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Laue optics for nuclear astrophysics: New detector requirements for focused gamma-ray beams

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ABSTRACT

Nuclear astrophysics presents an extraordinary scientific potential for the study of the most powerful sources and the most violent events in the Universe. But in order to take full advantage of this potential, telescopes should be at least an order of magnitude more sensitive than present technologies. Today, Laue lenses have demonstrated their capability of focusing gamma-rays in the 100 keV–1 MeV domain, enabling the possibility of building a new generation of instruments for which sensitive area is decoupled from collecting area. Thus we have now the opportunity of dramatically increase the signal/background ratio and hence improve significantly the sensitivity.

With a lens, the best detector is no longer the largest possible within a mission envelope. The point spread function of a Laue lens measures a few centimeters in diameter, but the field of view is limited by the detector size. Requirements for a focal plane instrument are presented in the context of the Gamma-Ray Imager mission (proposed to European Space Agency, ESA in the framework of the first Cosmic Vision AO): a 15–20 cm a side finely pixellated detector capable of Compton events reconstruction seems to be optimal, giving polarization and background rejection capabilities and 30 arcsec of angular resolution within a field of view of 5 arc min.

1. Introduction

In astrophysics, though the sub-Mev domain is very rich in physics, it is not trivial to perform deep and sensitive observations mainly because of the strong background induced in detectors by space environment, as cosmic rays, radiations belts, Earth albedo and Sun flares. To detect the extremely low fluxes produced by high-energy sources, instruments currently in use in the soft gamma-ray domain make use either of aperture modulation (coded mask) or Compton reconstruction to determine the origin of events and thus rebuilt an image. The common point of these techniques is that the collecting area is coincident with the detector area exposed to a source, which limits the possibilities of sensitivity improvement since the instrumental background scales with the volume of detectors.

A new approach consisting in concentrating gamma-rays is being studied since a decade and has proved to be feasible in the $\sim$100 keV$-$1 MeV domain. The Gamma Ray Imager (GRI) mission [1] that has been proposed to European Space Agency (ESA) in the frame of Cosmic Vision AO1, intends to use such a Laue lens optics to increase the sensitivity by one–two orders of magnitude over existing or past telescope (IBIS–SPI onboard INTEGRAL, Comptel onboard CGRO, or BAT onboard SWIFT).

Laue lens principle is described in the next section. Then the state of the art of development of Laue lens elementary constituents—metallic or semiconductor crystals—is given before tackling the heart of subject of this paper with the presentation of a Laue lens response. Evolution of point spread function (PSF) and effective area with the off-axis angle of a point source is shown through the example of the GRI mission. Finally, requirements for an ideal focal plane instrument are derived.

2. Laue lens principle

A Laue lens concentrates gamma-rays using Bragg diffraction in the volume of a large number of crystals arranged in concentric

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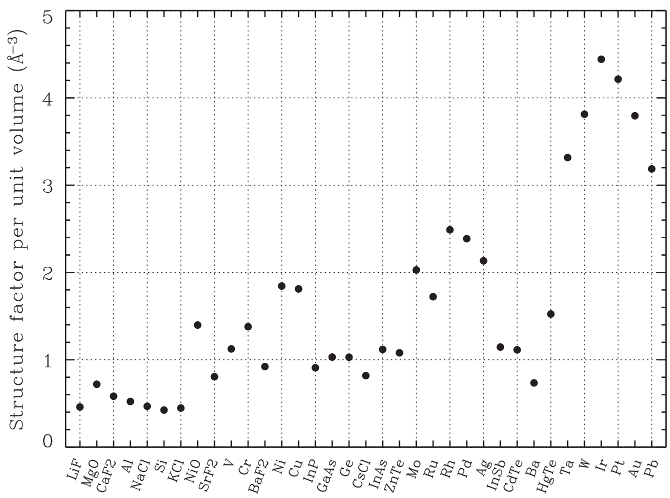

Fig. 1. Diffraction power of various crystals (defined as the ratio of the crystal structure factor over its lattice cell volume). See text for more explanations.

rings and accurately orientated in order to diffract radiation coming from infinity towards a common focus. Bragg's law $2d_{hkl}\sin\theta_B = n\lambda$ links the ray angle of incidence onto diffracting reticular planes θ_B to the diffracted wavelength λ, through the d-spacing d_{hkl} of the reticular planes of the crystal, n being the order of diffraction [2]. Suitable crystals for such application must have an energy bandpass such that neighboring rings create bandpass-overlaps resulting in a continuous energy coverage over a specified band, limiting the choice to crystals having either a mosaic structure or curved diffracting planes [3].

Depending of their electron density and crystalline lattice, intrinsic ability to diffract varies a lot between materials. Any mosaic crystal can reach the maximum diffraction efficiency (MDE)[1] of 50% [2] and this value reaches 100% in crystals with regularly curved planes [4,5]. But in any case diffraction efficiency decreases with both increasing energy and increasing mosaicity. The structure factor per unit volume hereafter called *diffraction power* (DP) shown in Fig. 1 indicates how a crystal behaves as energy or mosaicity increases; a crystal having an high DP will keep reaching MDE up to higher energy than a crystal having lower DP.

However, high DP crystals are not always suitable, as for low energies the optimal thickness of such crystal would be too thin to be mechanically robust enough. That is why the realization of a broad band Laue lens such GRI's one requires various complementary crystalline materials in order to reach everywhere the maximum diffraction efficiency, with a mosaicity of the order of 30 arcsec, and a reasonable thickness limiting the effect of absorption in crystals and the mass of the lens [3].

3. Development of efficient diffracting crystals

The CLAIRE project [6] has successfully demonstrated the principle of Laue lens, using 556 germanium mosaic crystals. Since then, several different type of crystals have been investigated to improve the 12% reflectivity which was achieved. Quality criterions are the mosaicity, which should range between 10 and 60 arcsec, the diffraction efficiency, the homogeneity and the reproducibility. Copper mosaic crystals produced at ILL (Grenoble, France) [7] have been extensively studied and are now showing very satisfactory results. Very low mosaicity have been measured with performance reaching the MDE. Fig. 2 shows as an example a rocking curve (RC) of a Cu sample of 8.6 mm of thickness measured at 489 keV, which reflectivity makes 24% despite the fact that the 220 reflection is used (less efficient that 111 reflection). The main problem of copper has long been the mosaicity which was too large for our application, but this is no longer the case.

An alloy of silicon and germanium with a varying relative concentration (inducing a curvature in diffracting planes) have been developed in cooperation with IKZ (Berlin, Germany) [8]. Added to the fact that this kind of crystals can have twice higher MDE than mosaic crystals, they produce a square-shaped bandpass [5] (angular acceptance, energy bandpass and profile of the diffracted beam are directly related), limiting the spread of photons over the focal plane, and thus allowing a better concentration of astrophysical signal. The RC shown on Fig. 2 comes from a 23 mm thick sample measured at 300 keV attaining a reflectivity of 26%. Our last measurements indicate that the mosaicity achieved with SiGe alloy crystals seems perfectly controlled and hence very reproducible.

Now that Ge (as used on CLAIRE lens), Cu, SiGe crystals are ready, our endeavor turns towards crystals for high energies. Latterly, three samples of gold mosaic crystals (produced by the Mateck company) have been measured, showing that this crystal can be produced with the right mosaicity range, which is truly the most critical constraint. Fig. 2 shows performances of a 2 mm thick sample reaching the MDE at almost 600 keV, giving an excellent reflectivity of 31%. Gold but also, silver, tantalum, tungsten and even platinum are currently under study at CESR, IASF, and ILL, opening the path to lenses really efficient and lightweight at energies up to 1 MeV.

4. PSF and effective area of the GRI Laue lens

The GRI mission proposes to cover energies from ~20 keV to ~1 MeV with unprecedented sensitivity, using single reflection deph-graded multilayer mirrors for the low-energy part up to 250 keV [9], and a Laue lens from 220 keV up to 1.3 MeV [1,3]. The focal length of both focusing optics was set at 100 m implying two formation flying satellites with optics carried by the one, and focal plane carried by the other. Both optics are co-axial, and focus on the same focal plane. We will concentrate hereafter on the Laue lens.

This lens has been designed using three kind of crystals, producing three different PSF as function of energy [10] divided in three regions: 220–330, 330–650 and 790–910 keV. In the following we will consider the high-energy PSF to describe general aspects of the beam produced by a Laue lens.

When a point source moves off-axis, the PSF evolves from a central spot to a circular ridge with an azimuthal modulation reflecting the azimuthal position of the source in the field of view (FoV) as shown in Fig. 3. At the same time, the effective area of the lens evolves (right panel of Fig. 3).

The field of view of the lens is limited by the focal plane size but also by the sensitivity loss resulting of the combination of spreading over of both signal onto a larger surface of focal plane and of the effective area.

Contours shown in Fig. 3 delimit the area minimizing the ratio of the square root of area of detector over the signal encircled, which is representative of the detection significance in the case of a spatially constant background. Quantitative analysis of these

[1] Diffraction efficiency is defined as the ratio of intensities in diffracted and transmitted (when no diffraction occurs) beams. Then applying the transmission coefficient leads to the reflectivity of the crystal.

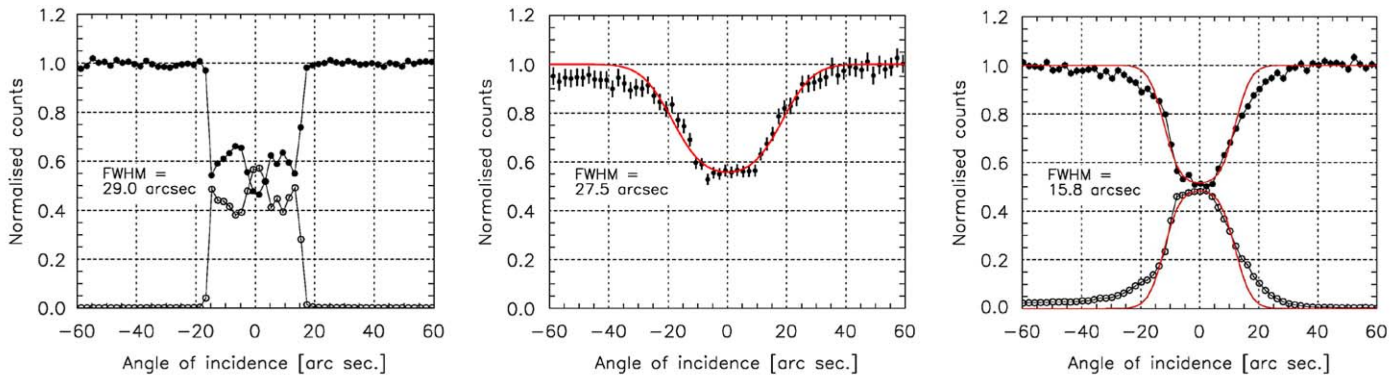

Fig. 2. Left: RC of a 23 mm thick SiGe gradient crystal measured at 300 keV (reflection 111). Center: RC of a 8.6 mm thick Cu crystal (220 reflection) realized at 489 keV. Right: RC of a 2 mm thick Au crystal (reflection 111) realized at 588 keV. Applying the transmission coefficient due to the absorption through the crystal, the achieved reflectivities are respectively: 0.26, 0.24 and 0.31. All these measurements have been performed at ESRF (Grenoble, France) on beamline ID15A.

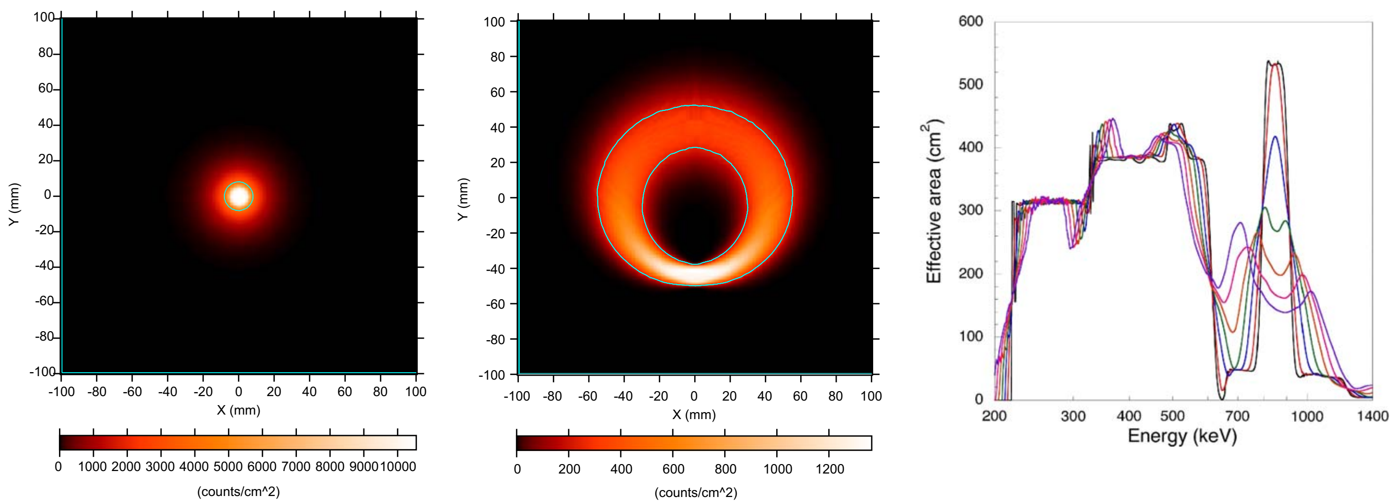

Fig. 3. Evolution of both spatial and spectral response of the high-energy band (~800–900 keV) of GRI Laue lens. Left and center panels show, respectively, the point spread function when the source is on-axis and 90 arc s off-axis. Right panel shows the effective area of the lens for a point source moving in the field of view; from on-axis to 3 arc min off-axis by steps of 0.5 arc min are represented.

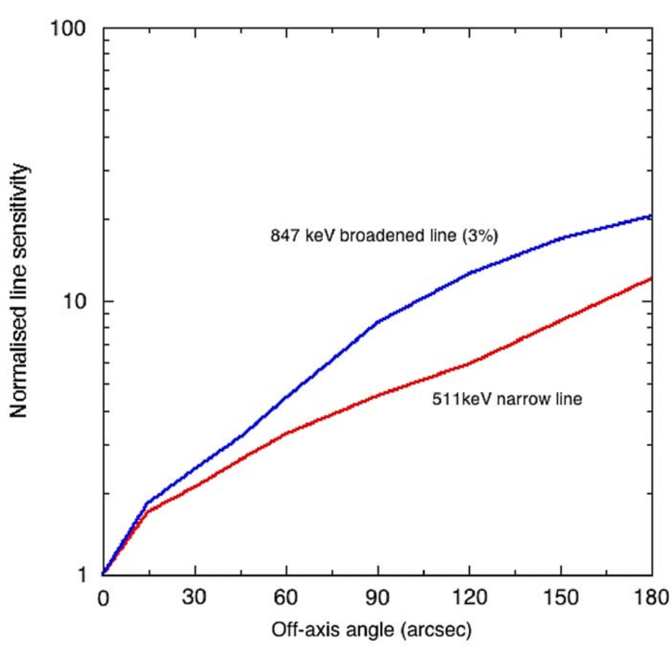

Fig. 4. Evolution of the sensitivity for the 511 keV narrow line and the 847 keV broadened line (3%) as function of the off-axis angle of the source, with the GRI's lens.

pictures gives an idea of the evolution of the sensitivity with off-axis angle; looking at the coverage of the 847 keV broadened line, the detector optimal area for an on-axis point source measures 2.4 cm^2 and encircles 46.7% of the signal concentrated by the lens which is given by the ~530 cm^2 of effective area. When the source is 90 arcsec off the axis, the optimal area onto the detector equals 58.5 cm^2, encircling 82.2% of the signal produced by the ~280 cm^2 of effective area. With a perfectly known background, this would engender a sensitivity loss by a factor of ~5. This is actually a minimum considering that the focal plane is not infinite, meaning that an extension of area lighted by signal implies a reduction of area to determine the background. These considerations lead to Fig. 4 showing the relative evolution of sensitivity of the GRI telescope in two lines of interest when the source moves off-axis.

5. Focal plane requirements

Considering the features described above, a fine pixelization would be the first requirement for the focal plane. This would allow to take fully benefit of the lens by looking for the signal only in areas lighted. Consequently, it becomes possible to monitor simultaneously the background, since the signal is confined in a defined area, allowing taking into account its time variability efficiently. This point pushes in favor of a square-shaped focal plane, in order to have the corners always free of signal even when the source is on the edge of the field of view.

Above a few 100 keV, the dominant interaction of photons in the detector material is Compton scattering. A finely pixelated detector allow to record energy and position of each event created by an incident photon, enabling the use of Compton reconstruction technique to constrain the original direction of the photon in a cone, and in many cases, to establish if the photon energy was fully recorded in the detector [11]. This makes a powerful tool to reject efficiently background by discriminating photons whose cone does not intercept the lens direction. Additionally, a Compton camera is inherently sensitive to gamma-ray polarization, which opens a new window on investigations of source's magnetic field configuration and geometry.

On the other hand, a pixelated detector permit to follow the excursions of the lens beam due to the relative motion of formation flying satellites and, of course, to take benefit of the off-axis response of the lens to reconstruct an image of the FoV. The angular resolution is related to the mosaicity of crystals used on the lens, which is of the order of 0.5 arc min for GRI.

As we have seen in the previous section, the sensitivity loss for a 2.5 arc min off-axis source is important, but still keep performance at a very interesting level considering that the value on-axis could be lower than 3×10^{-6} for nuclear lines (in 10^5 s observations) [1]. A field of view of 5 arc min requires a focal plane of $15\,\text{cm} \times 15\,\text{cm}$. Taking into account the PSF size, pixels of mm range are adapted, knowing that smaller pixels increase the accuracy of Compton determination of incidence direction and hence background rejection, but at the cost of a higher detector complexity.

Another criterion of prime importance, which relies more on the detector geometry, is the full peak efficiency. The baseline detector proposed for the GRI mission achieves more than 65% over the entire energy range covered by the lens: it is a CZT detector made of four pixellated layers (the first of 5 mm thickness and the three others of 20 mm) surrounded by pixellated side walls forming a collimator that can catch a large fraction of back scattered photons (see Ref. [10]). The entire detector is actively shield by BGO elements. An alternative design based on germanium strip planar detectors has been proposed, which advantage is the low shielding that allow the Compton telescope to work independently from the lens as an all-sky monitor [12,13], but with the drawback of needing to be cooled at liquid N_2 temperature and which geometry is less favorable to the full peak efficiency.

6. Summary

Thanks to ESA and CNES support, the development of Laue lenses is going forward. The critical point of diffracting crystals has made huge progresses giving now entire satisfaction. Ongoing development are now addressing high diffracting power crystals to enhance performance at high energy, and on the other hand, accurate crystals mounting (e.g. Ref. [14]). All these recent results show that gamma-ray lenses are becoming a real alternative for the realization of a sub-MeV telescope.

The ideal focal plane for such telescope will not exceed 20 cm a side, but will be pixellated and capable of Compton background discrimination. This will permit to access sources energy spectrum, spatial distribution (with moderate capabilities), and polarization. Compton all-sky survey undeniably adds a non-negligible value to the mission but this at the cost of heavy constraints on the detector design, limiting the possibility of shielding. A compromise can nevertheless be found with larger concept as proposed in Ref. [12].

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