New results on focusing of gamma-rays with Laue lenses

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ABSTRACT

We report on new results on the development activity of broad band Laue lenses for hard X-/gamma-ray astronomy (70/100-600 keV). After the development of a first prototype, whose performance was presented at the SPIE conference on Astronomical Telescopes held last year in Marseille (Frontera et al. 2008), we have improved the lens assembling technology. We present the the development status of the new lens prototype that is on the way to be assembled.

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

1. INTRODUCTION

Along with the hard X-ray astronomy up to 70/100 keV, also the gamma–ray astronomy above this energy is moving from direct sky-viewing telescopes to focusing telescopes. With the advent of focusing telescopes in this energy range, a big leap is expected, in both sensitivity and angular resolution. As far as the sensitivity is concerned, the expected increase is by a factor of 100-1000 with respect to the best non-focusing instruments of the current generation (e.g., BeppoSAX/PDS, Ref. 1; INTEGRAL/IBIS, Ref. 2). Concerning the angular resolution, the increase is expected by more than a factor 10 (from \textasciitilde 10 arcmin of the mask telescopes like INTEGRAL IBIS to less than 1 arcmin). The next generation of gamma–ray (>70/100 keV) focusing telescopes will make use of the Bragg diffraction technique from mosaic-like crystals in transmission configuration (Laue lenses). The expected astrophysical issues that are expected to be solved with the advent of these telescopes are many and of fundamental importance. A discussion of them is done in the context of the mission proposal Gamma Ray Imager (GRI), submitted to ESA in response to the first AO of the ‘Cosmic Vision 2015–2025’ plan (Ref. 3). For the astrophysical importance of the >100 keV band, see also Refs. 3–6.

Here we report on the status of our project HAXTEL (= HArd X-ray TELescope) devoted to developing the technology for building Laue lenses with broad energy passband (70/100–600 keV). The results of this development activity over the last few years have been reported and discussed (see Refs. 5, 7 and references therein) with a summary of them given in Ref. 8.

Last year we reported the first lens Prototype Model (PM) and its performance (see Ref.8). Before discussing the activity performed this year, we summarize the main features of the assembly technique and the performance of the first PM.

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2. THE LENS ASSEMBLY TECHNIQUE

The technique adopted is based on the use of a counter-mask provided with holes, two for each crystal tile. Each tile is positioned on the countermask by means of two cylindrical pins, rigidly glued to the tile, that are inserted in the countermask holes. The pin direction and the axis of the average lattice plane of each crystal tile have to be exactly orthogonal. The hole axis direction constrains the energy of the photons diffracted by the tile, while the relative position of the two holes in the countermask establishes the azimuthal orientation of the mean crystal lattice plane, that has to be orthogonal to the lens axis. Depending on the countermask shape and, mainly, on the direction of the hole axes, the desired geometry of lens can be obtained. In the case of a lens for space astronomy (i.e., parallel fluxes), the hole axes have to be all directed toward the center of curvature of the lens.

In the case of the developed PM, the hole axes are set parallel to the of the lens axis. This choice has been made to illuminate the entire lens with the available test gamma–ray beam, which is isotropical, being generated by an X–ray tube, and also highly divergent, as the source is only a small distance away ($d \sim 6$ m) from the lens.

The adopted mosaic crystals are made of Cu with chosen lattice planes (111). Once the average direction of the chosen lattice planes of each crystal tile has been determined, the two pins, inserted in a pin holder, are glued to the crystal. The pin holder direction is first made parallel to the gamma–ray beam axis and thus to the direction of the average crystalline plane chosen (in our case, the (111) planes).

Once all the crystal tiles are placed on the counter-mask, a frame is glued to the entire set of the crystals. Then the lens frame, along with the crystals, is separated from the counter-mask and from the pins by means of a chemical etching that dissolves the aluminum caps that cover the pin bases glued to each crystal.

The average direction of the chosen crystalline planes and of the pin axes are determined by means of an X–ray beam developed for this project and located in the LARIX (LArge Italian X–ray facility) laboratory of the University of Ferrara. For a LARIX description see Ref. 9. A view of the experimental apparatus in the current configuration is shown in Fig. 1. As discussed in Ref. 7, the developed apparatus includes an X–ray generator tube with a fine focus of 0.4 mm radius, a maximum voltage of 150 kV and a maximum power of $\sim 200$ W.
The photons coming out from the gamma–ray source box are first collimated, with the beam axis made horizontal and directed toward the centre of a large (30 cm diameter) X–ray imaging detector with image pixels of 300 µm. The collimator aperture can be remotely adjusted in two orthogonal directions in order to have the desired X–ray beam size (see Ref. 7). In addition to the X–ray imaging detector, a cooled HPGe detector and a position sensitive (2 mm) scintillator detector are available.

For each mosaic crystal tile, the direction of the average lattice plane can be determined with an accuracy better than 10 arcsec (see Ref. 7).

The first developed PM was composed of a ring of 20 mosaic crystal tiles of Cu(111) with a ring diameter of 36 cm. The mosaic spread of the used crystals ranged from ∼ 2.5 and ∼ 3.5 arcmin. The tile cross–section was 15×15 mm² while its thickness was 2 mm. The lens frame was made of carbon fiber of 1 mm thickness.

The PM was widely tested using the polychromatic X–ray beam described above, as reported in the Ref. 8.

The difference between the measured PSF and the simulated one is shown in Fig. 2. As can be seen, only the center part of the measured image (the black region) is subtracted by the simulated image. The corona still visible in the difference image is mainly the result of the cumulative error made in the crystal tile positioning.

The disagreement between the measured and the expected PSF is clear. It can be seen (see Ref. 8 for details) that at the radius at which the expected distribution of the focused photons reaches the saturation, only 60% of the focused photons are collected.

3. ERROR BUDGET ANALYSIS AND NEW IMPROVEMENTS

By shielding all the lens crystals but one, we have investigated the contribution of each lens crystal to the lens PSF and to the reflected photon spectrum. From these results, we have derived the positioning error of each crystal in the lens. In order to establish the true contribution of each assembling step to the cumulative error, we have performed further tests. In this way we have estimated the precision achieved in each assembling step.

On the basis of this analysis, we have started a new design of the lens assembling apparatus. The major changes have concerned the following parts.
3.1 New pin and crystal holders

A new pin holder has been developed (see Fig. 3). As the previous one (see Ref. 7), it can be rotated along a circle with its center in the vertical axis of the crystal holder, and can be tilted along two orthogonal directions as the crystal holder. However, while the alignment of the old pin holder to the beam axis was obtained by using the X-ray shadow projected by two Tungsten crosses located along the pin positioner, now we use a Silicon crystal in transmission configuration with the chosen lattice planes (220) that are orthogonal to the crystal surface within a few arcsec. The pins are located in mechanically worked holes with their axis orthogonal to the crystal surface. This angle is known with a precision better than 1 arcmin. Using the Bragg diffraction we can determine the direction of the chosen Si lattice planes (within a few arcsec) and thus perform the alignment of the pins to the gamma-ray beam axis.

Also the crystal holder (see Fig. 4) has been improved with respect to the previous one (Ref. 7), and now it can host crystals of different thickness.
3.2 New pin geometry
For the new lens prototype, half of the crystal tiles are positioned in the countermask using a pair of pins with cylindrical shape, as in the first prototype (see Ref. 8), while the other half of crystal tiles are positioned using new pins of conical shape with elliptical section. In this case it is sufficient one pin for each tile.

3.3 Clean room and temperature control of the lens assembling process
For the realization of the new prototype, all the measurements and the assembling process are now performed in a clean room of about 50000 class and an active temperature control within 1 °C. This temperature control is expected, from mechanical simulations, guarantee negligible distortions of the lens.

3.4 New counter mask and lens support
The new counter mask (see Fig. 5) can allocate either cylindrical pins and conical pins with elliptical shape.

The lens frame (see Fig. 6) is made of 8 layers of carbon fibers properly oriented in order to optimize and get isotropical its thermal conductivity and stress, thus avoiding distortions of the lens for temperature changes, that, in any case, should be held within ±2 °C (see above).

4. ALIGNMENT MEASUREMENTS
All the alignments have been performed using the gamma-ray beam available in the LARIX facility. For its properties see Frontera et al. 2008 (Ref 7).
4.1 Alignment of the pin holder to the gamma-ray beam
Taking into account the above description, the pin axes were made parallel to the beam exploiting the Si crystal, imposing that the diffracted beam at equal left and right angles, and at equal angles upward and downward, with respect to the beam direction, give coincident spectra. The final results for the pin alignments are shown in Figs. 7. When observed with an X-ray imager, the corresponding diffracted images are shown in Fig. 8.

4.2 Lens crystals, their average lattice plane direction determination and pin pasting
Once the axis of the pin holder has been made parallel to the beam axis, the lattice plane of each crystal has been determined and either a couple of cylindrical pins or one conical pin is glued to the crystal. This activity is being carried out.

As for the previous prototype the crystals used for this new lens prototype are made of Cu (111) with mosaic structure. The thickness all the crystal tiles is 3 mm and their cross section is 15×15 mm. The distribution of the mosaic spread of the 20 selected crystals is shown in Fig. 9.

An example of spectral response of a crystal tile, once its average lattice plane is determined and made parallel to the pin axis is shown in Fig. 10, after two cylindrical pins have been pasted to it.
Figure 9. Distribution of the mosaic spread of the Cu(111) crystals that will be used for the new Laue lens prototype.

Figure 10. Example of spectral response of a Cu(111) mosaic crystal tile when the X-ray beam is diffracted by the crystal at symmetrical angles with respect to the beam axis direction.

5. CONCLUSIONS

After the development and testing of the first Laue lens prototype (see Ref. 8), we have devoted a new effort to improve the lens focusing quality. In this paper we have described the new upgrading of the lens assembling system, that is being used for building a new lens prototype. This is expected to be ready in one–two months. The test results will be reported soon.

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