GI Collectors for EUV/BEUV Sources and Metrology

Ladislav Pina

Rigaku Innovative Technologies Europe, 142 21 Prague 4, Czech Republic

MOTIVATION

- **Collector optics and diagnostic tools for EUV/BEUV lithography**
- **Effective use of current state of the art EUV/XUV/SXR laboratory sources**
- **Effective use of current state of the art EUV/XUV/SXR matrix detectors**

Grazing incidence (GI) collectors for metrology EUV sources , EUV lithography studies and EUV microscopy are of increasing interest. GI collectors can be used for LPP, DPP, electron impact, synchrotron and FEL sources of EUV, BEUV, WW and SXR radiation.

High brightness EUV sources with optics to support mask and other lithography metrology remain a topic with high application potential.

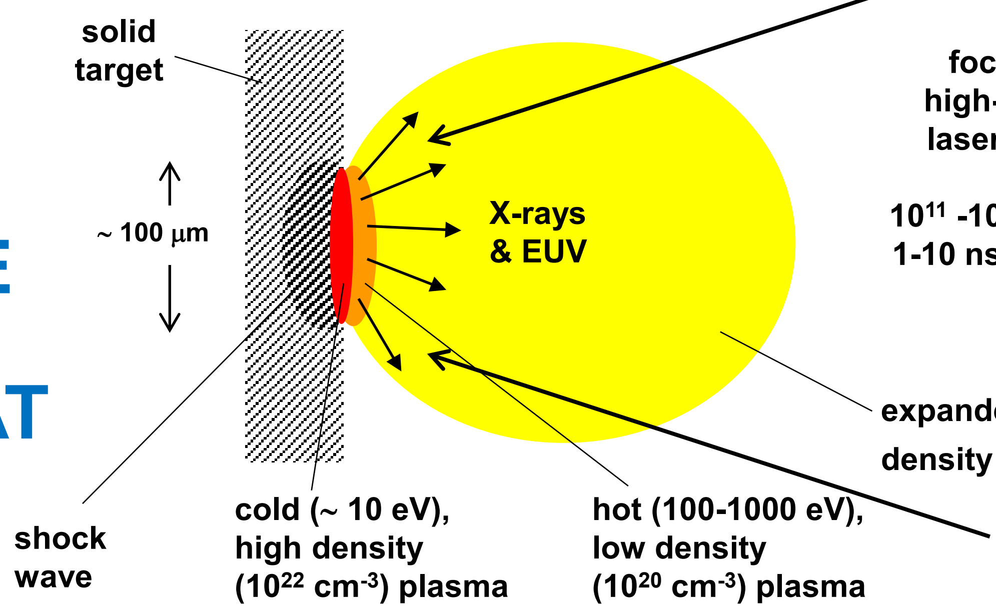
Reported GI collectors in combination with laboratory EUV lithography LPP and DPP sources have been developed and tested within collaboration of hot plasma and optical laboratories in Prague and Warsaw.

EUV/BEUV/SXR Sources

- Synchrotron Radiation (SR)
- Free Electron Laser (FEL)
- Hot Plasma - Laser Produced Plasma (LPP)
- Hot Plasma - Discharge Produced Plasma (DPP)
- Nonlinear Interaction - High Harmonic Generation (HHG)

Laser Produced Plasma (LPP) (solid/liquid target)

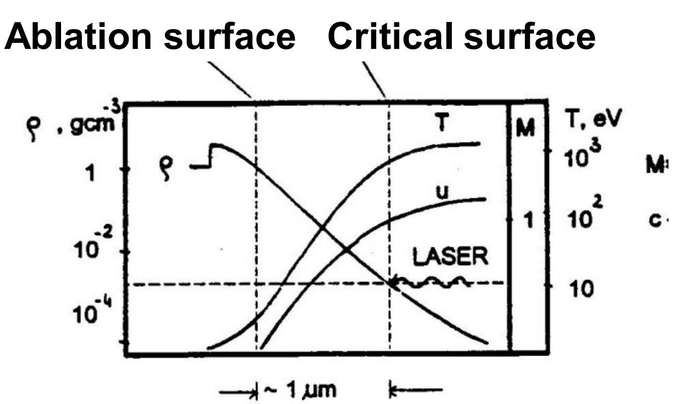
PALS
ELI
HiLASE
CTU
IOE WAT



focused high-power laser beam

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

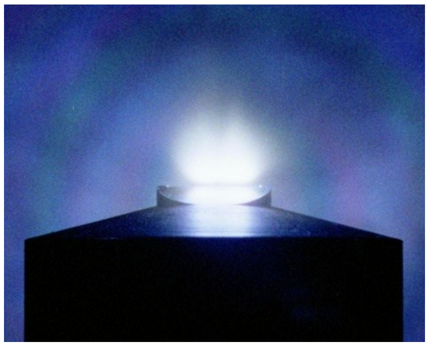
Nd:glass
Nd:YAG
KrF
CO_2

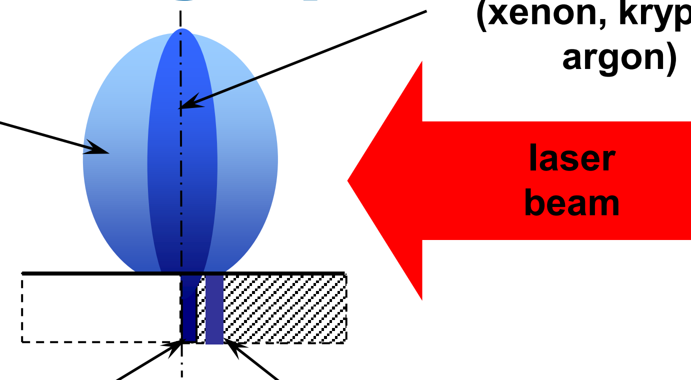


Laser plasma parameters for maximum EUV emission

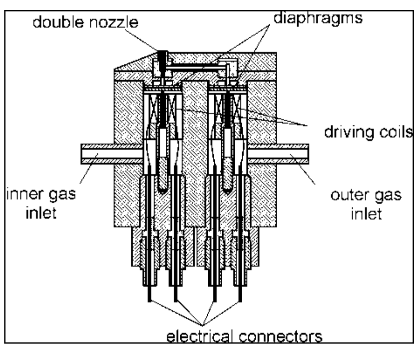
~ 40 eV, ~ 10^{19} cm^{-3}

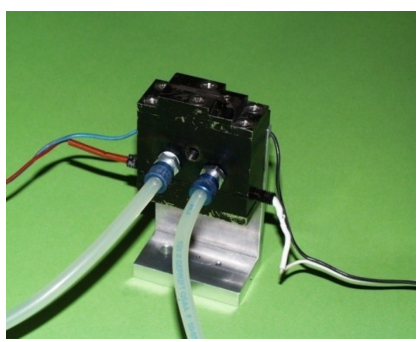
Laser Produced Plasma (LPP) (gas puff target)



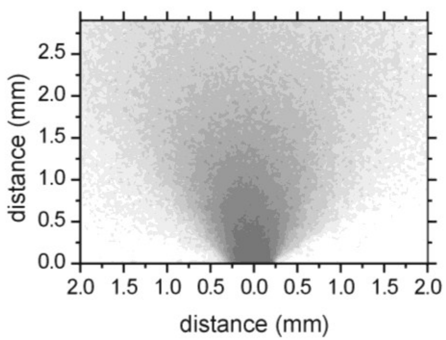


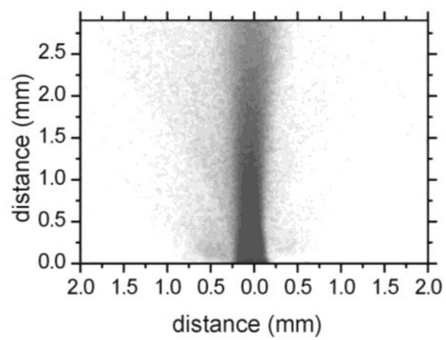
- electromagnetic valve system





- X-ray backlighting images

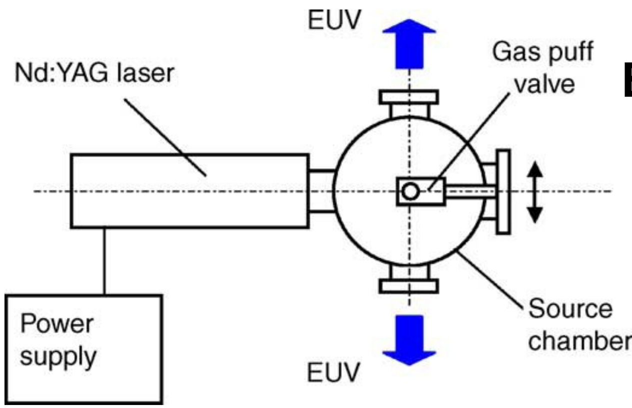




H. Fiedorowicz *et al. Appl.Phys. B 70 (2000) 305; Patent No.: US 6,469,310 B1*
WAT , Warszaw

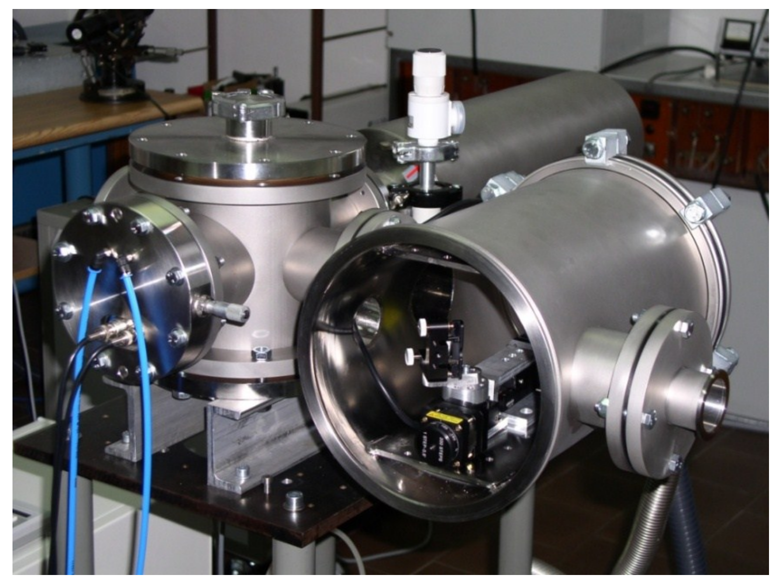
COMPACT LASER - PLASMA EUV SOURCE

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 by IOE WAT, Warsaw.



EUV source

EUV metrology setup



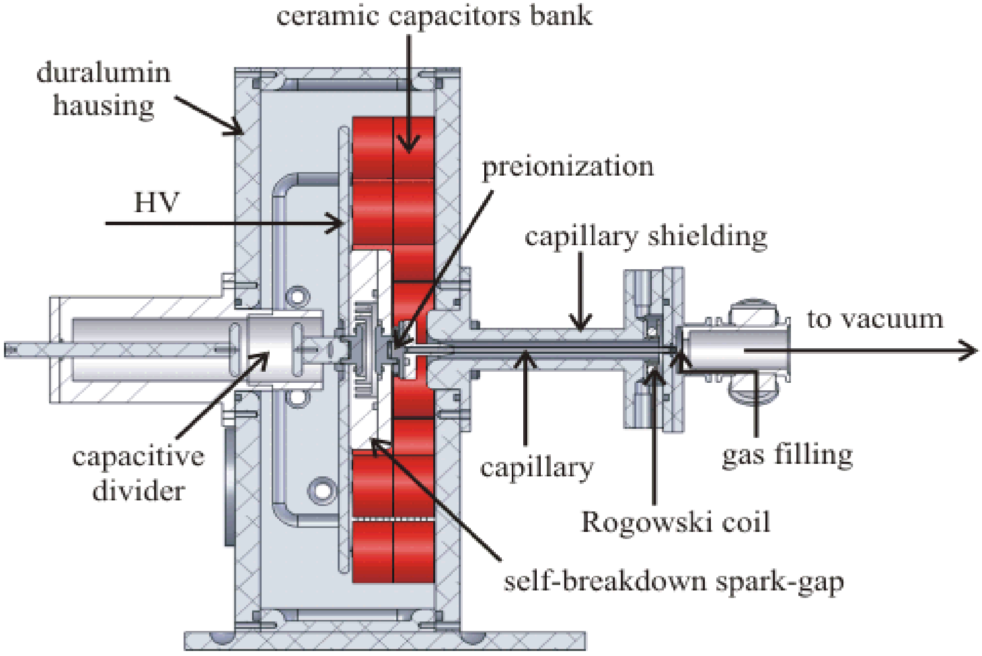
H. Fiedorowicz *et al., J.Alloys&Compounds* ***401*** *(2004) 99*

Laser Produced Plasma (LPP)
(gas puff target)
(Czech. Tech. Univ., Faculty of Biomedical Engineering)

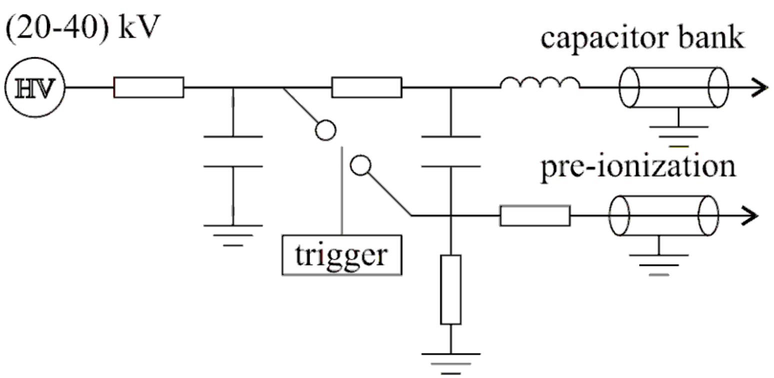
LPP source designed and delivered by
Dr. Klaus Mann
Dept. Optics – Short Wavelengths Laser-Laboratorium
Göttingen e.V.
Göttingen

Experimental LPP apparatus (M. Vrbova)
CTU Prague, Faculty of Biomedical Engineering

Pinching Discharge Produced Plasma (DPP)
Capillary Discharge Plasma
(Czech Tech. Univ. Faculty of Nuclear Sciences)



Main discharge unit

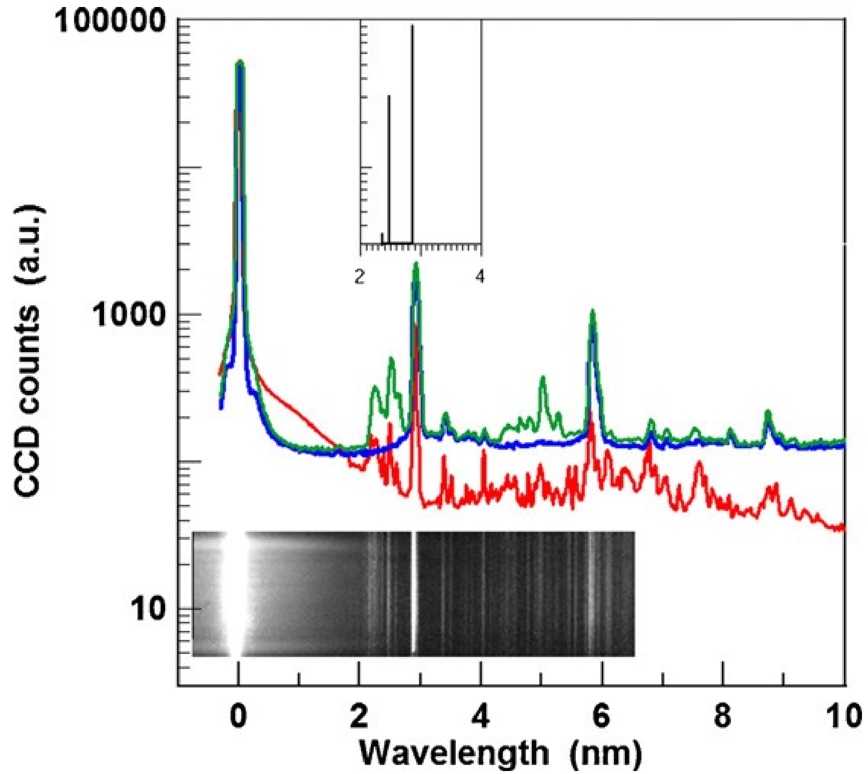


Charging circuit

- **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

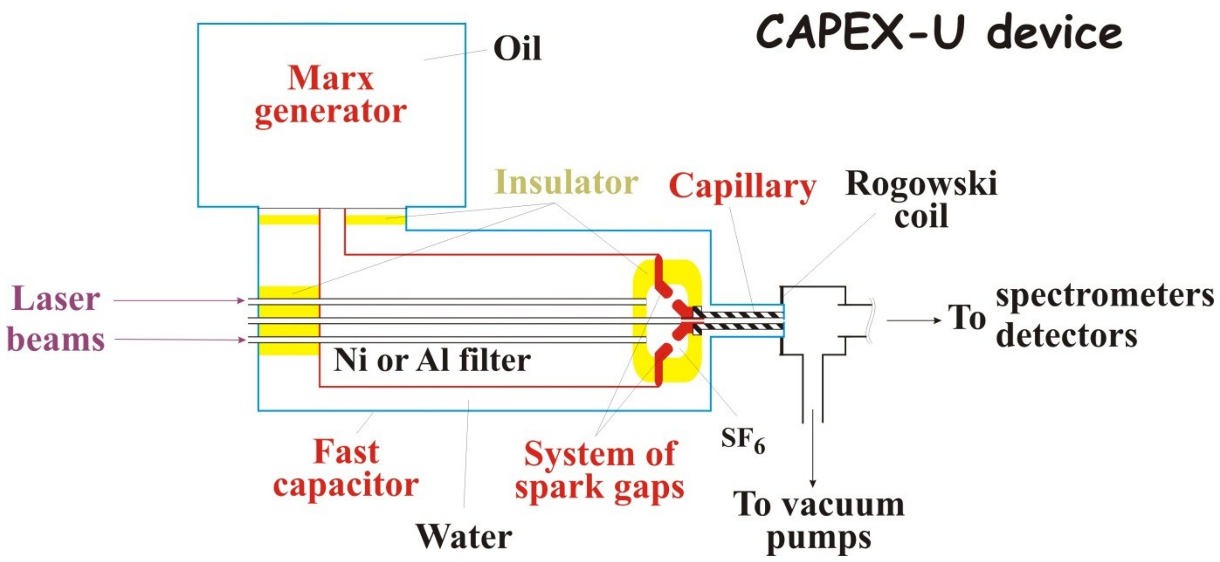
Pinching Discharge Produced Plasma (DPP)
Capillary Discharge Plasma (Czech. Tech. Univ.)

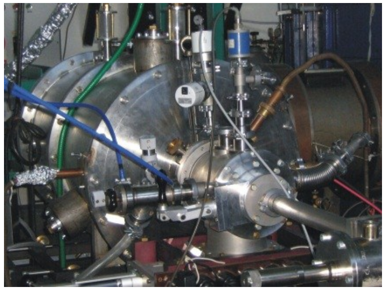


Spectral lines of helium-like nitrogen (TGS). EUV spectrum as registered by CCD camera (red line–200 um aperture without filter, green line – 400 um aperture and Cr filter, blue line – 400 um aperture and Ti filter).

Experimental capillary discharge apparatus (A. Jancarek, M. Nevrkla)
CTU Prague, Faculty of Nuclear Sciences

Pinching Discharge Produced Plasma (DPP)
Capillary Discharge Plasma (Czech Acad. of Sciences, Institute of Plasma Physics)





Experimental capillary discharge apparatus (K. Kolacek)
Czech Academy of Sciences, Institute of Plasma Physics, Prague

MARX GENERATOR
- 8 stages
- erected capacity 12.5 nF
- short-circuit inductance 14.2 μH
- erected voltage 800 kV

FAST CAPACITOR
- distilled water as a dielectric
- capacitance 12.7 nF
- inductance 37.3 nH
- char.impedance 1.7 Ω
- dimensions ϕ550 x ϕ426 x 730 mm

CAPILLARY
- thin-walled ceramic capillary
- filled by a needle valve or/and fast valve
- fast shutter
- diameter ϕ1-4 mm
- length up to 230 mm

SPARK GAPS
- laser-triggering system
- four parallel spark gaps (axially symmetric, 90 degree step)
- filled by SF_6 gas and/or another gas

Pinching Discharge Produced Plasma (DPP)
Capillary Discharge Plasma (Czech Acad. of Sciences, Institute of Physics)

Pulse energy: E ~10µJ

Pulse length: Δt = 1,2 ns

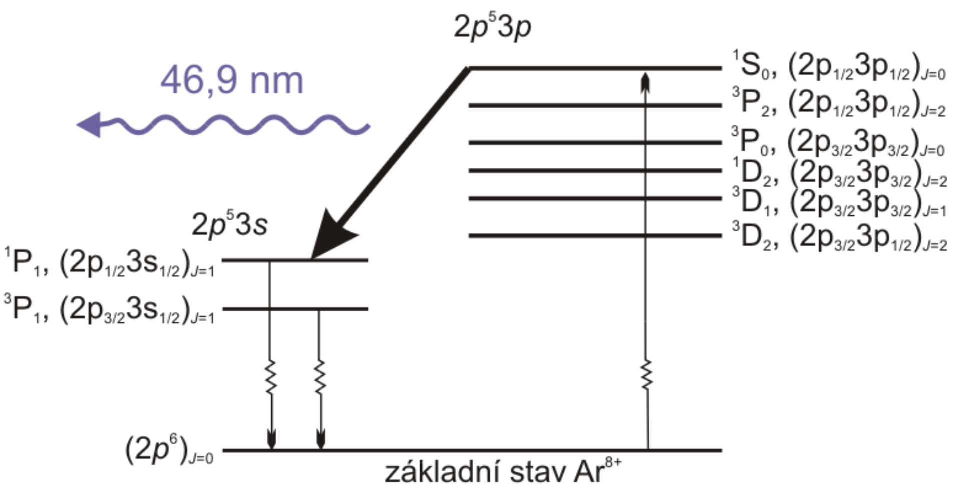
Wavelength: λ = 46,9 nm

Beam divergence: θ ~ 4,5mrad

Repetition frequency: max. 10Hz

CDD designed and delivered

by J.J. Rocca (Col. Univ.)

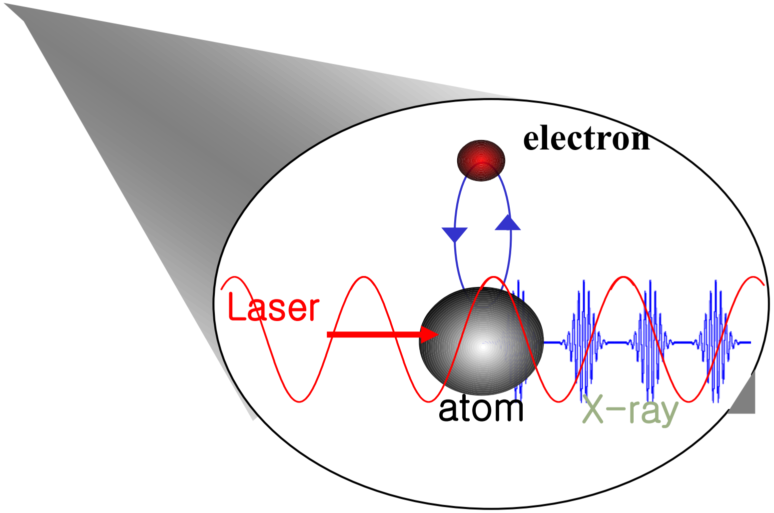


Experimental capillary discharge apparatus (L. Juha, J. Chalupsky)
Czech Academy of Sciences, Physical Institute, Prague

High Harmonic Generation (HHG)
(Femtosecond Laser – Gas Target Interaction)

Femtosecond Lasers - HHG Sources in Prague

- Czech Academy of Sciences
- Czech Technical University
- (IOE WAT Warsaw)



High Harmonic Generation (HHG)
(Femtosecond Laser – Gas Target Interaction)

Coherent XUV sources driven by ultrashort laser pulses at CTU Prague

K. Jakubczak[1, 2], M. Drahokoupil[2], V. Picková[2], J. Limpouch[2], T. Mocek[1], L. Pína[2, 3]

[1]Dept. of Physical Electronics, FNSPE, CTU, Prague
[2]HiLASE Project, Institute of Physics, AS CR, Prague
[3]Rigaku RITE, Prague

Laser parameters:
- E = up to 12 mJ
- Δt = ~ 60 fs
- D < ~ 1″
- Rep. rate 10 Hz

Faculty of Nuclear Sciences and Physical Sciences fs Lab

Collector Optics for EUV/BEUV/SXR Sources

- Zone Plates (Fresnel Lens)
- Multilayer Mirrors
- Grazing Incidence Mirrors
    - High Power Load
    - Polychromatic
    - Lower Cost

Grazing Incidence Collector Mirrors for EUV/BEUV/SXR Sources in Prague

- History of GI optics development in Prague
- Optical systems applicable for EUV/BEUV/SXR radiation
- Example Applications

Grazing Incidence Optics

Total external reflection

No monochromatisation, hard energy cut-off

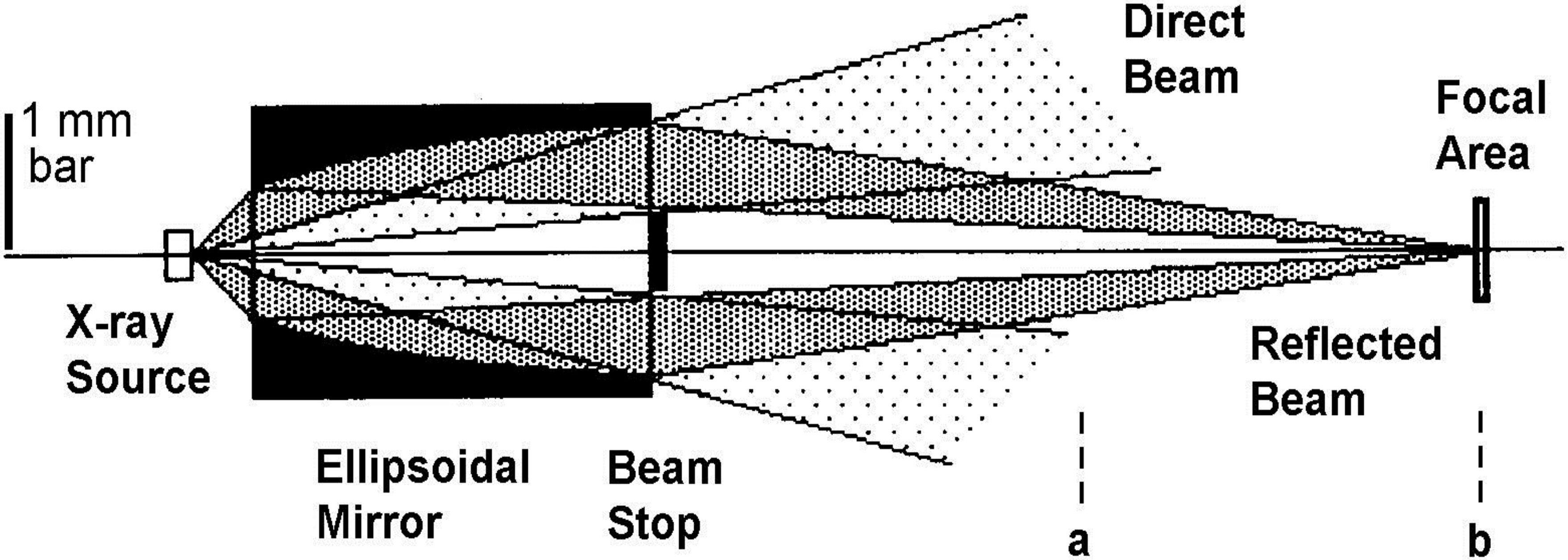
- Flat mirrors
- Capillaries, polycapillaries
- Parabolic, elliptic and foil mirrors, paraboloidal and ellipsoidal mirrors
- Kirkpatrick-Baez optic
- Wolter optic

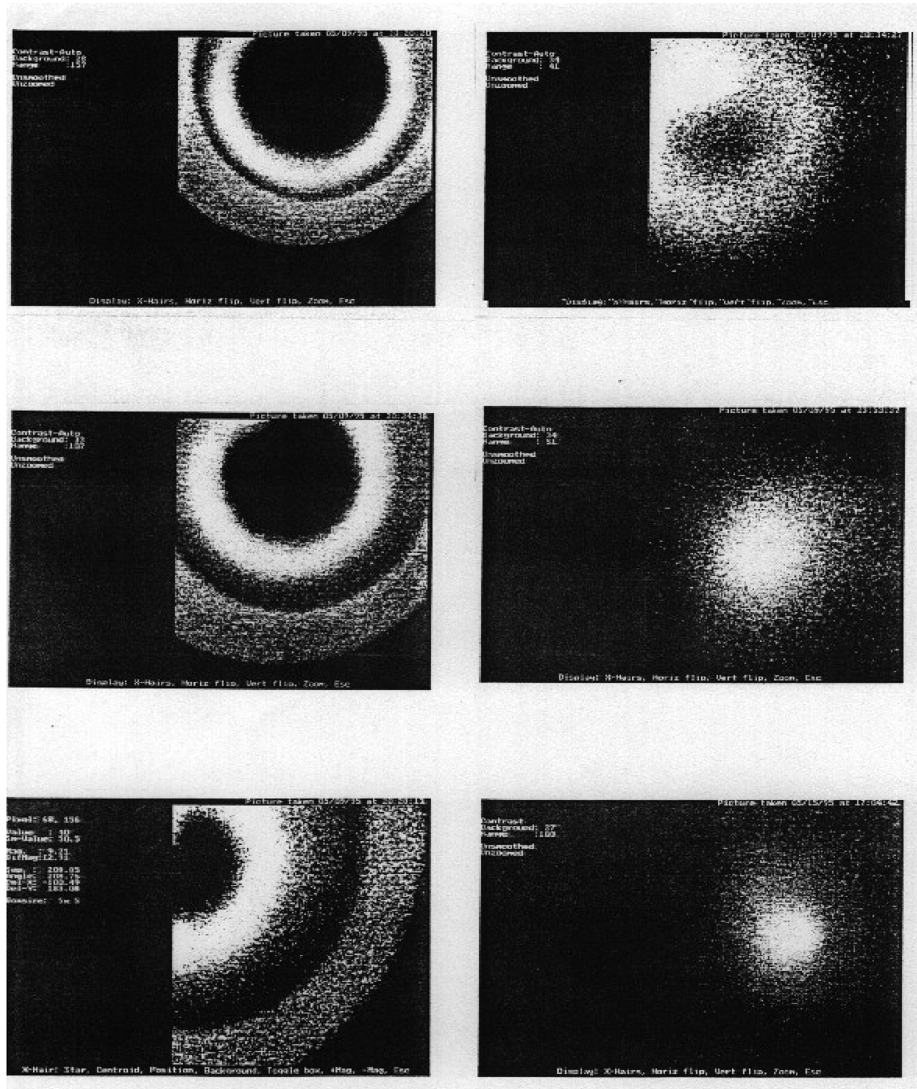
0 mm

Y-AXIS IN THE SAME SCALE AS X-AXIS

400 mm

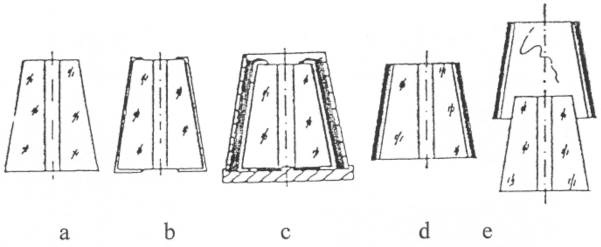
Y-AXIS NOT IN THE SAME SCALE AS X-AXIS



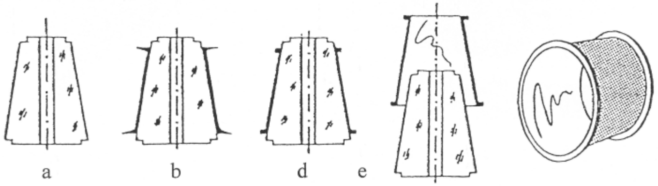

Display: X-Hairs, Horiz flip, Vert flip, Zoom, Esc
X-Hair: Star, Centroid, Position, Background, Toggle box, +Mag, -Mag, Esc

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

- 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



a - master, b - master with nickel layer,
c - flooding of the master,
d - cutting/finishing of the



- Laboratory application
  - objectives with Ø 20 mm
  - used for taking photographs of laser plasma in *Institute of Plasma Physics and Laser Microfusion in Varsava*

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

Astronomical Institute, Acad. Sci., B. Valnicek, R.Hudec

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

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

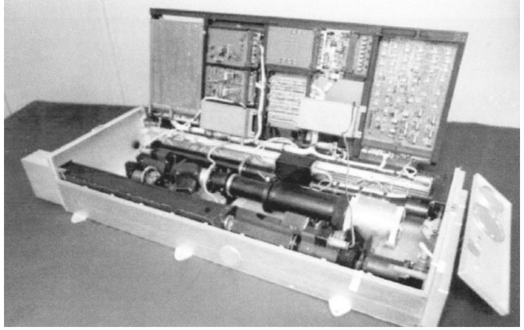
1979 First mirror flown in Space (2x Wolter, 240 mm nested)

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)

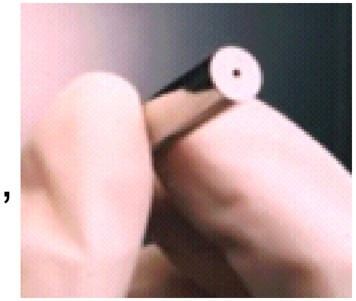
1985 — Applications for plasma physics (EH 17 mm, PP 20 mm)



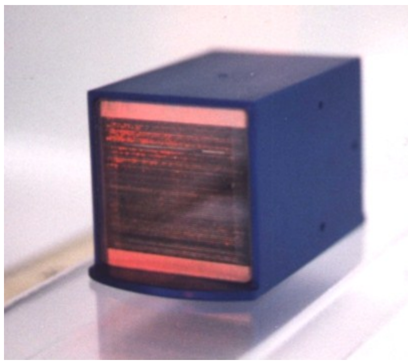
1988 — FOBOS 1 Mars probe, TEREK X-ray telescope

1989 — KORONAS I (Wolter 80 mm)

Post-Soviet era



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

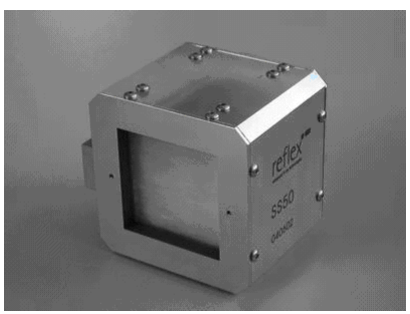


1993 — Collaboration with SAO (Cambridge, USA) WF X-ray optics

1996 — XRO group at Reflex

First Lobster Eye (Schmidt)

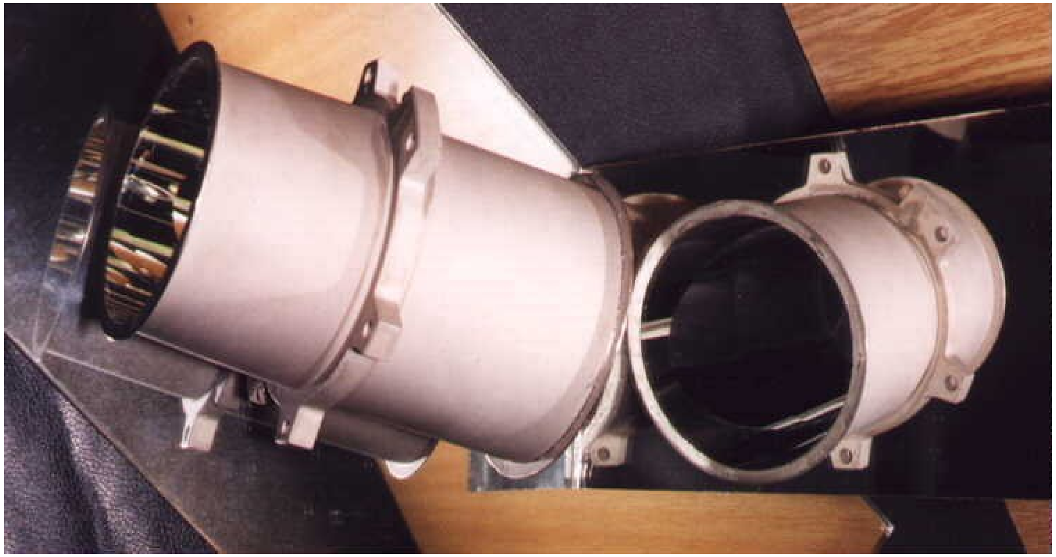
1999 — Lobster Eye (Angel)



2000 — Soller Slit

2001 — Multifoil optics

2002 — Micromirror with multilayers

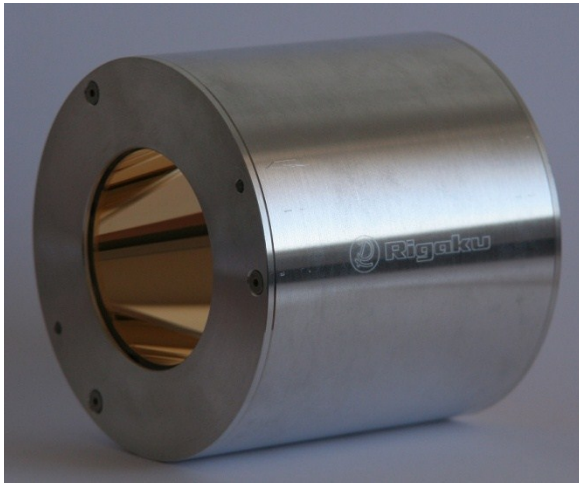


Application range

Replicated Wolter I X-ray mirrors of the KORONAS satellite (aperture 80 mm)

Replicated X-ray micromirror (aperture 0,4 mm, 8keV – grazing angle 0,5°)

EUV Condensor for Laser Plasma Research and EUV Litography

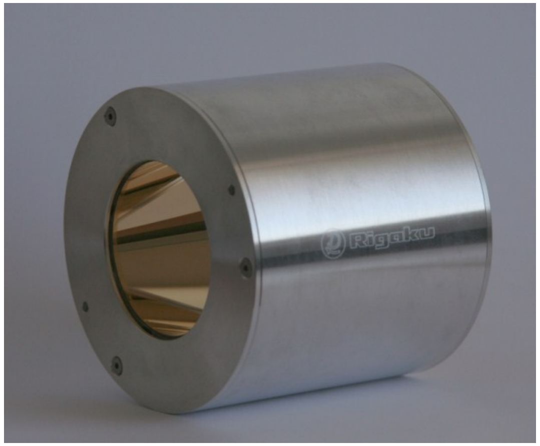


Rigaku Innovative Technologies Europe

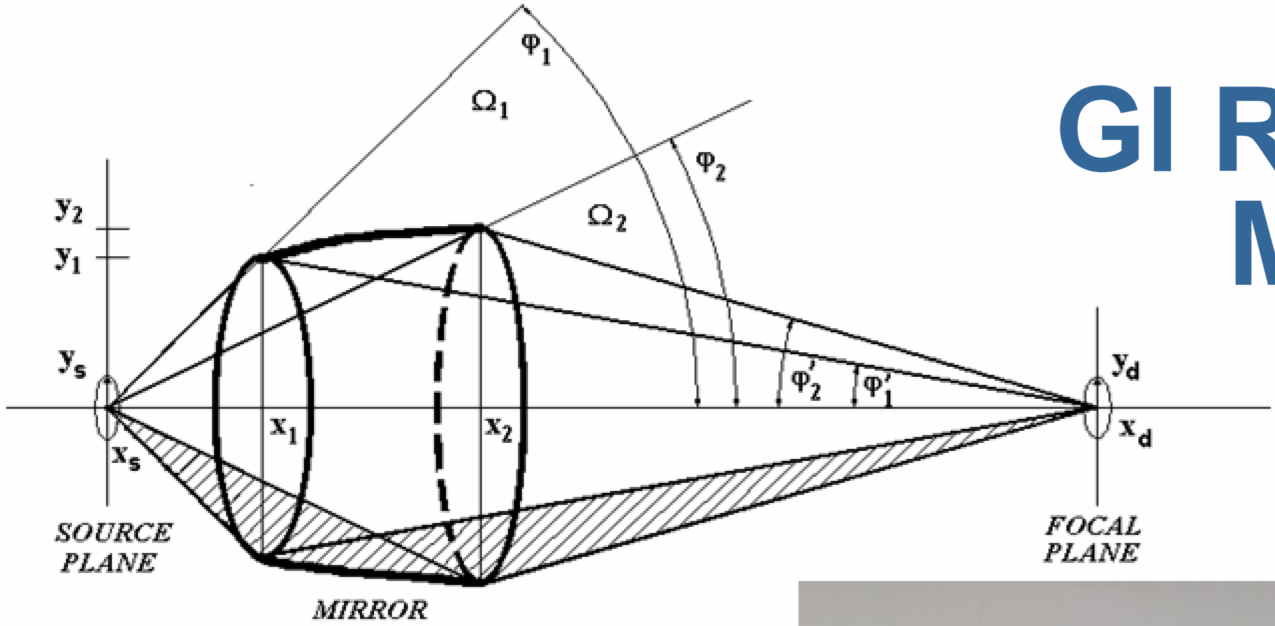
- A part of Rigaku Corporation group (Tokyo, Japan)
- Established in 2008 as European center for the design, development and manufacturing of **X-ray optics**, **X-ray detectors** and **X-ray sources**
- Colaboration with Prague Universities and Czech academic institutes

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

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

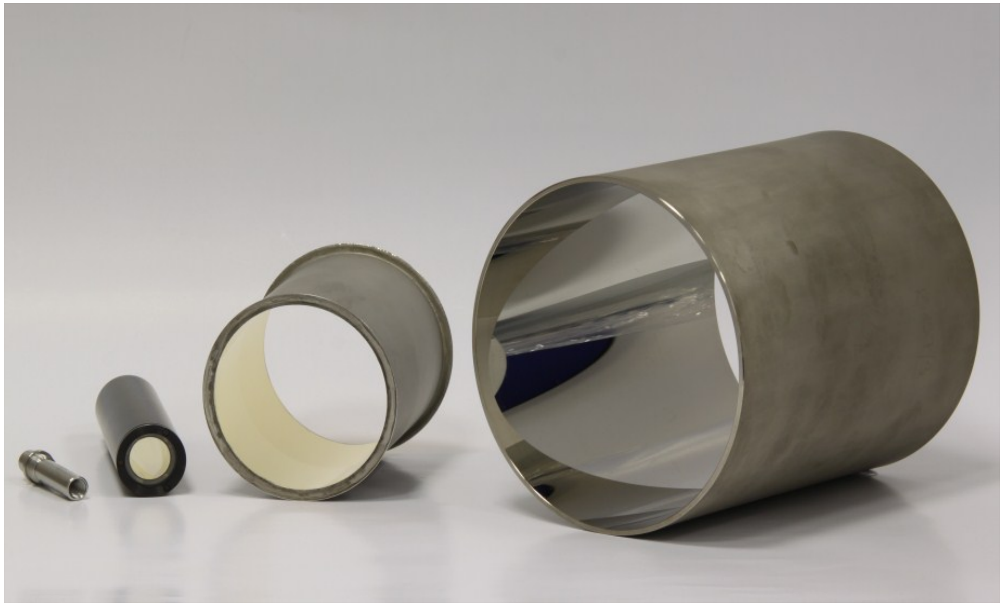


GI Replicated Mirrors



Example: Elliptical mirror

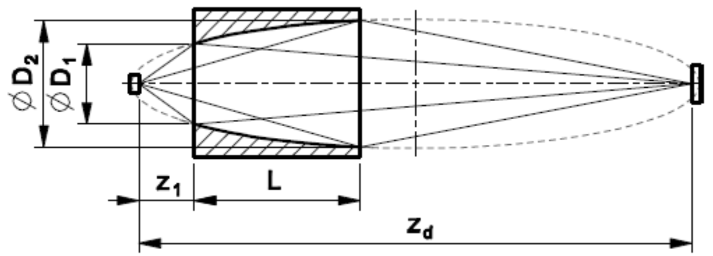
- Mirror surface has shape of rotational ellipsoid
- Source is placed in left focus
- Detector or sample is placed in right focus
- Radiation strikes mirror surface at grazing angles 0,5° ÷ 20°
- Mirror is focusing radiation from left focus on right focus

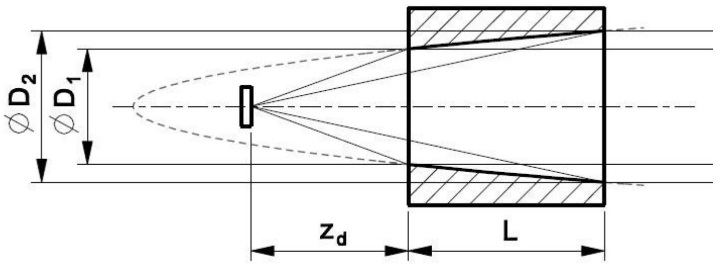


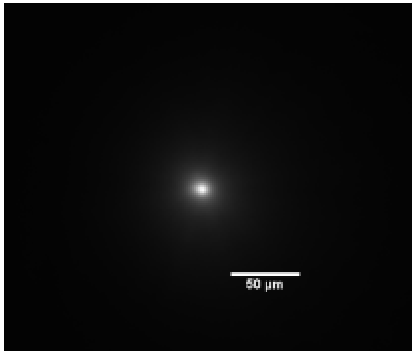
GI Replicated Mirrors

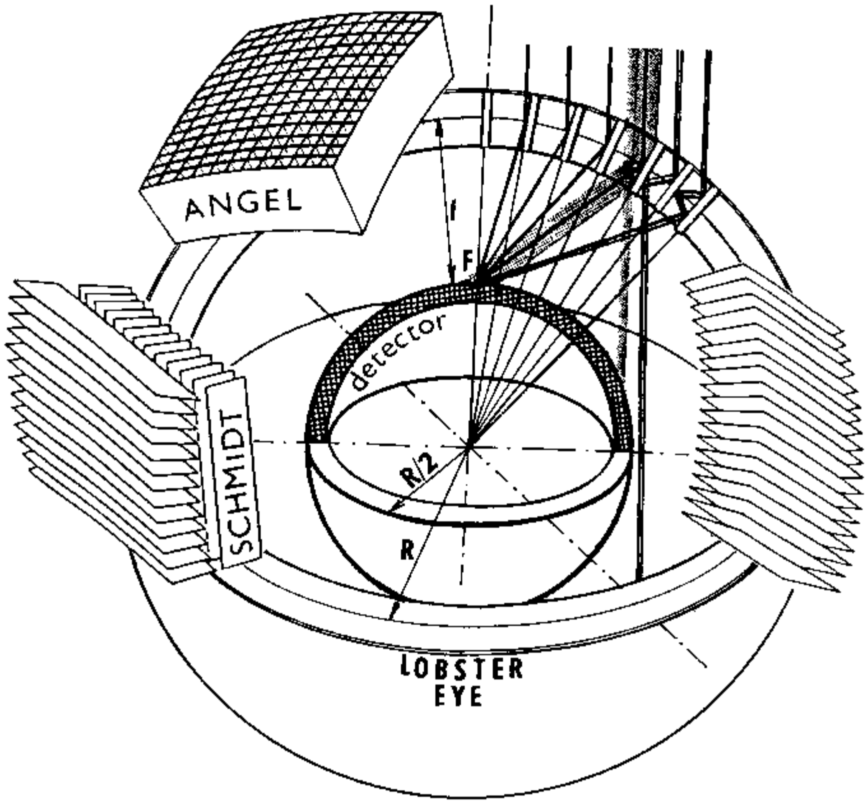
Parameters

- Suitable radiation:
    - EUV (60 - 200 eV)
    - soft X-rays (200 – 2 keV)
    - X-rays (2 - 10 keV)
- Optical shape:
    - Elliptical (point to point focusing)
    - Parabolic (parallel beam)
    - Other aspherical shapes on request
- Optical surface material: Au, Ni, etc.
- Typical surface roughness: Ra ≈ 0,5 - 2 nm
- Typical dimensions:
    - Diameter ∅D = 1 mm ÷ 100 mm
    - Length L = 10 mm ÷ 100 mm





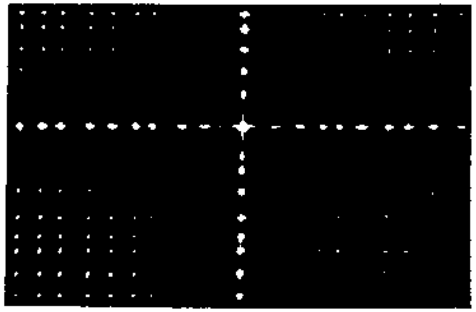


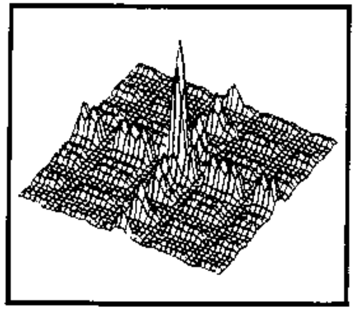


Lobster Eye (LE)

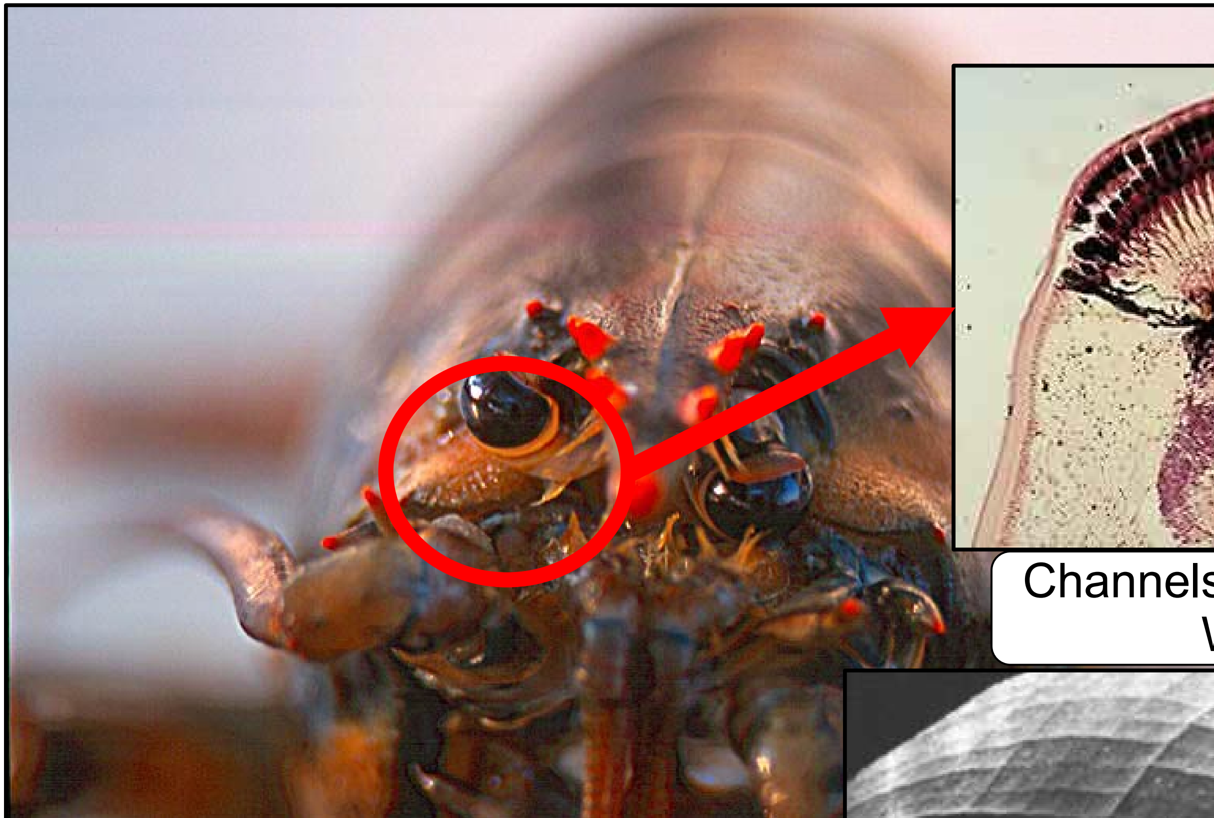
- One array of flat mirrors
  (1D LE)
- Two arrays of flat mirrors
  (Schmidt system)
- One matrix of square channels
  (Angel system)
- Grazing incidence reflection

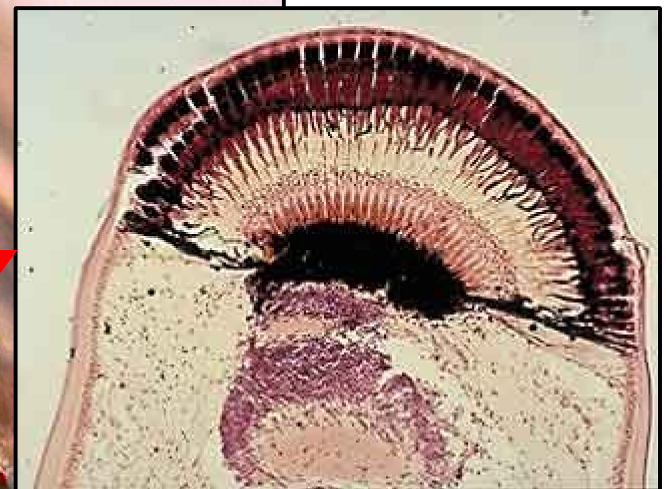
Large FOV
Low angular resolution
High collection efficiency



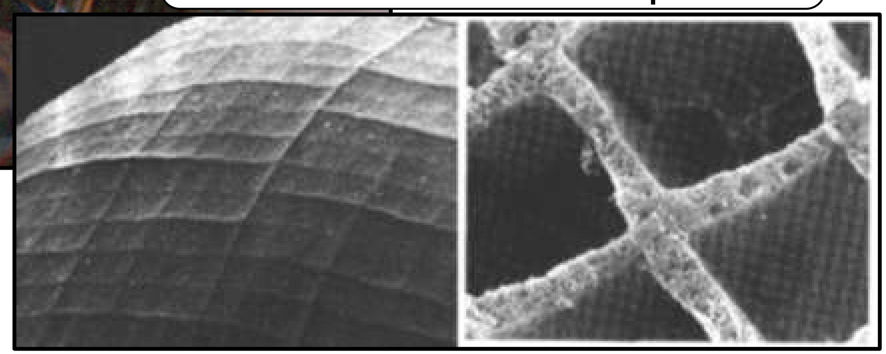


Lobster Eye



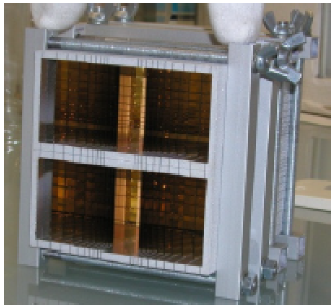


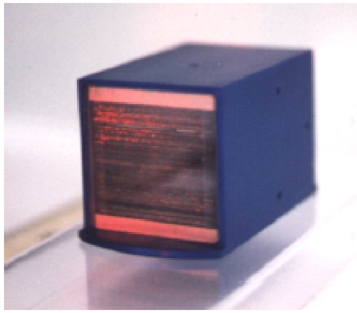
Channels – optical elements
Wide Field Optic

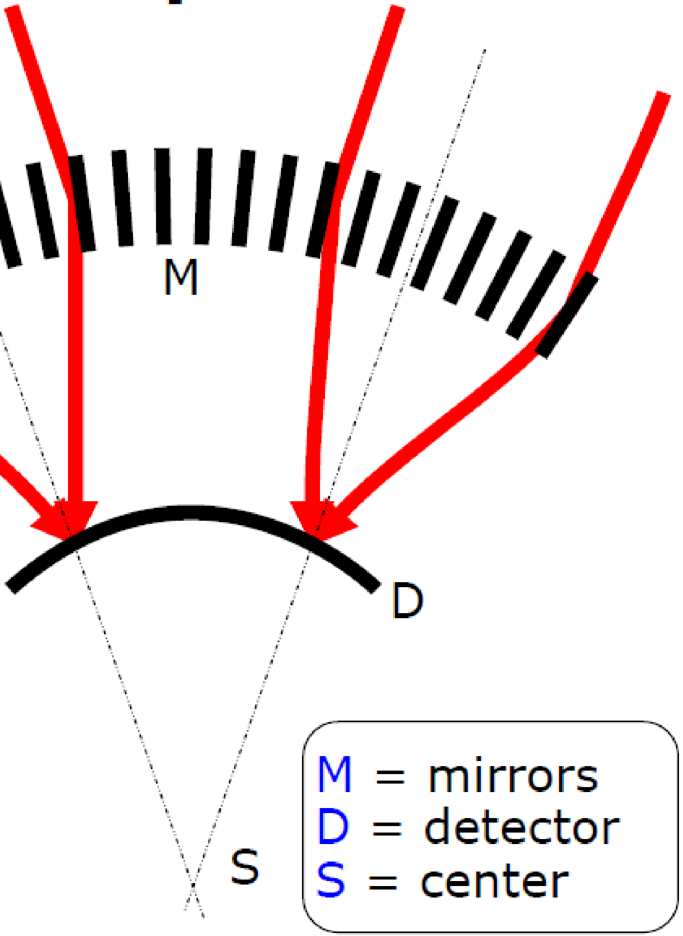


Lobster eye & multifoil optics

- 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

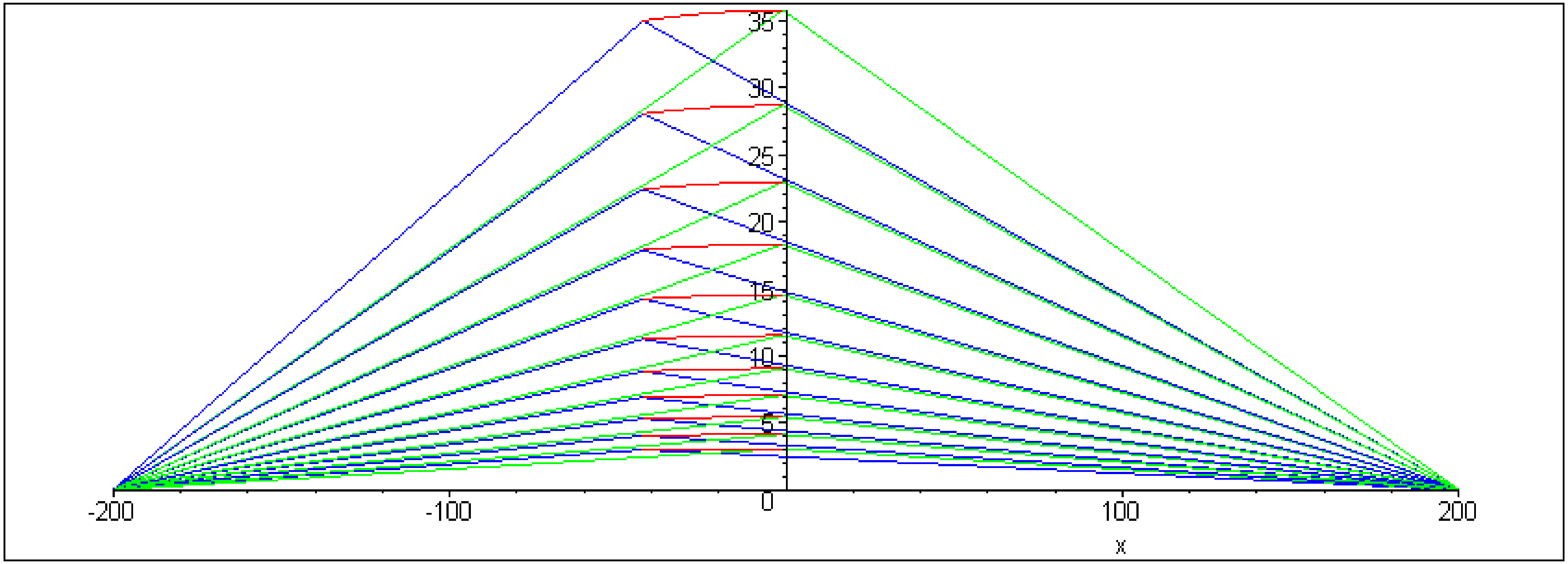






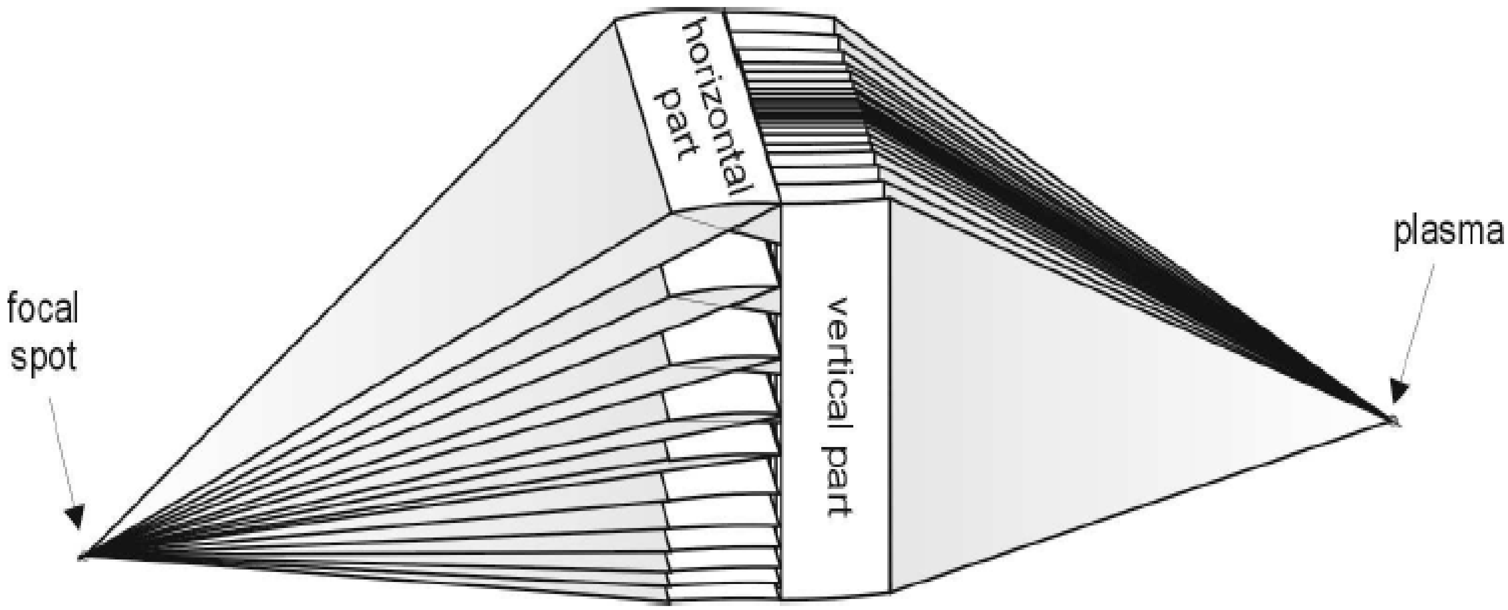
EUV MFO Condenser

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

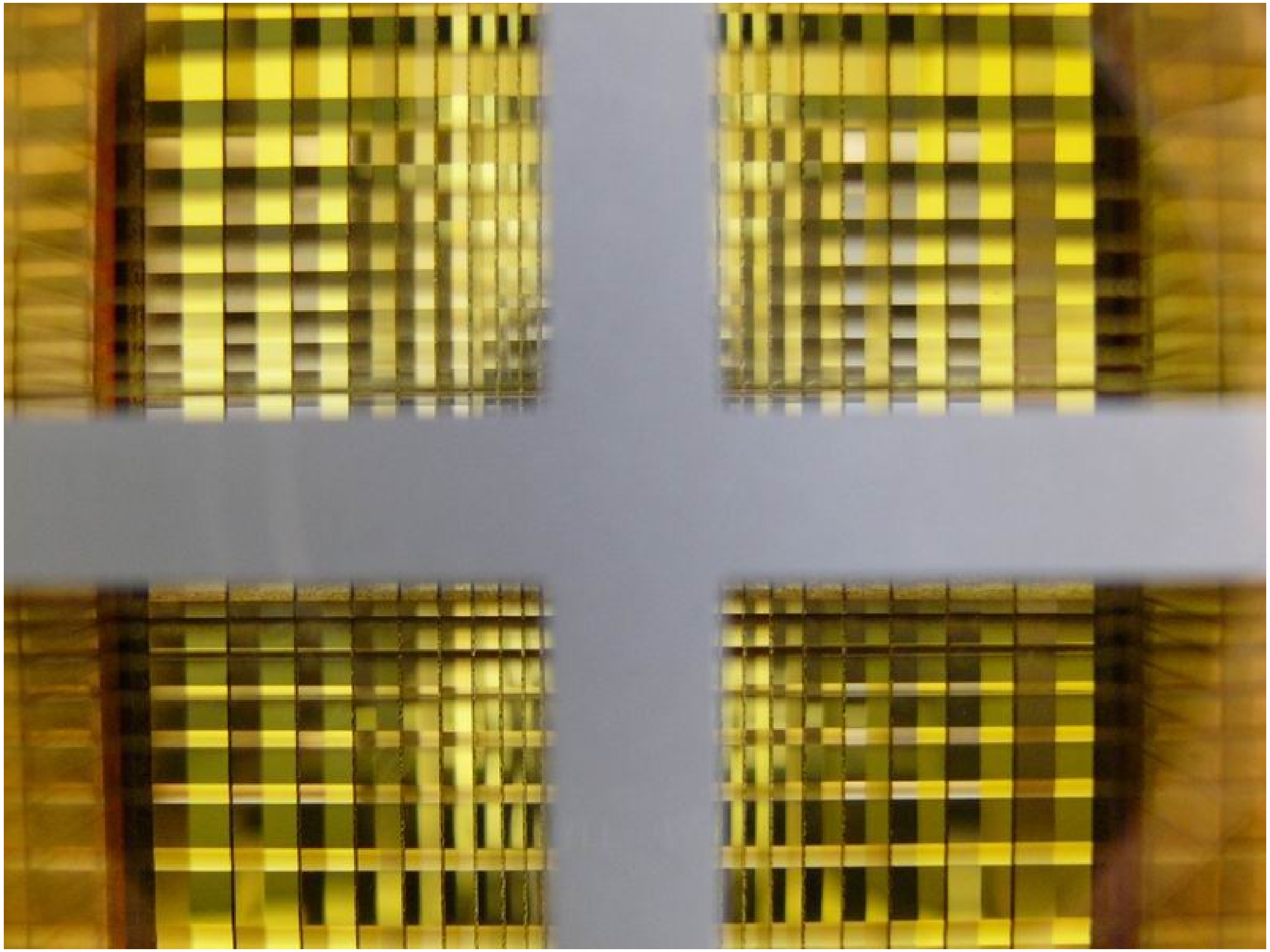


All dimensions in millimeters. Ellipsoidal mirrors, length 40mm, width 80mm.

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



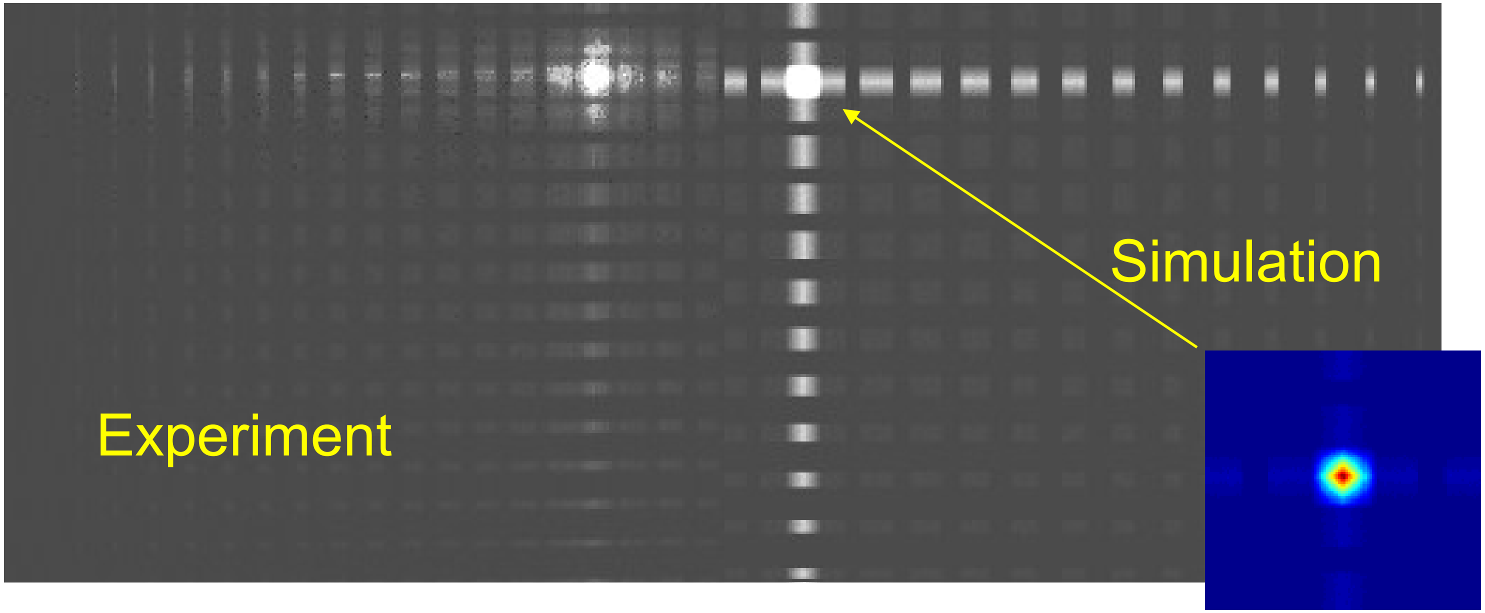
Schematic view of one half of the multi–foil (MFO) XUV bifacial Kirkpatrick-Baez condenser – experiments at WAT, Warsaw.



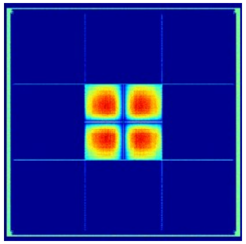
MF K-B system for EUV lithography

X-ray LE - experiment vs theory

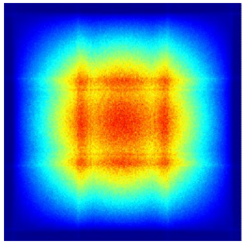
- Point-to-point focusing system
- Source: 20 μm size, 8 keV photons
- Source-detector distance: 1.2 m, 8 keV photons
- Detector: 512x512 pixels, 24x24 μm pixel size
- Intensity Gain: G=570 (experiment) vs. G=584 (comp. simulation)



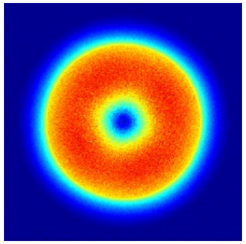
Ray tracing – intensity map behind the LE mirror
Homogenization of X-ray beam



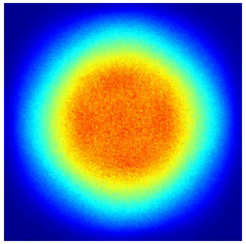
Lobster Eye INTENSITY MAP LE-50 L =6 X1 = 250 Xd = 750



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

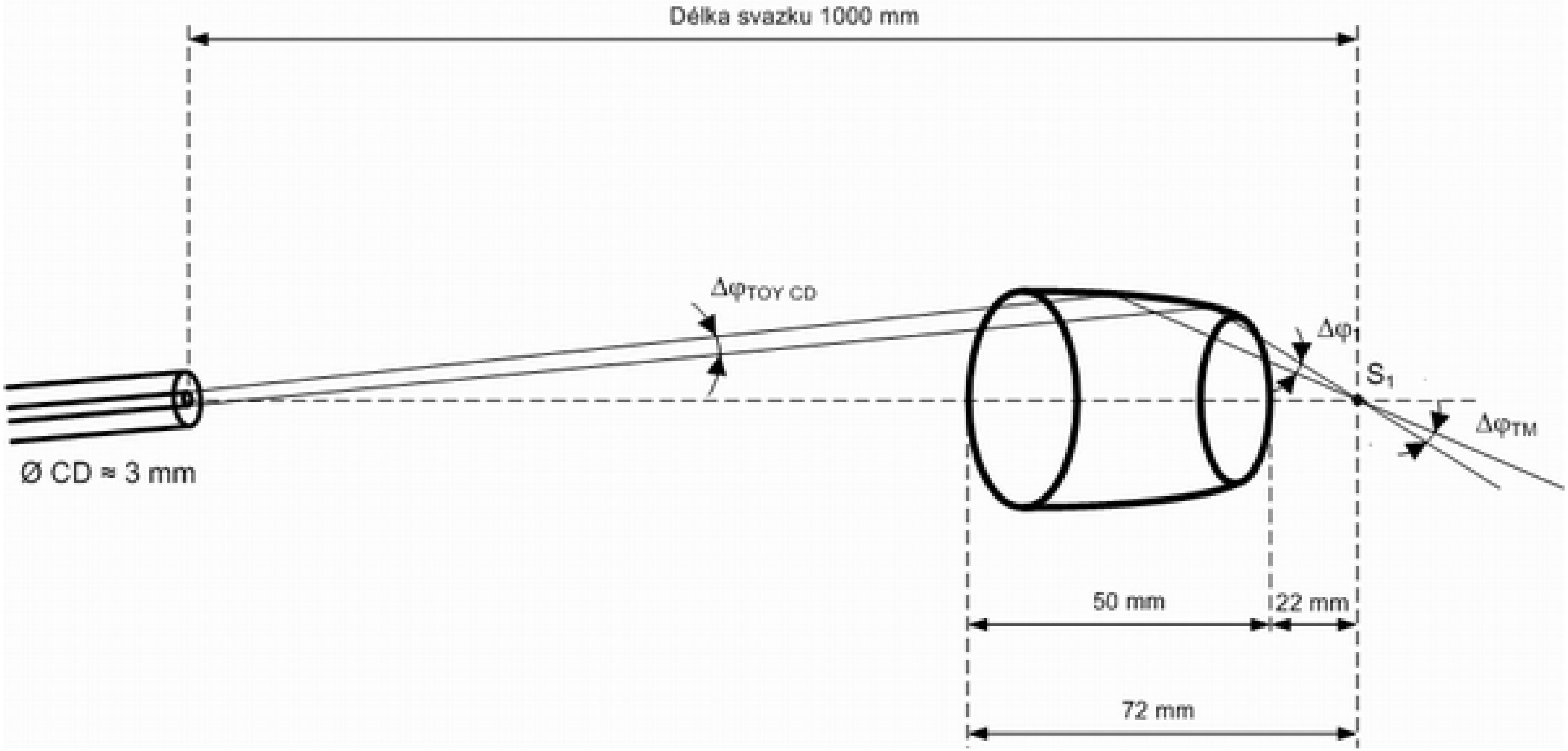


Lobster Eye INTENSITY MAP LE-50 L =6 X1 = 250 Xd = 750
(rotating LE mirror)



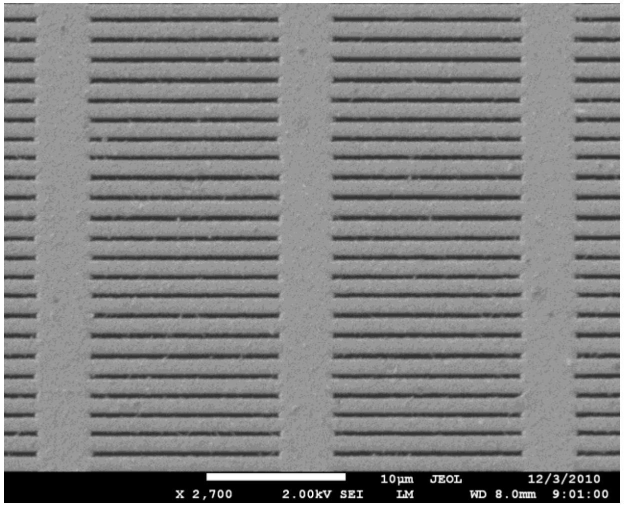
Lobster Eye INTENSITY MAP LE-50 L=6 X1 = 250 Xd = 750 (rotating
LE mirror + sweeping detector)

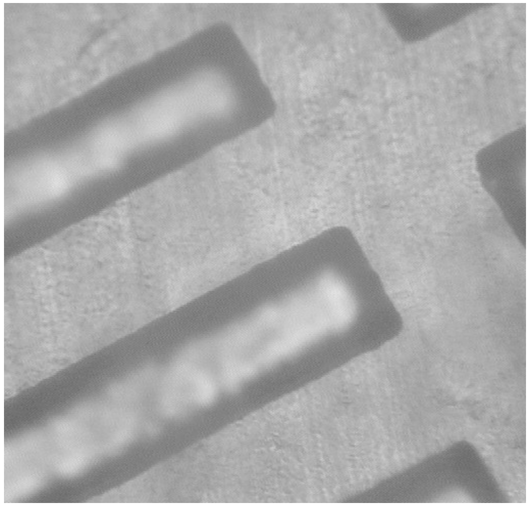
Focusing XUV radiation and XUV modification of materials (experiments at CTU, PALS and WAT)

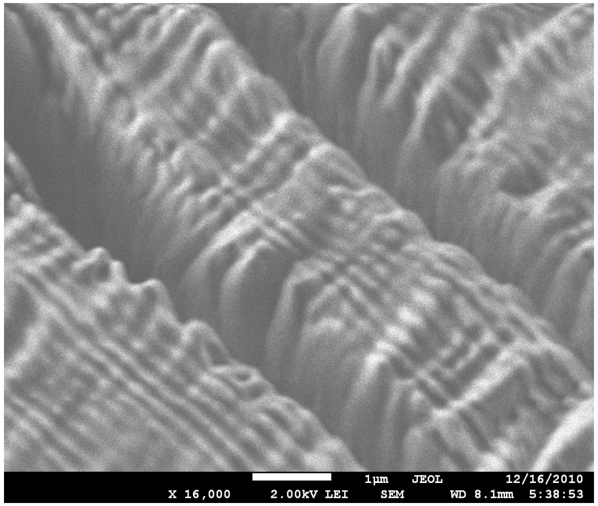


EUV beam intensity amplification - joint experiments of CTU Prague and WAT Warszaw

(EUV ablative lithography)







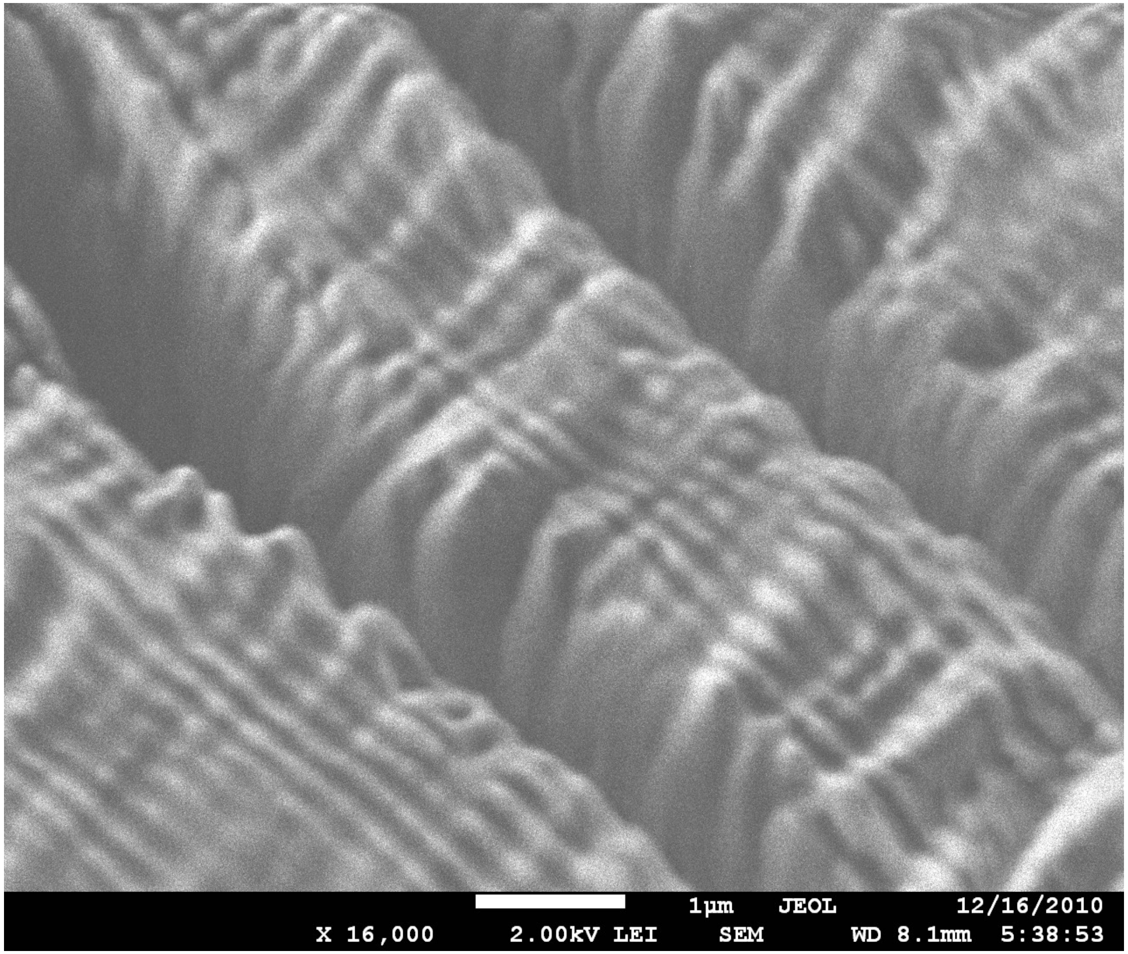
Microstructure made in PTFE by EUV lithography. EUV radiation from gas-puff laser plasma filtered by a metal mask.

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

(EUV ablative lithography)

Elipsoidal mirror
- Au surface

PMMA resist



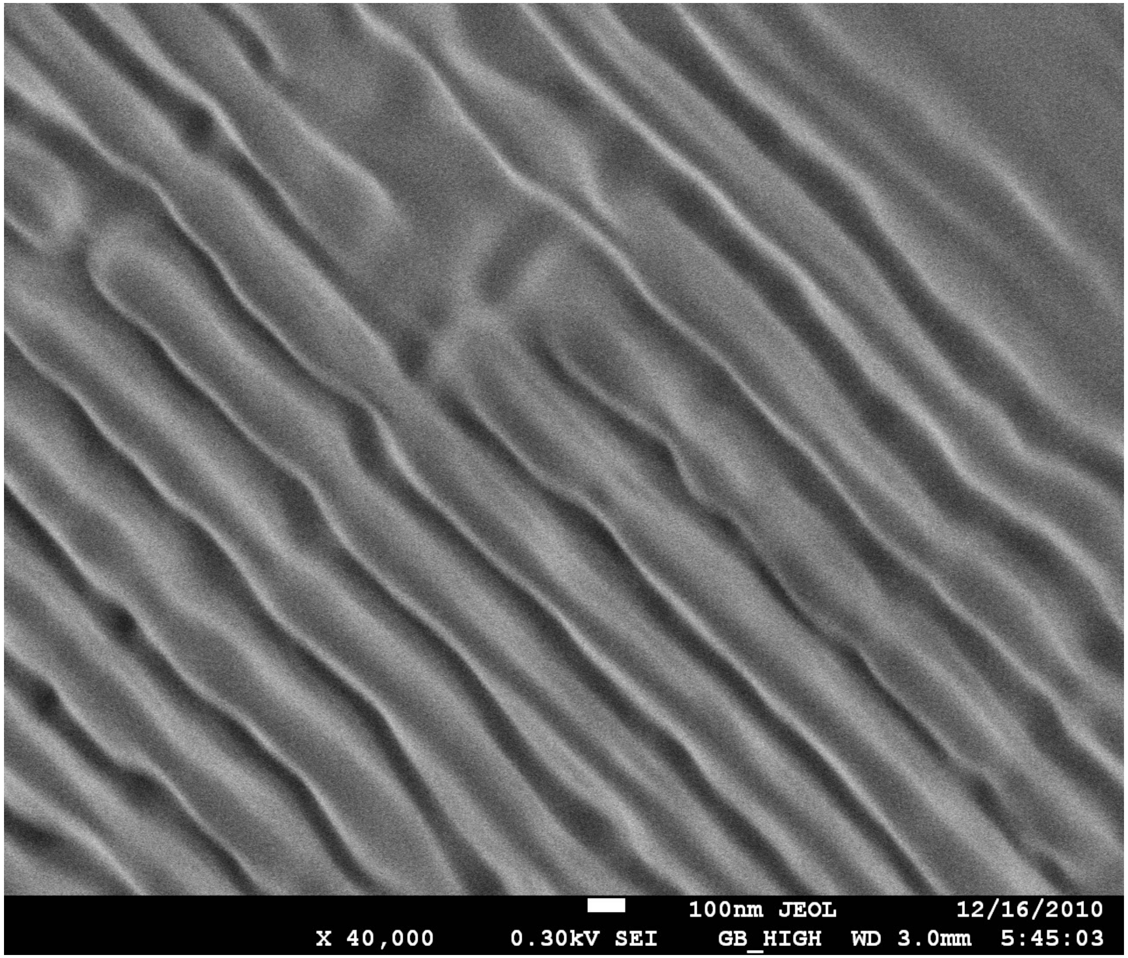
EUV beam intensity amplification - joint experiments of CTU Prague and WAT Warszaw

(EUV ablative lithography)

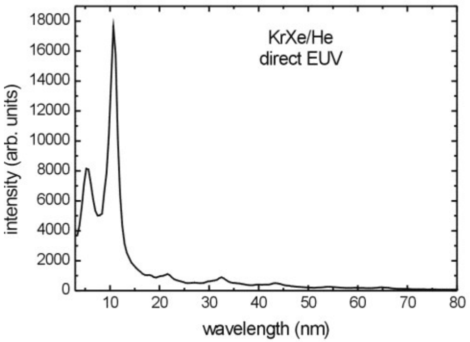
Elipsoidal mirror

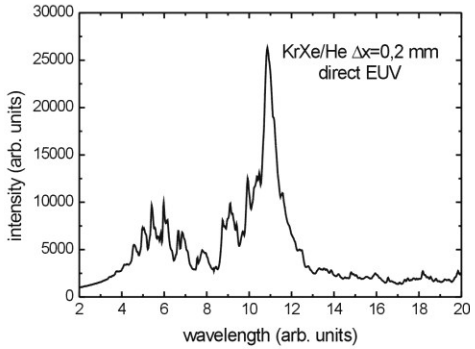
- Au surface

PMMA resist

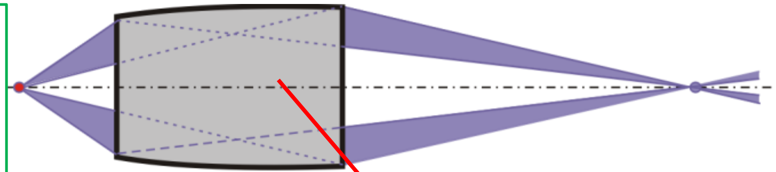


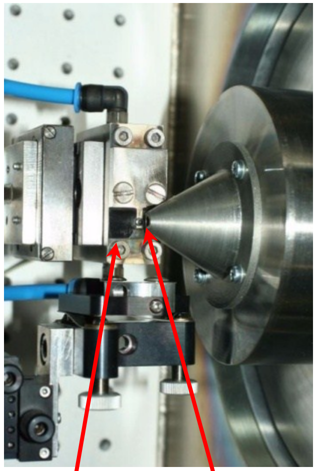
Laser-plasma produced EUV source: 0.8 J / 4 ns laser

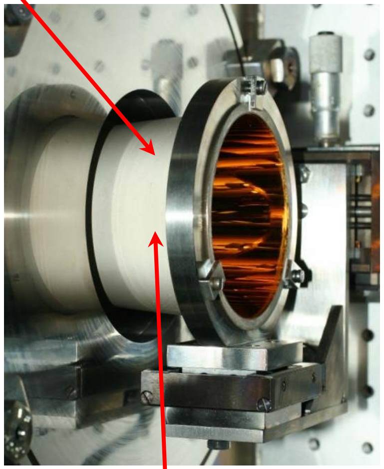




Low and high resolution EUV spectra of plasma radiation



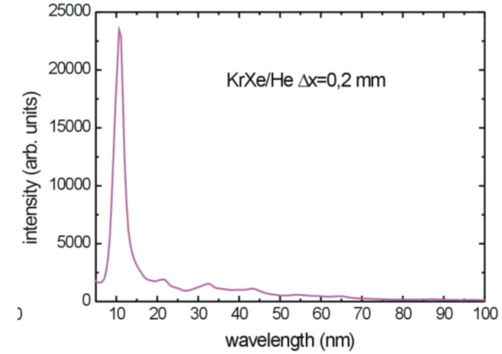


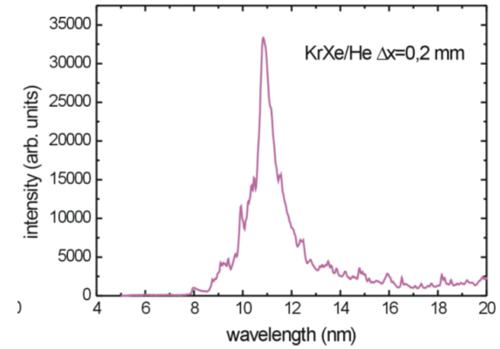


Gas puff valve

Orifice for differential pumping

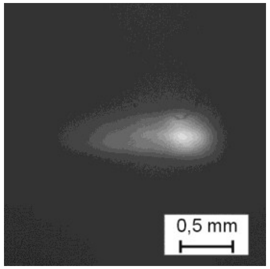
Ellipsoidal EUV collector



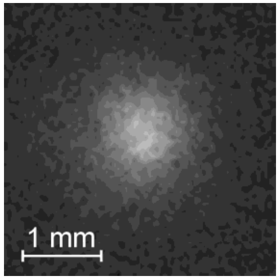


Low and high resolution EUV spectra of reflected radiation

Plasma image



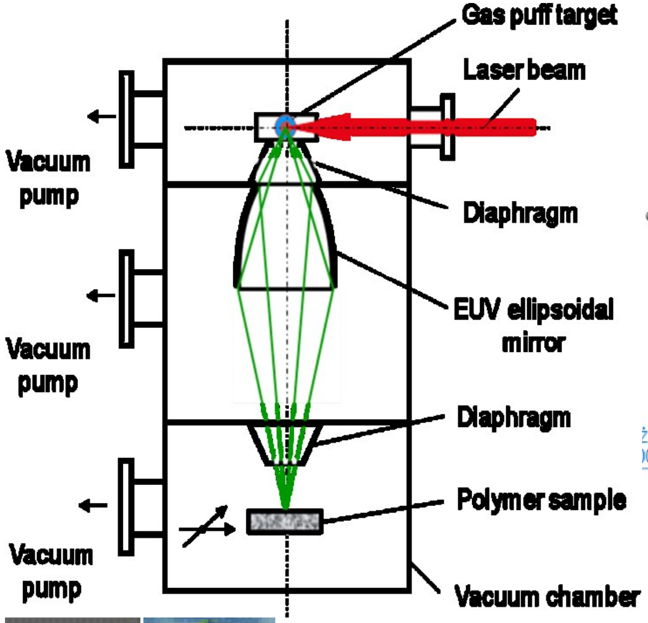
Focal spot image

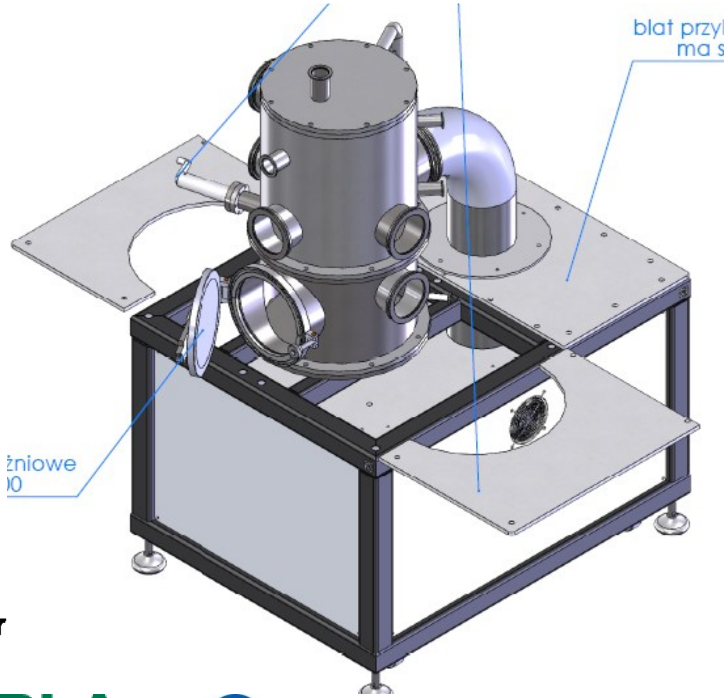


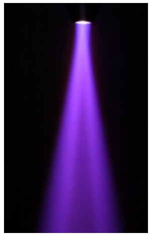
Laser plasma EUV source for processing polymers

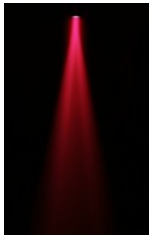
Bartnik et al. *Nucl. Instr. Methods A* 647 (2011) 125

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

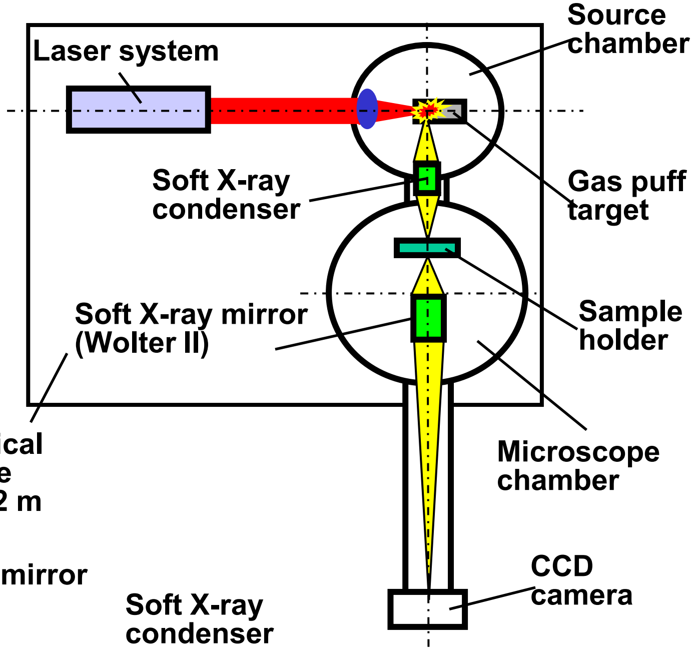


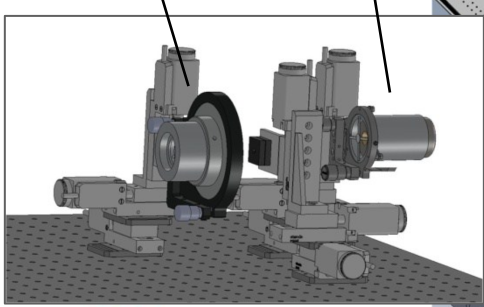


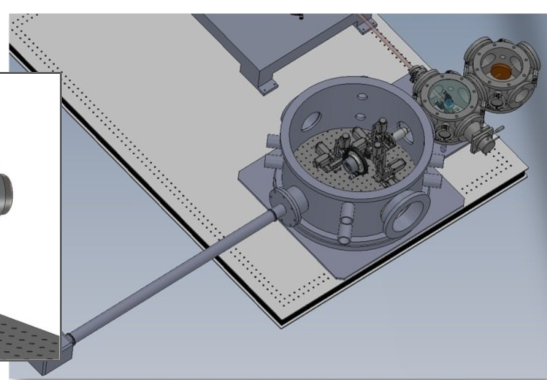


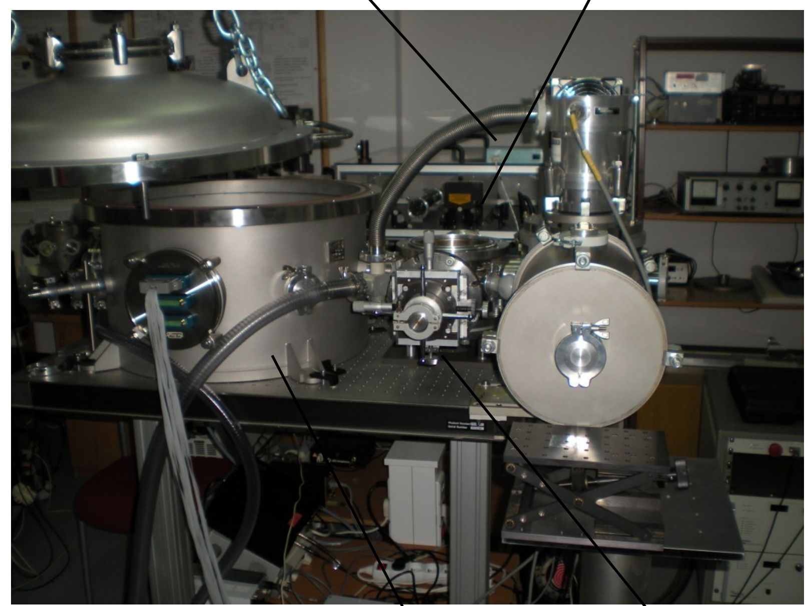


Desk-top soft X-ray microscope with a laser plasma source

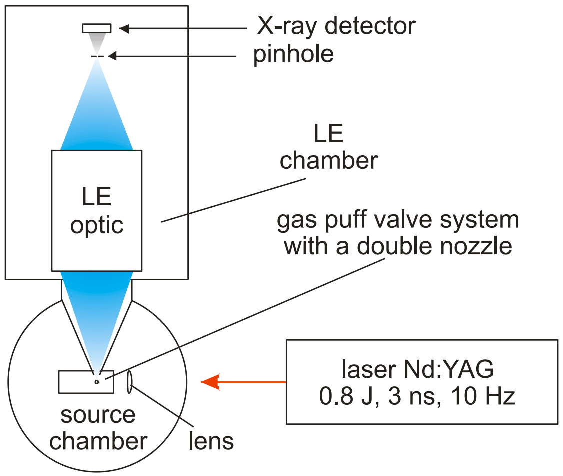


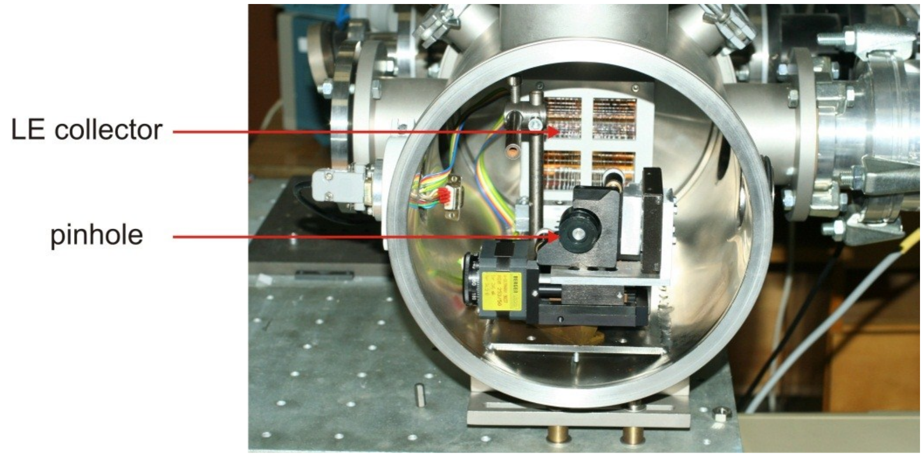




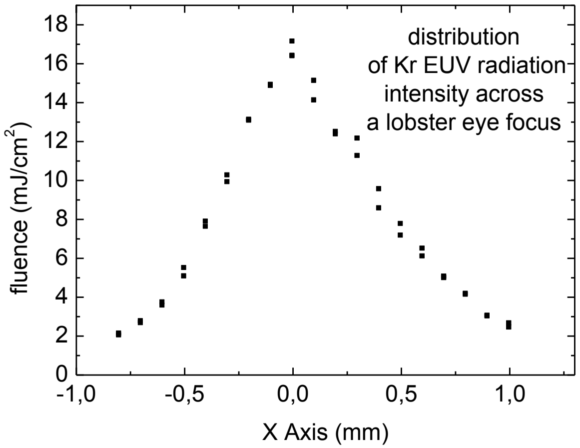


EUV intensity in the focal spot - multifoil collector





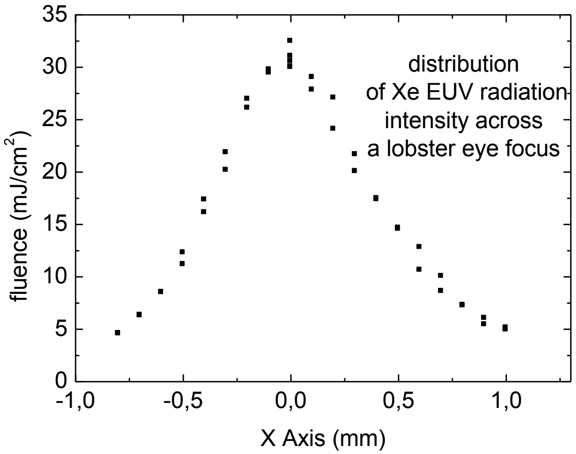
Experimental setup for measurements of intensity in the focal spot



Kr plasma

EUV fluence

~15 mJ/cm^2



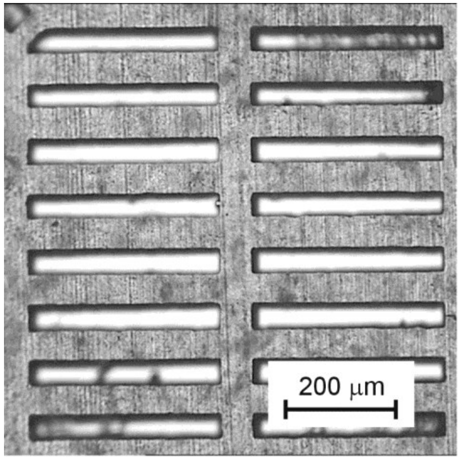
Xe plasma

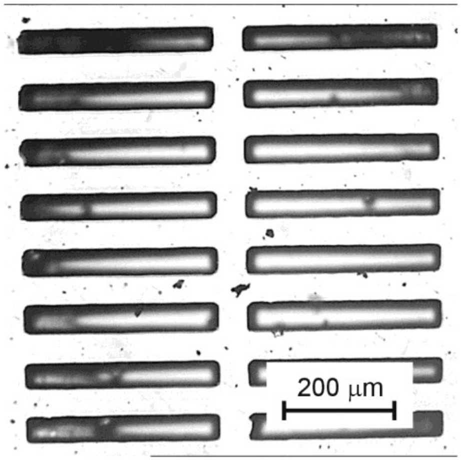
EUV fluence

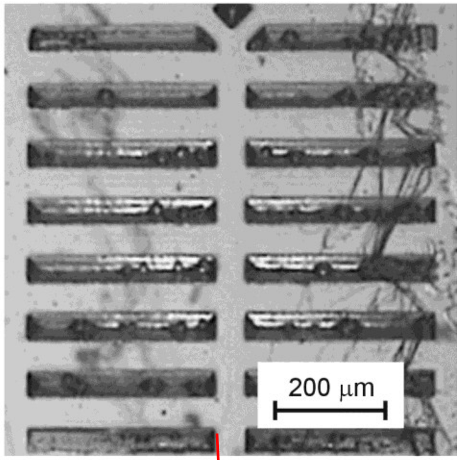
~30 mJ/cm^2

Creation of microstructures using the laser-plasma EUV source with collecting optic

Irradiation of PTFE, FEP and CsAP using Xe plasma with the multifoil collector, at the room temperature, 4 min, 10 Hz, EUV fluence ~30 mJ/cm²/shot



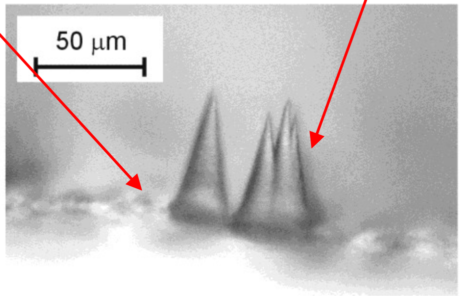


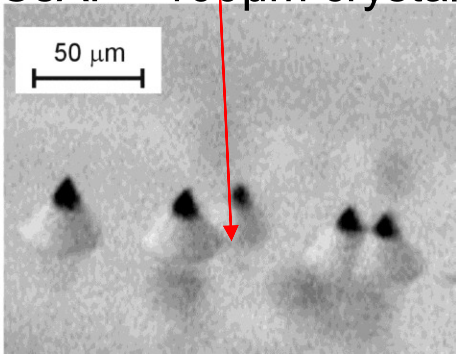


PTFE 50µm foil

FEP 50µm foil

CsAP >100µm crystal

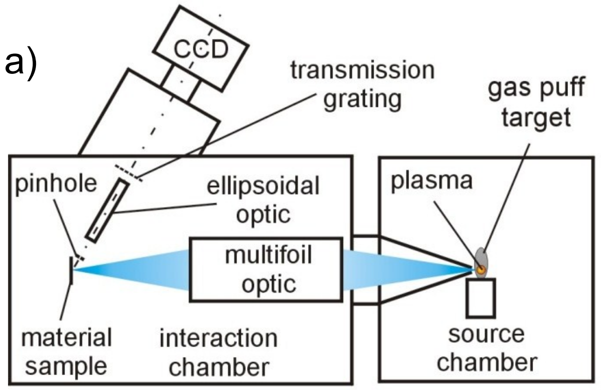




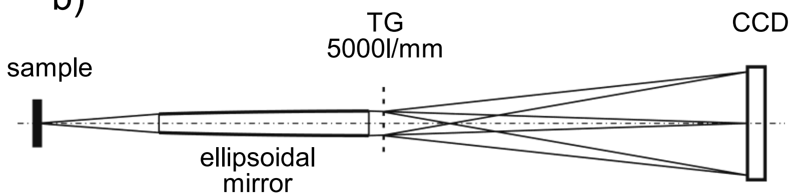
Fluorescence using the EUV source

Demonstration of using the laser-plasma source for EUV fluorescence experiments

a)

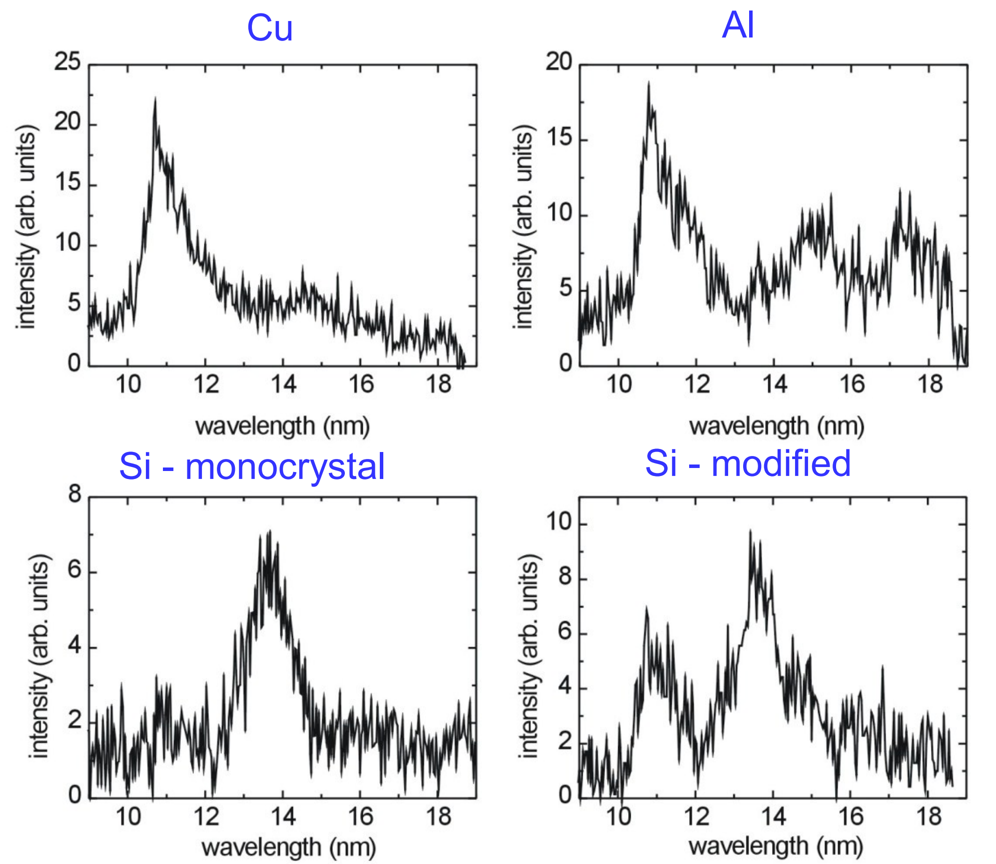


b)



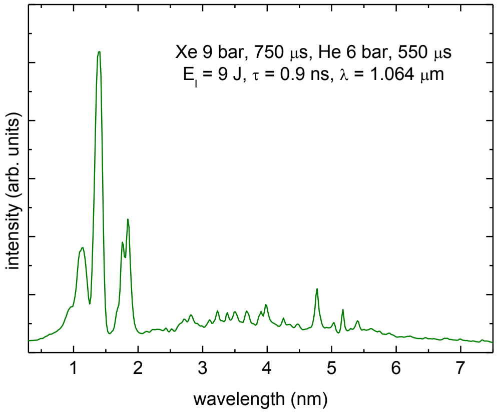
Schematic view of the measurement system:
a) experimental arrangement
b) transmission grating spectrofgaph

A. Bartnik et al, Appl. Phys. B: 93 (4) , 737-741



Fluorescence spectra obtained as a result of excitation of materials using the laser-plasma EUV source with Xe plasma. Features at around 11 nm with a slope towards long wavelengths come from elastic scattering of Xe radiation.

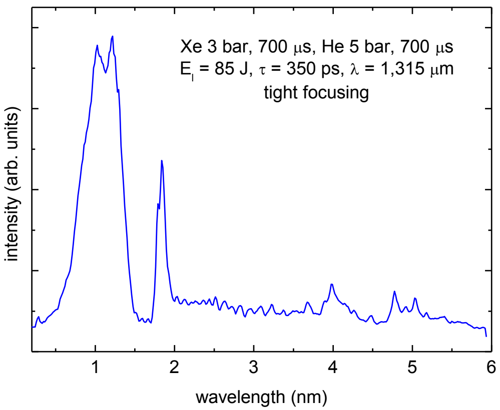
Focusing system prepared for a soft X-ray plasma source based on Xe gas target, driven by a 10 J/ 1ns/ 10 Hz Nd:YAG laser system



10J laser system

IOE, Warsaw

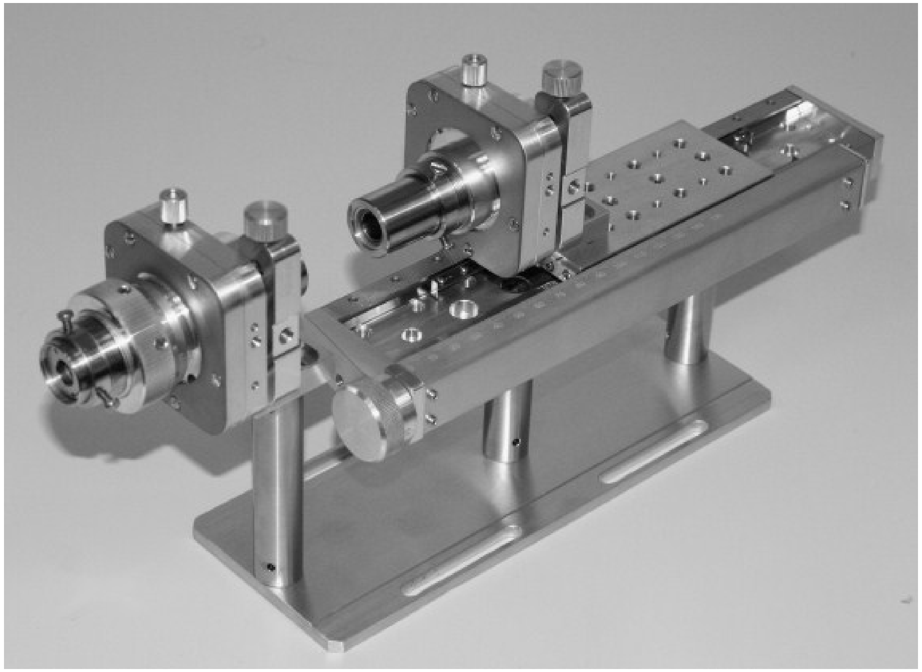
Spectrum for 9J



600J laser system

PALS , Prague

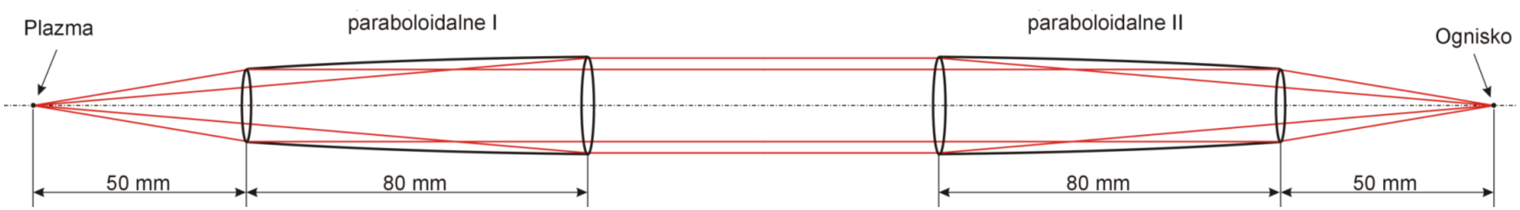
Spectrum for 85J



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

Plasma

Focal spot



THANK YOU FOR ATTENTION

Prague