ASTENA Polarization capabilities

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The ASTENA NFT instrument (baseline):

Laue Optics
• Pass-band: 50 - 700 keV
• 20 m focal length
• Si 111 + Ge 220
• Crystal dimensions: 30x10x (optimized thickness) mm³
• 43 rings
• $R_{\text{in/out}} = 18 \text{ cm} / 149 \text{ cm} (3 \text{ m diameter})$
• Filling Factor 93%
• Total Geometric Area 69800 cm² $\sim 7 \text{ m}^2$ !!
The ASTENA NFT instrument (baseline):

Focal Plane Detector

Main requirements
• Detection efficiency > 80% @ 700 keV
• 3D imaging capability = 400 μm (x, y, z direction)
• Fine spectroscopy response 1 % @ 511 keV

Geometrical characteristics:
❖ Material: CZT
❖ CZT units: Anode drift strip and orthogonally segmented cathode in PTF
❖ 4 layers of 8x8x2 cm³
❖ Sensitive volume 8x8x8 cm³
### ASTENA-NFT Heritage (GRI) Polarimetry Simulation

<table>
<thead>
<tr>
<th>Laue Lens</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu Mosaic Crystals</td>
<td>1.5x1.5x0.2 cm³</td>
</tr>
<tr>
<td>Focal Lenght</td>
<td>100 m</td>
</tr>
<tr>
<td>Ext. Diameter</td>
<td>2.5 m</td>
</tr>
<tr>
<td>Pass band</td>
<td>100-600 keV</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Focal Plane</th>
<th>Dimension</th>
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</thead>
<tbody>
<tr>
<td>Top Layer</td>
<td>16x16x0.5 cm³</td>
</tr>
<tr>
<td>N. 3 Bottom Layers</td>
<td>16x16x2 cm³</td>
</tr>
<tr>
<td>Pixel Size</td>
<td>2.5x2.5 mm²</td>
</tr>
<tr>
<td>Layer pixelisation</td>
<td>64x64</td>
</tr>
<tr>
<td>Gap between layers</td>
<td>20 mm</td>
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</tbody>
</table>

GRI like Laue Lens Telescope main characteristics

Double event distribution maps obtained for each CZT stack layer when irradiated by a 400 keV Laue lens PSF fully polarized source in axis. The polarization direction is indicated.
Relative efficiency of double events generated by a fully polarized Laue lens PSF source distribution for each stack detector layer.

Simulated modulation $Q$ factor obtained for each layer and the $Q$ factor obtained integrating the contribution of all layers, for an on-axis.
ASTENA-NFT: Improving Hard X ray Polarimetry

Determinant characteristics for improved polarimetric performance of the ASTENA NFT:

1. Laue lens using curved crystal tiles (Ge, Si): PSF Ø = 2 mm (figure)
2. CZT focal plane with fine spatial resolution: voxel size = 0.4x0.4x0.4 mm³
3. CZT focal plane with fine spectroscopy: 1% FWHM @ 511 keV

Advantages for polarimetry measurements sensitivity:

1. Small amount of background
2. High modulation factor of the detector
3. Reliable Compton event selection and filtering
Two scattering maps at 200 keV and with polarisation axis 30° inclined with respect to the detector ones:

**left** Imarad CZT with 2.5 pixel pitch, 5 mm thick, 2.75x2.75 mm²;

**right** Caliste CZT module with 0.58 mm pixel pitch, 2 mm thick, 9.3x9.3 mm²

MC Modulation curve for two different discretisation in voxel of the same volume obtained by selecting scattered events for which the two hits have the same coordinate in z (along the detector thickness)
The experimental Caliste modulation curve at 200 keV (blue line).
The modulation factor Q measured with Caliste, selecting double events with energy in the 139–148 keV window, was ~0.78, i.e. very close to the theoretical expected values of 0.9 (red line).
In black, the data obtained by a simple Caliste Monte Carlo model results are statistically consistent with the experimental results.

The modulation curve obtained with CZT Caliste 256 at 300 keV (98% linearly polarized) for different polarisation plane orientation; Double events selection within 181–197 keV.

The selection correspond to events that scatter at 90° : i.e. the optimal condition for polarimetry.
The reconstructed polarisation plane direction versus the real beam polarisation plane direction for two energies, and the comparison between the sensitivity to polarisation degree evaluated from ESRF data for the POLCA (IMARAD) and the CZT Caliste detectors.

The large difference between the two results is a further confirmation of the modulation factor improvement achievable with a fine spatial resolution coupled with fine spectroscopic performance.
Expected effective area with energy of a Laue lens made with bent Ge(111) tiles, 90 - 600 keV passband, and focal length of 20 m. (red) nominally bent and perfectly arranged tiles; (blue) crystals radially distorted in the range ±6 m with respect to nominal value of 40 m and uniformly misaligned in the range ±30 arcsec.

The expected lens background at LEO, compared with the INTEGRAL/SPI measured background, for a CZT focal plane with previous given main characteristics.
ASTENA-NFT: MDP preliminary evaluation

Polarimetric performance achievable by a 20 m focal length broadband (90-600 keV) Laue lens telescope with a fine (0.4 mm) spatial resolution focal plane in a LEO orbit.

(top) MDP vs observation time for a 10 mCrab source and two representative (an conservative) modulation factors (Q=0.3 all double events, Q=0.6 double events selected using both hit’s energy and coordinates);

(right) MDP vs source intensity (100% polarized) for a $10^5$ s observation.
ASTENA-NFT: Next step for Polarimetric performance study

The next steps to evaluate a reliable figure of merit for polarisation capabilities of the ASTENA NFT instrument will foresee:

- Finalizing the focal plane detector mass model design.
- Performing simulation of polarized different sources by using the available and verified ray-tracing tools to obtain the photon spatial and energy distribution on the focal plane detector (PSF files).
- Performing the GEANT4/MEGALIB simulation of the focal plane detector using the PSF files.
- Analysing MC data obtained with un-polarised source to study pixel geometry systematics.