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Grazing Incidence Astronomical X-ray Optics in the Czech Republic: 40 years of Development

René Hudec, Ladislav Pína, Adolf Inneman, Veronika Maršíková, Michaela Skulinová, Libor Švéda, Martin Mika, Jan Sik, Michal Lorenc

Astronomical Institute of the Academy of Sciences of the Czech Republic, Ondřejov

Czech Technical University, Prague

Rigaku Innovative Technologies Europe, Prague

Institute of Chemical Technology Prague

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

- **1st X-ray mirror in 1969/1970, for solar telescope in INTERKOSMOS program**
- **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 onboard 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 spacecrafts with Czech X-ray optics: 4**
- **Total number of space experiments with Czech X-ray optics onboard: 8**

Various replicated X-ray optics

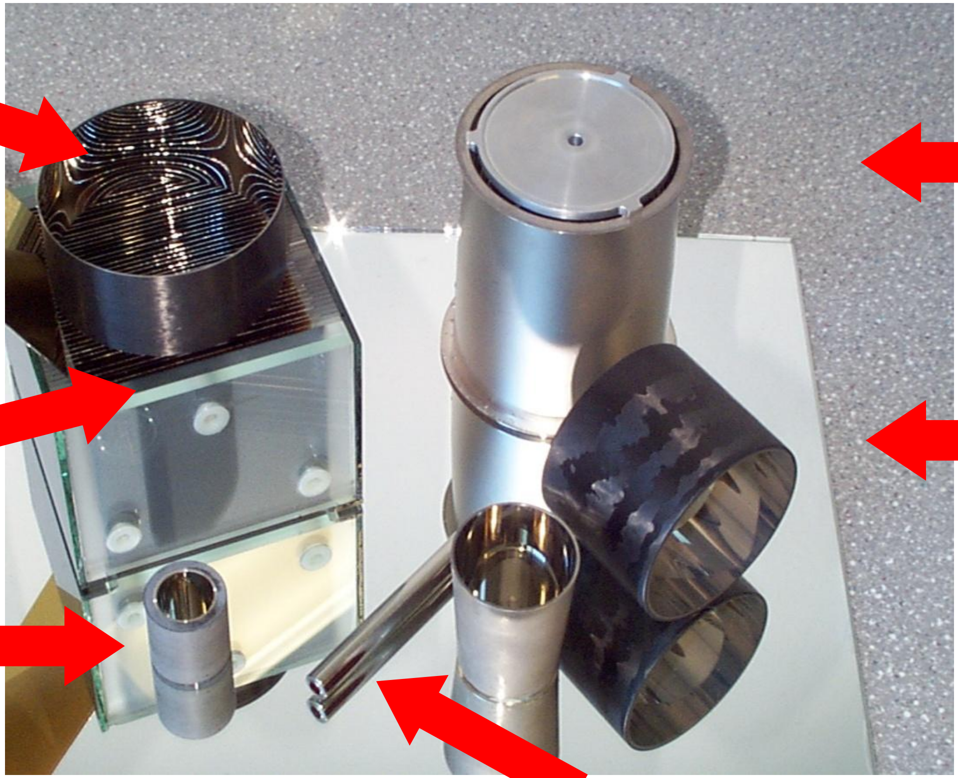
Thin CF mirror

Thin Ni Wolter shell

Double sided sandwich flats

CF mirror

CF+epoxy



X-ray micromirror

The Grazing Incidence Astronomical X-Ray Optics in the Czech Republic: 40 years of development

- 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)
- 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
- 1997 Lobster Eye Angel geometry project started
- 1999 first Lobster Eye test module produced, Angel geometry
- 2001 thin segmented X-ray mirrors

•1999 first Lobster Eye test module produced, Angel geometry
•2001 thin segmented X-ray mirrors
•2004 thermal glass forming of samples of laboratory X-ray optics started
•2005 replication of multilayers for X-ray optics
•2006 X-ray optics based on Si wafers, Si wafers shaping

Development before 1987 completely independent without any contact to other groups and without access to relevant literature and/or meetings and workshops

The development of galvanoplastic replication completely independent on Italian Brera efforts

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Replication Technologies Exploited I

- Galvanoplastic (electroforming) replication (GR) with massive Ni – adopted from gramophone industry
- GR with thin Ni reinforced by CF (cutted-casting technology), wired, and/or sticked (Prepreg)
- GR with thin Ni reinforced by filled epoxy (various filling)
- Masters: SITAL glass ceramics
- GR of flat mandrels up to 30x40 cm (flat Ni X-ray reflecting foils) – for SODART mission. Thickness homogeneity better than 2%

Replication technologies Exploited II

- Epoxy replication (without electroforming) – with various fillings
- Double sided replication (sandwich technology): collaboration with SAO USA

Collaborating Institutes

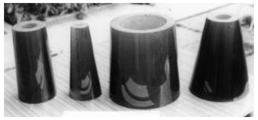
- **1969-1980. AI Ondrejov, CTU Prague, Institute of Gramophone Technology**
- **1980-1990. AI Ondrejov, CTU, State Institute for Material Research**
- **1991-2000. AI Ondrejov, Reflex sro, CTU**
- **2001-now. AI, CTU, Institute of Chemical Technology, ON Semiconductor, Semitec, Reflex, Rigaku**
- **Reflex sro, now Rigaku spin-off company of AI/CTU as consequence of political change in the CR and decision of the first director after the change the technology development should leave the Institute**

Projects

- 1969-1989: INTERKOSMOS: solar X-ray telescopes Vertikal, AUOS, FOBOS, KORONAS,SODART. Stellar X-ray telescopes Salyut 7. Laboratory microscopic mirrors.
- 1990-2000: X-ray micromirrors, LE X-ray optics
- 2001-now: new technologies: slumped glass, Si wafers, alternative technologies. KB systems.

Historical background

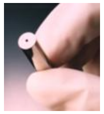
- 1969 – First considerations started
- 1970 – First X-ray mirror (Wolter 1; 50 mm)
- 1976 – Wolter 1; 115 mm
- 1979 – First mirror flown in Space (two Wolter 50 mm)



- 1981 – Salyut 7 orbital station (Wolter 240 mm nested)

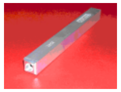
- 1985 – Applications for plasma physics, EH 17 mm, PP 20 mm

- 1988 – FOBOS 1 Mars probe, TEREK X-ray Telescope
- 1989 – KORONAS I, Wolter 80 mm



- 1990 – First micromirror (apertura less than 1 mm)
- 1993 – Collaboration with SAO, USA, WF X-ray optics started

- 1996 – First Lobster Eye (Schmidt)



- 1999 – Lobster Eye (Angel)

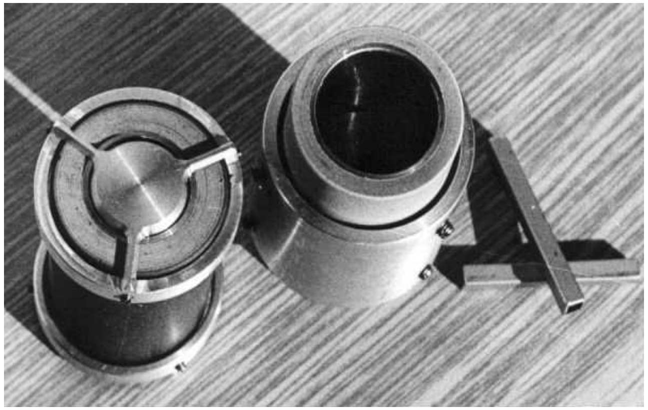
- 2000 – Soller Slit
- 2001 – Multifoil optic

- 2002 – Micromirror with multilayers

- 2003 – X-ray CCD camera (cooling)

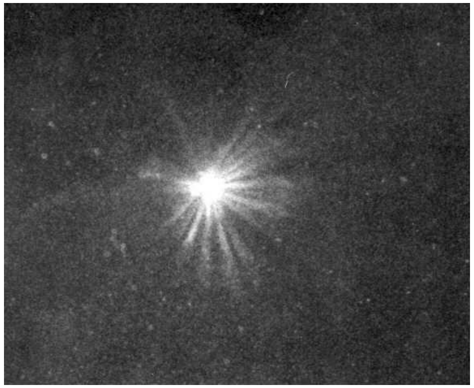
- 2004 – X-ray tube
- 2006 – Si wafer mirrors
- 2007 – Micromirror – test at HASYLAB

X - ray mirrors produced by replication in the Czech Republic (Hudec et al)



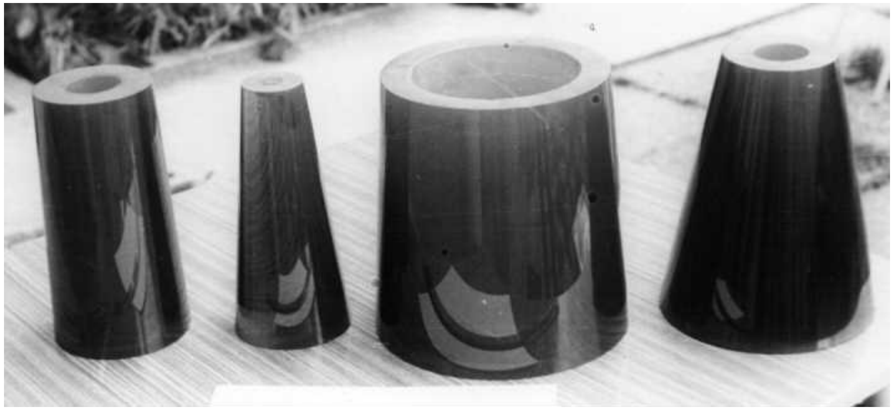
EH and PP microscopes

One of the first Czech X-ray Wolter mirrors, 1970, aperture 50 mm



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

Wollter mirror for Phobos 1 space probe

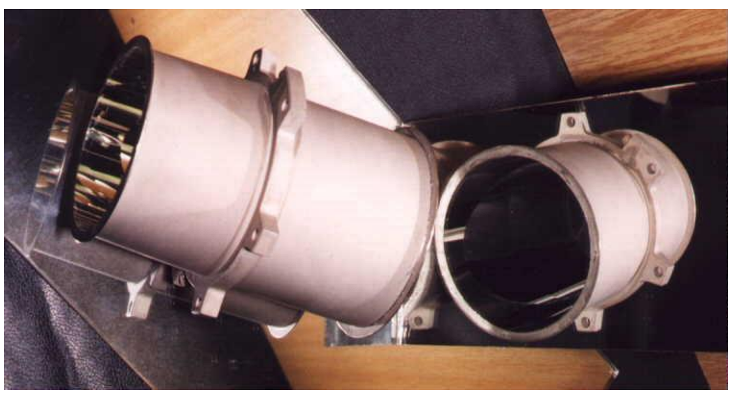


The four mandrel used for the manufacture of X-ray mirror nested array for the RT-4M soft X-ray telescope (Glass ceramics Sital). Flown onboard the space station Salyut 7 in 1981.

TEREK

Phobos 1

1988

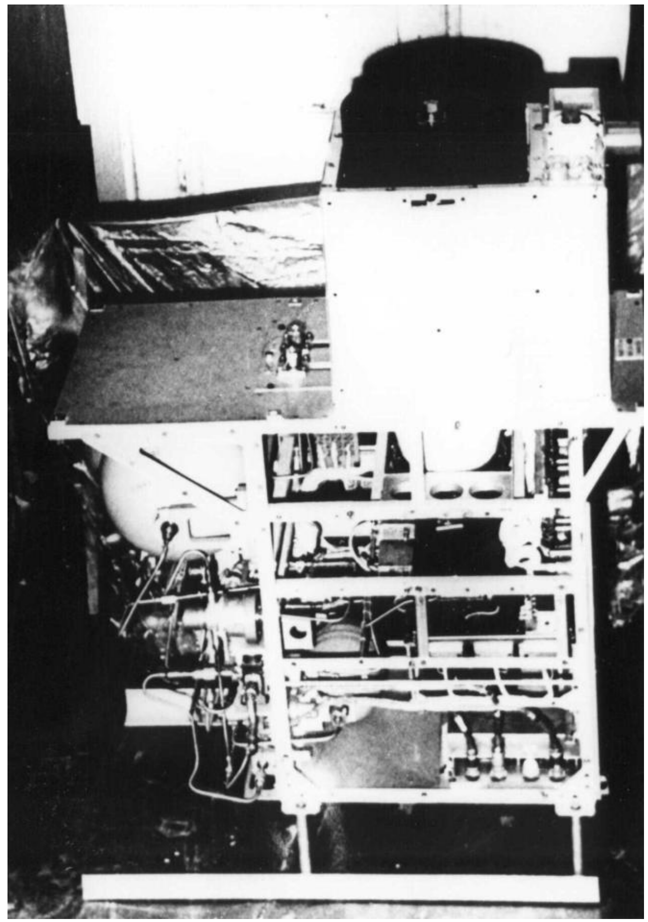


Replicated Wolter - 1 X-ray mirrors of the KORONAS satellite (aperture 80 mm), 1989

Two identical mirrors (large hyperbolas) of the RT-4M mirror array (Ni surfaces), 1981.

RT-4M on Salyut 7, 1981

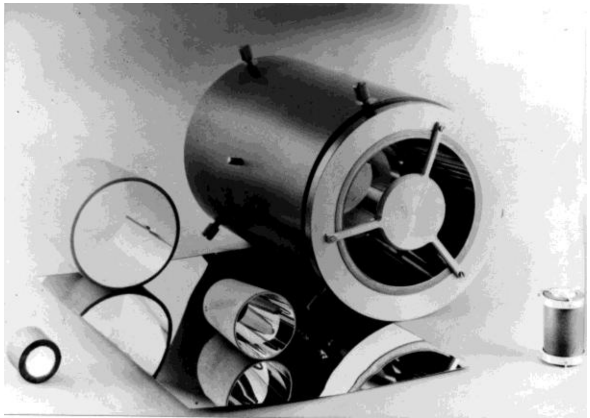
The soft X-ray telescope RT-4M with the Czech nested X-ray mirror array (top right) with the largest diameter 240 mm was flown onboard the space station Salyut 7. Result of a collaboration of Lebedev Physical Institute in Moscow with the Astronomical Institute in Ondrejov within the INTERCOSMOS program



Inner shell electroformed gold! Unique technology!

AXRO Prague 2009

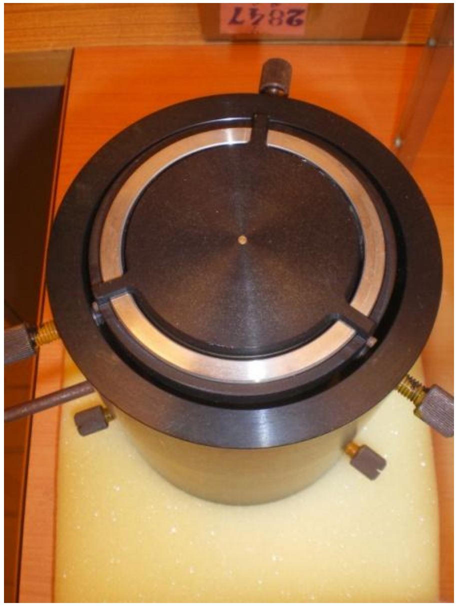
X-ray reflecting Ni foils for SODART



2 years of development of technology for high quality Ni foils for the SODART telescope, 1986-1988

Galvanoplastic replication of glass flat mandrels, sizes up to 300 x 400 mm

Thickness homogeneity improved from 8 to 2 %



The galvanoplastic (electroforming) replication adopted from gramophone industry

Solar X-ray Wolter mirror 8´0 mm thick Ni

115 mm aperture X-ray mirror for AUOS-S-IK, solar, FWHM < 10 arcsec, thick Ni

50 mm Wolter,
1974, thick Ni

Thin Ni mirror for DSRI, 1986, thin Ni, 150 mm

80 mm Wolter,
1970, thick NI

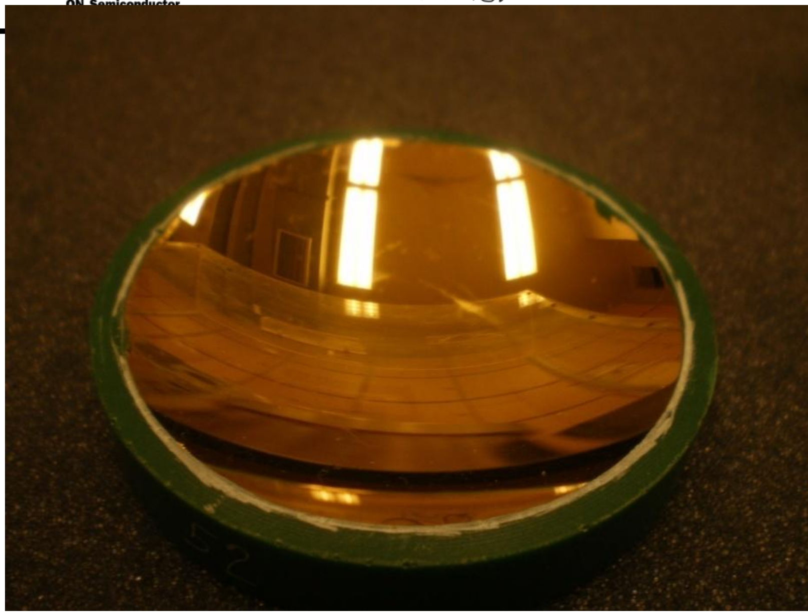
Microscopic X-ray mirrors, 1985
Thick Ni left,
Ni/epoxy right

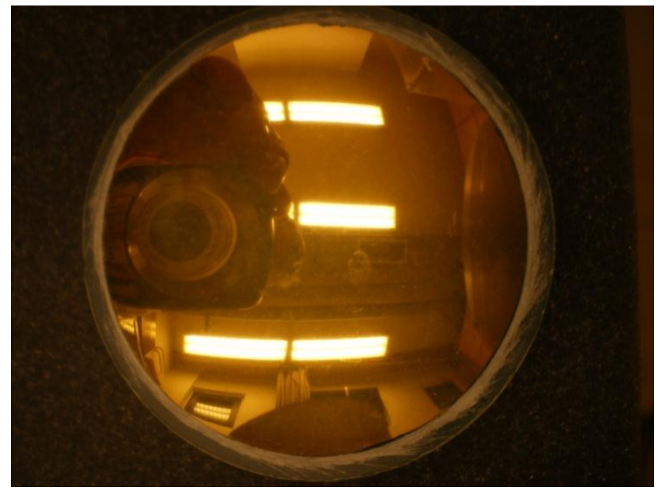
Ceramic mandrel 1977

First Czech X-ray mirror, Wolter 50 mm,1970

115 mm Wolter, Ni/epoxy, 1979

Tests of technology based on replication of evaporated glass layers by epoxy replication, 1977-78





Numerous technological tests have been performed since 1970 with hundreds of test mirrors and samples

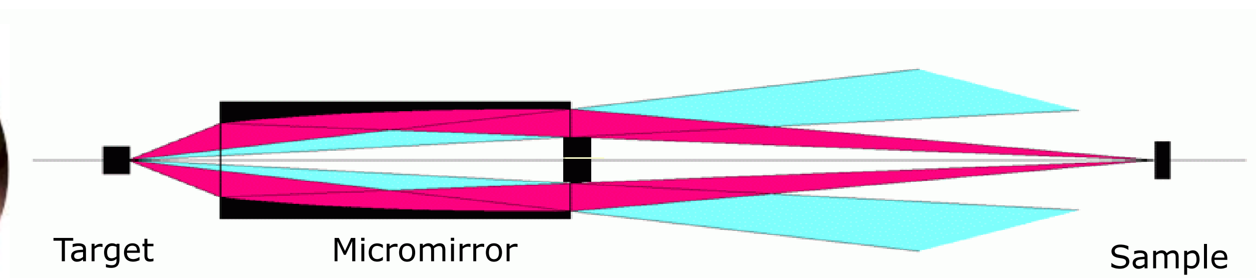
Mandrel (left) and replica (right)
Mostly glass and glass ceramics was used for mandrels, 1971

Ultra-thin Ni test mirror (thickness 0.2 mm) 1983

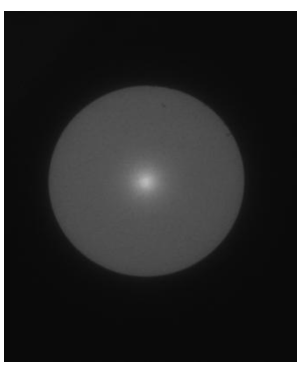
X-ray Optics laboratory at Astronomical Institute Ondřejov

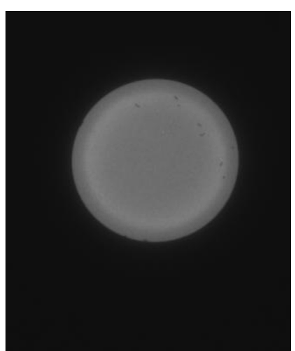
Focussing X-ray micromirrors: 1990-now

Hasylab proposal accepted, 3 years, 2007-2009, tests at synchrotron (ASU, RITE, CVUT)



Beam convergence angles as low as 1 miliradian full angle.

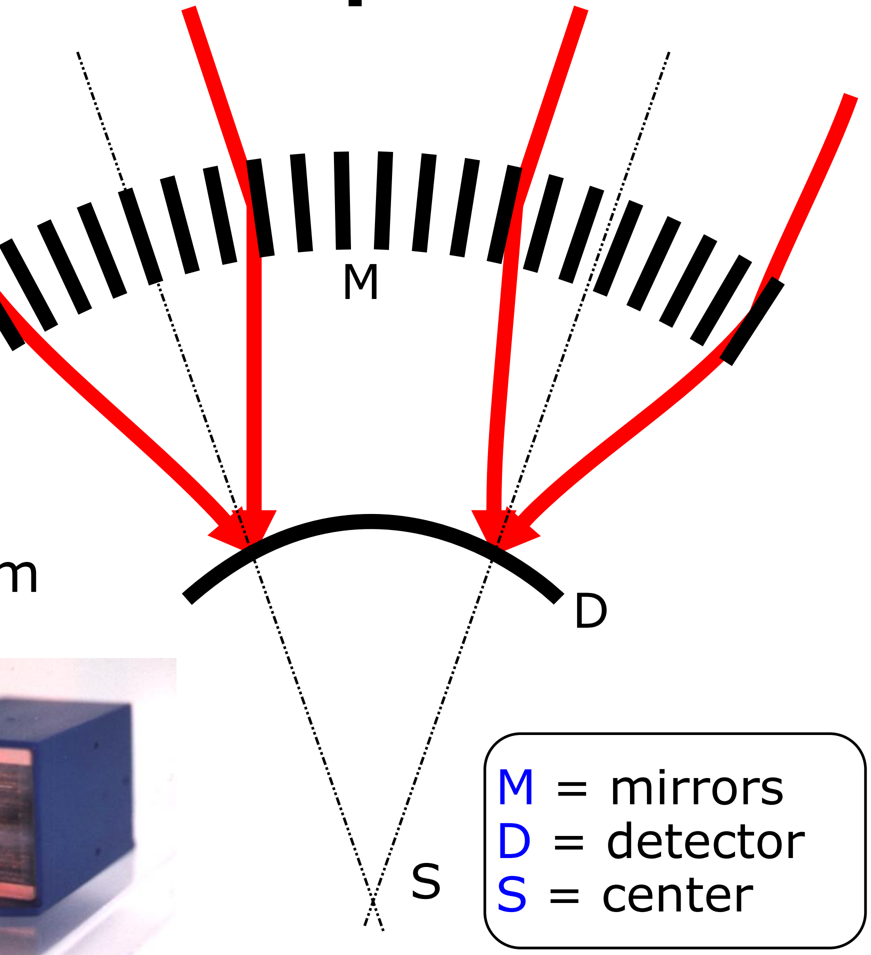


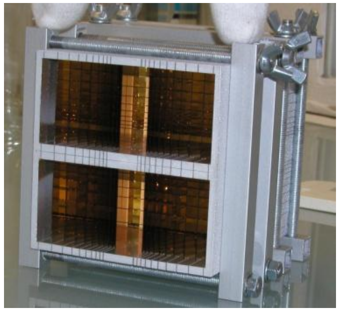


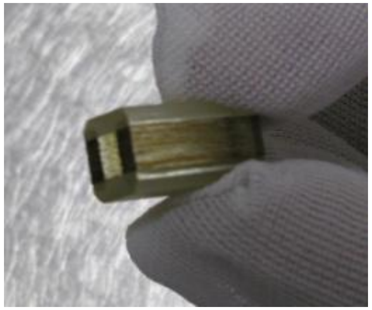
X-ray micromirror, aperture 0.7 mm, with replicated MLs inside (left) and with only Au (right), focal images at 8 keV. The influence of the ML deposition is clearly demonstrated.

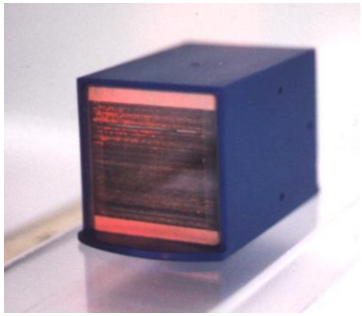
Lobster eye & multifoil optics

- 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

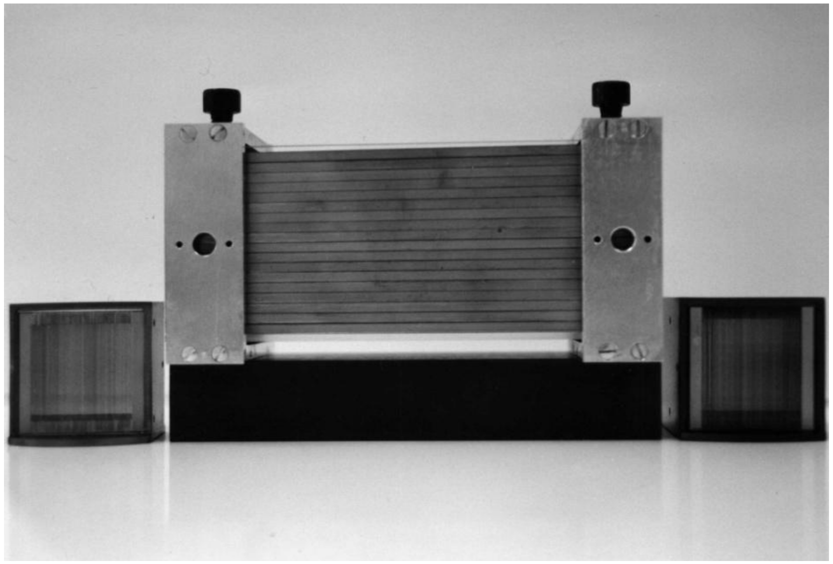


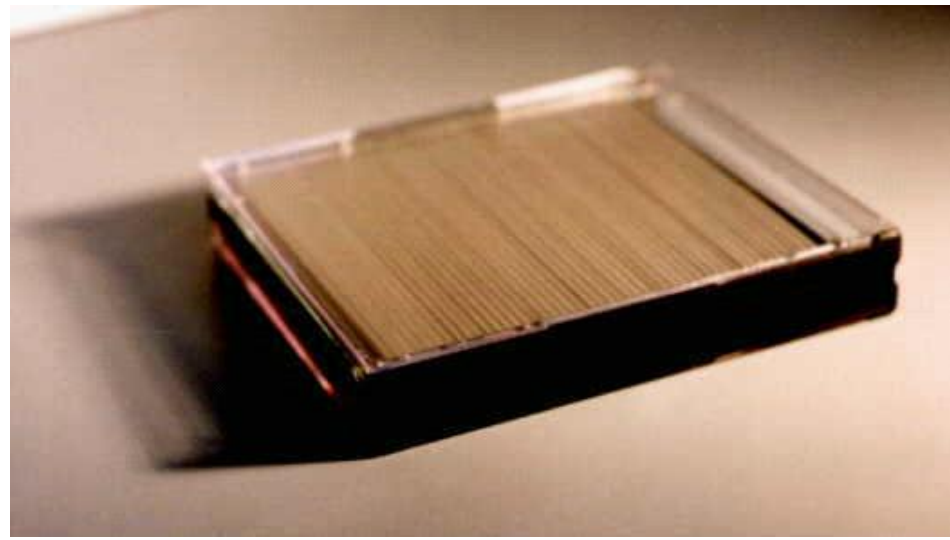






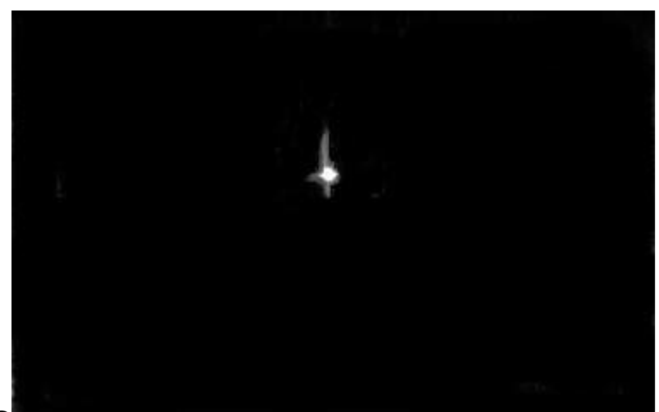
Early Lobster Modules, Angel





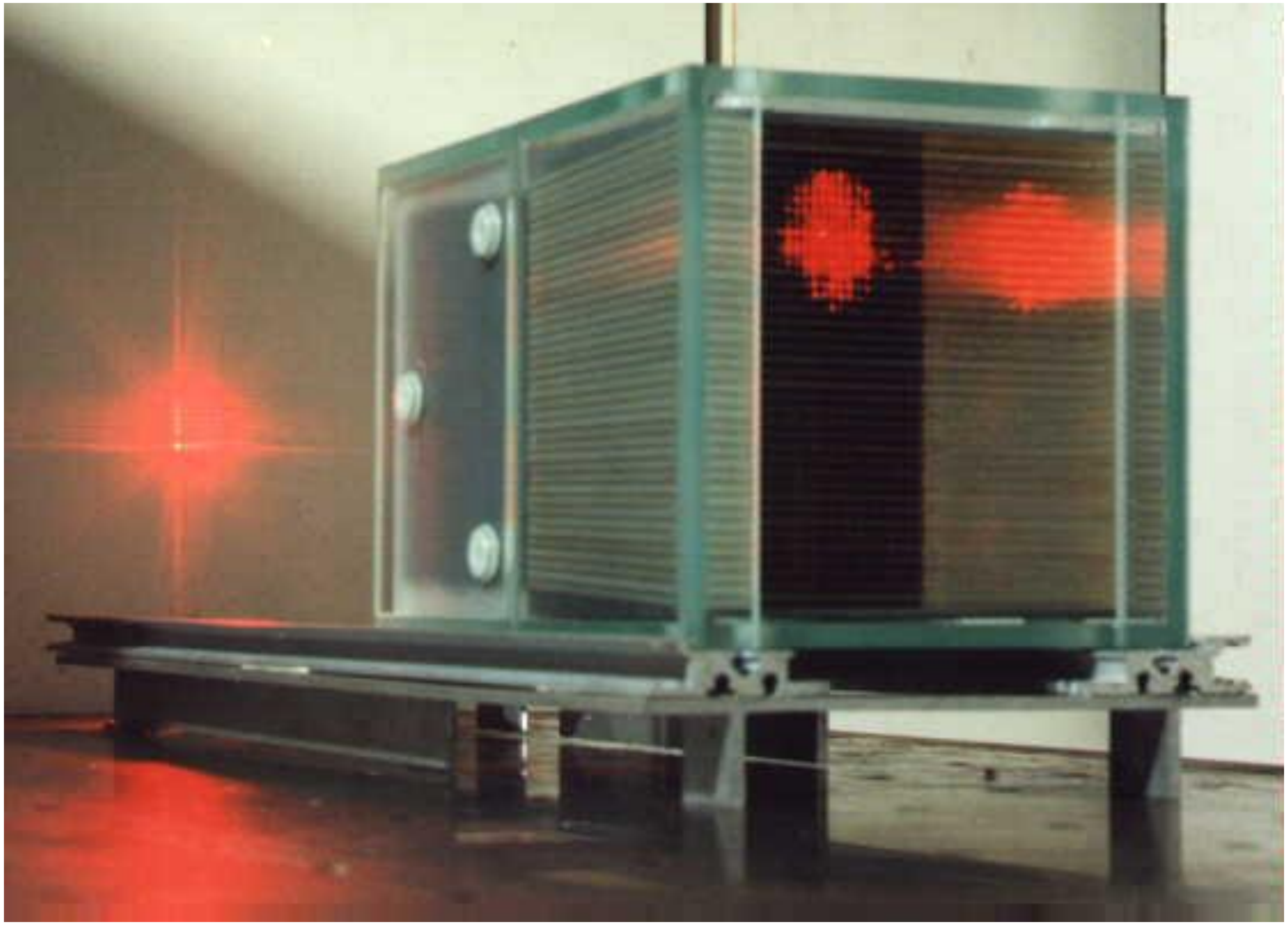
Angel telescope linear test module, 47 square cells

2.5 x 2.5 x 120 mm each.

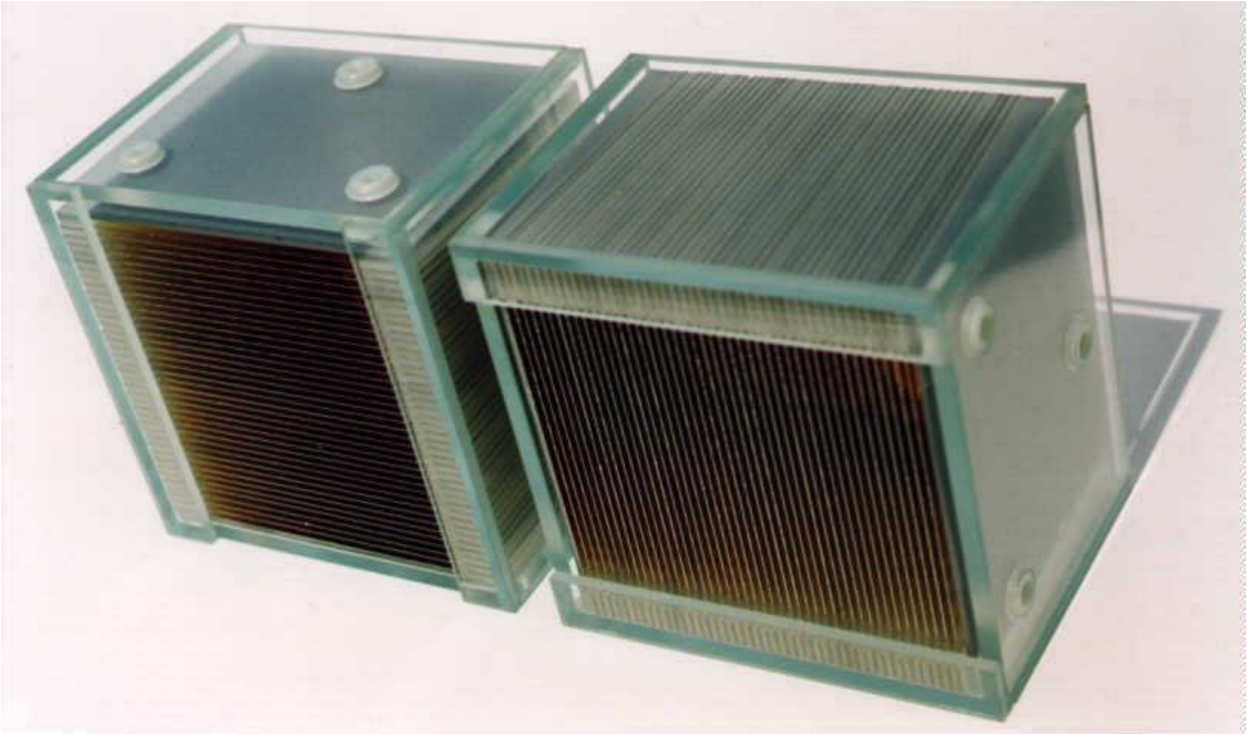


Early Lobster Modules, Schmidt

Lobster - Eye Schmidt telescope prototype, 2 modules, based on 36 and 42 planparalel plates 80 x 100 mm each.

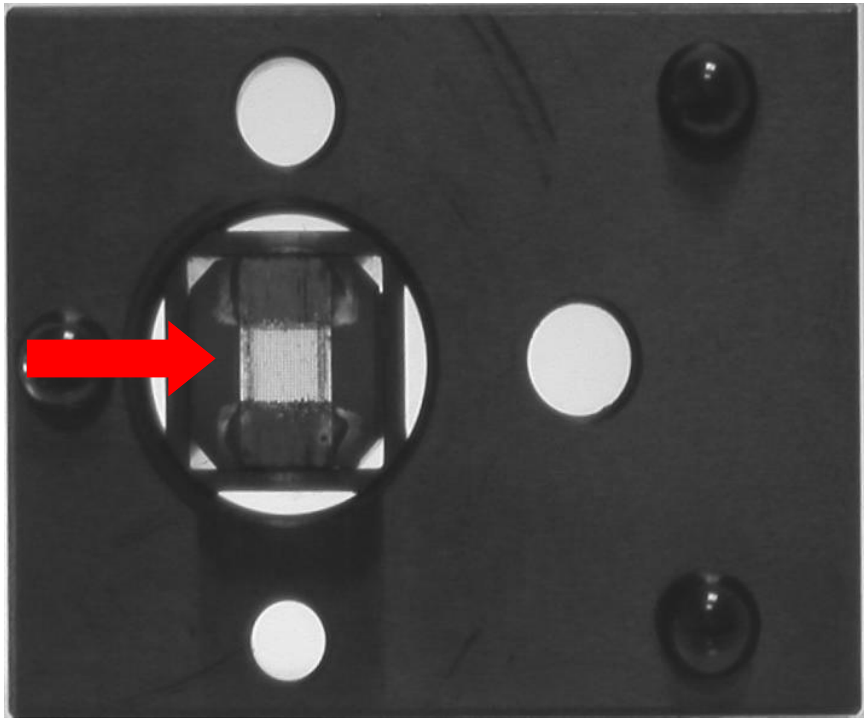


Schmidt X - ray telescope prototype, 80 x 100 mm plates



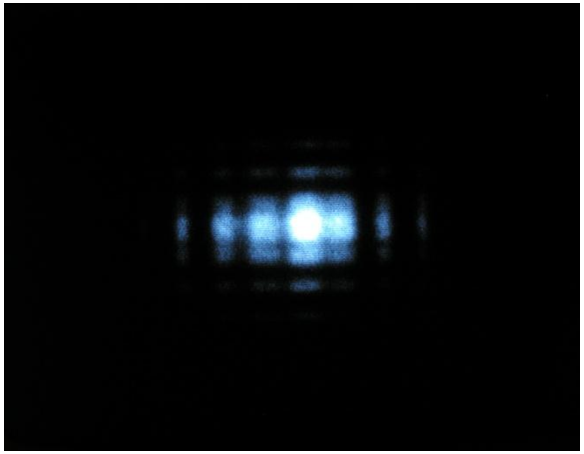
Two modules of the Schmidt telescope prototype, 80 x 100 mm plates

Lobster Eye X-Ray Optics



Micro LE: 3 x 3 x 14 mm module

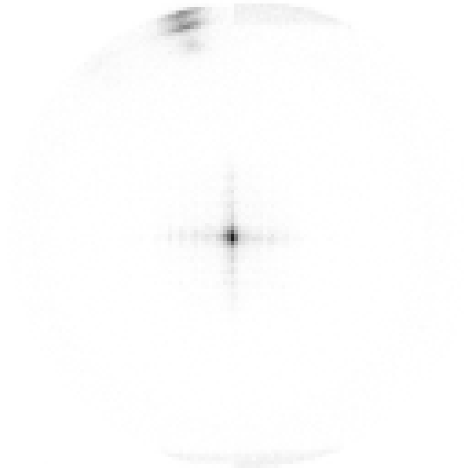
glass foils 30 μm thick separated by 70 μm

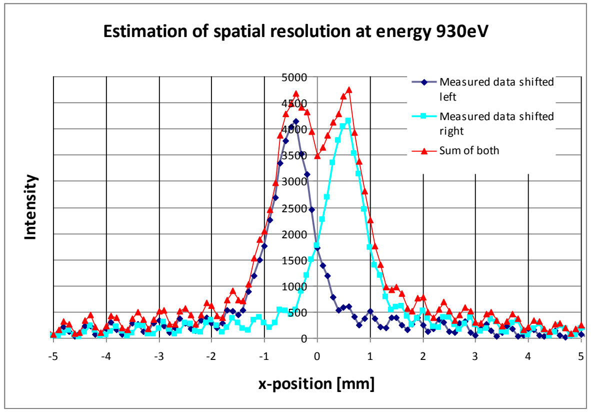


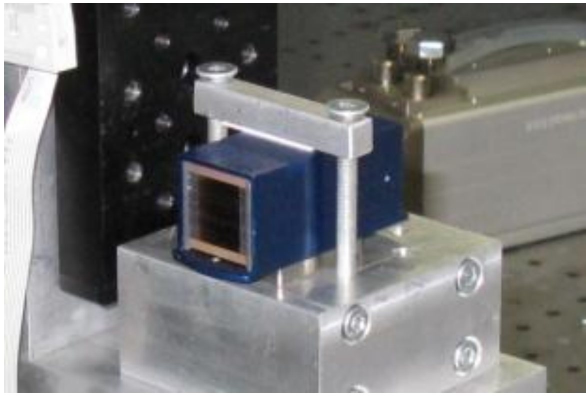
Focal image, 8 keV

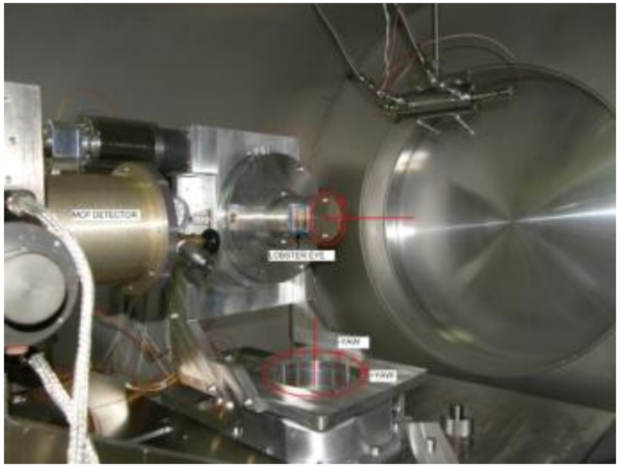
LE developments incl. detectors continue, see poster Tichy et al.

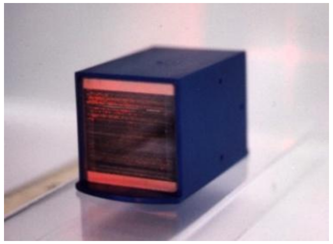
LE tests in Palermo X-ray test facility, 2009





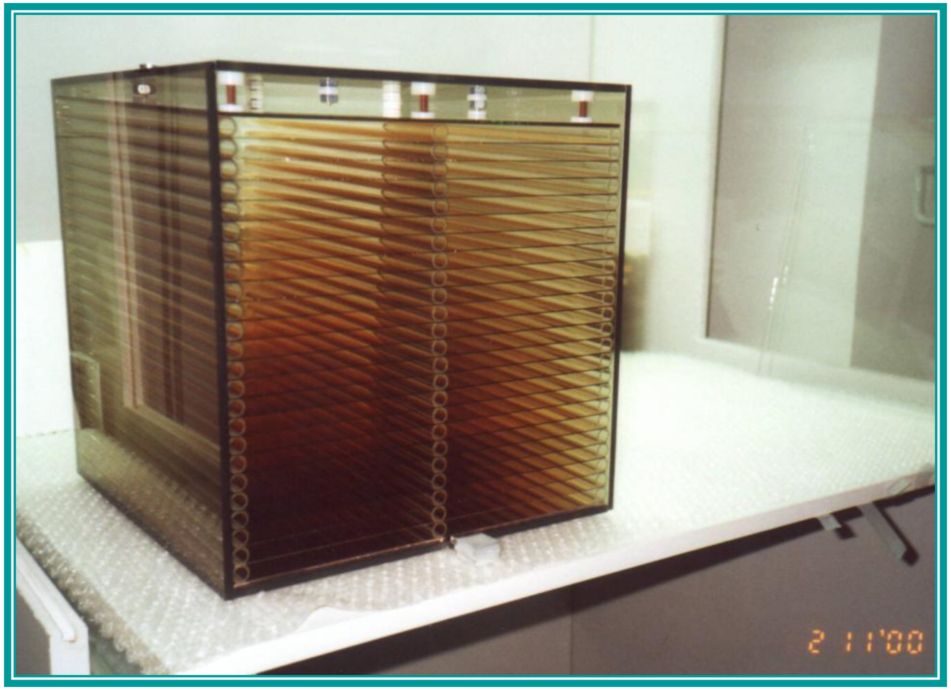




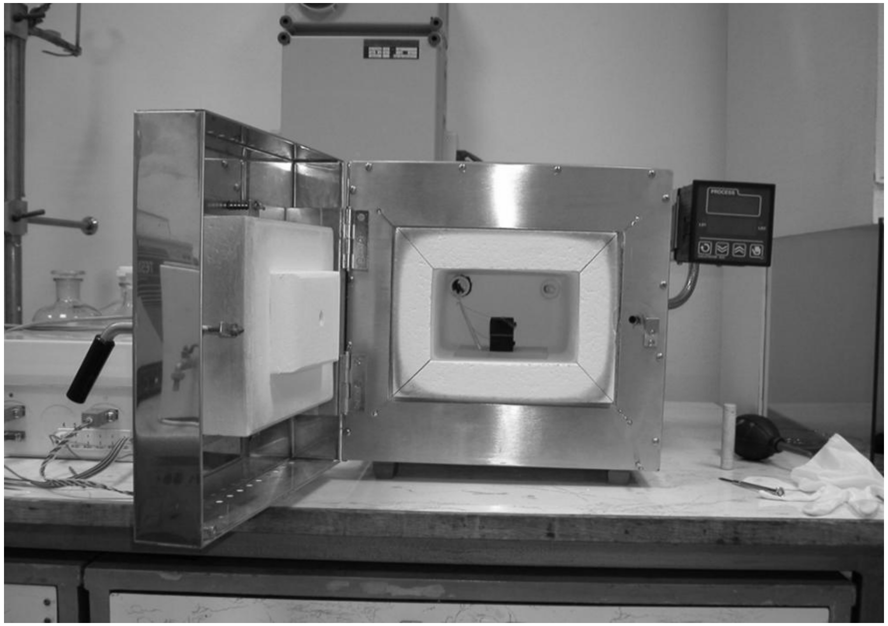


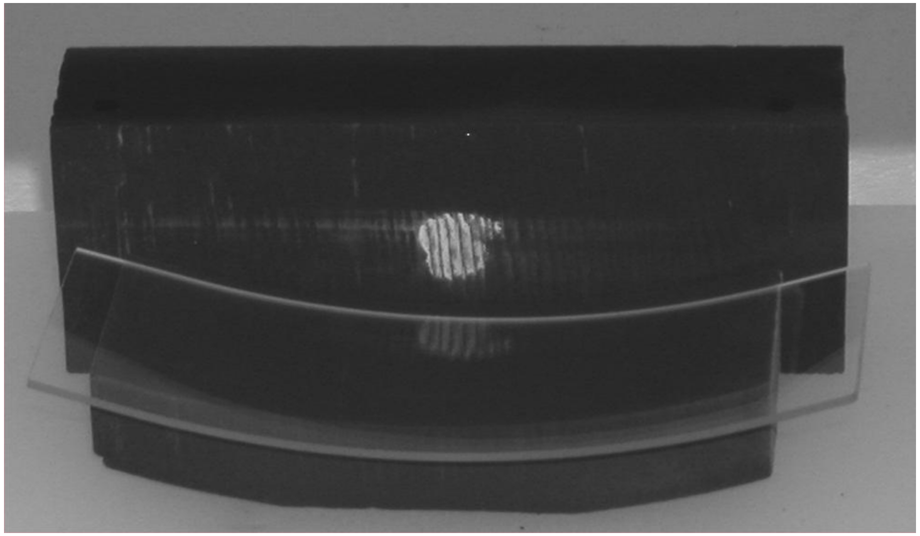
XEUS test module, 2002

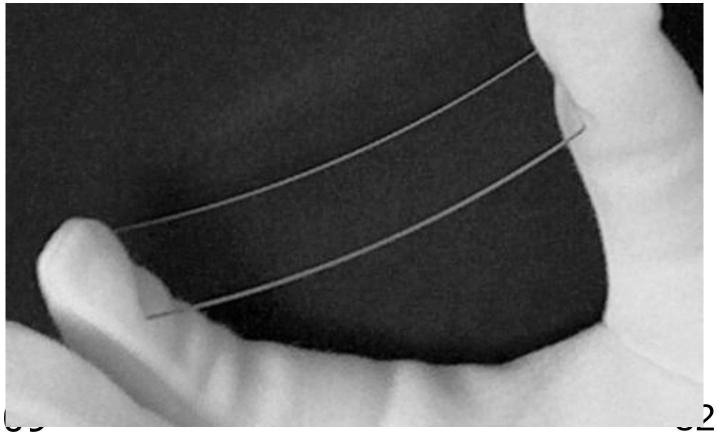
- **XEUS test module**
- **Based on gold coated glass foils,0.7 mm thick, 30 x 30 cm**
- **Parabolic profile**



Early Glass Sluping Experiments, 2004



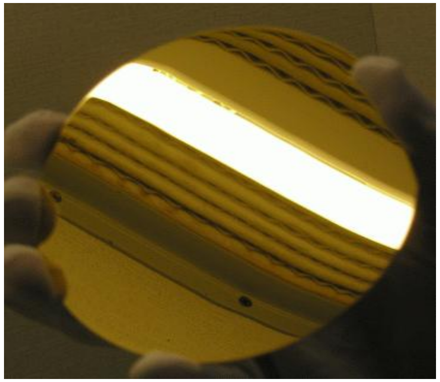




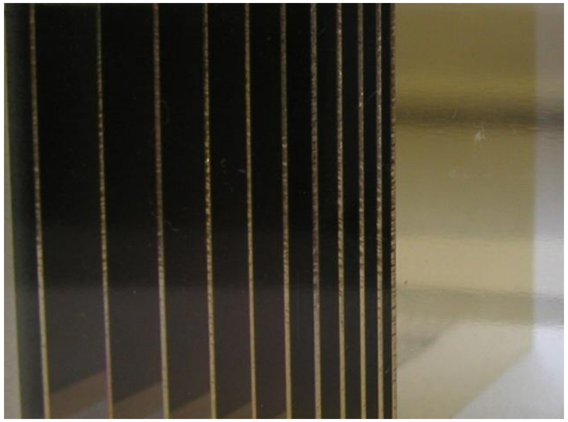
Glass slumping for X-ray optics continues until now at two Czech Institutions, RITE and ICT Prague

Si wafer – novel substrates: 2005-now

- very light (2.3 g*cm^{-3}, essential for space applications – ESA XEUS)
- RMS ~0.1 nm (need for precise optical shaping)
- very smooth with very good thickness homogeneity
- 1D bent (cylinder, aspheric, …), 2D bent (parabolic)
- 4 different technologies for precise optical shaping tested
- Single crystal: spectroscopic applications

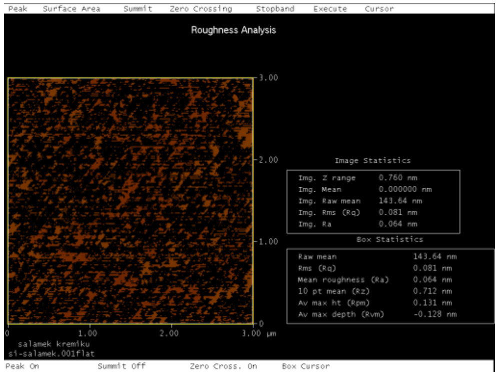


bent Si wafer

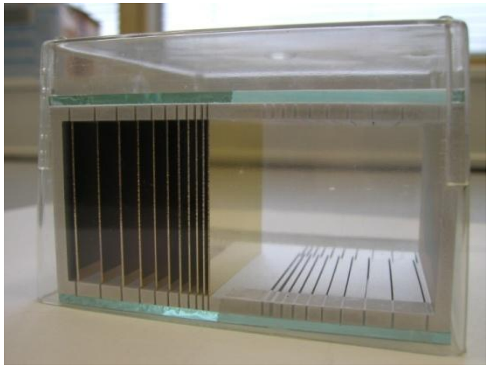


stacked Si wafer test module

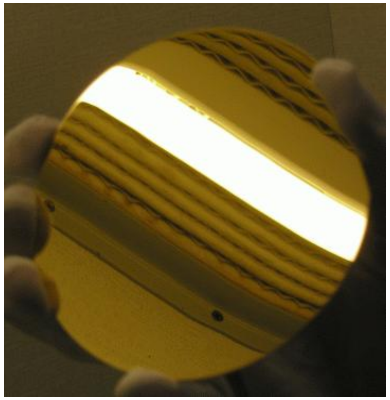
Si wafers



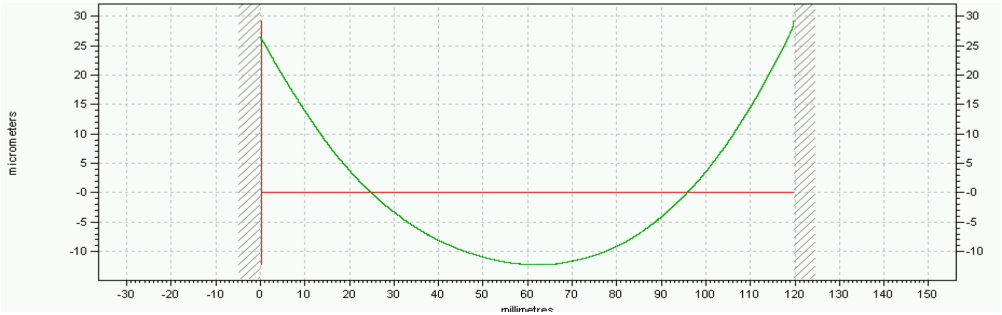
Microroughness
(rms ~0.1 nm)



Array of stacked
Si wafer mirrors



Optically formed Si wafer

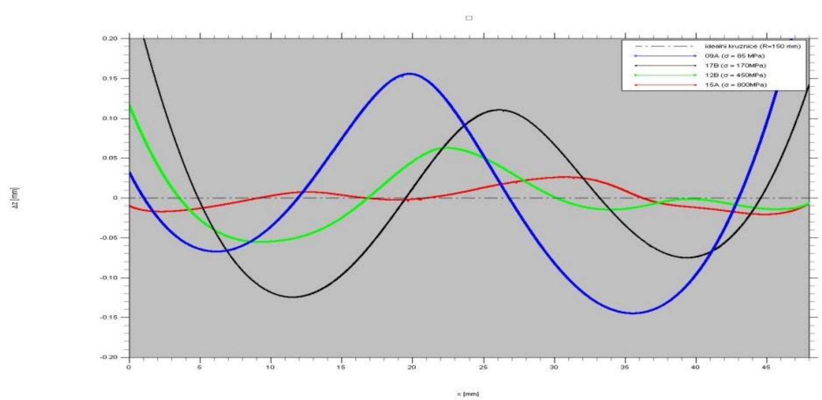


Si wafers need to be shaped to
very precise optical surfaces.

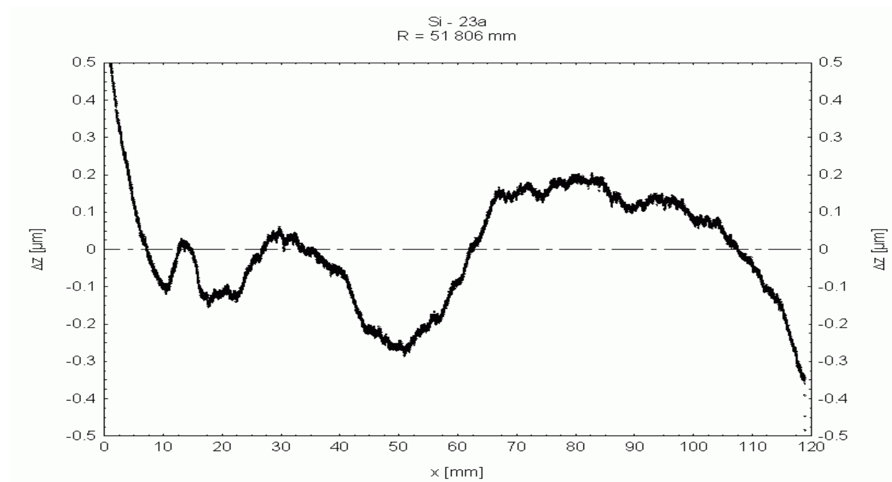
Si wafers is very promising substrate for large space X-ray mirrors.

Thermally formed Si wafers

Thermally (at T > 1000°C) formed Si wafer to test cylinder
(R = 150 mm, 72 x 23 x 0.325 mm)



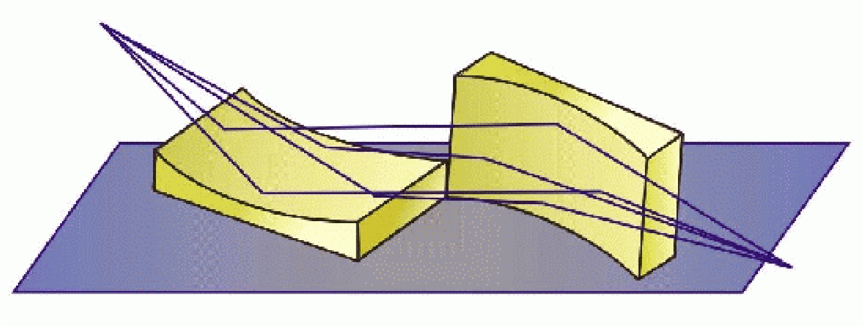
The effect of elastic tension on deviation from ideal surface.



Deviation from ideal shape
(D = 150 mm, t = 0.625 mm, parabolic shape).

Kirkpatrick Baez Systems:

Alternative X-ray imaging (investigated in a collaborative project with University of Colorado in Boulder)



Parameters of foils :

length 300 mm

width 100 mm

thickness 0.3 mm

Focus : 0.6 m

Future

Participation in ESA X-ray astrophysics projects (IXO) in new conditions – as a full ESA member state (now for one year): new technologies

Collaboration with NASA/CfA:Gen X, active X-ray optics

Collaboration with JAXA

Collaboration with Webster Cash: KB systems

LE experiments

More AXRO workshops

Summary

- The development of astronomical X-ray Optics in the Czech Republic has a long tradition (40 years)
- Numerous technologies have been developed and tested
- These technologies include galvanoplastic replication, epoxy/CF replication, LE optics, MFO optics, replicated Ni foils, glass foils, glass slumping, Si wafers shaping, plasma spraying, amorphous metals, and glassy carbon

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Thank you for your attention.

Contact: rhudec@asu.cas.cz