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Optical optimization for anti-coincidence detectors of a Hard X-ray Modulation Telescope

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ABSTRACT

The anti-coincidence detectors of Hard X-ray Modulation Telescope (HXMT) are designed to suppress the X-ray background induced by incident charged cosmic-ray particles. The main components of anti-coincidence detectors are thin flat plastic scintillators. In this work we apply the TracePro program to study the light transfer features in the scintillators, and we propose several optimized reflector configurations to significantly improve the light transfer efficiency. The simulation results are verified by measurements of the detector prototypes. We chose a particular optimized reflector configuration.

1. Introduction

The Hard X-ray Modulation Telescope (HXMT), which is based on the direct demodulation method [1], will be China's first satellite for X-ray astrophysics. Three instruments, the High Energy X-ray telescope (HE), Medium Energy X-ray telescope (ME), and Low Energy X-ray telescope (LE), cover X-ray energies that range from 1 keV to 250 keV. HXMT will operate in near-earth orbit with an altitude of about 550 km. At this orbit the high flux of charged particles interacts with the instrument materials and thus induces a massive X-ray background [2]. This fact will sharply deteriorate the performance of the HXMT unless there is background suppression.

The HXMT implements anti-coincidence detectors and uses pulse shape discrimination to actively shield against the incident charged particles that arrive from a solid angle of nearly 4π. The 3D drawing of the HE assembly is shown in Fig. 1. The layout of the HE detectors as well as the sizes and orientations of the rectangular apertures of the collimators is proposed using the direct demodulation method [1]. The anti-coincidence detectors consist of 6 top and 12 side plastic scintillators that cover most of the front 2π solid angle of the HXMT. Each group of three HE detectors corresponds spatially to one top and two side anti-coincidence detectors. Each scintillator assembly is mainly composed of a large thin flat scintillator (0.225 m^2 for top board and 0.1 m^2 for side board) coated with reflectors for photon collection and coupled to a 2-in. photomultiplier tube (PMT). The axis of the PMT on the top anti-coincidence detector is aligned with the geometric center of the triangle gap formed by the three main hard X-ray detectors right below it to avoid blocking the field of view. The position of the PMT on the side anti-coincidence detector has an offset of 2 cm relative to the geometric center to avoid interference with the support which is not shown in Fig. 1.

A charged cosmic ray particle that penetrates one of the anti-coincidence detectors will deposit a fraction of its energy in the scintillator, thus inducing lots of scintillation photons. Part of these photons are collected and converted to an electric signal by the PMT. This signal is finally sent to the HE controller to veto the corresponding X-ray event. However, because of the large amount of reflections and the long propagation distances, the large thin configuration (especially in the case of the top anti-coincidence detector) will induce a high absorption of scintillation photons. This may significantly decrease the number of scintillation photons collected by the PMT, thus lowering the signal-to-noise ratio. Therefore, improving the light transfer efficiency in the large thin plastic scintillators becomes one of the key issues in designing anti-coincidence detectors.

For this work we use optical simulations to study the light transfer behavior in scintillators coated with various reflectors. Several reflector configurations are proposed which we expect to

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significantly improve the light transfer efficiency in the detectors. Specific measurements on the prototypes validated the simulation results. An optimized reflector configuration is selected based on the test and simulation results.

2. Optical simulations and optimizations

2.1. Models

The models of the top and side detectors are shown in Fig. 2. The dark gray indicates Saint-Gobain BC408 plastic scintillators with a thickness of 6.4 mm, and the circular truncated cones are BC802 light guides. BC634A optical layers on the top surfaces of the light guides couple them to the 2-in. PMT. Each of the three light-gray circular regions on the top scintillator is aligned with one collimator of an HE main detector below. The thickness of the scintillator corresponding to the light-gray regions are thinned from 6.4 mm to 3 mm to increase the X-ray transmittance (e.g. from 75.0% to 87.4% at 20 keV). The Corning 7740 PMT window couples to the optical layer. The rest of the model surfaces are coated with reflective materials.

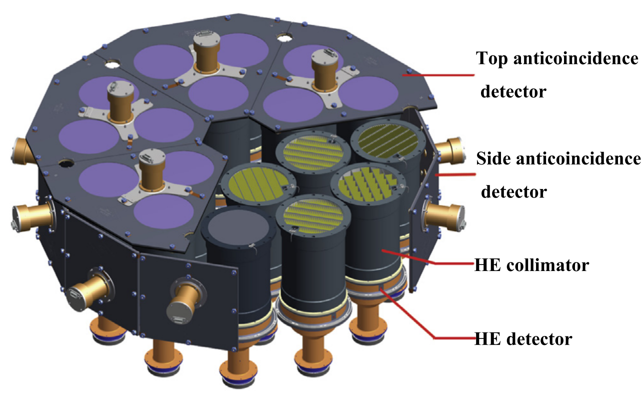

Fig. 1. A 3D sketch of HE assembly. Two of the top and side anti-coincidence detectors are hidden to illustrate the relative positions of the instruments inside.

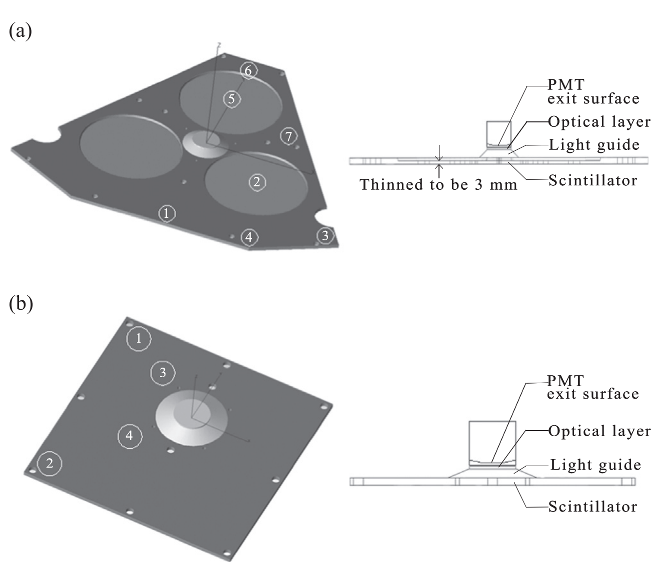

Fig. 2. Sketch of the scintillators of the top (a) and side (b) anti-coincidence detectors. The dark gray indicates the plastic scintillators. The circular truncated cones are light guides. The three circular light gray regions on the top scintillators are thinned to improve the transmittance of low energy X-rays. The numbers indicate the locations of the test points.

We use TracePro to study the light transfer behavior inside the scintillators. TracePro is a powerful tool that tracks the optical flux associated with each ray propagating throughout the solid model, and it is widely used in optical design and analysis [3–5]. To quantify the performances of different reflector configurations, a light transfer efficiency $\eta(x, y, \nu)$ is defined as the ratio of the flux at the exit surface (e.g. the PMT cathode) caused by the simulated source at test point (x, y) and the total flux of the source. Here, ν is the frequency of light emitted by the light source. The light source is modeled by a straight line representing the trajectory of a charged particle and is perpendicular to the scintillator. The material's properties, such as scintillation spectrum, body attenuation coefficient, and refraction index, are obtained from the manufacturer specifications. The parameters of the Bi-directional Scattering Distribution Function (BSDF), which characterize diffuse reflectors [6], are built in accordance with the scattering property described in the BC620 TiO_2 paint instruction book. This particular reflector is one of the reflectors used in the detector.

The numbers in Fig. 2 indicate the test points where the light sources are located. In the irregular top scintillation board, both the steps around the three sunken circular regions and the screw holes can partially change the propagation directions of the scintillation light. The combined effect of the steps and screw holes will increase the light loss when the source is far from the exit surface, and lead to a highly non-uniform light transfer efficiency in the top board. The test points labeled 1, 3, 4, 6, 7 in Fig. 2(a) potentially have the worst light transfer efficiency; they are close to the border or have steps or screw holes in-between the light guides. The test points labeled 2 and 5 are located at the thinner regions with fewer scintillation photons generated. The smaller size and simpler geometry of the side scintillation board let us predict a better light transfer efficiency than we get from the top scintillation board. The test points labeled 1 and 2 in Fig. 2(b) are at the corners far from the light guide, while the test points 3 and 4 are selected to check the uniformity of the light transfer efficiency.

2.2. The specular and diffuse reflector

Two types of reflectors are modeled: the Enhanced Specular Reflector (ESR) film from the 3M Corporation; and the diffuse BC620 TiO_2 painted reflector from the Saint-Gobain Corporation. The two simplest configurations of mono-specular and mono-diffuse reflectors are applied to the solid model of the scintillator. These two configurations are simulated with a light source placed at test point 1 in the side detectors (see Fig. 2). The total incident flux on the upper surface of these two models is shown in Fig. 3(a) and (b). The luminosity of the light source is normalized to 1.

The incident flux on the top surface indicates how many scintillation photons hit the area. A brighter region means more incident photons. Since a light ray (or a bunch of photons) reflected in the scintillator can hit a certain unit area several times and be recorded repeatedly, the total incident power on the top surface can be much greater than the luminosity of the light source. In the simulations the incident flux on the interface between the light guide and the scintillator is recorded independently, thus there is no record of incident flux at the light guide region on the irradiance map of the top surface. Fig. 3(a) shows that, in a detector with diffuse reflector, light cannot transfer far away and tends to be trapped and absorbed by the reflector and scintillator near the light source. In Fig. 3(b) the whole upper surface is illuminated as opposed to the diffuse reflector, indicating that a specular reflector tends to transfer light far away from source. This obvious result suggests that new hybrid reflector configurations may significantly increase the light transfer efficiency.