Design and Calibration of High Energy Particle Monitor on board HXMT(Insight)

Xuefeng Lu, Congzhan Liu, Shu Zhang, Yifei Zhang, Zhengwei Li, Xiaobo Li, Aimei Zhang, Xufang Li, Zhi Chang

*Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China

Abstract

High Energy Particle Monitor (HPM) on board Hard X-ray Modulation Telescope (HXMT) is used to detect the charged particles to give warning signals for the entry and exit of South Atlantic Anomaly (SAA). A typical design of plastic scintillator coupled with small photomultiplier tube (PMT) is adopted for its high stability and reliability. The window threshold for electron is about 1 MeV, and that for proton is about 20 MeV. In combination with the ground calibration and Geant4 simulation, a relation among the PMT high voltage and an average count rate of HPM in SAA is built in details. It supplies a recommended PMT high voltage to the HPM. The HPM in-orbit performance and the SAA area monitor map measured by the HPM are introduced in the last part of this paper. During more than two years flight, the HPM is found working well and steadily provides accurate warning signals for the HXMT.

Keywords: HXMT, particle monitor, SAA, ground calibrate

1. Introduction

The Hard X-ray Modulation Telescope (HXMT), also called Insight, was launched on 15th June 2017 with the altitude of 550 kilometers and an inclination of 43 degrees. It is mainly composed of three kinds of collimating telescopes that work together to detect X/gamma rays in the range 1-250 keV [1]. The High Energy X-ray Telescope (covering 20-250 keV), as the main payload, uses NaI(Tl)/CsI(Na) phoswich coupled with Photo-Multiplier Tubes (PMT). As is known to all, a large number of fluorescent lights irradiated by charged particles in scintillator will sincerely decrease the PMT characteristics because of the saturation and nonlinearity, and even shorten the lifetime. Therefore, it is very important to exactly turn off the power supply for the phoswich detectors when entering SAA to keep them safe. On the other hand, it is also necessary to turn on the power supply immediately after leaving the SAA to obtain the maximum observation time. Although the SAA map has been measured many times by other satellites, it is hardly to obtain the entry and exit time from the SAA boundary alone due to its evolution and drift [2]. Therefore, charged particle monitors onboard RXTE, BeppoSAX [3, 4] and Astrosat, are commonly used to carry out this mission, as well as the High Energy Particle Monitor (HPM) on HXMT.

A typical design of a small plastic scintillator coupled with photomultiplier tube is adopted in HPM like those on BeppoSAX and HEXTE for its high stability and reliability. The HPM is used to monitor particle flux in-orbit and supply a count rate in real-time to the electronic control system. When the count rate exceeds the threshold, the electric control system will be triggered, and then shut down the high voltage of the PMT in detectors to protect them from damage. The window threshold of the HPM for electrons is designed to be about 1 MeV, and that for proton is about 20 MeV. Benefited by the small size scintillator, the HPM count rate is estimated to be less than 2000 events per second, according to the electron and proton differential energy spectra in the SAA provided by the SPENVIS website. The average anode current of the PMT is estimated to be much less than 1 micro Ampere. In this case, the damage to the HPM is negligible in terms of the PMT manual [5]. In addition, there are three HPMs backing up each other on HXMT shown in Figure 1.

Figure 1: HPM position on the satellite.

References

[1]...

In this paper, the mechanic and electronic design of the HPM are described in detail respectively at first. Then we introduce the ground calibration of the HPM with radioactive isotopes and the temperature response of the HPM in the range -30-20 degree. In addition, a simulation is also made to obtain the detection efficiency of the HPM for electrons and protons.
Based on those results, a relation between PMT high voltage and an average count rate of HPM in SAA is calculated. It recommends a range of the PMT high voltage. The in-flight performances of the HPM are given at the last.

2. Detector design

The HPM, shown in Figure 2, is mainly composed of a plastic scintillator coupled with a PMT; an electronic system on-board two PCBs, a high voltage module, the aluminum shell and an electric coupler.

The plastic scintillator BC440M is used to detect the charge particles. Since a count rate of about 1 cps is expected outside the SAA, a detecting area of about 1 square centimeter is recommended according to the experience of the particle monitor on HEXTE. Here, we choose a cylinder scintillator with a diameter of 10 mm and a height of 10 mm. An aluminum cap with a thick of 1 mm is used to limit the detection thresholds of electron and proton to be 1 MeV and 20 MeV respectively. The scintillator surfaces except the light output side are successively covered by reflective paint BC620 and Teflon to obtain a high light collection efficiency. The scintillator is adhesively coupled through a thin layer of transparent two-component cured silicone rubber with a photomultiplier tube R647-1 whose pins are welded on the divider PCB. A silicone rubber fixer shown in Figure 4 is used to keep the scintillator in the center of the PMT cathode, and to absorb vibrations as well. A 2 mm thickness magnetic shield tube is installed around the PMT to shield the geomagnetic field. The PMT cathode is about 5 mm lower than the magnetic shield tube to avoid the edge effects. Experiment shows that the magnetic intensity in the center of the magnetic shield tube is about one thousandth of the normal value. In order to absorb the vibrations of the launch, a silicone rubber sleeve is insert between the magnetic shield tube and PMT. As the magnetic shield tube and divider PCB are fixed by screws to the bottom plate of the HPM shell, the PMT is installed perpendicular to the divider PCB and kept to be upwards.

The divider is designed based on the principle of equipartition of voltage, recommended by the PMT manual. Components are placed side by side in a rectangle PCB board, fixed to the bottom of the aluminum plate. A high voltage module S9100 from SITAEEL is used to supply -1250-0 V for the divider. It is covered by a polyamide plate and vertically fixed on the side aluminum plate through screws.

The PMT output electrons are collected by a charge sensitive amplifier followed by a RC filter and a main amplifier. Since the decay time of the plastic scintillator is a few nanoseconds, the electron pulse from the PMT is about tens of nanoseconds contributed by the transit time spread. Therefore, an integration time of hundreds nanoseconds is enough to collect those electrons and obtain a maximum pulse height. The pulse width is about 450 ns for normal events. This allows the HPM easily to detect high-flux charged particles in SAA without saturation. In addition, a differential output is adopted to reduce the common mode interference signals. The electronic noise is about 10mV. These components are placed on another PCB fixed to the side aluminum plate.

The HPM shell is composed of five mechanical structural components screwed together. A mechanical stop design is adopted by each one to keep out of the light and the electric field. The HPM outline dimension is 111 mm × 64 mm × 104 mm, mainly decided by the PMT and high voltage module. The detector design is very compact and has a high stability. Ground experiments have shown that the HPM can withstand 500 times the gravitational acceleration shock and work well in the range -30-20 degrees.

When a charge particle deposit energy into the scintillator, a voltage pulse with a height proportional to the energy will be output from the HPM. The voltage pulse is then sent to a comparator in the electronic system through a two meters long com-
munication cable. The comparator also will receive another DC reference voltage given by the electronic system. The initial DC voltage is 200 mV and can be adjusted by ground commands. When the pulse amplitude exceeds this value, the comparator will output a positive square wave pulse to drive the counter. If the count rate exceeds one certain value initially set to be 10 cps in three continuous seconds, the satellite will be considered as entering the SAA. The high voltage of the PMT in primary detectors will be turn off. On the contrary, it will return to normal outside the SAA.

3. Ground calibrations and simulations

The HPM was only used to count the charged particles that exceed the threshold, and did not obtain pulse height. However, ground calibrations were still taken to characterize the HPM and a Geant4 simulation was also made to obtain the responses of the HPM to electrons and protons. Based on those data, a relation between the PMT high voltage of the HPM and the average count rate in SAA is built carefully. It had provided a proper scale for the PMT high voltage of the HPM in-orbit.

3.1. Relation between detection threshold and high voltage

To figure out energy response of HPM, ground calibration test was carried out with radioactive sources Am$^{241}$, Na$^{22}$ and Cs$^{137}$. The calibration experiment setup block diagram can be seen in Figure 5. A plastic scintillator embedded with an Am$^{241}$ source was used to supply alpha signals for coincidence detection of 59.5 keV gamma rays signals from the HPM. For the radioactive source Na$^{22}$, a pair of gamma rays with 511.0 keV will be produced by positron-electron annihilation in the opposite direction. NaI detector CH132-06 made by HAMAMATSU was used to detect one gamma ray being a trigger signal to coincidently chose another one from the HPM. The pulse signal output from the plastic or NaI scintillation detector was shaped and stretched to be a rectangle pulse with a width of 5 us and a amplitude of 5 V. The pulse signal from the HPM also became a rectangle pulse with a width of 5 us. But the amplitude was the same as the original pulse height. The HPM detected directly 661.7 keV gamma rays and average energy of 32.9 keV X rays from the radioactive source Cs$^{137}$.

\[ H(E) = 0.4127 \times E - 1.028, \quad (1) \]

in which, \( H(E) \) stands for the pulse height, \( E \) the deposited energy and the constant -1.028 the baseline.

In addition, the full-energy peak of 59.5 keV gamma rays versus the PMT high voltage was tested and shown in Figure 9. A power law function is reasonably used to fit them according to the PMT handbook $[7]$. It is

\[ H(V) = 0.05103 \times V^{7.766} - 1.028, \quad (2) \]

in which, \( V \) is the PMT high voltage divided by 312.5. Other X/gamma-ray pulse of different energies vary in the same way.
Based on the above two expressions, the relation between the pulse height and the high voltage at different deposited energies can be expressed as

\[ H(E, V) = 8.57 \times 10^{-4} \times E \times V^{7.766} - 1.028. \]  

(3)

Assuming an electronic threshold to be \( H_T \), the detection threshold \( E_T \) at different PMT high voltage is given by

\[ E_T = \frac{H_T}{8.57 \times 10^{-4} \times V^{7.766} - 1.028}. \]  

(4)

This relation is appropriate to deposited energy ranging from several keV to MeV, since in which the energy response is linear. It is sufficient for us to calculate the count rate of the HPM in SAA.

![Figure 8: Energy response at PMT high voltage 2.2V.](image)

![Figure 9: High voltage versus pulse height corresponding to different deposited energy.](image)

3.2. Temperature response

Due to the influence of low temperature environment in outer space, the HPM will work at the temperature far below 20 degrees. This will remarkably change the HPM detection threshold obtained at room temperature, as the quantum efficiency of PMT photocathode is sensitive to temperature. At laboratory, temperature response of a HPM was tested in the range -30-25 degrees. The 59.5 keV gamma rays irradiated by an Am\(^{241}\) source were used to calibrate the HPM. It is obviously shown in Figure[10](image) that the pulse height almost linearly increased as the temperature decreased. The maximum gain variation of the HPM was about 15% through the whole experimental temperature range. A variation of -0.38%/degree was obtained by fitting the experimental data. It was used to correct the expression (4) by multiplying a coefficient of 1-0.38%\((T-20)\) to the item \(8.57 \times 10^{-4}\).

![Figure 10: Full-energy Peak of 59.5 keV gamma rays at different temperature.](image)

3.3. Detection efficiency by geant4 simulation

Since it was difficult to get the detection efficiency of the HPM to electrons and protons through the experiment, the widely used Geant4 simulation was adopted. The physical model was based on the flight HPM. The physical processes included ionization, multiple scattering, bremsstrahlung, Compton scattering, gamma conversion, and positron-electron annihilation. Electrons and protons were sampled isotropically in \(2\pi\) direction at the surface of the aluminum cap. The energetic electrons was in the range 1-20 MeV, and the protons in the range 20-400 MeV. Particles were detected when they deposited energies in the plastic scintillator over the detection threshold given by expression (4). The detection efficiency was defined as the ratio of the number of detected particles to the total number. Figure[11](image) shows the detection efficiency of electrons at different high voltage. Electrons below 1 MeV will not be detected due to the aluminum cap block. The detection efficiency increases as the energy increases and almost becomes a constant value about 24% when the energy are beyond 5 MeV at the maximum high voltage of 1250 V. This value is close to the surface area ratio of the scintillator to the aluminum cap. The similar behavior for protons is shown in Figure[12](image). The maximum detection efficiency of protons above 40 MeV is about 23%, slightly lower than that of electrons, due to the lower energy deposited by protons. When the proton energy is further increased, the deposition energy is decreased due to proton quenching effect and the detection efficiency is reduced.
3.4. Results and discussions

According to the orbital altitude of Insight, the AE-8 solar maximum model and AP-8 solar minimum model from SPENVIS were used to generate the differential energy spectra of electrons and protons in SAA. By convolving the simulated detection efficiency curves and the differential energy spectra, average count rates of the HPM in SAA were calculated at different PMT high voltage, as shown in Figure 13. The blue solid line was obtained at room temperature, and the upper red solid line at -30 degrees. The temperature drop results in a 30% increase in average count rate at the PMT high voltage of 312.5 V, while the temperature effect is negligible above 625 V. It also can be seen that the predicted average count rates increase quickly as the PMT control voltage varies from 1.0 V to 2.0 V, and reach a constant value when it beyonds 2.5 V. As the count rate of the HPM in the non-SAA region is a few, a count rate of hundreds is sufficient to judge whether the HPM is in SAA or not. Correspondingly, the PMT high voltage is recommended to be between 312.5 V and 531.3 V.

4. Status on orbit

The HPM onboard HXMT was launched on June 15th, 2017. After entering the orbit, the HPM power was turned on, and the PMT high voltage was set to be 437.5 V which is in the recommended scale. The HPM surface temperature varies between -18 and -22 degrees during flight. Figure 14 shows the real-time counting rate given by an HPM over a period of time. The pulses indicate that the HPM passes through the SAA region. A contour map of the count rate of an HPM in orbit is shown in Figure 15, from which the SAA region is clearly depicted. The HPM has only one event per second at most area outside the SAA, while there are thousands of events per second in the central area of the SAA. The average count rate of the HPM in SAA is about 424 cps, which is also marked in Figure 13 for comparison. The distinguish between the actual environment and the modeling environment given by the AE-8 MAX and AP-8 MIN may be responsible for the difference between the tested and predicted values.

5. Conclusions

The HPM is compact, reliable and has withstood various critical ground tests and space flight tests. The calibration results provide an effective reference for the adjustment of in-orbit high voltage and detection threshold. With the recommended PMT high voltage, the HPM works very well, and gives accurate pre-warnings for all the detectors. This method can also be applied to other similar particle monitors on future scientific telescopes. As the HPM works in safety, it will supply more and more useful data for low earth orbit radiation environment research.
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