

Simulation and Optimization of Soft Gamma-Ray Concentrator Using Thin Film Multilayer Structures

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We are reporting the investigation of channeling and concentrating soft gamma rays (above 100 keV) using multilayer thin films of alternating low and high-density materials. This will enable future telescopes for higher energies with the same mission parameters already proven by NuSTAR (Harrison et al. 2013, *Astrophys. J.*, 770, 103). Based on initial investigations at Los Alamos National Laboratory (LANL) (Tournear et al. 2008, *Appl. Phys. Lett.*, 92, 153502) we are investigating producing these multilayers with the required thicknesses and smoothness using magnetron sputter (MS) and pulsed laser deposition (PLD) techniques. A suitable arrangement of bent multilayer structures of alternating low and high-density materials will channel soft gamma-ray photons via total external reflection and then concentrate the incident radiation to a point. The high-energy astrophysics group at the UNH Space Science Center (SSC) is testing these structures for their ability to channel 122 keV gamma rays in the laboratory (Bloser et al. *Proc. SPIE*, 9603, 96031E). In addition to experimental work, we have been working on a gamma ray tracing model of the concentrator using IDL, making use of optical properties calculated by the IMD software. This modeling allows us to calculate efficiency and focal length for different energy bands and materials and compare them with experimental result. Also we will combine concentrator modeling results and detector simulation by Geant4 to archive a complete package of gamma-ray telescope simulation. If successful, this technology will 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 and providing greatly increased sensitivity for modest cost and complexity.

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 :

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

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):

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

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

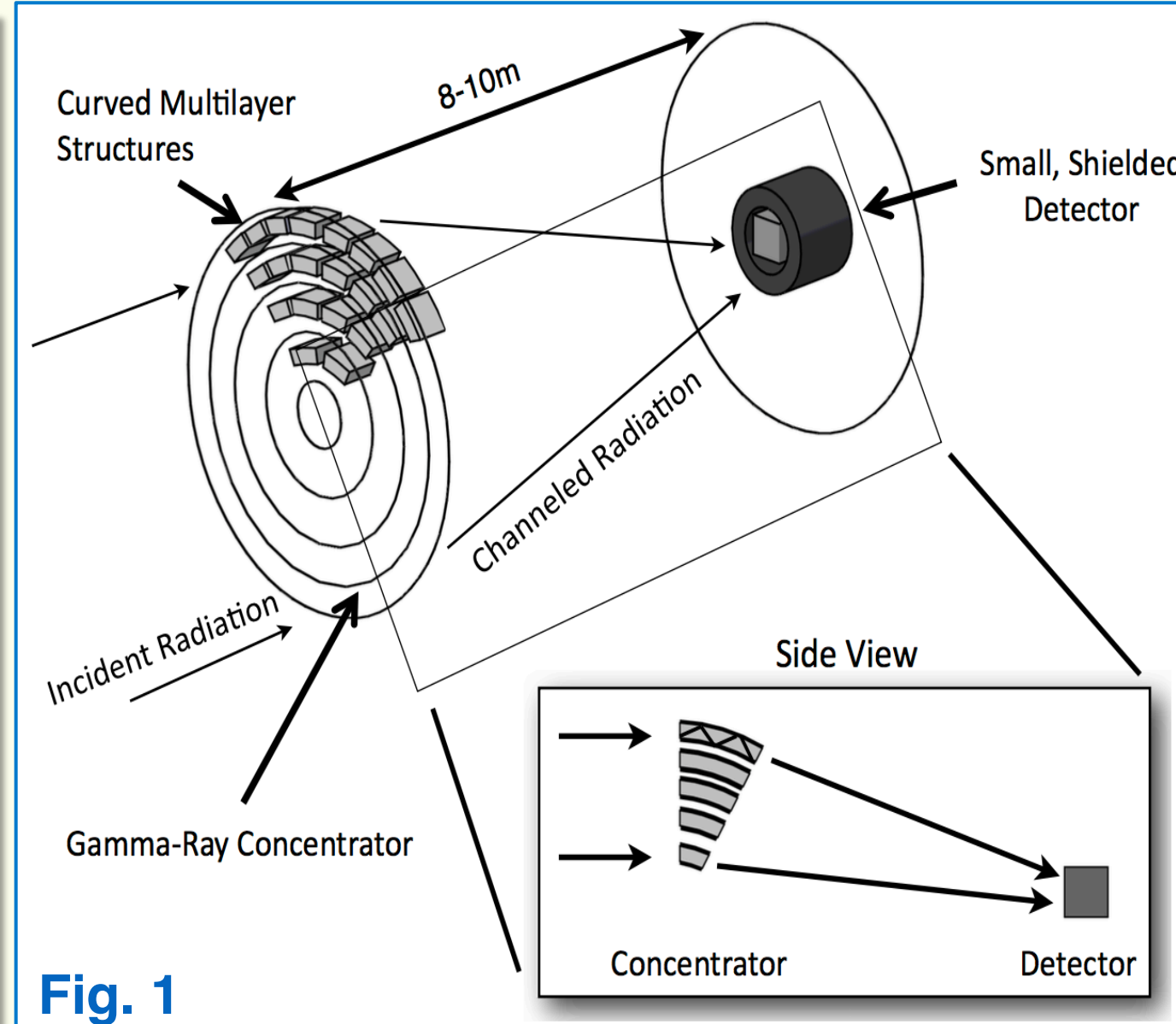


Fig. 1

Several issues are critical to the success of a gamma-ray channeling structure: The **difference in density** between the low- and high-density layers must be as large as possible so as to maximize the critical angle; the channeling layer must have as **low a density and mass attenuation coefficient** as possible so as to minimize absorption and Compton scattering; the layers must be made as **smooth** as possible to minimize reflection losses; and the channeling must be achieved using as **short a structure** as possible, again so as to minimize losses.

We illustrate these considerations using the theoretical example of a 20 cm diameter "lens" concentrating photons onto a small, shielded detector with a focal length of 8 m (Fig. 1), dramatically enhancing the signal-to-noise ratio for soft gamma-ray astronomy, suitable for either a balloon or spaceflight payload.

Production of Multilayers

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 (Fig. 2) with 150 bilayers (199 ± 10 nm thickness for the PMMA and 49 ± 9 nm for the AuPd with a rms roughness of 0.283 nm) for use in the channeling tests. Although the desired smoothness and layer thicknesses were achieved, the production of this multilayer took nearly a month.

We therefore investigated deposition of the PMMA by pulsed laser deposition (PLD), which is carried out in a vacuum chamber and compatible with the sputter 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. But our PLD-deposited PMMA films were too soft to obtain a good multilayer (Fig. 3).

Now we are trying deposition of C/Au-Pd multilayers (Fig. 4) 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.

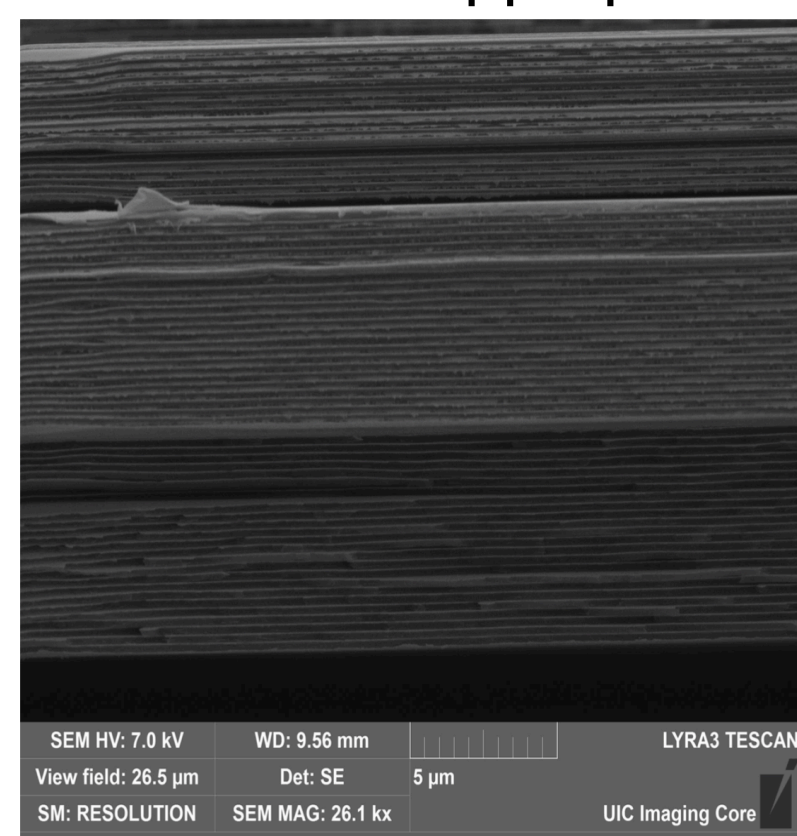


Fig. 2

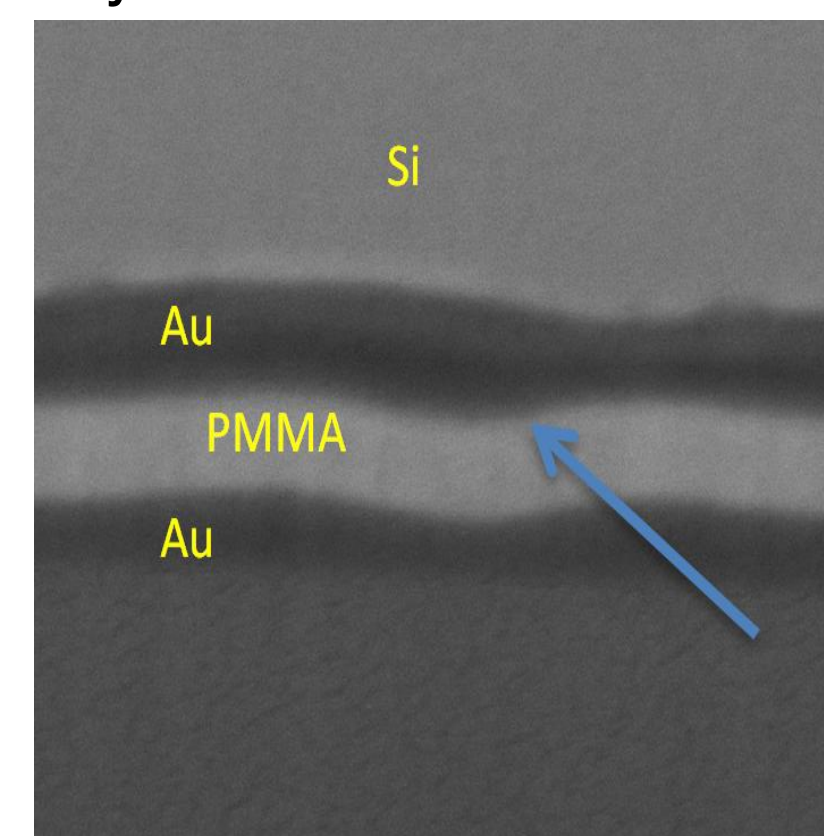


Fig. 3

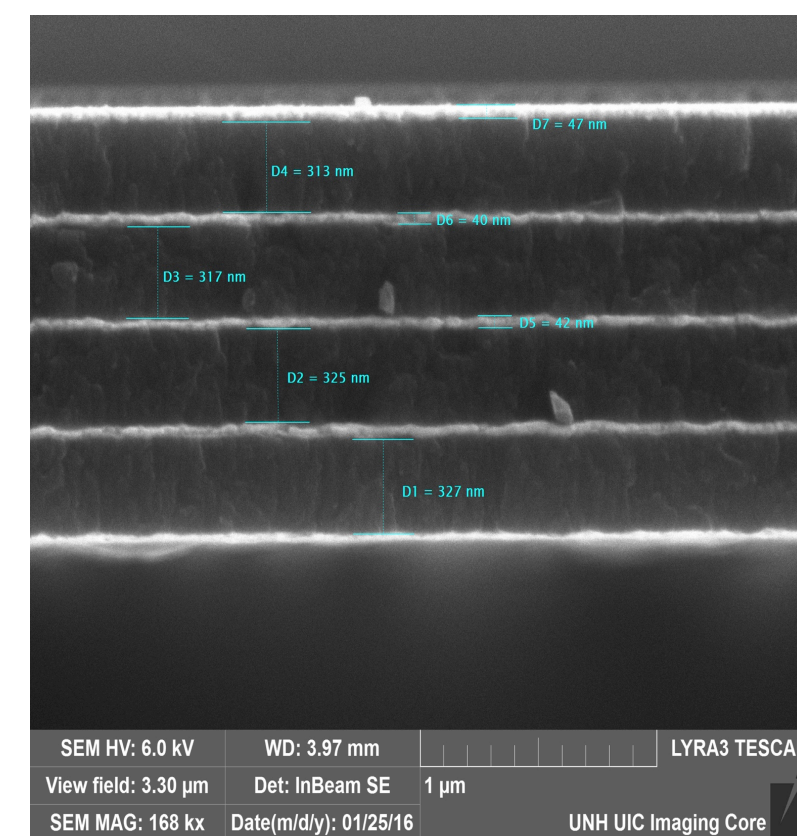
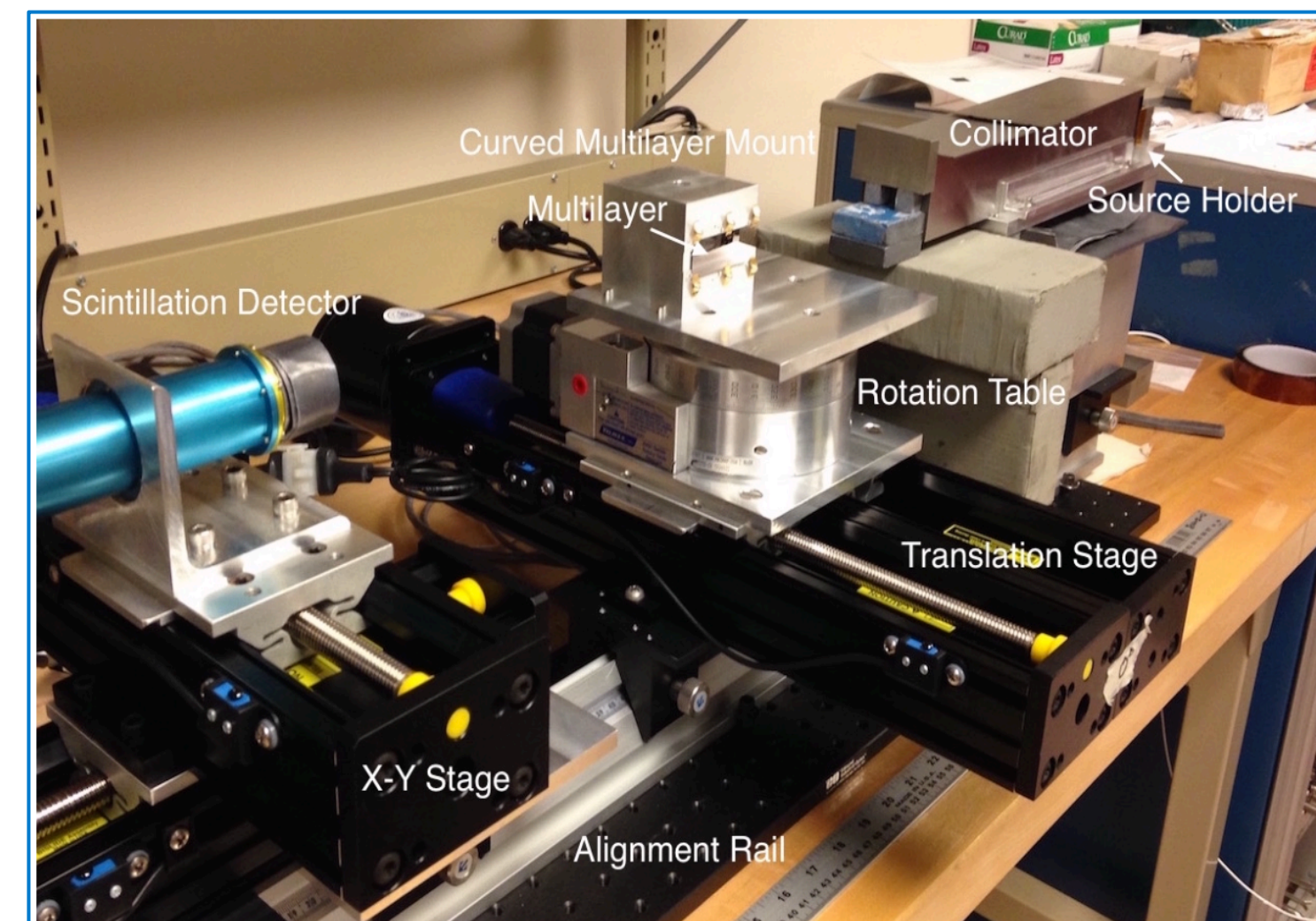
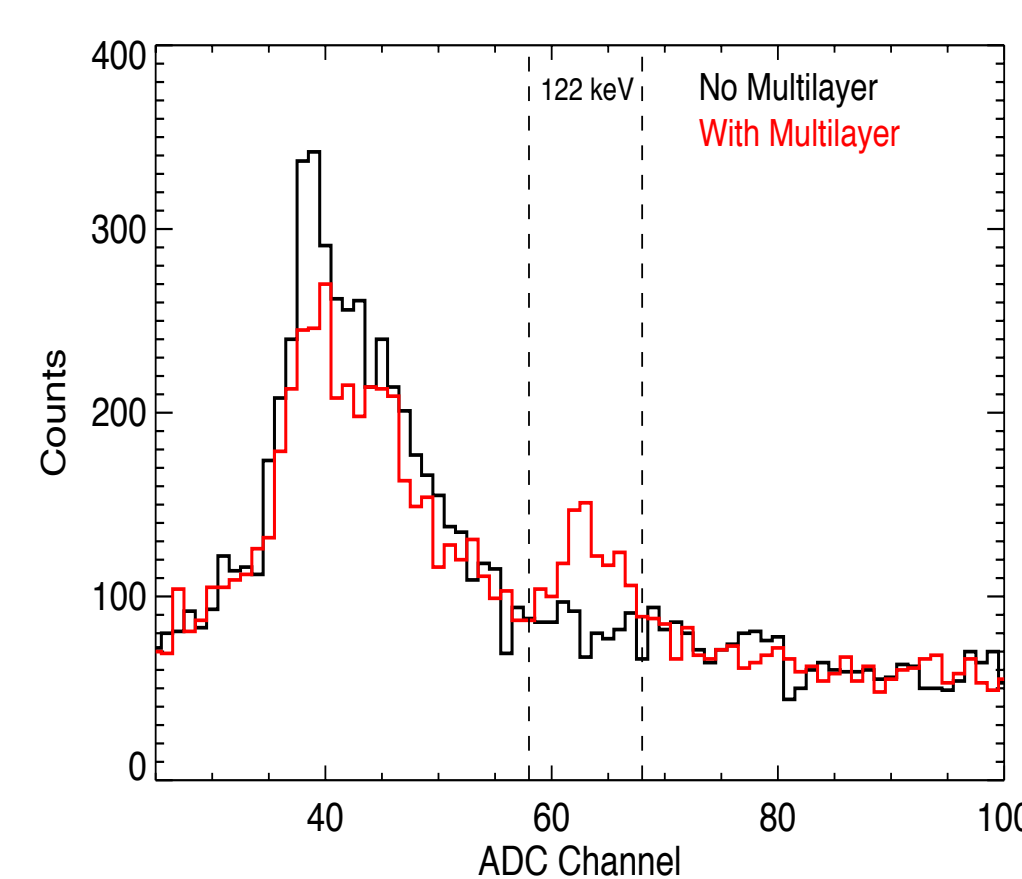


Fig. 4

Test Setup

A test setup was constructed (Bloser et al. 2015) to demonstrate the channeling of 122 keV gamma-ray photons from a ⁵⁷Co source over a bending angle of ~1° - 2° using the spin-coated multilayer.

We have identified areas within the (position, angle) space of our scans where 122 keV photons are clearly being detected off of the direct beam. When the multilayer is moved to the side, these photons do not reach the detector.



Multilayer Optical Properties Modeling

IMD software (Windt 1998, *Computers in Physics*, 12, 360) can compute the optical functions (reflectance, transmittance, etc.) not just versus energy and/or incidence angle, but also as a function of any of the parameters that describe the multilayer stack (e.g., layer thicknesses, roughnesses, etc.).

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 (Fig. 5).

The reflectance was calculated by IMD for several material combinations that could be deposited via MS, compared to PMMA/Au-Pd (Fig. 6). 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."

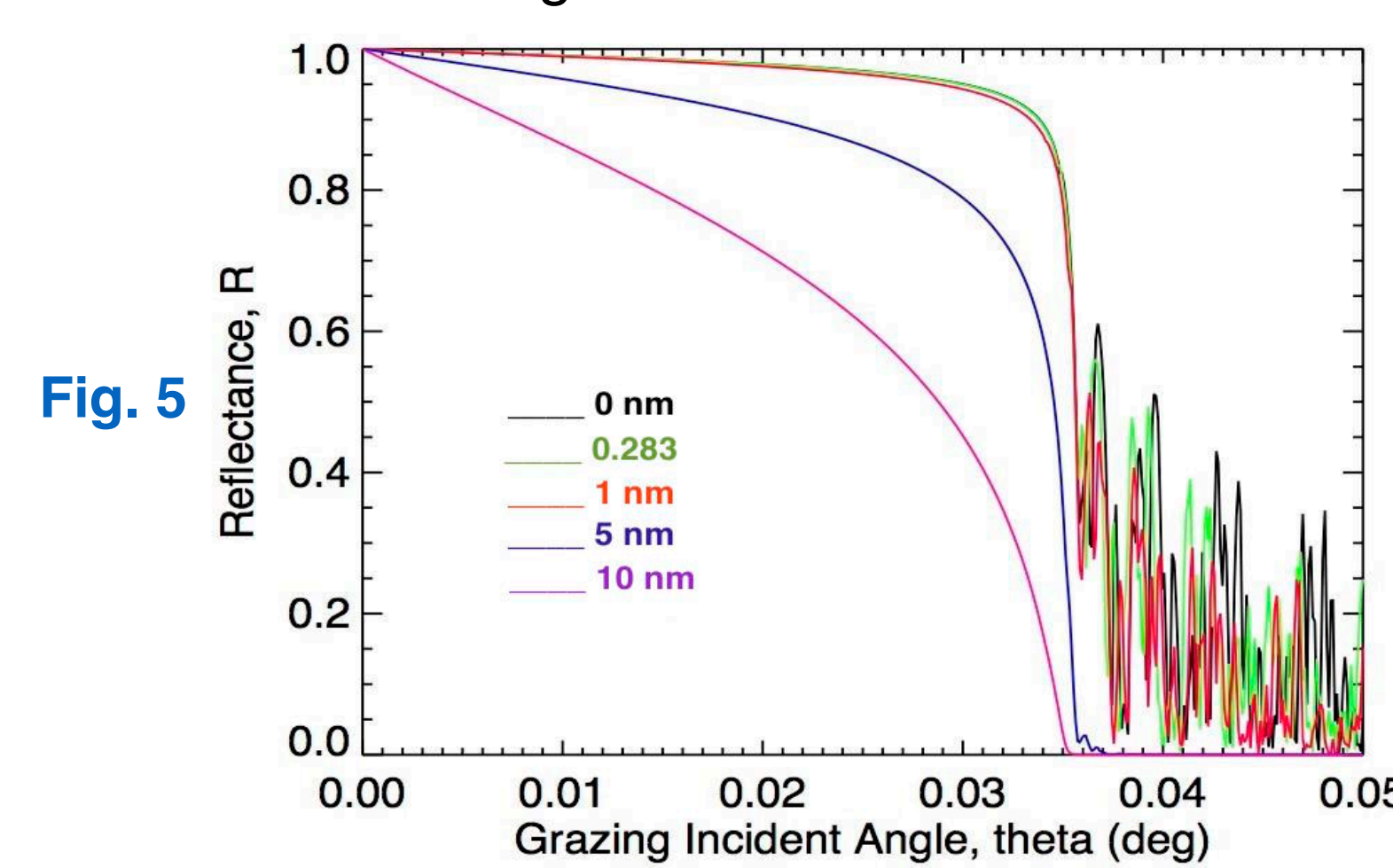


Fig. 5

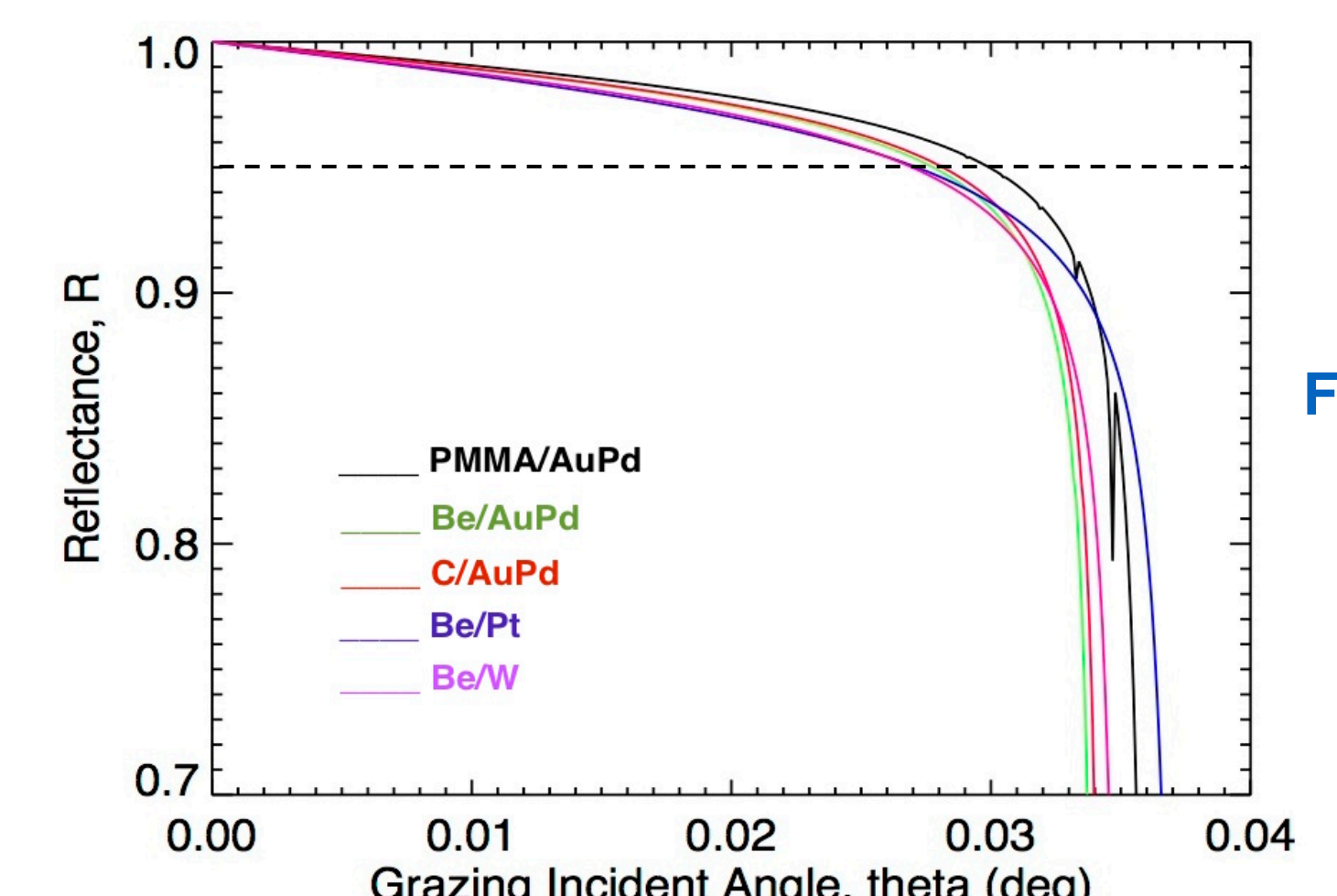
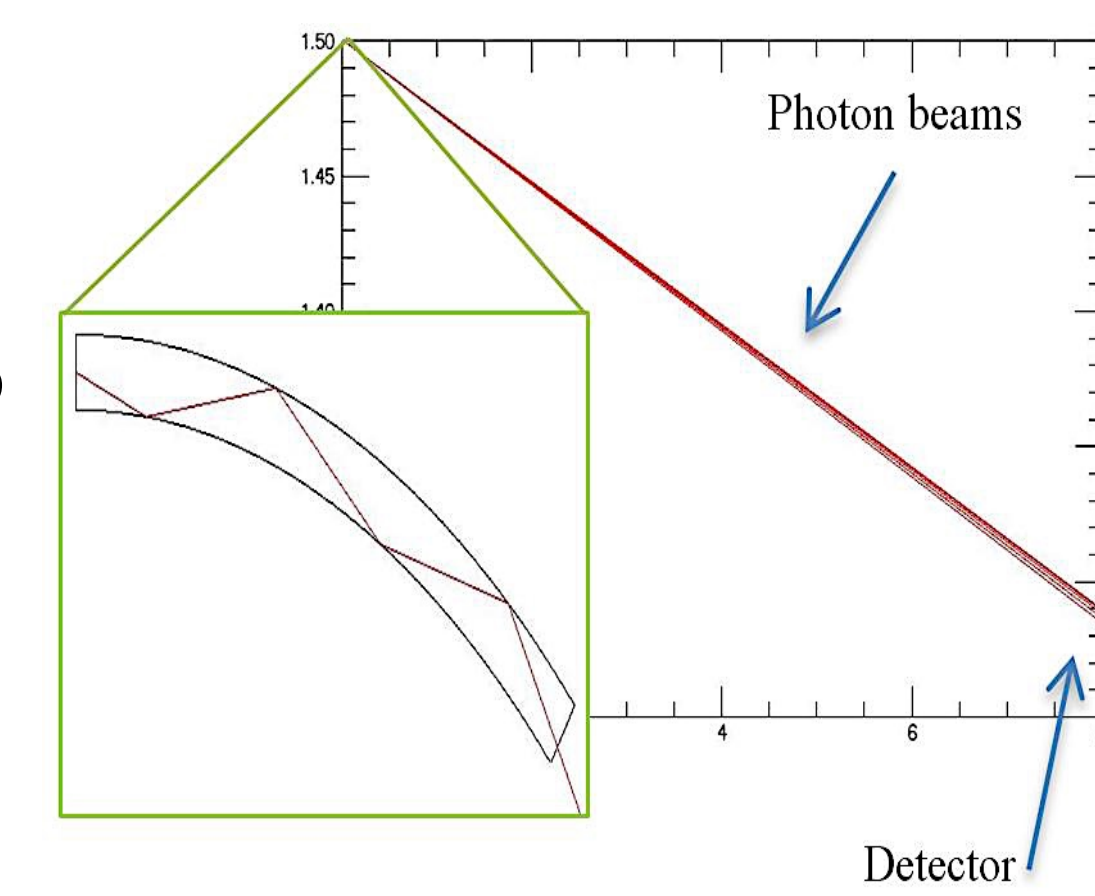


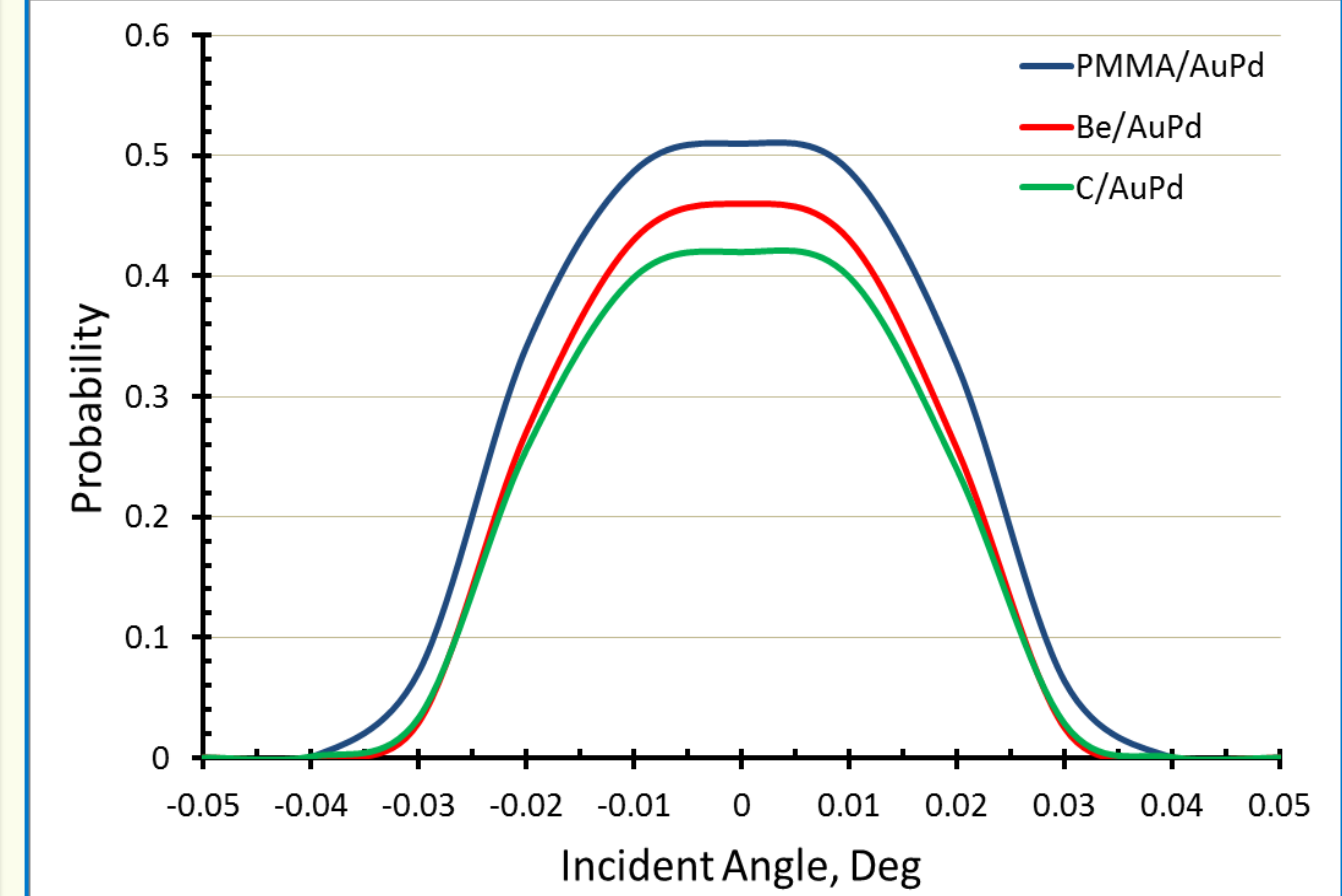
Fig. 6

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. The code selects an incident photon of the desired energy and incidence angle and location, calculates the path lengths through the channeling medium and the incidence angles at the high-density layers above and below, and uses the corresponding reflectivity from IMD and interaction probability (photoelectric absorption or Compton scattering) from XCOM to determine both the probability that it will exit the far end of the multilayer, and the angle at which it emerges.



The channeling probability at 122 keV for a total bending angle of 0.4°, calculated using our modeling tools for 200 nm layers of PMMA, Be, and C, shows that, while polymers would be optimal, C and Be perform nearly as well in combination with Au-Pd.



Preliminary Concentrator Design

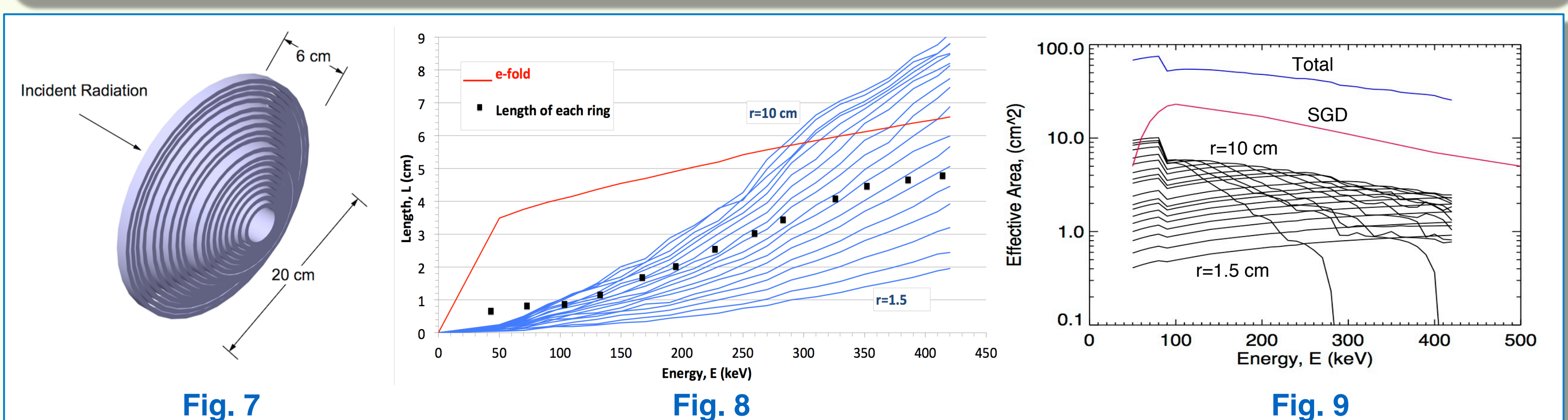


Fig. 7

Fig. 8

Fig. 9

We divide the strawman lens concept into concentric rings so that the channeling length may be adjusted based on the required bending angle at each radius. We choose eighteen rings, each 5 mm thick, starting at an inner radius of 1.5 cm and extending out to 10 cm (Fig. 7).

Path length required, based on radius, for each ring of the strawman lens (blue), and 1/e attenuation length in Be (red), was calculated by IDL modeling tools. The length of each ring must be selected in order to maximize the total effective area within the desired energy band pass. Longer lengths permit higher energies to be channelled, but also attenuate the lower energies more. Selected lengths for each ring are shown as black squares (Fig. 8).

The effective area has shown for each ring (black lines), and the total for the complete lens (blue line) that has a peak at a value of ~75 cm² at an energy of ~80 keV, just before the K-edge of gold. Also plotted is the effective area of the SGD (Watanabe et al. 2014, *NIM-A*, 765, 192), which peaks at ~25 cm² around 115 keV; the straw man concentrator has approximately double the effective area at this energy (Fig. 9).