Focussing crystals for use in broad band hard X/soft gamma-ray Laue lenses

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Abstract– **Hard X-/soft gamma-ray astronomy is a crucial window for the study of the most energetic and violent events in the Universe. To fulfil the scientific requirements in this regime, a new generation of telescopes with a broad operational band extending from tens up to several hundreds of keV and exploiting unprecedented sensitivity (50-100 times better that current instruments) is required.**

We report on diffractive bent crystals made of Gallium Arsenide (GaAs) that are suitable for the construction of high sensitivity X-/gamma-ray Laue lens space telescopes. Laue lenses, made of sets of diffractive crystals working in transmission, offer one possibility, albeit technically challenging, to build a new generation of focusing telescopes that can extend the energy band far beyond the 80 keV limit for current multilayer concentrators.

In particular, we present the results obtained from the characterization of crystals that will be used to realise a broad band Laue demonstrator. They have been studied in terms of focusing capability and diffraction efficiency by using a flat X-ray panel imager and an HPGe spectrometer as focal plane detectors.

The GaAs tiles, bent via a surface lapping procedure, have been developed at the IMEM/CNR in Parma (Italy) in the framework of the LAUE project funded by the Italian Space Agency. The main goal of the project was to build a broad band Laue lens demonstrator for hard X-/soft gamma-rays (80-300 keV).

I. INTRODUCTION

HARD X-/soft gamma-ray astronomy is a crucial window for the study of the most energetic and violent events in the Universe. With the advent of the NASA/NuSTAR mission [1] having on board two focusing telescopes operating in the 3–80 keV band, very sensitive (10^{-8} photons cm^{-2} s^{-1} keV^{-1}) studies of the hard X–ray sky finally are becoming possible. NuSTAR has already performed studies of single sources to resolve the Cosmic X–ray Background [2]. In the near future, NuSTAR will perform sensitive extragalactic and Galactic surveys, which will supplement the extended surveys beyond 20 keV, already performed or planned to be continued with both the ESA/ INTEGRAL and NASA/Swift satellites [3, 4]. Evidence of extended matter-antimatter annihilation emission (at 511 keV) from the Galactic Center and of Galactic nucleosynthesis processes has been found [5, 6]. Furthermore, polarization of the high energy photons (>400 keV) emitted from the Crab Pulsar and Cygnus X-1 has been clearly measured [7, 8].

In order to take full advantage of these results, we need a new generation of high sensitivity (50-100 times better than current instrumentation) focusing telescopes able to extend the energy band up to several hundreds of keV. A two–order of magnitude increase in sensitivity and angular resolution will allow a real step forward in our understanding of the hard X–ray Universe, as happened in the 1970's with grazing incidence optics in soft X–ray astronomy.

Currently, Laue lenses, based on diffraction from crystals in a transmission configuration, offer one, albeit challenging, technical solution to this problem. The advantage of Laue lenses is that the energy bandwidth can be increased up to 600 keV with a focal length of about 20 m, which is still feasible with a single satellite mission. Laue lens can also find interesting applications outside the astrophysical field. For instance, feasibility studies are ongoing in the biomedical engineering field, as Laue lenses are capable of providing a high-resolution image of the radioactivity distribution lying inside a restricted region of the patient's body [9].

II. BROAD BAND LAUE LENS DEVELOPMENT

Assembling of a Laue lens for space astronomy, made from thousands of crystals, requires the solving of different challenging technological issues. Herein, we report on the most recent progress and results obtained in the framework of a project funded by the Italian Space Agency (LAUE project) [10]. In the LAUE project, a portion (petal) of a broad band (90-300 keV) Laue Lens is going to be built (Fig. 1) using the LARIX facilities at Ferrara (Italy) University. The petal is made using both Gallium Arsenide (GaAs) and Germanium (Ge) bent crystals. The GaAs crystals (provided by CRN/IMEM, Parma) have curved diffracting planes obtained with a surface lapping procedure [11]. Each tile has been bent to a curvature radius of 40 meters to obtain a Laue lens with a focal length of 20 m. For the first time bent crystals have been

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used for a Laue lens instead of flat crystals, extensively utilized for other demonstrator models [12].

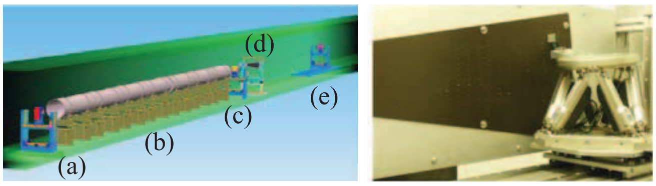

Fig. 1. (Left) Scheme of the LARIX facility built for the Laue project. It is based on a 350 kV X-ray tube (a), a vacuum beam line (b), a tunable collimator (c), a Laue petal support with crystal mounting system (d), and focal plane detectors at 20 meters (e). (Right) Detail of the Laue lens petal, under realization at the LARIX facility. The Laue petal support is made of 2.3 mm thick carbon fiber. In the forefront it is visible the 6-axis micrometric system used for the fine positioning of the crystal tiles.

III. GAAS BENT CRYSTAL FOCUSING PROPERTIES

While flat crystals are limited in terms of efficiency and focusing power, bent crystals can considerably increase the signal to noise ratio, as their diffraction efficiency can be greater than 50% [13] and, more importantly, they can focus into an area that is much smaller than the crystal surface.

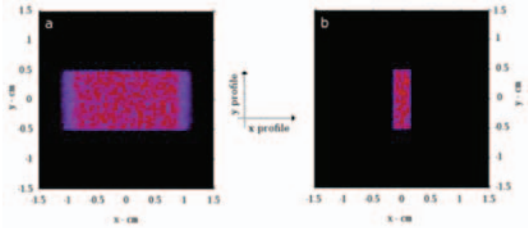

Fig. 2. Simulation of the diffracted image of a mosaic (15″ mosaicity) GaAs (220) crystal tile with incident beam size of 20×10 mm^2 and source of radiation placed at infinite distance from the target. (Left) The case of a flat tile. (Right) The case of a bent tile with 40 m curvature radius. In both cases, the detector is placed at 20 m from the target (crystal).

Fig. 2 shows the advantage of a bent crystal compared with a flat crystal. A Monte Carlo simulation of the extreme focusing power achievable with a bent crystal having size of 20×10 mm^2 is compared with the diffracted image obtained with a flat crystal of the same geometrical cross section. The experimental measurements, illustrated in Fig. 3, have confirmed the predictions of the Monte Carlo simulation and have validated the model.

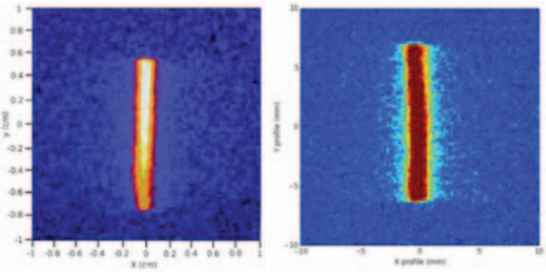

Fig. 3. Diffracted beams from two different GaAs crystals having 40 m curvature radius, measured at the crystal/detector separation of 11.5 m where the maximum focusing effect is expected, taking into account the curvature radius of the sample and the divergence of the source of radiation placed at finite distance (22 meters) in the LARIX facility.

The images in Fig. 3 have been obtained collimating the X-ray beam over a 20×10 mm^2 surface at the center of the 30×10 mm^2 GaAs tile. The dimensions of the diffracted image are ~14 mm in height due to the coupling between the beam divergence and the crystal-detector distance. Instead, in the other direction (along the crystal curvature) thanks to the focusing effect, the diffracted image FWHM shrinks to 1.2-1.5 mm, as expected.

In particular, we have performed an extensive study by using bent GaAs crystals to evaluate the influence of different parameters that can affect the final Laue lens prototype performance (e.g. the Point Spread Function) such as the X-ray beam divergence, the precision of the curvature radius of each tile and their intrinsic mosaicity.

Furthermore, we present the result of simulations of the diffracted beam from bent GaAs crystals both for the ideal case of a point-like source placed at infinite distance from the target, and for our experimental set-up, where a source with non-negligible dimensions is placed at a finite distance from the target (Fig. 4). The agreement between the experimental measurements and the Monte Carlo results (Fig. 5) gives us the confidence about the correctness of the numerical model we have developed and the reliability to use it to perform a correct evaluation of the Laue lens response in the case of cosmic ray source observations, which are the final goal of the Laue project.

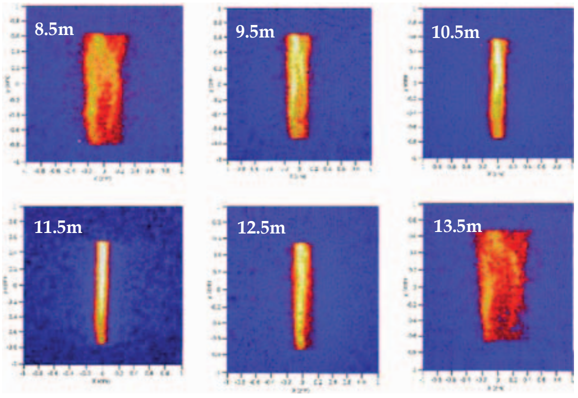

Fig. 4. Diffracted images at 150 keV at several distances between the GaAs crystal and the focal plane imager. The width of the diffracted image in the focusing direction reaches the minimum (best focusing) at 11.5 m rather than at the focal length of 20 m, due to the divergence of the X-ray beam at 22 m from the Laue lens support.

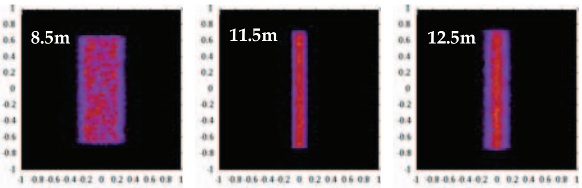

Fig. 5. Simulated diffracted images at three different distances between crystal tile and the focal plane imager. These results have been obtained with the Monte Carlo Ray tracing tools developed for the Laue project by considering a GaAs (220) crystal with 20″ intrinsic mosaicity and 40 meters curvature along the 30 mm dimension.

IV. OPEN ISSUES AND WORK IN PROGRESS

In the Laue project we have used a structural two-component epoxy adhesive as an interface between the frame and each crystal. The adhesive must have a fast curing time and low shrinkage in order to minimize the building time and maximize the gluing accuracy.

We have studied the stability of gluing as a function of the time. Fig. 6 on the left reports the comparison among the diffracted images acquired before gluing at zero position and with energy of 157.2 keV, after 20 min from gluing and after 1 day. We have measured a shift of 3 pixels and an energy of 158.3 keV in the first case and a shift of 8 pixels and an energy of 159,15 keV in the second.

The result of a more extensively crystal monitoring is shown in Fig. 6 on the right where the shift of the diffracted image (in detector pixels) is reported as a function of the time for 5 different crystals glued over the carbon fiber support. The holding time was 60 minutes. We didn't observe any motion as the sample was set into the clamp. After the release of the clamp, a common trend was observed which corresponded to a decrease of the Bragg angle and confirmed that the curing process induced an adhesive shrinkage, which rotated the crystal. The measured shift between the reference pixel (512) at the center of the detector and the experimental results is ~ 30-40 pixels, which corresponds to ~ 6-8 mm (about 100-140 arcsec). In order to minimize the focal spot shift we have used a low-shrink, low-outgassing, low-CTE optical adhesive and realized a mock-up with a thin adhesive layer (50- 100 μm). The support is transparent in order to use this single component paste, the curing of which is activated by optical and UV light.

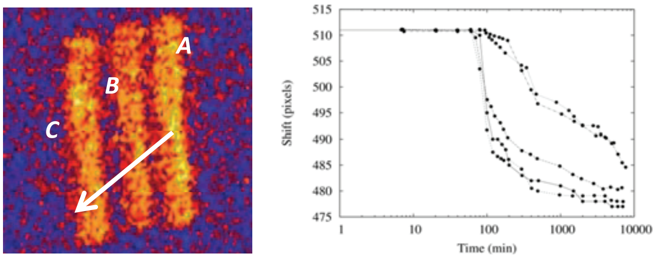

Fig. 6. (Left) GaAs tile diffracted images: just after the holder release (A), 20 minutes later (B), and after one day (C). (Right) Measured shift of the diffracted images centroid as function of the time for 5 glued GaAs crystals.

The mock-up is composed of 11 bent GaAs crystals glued on the frame by using the hexapod system in the configuration reported in Fig. 7 on the left.

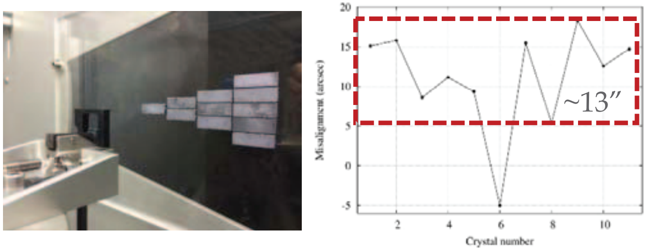

Fig. 7. (Left) The mock up based on a flat polymethyl methacrylate (PMMA) frame with 11 bent GaAs crystals. (Right) The misalignment of the 11 crystals measured after 48 hours from the last glued crystal.

The distance between the target and the measured position is expressed in arcseconds in the same figure on the right. We can observe that more than 90% of the crystals are correctly aligned within 13 arcsec. This result represents a satisfying improvement in the crystal gluing techniques, close to our goal of 10 arcsec.

V. CONCLUSIONS

The test and measurements performed up to now have demonstrated the feasibility of the development of a broad band Laue lens petal by using bent GaAs crystals with mosaicity less than 20" and the achievable performance.

Some crucial matters related to the mounting of the bent crystal tiles on the petal support have been identified and we are studying available solutions by using low shrinkage glue and by implementing a new support with the same curvature of the Laue lens.

In parallel to the technological activity we are developing different software tools to optimize the design of a space telescope, which implements a broad band Laue lens for the next ESA satellite mission calls. In particular, Monte Carlo physical and ray tracing software is under finalization for a performance study dedicated to characterize and optimize several features such as the sensitivity, FOV, angular resolution, Off-axis PSF as function of the crystals filling factor, crystal size, material and intrinsic mosaicity.

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