State-of-the-art of the hard X-/soft γ-ray focusing telescopes: The LAUE project status

E. Virgilli*, F. Frontera, P. Rosati
University of Ferrara - Physics and Earth Science Department,
via Giuseppe Saragat, 1 - 44122 Ferrara, Italy
**E-mail to: virgilli@fe.infn.it*
www.larixlaboratory.unife.it

E. Caroli**, N. Auricchio, J. B. Stephen
Istituto Nazionale di Astrofisica - Istituto di astrofisica spaziale INAF/IASF,
via Piero Gobetti, 101 - 40129 Bologna, Italy
***E-mail to: caroli@iasfbo.inaf.it*

We describe 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 designed to be composed of bent crystals made of of Gallium Arsenide (GaAs, 220) and Germanium (Ge, 111). For the first time, the focusing property of bent crystals has been exploited for this field of applications. We show the results concerning the adhesive employed to fix the crystal tiles on the lens support, the positioning accuracy obtained and possible further improvements. The final goal is to develop a focusing optics that can improve the sensitivity of the current hard X-/soft γ-ray telescopes in the defined energy band by 2 orders of magnitude.

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

1. Introduction

Missions like *Beppo*SAX, RXTE 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[1]. Nevertheless the development of direct view instrumentation appears to be close to its limits in terms of sensitivity due to the significant payload weight and cost required to increase it. Focusing telescopes overcome this limitation, thanks to the decoupling 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 capable 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.

One concrete possibility to focus hard X-rays (>100 keV) is through the use of Laue lenses that 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).

2. The LAUE project: An overview

In the LAUE project[4,5] the main goal 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. The Laue lens is assumed to be made of a number of petals. One petal, capable of focusing the radiation in the range 90–300 keV, is being realized within the project that also faces other tasks:

- 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 can be produced in large quantities with good reproducibility in terms of dimensions and mosaic spread. Unfortunately, their maximum reflectivity is limited to 50%[6,7] and their diffracted image in the focal plane depends on the crystal size. On the contrary, bent crystals (for the first time used for for astrophysical applications within our project) overcome the limits of flat crystals given that the diffracted images are smaller than the crystal cross section itself.

In the LAUE project a flat frame is used as a support for the crystal tiles composing the single petal. 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. The strategy of the LAUE project is to use a structural adhesive which works as interface between the frame support and the crystals. The adhesive must be selected in order to minimize both the curing time and the glue shrinkage. Especially the latter parameter is influenced by the environment conditions (temperature and humidity). For this reason the facility is equipped with a clean rom with thermal and hygrometric control (20 deg ± 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 crystals made of GaAs(220) and Ge(111) have cross section of $30{\times}10$ mm^2, with the longer side radially placed on the lens frame. Being the lens focal length set to 20 m their curvature radius must be of 40 m. The rectangular shape of the crystals is convenient given that the focusing effect occurs only in the radial direction. Such a shorter tangential dimension provides a smaller defocusing factor in the latter dimension.

Each crystal tile is positioned over the lens frame under the control of a gamma–ray beam that mimics a source placed at infinite distance from the lens. The pencil beam is obtained by moving simultaneously the aperture

Table 1. Properties of the tested adhesives for fixing the crystals to the petal frame.

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	30×10 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)

of a collimator and the X-ray tube in the vertical y-z plane, perpendicular to the beam propagation (x axis). Thanks to the motors accuracies, the X-ray beam is always parallel to the lens axis within 1.5 arcsec. Each single crystal is individually irradiated and oriented by using an hexapod system in order to focus the radiation onto the correct point. The degrees of freedom of the hexapod allow the 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 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 results in a shift of the diffracted image on the focal plane detector along the y axis. The adhesives shrinkage during the curing phase is the main responsible of each θ_z tilt from the nominal position. The spatial distribution of the diffracted beam and its correct positioning is measured thanks to the 200×200 μm^2 spatial resolution of the imaging detector. 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 desired PSF dimension, the barycenter of each crystal must be aligned within an uncertainty of $\pm$2 pixels (0.4 mm).

3.1. *Preliminary study of adhesives and methods*

As already pointed out in Sec. 3 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 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%

Various substrate have been considered in order to minimize the discrepancy between the ideal positioning and the real outcome. For each adhesive we analyzed the positioning accuracy and the curing time.

At first, a 2 mm thick carbon fiber frame was used. The crystal was fixed over the frame by injecting the adhesive through holes, with the crystal set at the correct position on the other side of the support. The structural DEVCON EPOXY GEL and the DELO AUTOMIX were used for their structural power. The stability of the gluing process was performed by means of a high precision coordinate measuring machine (Fig. 1). Each crystal was positioned to diffract the radiation at the detector center (pixel No. 512 in both directions). After the polymerization the stability of the crystal was monitored with the optical camera and at regular time intervals the camera was repositioned and the shift recorded.

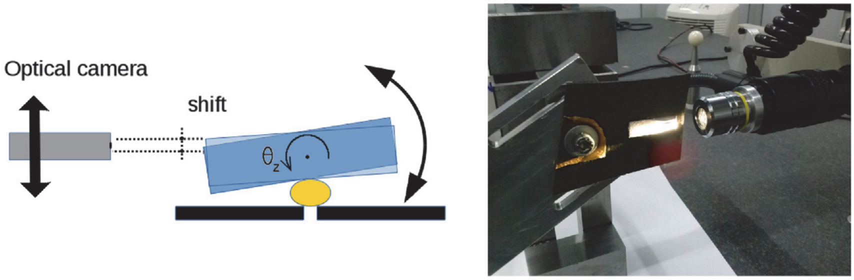

Fig. 1. Sketch and pictures of the optical camera used to measure the linear shift of the crystal during the polymerization phase of the selected adhesive.

Figure 2 (left panel) describes the shift induced by the DEVCON EPOXY GEL for 3 glued crystals. After several days the horizontal shift induced by the glue was roughly 20–25 μm. This amount would correspond to a shift of the diffracted image on the focal plane of ∼20 mm from the nominal position (misalignment of ∼5'). However, the measured shift is due to a combination of a rotation θ_z and a linear shift Λ of the crystal that shound does not significantly affect the position of the x-ray diffraction image. The Λ contribution was confirmed by the diffraction analysis over 5 crystals and shown in Fig. 2 (right panel) where only the crystal tilt influences the shift of the diffracted image. After the release of the clamp, a common trend was observed which corresponded to a decrease of the Bragg angle. 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).

To minimize the shift and to quicken the process the adhesives DYMAX OP-61-LS and DYMAX OP-67-LS have been tested. Both are a single component paste and the curing occurs with optical and UV light. They have shown similar performances, thus the following results are those obtained with the DYMAX OP-67-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.

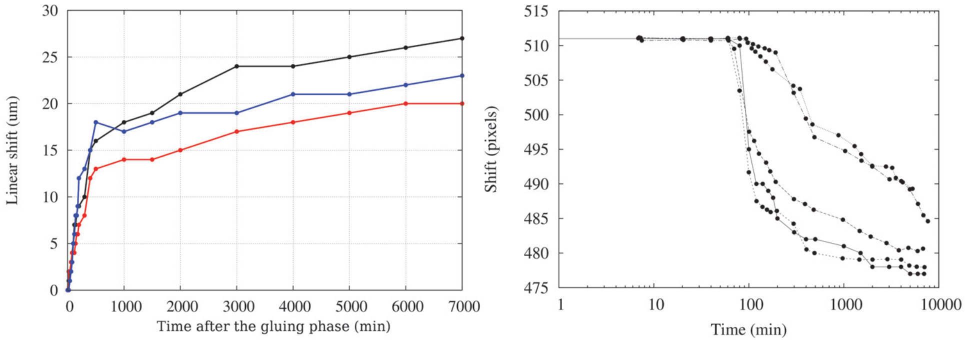

Fig. 2. *Left*: The linear shift of a crystal measured with the optical camera, as a function of time. *Right*: Shift of the diffracted image (in detector pixels) measured with the X–ray beam along the time for 5 crystals glued over a carbon fiber support.

As the adhesive reacts to UV light, a flat 10 mm substrate made of polymethyl methacrylate (PMMA) was adopted. A sample of 11 GaAs crystals were fixed over the substrate (Fig. 3, left panel).

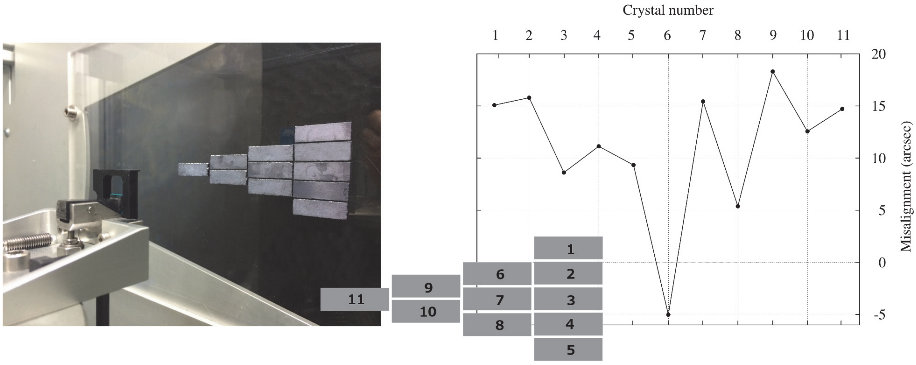

Fig. 3. *Left*: Sample of 11 GaAs(220) bent crystals fixed on an UV transparent PMMA flat frame. *Right*: Misalignment with respect to the ideal position for the 11 GaAs crystals mounted over the PMMA support. A drawing of the model with indicated the progressive crystal number is also indicated.

The adhesive thickness was typically between 50 and 100 μm with a total weight of $\sim$ 4-6 mg. After the UV curing, the crystal was left inside the clamp for 30 minutes before being released. Thanks to the fast curing time, this method allows a large number of crystals to be set per day compared with other methods or adhesives that require hours to fully polymerize. The accuracy in the positioning the crystals is shown in Fig. 3 (right panel) where the deviation between the desired and the measured position is expressed in arcseconds. All the crystals are correctly aligned within $\sim$23 arcsec while 10 of 11 are correctly aligned within 13 arcsec.

4. Conclusions

In this work we have summarized the LAUE project which is devoted to find a technology for building Laue lenses for astrophysical observations. One of the most challenging tasks was to find a suitable crystalline material with a good efficiency at the energies of interest. After a preliminary study of the adhesives, we have found an UV curable candidate to fulfill the requirement of a short polymerization time and obtaining a positioning accuracy within 15–20 arcseconds. We have demonstrated the feasibility of a Laue lens by minimizing the uncertainties related to the frame support and to the adhesive. The results are still not satisfactory but improvements in the mounting process chain are possible. A new prototype will be presented by using a curved frame with the same curvature of the crystals and by using a different source of light for the curing phase which is the most critical phase of the process.

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