LARIX-A Facility

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The LARIX (LARge Italian X-ray facility) laboratory is located in the Scientific-Technological Pole of the University of Ferrara in an underground building that includes a 100 m long tunnel with two large experimental rooms on each side. It hosts two hard X-ray installations, the 12 m long LARIX-A located in the experimental room A, and the 50 m long gamma-ray facility, LARIX-T, installed in the tunnel.

In this document we present a description of the LARIX-A. The facility is equipped with a x-ray tube, providing a total power of 1.8 kW with voltages up to 225 kV, and a Bragg-Bragg fixed exit monochromator, providing a monochromatic beam from 10 up to 200 keV. Thanks to the facility flexibility is ideal for performing linearity tests of hard X-ray detectors (Zavattini et al. 1997), for reflectivity measurements of X-ray reflector samples (Frontera et al. 1991, Frontera et al. 2008) and to perform ground calibration of entire hard X-ray experiments (Loffredo et al. 2003, regarding the JEM-X calibration for the INTEGRAL satellite)

We provide below a description of the instrumentation and software in the facility which is available for the national and international community, via collaborations or transnational access programs, such as AHEAD.

1 LARIX-A Overview

LARIX-A facility features a 12 m beamline and is equipped with the following instrumentation:

Source
● X-ray tube: Bosello: 9 - 225 keV; max. Power 1.8 kW ● X-ray beam path environment: vacuum system and helium
Optics
● Bragg-Bragg fixed exit monochromator. 2 × Si (111) ● Beam size: from 0.2 x 0.2 to 20 x 20 mm
Sample environment
● class 10^5 clean room ● Sample Holder: moves in 3 linear axis and 1 rotation axis ● Thermal control system with a stability of ±2°
Detectors
● Spectrometer: ORTEC nitrogen-cooled HPGe ● Imager: Thales 1024 x 1024 px; 0.3 mm pitch

The control room is separated from LARIX A by means of a wall 2.1 m high, made of Al+Pb. From the control room, it is possible to operate all the instrumentation of the beamline, while several BNC, RS-232, USB and Ethernet cables of different lengths are also available for the instrumentation of the users.

Four meters of the total beamline are contained inside a class 10^5 clean room where the sample holder and detectors are located. The clean room has a surface area of 12 m^2 and a height of 2.1 m. The room is equipped with a thermal control system with a stability of ±2°.

Figure 1 features pictures of the beamline components while, Figure 2 shows a CAD drawing of the beamline and Figure 3 shows the top view of the facility including the 3 rooms where the beamline extends, the control room and a small workshop with the basic mechanical and electrical engendering tools. If any custom design part is needed, it can be also made in the UniFe mechanical workshop depending on the workshop availability.

The laboratory is equipped with an UPS system where all the LARIX-A systems are connected. Several power outlets connected to it are also available for the users' instrumentation.

An overhead travelling crane (1000 kg weight–bearing, 20 m long) is installed parallel to the rails and can be used to place the instruments on the beamline.

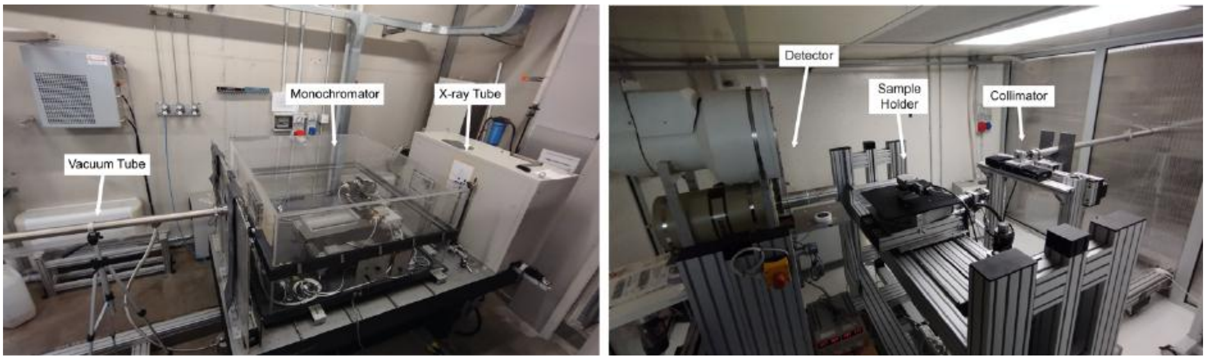


Figure 1: Pictures of the LARIX-A facility. Left: the room with the X-ray tube and the monochromator. Right: the clean room, where the sample holder and the detector carriages are placed.

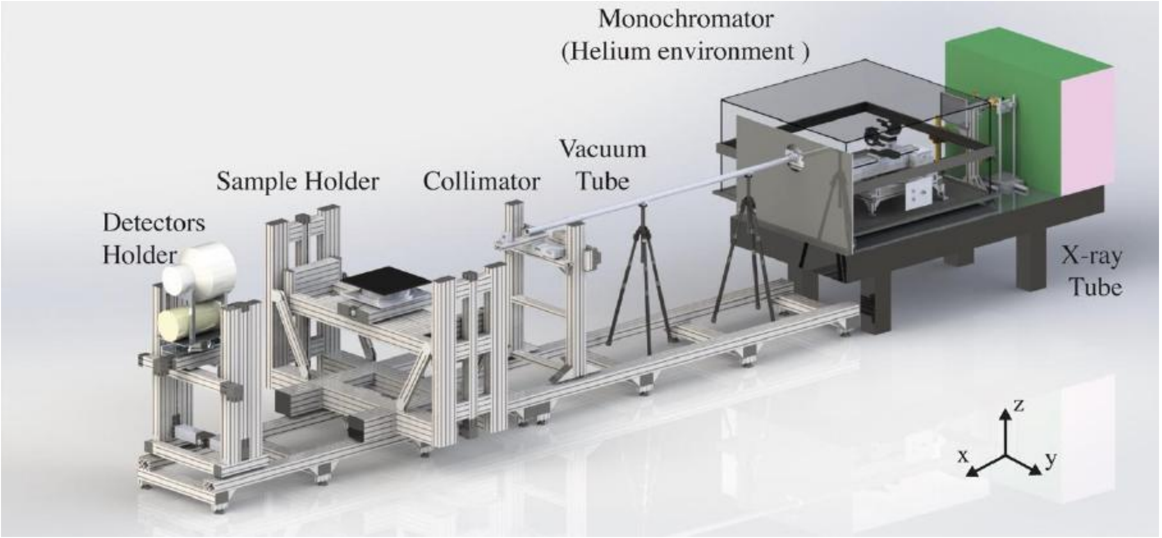


Figure 2: 3D CAD drawing of the recent configuration of the LARIX-A facility. From right to left: the X–ray tube, the monochromator system, the sample holder and the detector holder.

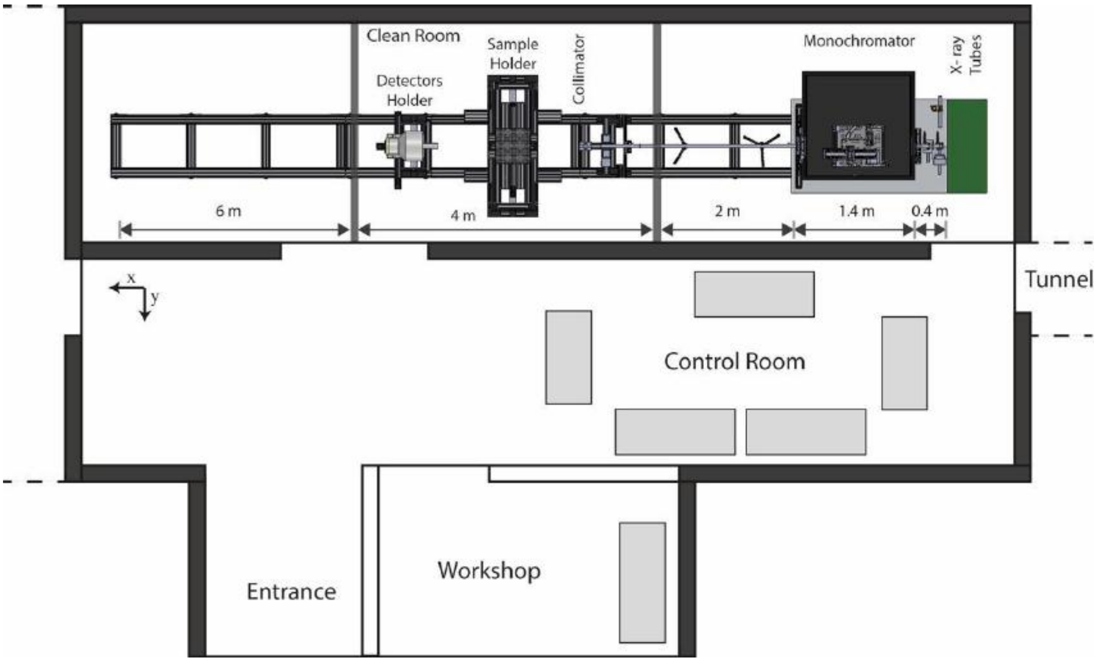


Figure 3: LARIX-A top view.

2 Equipment

2.1 X-Ray Tube

The X-ray tube available at the facility is produced by Bosello and is mounted onto an optical table located inside a well shielded (35 mm thick Lead) environment. The tube is equipped with a Tungsten anode and operates from 20 to 225 kV. It has two possible focal spot modes: a *fine mode*, with a focal spot of 0.4 mm diameter, and a *broad mode*, with focal spot of 1 mm diameter. The maximum power in the fine mode is 800 W, with current ranging from 0.2 to 10 mA, while in the broad mode the maximum power is 1800 W, with current from 0.2 to 20 mA. The output window is equivalent to a 0.8 mm thick Beryllium foil and fixes the low-energy threshold of the X-ray at 9 keV.

By means of remotely controlled manipulators, the X-ray tube can be moved in the vertical and horizontal directions, perpendicular to the X–ray beam. The minimum step size is 8µm for horizontal translations, 24µm for vertical motions, Figure 4.

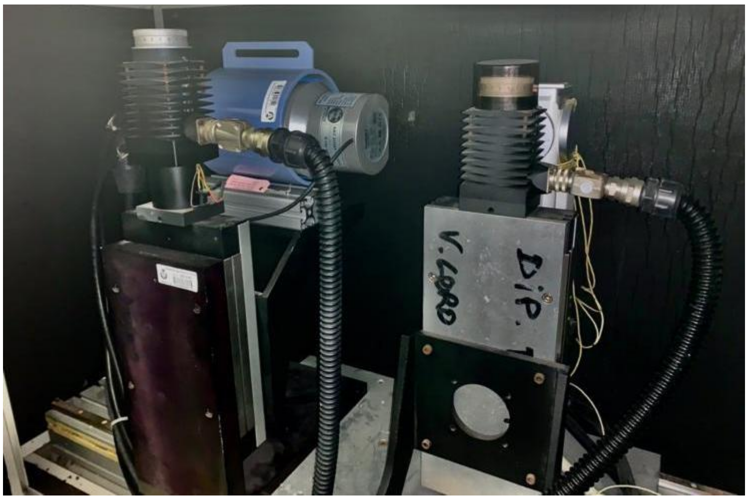


Figure 4: X-ray Tubes: Bosello on the left side of the picture and Philips on the right side (not in use).

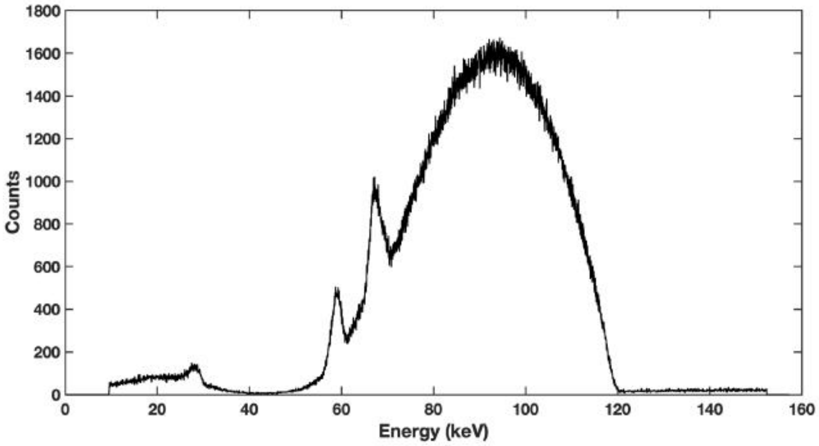


Figure 5: Polychromatic beam obtained with the Bosello X-ray tube at 120 kV and 0.2 mA with an x-ray filter of 1 mm Sn to avoid detector pile-up. The visible peaks are the Kα and Kβ of the Tungsten, at 59 keV and 67 keV respectively, and the Sn activation at 25 keV and 28 keV for the Kα and Kβ respectively.

2.2 Monochromator

The LARIX-A facility employs a monochromator in Bragg-Bragg configuration, Figure 6. This configuration involves the placement of two crystals in parallel on a rotating table centered at a fixed point. Each crystal gives a symmetric Bragg reflection: the first crystal has the role of selecting the desired wavelength from the incident polychromatic beam; while the second crystal re-directs the monochromatic radiation along a direction parallel to the incident beam. This results in a fixed-exit beam independently of the photon energy selected – the distance between the incident beam and the double diffracted monochromatic beam is always *2p*. The distance *p* is the distance between the incident beam and the centre of rotation and is selected according to a trade-off between different parameters as the efficiency, system mechanical limitations and background.

The monochromator uses a total of 8 PI motorized stages (Figure 7 left) to monochromatize the desired energy. A software, designed in Labview, does all the required movements by just selecting the energy (Figure 7 right). The crystals used are made of Si(111), size 80 x 40 x 2 mm, and with a mosaic structure (30” spread) in order to get a significant intensity of the monochromatic line.

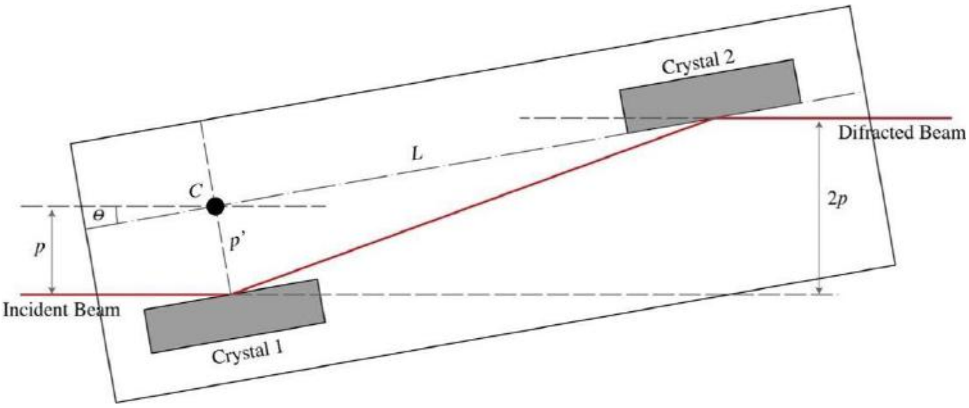
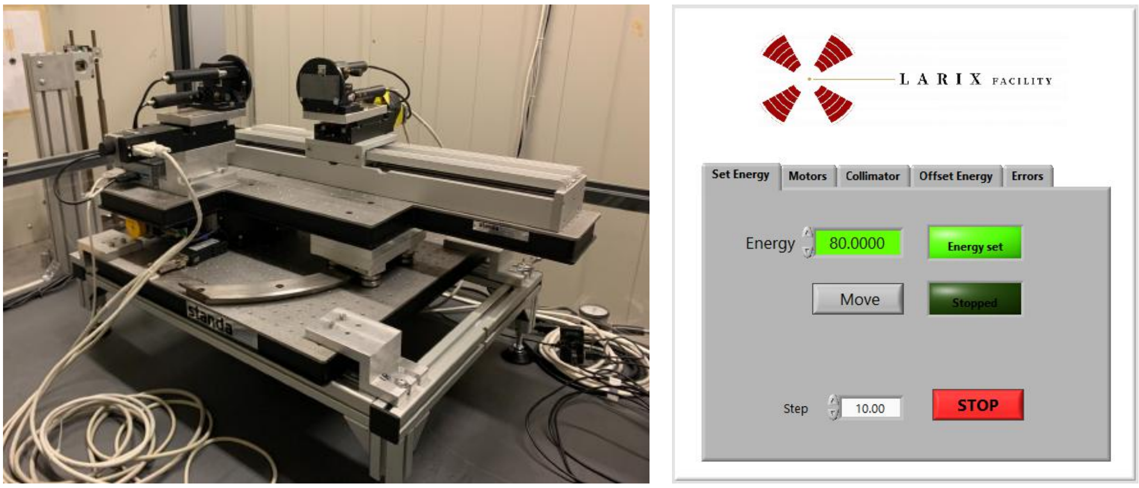


Figure 6: Top of view schematic of the Bragg-Bragg fixed exit configuration.



Energy 80.0000

Step 10.00

Figure 7: Left: Picture of the monochromator system in the LARIX-A facility. Right: Control panel of the Labview software which drives the monochromator.

2.3 X-ray beam path environment

To decrease the x-ray absorption due to the air along the path we adopted a hybrid solution using helium and vacuum.

The monochromator is placed inside the vacuum tight box made of Plexiglass with size 1.3 x 1.4 m. Inside, the air is replaced by helium to get a 1 atm helium environment. Helium is the best choice due to its very high transparency at low energy (few keV).

The remaining path of the beam is under vacuum. One cylindrical aluminium tube with 40 mm diameter is placed between the monochromator and sample holder inside the clean room. The length of the tube can be adjustable by coupling tubes of different sizes available in the lab. The X–ray entrance and exit windows of the vacuum tube are made of polyethylene terephthalate (PET) with a very high transparency down to low energies (few keV). The vacuum pump available allows to get ~10^{-4} mbar inside the tubes.

2.4 Collimators and filters

A set of three collimators limits the divergence and the size of the X–ray beam. The first collimator is placed in front of the X-ray source in a fixed position and its opening can be manually adjusted from a minimum of 0.1 x 0.1 mm^2 to a maximum of 20 x 20 mm^2. The second collimator, with the same minimum and maximum opening size, is placed after the monochromator. The third one is placed just before the sample to have an adjustable and parallel beam incident on the sample. It can be manually adjusted from 0.1 x 0.1 mm^2 to 20 x 20 mm^2 using precision feeler gauges.

The intensity of the X-ray tube can be attenuated by placing filters in front of the beam exit. The available filters and their thickness are listed in Table 1. (These filters are alternatives to the fixed exit monochromator).

Table 1: X-ray filters available at LARIX-A

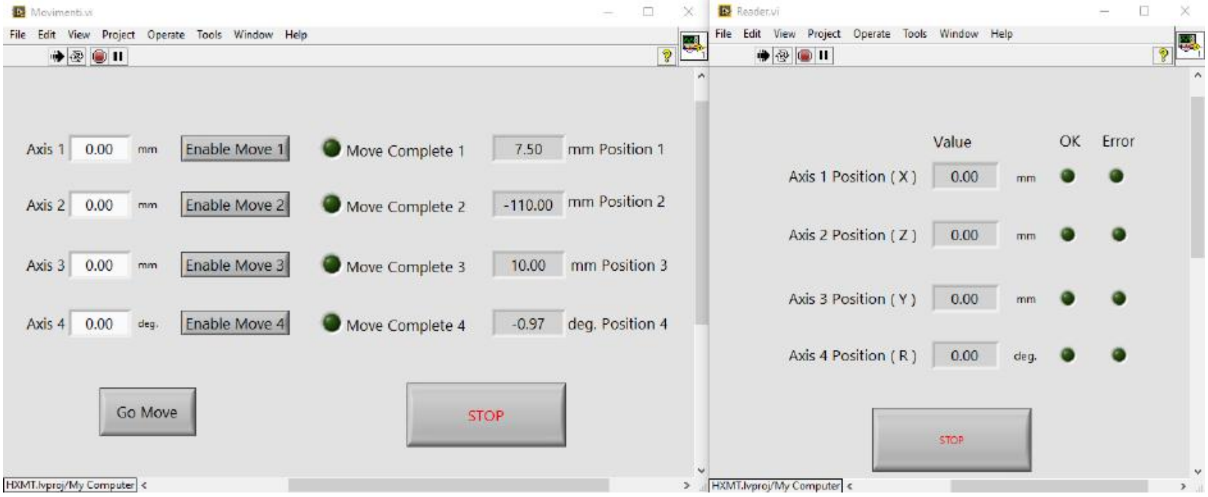
Material	***Thickness***
High Purity Aluminium	5 mm
Brass	5 mm
High Purity Copper	3 mm
Tin	1 mm
Lead	1 mm

2.5 Sampler Holder

The sample or detector to be tested is positioned on an optical table equipped with 4 motors allowing it to move it in three perpendicular directions (X,Y,Z) and rotate it around the vertical axis (z axis), Figure 9. An angular position accuracy of 3” can be achieved with a repeatability of 1”. The travel range for the y and z axis is 70 cm and 20 cm for the x axis. The sample carriage can also move manually along the rail (x axis).

A standard 45 x 45 cm^2 optical table with 25 mm spaced holes is attached on the top of the sampler holder to fix the samples. A software made in LabView allows the user to control all the 4 motors, Figure 10.

Figure 8: Picture of the sample holder.



Axis 1 0.00 mm ● Move Complete 1 7.50 mm Position 1
Axis 2 0.00 mm ● Move Complete 2 -110.00 mm Position 2
Axis 3 0.00 mm ● Move Complete 3 10.00 mm Position 3
Axis 4 0.00 deg. ● Move Complete 4 -0.97 deg. Position 4

	Value		OK	Error
Axis 1 Position (X)	0.00	mm	●	●
Axis 2 Position (Z)	0.00	mm	●	●
Axis 3 Position (Y)	0.00	mm	●	●
Axis 4 Position (R)	0.00	deg.	●	●

Figure 9: Control panel of the Labview software which drives the sample holder.

2.6 Detectors

Two detectors are available at LARIX-A: an ORTEC Nitrogen-cooled HPGe spectrometer, with a Beryllium entrance window; and a THALES X-ray imager detector made of CsI scintillators coupled with a CCD camera, granting a very fine (300 microns) pixel pitch. The main characteristics are in Table 2 and Table 3 respectively.

Table 2: Characteristics of the HPGe Spectrometer available at LARIX-A.

Detector Diameter	25 mm
Detector thickness	13 mm
Beryllium Window Thickness	0.254 mm
Energy Resolution (FWHM)	300 eV @ *5.9 keV* 545 eV @ *122 keV*

Table 3: Characteristics of the Thales imager detector available at LARIX-A.

Detector Diameter	30 cm
Pixel Pitch	300 µm
Pixel Number	1024 x 1024
Maximum Integration Time)	2 sec
Detection Efficiency	79% @*60 keV* 32% @*100 keV*

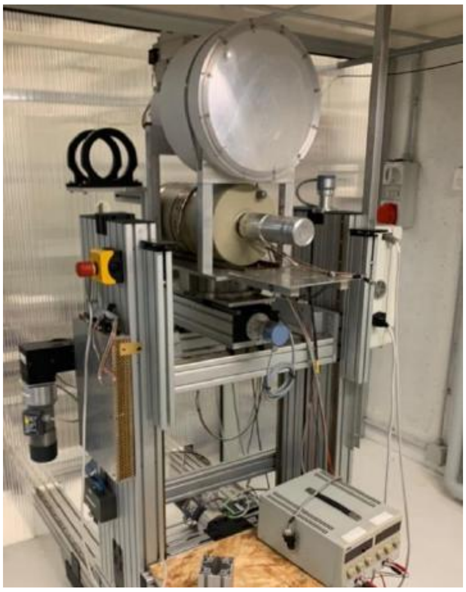


Figure 10: Picture of the Detectors holder carriage with the imager on top and spectrometer on bottom.

3 Performances

3.1 Beam Flux and FWHM

The performance of the LARIX-A monochromator was evaluated with the HPGe detector by making a scan in the energies between 12 keV to 190 keV. For these measurements the collimator 2 was set to a size of 1x1 mm^2 and the detector was placed ~5m of the collimator without any more instruments in between. The acquisition time was 120s for each energy. The typical spectrum of the beam detected with a HPGe detector is shown Figure 12, and in Figure13 is the measured flux and FWHM as function of the energy.

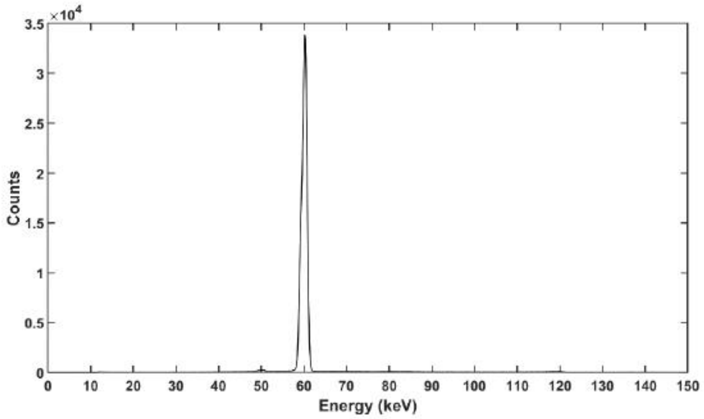


Figure 11: Spectrum of the monochromatic x-ray beam at 61.2 keV detected with the HPGe detector.

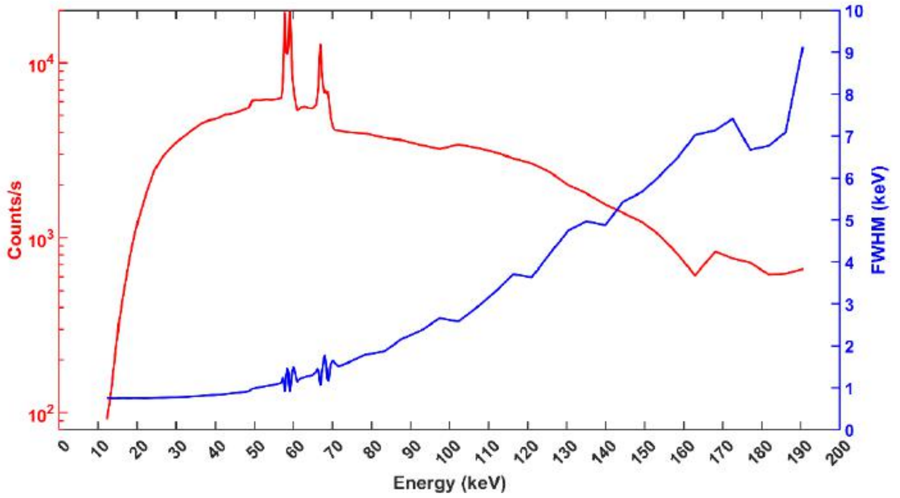


Figure 12: Left axis (red): Flux as function of the energy of the LARIX-A monochromatic beam. Right axis (blue): Energy FWHM as function of the monochromatic energy.

4 Last experiments in LARIX-A

4.1 Measure of the non-linear response of the GAGG:Ce scintillator for the HERMES mission (2022)

HERMES-SP (High Energy Rapid Modular Ensemble of Satellites - Scientific Pathfinder) is a mission concept based on a constellation of nano-satellites in low Earth orbit (LEO), hosting new miniaturised detectors to probe the X-ray temporal emission of bright high-energy transients such as Gamma-Ray Bursts (GRB) and the electromagnetic counterparts of Gravitational Wave Events (GWE) [1].

The HERMES detector is based on the so-called “siswich” concept, exploiting the dual intrinsic sensitivity of silicon to both soft X-rays and scintillation light, aiming at designing a compact instrument with a very wide sensitivity band, from 2 keV up to 2 MeV. The detector is thus composed by an array of scintillator pixels and by SDDs, Figure 14. The SDDs are used to both detect soft X-rays, by direct absorption in silicon, and to simultaneously readout the scintillation light (high energies) [2].

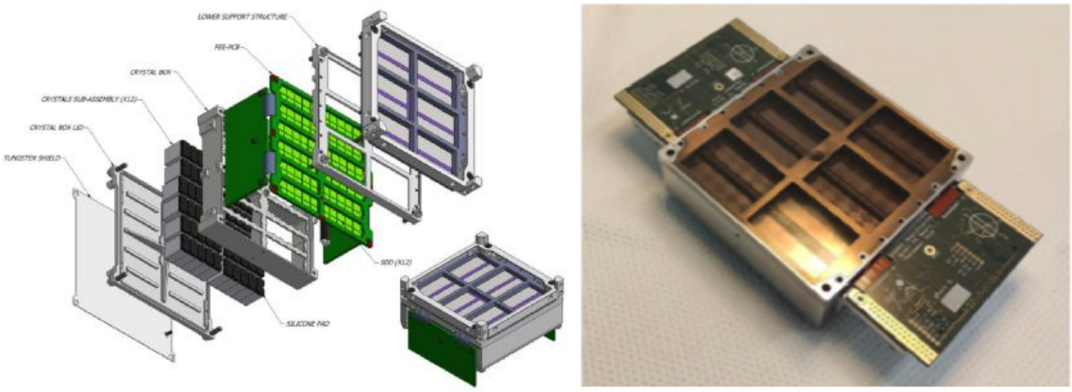


Figure 13: Left: Exploded view of the payload unit on board the HERMES nanosatellite. Right: Integrated detector assembly.

The inorganic scintillator selected for HERMES is the Cerium-doped Gadolinium-Aluminium-Gallium Garnet (GAGG:Ce). These scintillators present a discontinuity related to the k-shell of the Gadolinium at 50.23 keV. The objective of this work was to study the response, in terms of absolute amplitude and light output, of a GAGG:Ce scintillator coupled to an SDD. Due to the LARIX-A energy range (10-200 keV) we were able to study in detail this discontinuity. The prototype under test is shown in Figure 15, and consists of one scintillator crystal coupled with an SDD. Three different samples of scintillators were tested: two 6.94×12.10×15 mm^3 produced by the Japanese company C&A (the same type as those that will be used in HERMES), and one of 10×10×30 mm^3, produced by Advatech Inc., UK. The three samples were tested in the LARIX-A facility by using the monochromator beam from 20-160 keV. The samples were placed just after the monochromator, ~10 cm from the second collimator, Figure 14. The results obtained are shown in Figure 16 [3].

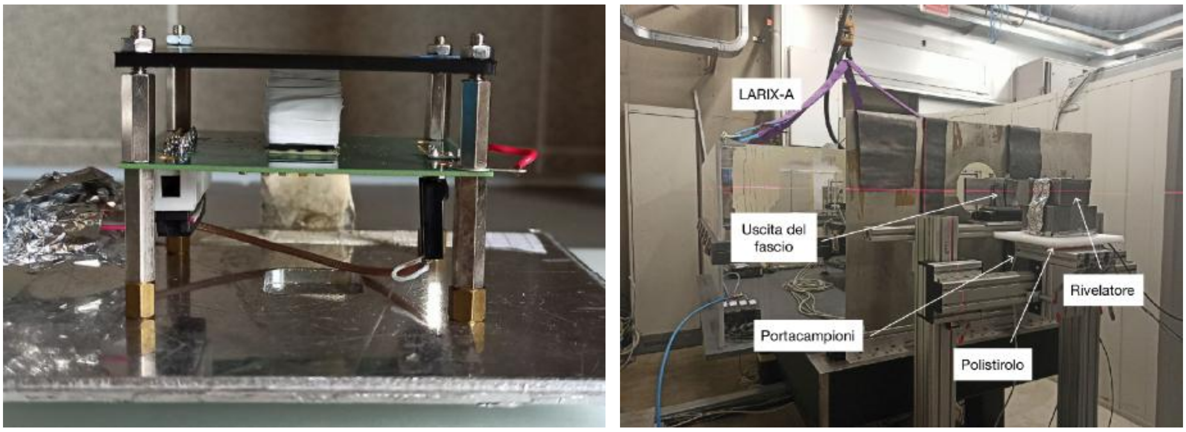


Figure 14: Experimental setup for the GAGG:Ce test campaign. The detector was placed ~ 10 cm from the second collimator [3].

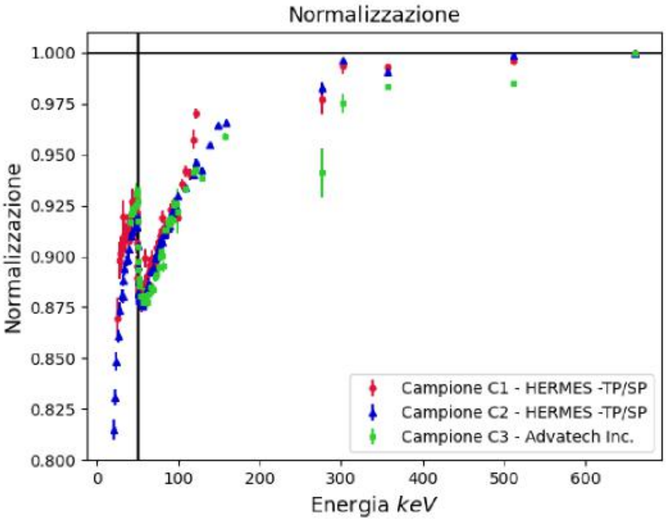


Figure 15: Normalised light output for the three samples. The discontinuity observed is related to the k-shell of the Gadolinium at 50.23 keV [3].

4.2 Crystal reflectivity measurements for ASTENA project

Hard x-/soft gamma-ray astronomy (>100 keV) is a crucial field for the study of important astrophysical phenomena such as the 511 keV positron annihilation line in the galactic centre region and its origin, gamma-ray bursts, soft gamma-ray repeaters, nuclear lines from SN explosions and more. However, several key questions in this field require sensitivity and angular resolution that are hardly achievable with present technology. A new generation of instruments suitable to focus hard x-/soft gamma-rays is necessary to overcome the technological limitations of current direct-viewing telescopes. One solution is using Laue lenses based on Bragg's diffraction in a transmission configuration, made of bent crystals of Silicon and Germanium, that diffract photons in the 50-700 keV band, with unprecedented angular resolution and sensitivity to continuum spectrum and to lines. Our studies on Laue lens are oriented to develop the technology for building the Narrow Field Telescope (NFT) on-board ASTENA, the Advanced Surveyor for Transient Events and Nuclear Astrophysics, a concept mission that we proposed for the ESA Call "Voyage 2050". The Narrow Field Telescope will be a revolutionary hard X/soft Gamma-ray focusing telescope working in the energy band 50-700 keV based on the technology of Laue lenses. The NFT will be made by a Laue lens optics of 3 m of diameter with 20 m focal length. The lens will be made of about 19500 crystal tiles of perfect Si(111) and Ge(111) of size 30×10×2 mm^3, bent to a curvature radius of 40 m [4], [5].

As an essential step in the workflow, the characterization of the crystals intended for use on the Laue lens is imperative. To achieve this goal, we installed a reflectivity measurement setup at LARIX-A, which comprises one goniometer and one rotation motor, Figure 16. While the goniometer aligns the crystal planes, the rotation motor enables us to obtain the crystals rocking curves. The central objective of this study is to assess the efficiency of bent crystals and its dependence with the curvature radius and energy, as well as comparing their performance to that of flat crystals, Figure 17.

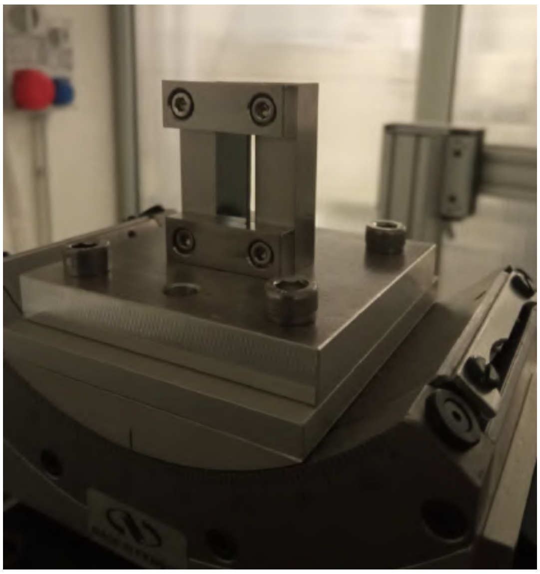


Figure 16: Crystal reflectivity setup at LARIX-A.

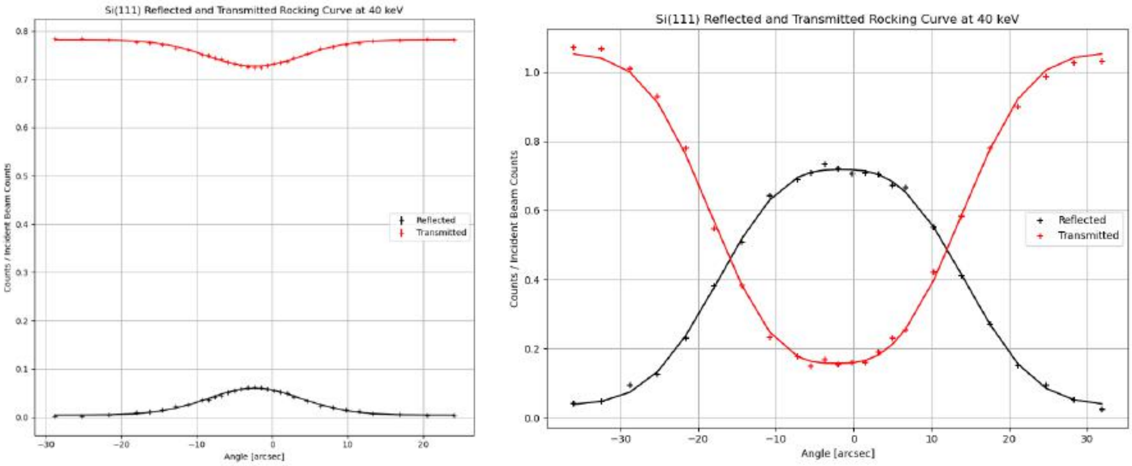


Figure 17: Rocking curves at 40 keV. Left: flat Si(111) crystal; Right: bent Si (111) crystal with 3.7 m primary curvature radius (12.6 m secondary curvature).

5 References

[1] "Hermes-SP – Progetto H2020." https://www.hermes-sp.eu/ (accessed Dec. 12, 2022).

[2] F. Fuschino *et al.*, "An innovative architecture for wide band transient monitor on board HERMES nano-satellite constellations," p. 167, 2020, doi: 10.1117/12.2561037.

[3] C. Evola, "Misura della non-linearità nella risposta dello scintillatore GAGG : Ce per la missione HERMES," Alma Mater Studiorum - Università di Bologna, 2022.

[4] F. Frontera *et al.*, "Understanding the origin of the positron annihilation line and the physics of supernova explosions," *Exp Astron (Dordr)*, vol. 51, no. 3, pp. 1175–1202, Jun. 2021, doi: 10.1007/S10686-021-09727-7/FIGURES/15.

[5] L. Ferro *et al.*, "The TRILL project: increasing the technological readiness of Laue lenses," *https://doi.org/10.1117/12.2629872*, vol. 12181, pp. 670–682, Aug. 2022, doi: 10.1117/12.2629872.