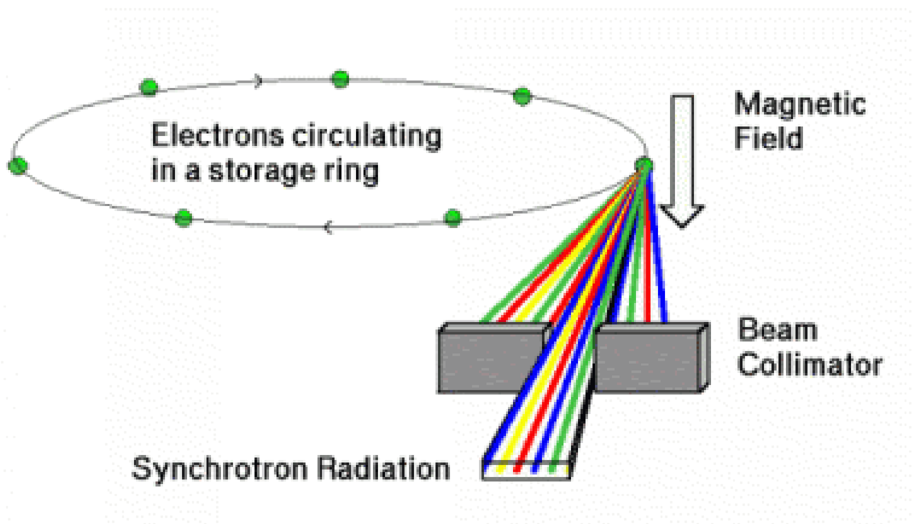
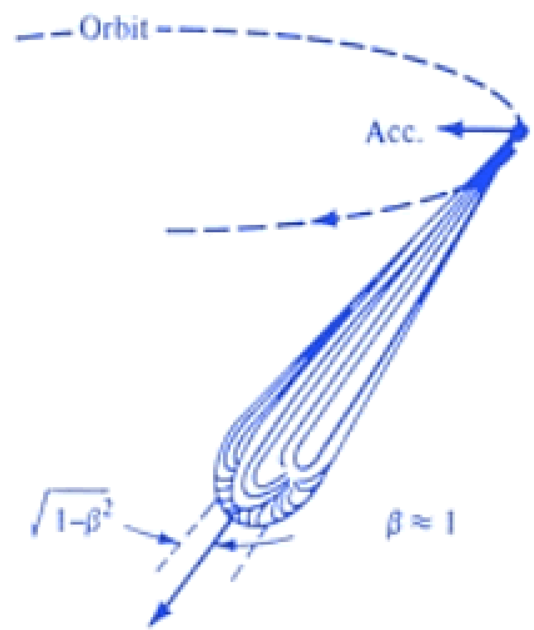
EUV/XUV/XR sources

Synchrotron radiation

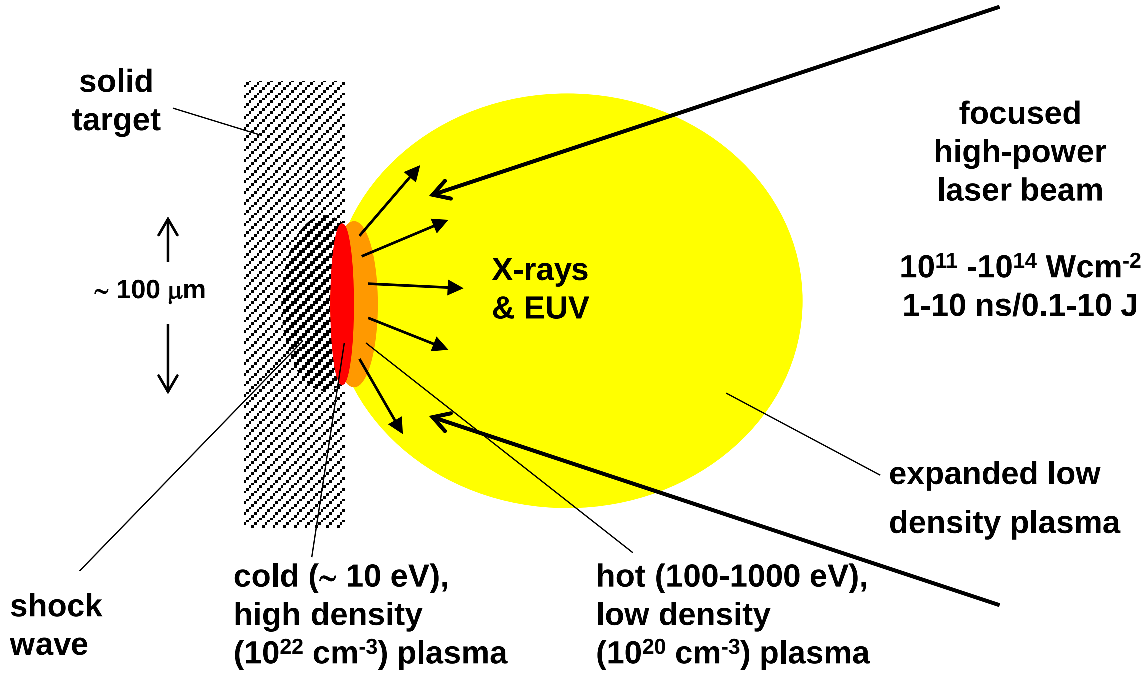




Characteristics of Synchrotron Radiation

- **High brightness: synchrotron radiation is extremely intense (hundreds of thousands of times higher than conventional X-ray tubes) and highly collimated.**
- **Wide energy spectrum: synchrotron radiation is emitted with a wide range of energies, allowing a beam of any energy to be produced.**
- **Synchrotron radiation is highly polarised.**
- **It is emitted in very short pulses, typically less that a nano-second.**

Laser Produced Plasma – solid (liquid) target



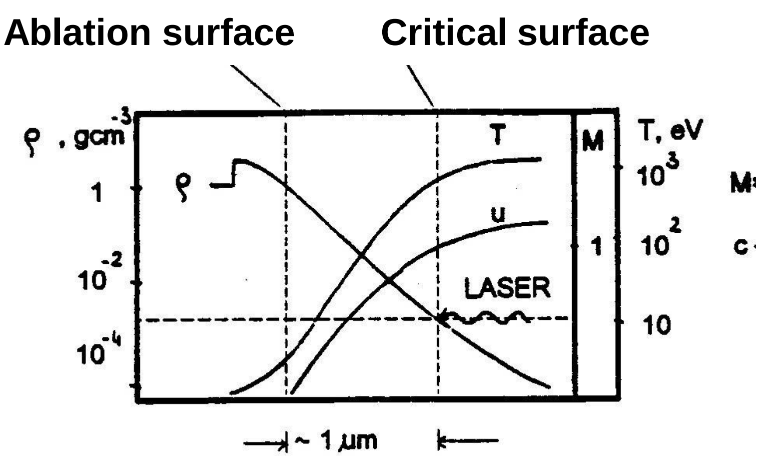
10^{11} -10^{14} Wcm^{-2}
1-10 ns/0.1-10 J

Nd:glass

Nd:YAG

KrF

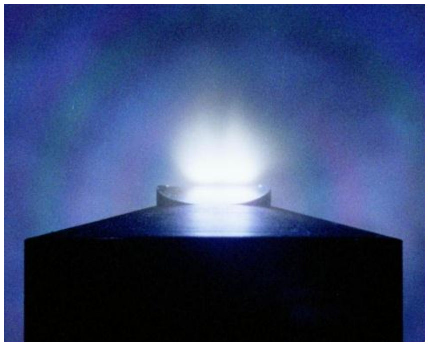
CO_2

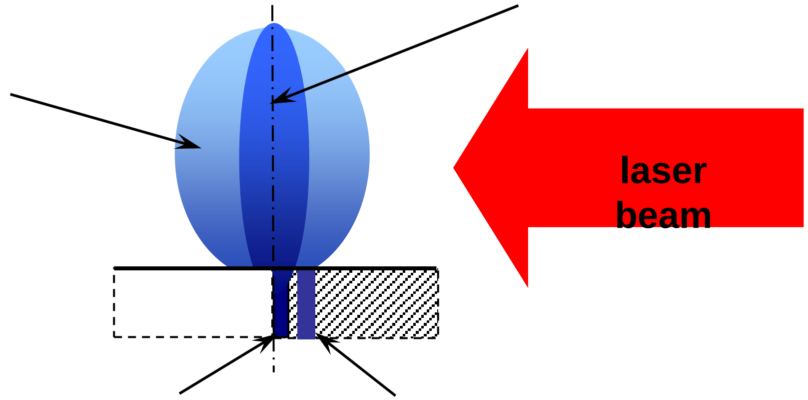


Laser plasma parameters for maximum EUV emission

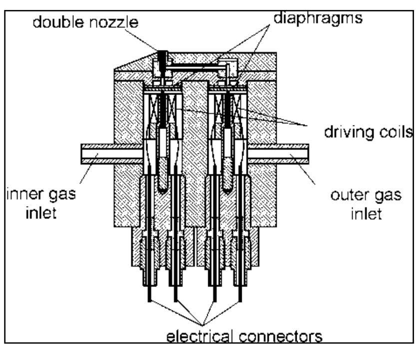
~ 40 eV, ~ 10^{19} cm^{-3}

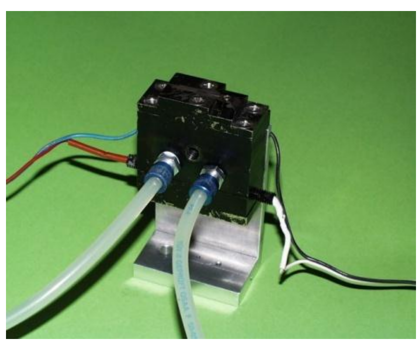
Laser Produced Plasma – gas puff target



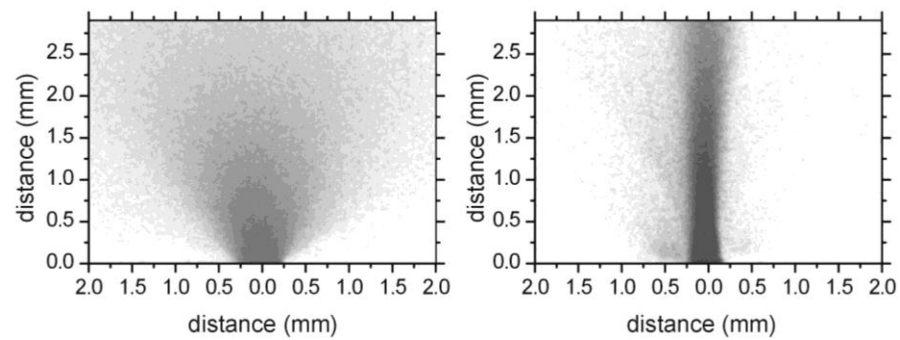


- **electromagnetic valve system**





- **X-ray backlighting images**

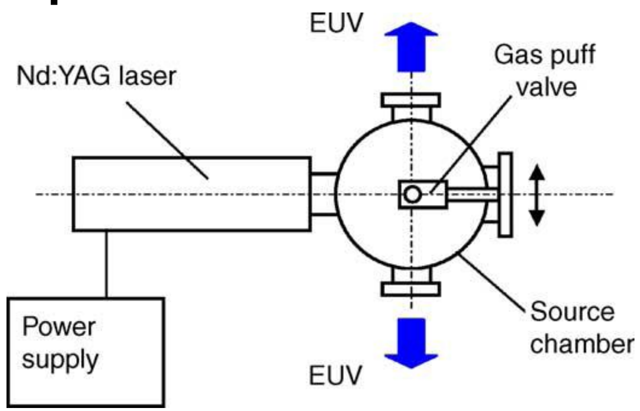


H. Fiedorowicz *et al. Appl.Phys. B 70 (2000) 305; Patent No.: US 6,469,310 B1*
WAT , Warszaw

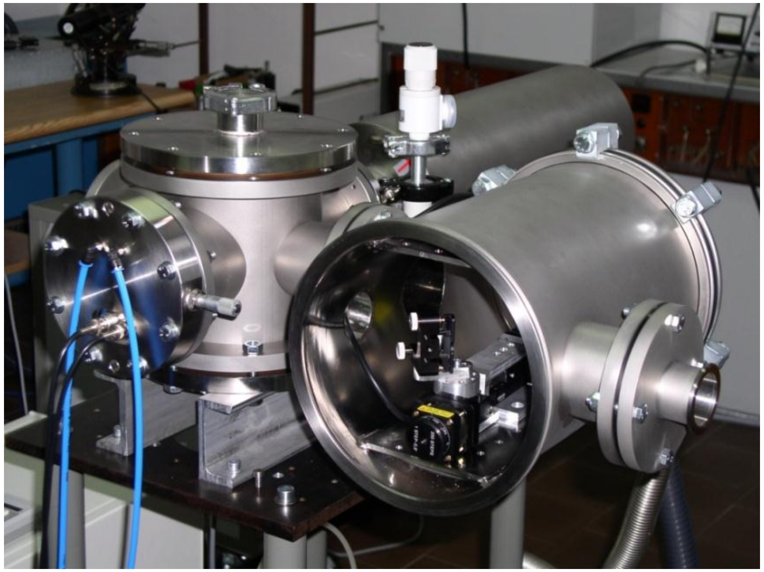
COMPACT LASER-PLASMA EUV SOURCE

- **compact laser-plasma EUV source based on a gas puff target irradiated with a commercial Nd:YAG laser (5ns/0.5J/10 Hz) was developed for EUV metrology**

EUV lamp

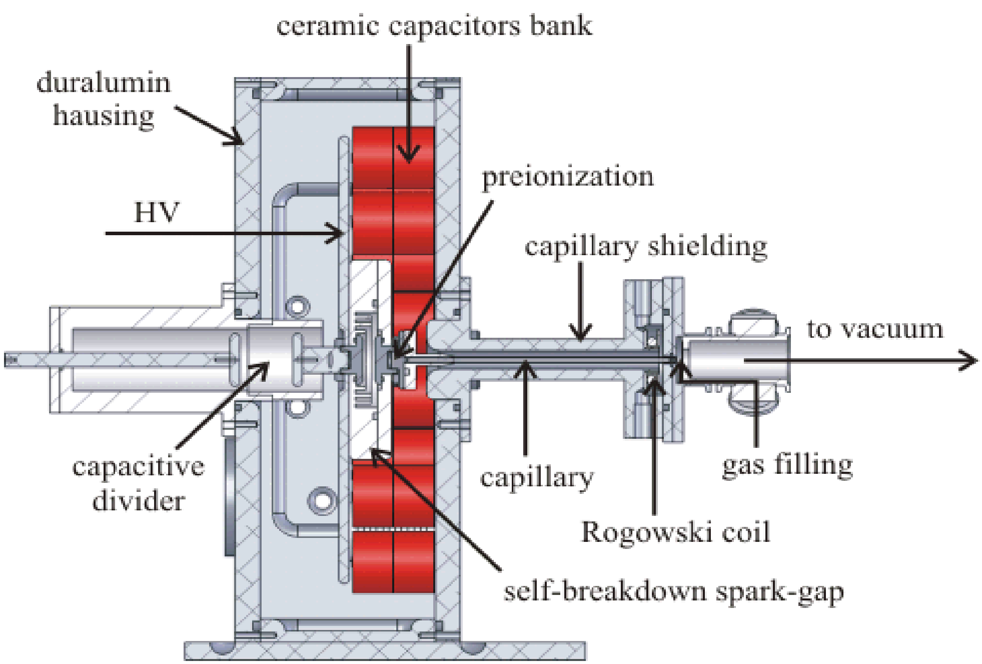


EUV metrology setup

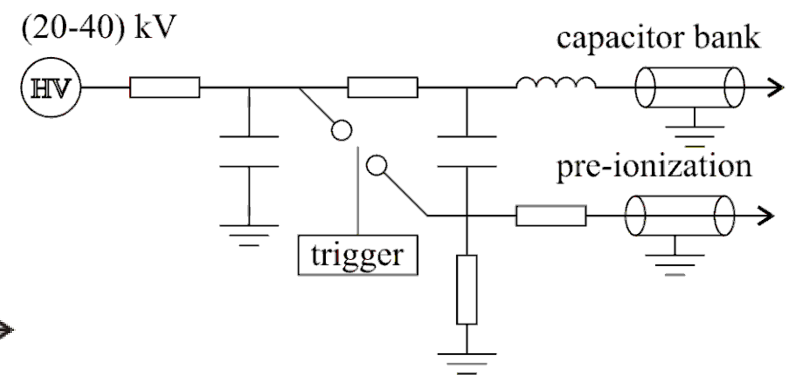


H. Fiedorowicz *et al., J.Alloys&Compounds 401 (2004) 99*

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.**

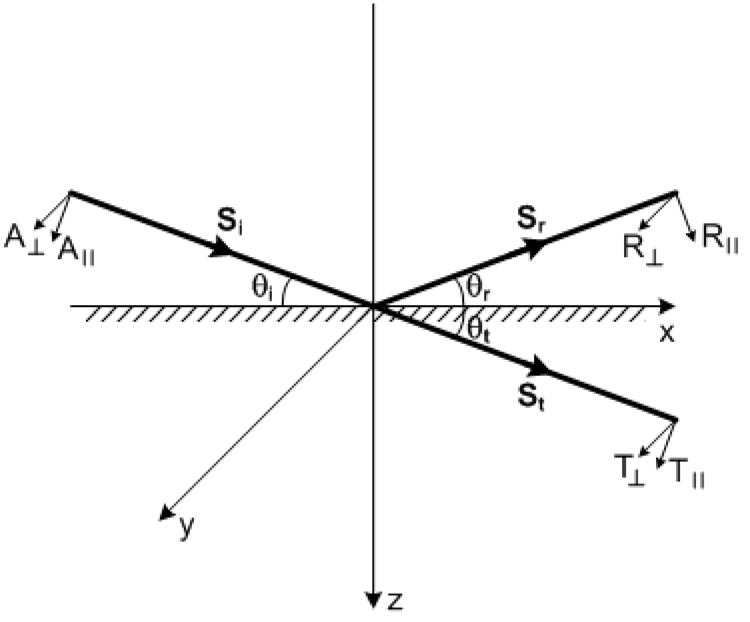
Design and construction of new experimental capillary discharge apparatus (A. Jancarek, M. Nevrkla)
CTU Prague, Faculty of Nuclear Sciences

Reflection of X-rays

Complex refractive index

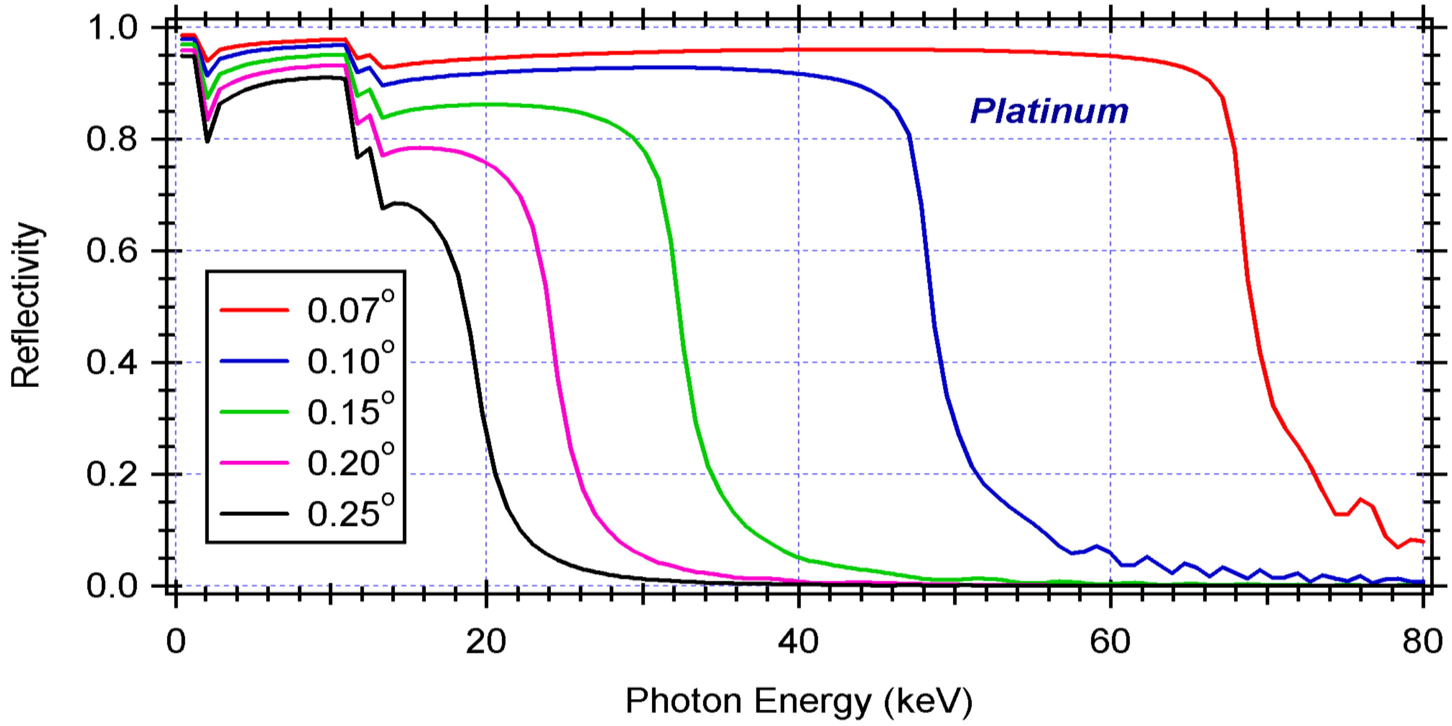
$$\tilde{n} = 1 - \delta - i\beta$$

Refraction and Reflection of X-rays

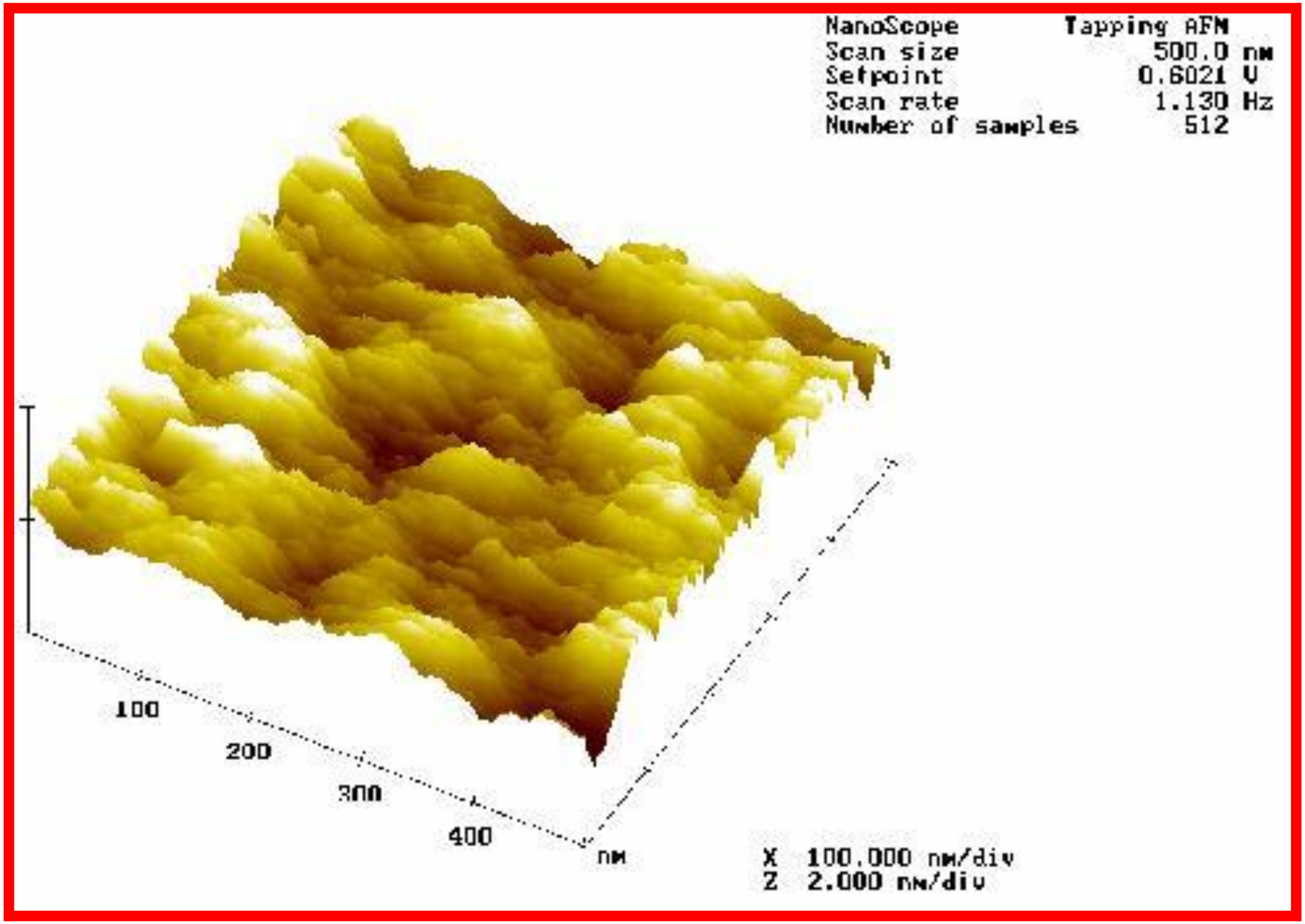


Total external reflection

Reflection of X-rays – photon energy



Reflection of X-rays – microroughness



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. Test facility at the Astronomical Observatory in Brera, Italy.

Grazing Incidence Optics

- Total external reflection
  - Flat mirrors
  - Capillaries, polycapillaries
  - Parabolic, elliptic and foil mirrors, paraboloidal and ellipsoidal mirrors
  - Kirkpatrick-Baez optic
  - Wolter optic
  - No monochromatisation, hard energy cut-off

History of Grazing Incidence X-Ray Optics in the Czech Republic

Early Stages

The early stages of the X-ray optics developments in the Czech Republic are closely related to the INTERKOSMOS Space Program (Soviet and East European equivalent of ESA operated until 1989). All of the X-ray imaging telescopes on board of Soviet spacecrafts were equipped with the Czech X-ray optics (exception: X-ray normal incidence mirrors in the special channel of the TEREK telescope). Later on, laboratory applications have started.

- Total number of X-ray mirrors produced: more than 50
- Total number of mirrors flown in space: 8
- Total space crafts with Czech X-ray optics: 4
- Total number of space experiments with Czech X-ray optics on board: 8

First steps towards X-ray optics in the Czech Republic

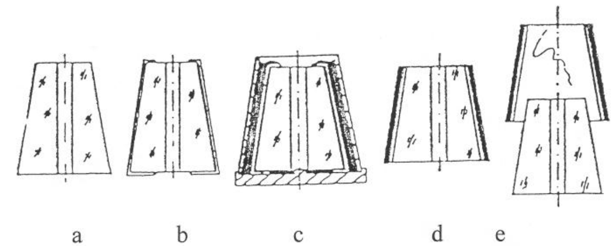
- Manufacturing of hollow aspherical mirror is based on the replication of a polished cone-shaped glass-ceramic mandrel
- Manufacturing of mandrels: *Optical Workshop of the Academy of Science in Turnov*
- Replication of the first objectives: *Gramophone Record Factory Lodenice*
    - nickel, shell thickness 6 mm, Ø 80 mm, length 120 mm, weight 3 kg
    - master was often destroyed during the replication process

History – list of projects (Acad Sci, CTU, Reflex, Rigaku)

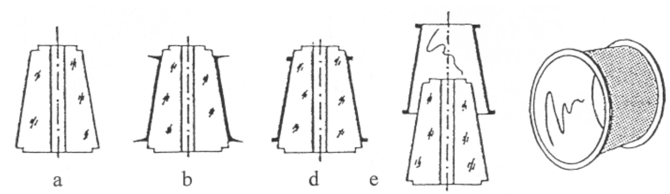
- **1969 First considerations started**
- **1970 First X-ray mirror produced (Wolter 1, 50 mm)**
- **1971 Wolter 1, 80 mm**
- **1976 Wolter 1, 115 mm**
- **1979 First mirrors flown in space (two Wolter 50 mm, Vertikal 9 rocket)**
- **1980 Vertikal 11 rocket (two Wolter 50 mm)**
- **1981 First large Wolter 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 - Reflex)**
- **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, Cambridge**
- **2006 MFO Kirkpatrick-Baez optic, University of Boulder, CO, NASA, USA**
- **2007 Innovative technologies for X-ray telescopes, PECS, ESA XEUS projects**

The early history of X-ray optics in the Czech Republic

- New replication technology: *National Research Institute for Materials*
  - 6-8 mirrors from one master
- Improvement of replication technology: A. Inneman et al.
  - no damage of the mandrel
  - reduced weight
- Laboratory application
  - objectives with Ø 20 mm
  - used for taking photographs of laser plasma in *Institute of Plasma Physics and Laser Microfusion in Varsava*



a - master, b - master with nickel layer,
c - flooding of the master,
d – cutting/finishing of the edges,
e - removing the mirror part



The early history of X-ray optics in the Czech Republic

1969 First considerations started (Academy of Sciences)

1970 First X-ray mirror (Wolter I, 50 mm)

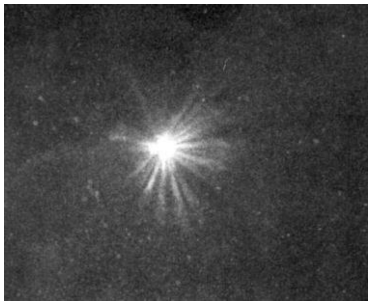
Mandrels for manufacturing X-ray mirror for RT-4M soft X-ray telescope on Salyut 7 (glass-ceramics Sital).

1976 Wolter I, 115 mm

1979 First mirror flown in Space (2x Wolter, 240 mm nested)

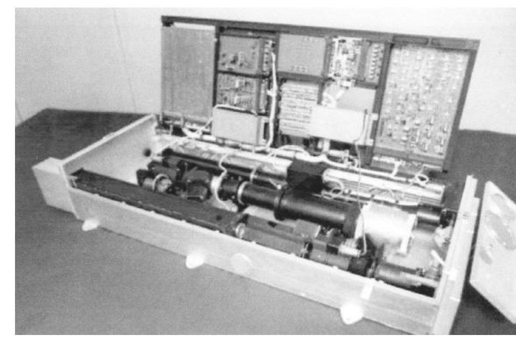
1981 Salyut 7 orbital station (Wolter I, 240 mm nested)

The early history of X-ray optics in the Czech Republic



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

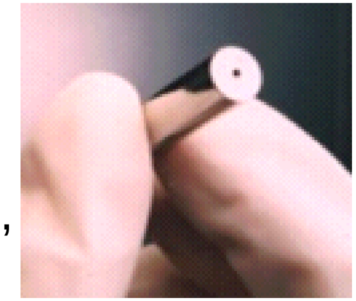
1985 — Applications for plasma physics (EH 17 mm, PP 20 mm)

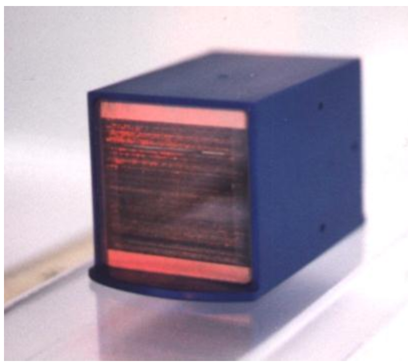


1988 — FOBOS 1 Mars probe, TEREK X-ray telescope

1989 — KORONAS I (Wolter 80 mm)

Post-Soviet era



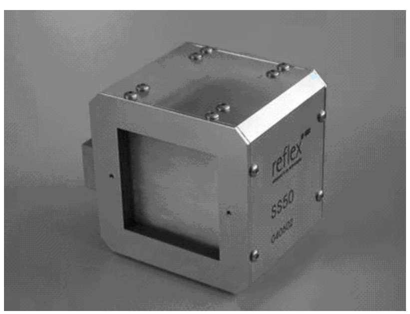


1990 — First micromirror (aperture 1 mm), collaboration with MRC, Cambridge, UK

1993 — Collaboration with SAO (Cambridge, USA) WF X-ray optics

1996 — XRO group at Reflex

First Lobster Eye (Schmidt)

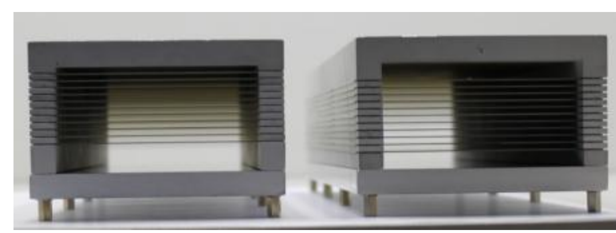


1999 — Lobster Eye (Angel)

2000 — Soller Slit

2001 — Multifoil optics

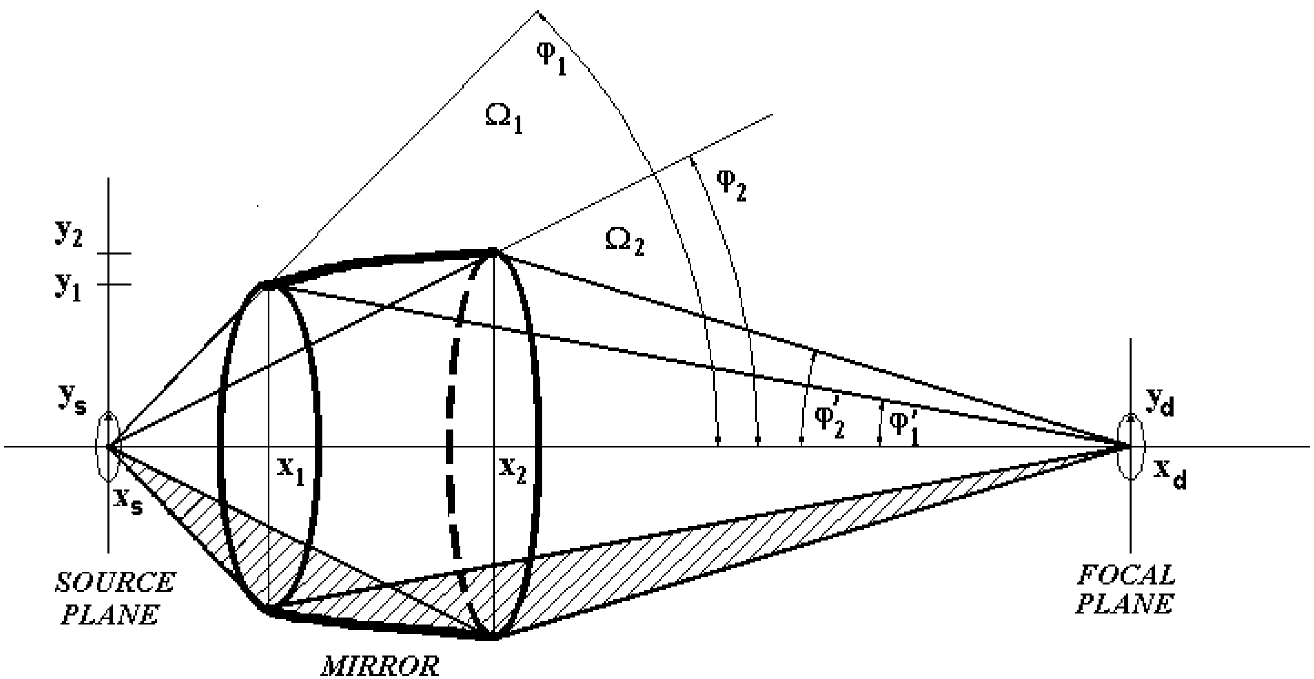
2002 — Micromirror with multilayers

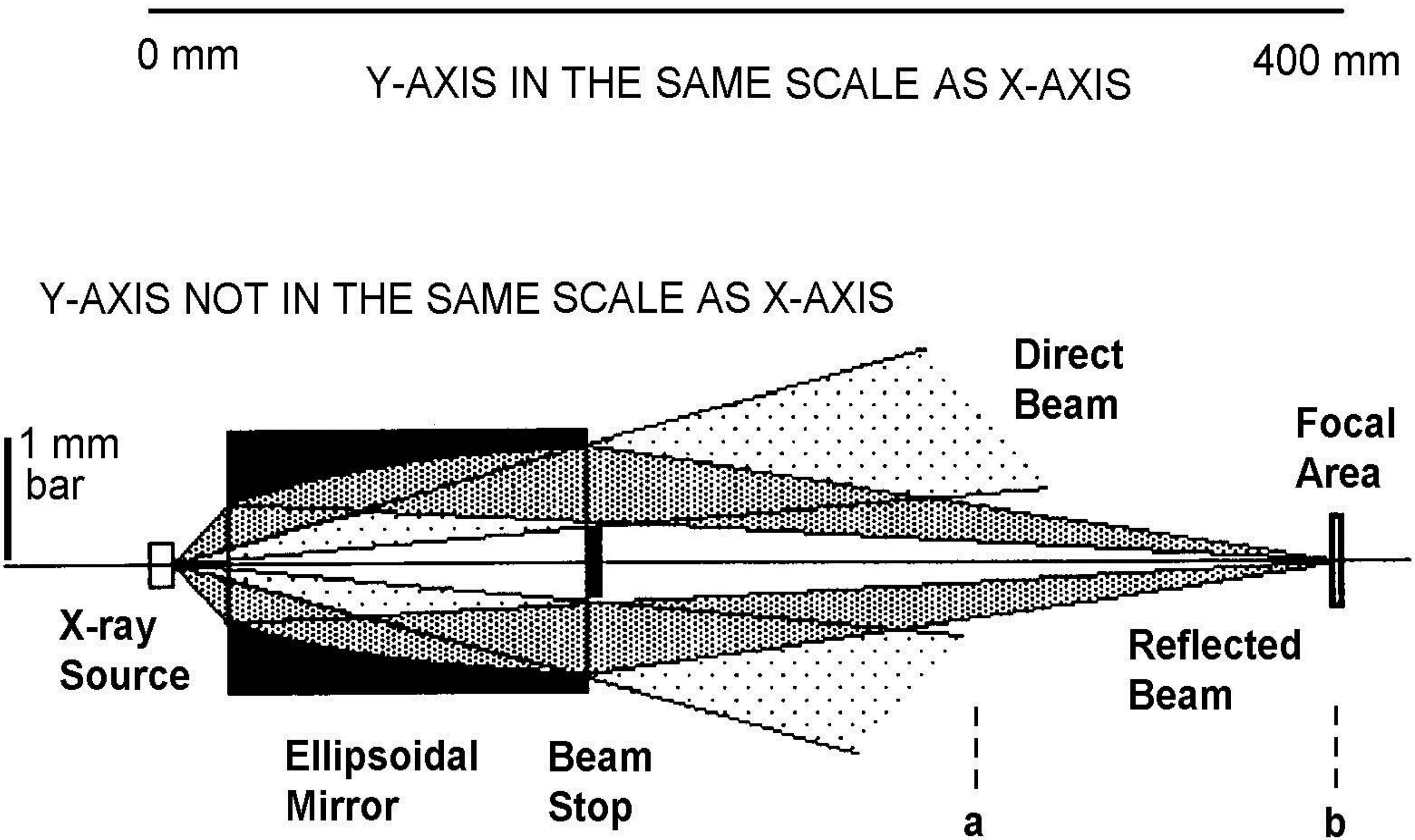


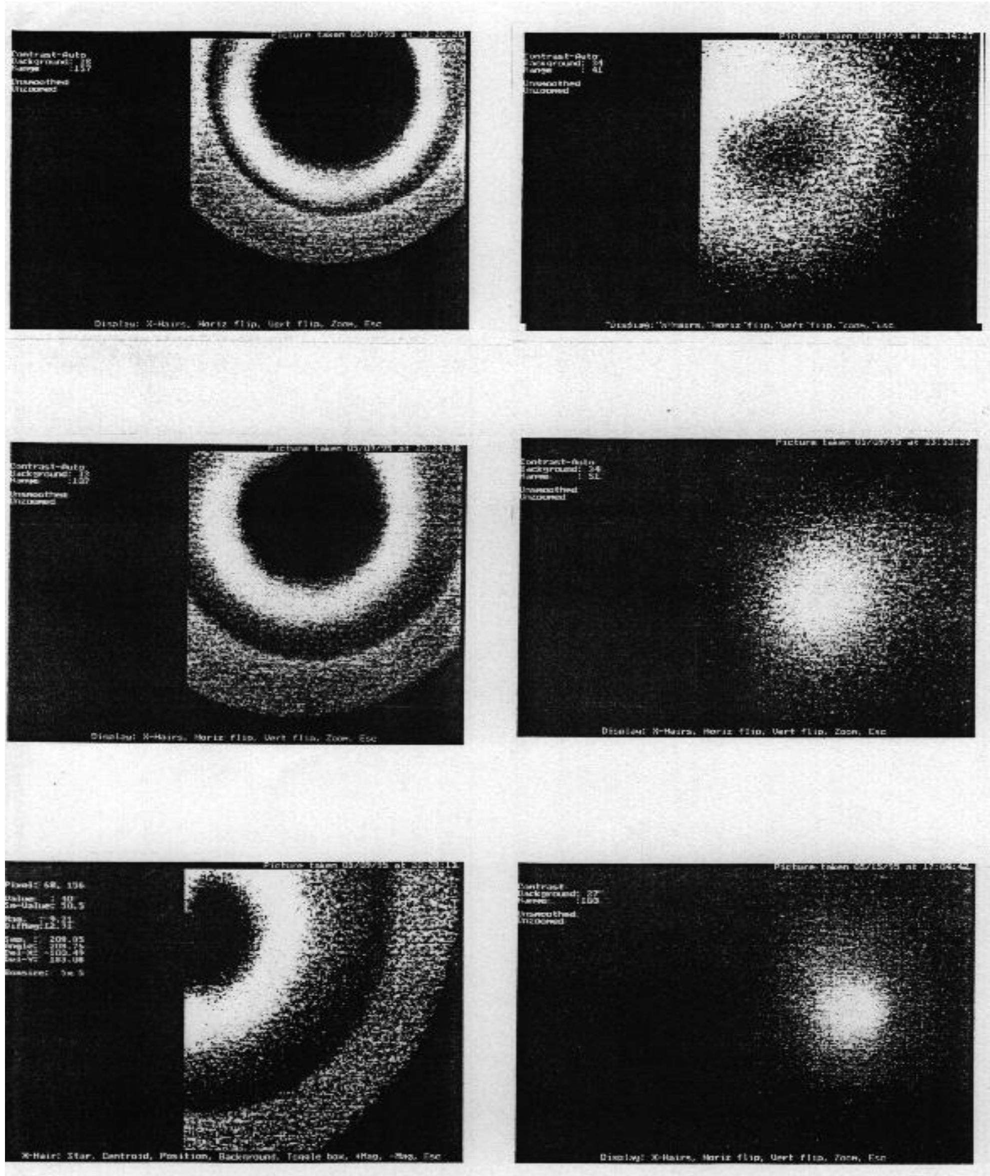
Micromirrors for macromolecular X-ray crystallography

- *Faculty of Nuclear Sciences and Physical Engineering (CTU), Astronomical Institute of the Academy of Science - 1989*
- Focus on miniaturization of X-ray optics
- Collaboration with *Medical Research Council in Cambridge, UK*
- "X-rays on the table" device for studying proteins

ELLIPSOIDAL MIRROR




0 mm
400 mm
Y-AXIS IN THE SAME SCALE AS X-AXIS
Y-AXIS NOT IN THE SAME SCALE AS X-AXIS
Direct Beam
Focal Area
1 mm bar
X-ray Source
Ellipsoidal Mirror
Beam Stop
Reflected Beam
a
b

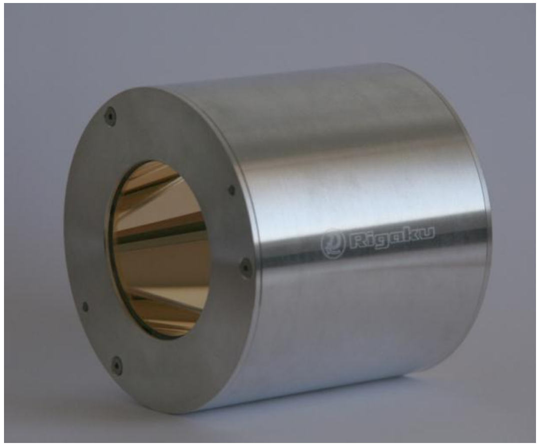


Rigaku Innovative Technologies Europe

- 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 institutes

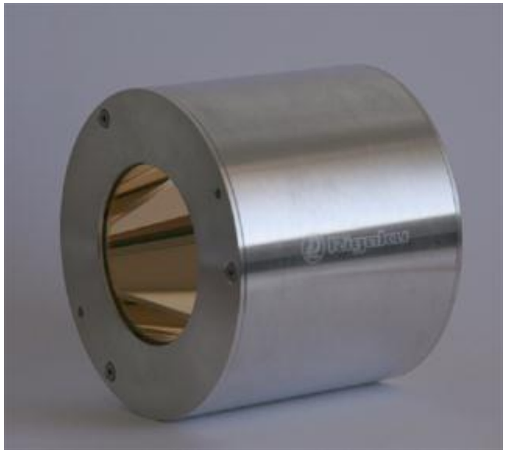
  Academy of Sciences of the Czech Republic, Czech Technical University, Chemistry University, …

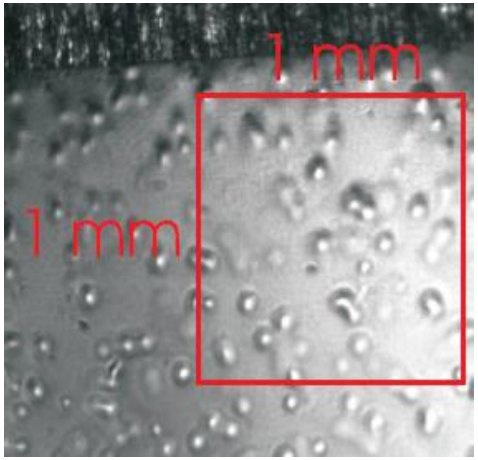
- Elliptical optics for XUV and EUV (laser plasma research)

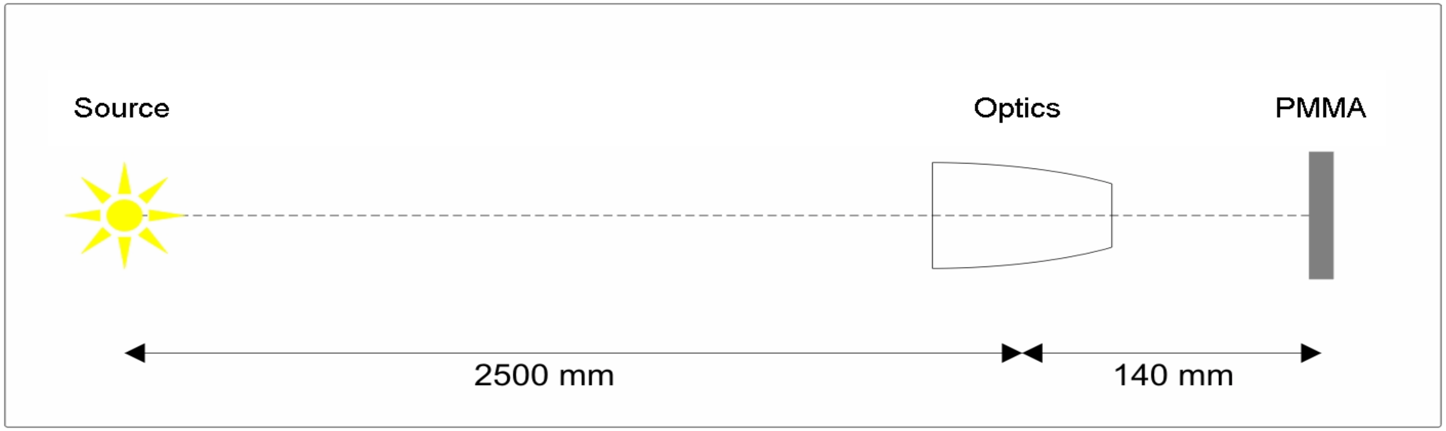


EUV laser beam focusing at PALS

- Ellipsoidal optic
- Au surface
- PMMA target

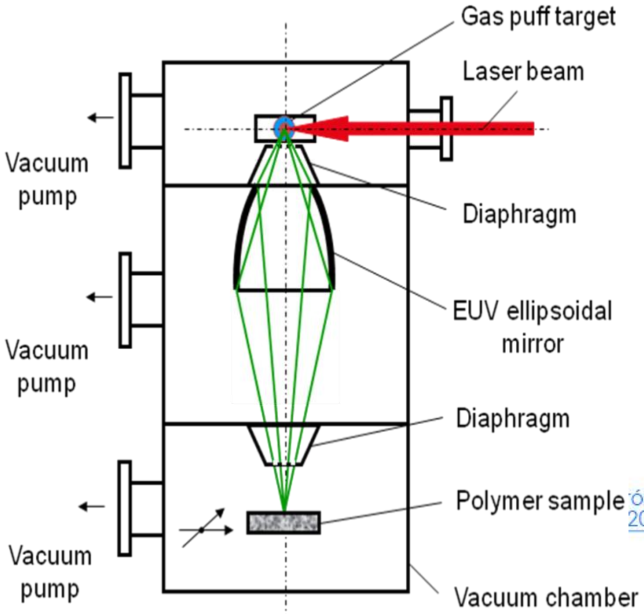


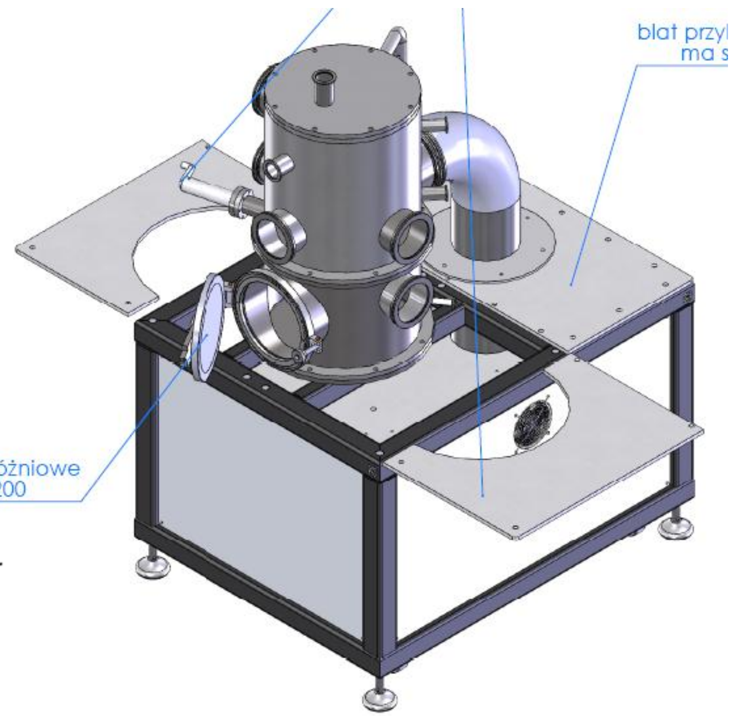




Laser plasma EUV source for processing polymers

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





EUV Dublin 08-11 October 2012

EUREKA

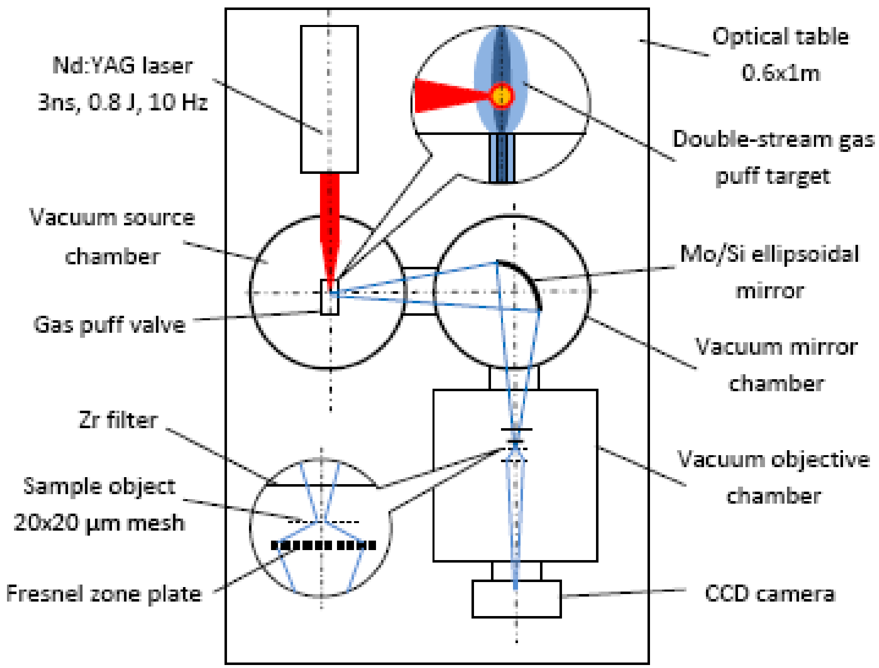
EKSPLA Rigaku

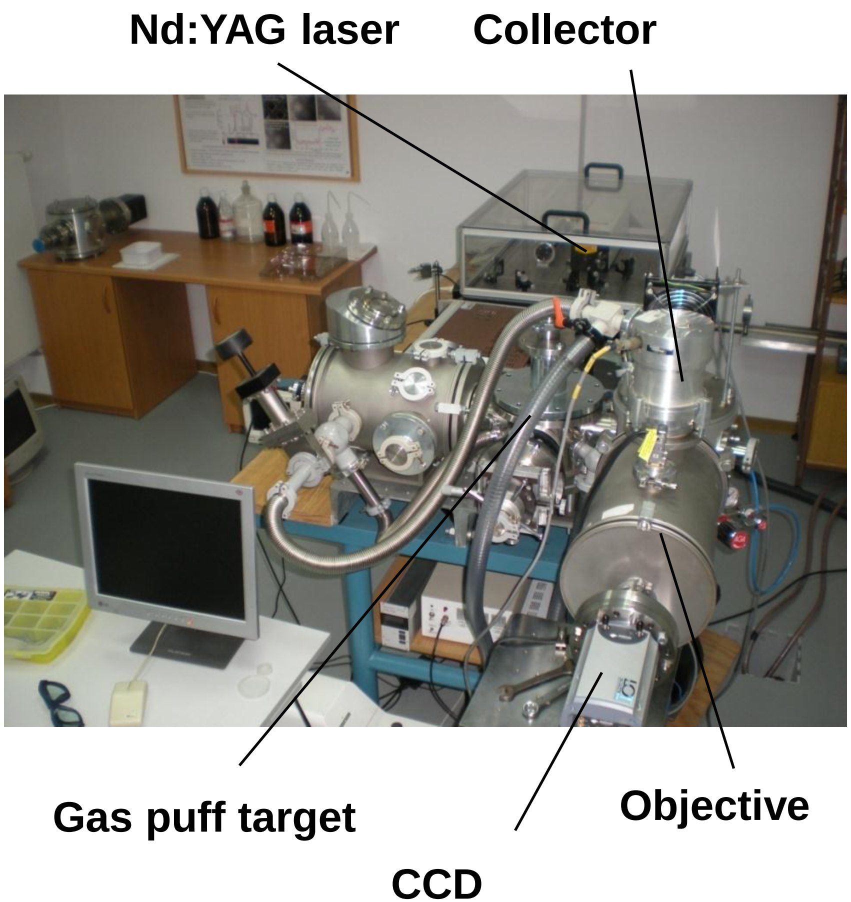
PREVAC PRECISION & VACUUM

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

EUV IMAGING IN A NANOSCALE

Desk-top EUV microscope with a laser plasma source

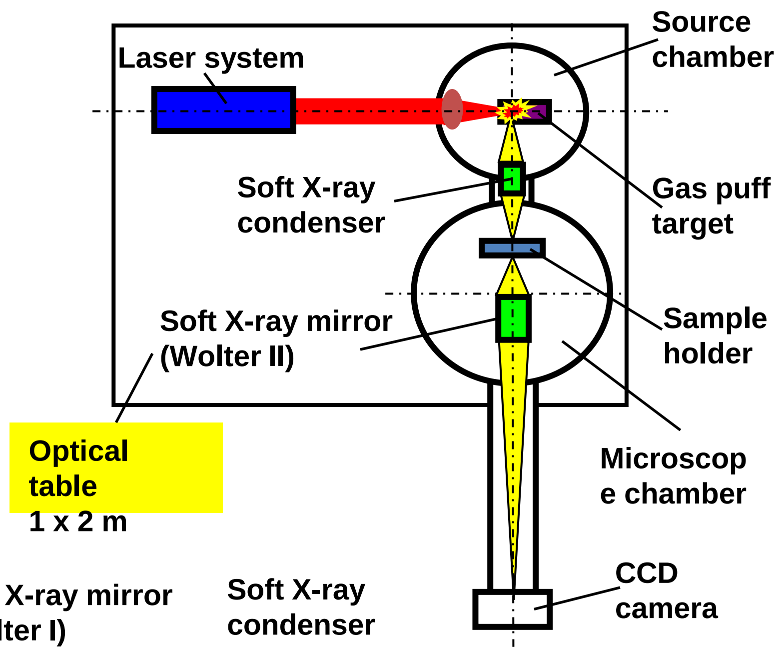


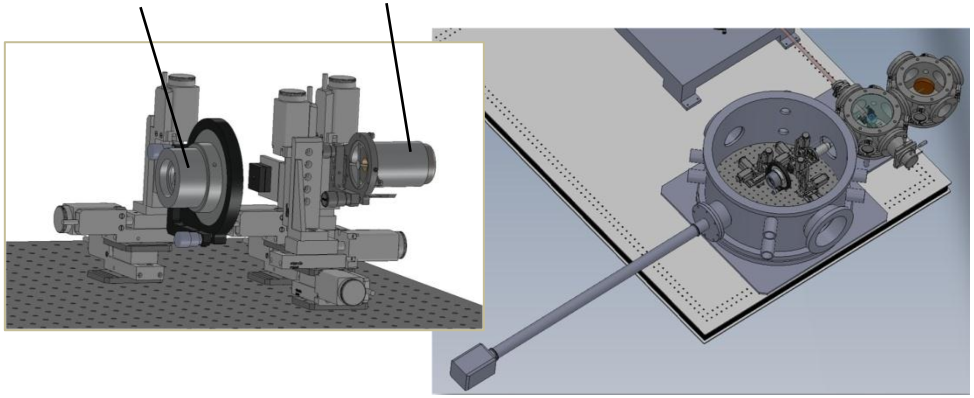


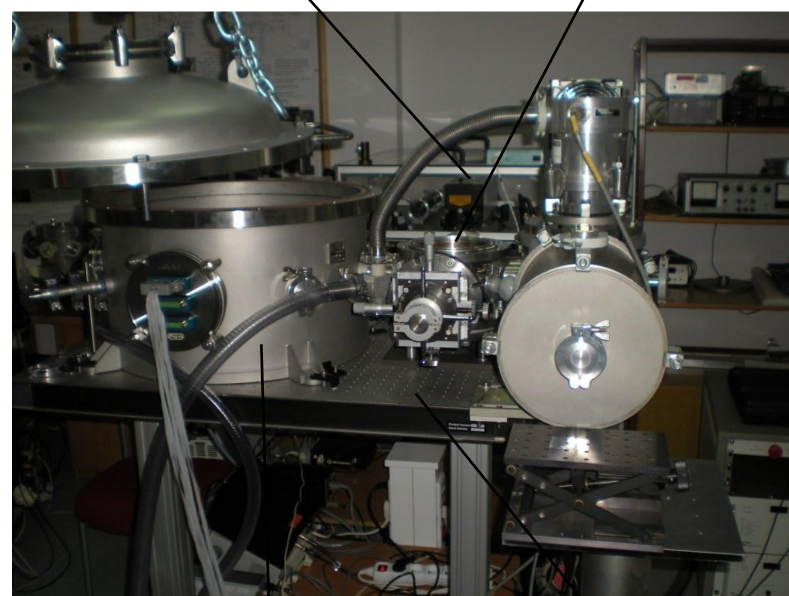
Optical table 0.6x1m

NANOIMAGING USING SOFT X-RAYS

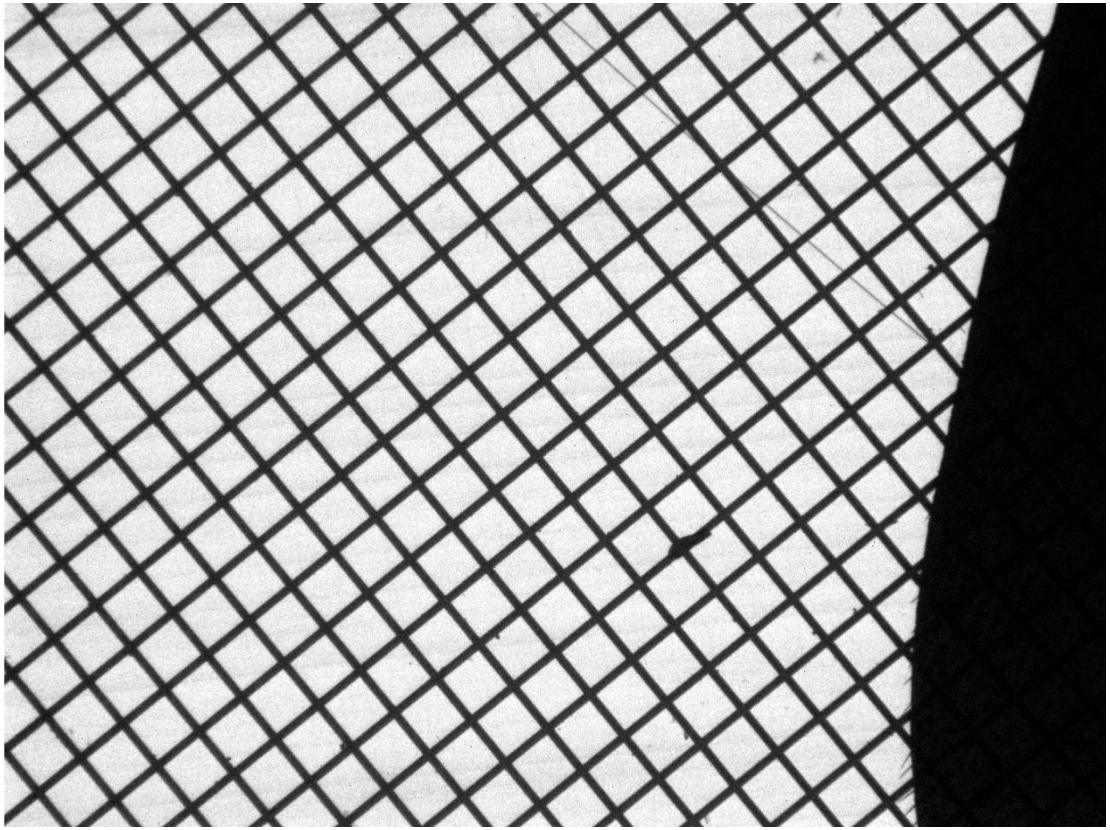
Desk-top soft X-ray microscope with a laser plasma source





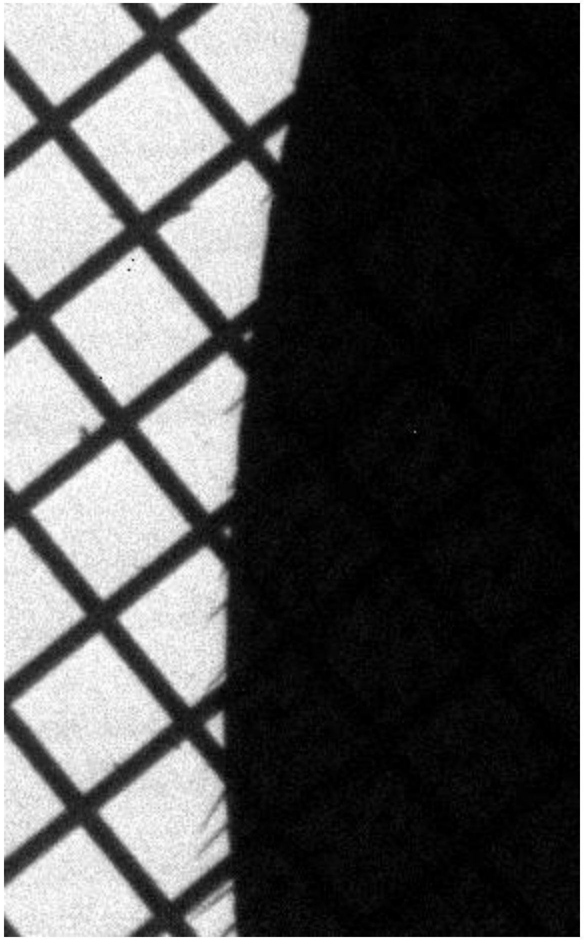


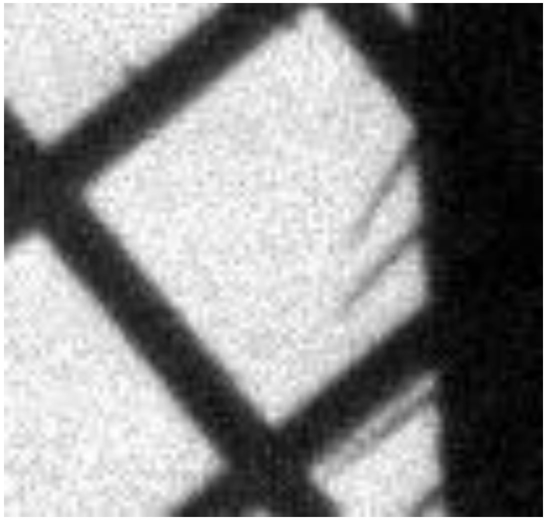
Projection XUV Submicron Microscopy
WAT gas-puff laser plasma facility (Warszaw, Poland)



Fly wing on Ni mesh, 5 μm bars, 0.65 μm pixel size

Projection XUV Submicron Microscopy
WAT gas-puff laser plasma facility (Warszaw, Poland)



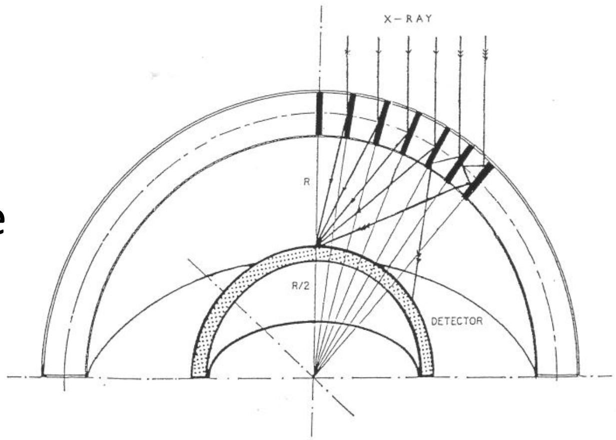


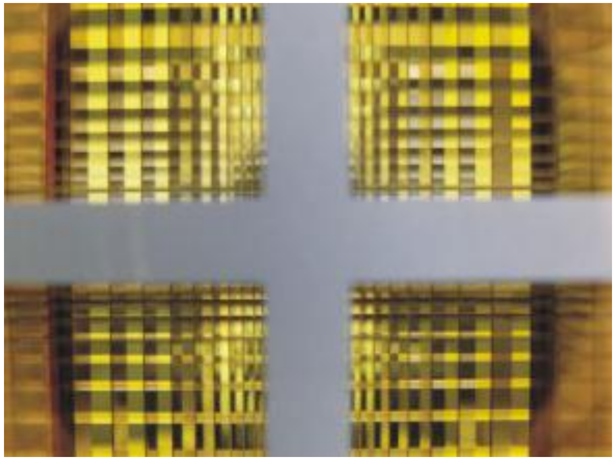
Fly wing on Ni mesh, 5 μm bars, 0.65 μm pixel size

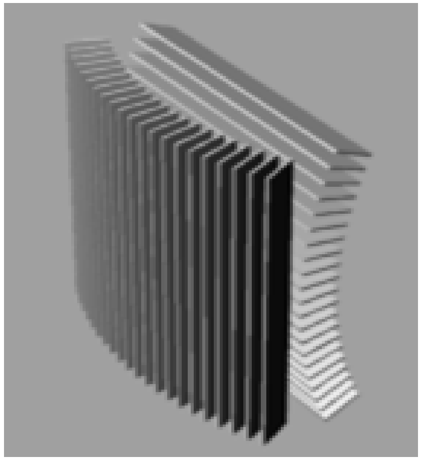
Projection X–ray Submicron Microscopy
RITE and CTU, microfocus X-ray tube 8 keV (Prague, Czech Republic)

Lobster Eye

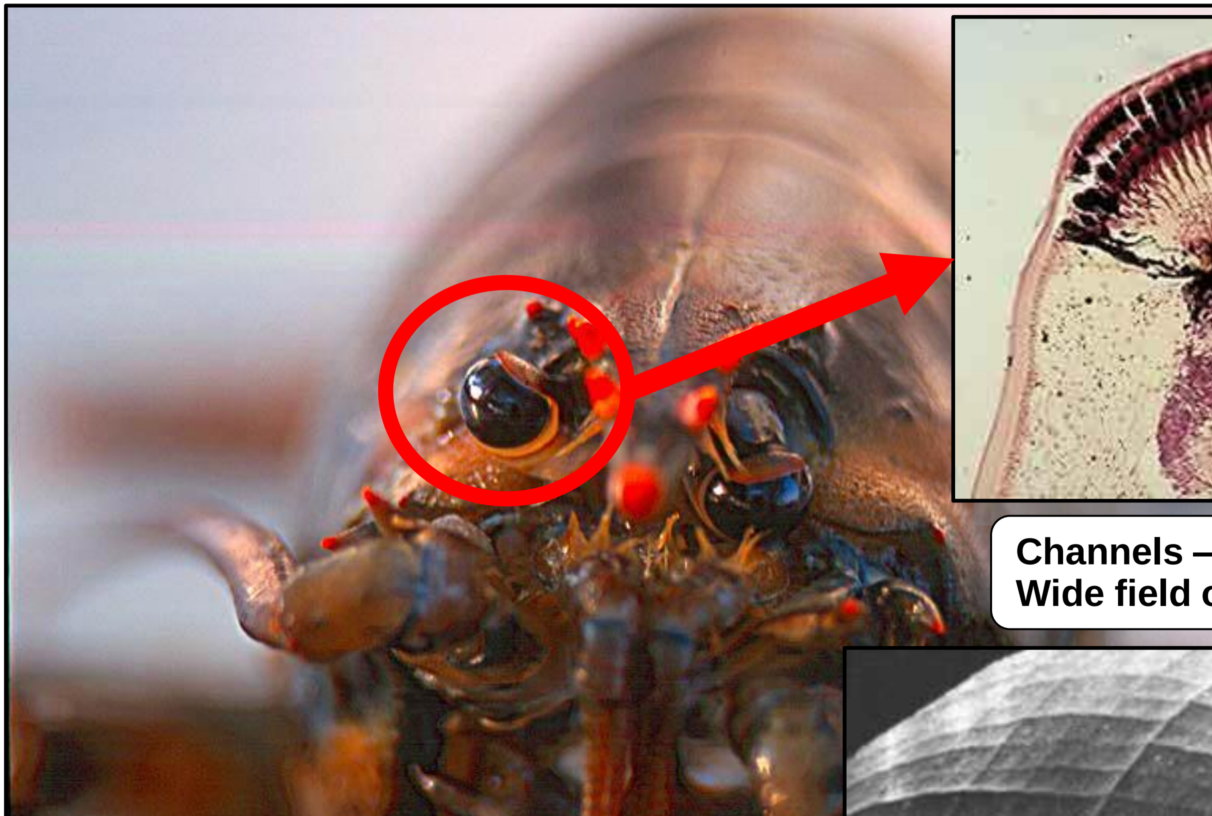
- Wide-angle imaging in X-ray region
- Composed of a set of double-sided reflective thin foils organized into a hemisphere
- Resolution is not high
- Observation of astrophysical sources in real time

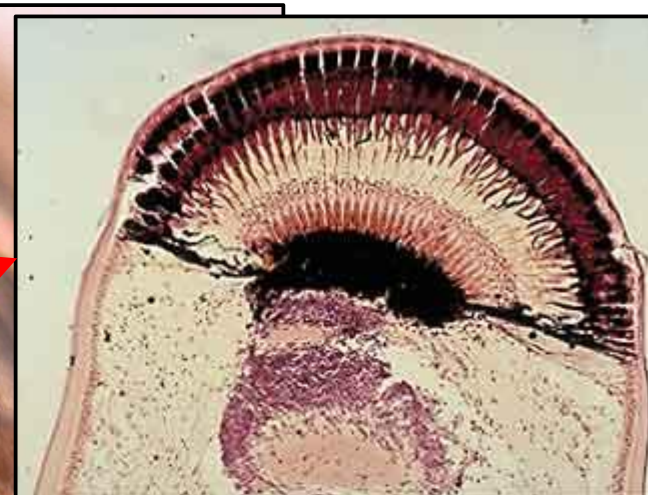




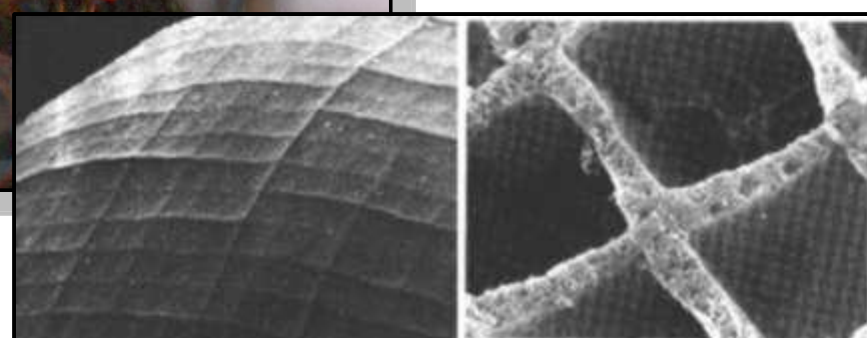


Lobster Eye



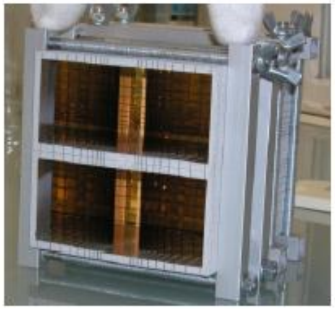


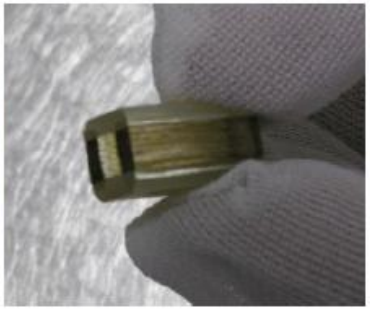
Channels – optical elements
Wide field optic

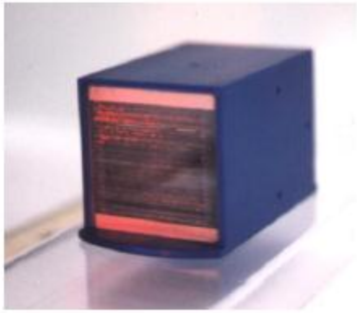


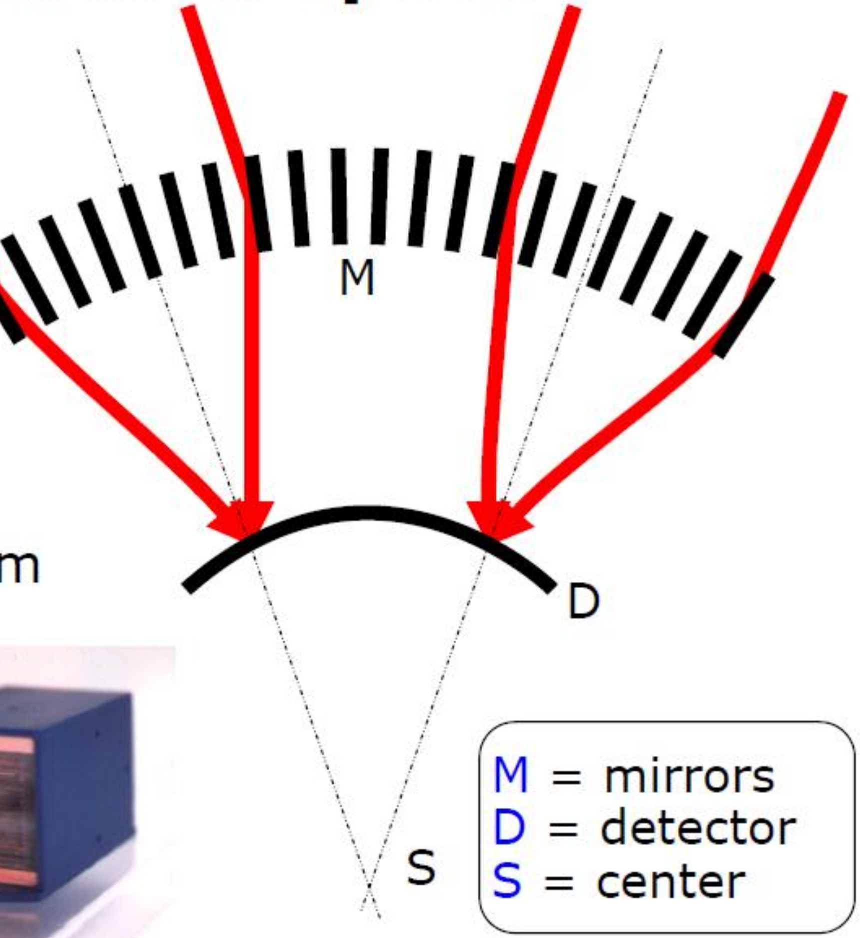
Lobster eye & multifoil optics

- Wide FOV
- Glass and/or silicon substrate for soft X-rays
- Planar & ellipsoidal mirrors
- Foils 3x3 mm to 300x300 mm
- Foil thickness from 30 µm to 1 mm



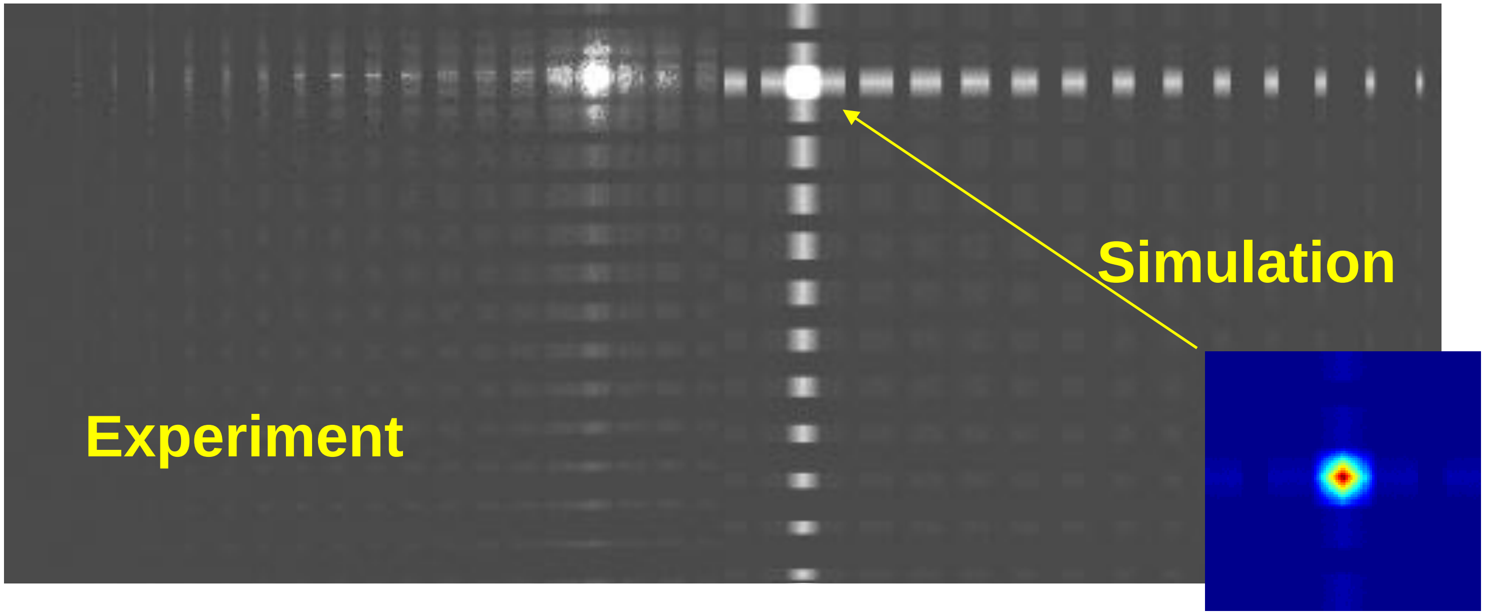


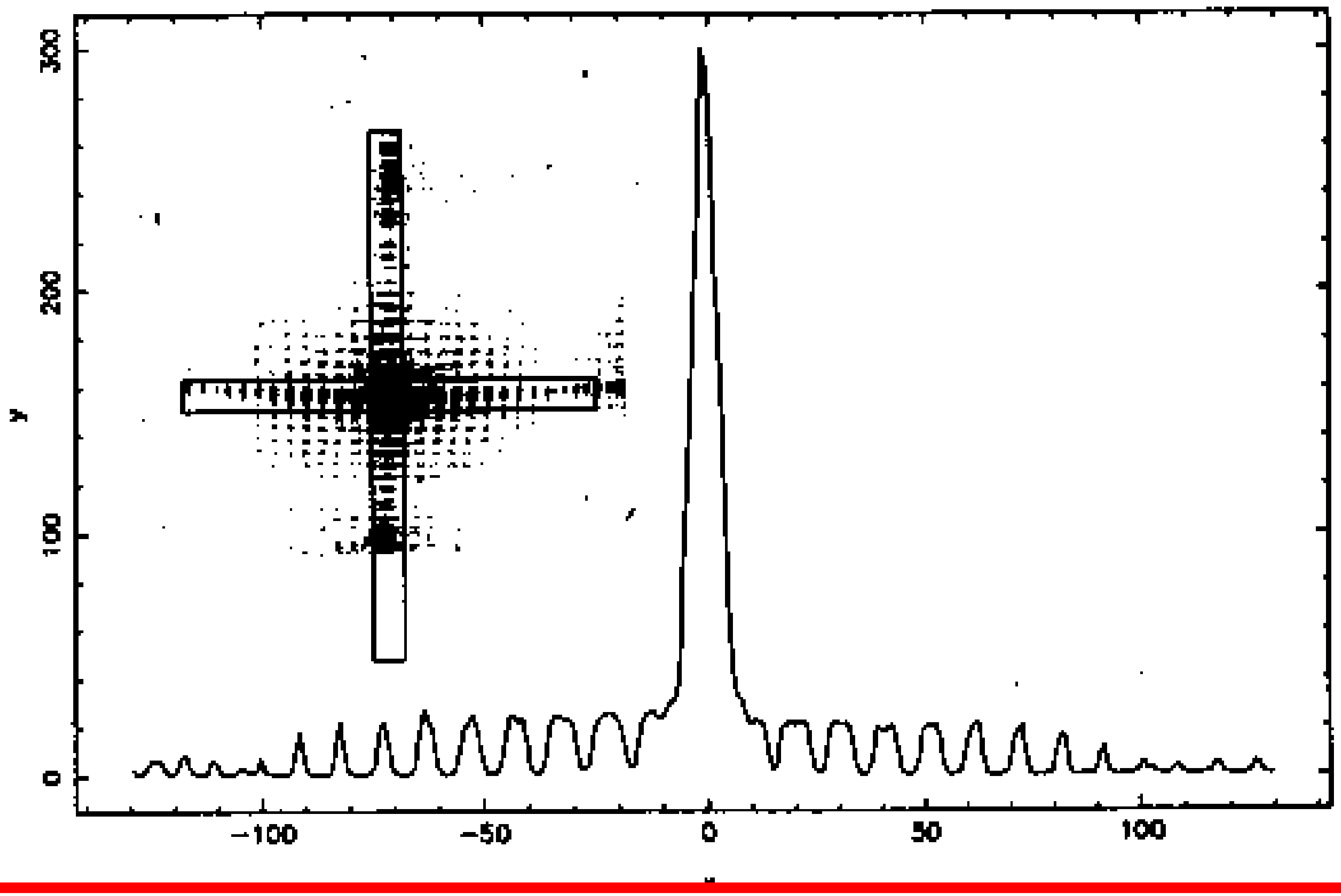




X-ray LE - experiment vs theory

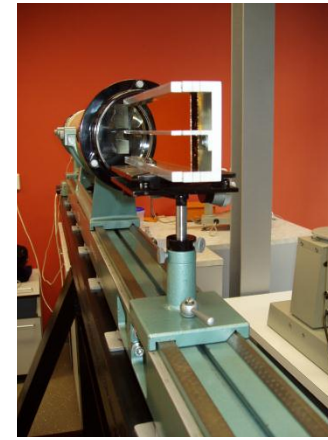
- Point-to-point focusing system
- Source: 20 μm size, 8 keV photons
- Source-detector distance: 1.2 m, 8 keV photons
- Detector: 512x512 pixels, 24x24 μm pixel size
- Intensity Gain: G=570 (experiment) vs. G=584 (comp. simulation)





X - ray focal image of the 80 x 100 mm Schmidt prototype (X-ray test facility, University of Leicester, UK). Measured intensity gain is G = 185

The last decade



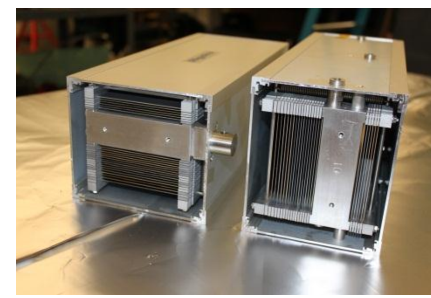
2003 — X-ray CCD camera

2004 — X-ray tube

2006 — KB collimator for soft X-ray

2007 — Micromirror tests at HASYLAB

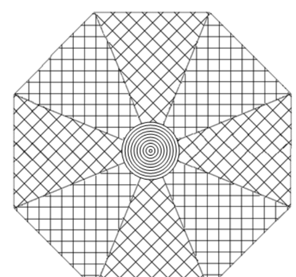
2008 — XRO group at RITE



2009 — Sub-micron X-ray camera

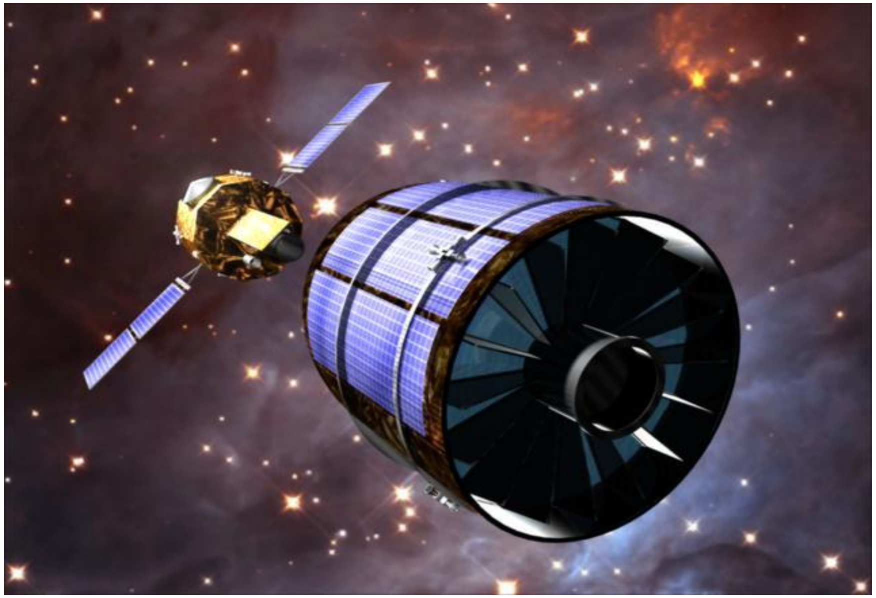
2011 — KB imaging system for astrophysics (Si wafers)

2012 — Novel design of X-ray telescope for space



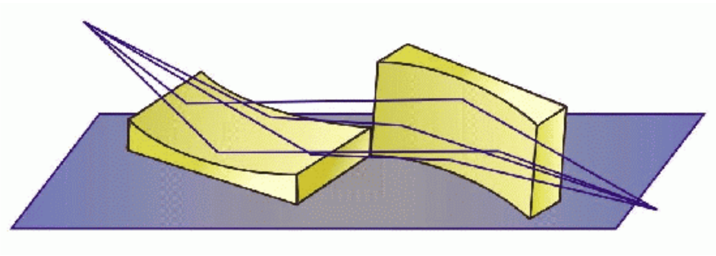
Technologies for X-ray Space Telescopes – XEUS, IXO, Athena

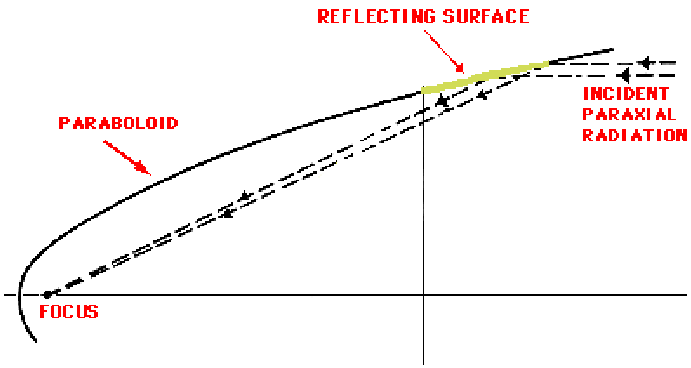
- First negotiations related to XEUS started around 1999
- ESA PECS project accepted for funding from Dec 2006, PI L. Pina
- Measurements of internal stress
- Measurements and metrology incl. stacked modules
- Irradiation analyses
- Investigation of alternative approach (backup technology)



Kirpatrick-Baez system

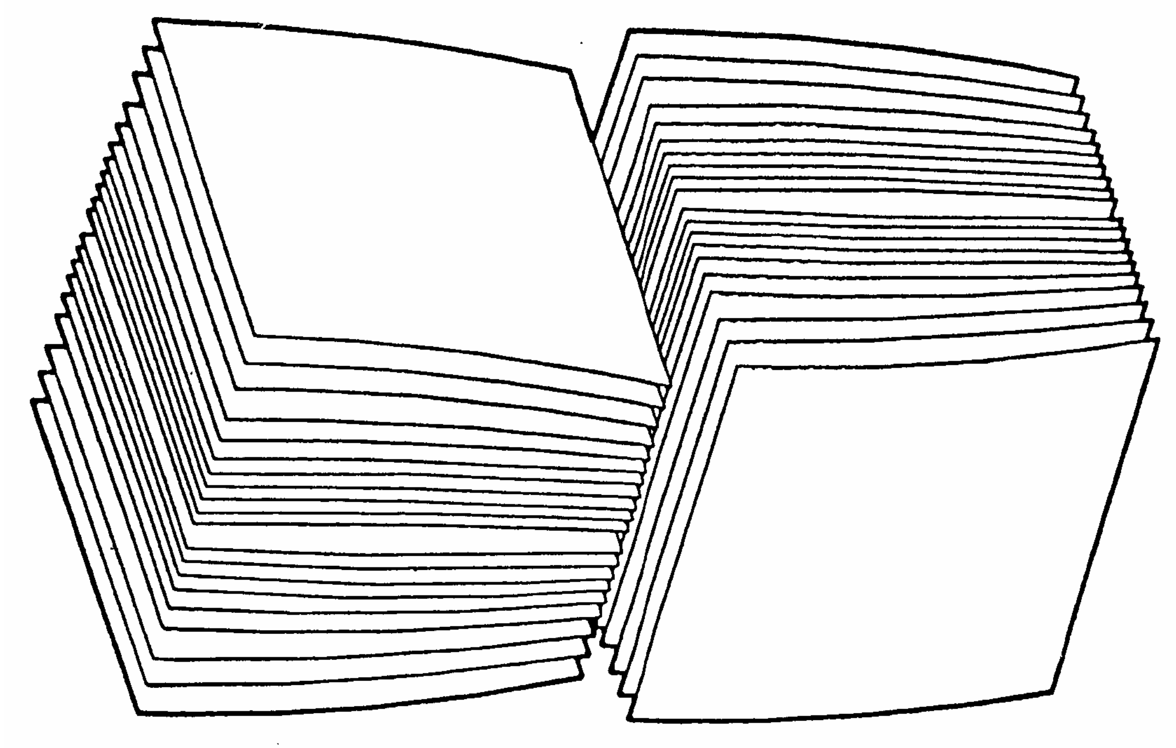
- Double reflection X-ray Optics
- Two mirror sets - vertical and horizontal
- Flat mirrors curved only in one direction to aspherical shape
- KB system can be manufactured from commercially available glass foils or silicon wafers
- Technology is not necessarily based on precise and expensive mandrel





http://imagine.gsfc.nasa.gov/

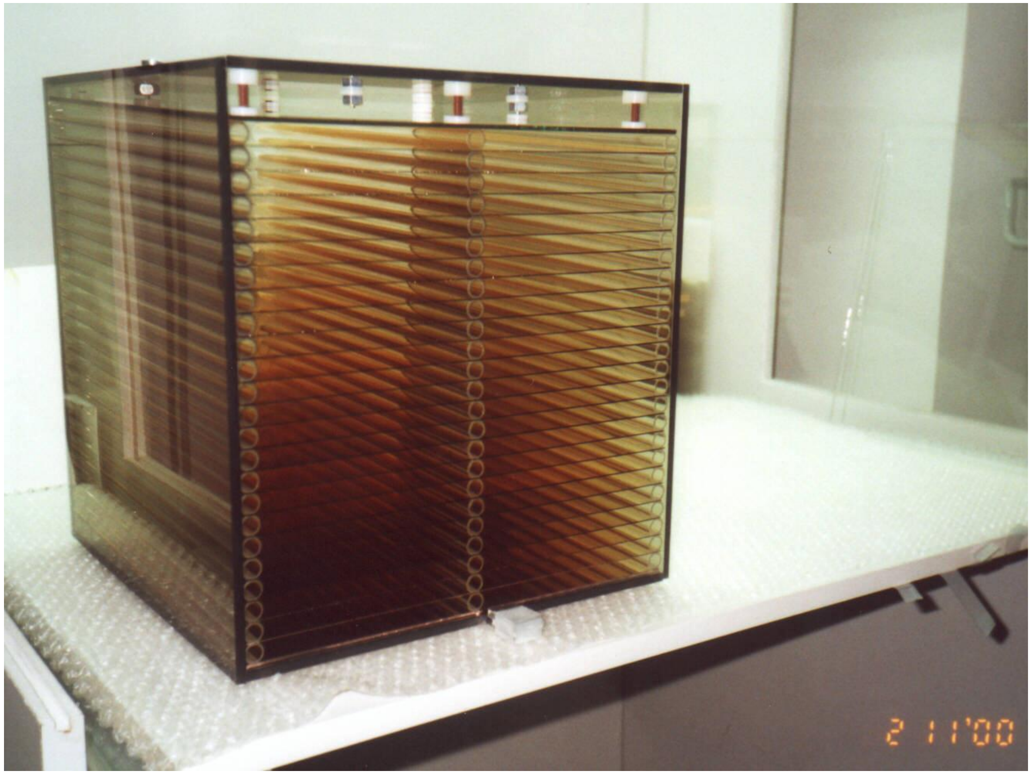
Kirkpatrick-Baez Multi Foil X-ray Optic



Kirkpatrick-Baez mirror consisting of orthogonal stacks of reflectors. Each reflector a parabola in one dimension.

X-ray Optics

X-ray telescope test study module (XEUS)



2D KB MFO mirror assembly

2D module,

30 x 30 cm glass foils

0.75 mm thickness of foils

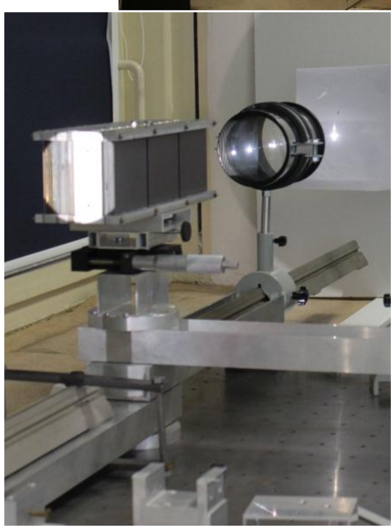
gold-coated by sputtering,

plates spaced at 12 mm.

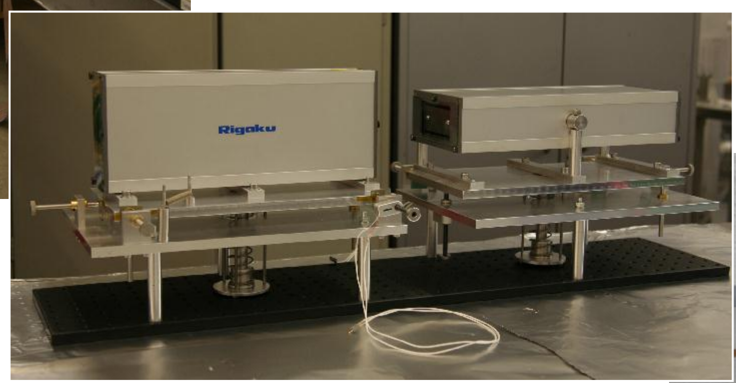
Tests of LE modules, XEUS modules, large K-B modules.

Light-weight (glass)

Multifoil optics for astrophysics

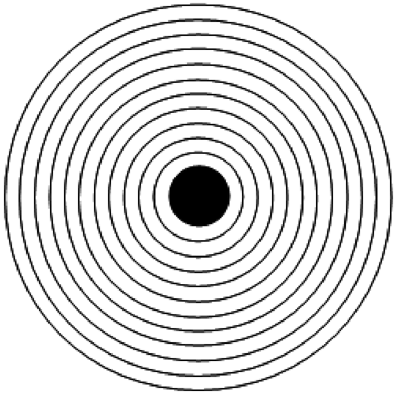


- International projects:
  - <u>Novel X-ray Optics Technologies for ESA X-ray Astrophysics Missions</u> (ESA PECS project, end 6/2011)
  - <u>Applications of Kirkpatrick Baez Imaging Systems in Space</u> – cooperation with Prof. W. Cash at al., *University of Colorado at Boulder* (Ministry of Education, Youth and Sports, end 12/2012)

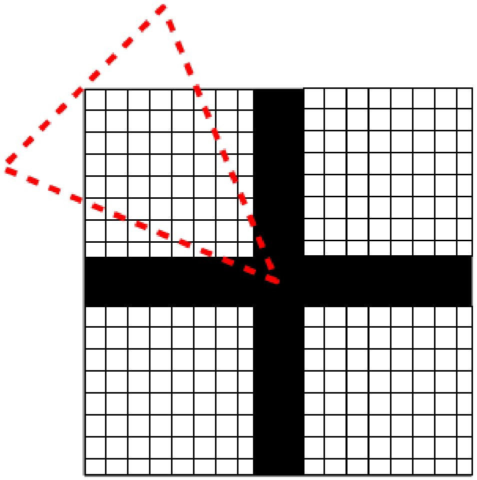


Novel design of X-ray optical system

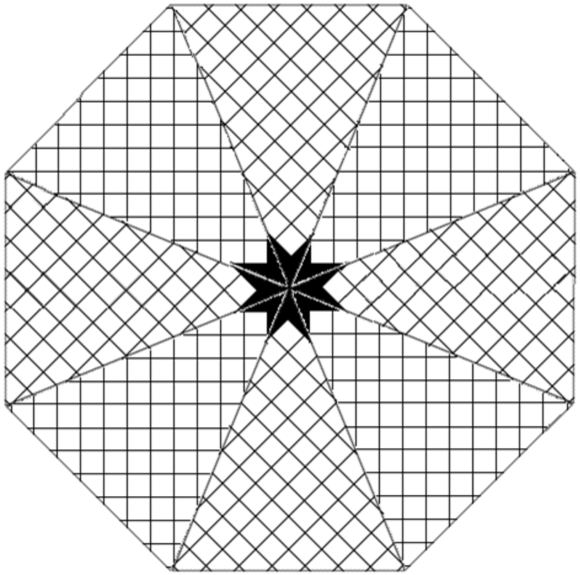
- Size limited by the critical angle – the same maximum incident angle for all systems for 1 keV
- Wolter I and KB systems have the same aperture size
- Flower system has more than two times larger aperture than the others



Wolter system



Kirkpatrick-Baez system

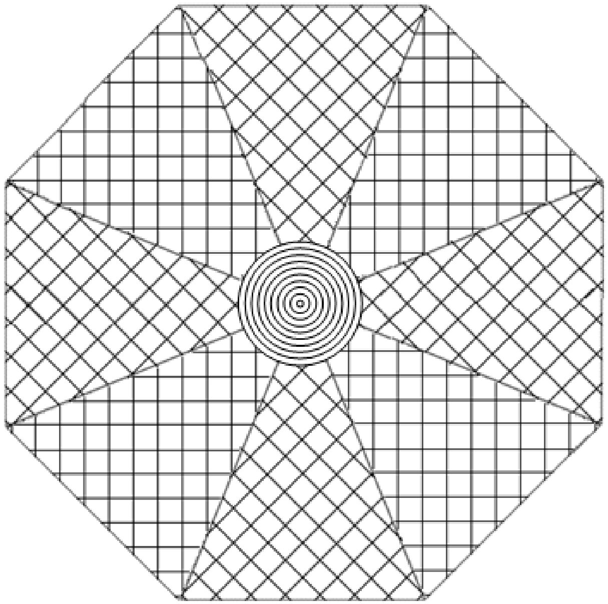


Flower system

Novel design of X-ray optical system

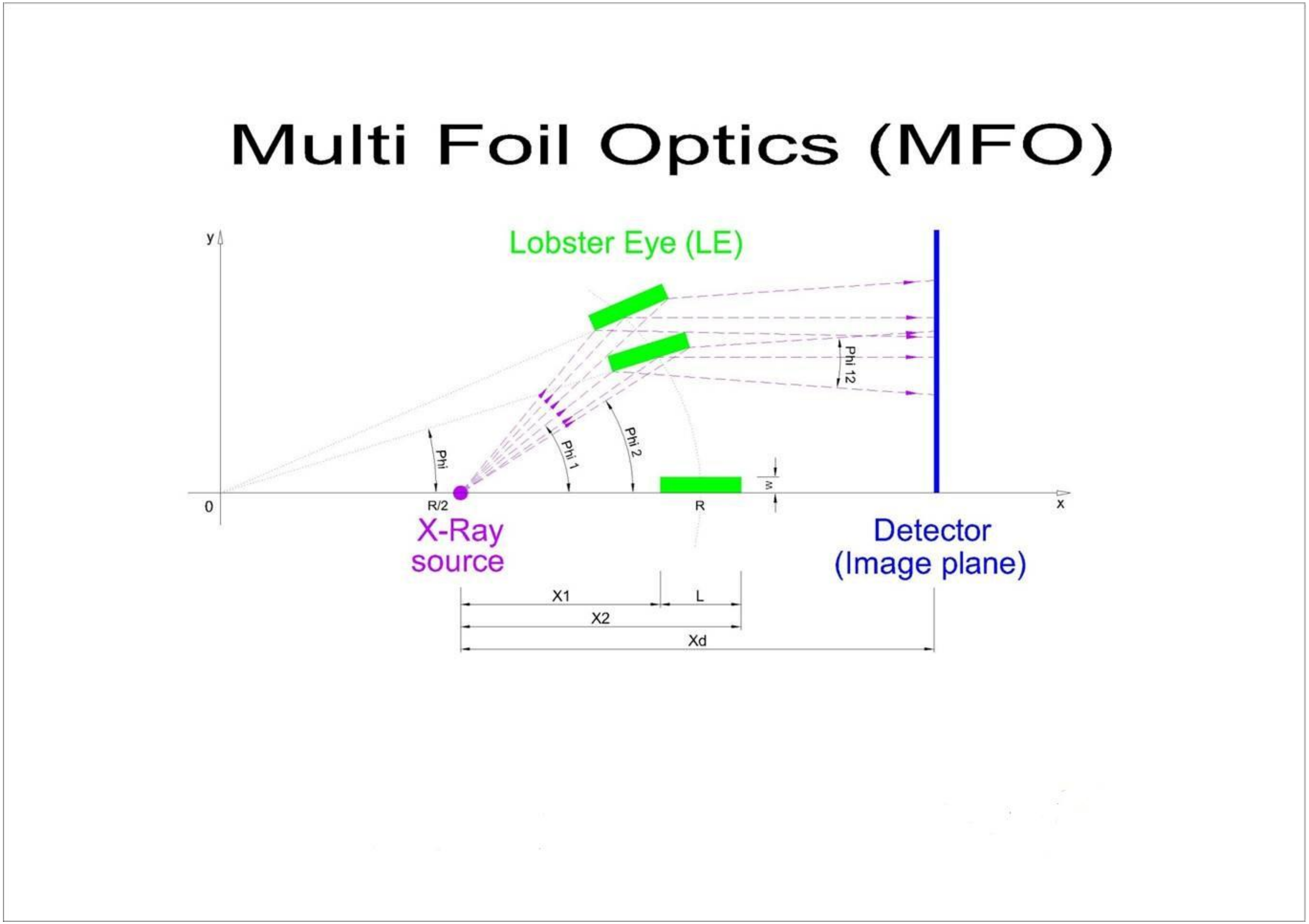
- Non-functional (blind) central area of Flower system can be filled with thin rotationally symmetric foils (classical nested mirrors with parabolic shape)

  => **improvement of Flower optical system aperture effective area for higher energies**



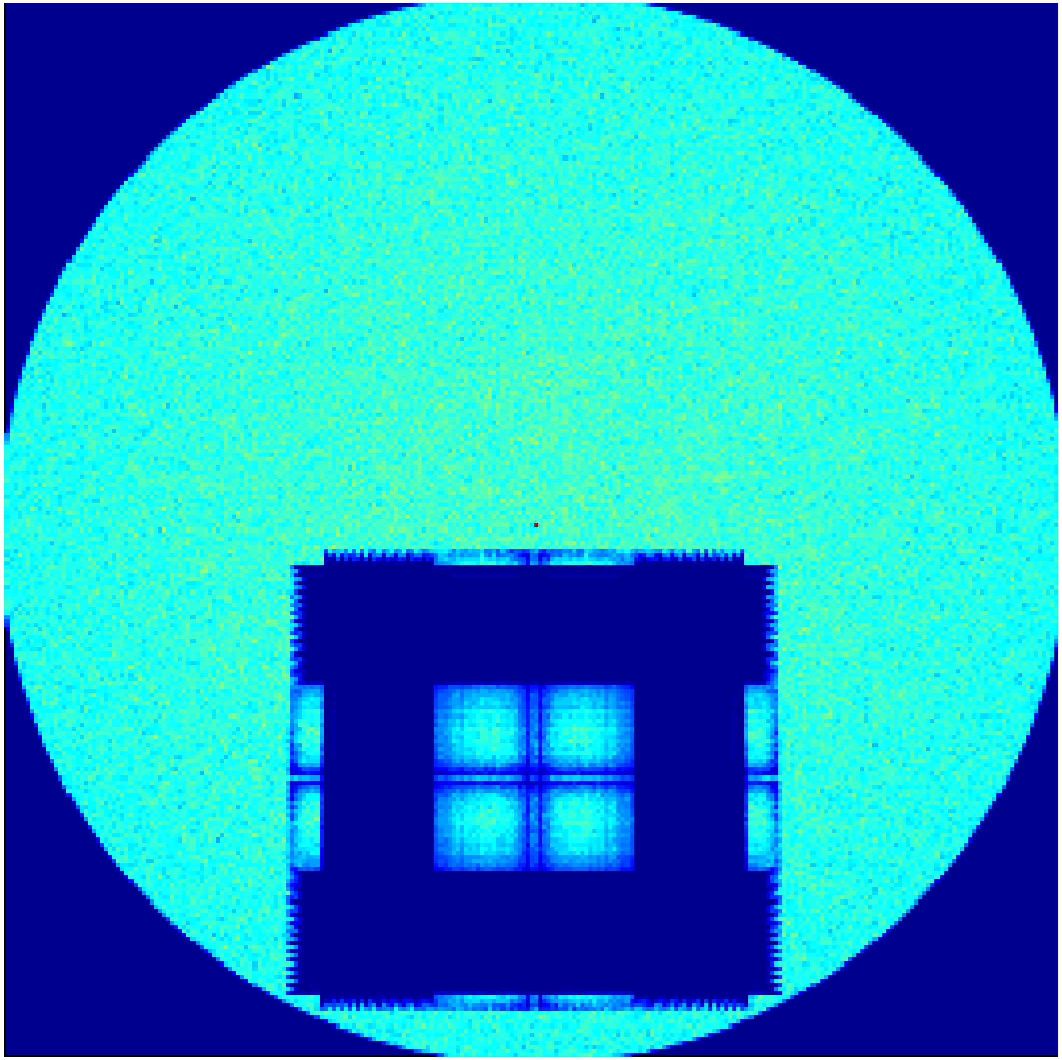
- Patent pending (PV 2011-297)
- Advantages:
  - the largest effective aperture in SXR region
  - higher efficiency in XR region
  - precise expensive mandrels are not needed for Flower part (silicon or glass thin planar mirrors can be used)
- Application in X-ray telescopes, XRF analysis, EUV/XUV microscopy, tomography and EUV/XUV lithography, focusing of electrons/neutrons, ...

Ray tracing – intensity map behind the LE mirror

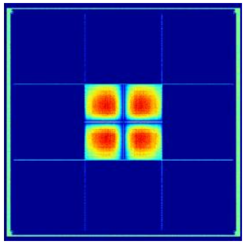


Ray tracing – intensity map behind the LE mirror

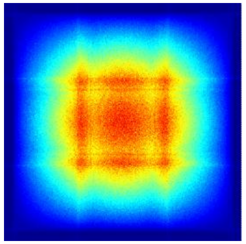
Lobster Eye INTENSITY MAP LE-18 inclined L =6 X1 = 85 Xd = 200 (true position)



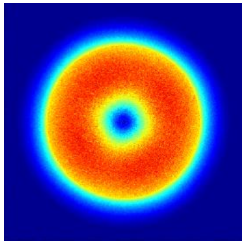
Ray tracing – intensity map behind the LE mirror
Homogenization of X-ray beam



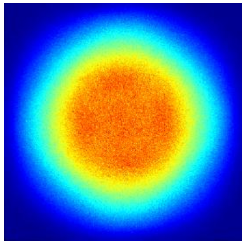
Lobster Eye INTENSITY MAP LE-50 L =6 X1 = 250 Xd = 750



Lobster Eye INTENSITY MAP LE-50 L =6 X1 = 250 Xd = 750 (11 mm detector sweep)



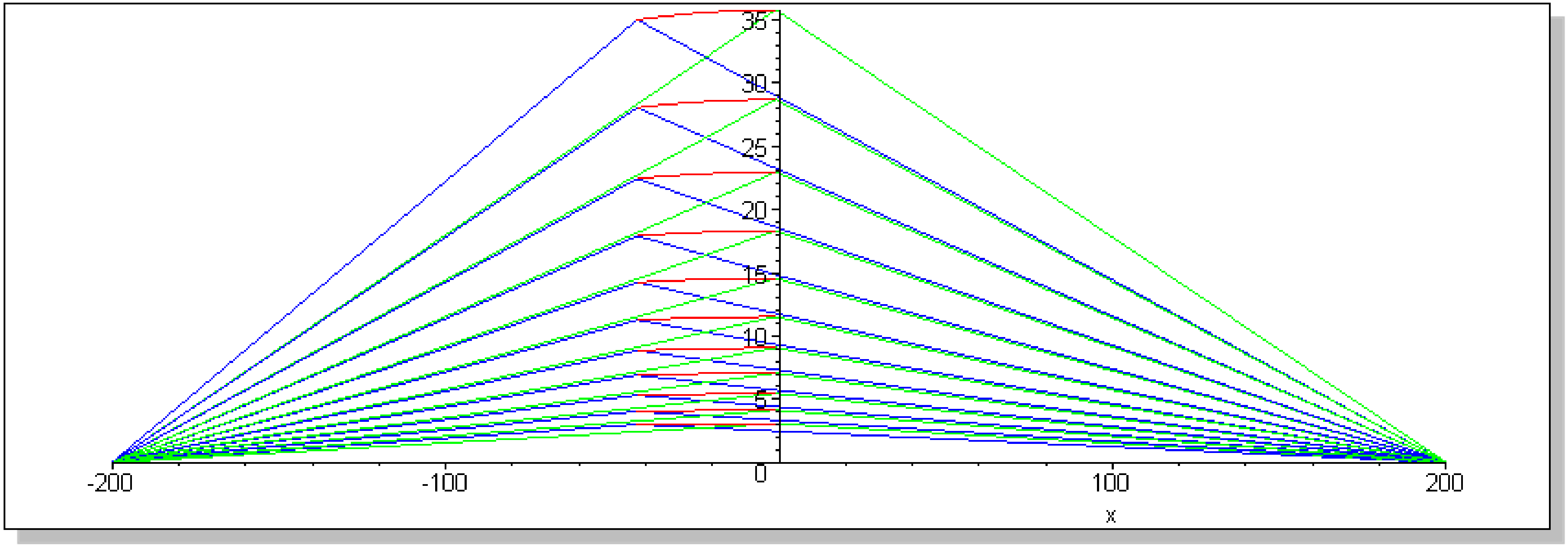
Lobster Eye INTENSITY MAP LE-50 L =6 X1 = 250 Xd = 750 (rotating LE mirror)



Lobster Eye INTENSITY MAP LE-50 L=6 X1 = 250 Xd = 750 (rotating LE mirror + sweeping detector)

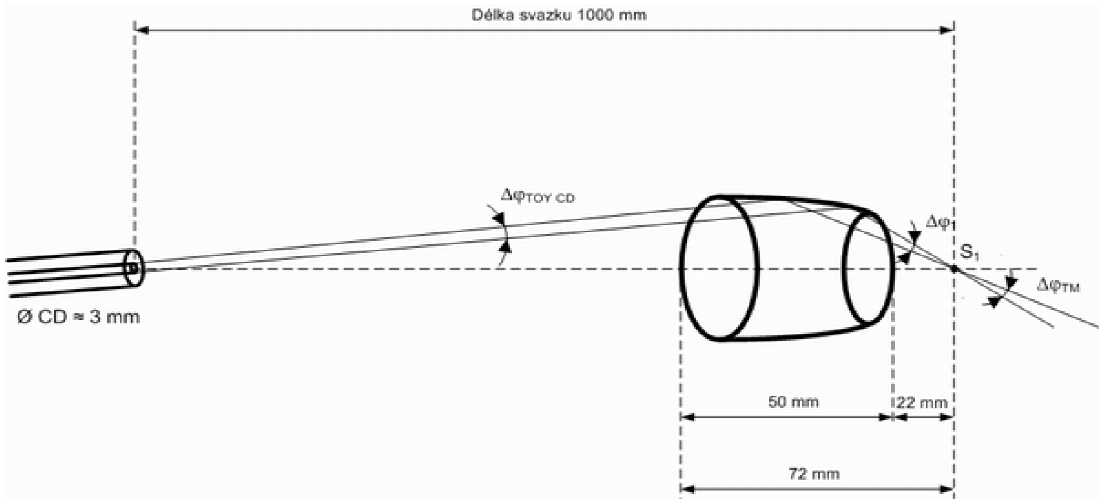
EUV MFO Condensor

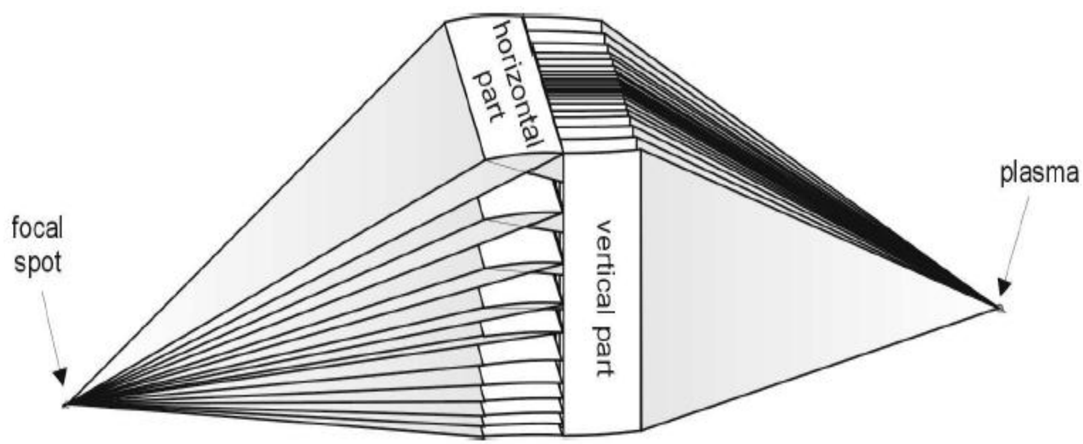
(one quarter of the Kirk-Patrick multi foil mirror system is shown)



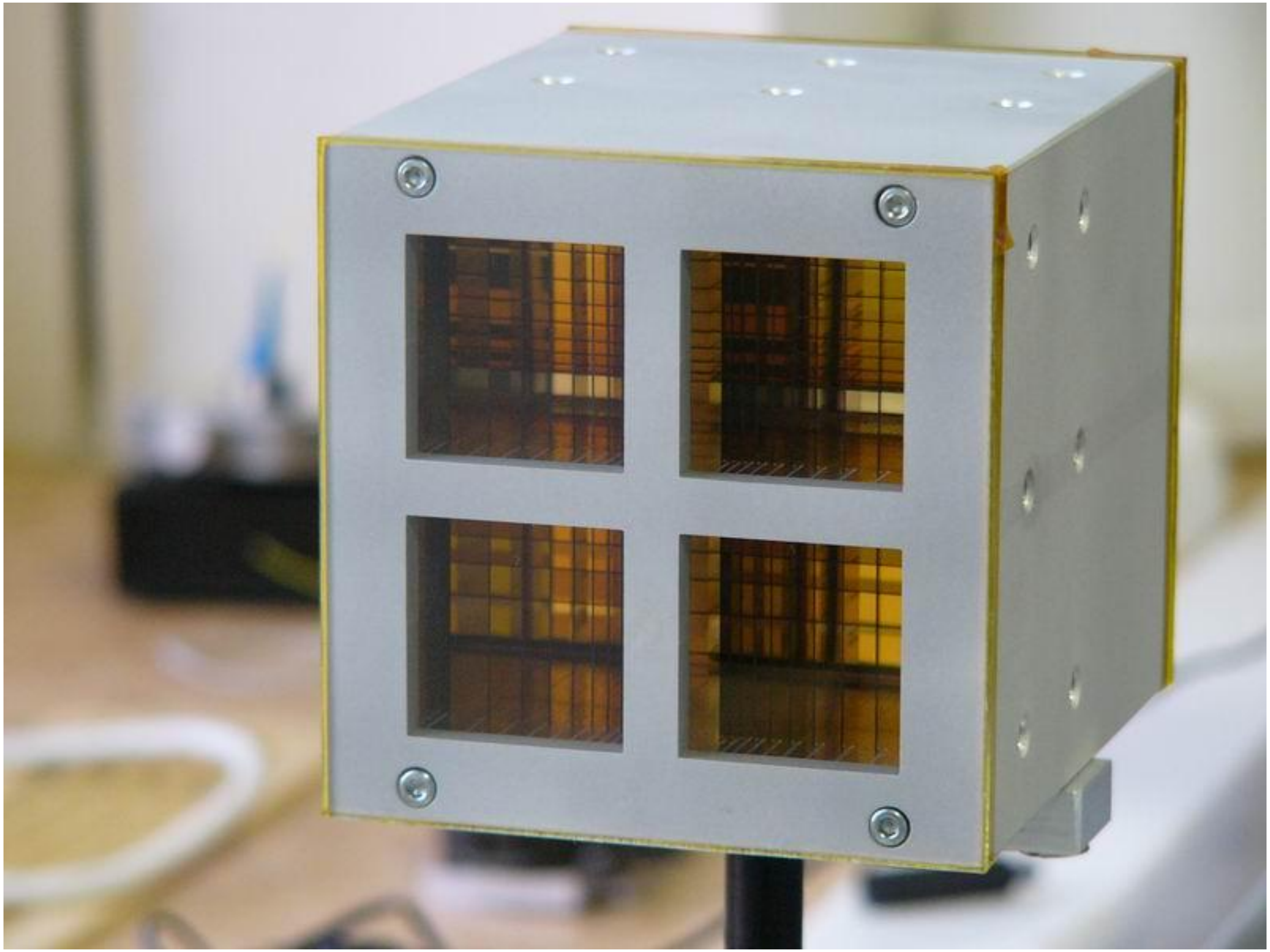
All dimensions in millimeters. Ellipsoidal mirrors, length 40mm, width 80mm.

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

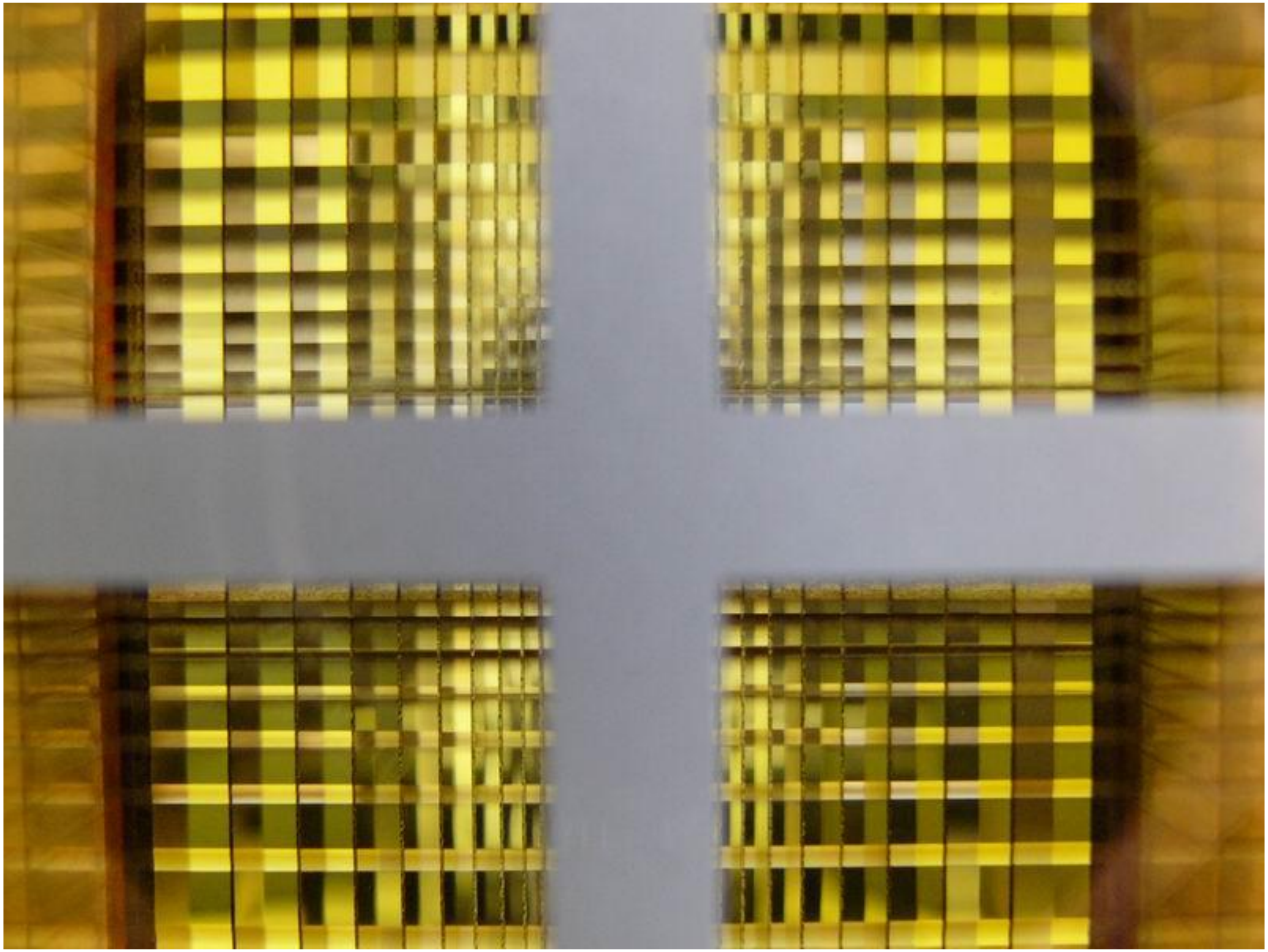




Schematic view of one half of the multi–foil (MFO) XUV bifacial Kirkpatrick-Baez condenser – experiments at WAT, Warsaw.



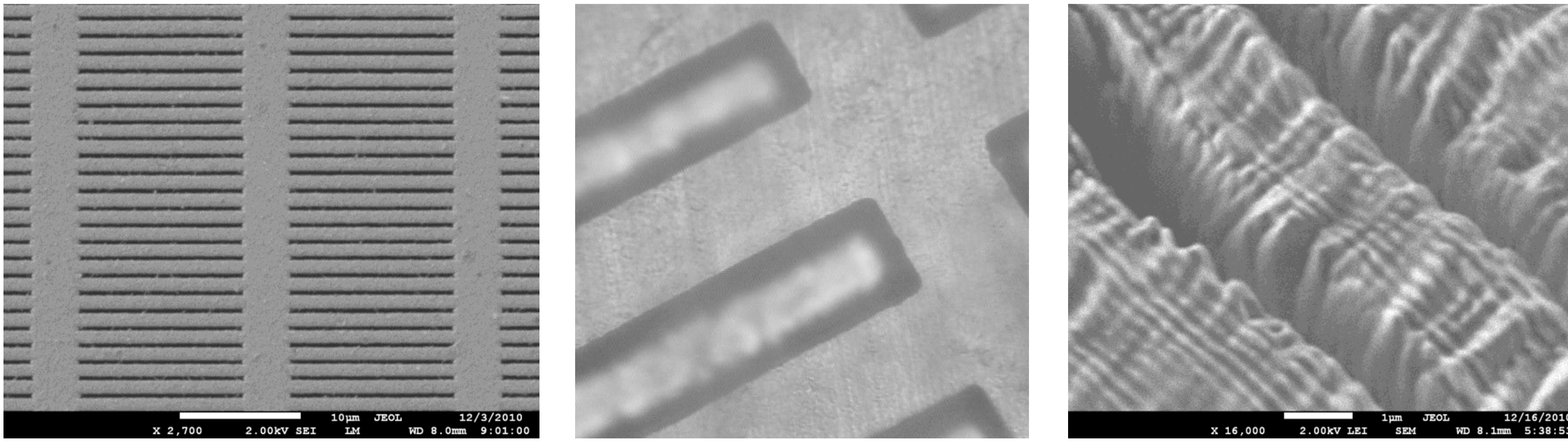
Multi-foil K-B system for EUV lithography



MF K-B system for EUV lithography

EUV beam intensity amplification - joint experiments of CTU Prague and WAT Warszaw

(EUV ablative lithography)



Microstructure made in PTFE by EUV lithography. EUV radiation from gas-puff laser plasma filtered by a metal mask.

THANK YOU FOR ATTENTION

Prague