#9905-207

A Concept for a Soft Gamma-Ray Concentrator Using Thin-Film Multilayer Structures

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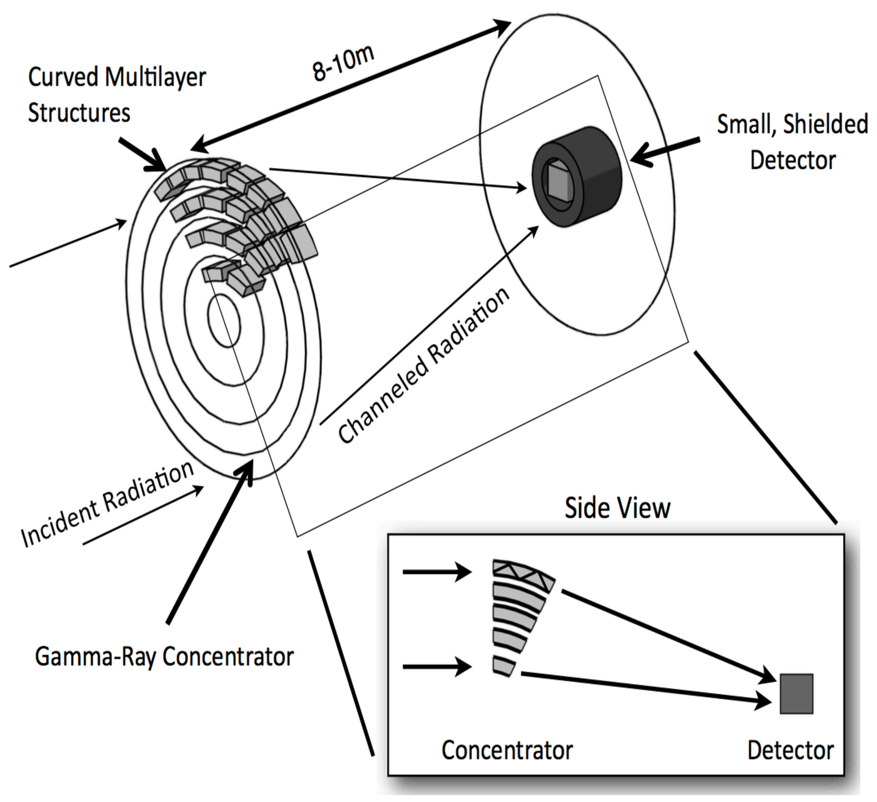
Introduction



Following pioneering work at LANL (Tournear et al. 2008, Appl. Phys. Lett., 92, 153502), we are investigating the use of thin-film, multilayer structures to form optics capable of concentrating soft gamma rays with energies greater than 100 keV, beyond the reach of current hard X-ray mirrors. Alternating layers of low- and high-density materials will channel soft gamma-ray photons via total external reflection. A suitable arrangement of curved structures will then concentrate the incident radiation to a point. Gamma-ray optics made in this way offer the potential for soft gamma-ray telescopes with focal lengths of less than 10 m, removing the need for formation flying spacecraft and opening the field up to balloon-borne instruments.

Gamma-Ray Channeling

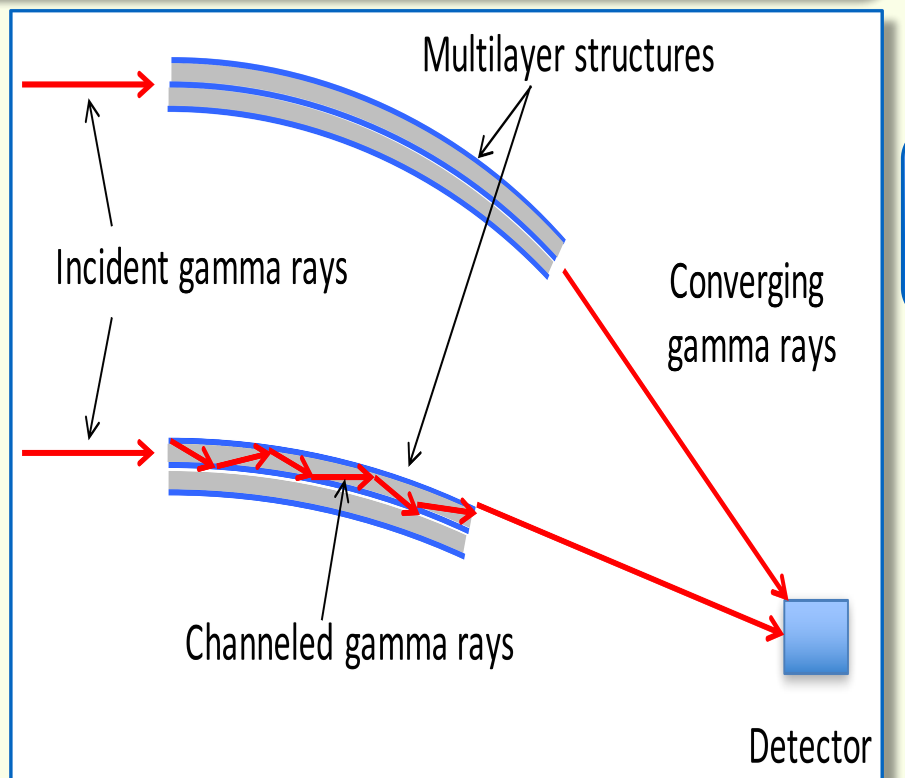
The soft gamma-ray channeling technique is based on total external reflection between layers with sharply differing indices of refraction. The refractive index n for high-energy photons is related to the electron density of a material N_e:

$$n \approx [1 - (\omega_p^2/\omega^2)]^{1/2} \qquad , \qquad \omega_p = (4\pi N_e e^2/m_e)^{1/2}$$

At these energies, therefore, low-density materials have higher refractive indices than high-density materials. This permits X-rays and soft gamma rays to be channeled within a low-density material between two high-density layers, as long as the angle of incidence is kept below the critical angle (Tournear et al. 2008):

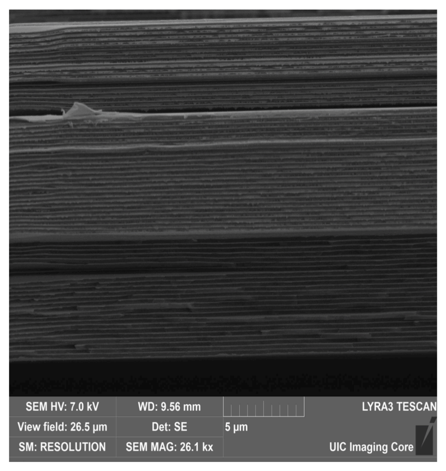
$$\theta_c \approx (\omega_{p2}^2 - \omega_{p1}^2)^{1/2}/\omega$$

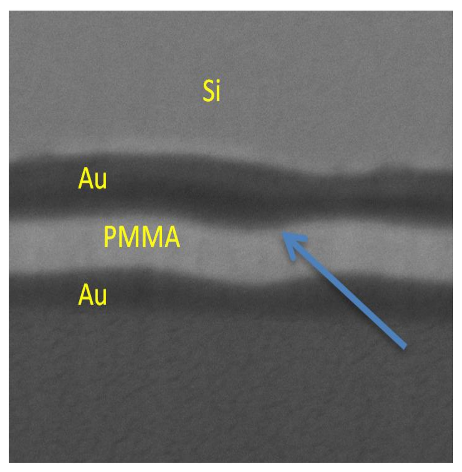
$$\theta_c \approx 6 \times 10^{-5}[(\rho_2 - \rho_1)/10\ g.cm^{-3}]^{1/2}[E/1\ MeV]^{-1}$$



Production of Multilayers

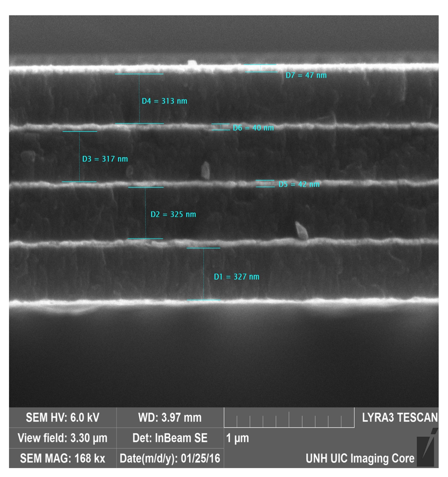
Following the work of Tournear et al. (2008), our first tests focused on producing PMMA layers using spin coating, with Au-Pd (20 wt% Pd) alloy layers formed by magnetron sputtering (MS). We produced a multilayer structure with 150 bilayers (199 ± 10 nm thickness for the PMMA and 49 ± 9 nm for the Au-Pd with a rms roughness of 0.283 nm). Although the desired smoothness and layer thicknesses were achieved, production of this multilayer took nearly a month.





We next investigated deposition of the PMMA by pulsed laser deposition (PLD), which is carried out in a vacuum chamber and compatible with the MS deposition method. Polymer/metal multilayers can be grown by PLD with high quality only if the polymer film has sufficient hardness to resist the stress in the metal layers. Our PLD-deposited PMMA films were too soft to obtain a good multilayer.

We are now testing deposition of C/Au-Pd multilayers by MS. One significant advantage of MS for thin film deposition is that the deposition rate is very stable and remains constant over long deposition times which is particularly important for our application, where many layers will need to be deposited in order to obtain the appropriate total multilayer thickness. Alternative low-density materials we will test include amorphous B and Si.

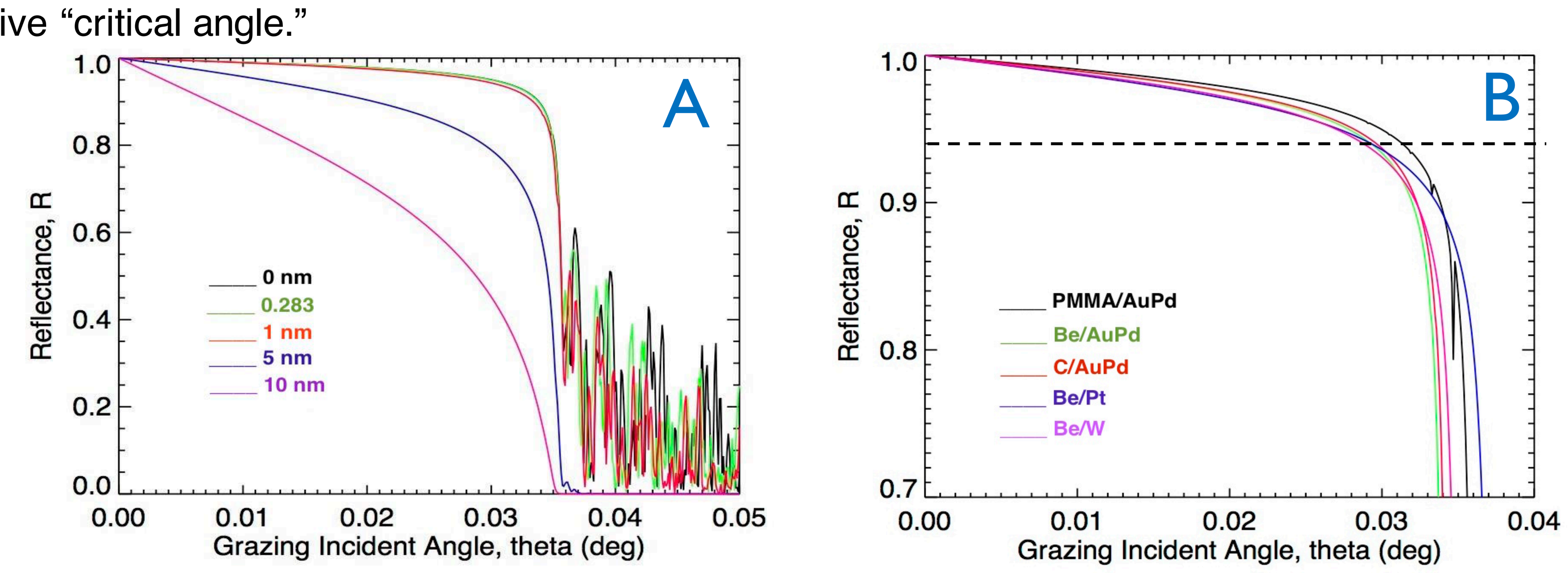


Modeling Multilayer Optical Properties

We use the IMD software (Windt 1998, Computers in Physics, 12, 360) to compute the optical functions (reflectance, transmittance, etc.) of the multilayers as a function of energy, incidence angle, layer thickness, and roughness.

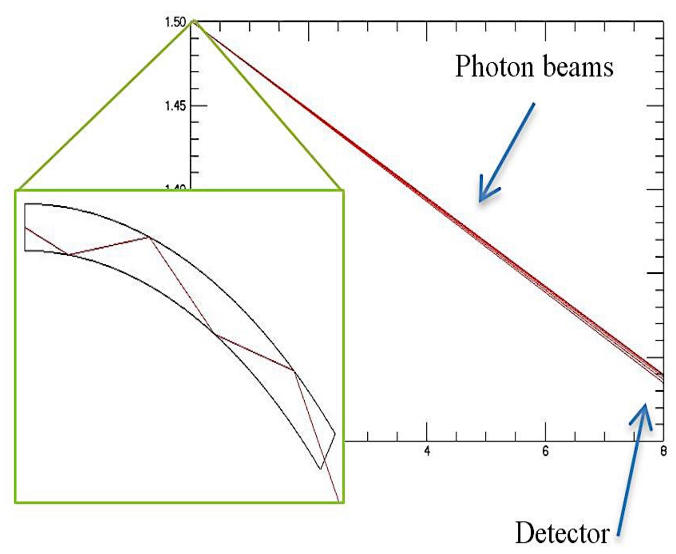
The calculation of the reflectivity of a PMMA/Au-Pd interface vs. angle, at 122 keV, for different roughness values shows that roughness < 1 nm (rms) is required (A).

The reflectivity was calculated by IMD for several material combinations that could be deposited via MS, compared to PMMA/Au-Pd (B). If we impose a minimum required reflectivity of 95%, it is clear that C and Be provide nearly as good performance as PMMA, with an only slightly lower value in terms of this effective "critical angle."

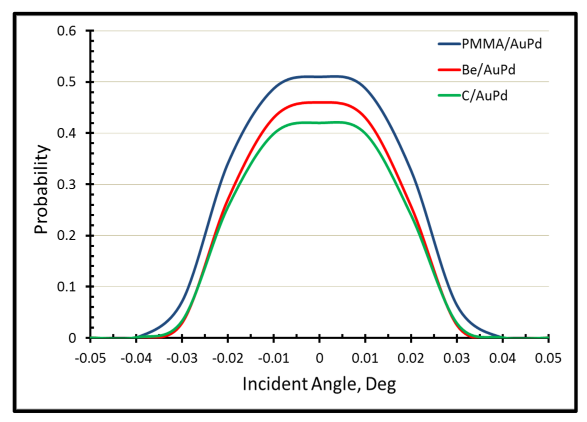


Gamma-Ray Tracing

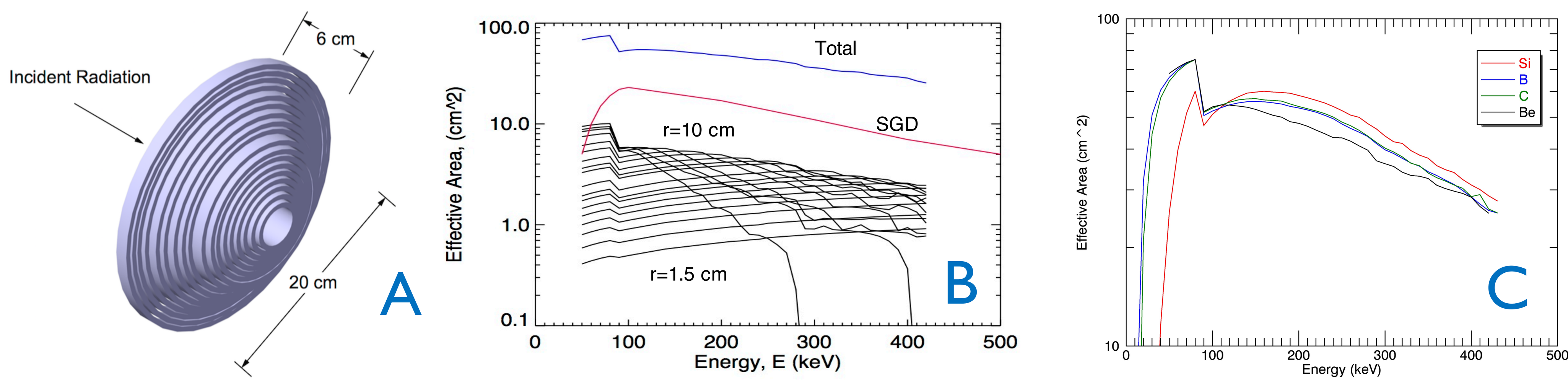
We make use of the IMD calculations in a custom ray-tracing code, written in IDL, that calculates the probability of channeling through a multilayer structure of a given material combination, roughness, length, and radius of curvature, including the photoelectric absorption or Compton scattering probabilities calculated by XCOM.



The channeling probability at 122 keV for a total bending angle of 0.4°, calculated for 200 nm layers of PMMA, Be, and C, shows that, while polymer would be optimal, C and Be perform nearly as well:



Preliminary Concentrator Design



We have developed a strawman lens concept composed of concentric rings (A). The channeling length of each ring is selected in order to maximize the total effective area within the desired energy band pass. The total effective area is the sum of the ring areas (B). Using Be for the channeling layer, the effective area is nearly double that of the *Hitomi* Soft Gamma-ray Detector (Watanabe et al. 2014, NIM-A, 765, 192). Different materials are better for different rings/energy ranges (C); the optimal concentrator will be composed of a combination of materials. Using the Be lens effective area (B), we have estimated the polarization sensitivity of a balloon payload to the Crab and Cyg X-1 for a single transit.

Simulated Polarization Sensitivity

Source	Energy (keV)	$MDP_{99\%}$
Crab	30-150	7.4%
	150-250	19.1%
	230-370	34.3%
Cyg X-1	30-150	3.3%
	150-250	8.8%
	230-370	18.4%

For more information, please contact Peter.Bloser@unh.edu

This work was supported by NASA grant NNX14AH57G