Hard X–ray broad band Laue lenses (80–600 keV): building methods and performances

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ABSTRACT

We present the status of the LAUE project devoted to develop a technology for building a 20 meter long focal length Laue lens for hard X–/soft gamma–ray astronomy (80–600 keV). The Laue lens is composed of bent crystals of Gallium Arsenide (GaAs, 220) and Germanium (Ge, 111), and, for the first time, the focusing property of bent crystals has been exploited for this field of applications. We show the preliminary results concerning the adhesive employed to fix the crystal tiles over the lens support, the positioning accuracy obtained and possible further improvements. The Laue lens petal that will be completed in a few months has a pass band of 80–300 keV and is a fraction of an entire Laue lens capable of focusing X-rays up to 600 keV, possibly extendable down to ∼20–30 keV with suitable low absorption crystal materials and focal length. The final goal is to develop a focusing optics that can improve the sensitivity over current telescopes in this energy band by 2 orders of magnitude.

Keywords: Laue lenses, focusing telescopes, gamma–rays, astrophysics.

1. INTRODUCTION

Past and present missions like *Beppo*SAX, XTE and INTEGRAL have demonstrated the key importance of X–ray broad band (0.1–200 keV and beyond) observations to investigate and to explain a large number of astrophysical phenomena occurring in compact stars, active galactic nuclei or in diffuse emission (for an extensive list of astrophysical issues that are expected to be solved with focusing telescopes see e.g. [1]). Nevertheless, these missions exhibited the limits of non focusing telescopes in which, for instance, to increase the sensitivity by only a factor ∼3, the collecting area must be increased tenfold, with a consequent increase in terms of payload weight and, more importantly, of the detector noise. Focusing telescopes overcome this limitation, thanks to the physical separation between collecting area and sensitive surface. As the detector noise is roughly proportional to its volume, it turns out that focusing telescopes represent a key tool with which to maximize the signal-to-noise ratio. It has been shown that focusing telescopes in the 60–600 keV energy band could overcome the sensitivity limits of the current generation of non focusing gamma–ray telescopes[2,3] by a factor ∼10–100.

Focusing telescopes in the soft X-ray energy band (∼0.2–10 keV) are still operating since the late 90's. The upper limit has been extended to ∼70–80 keV with the employment of multilayer coatings (NuSTAR[4]). Unfortunately, above 80 keV there is not yet a solid technology comparable with the well established low and medium energy instrumentation. For hard X-rays (>100 keV, but also applicable down to the 20/30–100 keV energy range) one concrete possibility to focus the radiation is offered by the use of Laue lenses which exploit Bragg diffraction by crystals. Besides order of magnitudes increase in sensitivity, Laue lenses have the great advantage of improving the angular resolution of current X and gamma-ray telescopes, the best now being obtained with coded mask telescopes (about 15 arcmin in the case of INTEGRAL/ISGRI).

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2. THE LAUE PROJECT: AN OVERVIEW

The LAUE project,[5,6] funded by the Italian Space Agency, is currently running in the LARIX laboratory of the Physics and Earth Sciences Department of Ferrara University (Italy). The main objective of the project is to develop a technology for building a Laue lens with a broad energy band (70/100–600 keV) and long focal length (20 m), for astrophysics observations. In the project, the Laue lens is assumed to be made of a number of sectors, called petals. Assembling one of them, capable of focusing the radiation in the range 90–300 keV, is the starting goal of our project. Within this activity, other main tasks have been conducted:

- to realize a technology to produce a large number of diffractive crystals with high efficiency;
- to find a method for assembling the crystals and fixing them in place with high accuracy in a relatively short time.

Flat crystals have the advantage of being relatively easily produced in large quantities with good reproducibility in terms of dimensions and mosaic spread. Unfortunately, their maximum reflectivity is limited to 50%[7,8] . Furthermore, a flat mosaic crystal tile does not display a focusing effect. Its diffracted image in the focal plane mainly depends on the crystal size and on the crystal mosaic spread which results in a defocusing effect[9] . In the LAUE project, for the first time a large number of bent crystal tiles are being employed in order to exploit their focusing effect. Bent crystals can overcome the limit of flat crystals given that the diffracted image exhibited by a crystal with curved crystalline planes is smaller than the crystal cross section itself.

Bent crystals can be produced in a variety of methods[10] . For our purposes, mechanically bent crystals appear to be the most suitable. Self-standing Si and Ge perfect bent crystals were produced and characterized at the Sensor and Semiconductor Laboratory (LSS, Ferrara - Italy) through mechanical grooving of one of their surfaces[11] . An extremely uniform and highly reproducible curvature is achieved even if the grooves cause damage and fragility of the crystals[12] . Instead, a self-standing curvature is obtained by IMEM/CNR Parma by means of a controlled mechanical damaging of one surface of the sample[13] . This lapping procedure introduces defects in a superficial layer of a few microns, providing a highly compressive strain responsible for the convexity appearing in the crystal.

In the LAUE project a flat frame is used as a support for the crystal tiles composing the single petal. During the entire building phase the petal frame is kept fixed while a pencil beam of radiation is moved in front of the petal frame to mimic the presence of an astronomical gamma-ray source. The source of radiation is also directly used to control the correct positioning of the crystals. The total number of crystals that composes the designed petal is 275 and the tiles are distributed in 18 concentric ring sections.

Positioning each crystal with the correct diffraction angle and keeping this orientation unchanged is the most challenging phase. Previous attempt to build Laue lenses have been made by using mechanical micro adjusters for positioning each tile with good results[14] . Nevertheless, using a micro-controller for each crystal appears to be a very hard solution for an entire Laue lens made of thousand of crystals, considerably increasing the lens complexity and the total weight. Therefore the strategy of the LAUE project is to use a structural adhesive which works as an interface between the frame support and the crystal itself. The adhesive must have a fast curing time and as low a shrinkage as possible, to minimize the building time and maximize the gluing accuracy, which is the most critical part. The elements that influence the gluing process are various. The temperature and the humidity of the building environment play a crucial role in the stability of the crystal/adhesive/support system. For this reason in the LARIX facility a clean room with humidity and temperature stability control was set up (20 deg $\pm$ 1 deg, relative humidity $\Phi = 50 \pm 5\%$).

3. CONFIGURATION OF THE PETAL

In Table 1 the main properties of the petal which is being built are reported. The energy pass band defines the inner and the outer radius of the Laue lens petal. The crystal cross section has been chosen to be $30{\times}10$ mm^2, with the longer side radially placed on the lens frame. The rectangular shape of the crystals gives a twofold advantage. Firstly, as the focusing effect occurs only in the radial direction a shorter tangential dimension provides a smaller defocusing factor in the latter dimension. Secondly, a bigger radial dimension reduces the total number of crystals required, thereby reducing both the lens mounting time and the error budget potentially caused by each crystal misalignment contribution. The designed lens focal length was set to 20 m. Consequently, the crystal elements must have a 40 m curvature radius. The total number of crystals was equally subdivided into tiles made of Gallium Arsenide (220) (provided by IMEM/CNR Parma) and Germanium (111) (provided by LSS Ferrara). Employing the two types of crystals allows a Laue lens to be built which is sensitive to the required energy pass band whilst keeping both inner and outer lens radius sufficiently small. Both IMEM/CNR and LSS can provide the crystals with an accuracy in the curvature radius estimated to be within 5% (40 ± 2 m).

Table 1. Main properties of the petal that is being built in the framework of the LAUE project.

Materials and selected planes	Ge(111), GaAs(220)
Energy passband	80–300 keV
Focal length	20 m
Petal inner/outer radius	20/80 cm
Petal dimension (lens diameter)	∼60 cm (∼150 cm)
Crystal cross section	$30{\times}10$ mm^2
N^o of crystals per petal (entire lens)	274 (5480)
N^o of rings	18
Weight of the petal (entire lens)	1.3 kg (27.2 kg)

3.1 Alignment method

In our reference system the x axis is directed parallel to the x-ray beam impinging on the crystal while the y and z directions correspond to the crystal principal axis, the former along the crystal longer dimension which is also the focusing direction.

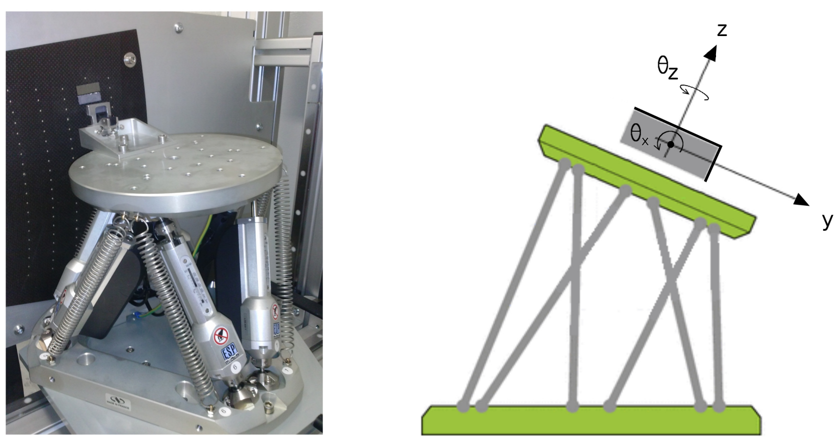

Figure 1. Picture of the mechanical system (hexapod) adopted for positioning the crystal over the frame. On its top, a crystal holder with a clamped tile is mounted.

The goal of the LAUE project is to develop a focusing lens capable of producing a photon distribution on the focal plane with a spatial extension of ∼2 mm FWHM, which corresponds to a PSF of 30 arcsec. This value includes the crystal mosaicity (15 arcsec for GaAs) and all the contributions caused by the uncertainties during the alignment phases. All of the contributions must be considered separately and minimized. The lens assembly method consists in the positioning of each crystal tile on the lens frame under the control of a gamma–ray beam. The source employed must mimic a source at infinity. For this reason the X-ray tube and the final collimator are moved together in the y-z plane in front of each crystal slot. Thanks to the mechanical precision of the carriages, the X-ray beam is parallel to the lens axis within about 1.5 arcsec. Each single lens crystal is individually irradiated and appropriately oriented by using a hexapod (see Fig. 1) in order to focus the radiation onto the correct point. The degrees of freedom of the hexapod allowthe crystal to be aligned with an accuracy of 0.01 mm for the three translations and with $\sim$ 1.5 arcsec for the rotations. The spatial distribution of the diffracted signal and its correct positioning is observed with a 1024×1024 pixels X-ray imaging detector with 200×200 μm^2 spatial resolution.

The most critical movement of the crystal is its rotation around its z axis (θ_z). A variation of θ_z changes the Bragg angle (and consequently also the diffracted energy) and results in a shift of the diffracted signal on the detector plane which is directed along the y axis. The measured shift is proportional to the distance between the crystal and the detector itself. Instead, a variation of θ_x shifts the diffracted beam along a circle centered at the focal axis whose amount is proportional to the distance between the crystal and the axis of the lens. The adhesives used to set the crystals suffer from a shrinkage effect that occurs during the curing phase and cause a change on both θ_z and θ_x angles.

The procedure of mounting each crystal at the proper position is driven by the focusing power of the tiles. The best focusing is obtained at the nominal focal distance, if the source radiation is not divergent. Otherwise, the best focusing depends on the source divergence. The focusing effect of bent crystals has been discussed and experimentally confirmed elsewhere[15] finding that the best focal distance depends on the combination of the sample curvature and the distance of the crystal from the radiation source. This distance is less than the nominal focal distance and for our facility set-up it turns out to be 11.40 m (see Fig. 2). Therefore, the mounting strategy for an astronomical Laue lens with 20 m focal length is to acquire the diffracted radiation from each crystal which are correctly oriented with the imaging detector positioned at the distance of 11.40 m from the crystals. Using crystals with the cross section 30×10 mm^2 the focusing effect makes the radial dimension of the diffracted beam of the order of 1.3–1.5 mm (depending on the intrinsic mosaicity/quasi-mosaicity[16]) while in the tangential direction (where no focusing effect is expected) it reproduces the crystal dimension itself enlarged by the divergence effect.

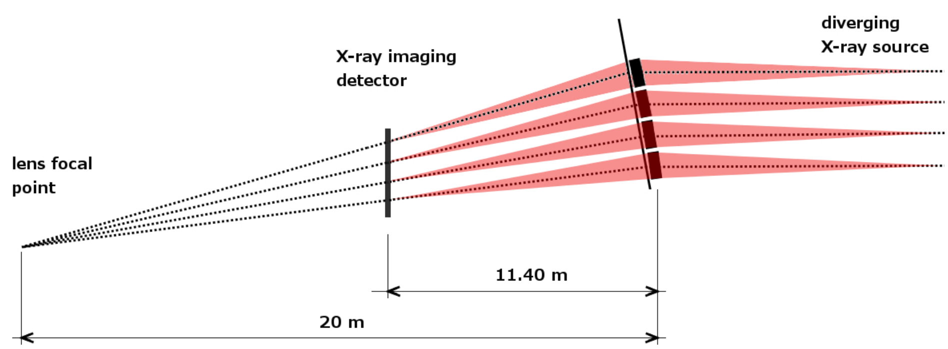

Figure 2. Sketch of the Laue lens explaining the effect of focusing x-rays from a diverging source. The collective behavior of the crystals is to focus the radiation at the distance of 20 meters from the lens but each crystal has its best focusing effect at a closer distance, depending on the distance between the source of radiation and the crystal.

Using the X-ray imaging detector and by fitting the diffracted profile with a Gaussian function, the position of the barycenter can be estimated with an uncertainty of $\sim$0.5 arcseconds. On the basis of the previous considerations and considering the desired PSF dimension, the barycenter of each crystal must be aligned at its proper reference pixel with an uncertainty of $\pm$2 pixels.

3.2 Preliminary study of adhesives and methods

Various different methods to set the crystals at the correct diffraction angle have been considered. All the procedures were based on setting the crystals over a frame and the match between crystal and substrate was made with a structural adhesive. As already pointed out in Sec. 3.1 the most critical effect while positioning a crystal is the rotation around the z axis. Once the crystal is positioned, the curing process induces a differential adhesive shrinkage that results in a non negligible tilt around that axis. In Table 2 are reported the properties of the adhesives that have been tested.

Table 2. Properties of the tested adhesives for fixing the crystals to the petal frame.

Adhesive name	properties	curing time	shrinkage
DEVCON Epoxy Gel	Two-component	1 min	1-2 %
DELO Automix 03 rapid thix	Two-component	5 min	2 %
Polyuretanic PUR 105	Two-component rigid	5 min	$< 1\%$
Polyuretanic PUE 205	Two-component semi-rigid	10 min	$< 1\%$
DYMAX OP 61 LS	UV curing	10-20 sec	$< 0.06\%$
DYMAX OP 67 LS	UV curing	10-20 sec	$< 0.06\%$

Different substrates have been studied and compared, in order to minimize the discrepancy between the ideal positioning and the real outcome. For each adhesive we analyzed pros and cons in terms of positioning accuracy, mounting time and stability with time. The petal frame is made of carbon fiber 2 mm thick with a hole for each crystal. The fixing of the crystals to the frame was designed to be made by injecting the adhesive through the hole, with the crystal set at the correct position on the other side of the frame support. At first, the structural DEVCON Epoxy Gel and the DELO Automix were used for their relatively short curing time and the structural power. The stability of the gluing was initially performed by means of a high precision coordinate measuring machine (Fig. 3).

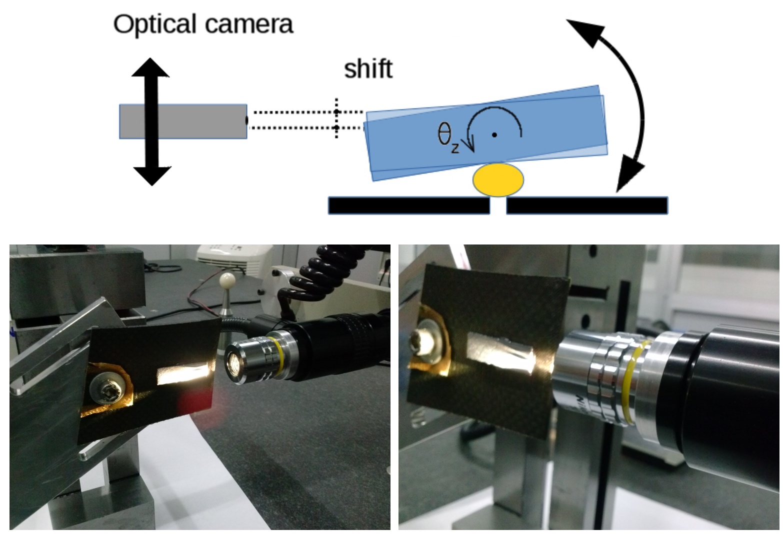

Figure 3. Sketch and pictures of the optical camera used to measure the linear shift of the crystal during the polymerization phase of the selected adhesive.

Each crystal was positioned in such a way that the barycentre of the diffracted image was in the center of the detector (pixel No. 512 in both directions). After 60 minutes from the glue injection and at regular time intervals thereafter, the focused point was monitored with the optical camera and, if needed, the camera was repositioned and the shift recorded.

The results obtained with the DEVCON Epoxy Gel for 3 glued crystals is shown in the left panel of Fig. 4. As can be seen, after ∼5 days the horizontal shift induced by the glue was roughly 20–25 μm. This amount would correspond to a shift of the diffracted image of ∼20 mm if the detector was positioned at the best focal distance of 11.40 m (misalignment of ∼5’). However, the measured shift can be due to a combination between a rotation Ω of the crystal, which is the main factor responsible of the diffracted beam movement, and a linear shift Λ that does not significantly affect the position of the x-ray diffraction image. The cross check was done using the X-ray beam by gluing a sample of 5 crystals to a support frame, and testing the adhesive behaviour with the X–ray beam.

The results of the crystal monitoring is shown in the right panel of Fig. 4. For the first 60 minutes the sample was set into the clamp and no motion was observed. After the release of the clamp, a common trend was observed which corresponded to a decrease of the Bragg angle. Even though the trend is monotonically decreasing for all curves, the effect is not systematic. The behavior is the same as suggested by the optical analysis but it confirms that the glue shrinkage behaves both in rotating the crystal and shifting it towards the frame support. The gap between the reference pixel (512) and the experimental results is in the range 30–40 pixels which corresponds to a shift of 6–8 mm (∼100–140 arcsec), which is almost half of the amount estimated with the optical camera but is still far from our goal.

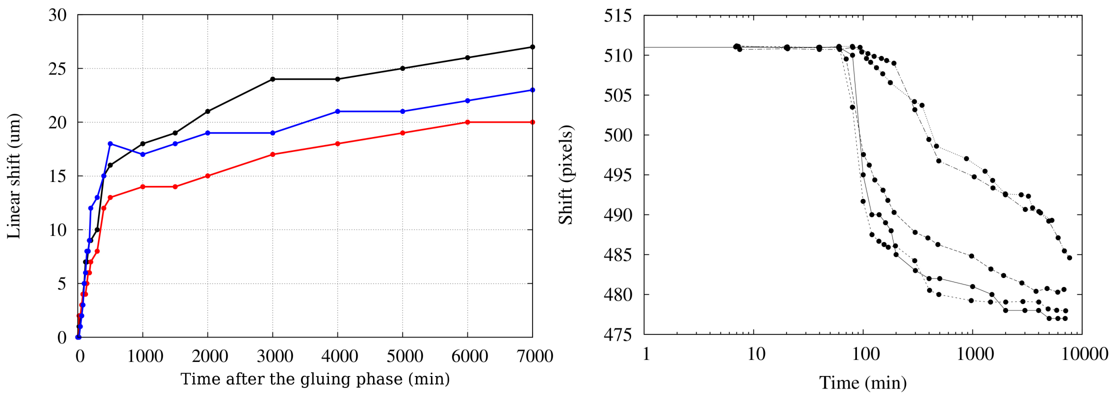

Figure 4. *left*: The linear shift of a crystal measured with the optical camera, as a function of time. The total shift (20-25 μm) corresponds to a combination of rotation and translation of the crystal caused by the glue shrinkage. *right*: Shift of the diffracted image (in detector pixels) measured with the X–ray beam as a function of time for 5 different crystals glued over a carbon fiber support. The glue injection was made through a hole performed through the support.

The carbon fiber was also used in a different configuration where the crystals were settled in cells and the glue was spread on the lateral edges of the crystals. In this configuration both the epoxy and the polyuretanic adhesives were tested. Thanks to the lateral gluing points the holding is more efficient even if the results are still within an uncertainty of 10–20 pixels (40-80”). The improved result with respect to the single gluing point can be explained by assuming that the single gluing point allows a pivoting of the crystal around the fixing point while two lateral strips inhibit the shrinkage contributions.

Both the methods have shown the limits introduced by the glue shrinkage which is not negligible for our purposes. For this reason we moved to a very low shrinkage single component adhesive which needs an activation given by UV light.

4. MOCK-UP ASSEMBLY

To minimize the shift and to quicken the process the adhesives DYMAX OP-61-LS and DYMAX OP-67-LS have been tested. They are low-shrink, low-outgassing, low-CTE optical adhesives. Both are a single component paste and the curing occurs with optical and UV light. They have been chosen mainly for their extremely low shrinkage coefficient < 0.08 % (other adhesives exhibited a shrinkage of 1–2%). They have comparable physical properties but different viscosity (60000 cps for the OP-61-LS, 135000 cps for the OP-67-LS) and curing time (from our experience the OP-67-LS cures ∼5 times faster than OP-61-LS). The convenience of using a UV curing paste is that the adhesive can be applied to the crystal before the fine alignment and the curing only occurs when the UV light is triggered. As the adhesive reacts to UV light, a flat 10 mm thick transparent support made of polymethyl methacrylate (PMMA)is adopted. For the mock-up, 11 GaAs crystals were fixed over the frame with the configuration shown in Fig. 5 by using the hexapod system. For its higher viscosity and short polymerization time, the DYMAX OP-67-LS was selected.

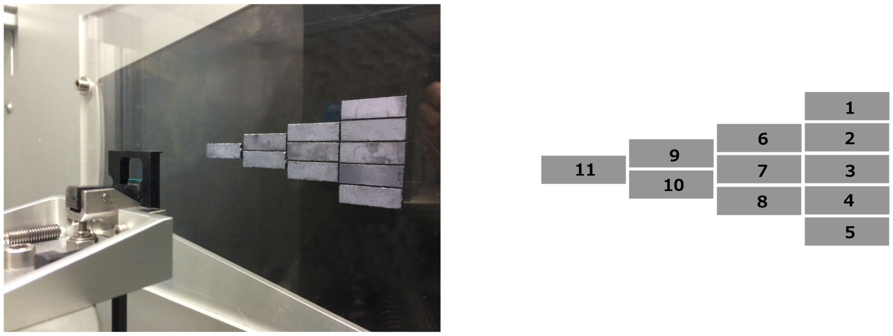

Figure 5. *Left*: picture of the mock-up made of 11 GaAs(220) bent crystals fixed on an UV transparent PMMA flat frame. *Right*: drawing of the model with indicated the progressive crystal number reported with Fig. 6.

Given that we were not interested in obtaining a tight packaging factor, the spacing between the tiles was set to 1 mm so as to avoid any problem of accidentally bumping one glued crystal while mounting the next. As mentioned in Sec. 3.1, during the mounting process each crystal was properly oriented in order to focus the radiation to the correct reference pixel. The crystal is first positioned at 10 mm far from the frame for a rough alignment. The estimation of the diffraction angle allows the definition of the minimum distance at which the crystal can be set close to the frame, in order to minimize the adhesive thickness (typically between 50 and 100 μm). A fine alignment is made by measuring the position of the diffracted image barycenter with the crystal set at the final distance from the frame and correcting the diffraction angle with the hexapod until the correct alignment is obtained. A UV lamp with light guide is then irradiated at an appropriate distance from the crystal, in order to slowly cure the adhesive while minimizing the stress during this critical phase.

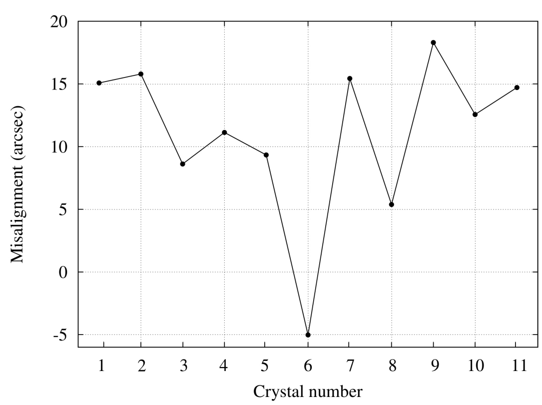

Figure 6. Misalignment with respect to the ideal position for the 11 GaAs crystals composing the mock-up model after the procedure of gluing over the PMMA support.

The crystal is then left inside the clamp for 30 minutes before being lightly released. Thanks to the relatively fast curing time, this method allows a large number of crystals to be set per day (the mock-up model was built in 2 days) compared with other methods or adhesives that require 5-10 hours to fully polymerize. The test of the correct positioning was done after ∼48 hours from the last glued tile and the results are shown in Fig. 6 where the deviation between the target and the measured position is expressed in arcseconds. It can be observed that all the crystals are correctly aligned within ∼23 arcsec while more than 90% of them is correctly aligned within 13 arcsec.

The results are still not satisfactory, but a significant improvement in the crystal gluing process has been obtained. Further work is needed.

5. CONCLUSIONS

In this paper we have described the LAUE project which is devoted to finding and using a new technology for building Laue lenses for astrophysical observations. A dedicated facility was developed for the assembling and testing phase of Laue lenses. One of the most challenging tasks was to find a suitable crystalline material with a good efficiency at the energies of interest. Gallium Arsenide and Germanium with bent crystalline structure appeared to be valid candidates for their good efficiency with also the substantial feature of focusing capability. The possibility of focusing the radiation must be coupled with an assembling method whose main features have to be the high positioning accuracy and a convenient short mounting time for each single crystal tile. After a preliminary study of adhesives, we have found a satisfactory UV curable candidate to fulfill the requirement of a short polymerization time and obtaining a positioning accuracy within 15–20 arcseconds.

Improvements in the mounting process chain are possible. One possibility is to use the carbon fiber frame with a large number of holes for each crystal. In this way the holes will ensure an effective curing phase of the UV adhesive and a minimal radiation absorption. Using a different design for the holding system could be also helpful to firmly hold the tiles preserving their curvature.

Thanks to the experience gained in the past years and within the LAUE project itself, we believe that Laue lenses will offer in the near future a new tool for high-sensitivity astrophysical observations in the hard X–/soft gamma–ray energy band, which will ultimately replace the current non-focusing telescopes.

ACKNOWLEDGMENTS

The authors wish to thank the Italian Space Agency for its support to the LAUE project.

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