Focusing Optics for Neutrons:

From x-ray telescopes to Compact Neutron Sources

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MIT Reactor: a “compact source” at 6 MW

• Students training and preliminary experiments
• Thermal neutron diffractometer (~ $10^7$ n/s @ 14.7 meV)
• Thermal neutron imaging facility

• Neutron-optics test station
• Student time-of-flight spectrometer with on-line capabilities
Motivation for focusing neutron optics

Preservation of source brilliance \((n/s \Delta_x \Delta_y \Theta_x \Theta_y \Delta \lambda)\)

while trading-off beam size and angle
Choices for focusing optics for thermal neutrons

- **Diffractive optics:**
  - monochromatic applications only

- **Refractive optics:**
  - strong chromatic aberrations: \( f \sim \frac{1}{\lambda^2} \)
  - very long focal length (~100 m for thermal neutrons)

- **Reflective optics:**
  - critical angle for thermal neutrons similar to that for hard x-rays
  - use technologies developed for x-ray telescopes
Current state-of-the-art: focusing guides

Preservation of source brilliance \((n/s \, \Delta_x \, \Delta_y \, \Theta_x \, \Theta_y \, \Delta\lambda)\) while trading-off beam size and angle

Figure from: P. Böni and collaborators
Kirkpatrick-Baez (KB) mirrors

Gene Ice and collaborators

- Relatively easy to produce
- Excellent for creating very small beams at synchrotrons

But

- Not very practical for neutron beam sources > 1 mm
- Only one reflection limits collection efficiency
New approach: axysimmetric Wolter optics

Advantageous for large neutron sources

Collect larger solid angle than KB and increase high-energy efficiency

Practically aberration-free: useful for some ToF methods
Wolter optics geometry

Magnification:
\[ M = \frac{f_i}{f_s} = \frac{\Theta_1}{\Theta_2} < 1 \]

\[ r_i = 0.05 \div 0.5 \text{ m}, \]
\[ f_s = 2 \div 25 \text{ m} \]
How to implement Wolter design

Utilize state-of-the-art technology for hard x-ray optics, telescopes and medical imaging optics, developed at NASA and Harvard-Smithsonian Center for Astrophysics

1. CNC machine, mandrel formation from Al bar
2. Chemical clean and activation & electroless nickel (EN) plate
3. Precision diamond turning to 20 Å, 1/3 um figure accuracy
4. Polish & superpolish to 3-4 Å rms finish
5. Metrology on mandrel

6. Ultrasonic clean and passivation to remove surface contaminants
7. Deposit multilayers on mandrel
8. Electroform Ni/Co shell onto mandrel
9. Separate optic from mandrel in cold water bath
Demonstration at MIT
Focusing of a thermal neutron beam

Neutrons in the focal spot are below 5 meV: cold neutron filter

Image of a 2mm diameter aperture in the beam at the MIT Reactor, using two nested Ni shells.

Focal distance = 3.2 m, mirrors length = 60 mm, demagnification = 4.

Both the source and detector are in focii.

Exposure = 10 sec, reactor power = 4.2 MW (maximum 6 MW).
Off-focus image showing reflections from two nested concentric mirror shells

Two concentric rings formed by the neutrons reflected by the two nested mirror shells

Rings of 20 mm diameter measured 440 mm upstream from focus
Example: optimization of Wolter optics for collection by
ray-tracing

Flux collection:
- Solid-angle coverage $\sim (\sin^2(\theta_1) - \sin^2(\theta_2))$
- Nesting increases solid-angle coverage by $\theta_1$

nested mirrors
$m = 3$ supermirror coating
$E = 5$ meV
Source-to-image distance 10 m and 25
Magnification: $1 \div 10$
Example: ray-tracing optimization of Wolter optics for flux collection

Concentration ratio = (Image flux density)/(Source flux density)

Magnification = M

Theoretical limit of concentration = M^2 = 100
Phase-space conservation dictates that the maximum flux concentration is determined by the number of reflections.

\[ \theta_{\text{out,MAX}} = 2N \theta_c + \theta_{\text{in}} \]

\[ C_{\text{flux}} \leq \left( \frac{\sin \theta_{\text{out}}}{\sin \theta_{\text{in}}} \right)^2 \leq (2N + 1)^2 \]

\( C_{\text{flux}} \) is the ratio of the flux densities at the sample and the source.

2 reflections work best for systems of up to 10 m.

For longer systems, 3 or 4 reflections are advantageous.

Application: replace guides close to moderator to reduce congestion.
Applications: Neutron Imaging

Aberration-free optics ➔
same time of flight for all neutrons object to focus
Imaging simulations

M = 1, L = 10 m, radii = 15-19 cm

Cut across image 5mm above center

Cut across image 5mm above center
Imaging at HFIR:
same short Ni mirrors, magnification = 4

Resolution is limited by the detector
SANS with focusing mirrors: adjustable resolution

Aperture | Mirrors | Sample | Detector
--- | --- | --- | ---

Higher resolution, lower flux density on a sample

Lower resolution, higher flux density
Example of optimization: Paraboloid-paraboloid optics for SANS

Magnification $M = 1$

$L_p = 0.2 \text{ m}$

Source-detector distance $L = 8 \text{ m}$
Intensity at Focus as Function of $r_i, f_h, m=3.0$
Flux density at the detector

PP Flux Density at Focus vs $r_i$, ($f_h = 3.6$)
Example of optimization: Paraboloid-paraboloid optics for SANS

Magnification $M = 1$

$L_p + L_h = 0.2 \text{ m}$

Source-detector distance $L = 8 \text{ m}$
Flux density at the detector

HPPH vs PP Flux Density at Focus vs $r_i$, ($m=1$)
Optics for spin-echo applications

Symmetric ellipsoid-ellipsoid optics:
no aberrations $\Rightarrow$ time-of-flight is the same for all neutrons

If a sample is placed in between, the spin-echo can be realized
Conclusions

• Major advantages of Wolter mirrors:

  Very flexible

  Excellent collection efficiency, comparable or better to that of focusing guides and KB

  Possibility of nesting

  Same time of flight for all neutrons reflected from one mirror

• Applications: SANS, imaging, guides replacement, neutron beam collection, ToF and spin-echo methods

• We are getting ready to test neutron (and x-ray) supermirror coating

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