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ORIGINAL ARTICLE

Introduction to a calibration facility for hard X-ray detectors

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Abstract This paper introduces the current configuration of the Hard X-ray Calibration Facility (HXCF) in 2014, which is used to calibrate the high energy X-ray detectors that will be onboard the Hard X-ray Modulation Telescope (HXMT) satellite, China's first astronomy satellite. The HXCF consists of an X-ray tube, a skid platform system, a double crystal monochromator, a "T" structure mechanism, a collimator, an adjustable beam, a background shielding box, as well as the box of the control system. The HXCF covers 15–100 keV energy band and has a high fraction of monochromatic light (exceeding 92 % at 15–100 keV) and good monochromaticity (1‰ level). The flux of the monochromatic light is around 10^4 photons cm^{-2} s^{-1}. This HXCF could be used to calibrate the energy linearities, the energy resolutions and detection efficiencies of hard X-ray detectors.

Keywords Hard X-ray · Calibration · Monochromator · Double crystal · HXMT · HE

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1 Introduction

The Hard X-ray Modulation Telescope (HXMT) is the first high energy astrophysics mission in China [1]. The High Energy X-ray Telescope (HE) is a core payload of HXMT. It has a cylindrical structure, consisting of 18 NaI (Tl)/CsI (Na) phoswich modules that are sensitive to X-rays in 20–250 keV. To ensure the reliability of the space observational results, the detectors need to be well calibrated on the ground, by measuring the response of the detectors to incident X-ray photons. Its ground calibration mainly includes measurements of the energy linearity, the energy resolution and the detection efficiency.

In order to calibrate the space-borne X-ray detectors, there are a few dedicated X-ray calibration facilities in the world. The PANTER facility in the southwest of Munich in Germany is mainly used for calibration in the soft X-ray energy band, with the capability of calibration at energies up to 50 keV. So it's very relevant for HXMT. In order to generate a nearly parallel light beam, the distance from the X-ray sources to the entrance of the instrument box is 123.6 m, and the instruments operate in a high vacuum of $\leq 10^{-6}$ mbar. It has four X-ray sources, which provide characteristic X-ray lines of the target elements between 0.28 and 12 keV. A filter wheel is used to suppress parts of the continuum emission and the fluxes are of the order of 10^4 photons $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$. To extract mono-energy X-ray emission, a reflection grating and a double crystal monochromator are used in PANTER. The reflection grating monochromator covers the softer energy band (0.25–1.0 keV, up to 2 keV if the second order light is used), and the double crystal monochromator works in the 1.5–25 keV energy band [2]. The current PANTER X-ray test facility has a 120 m long and 1 m diameter vacuum tube. There is a 12 m long and 3.5 m diameter clean experiment vacuum chamber at the one end. Also, it has a 1 m diameter beam. This facility is quite unique now for its sophisticated system of translation and tip/tilt stages along with various X-ray spectroscopic focal plane cameras. Finally, this facility is operated all year [3]. The X-ray calibration facility at the University of Ferrara of Italy covers 6–140 keV. Its main components are two X-ray tubes, a monochromator system, a four-axis table used as the sample holder, a three-axis table as detector holder, a hybrid vacuum-helium system with vacuum tubes and a system of collimators plus a Pb shield to stop the scattered radiation in the testing room. One of the two X-ray tubes works at 6–60 keV and another at 15–140 keV, the spot sizes are both 5*5 mm^2 [4, 5]. The X-ray calibration facility (XRCF) at the Marshall Space Flight Center of the US National Aeronautics and Space Administration has a 518 m long vacuum tube and contains an X-ray source, a detection system, a control system, a temperature control system, a vacuum system, a contamination control, a clean room, and a cryogenic system. The energy range is 0.09–1.5 keV for the raster monochromator, and that for the double crystal monochromator is 1–10 keV [6]. The NuSTAR satellite has been calibrated by the facility RaMCaF at Nevis Laboratories in New York. The RaMCaF has a high power X-ray tube that can produce the hard X-ray continuum up to 100 keV. The beam size of the RaMCaF is 175 m long and 48 cm diameter, and its energy range is 5–100 keV. The facility can carry out detailed studies of large diameter optic elements, such as the NuSTAR optics, as well as flat multilayer coated Silicon wafers [7, 8]. The Italian calibration facility XACT was built at Palermo in 1990 and has been updated. After rebuilding, the length of the vacuum tube was increased from 18 to 35 m, and a telescope testing room was added. It also has two monochromators. The soft X-ray grating monochromator covers the 0.1–2.0 keV energy band, and the double crystal monochromator covers 0.5–30 keV [9]. A small facility has also been built in China to calibrate the X-ray detectors onboard its lunar rover. It has a vacuum target box and 3 m long vacuum tube, and covers 1–10 keV.

The hard X-ray calibration facility (HXCF) reported in this paper was built at the National Institute for Metrology in Beijing to calibrate the NaI/CsI main detectors of HXMT/HE, since there was no such facility available in China previously. We will introduce its configuration, main performance and other parameters.

2 The HXCF's current configuration

Figure 1 shows the current configuration of the HXCF (scale not in proportion). It mainly includes an X-ray tube (the high voltage range is 15–320 kV), a double crystal monochromator used for getting a fixed beam direction, and two collimators with lead shield. At the two ends of the collimator, there are apertures to limit the beam size, in order to ensure the monochromaticity of the output X-rays. A laser is installed at the fore-end of the first collimator; it helps regulate the direction of the beam, because it is visible and can simulate the light path of the X-rays. Using the laser and the X-ray beam, the "T" structure mechanism [10] and the angle rotator can be installed or adjusted to change the relative position of the two crystals, until the light path does not vary with photon energy. The "T" structure mechanism is installed on the double crystal monochromator and it has two stepping motors. One motor can alter the pitch angle of the second crystal and another can alter the roll angle of the second crystal. The location of the detectors can be adjusted through a linear translation stage and a rotation stage in the testing box.

2.1 X-ray tube

The X-ray system of the HXCF is YXLON MG325 (http://www.yxlon.com/Resources/Products/X-ray-tubes-and-generators-en), the parameters of which are listed in Table 1. The anode plate is made of tungsten, the size of the focal spot is 1.9 mm, and 0.8 mm thick beryllium is used as the exit window. The uniform field (99 %) 1 m away from the

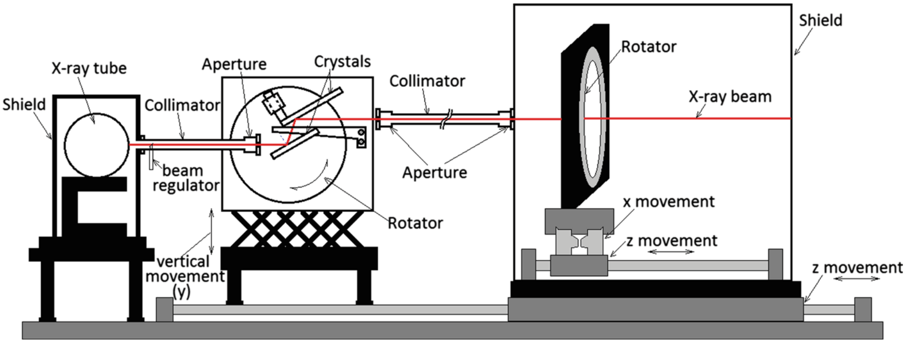

Fig. 1 The schematic diagram of the HXCF

Table 1 Parameters of the X-ray tube (YXLON MG325)

Nominal voltage	Adjustable range	15–320 kV
	Step	0.2 kV
	Accuracy	±0.01 %
	Temperature drift	0.008 %/°C
Current at nominal voltage	Adjustable range	0–22.5 mA
	Step	0.05 mA
	Accuracy	±2 μA
	Temperature drift	0.005 %/°C

window is 8 cm in diameter. Although the X-ray tube has a 2 mm thick lead shield, there is serious light leakage in the high energy region. Therefore, we build a testing box which contains 7 mm thick lead in the wall. The environmental background can be reduced effectively when the detectors are tested in this box.

2.2 CdTe detector

After calibrating the absolute detection efficiency of the CdTe detector (Amptek, X-123) (http://www.amptek.com/x123cdte.html), we use it as the standard detector of the HXCF. Then we can switch the tested detector and the standard detector to calibrate the absolute efficiency of the tested detector. The effective area of the CdTe detector is 5*5 mm, the effective thickness is 1 mm, and the beryllium window is 0.1 mm thick. Therefore the detection energy range is from 5 to 150 keV. The energy resolution (FWHM) is better than 1.2 keV at 122 keV. The efficiency is nearly 100 % for the 10–60 keV X-rays, and the maximum count rate it can detect is $2*10^5$ cps.

2.3 Double crystal monochromator

As shown in Fig. 2, the double crystal monochromator contains two crystals of different lengths, and it extracts mono-energy X-ray photons from the source using Bragg diffraction [11]. The first crystal (AA′) monochromatizes the X-rays by the Bragg diffraction, and the second crystal (BB′) makes the direction and location of the monochromatic light fixed. The centre of the first crystallographic plane goes through

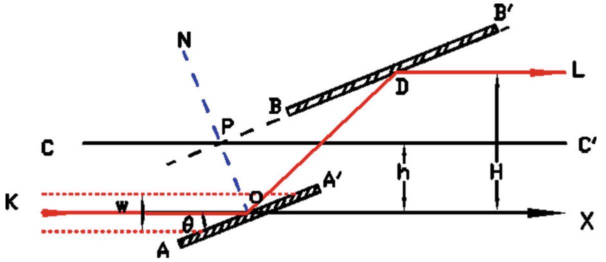

Fig. 2 The schematic diagram of the Si double crystal monochromator: the *red line* is the light path, point *O* is the spindle, *θ* is the Bragg angle, point *P* is the fulcrum of the fixed crystal, and *w* is the width of the beam line

the angle rotator's axis (point O). The distance *h* is from the fulcrum of the fixed structure of the second crystal (point P) to the horizontal line through point O (KOX). We control the second crystal by adjusting the "T" structure to make *h* constant. Because the rotator axis is stationary, the height *H* between the incident beam (KO) and the output beam (DL) ($H=2*h$) remains constant, then the position of the beam is fixed. When the Bragg angle θ increases, the Bragg diffraction site D at the second crystal moves from B to B′. In order to generate monochromatic X-ray light in a wide energy range, we make sure that the Bragg angle θ can change in a large range and the second crystal is as long as possible.

The Si220 crystals are chosen because it can meet the requirements of the monochromatic light in 15–100 keV. Moreover, two sets of crystals are used to extend the energy coverage of the output beam. The Si111 crystals can be used to calibrate the detector's response to X-rays below 15 keV, while the Si511 crystals are for the calibration above 100 keV.

We have tested the performance of the HXCF by the CdTe detector. The monochromatic light of different energies X-ray (continuum up to 100 keV) is obtained by adjusting the Bragg angle. Figure 3 shows one of the spectra measured by the CdTe detector, in which the highest peak is the first order diffraction peak of the Bragg diffraction. Because the CdTe detector contains the Cd and Te elements, a few escape peaks can be seen in the spectrum.

Shown in Fig. 4 is the relation between the measured monochromatic light energy and the Bragg angle, and the theoretical curve of the Bragg diffraction is drawn in the figure for comparison, which fits the data points very well. We find that the small deviation comes from the accuracy of the angle rotator installation.

2.4 Collimators

HXCF contains the front and rear collimating structures. The front collimating structure is 1 m long. It is located between the X-ray tube and the double crystal monochromator,

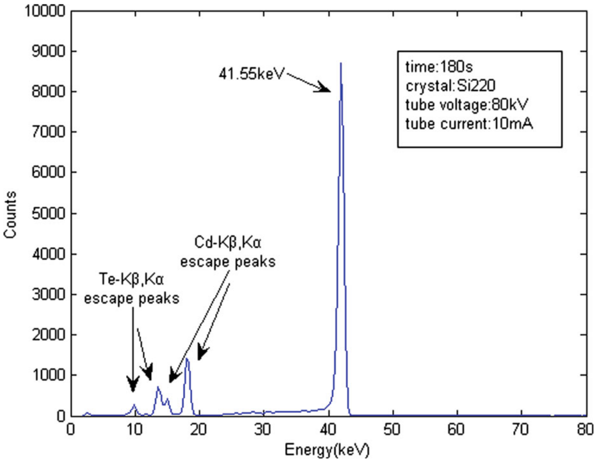

Fig. 3 The energy spectrum of the monochromatic light obtained by using a Si220 double crystal monochromator. It is detected by a CdTe detector, and so several escape peaks appear

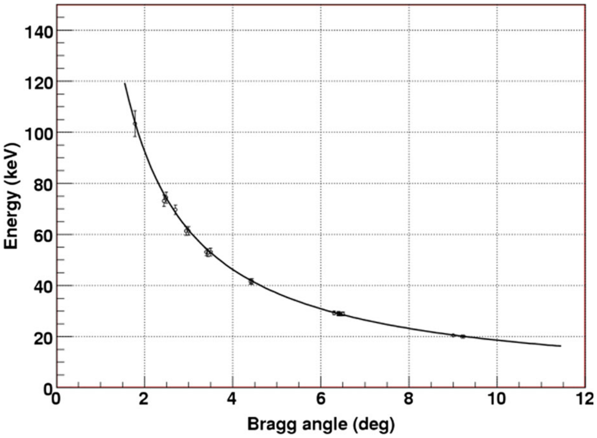

Fig. 4 The measured energy of the output X-ray beam and the Bragg angles, with the theoretical curve added. The Bragg Law: 2dsinθ = nλ, where θ is the Bragg angle, λ is the wavelength of a beam of x-rays incident on a crystal with lattice planes separated by distance d, and n is an integer

and includes a collimator tube, a beam regulator, a diaphragm aperture, and a supporting structure. The front collimator tube can shield the stray light. The aperture can limit the shape and the size of the incident light spot to ensure monochromaticity. We have also designed a beam regulator at one side of the front collimator to simulate the X-ray light path. This simulated light path helps us adjust the positions of different components of the HXCF to make the position of the beam fixed possibly in the assembly process. The different components of the HXCF mainly include the direction of the front collimating structure, the relative location of the two crystals. The length of the rear collimating structure can be chosen from 1 to 3 m. It is composed by a collimator, an aperture and a supporting structure. The rear collimator is lined with 2 mm lead shielding layer to shield the stray light.

2.5 Terminal testing box

The terminal testing box has an aluminum–lead–aluminum sandwich structure. The thickness of the lead shielding layer is 7 mm. The internal dimensions are 1,000*1,000*800 mm. The front face of the testing box has a window for the X-ray beam; the back of the box has a door for the installation and disassembly of the detectors. Inside the testing box a linear translation stage is installed perpendicular to the X-ray beam line. There is a rotation stage on the linear translation stage, and the tested detector is mounted on the rotation stage. The X-ray beam line can illuminate any position of the tested detector surface by moving the two stages. The standard detector is also installed on the rotation stage. Its surface is parallel to the surface of the tested detector. We can switch the standard detector and the tested detector by moving the linear translation stage. The whole terminal testing box is installed on a sliding table parallel to the X-ray beam line. Through moving the sliding table, we can adjust the distance between the tested detector and the X-ray tube from 1 to 4 m.

Table 2 The main performance indexes of the HXCF

Energy range	15–100 keV
Bragg angle range	1.84–12.38° to Si220 crystals
Energy interval	1.20 eV@ 15 keV 13.55 eV@ 50 keV 54.30 eV@ 100 keV
Proportion of monochromatic light	91.8 %@27.0 keV; 93.6 %@45.5 keV; 93.7 %@76.9 keV; 92.3 %@96.0 keV
Flux of monochromatic light[a]	~$4.6*10^4$ cts cm^{-2} s^{-1}@27.0 keV[b]; ~$1.3*10^4$ cts cm^{-2} s^{-1}@45.5 keV[b]; ~$5.7*10^4$ cts cm^{-2} s^{-1}@76.9 keV[c]; ~$1.3*10^5$ cts cm^{-2} s^{-1}@96.0 keV[c]
Spot size	0.5–10 mm, adjustable
Monochromaticity	0.60 %@59.5 keV; 0.72 %@26.3 keV; 0.96 %@13.9 keV
Location of beam line	Deviation<2.4 mm
Stability	Flux of monochromatic light<2 %@1 h; Proportion of monochromatic light<1 %@1 h

[a] The efficiency modification of the CdTe detector is ignored at different energies

[b] Tube voltage: 80 kV, tube current: 10 mA

[c] Tube voltage: 140 kV, tube current: 10 mA

2.6 The main parameters of the HXCF and other X-ray calibration facilities

The main performance indexes of the HXCF is shown in Table 2. And Table 3 provides the compare of the main X-ray capbilities in the world.

Table 3 Some descriptions of the main X-ray calibration facilities in the world until 2014

Calibration facility	PANTER	Ferrara	XACT	XRCF	RaMCaF	HXCF
Country	Germany	Italy	Italy	USA	USA	China
Energy range (keV)	0.25–50	15–140	0.1–30	0.09–10	5–100	15–100
Flux (photons cm^{-2} s^{-1})	10^4	–	10^5	–	–	10^4
Spot size (diameter, cm)	100	0.5	0.1	400	48	0.2
Beam length (m)	120	100	35	518	174	15
Clear room	Yes	Yes	Yes	Yes	Yes	No
Vacuum environment	Yes	Yes	Yes	Yes	Yes	No
Characteristic	Big chamber	Big chamber	Small chamber	Big chamber	Big chamber	Small chamber
Calibrated satellites	EXOSAT ROSAT BeppoSAX Chandra XMM-Newton Swift HXMT IXO	INTEGRAL BeppoSAX HXMT	AXAF	AXAF Chandra JWST	NuSTAR	HXMT

Other X-ray calibration facilities may not be listed in the table above. Some parameters or descriptions may be inaccurate and outdated

3 Discussion and summary

The HXCF can be used to calibrate the energy responses of X-ray detectors in the 15–100 keV energy band. Currently the HXCF is mainly used to calibrate the HXMT/HE detectors. In the future, it will provide services to the calibration of the other hard X-ray detectors.

Since the X-ray tube of the HXCF is also used in daily ionizing radiation metrology test, we need to assemble and remove the HXCF during the calibration test. Currently a larger laboratory is being built on the new campus of the National Institute of Metrology. The HXCF will be upgraded to have a 15 m beam line after the laboratory set up. The new X-ray system of the HXCF is YXLON MG226 (http://www.yxlon.com/Resources/Products/X-ray-tubes-and-generators-en). The light spot can be further larger and the proportion of monochromatic light is higher. The upgraded HXCF will be a dedicated space hard X-ray detector calibration facility. Based on the HXCF, another new calibration facility is being built in the institute of high energy physics, CAS in Beijing. This new facility will have a 100 m beam line, an 8 m long and 3 m diameter experiment vacuum chamber, more than two X-ray tubes for wider energy range and the spot size exceeding 500 mm. Besides all of the calibration items of the energy response, the new calibration facility can be also used to calibrate the Point Spread Function (PSF) of X-ray telescopes to some extent.

In addition, the HXCF can be also upgraded to an X-ray polarization source. When the X-ray is incident on the different lattice planes of the different crystals with an angle of 45°, the linearly polarized X-rays of different energies can be obtained after the Bragg diffraction. Then the HXCF can also be used to calibrate X-ray polarization detectors.

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