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X–ray facility for the ground calibration of the X–ray monitor JEM-X on board INTEGRAL

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Abstract. We describe the X–ray facility developed for the calibration of the X–ray monitor JEM-X on board the INTEGRAL satellite. The apparatus allowed the scanning of the detector geometric area with a pencil beam of desired energy over the major part of the passband of the instrument. The monochromatic radiation is obtained with the use of a double crystal monochromator at fixed exit. We discuss the facility performance.

Key words. instrumentation: miscellaneous – methods: laboratory – techniques: miscellaneous – instrumentation: detectors

1. Introduction

The accurate calibration of an X–ray detector for space astronomy is crucial to exploit its capabilities in flight. It allows the derivation of the instrument response function, which is needed to derive the source flux of the observed sources, the source spectrum and the best fit parameters of the spectral models assumed. For the position sensitive detectors, which see the sky through a coded mask or a focusing optics, in addition to the above information, an unbiased knowledge of the instrument gain in each point of the detector surface is very important to derive the position of the sources in the telescope field of view. Scanning with a pencil beam of monochromatic radiation is the best way to derive the instrument response function to different directions of the incident radiation. In addition, the possibility of selecting the beam energy is of key importance for deriving an accurate response function with energy. Radioactive sources for this goal are in general no so satisfactory given the limited photon energies available with them and the difficulty to get a parallel and, at the same time, sufficently strong beam.

At the Physics Department of the University of Ferrara, we have developed an apparatus which transforms a polychromatic beam provided by an X–ray tube in an almost monoenergetic beam with fixed direction independently of the photon energy desired. With this apparatus we have performed the ground calibration of the position sensitive detector of the JEM-X (Joint European X-ray Monitor) telescope on board the INTEGRAL satellite (Winkler et al. 2003). Three models of JEM-X were tested: 2 Flight Models (FM1 and FM2) and a Flight Spare (FS). Due to a discharge problem after its calibration and integration aboard the satellite, FM1 was replaced by FS. INTEGRAL was successfully launched on 17 October 2002. A description of JEM-X can be found elsewhere (Budtz-Joergensen et al. 2003; Lund et al. 2003). On INTEGRAL, JEM-X plays the important role of identifying and spectrally determining the X–ray counterparts of the gamma–ray sources detected and localized with the main instruments, the imager IBIS (Ubertini et al. 2003) and the spectrometer SPI (Vedrenne et al. 2003). JEM-X is made of two coded mask imaging telescopes, each with a nominal energy passband from 3 to 35 keV and arcminute angular resolution in its field of view of 13.2° × 13.2° (full width at zero response), which is obtained with a graded shield square collimator. Each detector consists of a position sensitive gas proportional counter with a micro-strip readout system. The coded mask is located at a distance of 3.4 m from the detectors. The gas is a mixture of 90% Xenon and 10% CH_4 at a pressure of 1.5 atm. The X–ray entrance window is made of beryllium 0.25 mm thick.

Here we present a description of the X–ray facility and its performance.

2. The Ferrara X–ray facility

A description of the X–ray facility in the version which was operative since early nineties was reported by Frontera et al. (1993), while the upgrading project of this facility for the ground calibration of the JEM-X detectors can be found

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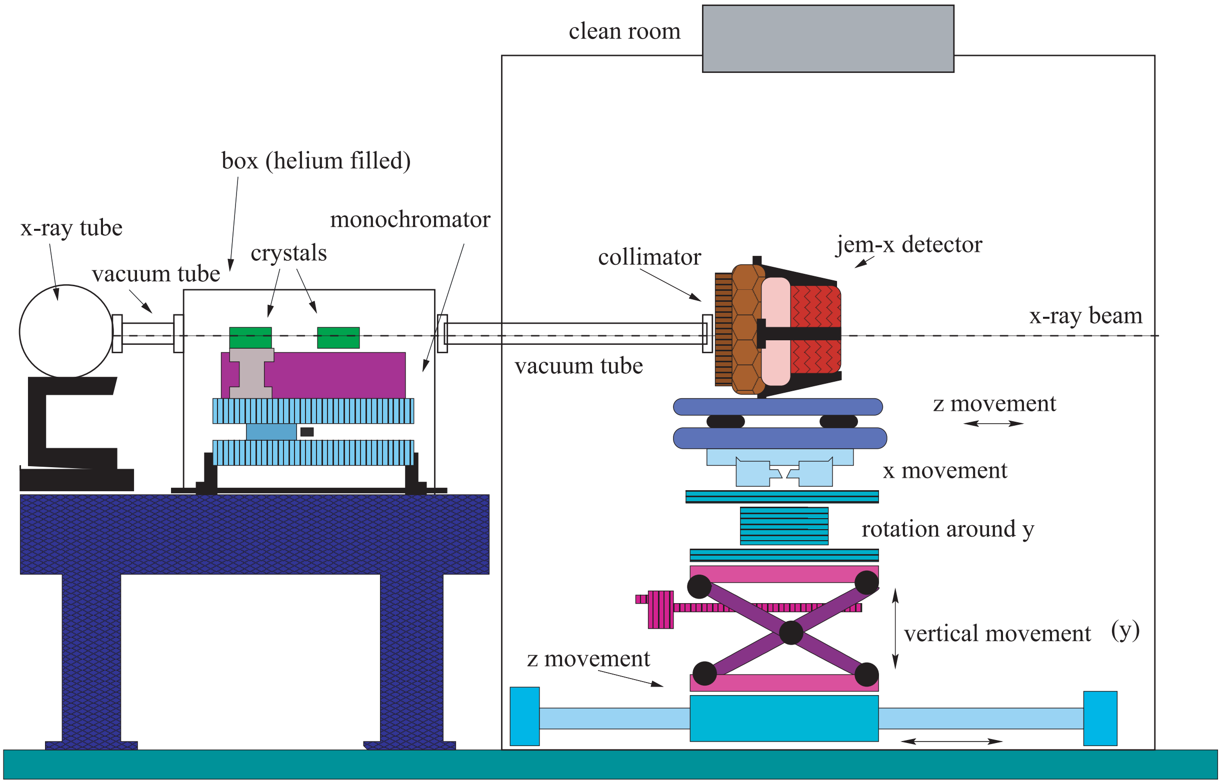

Fig. 1. Sketch (not to scale) of the Ferrara X–ray facility. From the left: the X–ray tube, the monochromator system, the platform which holds the JEM-X detector. The X–ray beam travels partially within an evacuated tube and partially in a helium atmosphere.

elsewhere (Pelliciari et al. 1999, 2001). For this calibration, the facility was equipped with two X–ray tubes, a monochromator system, and a platform to hold the JEM-X detector. The platform and thus the JEM-X detection unit to be tested were located within a clean room. A CdZnTe X–ray detector was used to calibrate the beam energy. Figure 1 shows a sketch (not to scale) of the the X–ray facility and its main subsystems. In the following sections we give a description of each subsystem.

2.1. The X–ray sources

Two X–ray sources were available for the JEM-X calibration. They are the two X–ray tubes mounted onto an optical table and powered by independent high voltage supplies. Both tubes can be moved up and down and translated along a direction perpendicular to the X–ray beam. The minimum step size is 8 μm for horizontal translations, 24 μm for vertical motions and 30″ for rotations around the vertical axis.

One of the tubes is equipped with a Molybdenum anode, with its voltage which can be varied from 20 to 60 kV and the circulating current from 10 to 60 mA. The other tube is equipped with a tungsten anode, with its voltage which can be set in the range from 40 to 140 kV and its current from 0.1 to 5 mA. The X–ray output window of the first tube is equivalent to a 0.3 mm thick beryllium foil, while that of the second tube is equivalent to a 1.5 mm thick aluminium foil. The window thickness fixes the low energy threshold of the X–ray beam: about 6 keV with the first tube, 15 keV with the second. Given that the 6 keV beam intensity resulted to be not adequate for the JEM-X calibration, we made use of a strong radioactive source of Fe^{55} incapsulated in a small box with a slit. The source was positioned along the path of the beam coming from the X–ray tubes.

2.2. Monochromator

The polychromatic beam provided by either X–ray tube was monochromatized with a double-reflection, separated crystal diffractometer. The principle of operation of the monochromator and its advantages are discussed by Mills & King (1983). One of its main features is that it provides a fixed-exit beam independently of the photon energy selected. Two geometrical configurations of the reflecting crystals are possible with this fixed-exit monochromator: Bragg–Bragg and Laue–Bragg (Mills & King 1983). We adopted the first to meet the limitations of the available crystals (see below). In the adopted configuration, the monochromator makes use of two parallel crystal analyzers, each giving rise to a symmetric Bragg reflection. The first crystal (No. 1) has the role of selecting the desired wavelength from the incident polychromatic beam, while the second crystal (No. 2) re-directs the monochromatized radiation along a direction parallel to the incident beam. In order to get a fixed-exit direction of the double-reflected beam, the first crystal has to be properly translated perpendicularly to its X–ray reflection surface. The monochromator is tunable over a wide range of X–ray energies (6–120 keV), by rotating the crystals 1 and 2 and translating the crystal 2 along the direction parallel to its external surface.

In order to maximize the brightness of the monochromatized beam, mosaic crystals are the best solution. We made use of Si(111) crystals, which showed a mosaic structure for a small depth of their thickness, so they exhibit better performance in reflection configuration. These crystals were specially developed for this project (Pareschi et al. 1997). The measured angular spread in the reflection configuration was ≈30 arcsec (FWHM). The crystals could be rotated around the vertical and tilted around an horizontal axis in order to match the incident polychromatic beam from the X–ray source. Just before the first crystal a tungsten collimator with adjustable aperture in two orthogonal directions could change the beam size. The chosen collimator aperture was 0.5×0.5 mm. From the crystal spread and divergence of the polychromatic X–ray beam (about $3'$) impinging on the crystal 1, the expected energy width ΔE of the exit beam ranges from 0.1 to 2.1 keV (FWHM) in the 10−50 keV band, respectively.

A similar collimator was positioned after the monochromator and another one close to the JEM-X detector under test. The final cross section of the pencil beam was 0.5×0.5 mm^2. In this way, the focal spot was comparable to the expected JEM-X position resolution.

2.3. X–ray beam path environment

To decrease the X–ray absorption due to the air along the beam path, two devices were adopted. The monochromator system was positioned within a plexiglass box, where helium was pumped. With a mass-spectrometer, we verified that, during the measurements, the amount of helium in the box was ~90% of the total gas mass. The X–ray entrance and exit window of the helium box was made of polyethylene terephthalate (PET) 75 μm thick with a very high transparency at the calibration energies. Outside the helium box, the X–ray beam traveled in evacuated tubes (10^{-3} mbar) up to the JEM-X detector.

2.4. Clean room

The JEM-X detector under test was located within a clean room of class better than 100 000. The room floor was covered with a conductive layer with a resistance of about $10^6\,\Omega$ to avoid electric discharges.

2.5. JEM-X mounting platform

To perform the calibration of the JEM-X position sensitive detectors, as above discussed, a scan of the surface area by the pencil beam was requested. To this end, the JEM-X detector was positioned on a special platform. The platform could be moved in three perpendicular directions (X, Y, Z) and rotated around the vertical axis. The minimum step size of the translation stages was 1 μm, with linear speed from 0.025 to 8 mm/s. The travel stages were 300 mm long. The platform could support 95 kg with angular deformation lower than 0.3 mm/m (the mass of each JEM-X detector is about 30 kg). The table movements were monitored with an external system of optical encoders of 5 μm sensitivity. In this way the true position of the detector and the performances of the XYZ table could be measured. The angular deformation of the table during the movement of the detector on the horizontal stage perpendicular to X–ray beam was ≤0.5 mm, a figure consistent with the JEM-X requirements.

The rotation around the vertical axis was requested for various reasons: to check the perpendicularity of the X–ray beam to the detector cross section, to perform the position scan of the detector at different incident angles of the X–ray radiation, and to test the angular response of the collimators. The angular stage had a minimum step size of $0.45''$.

2.6. CdZnTe detector

A cadmium zinc telluride (CZT) X–ray detector, Peltier–cooled to 250 K, calibrated with an Am^{241} radioactive source, was used to monitor the intensity and the energy of the pencil beam incident on the JEM–X detector. The CZT has the advantage of being compact and highly efficient to the beam photon energies selected. In addition it shows a very good energy resolution (0.94 keV at 60 keV). The CZT was supplied by Amptek (XR-100T-CZT model). Its cross section is 5×5 mm^2, its thickness 2 mm, while its X–ray entrance window is made of a 0.25 mm thickness beryllium layer.

2.7. Data acquisition system

The X–ray facility was managed by a remote console room, by means of three well equipped Personal Computers. One of them managed the monochromator system and the power supply of the X–ray tube, the other PC checked the movements of the XYZ table and the optical encoders, the last PC was devoted to the on-line data analysis. An additional PC was used to manage the communications with the JEM-X Electrical Ground Support Equipment (EGSE).

An 8 s clock pulse from the JEM-X EGSE was recorded in the same file which contained the XYZ table positions versus time. The clock was used to tag the events recorded by JEM-X with the XYZ table position. The accuracy of temporal synchronization was better than 50 ms. The PCs and the motor drivers were connected to the UPS (Uninterrupted Power Supply System) in order to protect them in case of short-duration interruption of the electrical power. All PCs were connected in a network.

3. Facility performance during the JEM-X ground calibration

The ground calibration of the JEM-X detectors required two types of scans, position scans and energy scans. With the position scans, the entire detector surface was calibrated at 3 different energies in the 6−50 keV energy range. With the energy scans, the gain of the instrument with energy from 6 to 50 keV was derived in 4 different positions of the detector area.

Before the instrument calibration, a calibration of the X–ray facility was performed. To this end, we performed an energy scan from 11 keV up to 51 keV with steps of 2−3 keV. The CZT detector was positioned in the same location of the

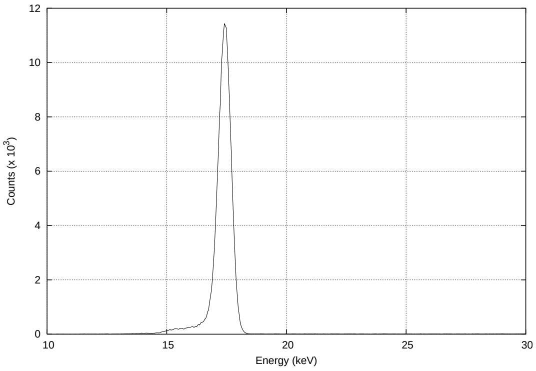

Fig. 2. Spectrum of the monochromatized X–ray beam at 17.4 keV, which was available for the JEM–X calibration.

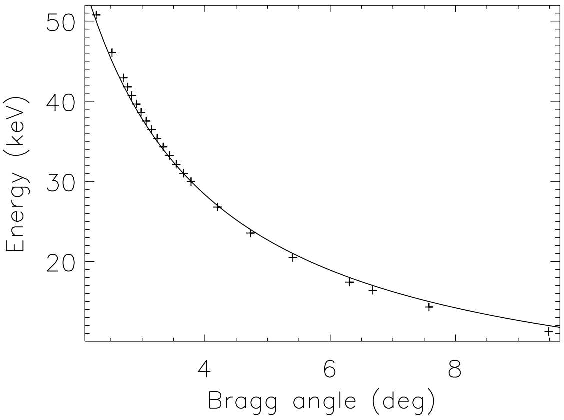

Fig. 3. Energy measured of the X–ray beam as a function of the Bragg angle of the crystal No. 1 of the double–crystal monochromator. The expected energy, derived from the Bragg law, is also shown.

JEM-X detector under test. For each selected diffraction angle of the monochromator, the photons detected by the CZT detector were pulse height analyzed and the spectra stored. As an example, Fig. 2 shows the typical spectrum of the beam detected with the CZT for a fixed Bragg angle. Each spectrum was fitted with Gaussian function in order to evaluate the centroid energy and the Full Width at Half Maximum (FWHM) of the Gaussian peak. The detector background level, even if negligible, was subtracted from each spectrum. The centroid energy derived as a function of the diffraction angle is shown in Fig. 3. For comparison, the nominal photon energy expected from the Bragg law is also shown. As can be seen, expected and measured photon energies are consistent with each other within 1 keV. The deviation from the expected curve is likely due to the motor positioning accuracy of the monochromator system. We used the measured values to establish the beam energy at different Bragg angles of the monochromator. Figure 4 shows the FWHM of the monochromatized radiation with energy. The values shown have been corrected for the energy resolution of the CZT detector. The FWHM behaviour is consistent with that expected.

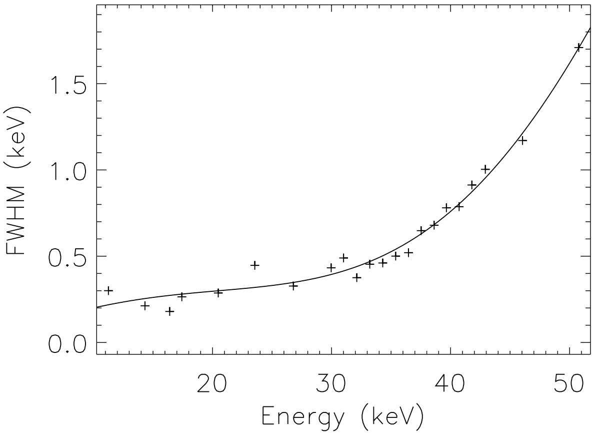

Fig. 4. Intrinsic FWHM of the X–ray beam energy vs. energy. The values are corrected for the energy resolution of the CZT detector. Continuous line gives the best fit curve of the data.

4. Conclusions and prospects

The Ferrara X–ray facility fully satisfied the requirements of the JEM–X ground calibrations. Its good performance was also exploited, soon after these calibrations, for deriving the X–ray transparency of the IBIS support mask. In the near future the X–ray facility will be moved to the new building of the Physics Department of the University of Ferrara, where it will be extended in energy (up to 400 keV) and length (100 m beam line) to become also suitable for calibration of hard X–ray optics.

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