THE LAUE PROJECT FOR BROADBAND GAMMA-RAY FOCUSING LENSES

E. VIRGILLI*, F. FRONTERA*, V. VALSAN*, V. LICCARDO*, E. CAROLI†,
 J. B. STEPHEN‡, F. CASSESE‡, L. RECANATESI‡, M. PECORA§,
 P. ATTINÁ¶, S. MOTTINI§ and B. NEGRI||

**Physics Department, University of Ferrara
 via Saragat 1, Ferrara, Italy*

†*IASF-INAF via P. Gobetti, Bologna, Italy*

‡*DTM, Modena, Via Tacito, I-41100 Modena, Italy*

§*Thales Alenia Space-Italy, Milan, Italy*

¶*Thales Alenia Space-Italy, Turin, Italy*

||*ASI, Agenzia Spaziale Italiana
 Viale Liegi 26, I-00198 Roma, Italy*

We present the LAUE project devoted to develop an advanced technology for building a high focal length Laue lens for hard X and soft gamma-ray astronomy (80–600 keV). The final goal of the project, supported by the Italian Space Agency, is to build and test a focusing optics that can improve the current sensitivity in the above energy band by 2 orders of magnitude.

Keywords: Laue lenses; atrophysics; X-rays.

1. Introduction

The importance of the X-ray broad band (0.1–200 keV and beyond) in the astrophysical field has been demonstrated by past and present missions like *BeppoSAX*, *XTE* and *INTEGRAL*. The extension of the band beyond 70/100 keV is crucial to study non thermal processes (see i.e. the discussion by Frontera *et al.* 2012 this Volume).

The focusing telescopes in the soft gamma-ray band are nowadays taking key relevance to overcome the sensitivity limits of the current generation of gamma-ray telescopes which observe the sky through mechanical telescopes (see, e.g., Ref. 1) or coded mask systems (see, e.g., Ref. 2).

Low energy focusing telescopes up to ~ 70 –80 keV have been successfully built (e.g. *ASTRO-H*³ and *NuSTAR*⁴), but beyond 100 keV an efficient way to focus photons appears to be the use of diffraction techniques from crystals. The use of gamma-ray focusing optics is also crucial for improving the angular resolution, the best being now obtained with coded mask telescopes (about ~ 15 arcmin of the mask in the case of *INTEGRAL/ISGRI*).

2. The LAUE Project: A Focusing Lens for Soft Gamma-Rays

Objectives of the LAUE project

The main goal of the LAUE project, which is supported by the Italian Space Agency, is to develop an advanced technology for building a Laue lens with a broad energy passband (70/100–600 keV) and long focal length (up to 20 m and beyond) for space astrophysics.

Related to the main goal, a number of important issues are being faced. A challenging task is to develop a technology for a massive production of crystals for diffraction, with high efficiency and desired spread ($20 \div 30$ arcsec). Another task is that of developing a technology for a fast positioning with accuracy better than 10 arcsec. For these purposes a new facility devoted for assembling the crystals on a petal with the required accuracy and for the performance tests is being installed. The lens is assumed to be made of a number of petals. The adopted technology consists in the positioning of the crystal tiles on a petal frame under the control of a gamma-ray beam. Each crystal is correctly oriented when it focuses the beam photons in the lens focal plane. The position of the crystal tile will be kept steady by gluing each tile upon the petal frame which is kept fixed during the assembling phase.

One of these petals will be developed as a result of the LAUE project. Given that, at the moment we have a gamma-ray source with maximum energy of 300 keV, the petal prototype will have a passband from 80 to 300 keV.

The LARIX facility

The apparatus for the lens assembling is being installed the Large Italian X-ray Facility (LARIX, see Fig. 1) of the Physics Department of the University of Ferrara. For the lens assembling an X-ray source with a fine focus of 0.2 mm radius with a maximum voltage of 320 kV and a maximum power of ~ 1800 W will be used. The generated X-rays pass through a 20 m long under-vacuum beamline. The output beam from the beamline is then collimated before impinging on the crystal tile to be tested and correctly positioned in the lens petal. This lens petal assembling is performed in a clean room (class $< 10^5$) which is thermally and hygrometrically

Fig. 1. Layout of the LARIX facility in which the petal will be built and tested.

controlled ($\pm 1^\circ\text{C}$ accuracy, relative humidity $\Phi = 60\%$ within an error of 10%). The the collimator aperture can be remotely adjusted in two orthogonal directions for beam direction and divergence control. The beam through the final collimator is thus used to establish the correct crystal orientation in the lens. For both the assembling and the test phases two detectors are placed in the lens focal spot: an X-ray imaging detector with spatial resolution of $300\ \mu\text{m}$ and a cooled HPGe spectrometer with a 200 eV spectral resolution.

Petal configuration

The crystals adopted for the lens petal prototype are bent crystals of Germanium (220), Germanium (111) Silicon (111), Gallium Arsenide (111) and Gallium Arsenide (220). They are expected to provide good efficiency and a better focusing capability than flat mosaic crystals.⁸

The crystal cross section has been chosen to be $30 \times 10\ \text{mm}^2$, with the longer side radially placed on the lens frame. The thickness t of the crystal tiles, for each type of crystal material, is a compromise between the need of a high effective area and the current limitation in the thickness imposed by the current status of the bending technology adopted. The best distribution of the crystal materials within the lens is being investigated by using a proper Monte Carlo code, in order to optimize the lens properties (i.e. maximization of the total effective area, best focusing). A sketch of the petal that will be built is given in Fig. 2.

Fig. 2. Sketch of the petal extracted from an entire Laue lens, that will be built and tested in the Ferrara LARIX facility. The petal is assumed made of flat $1.5 \times 1.5\ \text{cm}^2$ crystals, and the petal dimension is defined by the beam line diameter (black circle line). Different colors refer to different energies diffracted by each single crystal depending on the assumed position.

Fig. 3. Simulated PSF for a ring made of curved crystals (*left panel*) and flat mosaic crystals (*right panel*).

3. Expected lens Performances

The expected Point Spread Function (PSF) of a single ring of Laue lens made of bent crystals is shown in Fig. 3 together with the PSF obtained with flat mosaic crystals, for comparison. In the simulation, the chosen ring focuses photons in a narrow band centred at 150 keV. In both cases a crystal cross section of $1.5 \times 1.5 \text{ cm}^2$ of each crystal tile is assumed and a perfect ideal alignment is considered. As can be seen from the figure, the obtained PSF with bent crystals is significantly narrower than that obtained in the case of flat mosaic crystals. The number of photons collected in the center of the focal spot is more than one order of magnitude higher in case of bent crystals.

4. Conclusions

From the already gained experience on Laue lenses (see, e.g., Refs. 6, 11), we have started a new project, LAUE, supported by the Italian Space Agency (ASI), devoted to the development of an advanced lens assembling technology that we expect it will allow to accurately build Laue lenses for space astrophysics. The expected accuracy in the lens assembling would allow to build lenses even with very long focal lengths (up to 100 m). In addition to the development of the lens assembling technology, the LAUE project is facing the crystal production of proper crystals for Laue lenses and a suitable technology to correctly assembly a Laue lens made of a large number of

crystals in a relatively short time. Bent crystals appear the most suitable for the project. As a demonstration of the validity of the proposed technology, a petal of Laue lens with 20 m focal length will be entirely assembled and tested in the LARIX facility of the Ferrara University.

Acknowledgments

The authors acknowledge the Italian Space Agency (ASI) for the financial support to the LAUE project through the contract I/068/09/0.

References

1. Frontera, F., Costa, E., dal Fiume, D., Feroci, M., Nicastro, L., Orlandini, M., Palazzi, E., and Zavattini, G., "Pds experiment on board the beposax satellite: design and in-flight performance results," in [*EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy VIII*], Siegmund, O. H. and Gummi, M. A., eds., 206–215, Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference (1997).
2. Ubertini, P., Lebrun, F., Cocco, G. D., Bazzano, A., Bird, J. A., Broenstad, K., Goldwurm, A., Rosa, G. L., Labanti, C., Laurent, P., Mirabel, F. I., Quadrini, E. M., Ramsey, B., Reglero, V., Sabau, L., Sacco, B., Staubert, R., Vigroux, L., Weisskopf, M. C., and Zdziarski, A. A., "Ibis: The imager on-board integral," *Astron. & Astrophys* **411**, L131–L139 (2003).
3. Kunieda, H., Awaki, H., Furuzawa, A., Haba, Y., Iizuka, R., Ishibashi, K., , Ishida, M., Itoh, M., Kosaka, T., Maeda, Y., Matsumoto, H., Miyazawa, T., Mori, H., Namba, Y., Ogasaka, Y., k. Ogi, Okajima, T., Suzuki, Y., Tamura, K., Tawara, Y., Uesugi, K., Yamashita, K., and Yamauchi, S., "Hard x-ray telescope to be onboard astro-h," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference*], Volume 7732, pp. 773214–773214–12, SPIE (2010).
4. Hailey, J., An, H., Blaedel, K., Kenneth, L., Brejnholt, N., Christensen, F., Craig, W., Decker, T., Todd, A., Doll, M., Gum, J., Koglin, J., Jensen, C., Hale, L., Mori, K., Pivovarov, M., Sharpe, M., Stern, M., Tajiri, G., and Zhang, W.
5. Frontera, F. and Ballmoos, P. V., "Laue gamma-ray lenses for space astrophysics: status and prospects," *astro-ph.IM* (2011).
6. Frontera, F., Loffredo, G., Pisa, A., Nobili, F., Carassiti, V., Evangelisti, F., Landi, L., Squerzanti, S., Caroli, E., Stephen, J. B., Anderson, K. H., Courtois, P., Auricchio, N., Milani, L., and Negri, B., "Focusing of gamma-rays with laue lenses: first results," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], 7011, SPIE (2008).
7. Smither, R., Saleem, K., Beno, M., Kurtz, C., Khounsary, A., and Abrosimov, N., "Diffraction efficiency and diffraction bandwidth of thermal-gradient and composition-gradient crystals," *Review of Scientific Instruments* **76**, 123107–123107–19 (2005).
8. Bellucci, V., Camattari, R., Guidi, V., Neri, I., and Barriere, N.
9. Malgrange, C., "Crystal research and technology," **37**, 654–662 (2002).
10. Keitel, S., Malgrange, C., Niemller, T., and Schneider, J., "Diffraction of 100 to 200keV x-rays from a $\text{Si}(1-x)\text{Ge}(x)$ gradient crystal," *Acta Cryst.* **A 55**, 855–863 (1999).
11. Virgili, E., Frontera, F., Valsan, V., and Liccardo, V., "Laue lenses for hard x-/soft gamma-rays: new prototype results," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference*].