Proton irradiation effect on SCDs[*]

YANG Yan-Ji(杨彦佶)[1,2;1]   LU Jing-Bin(陆景彬)[1]   WANG Yu-Sa(王于仁)[2]   CHEN Yong(陈勇)[2]

XU Yu-Peng(徐玉朋)[2]   CUI Wei-Wei(崔苇苇)[2]   LI Wei(李炜)[2]   LI Zheng-Wei(李正伟)[2]

LI Mao-Shun(李茂顺)[2]   LIU Xiao-Yan(刘晓艳)[1,2]   WANG Juan(王娟)[2]   HAN Da-Wei(韩大炜)[2]

CHEN Tian-Xiang(陈田祥)[2]   LI Cheng-Kui(李承奎)[2]   HUO Jia(霍嘉)[2]   HU Wei(胡渭)[2]

ZHANG Yi(张艺)[2]   LU Bo(陆波)[2]   ZHU Yue(朱玥)[2]   MA Ke-Yan(马克岩)[1]   WU Di(吴帝)[2]

LIU Yan(刘琰)[2,3]   ZHANG Zi-Liang(张子良)[2]   YIN Guo-He(尹国和)[2]   WANG Yu(王宇)[2]

[1] College of Physics, Jilin University, No.2699, Qianjin Road, Changchun 130023, China
[2] Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences (CAS),
19B Yuquan Road, Beijing 100049, China
[3] School of Physical Science and Technology, Yunnan University, Cuihu North Road 2, Kunming 650091, China

Abstract: The Low Energy X-ray Telescope is one of the main payloads on the Hard X-ray Modulation Telescope satellite. Swept charge devices (SCDs) are selected as detectors for the Low Energy X-ray Telescope. As SCDs are sensitive to proton irradiation, irradiation tests were carried out on the HI-13 accelerator at the China Institute of Atomic Energy. The beam energy was measured to be 10 MeV at the SCD. The proton fluence delivered to the SCD was 3×10^8 protons/cm^2 over two hours. By comparing the performance before and after irradiation, it is concluded that proton irradiation affects both the dark current and the charge transfer inefficiency of the SCD. The energy resolution of the proton-irradiated SCD is 212 eV@5.9 keV at $-60\,^\circ$C, while it before irradiated is 134 eV. Moreover, better performance can be reached by lowering the operating temperature of the SCD in orbit.

Key words: SCD, HXMT, proton irradiation, energy resolution, readout noise

PACS: 29.40.Wk   **DOI:** 10.1088/1674-1137/38/8/086004

1 Introduction

The Low Energy X-ray Telescope (LE) is one of the main payloads on the Hard X-ray Modulation Telescope (HXMT) satellite [1], which is planned to be launched in about 2015 in a 550 km circular orbit around the earth, with a planned mission duration of 4 years. The LE is required to detect X-rays from 1 to 15 keV with energy resolution of the full width at half maximum (FWHM) better than 450 eV@5.9 keV and time resolution of no more than 1ms. Swept charge devices (SCDs) [2] were therefore selected as the detection method for the LE.

SCDs are a new type of charged coupled device (CCD). The dark current of an SCD is much lower when operated in inverted mode operation (IMO) [3]. An SCD gains faster readout speed by abandoning position information, allowing the readout time of the whole frame to be less than 1 ms [3]. The SCD (CCD236) is especially designed to meet the scientific objectives of LE. It is also used on Chandrayaan-2 [4].

In space, there are many protons of all energies, which can degrade the energy resolution of the CCDs. Radiation received by the CCD is specified by two different units. For bulk damage effects, the incoming radiation is specified as a fluence, which increases the charge transfer inefficiency (CTI). For ionization damage, radiation is specified in terms of the total dose, which increases the dark current [5]. For LE, the total proton dose received by the detector in 4 years will be 10 MeV-equivalent fluence of 3×10^8 p/cm^2. To evaluate the performance of the SCDs after irradiating the total dose of the four-year mission, a proton irradiation experiment has been conducted on the HI-13 accelerator at the China Institute of Atomic Energy.

2 Experimental setup

The proton irradiation experiment was carried out at the HI-13 accelerator at the China Institute of Atomic Energy in May, 2012. The SCD was fixed at the back of a plastic plate, which was installed on a mounting plate. The SCD was linked to a pre-amp board with a flexible

board inside the chamber (Fig. 1, Fig. 2). The readout system outside the chamber supplied power to the SCD via sub-D connectors and received the signals from the SCD by Bayonet Nut Connectors (BNC).

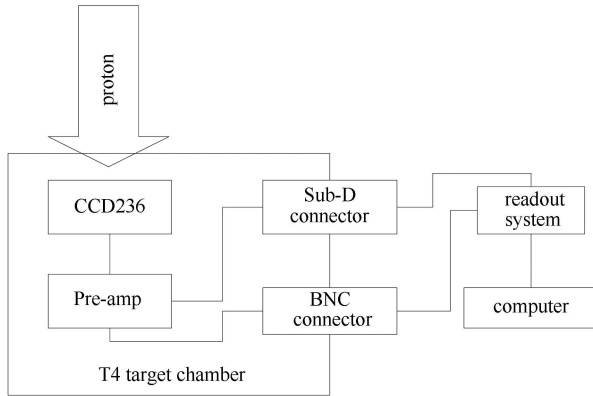The SCD device was operated at 83.3 kHz. The operating voltages for the SCD are given in Table 1.

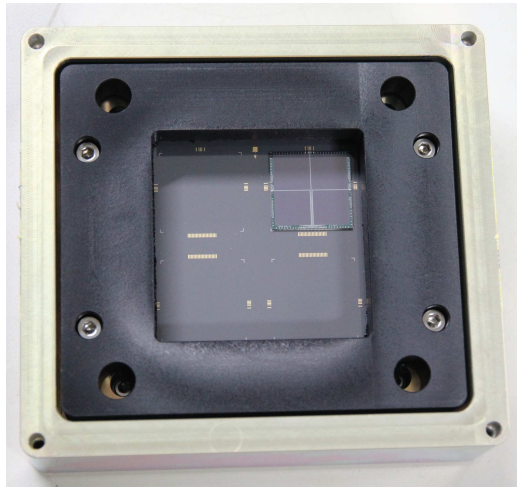Fig. 1.   The schematic of the SCD proton irradiation experiment.

Fig. 2.   The SCD to be irradiated by protons.

Table 1.   Operating voltages of the SCD.

parameter	voltage/V
substrate	9.0
output gate	2.5
reset gate2	17.0
output drain	30.0
clock phase	7.0

The SCD was irradiated by the protons at room temperature. The beam energy was measured to be 10 MeV at the SCD labeled as CCD236-20-4-D94.006. The proton fluence delivered to the SCD was 3×10^8 p/cm^2 over 2 h.

3   Results and discussions

As there were several difficulties in cooling down the SCD in a beam chamber, the SCD was tested in the vacuum tank at the Institute of High Energy Physics (IHEP). The SCD was glued to a copper plate cooled by liquid nitrogen as shown in Fig. 3. The plate started to cool down after the chamber was vacuumized. When the SCD reached about -110 ℃, the cooling was stopped and the SCD started to warm slowly at the rate of less than 0.2 ℃/min. The parameters, including the FWHM and the readout noise, were obtained by processing the spectra every 2 min continuously. A 1mCi ^{55}Fe was also used to determine the performance in the chamber [6].
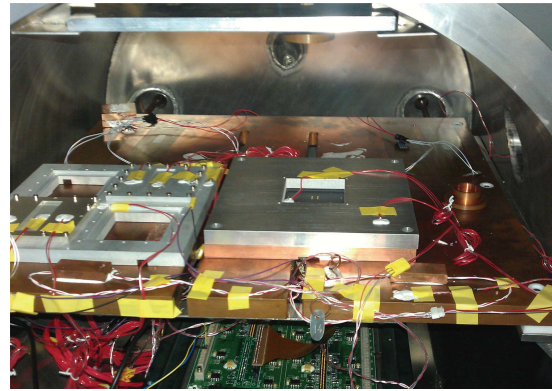

Fig. 3.   The vacuum chamber for SCD tests.

Two kinds of events are acquired from the SCD, single events and split events. The single events, which are also called single pixel events, are X-ray events that occupy a single pixel, while the split events are X-ray events that occupy more than one pixel [5]. In the data, the events are selected as follows. If there are events with amplitude higher than the threshold during more than 2 sequential drive clocks, the events are split. The rest of the events are single. Split events can be either abandoned or combined to reduce the background and improve the energy resolution.

Three ^{55}Fe spectra using the same SCD data are shown in Fig. 4. Every event reading from the data shows directly without any processing in the raw spectrum. There are only single events in the single spectrum, whereas there are single events and split events with combined amplitudes in the combined spectrum. Several peaks can be obtained from the spectra. From the plot, it can be learnt that both the single and the combined spectra can reduce the level of the background. However, as we know, each event of the split events is read out with one readout noise. Combining the split events will inevitably accumulate the readout noise at least twice, which causes worse energy resolution. Therefore, the single spectrum will be used for discussing the

performance both before and after the irradiation.

The spectra both before and after irradiation are shown in Fig. 5 and Fig. 6. It is obvious that the performance post-irradiation has been reduced a little at −75.1 ℃ in Fig. 5, for the dark current has little impact on the resolution. When the operating temperature of the SCD is much higher, the post-irradiation spectrum is much worse, as shown in Fig. 6.
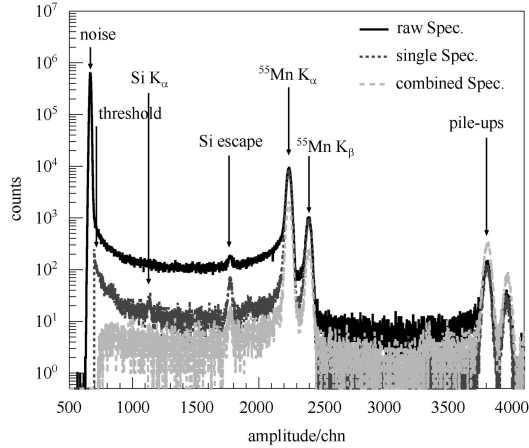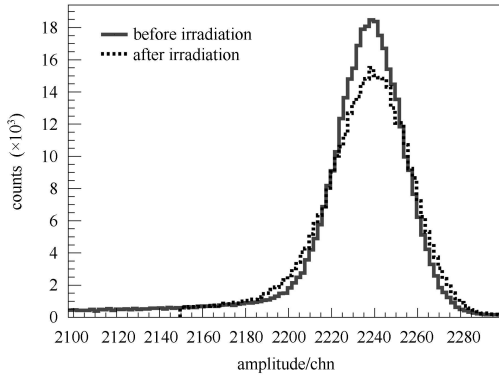

Fig. 4.   The ^{55}Fe spectra of the SCD at −75.1 ℃.

Fig. 5.   The ^{55}Mn K$_\alpha$ peak of single events at −75.1 ℃.

3.1   Readout noise performance

When there are no incoming photons, the output amplitude of the CCD is not zero, because there is still dark current and other electronics noise in the output. The dark current noise comes from the detector itself, and the electronics noise comes from on the electronics system. As the electronics system is placed at normal pressure and temperature in these two tests, the electronics noise can be considered constant. In Fig. 7, when the temperature of the SCD is below −60 ℃, the noise mainly comes from the electronics noise. When the temperature of the SCD is above −60 ℃, the dark current increases as the temperature rises. Furthermore, the noise after irradiation increases much faster than before irradiation.
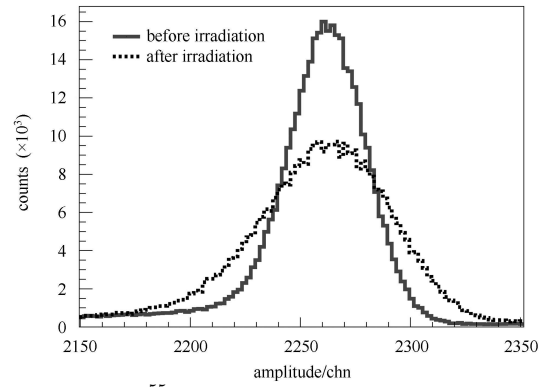

Fig. 6.   The ^{55}Mn K$_\alpha$ peak of the single events at −31.1 ℃.
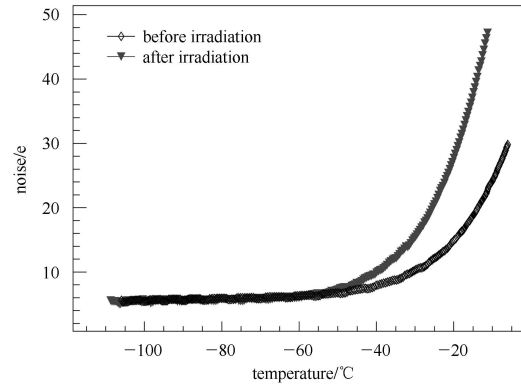

Fig. 7.   Readout noise before and after the irradiation vs. the SCD operating temperature.

3.2   Energy resolution performance

The energy resolution of the FWHM at the Mn K$_\alpha$ peak (5.9 keV) is used to evaluate the effect of the proton irradiation. Comparing the performance before and after irradiation, the FWHM after irradiation is much higher than before, as shown in Fig. 8. The FWHM will be higher than 450 eV when the operating temperature of the SCD is 0 ℃. However, it is unfortunate that the performance above 0 ℃ cannot be measured, as the amplitude of the signal is out of range. It is therefore a good choice to operate the SCD in orbit below −20 ℃.

The energy resolution largely depends on three factors, including the shot noise, the CTI and the readout noise, which can be described as follows.

$$\mathrm{FWHM} = 2.355 \times \omega \times \sqrt{\frac{F \times E}{\omega} + n_{\mathrm{CTI}}^2 + n_{\mathrm{noise}}^2}. \quad (1)$$

In the equation, ω is the binding energy of the electrons and the hole, which is taken as 3.70 eV/e$^-$ [7]. F stands for the Fano factor, which is 0.12 here. E is the energy of the incoming photons, which is 5899 eV for the Mn K$_\alpha$. n_{CTI} is the noise caused by the CTI, n_{noise} is the readout noise.
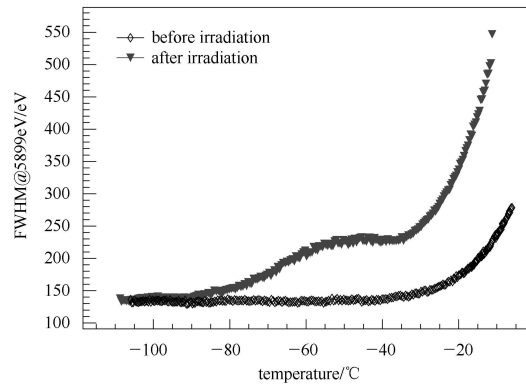
Fig. 8.   The FWHM before and after irradiation vs. the SCD operating temperature.
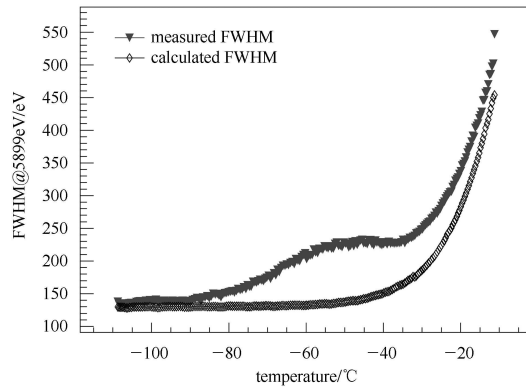

Fig. 9.   The measured and calculated FWHM, ignoring CTI, after irradiation vs. the SCD operating temperature.

In Fig. 9, the calculated FWHM curve is plotted without considering n_{CTI}, with n_{noise} from the post-irradiation curve in Fig. 6. The curve can be split into 3 parts, as can be seen clearly in Fig. 10. The first part is above -30 ℃, when the dark current dominates the energy resolution. The second part is from -30 ℃ to -95 ℃, when the CTI dominates. The third part is below -95 ℃, when both the CTI and the dark current contribute little. When it is below -95 ℃, the calculated FWHM is close to the measured value, indicating that both the CTI and the dark current contribute little to the FWHM. When it is between -60 ℃ and -95 ℃, the dark current is near zero, while CTI contributes the most to the FWHM [8]. When it is between -30 ℃ and

-60 ℃, the dark current, which is not near zero any more, is still smaller than the CTI, which contributes most to the FWHM. When it is above -30 ℃, the noise from the dark current is so high that the CTI noise can be ignored. However, it has to be pointed out that there may be some errors in the section of the n_{CTI} curve above -60 ℃, because the dark current can also fill the traps in the proton-irradiated SCD, which leads to the decline of n_{CTI} in the curve. Another test for illustrating that problem has previously been carried out [8].
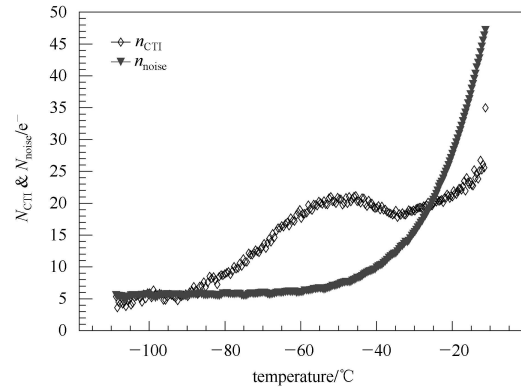

Fig. 10. n_{CTI} and n_{noise} after irradiation vs. SCD operating temperature.

4   Conclusion

It can be concluded that proton irradiation affects the performance of the SCD. Due to the performance of the SCD, the dark current increases significantly when the temperature is above -60 ℃. The dark current can be ignored when the SCD is below -60 ℃. The dark current noise of the proton-irradiated SCD increases faster than a non-irradiated SCD. When the temperature is below -30 ℃, the noise of the CTI dominates the energy resolution. When it is below -95 ℃, both the CTI and the dark current contribute little to the energy resolution. At that point, the best way to eliminate or weaken the proton irradiation effects is to lower the operating temperature of the SCD. In the test, the best temperature range for operating the proton-irradiated SCD is -110 ℃ to -100 ℃. Better performance can also be reached by lowering the operating temperature of the SCD in orbit.

References

1 LI T P. Nuclear Physics B Proceedings Supplements, 2007, **166**: 131–139
2 Holland A D. Pool P. Proc. of SPIE, 2008, **7021**: 702117-1
3 Lowe B G. Holland A D, et al. Nuclear Instruments and Methods in Physics Research A，2001, **458**: 568–579
4 Smith P H, Gow J P D et al. Proc. of SPIE, 2012, **8453**: 84530R-1
5 Janesick J R. Scientific Charge-Coupled Devices, Bellingham, Washington: SPIE Press, 2001. 387–390
6 WANG Yu-Sa, CHEN Yong, XU Yu-Peng et al. Chinese Physics C (HEP & NP), 2009, **33**: 1–5
7 Mazziotta M N. Nuclear Instruments and Methods in Physics Research A, 2008, **584**: 436–439
8 WANG Yu-Sa, YANG Yan-Ji, CHEN Yong et al. Chinese Physics C, 2014, **38**: 066001