X-ray Optics and Imaging

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• **X-ray systems R&D**
  • Laboratory and space optics
  • Plasma sources
  • Detection techniques

• **X-ray applications**
  • Capillary discharge EUV source equipped with focusing optics
  • X-ray lithography
  • X-ray tomography (50 - 420 kV)
  • X-ray all sky monitor simulations
  • Future x-ray telescopes

**Cooperation**

• Academy of Sciences of the Czech Rep.
• Rigaku Innovative Technologies Europe s.r.o. – hi-tech Ltd., x-ray optics, detectors, sources
• Institute of Opto-Electronics Warsaw, Poland
• Others (ESA, NASA, industry, academic institutions ...)

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Spectrum of X-ray Radiation

- EUV (50 eV)
- XUV (100 eV)
- SXR (100 eV – 1 keV)
- XR (1 keV – 10 keV)
- HXR (100 keV)
- Gamma Rays (100 keV – 100 TeV)
Electromagnetic radiation spectrum


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
Applications of X-ray Radiation

- Medicine – radiography, tomography, therapy
- Industry – NDT, material research
- X-ray diffraction - crystalography, genetics, pharmaceutical industry
- EUV lithography – nanopatterning, semiconductor industry
- Diagnostics of hot plasmas – spectroscopy, imaging, basic research
- Astrophysics – stars, black holes, gamma bursts
Generation of X-ray Radiation

- Change of velocity vector of charged particle – continuum spectrum - Brehmstrahlung
- Change of state of quantum system – quantum transitions - line spectrum

Typical Sources of X-ray Radiation

- X-ray Tube (electron beam interacting with a solid target)
- Synchrotron
- Free Electron Laser
- Hot Plasma (Laser plasma, Tokamak, Z-pinch, Plasma focus, Stellar objects)
Characteristics of X-ray Tube

- Relatively low brightness
- $2\pi$ sterad diverging beam
- Wide energy spectrum: Characteristic and Bremsstrahlung (2 keV to 430 keV)
- Not polarised.
- Continual
- Microfocus
- Stable solid anode, rotating anode, liquid metal jet anode
- Coupling to XR optics possible
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 than a nano-second.
Laser Produced Plasma - solid target

Solid target

~ 100 μm

Focused high-power laser beam

10^{11} - 10^{14} W cm^{-2}

1-10 ns/0.1-10 J

X-rays & EUV

Nd:glass
Nd:YAG
KrF
CO₂

Shock wave

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

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

Expanded low density plasma

Ablation surface

Critical surface

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

Capillary Discharge Plasma

- Ceramic Capacitors (1.25 ÷ 31 nF).
- Al$_2$O$_3$ capillary, 3.2mm dia., 20cm long.
- Low inductance -> high dI/dt.
- Pulse-charged: 1x Marx + coil.
- Rogowski coil.

CTU Prague, Fac. of Nucl. Sci
Capillary Discharge Plasma

Nitrogen spectra 1 ÷ 25 nm
(water window radiation source 200 eV – 500 eV)

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Interaction of X-ray Radiation with Matter
The scattered amplitude:

The factors $f_1$ and $f_2$:

The atomic photoionization cross section:

$$\alpha(E) = \frac{A_{li}}{N_0}$$
The macroscopic factors $n$ and $\beta$:

$$n = \frac{\mathcal{N}}{2 \pi r_e^2}$$

$$\beta = \frac{\mathcal{N} \bar{f}_2^2}{2 \pi r_e^2}$$

The average atomic scattering factors:

$$\bar{f}_1 = \sum_j f_j$$

$$\bar{f}_2 = \sum_j f_j$$

where $N_j$ is the number of atoms of type $j$ per unit volume.
And consequently, using the relation

\[
E = \frac{hc}{\lambda}
\]

where \( N \) is the total number of electrons of type \( j \) per unit volume.

Variation of the absorption coefficient away from an absorption edge:
Reflectivity in X-ray region

- Complex index of refraction
- Fresnel equations
- Microroughness
Complex refractive index

$n = 1 + i\delta$

Refractive and Reflection of X-rays

Total external reflection
Fresnel formulas:
Reflectivity $R_p$ and $R_s$:

\[
R_p = \frac{R}{A} \left( \frac{R}{A} \right)^* \\
R_s = \frac{R}{A} \left( \frac{R}{A} \right)^*
\]

Surface microroughness is important:

\[
R = R_F R_\sigma \\
R = \exp(-4\pi \sigma \phi / \lambda)
\]
X-Ray Optics

Reflective optics
Capillaries, polycapillaries, parabolic, elliptic and foil mirrors, paraboloidal and ellipsoidal mirrors. K-B system, Wolter system
No monochromatisation, but hard energy cut-off

Refractive optics
Multiple Lenses
Microfabricated Kinoform structures

Diffractive optics
Crystals
Multilayered structures
Fresnel lenses
X-RAY OPTICS BASED ON REFRACTION
**X-RAY LENS**

**REFRACTIVE INDEX**

\[ n = 1 - \delta - i\beta \]  

\[ \delta = 0.5 \left( \frac{E_p}{E} \right)^2 \approx 10^{-4} - 10^{-7}, \quad \beta = \frac{1}{4\pi} \mu \lambda \approx 10^{-3} - 10^{-5} \]

\( E_p \) – plasmon energy, \( E \) – photon energy, \( \lambda \) – wavelength, \( \mu \) – absorption coefficient.

\( R \)– curvature radius, \( d \)– lens thickness.

**Lens focal length**

\[ F = \frac{R}{2\delta} \]  

**Fig. 1**
COMPOUND X-RAY LENS

Compound lens focal length: \( F = \frac{R}{2\delta N} \) (1),

\( N \) – number of individual lenses


15 keV X-rays

![Diagram of compound lens focusing 15 keV X-rays]

\( R = 0.3 \text{ mm}, \ N = 30, \ \text{intensity gain} \ G = 3 \)

Fig. 1
Fig 1. Paths of 8 keV X-rays forming a focal spot of the X-ray lens. Individual lens radius is 100 microns. The number of microlenses is N = 103.
Photographs of epoxy microcapillary compound refractive lens

Capillary diameter = 0.8 mm

Capillary diameter = 0.2 mm
GRAZING INCIDENCE
X-RAY MIRRORS
Grazing Incidence Optics

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

\[ \gamma = \frac{\alpha + \beta}{2} \]
Refractive index $n < 1$, total external reflection. Critical angle rises with atomic number as $Z^{1/2}$. Beyond critical angle intensity falls as $\theta^{-4}$ or faster.
Grazing-incidence reflectivity for Au, Ni and Si

Absorption reduces reflectivity near the critical angle
Variation of reflectivity with X-ray wavelength (Au)
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.
Effect of Grazing Angle

Platinum

Reflectivity

Photon Energy (keV)
Effect of Surface Microroughness

Unlike the reflectivity beyond the critical angle, the effect of roughness is relatively small. Loss of only 5% for roughness of 1nm (10Å)
Monocapillary (SC) geometry and description
TAPERED MONOCAPILLARY
Paraboloidal Mirror

Highly parallel beam (< 1 mr)
Large area - circa 1 mm diameter
Hole in the middle

Optimum efficiency in coupling to monochromator
Precise alignment necessary
X-ray Optics

Multilayer Mirrors

\[ n \lambda = 2d \sin \theta \]
ELLIPSOIDAL MIRROR
Replicated Wolter 1 X-ray mirrors of the KORONAS satellite (aperture 80 mm)
MANDREL
Grazing Incidence X-Ray Optics

Samples of replicated grazing incidence X-ray optics

- Thin CF mirror
- Double sided sandwich flats
- CF+epoxy
- X-ray micromirror
- Thin Ni Wolter shell
- CF mirror
- 36 years of development - from astronomy to laboratory
Ellipsoidal X-ray Mirror
Ellipsoidal Micromirror™

- 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)
Vacuum Test Bench for X-ray Cameras and Optics
Ellipsoidal X-ray Mirror as a Spectral Filter
Wolter Optic
Computer simulations

(virtual CCD images)
Graphs \( a \) to \( c \) show the effect of point-like X-ray source off-axis displacement on the detector intensity distribution for ellipsoidal mirror.

<table>
<thead>
<tr>
<th>Graph</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>0 ( \mu )m source displacement,</td>
</tr>
<tr>
<td>( b )</td>
<td>200 ( \mu )m displacement,</td>
</tr>
<tr>
<td>( c )</td>
<td>400 ( \mu )m displacement.</td>
</tr>
</tbody>
</table>
Focal spots for off-axis source position

Detector intensity distribution for line X-ray source for ellipsoidal mirror.

**c** – asymmetric line X-ray source 0 - 100 μm from the axis,
**d** – symmetric line X-ray source 0 to +50 μm and 0 to +50 μm around the axis.
The focus may be changed from spot to line electronically.

- Stability of focal spot assured.
- Modular design allows ease of access for tube changes.
- Patents.
- Focal spot size, shape and position are controlled automatically.
Two examples of micromirror gain as a function of X-ray source diameter (Computer ray-tracing calculations).
Nonius KappaCCD_{2000}

Lysozyme single crystal

Unit cell aligned to the direction of the X-ray beam using 180 secs per 2° rotation

Excellent performance in terms of brightness, low background noise, small beam size, and ease of use

Courtesy of Nonius B.V.
Powder Diffraction

Silver Behenate

Microsource 25W

2 mrad Micromirror

Sealed tube 2kW
• X-ray optics based on multiple thin X-ray foils
• Various foil materials
  • glass
  • Si
  • metal ...
• Various arrangements and geometries
  • Lobster Eye
  • KB system
  • Wolter
  • Double conical approximation to Wolter...
Motivation – wide field imaging

- Astronomical sources
  - Imaging
  - Image reconstruction
  - Scanning observations

- Laboratory sources
  - Imaging
  - Image reconstruction

- Other optic types
Lobster Eye

Channels – optical elements
Wide field optic
Lobster Eye (MFO) Geometry

- Reflection from two orthogonal stacks of planar mirrors (Schmidt)
- Wide field imaging
- LE modification - planar mirrors replaced by elliptical mirrors (MF KB, MFO)
- Focusing (no wide field feature)
Lobster Eye (MFO) Optic Concept
Multi-Foil X-ray Optics

Various examples of Lobster Eye and MFOs

- foil thicknesses from 30 µm to 1 mm
- foils 3 x 3 mm to 300 x 300 mm
- planar & ellipsoidal
Single Point Imaging – Typical PSF

Intensity (AU)

x [px]  y [px]
X-ray focal image of the 80 x 100 mm Schmidt prototype at 1.5 nm (X-ray test facility, University of Leicester, UK). The measured gain is 185
Multi-Foil X-ray Optic

- thin foils
- additional coatings
- shape variations

20 x 20 mm front area
100 μm thickness, 300 μm spacing

EXTATIC Prague, September 2017
Experimental setup
The X-ray shadowgram of the LES module showing the 100 micron thick gold plated flats and approx. 300 micron spaces separating them (and also confirming the high optical quality of used flats).

Right: The X-ray focal spot image (LES module).
LE X-ray 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
- Gain: ~570 (experiment) vs. ~584 (comp. simulation)
Kirkpatrick-Baez mirror consisting of orthogonal stacks of reflectors. Each reflector a parabola in one dimension.
XEUS test 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)
The Cassiopea constellation as seen by the Angel type Lobster - eye telescope (computer ray - tracing)
Typical X-Ray Telescope
MFO EUV condensor

Optic profile – a quarter of the optic system is displayed, all dimensions in millimeters. Ellipsoidal mirrors, length 40mm, width 80mm.
MFO EUV condensor

focal spot
going horizontal part

vertical part
plasma
Experimental setup of MFO condensor

Two orthogonal sets of elliptical mirrors
Ray-tracing for point source

Focal spot for point source, 1\(\mu\)m pixel size, 256x256 pixels each. Linear intensity scale on the left, sqrt intensity scale on the right.
TEFLON layer exposed by EUV radiation
X-RAY OPTICS BASED ON Si WAFERS
Slightly parabolized D = 150 mm Si wafer
(ON Semiconductor Czech Republic)
Flatness measurements of Si wafer produced by ON Semiconductor Czech Republic

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>min. thickness</td>
<td>686.07 μm</td>
</tr>
<tr>
<td>max. thickness</td>
<td>687.75 μm</td>
</tr>
<tr>
<td>ave. thickness</td>
<td>687.18 μm</td>
</tr>
<tr>
<td>cen. thickness</td>
<td>686.92 μm</td>
</tr>
<tr>
<td>TTV Total Thickness Variation</td>
<td>1.68 μm</td>
</tr>
<tr>
<td>TIR Total Indicated Reading</td>
<td>1.81 μm</td>
</tr>
</tbody>
</table>

Flatness and thickness uniformity of a Si wafer (diameter 150 mm)
Si WAFERS SHAPING

test cylindrical samples
gold-coated, d=100 mm, thickness 0.8 mm, R=1.3 m
XR/XUV Micron to Submicron Resolution Laboratory Microscopy and μCT

Spatial resolution is determined by the outer zone width $\Delta r \sim 15\text{-}50\text{nm}$
Xsight™ Micron X-ray CCD Camera

Applications:
• X-ray microscopy
• X-ray microtomography
• X-ray optics adjustment & metrology
• Phase contrast X-ray imaging

Field of view: 0.90 mm x 0.67 mm
Resolution: ≤ 1 µm (@ 8 keV)
Spectral range: 50 eV to 35 keV
Exposure time range: 20 µs to 500 s
Dynamic range: 70 dB
Dimensions: 60 x 70 x 250
Weight: 2.5 kg
Projection X-ray Microscopy
RITE and CTU, microfocus X-ray tube 8 keV (Prague, Czech Republic)
Projection X-ray Microscopy

X-ray image of Ixodes Ricinus
(Taken by XSight Micron at RITE laboratory using 80 W microfocus X-ray tube with Cu target)
Projection X–ray Microscopy

X-ray image of Ixodes Ricinus
(Taken by XSight Micron at RITE laboratory using 80 W microfocus X-ray tube with Cu target)
Projection X–ray Microscopy
Advanced Photon Source synchrotron facility (USA)

„Image of non-focused X-ray beam reflected by a bimorph mirror at beamline 21ID of the Advanced Photon Source. Separate peaks correspond to reflections by the mirror segments“, by courtesy of Dr. Elena Kondrashkina, Synchrotron Research/LS-CAT, Northwestern University. RITE Xsight Micron camera, pixel size 0.65 μm
# Ultra High Resolution 3D X-ray Tomography

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>POWER</strong></td>
<td>Ultra High flux, up to 1200 W</td>
</tr>
<tr>
<td><strong>ENERGY</strong></td>
<td>Cr, Cu, Mo</td>
</tr>
<tr>
<td><strong>DETECTOR</strong></td>
<td>3300 x 3300 x 2500 Matrix</td>
</tr>
<tr>
<td><strong>OPTICS</strong></td>
<td>No projection magnification</td>
</tr>
<tr>
<td><strong>EASY</strong></td>
<td>Minimal Alignment or optimisation</td>
</tr>
</tbody>
</table>
High Contrast X-ray Imaging and Tomography of Material Samples

6 μm Carbon Fibres
THANK YOU FOR ATTENTION

Prague