Grazing Incidence Neutron Optics based on Wolter Geometries

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Total External Reflection

The optical properties of materials with respect to neutrons are characterized by their refractive indices which are a function of the neutron wavelength λ :

$$n = 1 - \delta + i\beta$$

With $\delta = \frac{\lambda^2 N_d b}{2\pi}$ and $\beta = \frac{\lambda N_d \sigma_a}{4\pi}$

Where N_d is the atomic number density, b is coherent scattering length, σ_a is the absorption cross section.The refraction index is less than unity for most of materials for neutrons and x-rays.

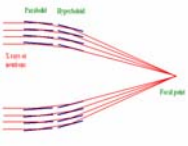
Imaging optics based on the Wolter optical geometries developed for the x-ray grazing incidence beams can be designed for the neutron beams.

Wolter geometries for x-rays and neutrons

Neutron optics based on total external reflection are achromatic, but to date these have been limited to toroidal single-bounce mirror systems with higher aberrations than refractive lenses, or Kirkpatrick-Baez optics. The latter feature two successive reflections in orthogonal directions but their approximation to cylindrical geometry limits their performance for anything other than small beams. Reflective optics based on the so-called Wolter geometries that are used extensively in x-ray astronomy because they minimize optical aberrations for off-axis rays, can also be designed for use with neutron beams.

These configurations gives near-coma-free imaging off axis:

Infinite source – Telescope



Paraboloid-hyperboloid or Paraboloid-ellipsoid

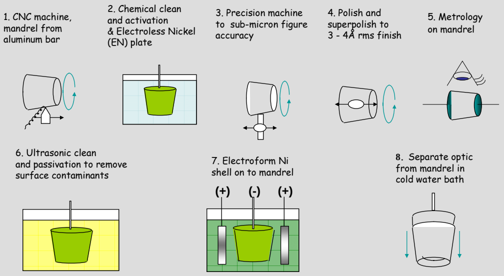
Finite source – Microscope

Hyperboloid-ellipsoid or Paraboloid-paraboloid

Neutron sources are diffuse, so the classical Wolter configurations for finite sources would need to be modified to achieve uniform optical performance for on axis and off axis. Typically polynomial approximations to the Hyperboloid-ellipsoid and Paraboloid-paraboloid configurations are applied to improve off-axis performance. The optical configurations would depend on the source-to-optic and the focal distances, i.e. the particular optical scheme and, hence, the its optical performance would be beam-line specific.

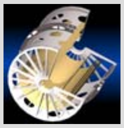
The shallow critical angles for cold and thermal neutrons dictate the use of nested grazing incidence optics. The most developed technology for fabrication of thin grazing incidence mirrors is the electroform nickel replication process. In this technique, pure nickel mirror shells are electroformed onto a figured and superpolished nickel-plated aluminum cylindrical mandrel from which they are later released by differential thermal contraction.

Mirror fabrication by the electroformed nickel replication process



1. CNC machine, mandrel from aluminum bar
2. Chemical clean and activation & Electroless Nickel (EN) plate
3. Precision machine to sub-micron figure accuracy
4. Polish and superpolish to 3 - 4Å rms finish
5. Metrology on mandrel
6. Ultrasonic clean and passivation to remove surface contaminants
7. Electroform Ni shell on to mandrel
8. Separate optic from mandrel in cold water bath

Nickel replicated optics at Marshall Space Flight Center



HXT Model

23 mm diameter, 100-micron-thick shell mirror coated with x-ray multilayers

- ✓ Resolution as good as 10 arc sec HPD (30keV x-ray).
- ✓ Diameters from 2 cm to 0.5 m
- ✓ Focal distances from 1 to 10 m
- ✓ Thickness 50 micron demonstrated
- ✓ Bare nickel, Gold, Iridium or multilayer coatings
- ✓ Optics for soft and hard (up to 70 keV) x-rays

0.5 m x-ray mirror

RAT mandrel and mirror

MSFC-Fabricated Neutron Mirror

Mirror parameters

Diameter	62 mm,
Length	175 mm,
Focal distance	1 m
Thickness	1 mm
Graze angle	8.0 mrad
Material	pure nickel
Microroughness (mandrel)	4.0 Å rms
Cut-off neutron wavelength	4.6 Å
Prescription	Wolter-1

Mandrel was originally designed as a 1/10-scale version of the innermost mirror of NASA's Chandra X-Ray Observatory.

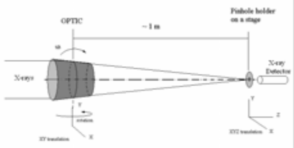
The electroform nickel replication process was adopted for the development of the neutron optics

X-ray test

An evaluation of the x-ray performance of the mirror was carried out at the Stray Light Facility at MSFC. The optic was placed 100 meters from a 0.2-mm-diameter x-ray source.

The x-ray angular resolution of the mirror (6 to 8 keV) was found to be 0.140 ± 0.003 mrad, which corresponds to a focal spot size of about 140 micron diameter.

The Stray Light Facility at MSFC



The x-ray test schematic

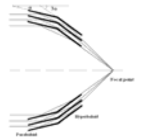
Cold Neutron test

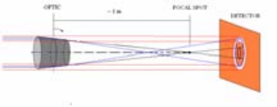
NG-7 beam-line

- ✓ Beam diameter is 25 mm – only sub-aperture test and maximal geometric area of the mirror is 17.7 mm². The footprint area of the mirror at the beam is only 44 mm²
- ✓ Neutron wavelength range is from 5 to 20 Å
- ✓ The shortest distance between detector and the mirror focal spot is ~ 1.5 m, the detector resolution is 5 mm – extra-focal measurements.

The test mirror installed in the neutron beam-line National Institute of Standards and Technology's Center for Neutron Research

Neutron Mirror Alignment





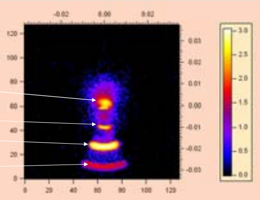
The schematic of the cold neutron test

The mirror was aligned with the NG-7 quasi-parallel beam using 10 Å neutrons and all the instrument neutron guides inserted

Neutron-Beam Image

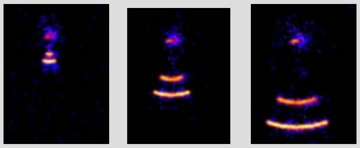
(from top to bottom):

1. Straight through
2. Single bounce component from parabolic section only
3. Double bounce component
4. Single bounce component from hyperbolic section only



Extra-focal image measurements

The performance of the mirror was investigated at neutron wavelengths of 6 Å, 10 Å and 20 Å. All the instrument's neutron guides were moved out to obtain the lowest possible beam divergence



0.67 m 2.67 m 4.67 m

Distance from the focal spot to the detector

The mirror focal spot size was estimated to be 1.15 mm (FWHM) with the divergence of the neutron beam of ~1 mrad. The neutron current gain estimated is shown in table

Neutron wavelength, Å	Effective area, mm²	Gain
6	17.9±0.4	8.5
10	17.1±0.2	8.2
20	15.8±1.6	7.6

Possible Applications

- ➢ Neutron imaging or concentration
- ➢ High resolution water mapping on Lunar or Martian surface
- ➢ Neutron microscopy and radiography
- ➢ Medical therapies
- ➢ Small-Angle Neutron Scattering Analysis (SANS) For this application the use of optics would lead to significant decrease in beam penumbra. It can be achieved if the focus of the mirror was placed at the detector resulting in lower values of obtainable scattering angles.

Surface microroughness requirement

For high quality neutron focusing, especially for SANS experiments, it is important to limit the neutron scattering from the mirror surface due to surface microroughness. With a fixed grazing angle the neutrons with a given wavelength will be scattered by the roughness with spatial frequency *f* at the angle θ. The neutron flux excluded from an angular aperture with radius θ or TIS is

$$\text{TIS} = \int_{\theta'} \psi_{sc} 2\pi\vartheta' d\vartheta' = \left(\frac{4\pi\sin\alpha}{\lambda}\right)^2 \int_{\theta\sin\alpha/\lambda} PSD(f')df' = (4\pi\sin\alpha)^2\left(\frac{\sigma}{\lambda}\right)$$

where is single reflection point spread function, PSD is power spectrum density function of the surface and is the surface roughness (the rms value). The formula describes the single reflection case and for double reflection, as for the Wolter optics, the single reflection point spread function has to be multiplied by factor of two. The surface microroughness required to achieve the contrast between the focused and scattered neutron currents of 1 x 10^5 is estimated using this formula to be ~1-2 Å rms.

MSFC x-ray module with 12 nested mirrors

Conclusions

The feasibility of grazing-incidence neutron imaging optics based on the Wolter geometries have been successfully demonstrated. Biological microscopy, neutron radiography, medical imaging, neutron crystallography and boron neutron capture therapy would benefit from high resolution focusing neutron optics.

Two bounce optics can also be used to focus neutrons in SANS experiments. Here, the use of the optics would result in lower values of obtainable scattering angles. The high efficiency of the optics permits a decrease in the minimum scattering vector without lowering the neutron intensity on sample. In this application, a significant advantage of the reflective optics over refractive optics is that the focus is independent of wavelength, so that the technique can be applied to polychromatic beams at pulsed neutron sources.