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The Narrow Field Telescope on board the ASTENA mission

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Abstract. The ASTENA mission concept consists of a broad band Wide Field Monitor Imager and Spectrometer and a broad band Narrow Field Telescope. The latter is a Laue lens (∼3 m diameter, 20 m focal length) sensitive to the 50 – 600 keV energy pass-band made of Silicon and Germanium cylindrical bent crystals. Such crystals allow the radiation to be focused into a narrow point spread function never achieved so far. In the presented configuration the instrument field of view is ∼ 4 arcmin with angular resolution of ∼30 arcsec. The Laue lens is coupled with a high efficiency (>80% above 600 keV) focal plane position sensitive detector, with 3D spatial resolution of 300 μm in the (X,Y) plane, fine spectroscopic response (1% at 511 keV) and polarization sensitivity. In this paper we present an overview on the satellite configuration and we mainly focus on the Narrow Field Telescope design and performances estimated with Monte Carlo simulations.

Key words. Instrumentation: focusing telescopes – hard X-/soft gamma-rays – GRBs – nuclear astrophysics

1. Introduction

Past and present missions like *Beppo*SAX and INTEGRAL have demonstrated the key importance of the hard X-/soft gamma-ray band (10 keV - ∼1 MeV) to study a large number of astronomical phenomena. A further increase of the instrument sensitivity is achievable only with focusing techniques.

The soft X-ray energy band ($\lesssim$ 80 keV) has already exploited focusing telescopes through the use of multilayer coatings (e.g. NuSTAR,

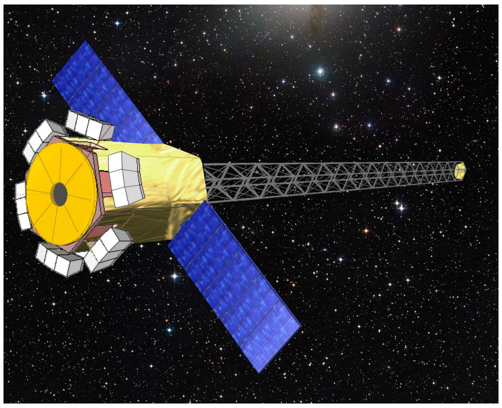

Fig. 1. Artistic view of the ASTENA concept mission. The NFT optics (orange area) is a Laue lens made of petals with a focal plane detector which is kept at 20 m focal distance with an extendable boom. The focusing instrument is surrounded by the 6 blocks of 3 WFM-IS units (white elements). Six of these units are co-aligned with the NFT.

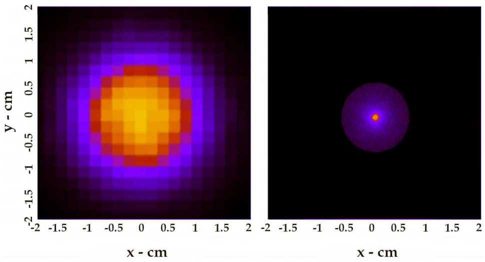

Fig. 2. The PSF of the NFT using flat (left) and bent (right) Silicon or Germanium crystals (30 × 10 mm^2 cross section).

Harrison et al. 2013). Unfortunately, at the moment, this technology cannot be efficiently extended to energies of hundreds keV due to the small reflection angles. Bragg diffraction in transmission configuration (Laue) represents a viable method to focus X and gamma-rays from few tens keV up to the MeV domain. Laue lenses can provide large collecting areas and narrow Point Spread Function (PSF), which contribute to significantly increase the sensitivity with respect to the currently operational non focusing instruments.

ASTENA, whose schematic view is shown in Fig. 1, is a mission concept designed within the AHEAD consortium (Piro et al. 2015). ASTENA includes a Wide Field Monitor Imager and Spectrometer (WFM-IS) with energy pass-band from 2 keV to 20 MeV and a Narrow Field Telescope (NFT) with a nominal energy pass-band (50–600 keV). For further information about ASTENA see the paper by Frontera et al. in these proceedings.

2. Optimization of the ASTENA/NFT

Starting from the scientific requirements and after an evaluation of the technical possibilities, we have developed a software that, through ray tracing and Monte Carlo simulations, allows us to derive the expected Laue lens performances (Virgilli et al. 2017). The software consists of a number of functions each of which carries out a given task (photon production, crystal definition, lens geometry, physics of the processes, data acquisition). The user provides a set of parameters for the definition of the lens properties, including the crystals material, the diffraction planes (defined through the Miller indices) and the crystal dimensions. The tile positions and their orientations are independently calculated by the software once the Laue lens radial extension and focal length are provided. The crystals can be either flat or bent and, in the latter case, the curvature radius of each tile must be provided. The total number of crystals and the filling factor[1] are determined, depending on the mutual distances between contiguous tiles. Once the lens geometry is defined, the interaction is described by the Bragg law to get the propagation direction of the emerging beam. The NFT has been optimized through this tool and its performances evaluated. In order to fully exploit the imaging capability of a Laue lens, bent crystals have been considered. The main advantage of using bent crystals is their capability of focusing the radiation in a region smaller than the crystal cross section itself (Buffagni et al. 2013). Using bent crystals ensures that the Half

[1] The “filling factor” is the ratio between the area covered by the crystals and the total lens footprint.

Power Diameter (HPD) of the PSF is about 30 arcsec. Instead, Monte Carlo simulations show that with flat crystals the HPD and the PSF area increase by a factor of 10-15 (Fig. 2) and ~100, respectively. Given the required NFT nominal pass-band (50–600 keV), the best crystals to be used for the Laue lens are Germanium and Silicon due to their high diffraction efficiency.

The focal length of 20 m and the spacecraft diameter limit of 3 m are best matched by arranging the crystals in 43 concentric rings with a filling factor of ~0.87. This diameter provides an unprecedented large geometric area of 7 m^2 with a moderate weight of 120 kg. The Laue lens PSF is mostly sensitive to crystal manufacturing and assembling. Furthermore the performances of the NFT depend on the stability of the crystals positioning over the mission lifetime. All these factors need to be accurately considered. In the developed Laue lens software, each crystal can be correctly oriented at its nominal position or misaligned, with a uniform or Gaussian distribution, within a given range with respect to the nominal orientation. Also the crystal curvature radius can be either set at the nominal value or can be distorted over a range of curvature radii centered at the nominal radius, following a uniform or Gaussian distribution.

For perfect crystals we have found that, if the imposed curvature radius is within 5% of its nominal value, the HPD of the PSF remains within 30 arcsec which is our main goal. Moreover, if the mounting accuracy is better than 10 arcsec the same requirement is also accomplished. It is worth noting that the most demanding positioning accuracy refers only to the Bragg angle, while the remaining positioning angles do not affect significantly the position and the sharpness of the PSF.

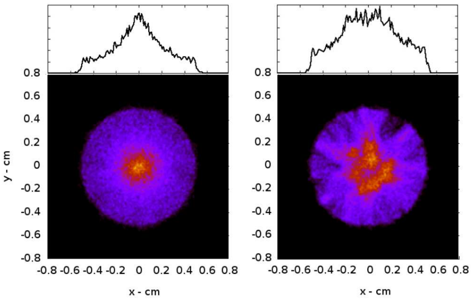

Fig. 3. Monte Carlo simulations of the PSF for the NFT if the curvature radius of the crystals following a Gaussian distribution centred at the correct value of 40 m with a FWHM of of 4 m (left), or crystals with misalignment following a Gaussian distribution centred at zero misalignment and with FWHM = 30 arcsec. Both cases do not fit the requirement of HPD < 30 arcsec. In the text are indicated the limit values that satisfy the goals. On top of each photon distribution are also reported the intensity profiles along the x axis at the central region of the image.

3. Experimental activity in support to the ASTENA/NFT realization

In addition to the feasibility study with simulations, the ASTENA team is active on experimental aspects devoted to increase the Technological Readiness Level (TRL) of the main components of the mission concept. At the moment, thanks to the realization of a number of laboratory prototypes (Frontera et al. 2007; Virgilli et al. 2011) the TRL of the Laue lenses is of the order of 3. To push forward the TRL value to 5, an activity, supported by the National Institute of Astrophysics INAF and the Italian Space Agency, has started. The main goal of this project is to realize a Laue lens petal made of a number of modules. Such modular strategy has been already successfully employed for operative space missions (e.g. NuSTAR) and for the ATHENA mission in phase A study (Nandra et al. 2013). In particular for Laue lenses, the modular approach is expected to shrink the integration time and to improve the positioning accuracy. In Fig. 4 it is shown the modular concept adopted for the Laue lens under development. The lens is made of petals and each petal is made of a number of modules that can accommodate a few tens of crystals. Thanks to the implemented bonding method, the mounting accuracy can be of the order of 10 arcsec. Each module can be realized in a considerably short time (~ 1 week). Furthermore modules with a limited number of crystals can be easily set up in dedicated facilities for environmental tests, in order to assess

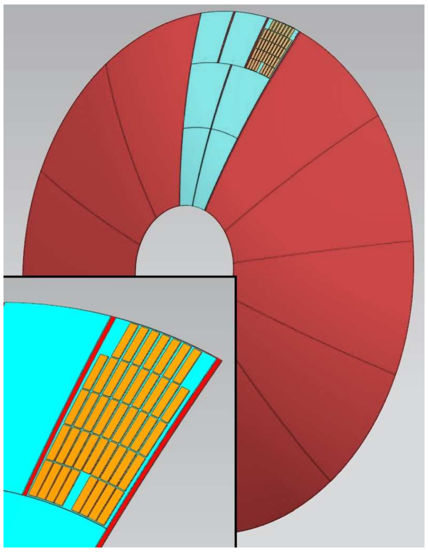

Fig. 4. Drawing of the NFT which is made of petals (red structures). One petal is being realized as a demonstrator of capability to improve the Laue lenses TRL to 5. For this goal, a number of modules will be realized and properly assembled. The inset shows a sketch of one module where few tens of crystals (orange rectangles) are arranged.

their strength and the stability of the bonding process.

4. Conclusions

An innovative mission concept named ASTENA is being investigated within the AHEAD consortium, based on a WFM-IS and on a NFT. The ASTENA/NFT instrument is designed a as broad energy pass-band, light and large effective area Laue lens made with bent Silicon and Germanium crystals. We have described the NFT properties and the two main sources of PSF broadening, namely the realization of the proper crystals curvature and their correct mutual alignment. Using our ray-tracing, the NFT field of view has been estimated to be 4 arcmin, which matches the requirements of a narrow field instrument devoted to the observation of known sources or to transient events localized with 1 arcmin accuracy. The NFT shows unprecedented sensitivity in its energy pass-band (see paper by Frontera et al. in these proceedings).

Experimental activities on the NFT are currently conducted at the University of Ferrara together with INAF-OAS Bologna and CNR-IMEM Parma. The realization of a prototype of a lens petal is expected to be developed in a relatively short time. In particular, we are tackling the tasks of improving the quality of the crystals and the assembly method. The crystals are bent with a lapping machine that allows a highly reproducible process. Instead, the latter aspect involves a modular approach, in which the lens is composed of petals which, in turn, are made of modules. After their assembly, the modules need to be co-aligned through a system made of micro screws which is being designed within the project.

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References

Buffagni, E., Bonnini, E., Zappettini, A., et al. 2013, Proc. SPIE, 8861, 88610E

Frontera, F., Loffredo, G., Pisa, A., et al. 2007, Proc. SPIE, 6688, 66880N

Harrison, F. A., Craig, W. W., Christensen, F. E., et al. 2013, ApJ, 770, 103

Nandra, K., Barret, D., Barcons, X., et al. 2013, arXiv:1306.2307

Piro, L., Natalucci, L., & AHEAD Consortium. 2015, in Exploring the Hot and Energetic Universe: The first scientific conference dedicated to the Athena X-ray observatory, 74

Virgilli, E., Frontera, F., Valsan, V., et al. 2011, Proc. SPIE, 8147, 81471B

Virgilli, E., Valsan, V., Frontera, F., et al. 2017, Journal of Astronomical Telescopes, Instruments, and Systems, 3, 044001