# Development status of a Laue lens project for gamma-ray astronomy

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## ABSTRACT

We report the status of the HAXTEL project, devoted to perform a design study and the development of a Laue lens prototype. After a summary of the major results of the design study, the approach adopted to develop a Demonstration Model of a Laue lens is discussed, the set up described, and some results presented.

Keywords: Laue lenses, gamma-ray instrumentation, focusing telescopes, gamma-ray observations

# 1. INTRODUCTION

The hard X-/gamma-ray astronomy is moving toward a new generation of telescopes: from direct sky-viewing telescopes to focusing telescopes. Nowadays it is happening something similar to what happened in the late '70s to the soft X-ray astronomy (<2 keV) and in the '90s to the 2-10 keV X-ray astronomy, in the first case with the Einstein satellite, in the second case with the launch of the ASCA and BeppoSAX satellites, when the first X-ray focusing telescopes were flown. With the advent of focusing telescopes in the hard X-/gamma-ray astronomy, it is expected a big leap in sensitivity, by a factor 10-100 with respect to one of the most sensitive instruments of the current generation, and a significant increase in angular resolution (from  $\sim$  10 arcmin of the mask telescopes like the INTEGRAL IBIS to less than 1 arcmin).

Both the hard X-ray (<100keV) and the gamma-ray (> 100 keV) focusing telescope generation make use of the Bragg diffraction technique, in the first case, from multilayer coatings (ML) in reflection configuration (supermirrors), in the second case, from mosaic crystals in transmission configuration (Laue lenses).

A mission proposal that makes use of both supermirrors and Laue lenses, named  $Gamma\ Ray\ Imager$  (GRI), has been recently submitted to ESA in response to the first AO of the 'Cosmic Vision 2015–2025' plan. It covers with unprecedented sensitivity the energy band from 10 keV to 1 MeV. While below 100 keV other missions are now under study, like Simbol-X<sup>2</sup> and NeXT, above 100 keV GRI is unprecedented. For the astrophysical importance of the >100 keV band see, e.g., Refs. 4–6.

Here we report on the current status of our project HAXTEL (= HArd X-ray TELescope) devoted to develop the technology for building broad energy passband Laue lenses, mainly for the study of the continuum emission of celestial sources above 100 keV.

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#### 2. SUMMARY OF THE LENS DESIGN STUDY RESULTS

Results of the previous activity have been reported and discussed in Ref. 5. In short, the activity has mainly concerned a theoretical design study to establish the best design of a Laue lens telescope,<sup>7,8</sup> Monte Carlo simulations of the expected optical properties of Laue lenses,<sup>9</sup> reflectivity measurements of mosaic crystal samples of Cu[111].<sup>10</sup> We have investigated the geometry of the lens, the crystal material and lattice configuration that optimize the crystal reflectivity and energy passband. Given that we have to cover with good reflection efficiency a relatively broad energy band (several hundreds of keV), special crystals, with properly controlled lattice deformations, appear to be more useful. Crystals of this kind include mosaic crystals, bent crystals and crystals with non constant lattice spacing d induced by doping materials or thermal gradients. For our project we have assumed mosaic crystals, made of crystallites misaligned each with other with controlled angular spread  $\beta$  (FWHM of the Gaussian-like angular distribution of the crystallite misalignments). The growing technique of mosaic crystals with the desired spread is now being consolidated (e.g., Courtois et al.<sup>11</sup>).

Crystal tiles of thickness t are assumed to have their mean crystalline plane normal to the tile main facets, which are assumed to be square of side l.

To correctly focus photons, the direction of the vector perpendicular to the mean lattice plane of each crystal has to intersect the lens axis, while its inclination with respect to the focal plane has to be equal to the Bragg angle  $\theta_B$  (see figure in Ref. 10). The angle  $\theta_B$  depends on the distance r of the tile center from the lens axis and on the focal length f. For a correct focusing, it is needed that  $\theta_B = 1/2 \arctan(r/f)$ . Once the crystal material is established, the Bragg angle increases with r/f, while the energy of the focused photons decreases with r/f. More generally, once the focal length is established, the outer and inner lens radii,  $r_{max}$  and  $r_{min}$ , depend on the nominal energy passband of the lens  $(E_{min}, E_{max})$  and on the crystal lattice spacing: higher  $d_{hkl}$  implies lower radii.<sup>5</sup> For given crystal material, outer lens radius and the focal length, the minimum energy that can be focused is established.

Thus, for a fixed inner and outer radius, the lens passband can be established by the use of a combination of different crystal materials. Among the candidate materials for their high reflectivity and for which the mosaic technology has been developed (see, e.g., Ref. 11), Cu[111] appears very promising for the hard X-/gamma-ray range.<sup>5</sup> However, for a long focal length (100 m), like in the case of the GRI mission, given the low lattice spacing value  $d_{111} = 2.087$  Å of Cu[111], the minimum photon energy that can be focused is 320 keV for an outer lens radius of 185 cm (that of GRI lens). The extension of the Laue lens passband below 320 keV can be obtained by the use of other crystal materials, e.g., Ge[111] with mosaic structure ( $d_{111} = 3.266$  Å) or Si<sub>1-x</sub>Ge<sub>x</sub>[111] (Silicon  $d_{111} = 3.135$  Å) with a composition–gradient.<sup>12</sup>

Mosaic spread and, for a fixed material, crystal thickness are the most crucial parameters for an optimization of the lens performance. A single crystal thickness is not the best solution for optimizing the lens effective area in its entire passband. However the optimization of the lens effective area at the highest energies could imply large thicknesses, that could be incompatible with lens weight constraints. We have investigated this issue, <sup>9</sup> finding that a good compromize between crystal thickness and lens weight can be found.

Also the mosaic spread  $\beta$  issue has been investigated. A higher spread gives a larger effective area, but also produces a larger defocusing of the reflected photons in the focal plane. By introducing a focusing factor G

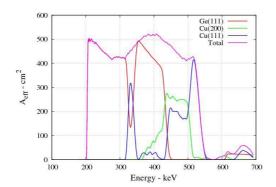
$$G = f_{ph} \frac{A_{eff}}{A_d} \tag{1}$$

in which  $A_{eff}$  is the effective area of the lens and  $A_d$  is the area of the focal spot which contains a fraction  $f_{ph}$  of photons reflected by the lens, it is found that, for long focal lengths like in the case of GRI (100 m), for its maximization, a very low spread ( $\sim 30$  arcsec) is requested. However a lower spread requires a higher accuracy in the positioning of the crystals in the lens. A compromize has to be found.

Another issue we have investigated is the disposition of the mosaic crystal tiles in the lens for a uniform effective area of the lens passband. The best crystal tile disposition is an Archimedes' spiral that provides a smooth behavior of the lens effective area  $A_{eff}$  with energy. However the Archimedes' spiral becomes less important for long focal lengths (> 30 m) and other approaches are needed.

#### Parameter

Focal length (m)	100
Nominal passband (keV)	200-530
Inner radius (cm)	88
Outer radius (cm)	185
Crystal material	Ge[111], Cu[111], Cu[200]
Mosaic spread (arcmin)	0.5
Tile cross section (mm <sup>2</sup> )	$15 \times 15$
Tile thickness (mm)	optimized
Number of crystal rings	61
No. of tiles	17661 (Ge[111]), 3254 (Cu[200]), 3386 (Cu[111])
Crystal weight (kg)	155
Effective area $(cm^2)$ @ 200 keV	500
Effective area $(cm^2)$ @ 400 keV	530
Effective area (cm <sup>2</sup> ) @ 511 keV	430
Half power radius(mm)	12



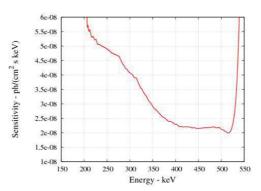


Figure 1. Properties of the Laue lens described in Table 1 in the 200–530 keV band for an on-axis source(see text). Left panel: On-axis effective area. Right panel: the corresponding  $3\sigma$  sensitivity for an observation time of  $10^6$  s and energy channel width  $\Delta E = E/2$ .

Also the required accuracy of the crystal tile positioning in the lens has been investigated.<sup>7</sup> It depends not only on the mosaic spread but also on the focal length. Higher focal lengths require higher positioning accuracies, which at the current stage of development is one of the major problems to be faced for the realization of a Laue lens

Results from a Monte Carlo (MC) code, that has been developed to derive the properties of different lens configurations, like their Point Spread Functions (PSF), for either on–axis and off–axis incident photons, have been already reported.<sup>5,8,9</sup> They confirm the results obtained from the theoretical investigation and extend them.

We show in Fig. 1 the expected on–axis effective area and  $3\sigma$  sensitivity of the lens described in Table 1. This lens configuration nicely fits also the GRI requirements.

The expected angular resolution of the lens is better than 1 arcmin.

Results of reflectivity measurements of Cu[111], discussed elsewhere, <sup>10,13</sup> confirm our expectations.

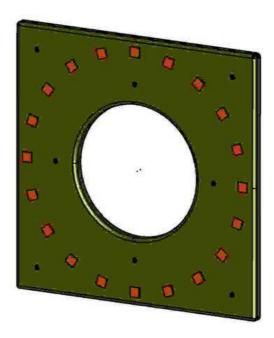


Figure 2. Drawing of the lens Demonstration Model.

#### 3. DEMONSTRATION MODEL DEVELOPMENT

A lens Demonstration Model (DM) is being developed. Unlike the Laue lens in Ref. 14, the lens under development will be made of crystal tiles rigidly fixed to the lens frame, without mechanisms for adjustment of their orientation. Thus their positioning in the lens has to be correctly performed during the lens assembling. The goal of the DM development is just to establish the best crystal assembling technique of the lens. Figure 2 shows the drawing of the DM under development.

It is composed of a ring of 20 mosaic crystals with diameter of 36 cm. The tiles are made of Cu[111] with  $\sim 3$  arcmin spread,  $15 \times 15$  mm<sup>2</sup> front surface and 2 mm thickness.

# 3.1 Lens assembly technique

The adopted lens assembling technique is based on the use of a counter-mask (see Fig. 3). The counter-mask is provided with holes, two for each crystal, with their axes directed toward the center of curvature of the lens. Actually, in the case of the DM under development, the hole axis is parallel to that of the lens axis. This simplification has been adopted in this phase in order to focuse gamma–rays coming from a source at finite distance d from the lens. In our case  $d \sim 6$  m.

Each crystal tile is positioned on the counter-mask by means of two pins (see Fig. 4) that are glued to each crystal with their axis parallel to the direction of the average crystalline plane.

Once each crystal is positioned on the counter-mask, the lens frame is glued to all the crystals. The lens frame is made of carbon fiber and is obtained starting from a mould. The lens is then separated from the counter-mask by means of a chemical treatment that dissolves an aluminum cup that covers the pin base closest to the crystal.

Thus the assembling of the DM lens comprises the following main activities:

- Proper alignment of each crystal on the X-ray optical bench;
- Mounting of two support pins and bonding of pins to each crystal on the bench (see Figs. 4 and 5);
- Positioning of all crystals (with support pins) on the counter-mask;
- Bonding of all crystals to the lens frame;



Figure 3. DM counter-mask. The counter-mask is made of stainless steal. The holes, 2 per each crystal tile, are apparent.



Figure 4. Configuration of a crystal provided with 2 pins.



Figure 5. A view of the set up for the crystalline plane determination and control and for the pin positioner.

• Chemical etching of the support pins, and removal of the counter-mask.

### 3.2 Test facility

The set up for the crystalline plane determination and for the alignment of the two pins with the crystalline plane direction, along with the gluing system of the pins to the crystal tiles, is shown in Fig. 10.

It is located in the X-ray facility LARIX (LARISE Italian X-ray facility) of the University of Ferrara (for a description see Ref. 15). The gluing is performed when the crystal correctly reflects the X-ray beam toward the lens focus.

A view of the experimental apparatus for assembling and testing the lens DM is shown in Fig. 6. The apparatus includes an X–ray generator tube (see Fig. 7) with a Tungsten target, a fine focus of 0.4 mm radius, a maximum voltage of 150 kV and a maximum power of  $\sim 200$  W. The X–ray tube, mounted on (X,Z) translation stage, is located in a lead box in which a hole is made in correspondence of the X–ray. The X–ray photons coming out from the hole are collimated by a pyramidal collimator, at the end of which it is mounted a Tantalum slit with selectable aperture along the vertical and the horizontal directions, both perpendicular to the pyramid axis. The slit can be also translated perpendicularly to the pyramid axis (see Fig. 8). The slit defines the cross section of the X–ray beam that irradiates the crystal main surface.

The radiation coming out from the slit collimator is used to both determine the mean lattice crystalline plane of the crystal tile and to align the pins to the X–ray beam. The image and spectrum of the X–ray beam, either the direct one or that transmitted through the crystal tile or that diffracted, can be detected. The available detectors include an X–ray imager, a cooled HPGe detector and a position sensitive scintillator detector (see Fig. 9). All of them can be rotated along the horizontal axis, and can be translated along the vertical and along the horizontal. The position resolution of the X–ray imager is 0.3 mm.

#### 3.3 Determination of the average crystalline plane

In order to determine the direction of the average lattice plane of the mosaic crystal tiles using the set up shown in Fig. 5, the crystal tile is located on a crystal positioner. This can be rotated around a vertical axis and tilted along two orthogonal axes until the diffracted beam from two symmetrical orientations of the crystal tile give symmetrical images and coincident spectra (see Fig. 10). An accuracy better than 10 arcsec in the determination of the average crystalline plane is achieved.

## 3.4 Alignment of the pin axis to the average crystalline planes

The 2 pins needed for each crystal are mounted on the pin positioner (see Fig. 5). This can be rotated along a circle with its center located in the vertical axis of the crystal positioner, and can be tilted along two orthogonal directions like the crystal positioner. The pin axis is requested to be parallel to the beam axis, previously made parallel to the average crystalline plane. This alignment is obtained by using X-ray shadow projected by two Tungsten crosses located along the pin positioner, with their axes parallel to the pin axes (see Fig. 11).



Figure 6. A view of the apparatus for assembling the lens DM. The apparatus is located in the LARIX facility of the University of Ferrara.



Figure 7. A view of the X–ray generator tube, located in a lead box.



Figure 8. A view of the pyramidal collimator during its assembling phase. In front of the collimator a movable Tantalum slit is visible.



Figure 9. A view of the detector set. The largest detector is the X–ray imager.

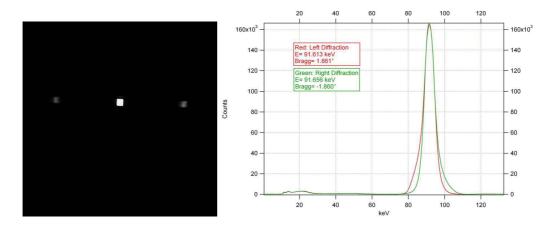


Figure 10. Left panel: Superimposed images of the transmitted and diffracted X–ray beam, once the crystalline plane is found. Right panel: Diffracted spectra once the crystalline plane is found.

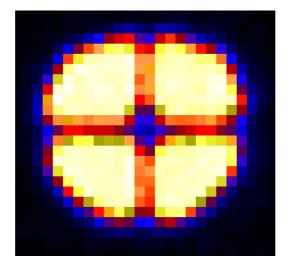


Figure 11. Image of the X-ray shadow projected by the two crosses when their axes are almost aligned to the X-ray beam.

#### 4. DM ASSEMBLING STATUS

A preliminar DM model with few mosaic crystal tiles of Cu[111] with  $\sim 3.5$  arcmin spread is expected to be assembled and tested in a short time to evaluate the cumulative error budget of the assembling technique. Soon after, the DM model made of a ring of Cu[111] mosaic crystal tiles will be assembled. Results of the first rigid Laue lens are expected in a few month time.

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