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Demonstration of multilayer reflective optics at photon energies above 0.6 MeV

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Abstract: Focusing optics operating in the soft gamma-ray photon energy range can advance a range of scientific and technological applications that benefit from the large improvements in sensitivity and resolution that true imaging provides. An enabling technology to this end is multilayer coatings. We show that very short period multilayer coatings deposited on super-polished substrates operate efficiently above 0.6 MeV. These experiments demonstrate that Bragg scattering theory established for multilayer applications as low as 1 eV continues to work well into the gamma-ray band.

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1. Introduction

In the quest for sensitive optics operating in the hard X-ray to soft gamma-ray photon energy range above 50 keV, two approaches have seen significant resources devoted to investigating applications and fielding instruments [1–7]. One of these approaches employ diffraction in bulk crystals, i.e. Laue transmission geometry [8], to concentrate rays in the focal plane. These so-called Laue lenses promise to significantly increase sensitivity compared to existing collimator optics [9–11], in particular in the 0.1–1 MeV range. Although Laue lenses are not true imaging systems, deconvolution techniques exist for reconstruction of the field of view [12]. This makes Laue lenses an appealing option for limited field of view applications, such as space-born telescope observations of Type Ia supernovae and compact objects.

The second approach relies on grazing incidence specular reflections following Bragg's law [13] off of multilayer-coated mirrors. Such Bragg reflectors can provide true imaging capability, when coupled with well-established optical principles [14, 15]. The most prominent example of a multilayer-coated hard X-ray optic [16] is the NASA NuSTAR satellite [17]. Its improved sensitivity and angular resolution, when compared to past missions that utilize absorptive collimator technologies, e.g. the European INTEGRAL satellite [9], has already led to several important discoveries [18, 19].

Recent research has shown that multilayer coatings can reflect X-rays efficiently at 0.38 MeV [20] where incoherent scattering effects become non-negligible. With the present work, we have nearly doubled the proven range of operation to 0.65 MeV an improvement that may enable new

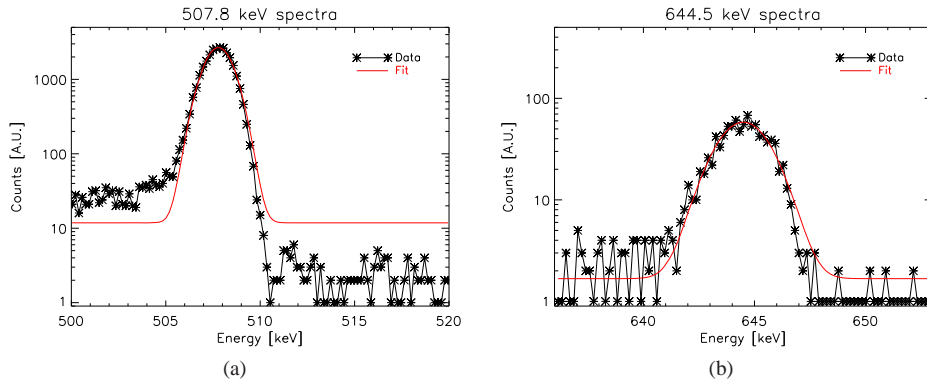


Fig. 1. Spectra acquired at 0.51 MeV (a) and 0.65 MeV (b) with a Canberra HPGe detector. The spectra were calibrated using a ^{133}Ba source mounted on the detector.

applications, e.g. imaging of electron-positron annihilation for laser-plasma diagnostics [21] or nuclear medicine studies [22].

2. Experiment

The multilayer mirror used was selected based on its good reflective properties, as characterized in previous X-ray campaigns at lower photon energies. The multilayer coating consists of $N=300$ bilayers of WC/SiC with a period of $\sim 15 \text{ \AA}$. The substrate is super-polished quartz with $< 3 \mu\text{rad}$ RMS figure over the entire $150 \times 150 \text{ mm}^2$ substrate surface area and 3.3 \AA RMS mid- and 0.5 \AA RMS high spatial frequency roughness.

Specular reflectivity data were acquired off of the mirror at beamline ID15A at the European Synchrotron Radiation Facility (ESRF) in a $\theta - 2\theta$ geometry with a vertical plane of incidence. The (511) plane of a Ge(400) double crystal monochromator was used to ensure a narrow spectral band width and to suppress second order terms. Data was acquired at 0.51 MeV and 0.65 MeV with a 5 mm thick CyberStar NaI(Tl) detector. The beam spectrum was measured with a Canberra GL0110P high-purity germanium detector, refer to Figure 1.

In the spectral range of interest, the heat load on the monochromator crystal cause significant fluctuations in the available flux. To decrease the fluctuations, the white beam was collimated to $3 \text{ mm} \times 60 \mu\text{m}$ before impinging on the monochromator, thereby reducing the thermal variations. The reduction lowered the direct beam fluctuation to $\sim 2\%$ at 0.51 MeV and $\sim 12\%$ at 0.65 MeV, refer to Figure 2. At lower energies, residual fluctuations can be accounted for during data acquisition by using an inline beam monitor. However, as the available silicon photo diodes become transparent above 0.4 MeV beam fluctuations are averaged out through repeated $\theta - 2\theta$ scans. Individual scans are normalized using a model of the incident beam intensity as a function of synchrotron current over time. The current is read out along with the detector signal. The derived model is shown in Figure 2 along with direct beam data from several scans.

The beam was collimated 13.4 m upstream from the mirror, limiting background in the detector hutch and reducing beam divergence to $0.54 \mu\text{rad}$. While a vertical beam height on order $10 \mu\text{m}$ is preferable to minimize the projected illuminated area (i.e. beam footprint) at grazing incidence angles this experimental configuration comes at the expense of beam intensity. The beam used was $65 \mu\text{m}$ in the vertical direction, resulting in a $\sim 110 \text{ mm}$ beam footprint at the first order Bragg angle for 0.65 MeV photons ($\sim 0.0375^\circ$). At these angles it was necessary to utilize a step size of less than $1''$ to ensure the reflectance peak was sampled. The beamline

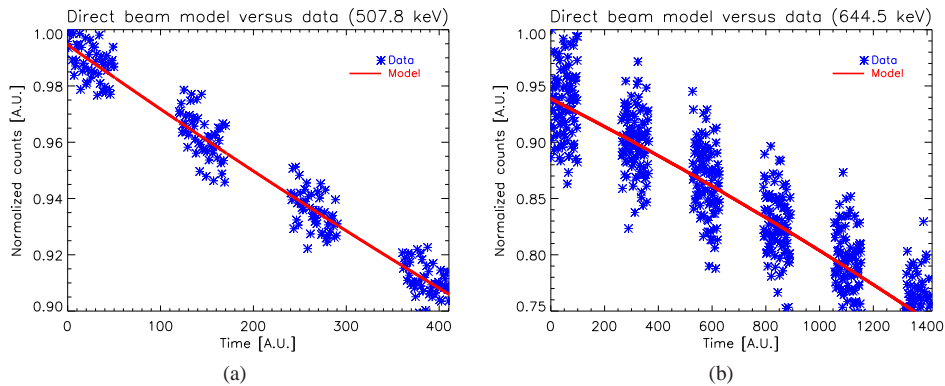


Fig. 2. Inline beam monitors are transparent above 0.4 MeV. To normalize the specular reflectivity data, the incident intensity from direct beam measurements is instead related to the synchrotron current and used to create a model at 0.51 MeV (a) and 0.65 MeV (b). The model interpolates between the direct beam data points shown in both figures. Specular reflectivity is measured between direct beam data acquisitions.

motors are equipped with encoders allowing for fractions of an arc second angular precision.

3. Results

The specular reflectivity data at 0.51 MeV and 0.65 MeV are shown in Figure 3. The reflectivity was modeled using the IDL software package IMD [23]. IMD implements the Fresnel equations, including Névo-Croce factors to account for interface imperfections. Additional custom software was written to allow for the spectral shape of the beam to be taken into account and the response to be smoothed in accordance with the substrate figure. The additional software also enables an incoherent scattering component to be added. Incoherent scattering in the multilayer and beamline hardware was simulated with a Monte Carlo particle transport code (MCNP6 [24]) at each energy. At 0.51 MeV the incoherent scattering contribution is less than 1% of the detected counts while it increases to 2.5% at 0.65 MeV.

Two reflectivity models are shown in Figure 3. The idealized model describes the location and shape of the reflectance peaks at both energies relatively well, in accordance with classical wave physics, taking into account beamline characteristics and substrate figure error. However, a shoulder is apparent in the data towards lower angles of incidence. The primary contribution to the shoulder derives from a non-uniform multilayer period over the area sampled by the beam. The non-uniformity has been mapped with soft X-rays (800 eV) and preliminary results from this study were used to simulate the current best model also shown in Figure 3. The study found a multilayer period variation of 0.6 \AA (4%) peak-to-valley over the illuminated area of $\sim 110 \text{ mm} \times 2 \text{ mm}$ at the first order Bragg peak (for $E=0.65 \text{ MeV}$). With a range of multilayer periods present, Bragg's law is fulfilled at additional angles of incidence thereby broadening the response. The feature did not present itself in previous X-ray campaigns at lower photon energies, on account of the relatively small beam footprints (10 mm, [20]) along the direction of the beam. The reduced grazing incidence angle and increased beam vertical size in use above 0.5 MeV results in an order of magnitude longer footprint. The relationship between wavelength, multilayer period and grazing incidence angle given by Bragg's law can be used to show that a non-uniformity better than 0.15 \AA (1%) peak-to-valley would be required to match the small peak broadening deriving from the narrow spectral width and beam divergence of ID15A. De-

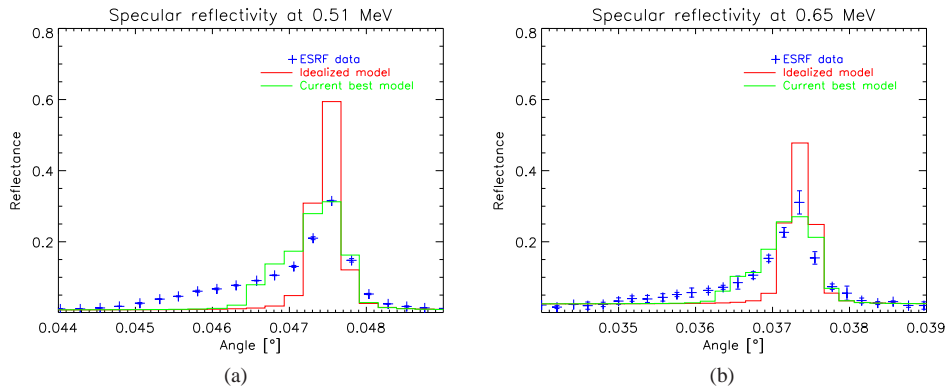


Fig. 3. Specular reflectivity data acquired at 0.51 MeV (a) and 0.65 MeV (b) is shown (blue). The data was normalized using the direct beam model (Figure 2). The expected response of an idealized (uniform) multilayer coating has been modelled (red) taking into account beamline characteristics and substrate figure. Also shown is the simulated response taking into account the non-uniformity determined with soft X-rays (green).

pending on the intended application, such high uniformity may be required. Magnetron sputter deposition has demonstrated the capability of achieving this on large area multilayer coated mirrors [25].

It should be noted that substrate figure distortion could, in theory, be a contributing factor to the shoulder in Figure 3. However, a $\sim 30 \mu\text{rad}$ RMS figure would be required to produce the effect. Full aperture white-light interferometry measurements carried out before and after the X-ray campaign confirmed the figure to be $< 3 \mu\text{rad}$ RMS, so this potential source of degraded performance cannot be responsible for the observed shoulder.

4. Discussion

The results demonstrate that multilayer coated mirrors can perform well up to 0.65 MeV. A study is underway to ascertain whether the multilayer response can be modeled well based on lower energy data (0.8-8 keV). This would allow future research and optic designs to rely primarily on models derived from more accessible, low-energy measurements to describe the multilayer structure, and then extrapolate the response to higher energies.

Multilayer optics working in the half MeV range offer increased sensitivity and efficiency when compared to other approaches like absorptive collimation, e.g. coded apertures, and transmission geometry, e.g. Laue lenses. This improved performance can be used in a few broad areas like detection of weak sources, where a focusing optic has an increased signal to noise ratio by using a smaller detection area. Another advantage of true imaging is that, unlike synthetic imaging techniques that use a shadow mask, there is no intrinsic dynamic range limitation, which can inhibit the detection of a weak source in the presence of a brighter one.

Although gamma-ray optics have shown some promise for applications like nuclear medicine [1] and nuclear non-proliferation [7], the scientific field that would most readily benefit from this technology is astrophysics, including the sub-disciplines of Galactic and Extragalactic astronomy, solar astronomy, cosmic-ray research and potentially observational cosmology, particularly with the current study having shown the conceivability of mapping the 511 keV emission line from electron-positron annihilation.

Implementing these novel optics will present challenges to researchers and instrument de-

signers on account of the shallow grazing incidence angles and subsequent long focal lengths, as well as the required quality of the mirror substrates. One group has performed a feasibility study [5] that shows telescopes invoking multilayer systems similar to those used in the present work, can provide significant sensitivity to 400 keV. Such a satellite-based observatory notionally fits within the types of future missions being considered by major space agencies.

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