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Opening the path to hard X-/soft gamma-ray focussing: the ASTENA-pathfinder mission

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Summary. — Hard X-/soft gamma-ray astronomy is a crucial field for transient, nuclear and multimessenger astrophysics. However, the spatial localization, imaging capabilities and sensitivity of the measurements are strongly limited for the energy range >70 keV. To overcome these limitations, we have proposed a mission concept, ASTENA, submitted to ESA for its program "Voyage 2050". We will report on a pathfinder of ASTENA, that we intend to propose to ASI as an Italian mission with international participation. It will be based on one of the two instruments aboard ASTENA: a Laue lens with 20 m focal length, able to focus hard X-rays in the 50-700 keV passband into a 3-d position sensitive focal plane spectrometer. The combination of the focussing properties of the lens and of the localization properties of the detector will provide unparalleled imaging and spectroscopic capabilities, thus enabling studies of phenomena such as gamma-ray bursts afterglows, supernova explosions, positron annihilation lines and many more.

1. – Rationale and mission configuration

High energy astrophysics has still unanswered questions mainly due to the poor sensitivity of the present instrumentation: transient events like gamma-ray bursts and in particular their X-ray afterglow emission, blazars and magnetars spectra are just a few examples of science that would benefit from higher sensitive instruments. An exhaustive review of the science that can be tackled with future focusing optics can be found in [1, 2]. A substantial increase in sensitivity can be achieved by enabling hard x-ray focusing. At the moment, the only technology that would enable the focalization of hard X-rays is through Laue lenses which are based on diffractive crystals. Unfortunately, due to the outstanding accuracy required for optics alignment and the non-trivial requirements for an efficient focal plane soft gamma-rays detector, such a technology has not yet been used in space. At present, new technologies for the production of effective optics and new materials for gamma-ray detection make the use of Laue's lenses more mature and feasible. A hard x-ray mission concept named ASTENA (Advanced Surveyor of Transient Events and for Nuclear Astrophysics) has been proposed for focusing photons in the 50 – 700 keV energy range. The ASTENA mission consists of two complementary

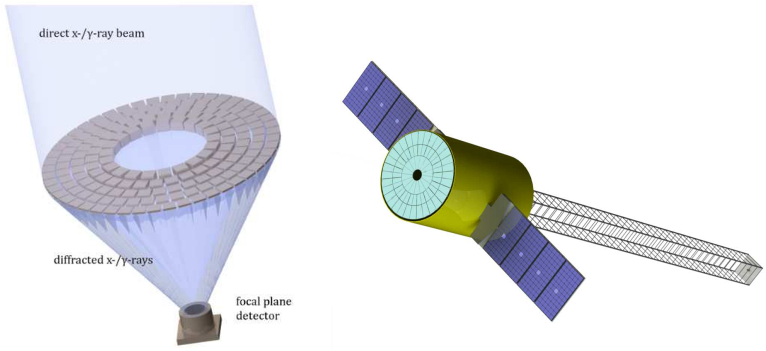

Fig. 1. – Left: Drawing of the Laue lens concept. Right: Drawing of the ASTENA pathfinder. The blue circular area represents the Laue lens, which is divided into independent modules. A position-sensitive detector is located at a focal distance of 20 m through an extendable mast.

instruments: a Wide Field Monitor with Imaging and Spectroscopic capabilities (WFM-IS), based on the same technology of the THESEUS/XGIS instrument [3] and a Narrow Field Telescope (NFT). The NFT is based on a Laue lens made from bent crystals of silicon and germanium. The lens has a diameter of 3 m and a focal length (FL) of 20 m. As a precursor for the ASTENA mission, we propose an experiment based on NFT alone whose total weight would be suitable for the size of a possible light national mission, in response to the next upcoming ASI call. This configuration, called ASTENA-pathfinder, will allow us to tackle a relevant scientific case with a low mission weight ($<$ 200 kg).

2. – Technical Development Activities

Technical Development Activities have been conducted in recent years in order to increase the maturity of a space instrument for focusing gamma-rays. The following sections describe such development activities separately for the Laue concentrator and the focal plane detector.

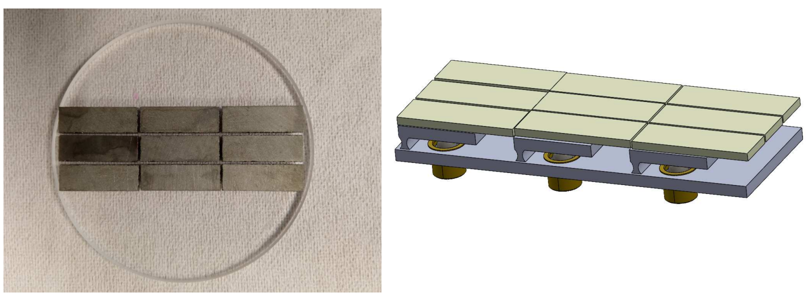

Fig. 2. – Left: prototype of Laue lenses realized at Karlsruher Institut für Technologie (KIT) made with 9 bent Germanium crystals mounted on a 4 mm quartz substrate with a bonding method adapted from the ball-bonding/ flip-chip technique largely used in microelectronics. Right: drawing of a 9 elements prototype which exploits the lamellae adjustable through micrometric screws.

2˙1. *Developments of Laue lenses*. – Laue lens technology is mainly limited by the large number of basic optical elements to be accurately prepared and properly oriented

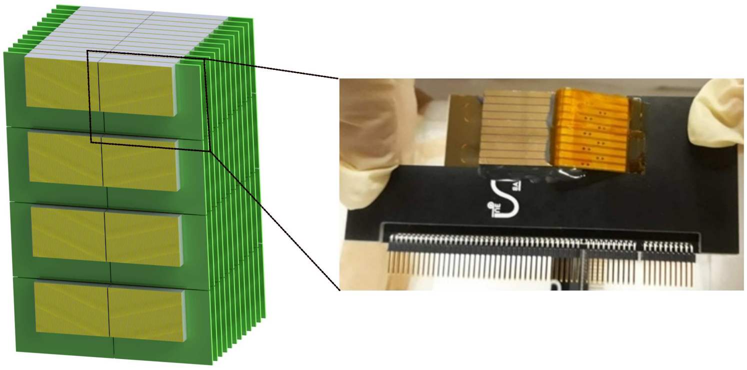

Fig. 3. – Left: the configuration of a possible focal plane detector based on a stack of CZT crystals. Right: detail of one CZT detector developed within the 3DCaTM project, supported by ASI-INAF (adapted from [4]).

towards a common focal point. As these processes are currently performed manually, are prone to inaccuracy and time-consuming. Our goal is to automate the process to reduce uncertainties and processing time. Several R&D activities have been made in the past for increasing the maturity of the Laue lenses. Within the recent TRILL project [5], funded by ASI-INAF, CNR/IMEM (Parma) has optimised a method based on lapping one of the largest faces to provide the crystals the defined curvature. We have provided and qualified dozens of crystals by demonstrating the reproducibility of the crystal bending process at the nominal radius of 40 m (twice the FL). Various methods for positioning and bonding crystals were also investigated with the aim of finding a repeatable technique for a large number of crystals and with an accuracy of the order of a few arcsec. The flip chip bonding technology, largely used in microelectronics, has been used in our specific application at Karlsruher Institut für Technologie (KIT). This method allows to set at the same angle several crystals per minute with an accuracy better than 10 arcsec. However, it does not allow setting each crystal at its nominal angle that also depends on the miscut angle with respect to the external surface, therefore the alignment procedure relies also on the accuracy of the preparation of the sample. A method enabling bonding and fine alignment of the optical elements involves the use of elastically adjustable supports (called lamellae) operated by micro screws (Fig. 2-b). Each crystal is bonded through adhesive on the top of a lamella and fine threads micro screws ensures an alignment accuracy of the order of a few arcsec. A prototype with 9 crystals has been designed and will be realized and tested soon.

2·2. *Development of gamma-ray focal plane detector*. – Technological activities are being performed by different groups in Europe [6, 4] with the goal of developing semiconductor spectroscopic imagers suitable as focal plane for hard X-ray space telescopes. In order to take advantage of a focusing instrument, requirements on the energy and spatial resolution, and on detection efficiency must be set. The requirements for such a detector are a high detection efficiency (>80% @ 500 keV), in the energy range 10-1000 keV and high performance spectroscopy (≤1% FWHM @ 511 keV). In addition, sub-millimeter spatial resolution in three dimensions (≤ 300 μm), fine timing resolution (≤1 μs) and polarimetry capability are needed. In this perspective, Cadmium Zinc Telluride (CZT) have very high detection efficiency in the sub-MeV range even with only a few cm of materials, with good spectroscopic capability of about 1% FWHM @ 511 keV. They result to be particularly interesting as they provide high performance with the advantage of being usable at room temperature. The baseline technology for these detectors is based on the segmentation of anodes and cathodes associated with a drift strip configuration for the anodic reading of the signals. The use of anode and cathode strips allows to achieve a highly segmented sensor providing thousands of equivalent sub-millimetric voxels with a few tens of read-out channels (Fig. 3) for each CZT sensor unit. In order to reach the required thickness, a stack of crystals is necessary.

3. – Conclusions

We have presented an experiment called ASTENA-pathfinder based on a lightweight Laue lens made with curved Silicon and Germanium crystals. Thanks to the sensitivity achievable for both continuum and nuclear line observations, the ASTENA-pathfinder will represent a turning point for a number of still unanswered scientific questions. ASTENA-pathfinder is a scientific and technological pioneer of the ASTENA mission concept which includes, in addition to the Laue lens of the NFT, a WFM-IS with unprecedented broad energy pass-band (2 keV - 20 MeV). Current technological activities, supported by ASI and INAF, address both the complexity of building a Laue optics, that requires great precision for the alignment of thousands of basic components, and the realisation of a focal plane detector with fine 3-d segmentation, fast timing capabilities, high detection efficiency and high energy resolution.

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