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Radiation hardness of a p-channel notch CCD developed for the X-ray CCD camera onboard the XRISM satellite

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ABSTRACT: We report the radiation hardness of a p-channel CCD developed for the X-ray CCD camera onboard the XRISM satellite. This CCD has basically the same characteristics as the one used in the previous Hitomi satellite, but newly employs a notch structure of potential for signal charges by increasing the implant concentration in the channel. The new device was exposed up to approximately 7.9×10^{10} protons cm^{-2} at 100 MeV. The charge transfer inefficiency was estimated as a function of proton fluence with an ^{55}Fe source. A device without the notch structure was also examined for comparison. The result shows that the notch device has a significantly higher radiation hardness than those without the notch structure including the device adopted for Hitomi. This proves that the new CCD is radiation tolerant for space applications with a sufficient margin.

KEYWORDS: Radiation damage to detector materials (solid state); X-ray detectors and telescopes

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1 Introduction

The X-Ray Imaging and Spectroscopy Mission (XRISM), recently renamed from XARM, is the seventh Japanese X-ray astronomical satellite planned to be launched in the early 2020's [1]. XRISM will carry two identical X-ray mirror assemblies. One of the focal plane detectors is an X-ray microcalorimeter array, which will provide unprecedented high-resolution X-ray spectroscopy with a relatively narrow field of view (FOV) of $3' \times 3'$ [2]. The other is an X-ray charge-coupled device (CCD) camera, which has moderate energy resolution with a large FOV of $38' \times 38'$ [3]. These two instruments play complementary roles to each other and will open up a new view of the X-ray universe.

The XRISM CCD has basically the same characteristics as the one used in the previous Hitomi satellite [4], a p-channel back-illuminated device with a full-depletion layer with a thickness of $200\text{ }\mu\text{m}$. As is the case with Hitomi, XRISM will fly in the low earth orbit with an altitude of 575 km and an inclination angle of 31° . Devices in this orbit are exposed to a large number of cosmic rays, dominated by geomagnetically trapped protons in the South Atlantic Anomaly, and the average dose rate of protons is estimated to be 260 rad year^{-1} in the case of the Hiromi CCD [5]. The non-ionizing energy loss of cosmic-ray protons results in bulk damage in silicon. It increases the charge transfer inefficiency (CTI) defined as a fraction of charge loss per one-pixel transfer and degrades the spectroscopic performance of X-ray CCDs in space.

In the case of Hitomi, in order to mitigate the radiation damage effects, we cooled the CCD temperature down to -110°C and employed the charge injection (CI) technique, which reduces signal packet loss by filling traps with regularly spaced injected charges [6, 7]. For further improvement, we newly introduced a “notch” structure to the XRISM CCD. The notch structure is a narrow implant in the CCD channel confining a charge packet to a fraction of the pixel volume in an additional potential well and has been known to reduce the CTI [8, 9].

In this paper, we report the results of radiation damage experiments for studying the radiation hardness of our new notch device, especially paying attention to the application to the XRISM satellite.

2 Experiment

Table 1. Specifications and operation parameters of the CCDs under test.

architecture	frame-transfer
channel type	p-channel
clock phase	2
pixel size	$24 \times 24 \mu\text{m}^2$
pixel format	$320(\text{H}) \times 256(\text{V})$
imaging area size	$7.7 \times 6.1 \text{ mm}^2$
binning	2×2
frame cycle	4 s
operating temperature	-110°C

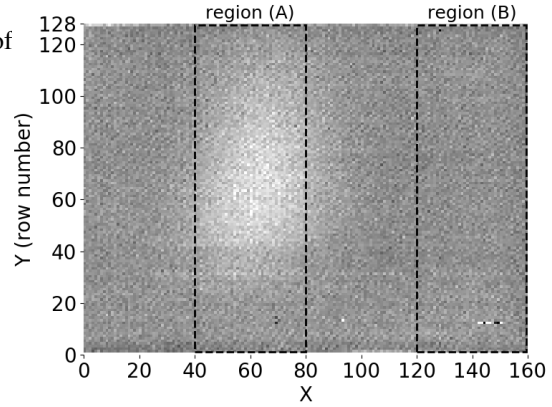


Figure 1. Dark current distribution of the notchless CCD after the irradiation. The lighter the color, the higher the dark current value.

Table 1 shows the specifications and operation parameters of the CCDs under test. The devices are the same as the flight model except for their smaller pixel format [3]. Since the on-chip 2×2 binning is applied, the frame format obtained is effectively a quarter of the pixel format. In order to evaluate the effect of the notch structure, we fabricated two CCDs. One device has a notch structure, and the other does not. We hereafter call them “notch CCD” and “notchless CCD”.

The radiation damage experiments were performed at HIMAC, which is a synchrotron facility for heavy ion therapy at the National Institute of Radiological Sciences in Japan. The beamline used in the experiment was PH1, which can provide a proton pencil beam with transverse profile approximated by Gaussian-shape with a standard deviation of $\sim 1 \text{ mm}$, much smaller than the CCD size of $\sim 7 \text{ mm}$. The beam of 100 MeV protons was directly incident on the devices under atmospheric pressure and at room temperature. We repeated the same experiment for the notch and notchless CCDs, and the numbers of incident protons were 5.64×10^9 and 3.38×10^9 , respectively. After the irradiation, CTI was measured with an ^{55}Fe source at -110°C in our laboratory. Figure 1 represents the dark current distribution of the notchless CCD after the experiment. The notch CCD also showed a similar profile to the distribution. It is clear that pixels with higher dark current are localized due to the concentration of the proton beam around the center of the imaging area. In the following analysis, we focus on region (A) in $40 \leq X \leq 80$ and (B) in $120 \leq X \leq 160$ to represent severely and scarcely damaged areas, respectively (figure 1).

3 Analysis & result

Figure 2 shows the pulse heights of X-ray events produced by the $\text{Mn-K}\alpha$ line from an ^{55}Fe source as a function of the row number of Y. The Y value corresponds to half the number of transfers because of the 2×2 binning. The single pixel events in which signal charges are confined in one pixel are used. In region (B), where the proton fluence was almost zero, pulse heights barely reduce with increment in the number of transfers. On the other hand, the events in region (A), where the

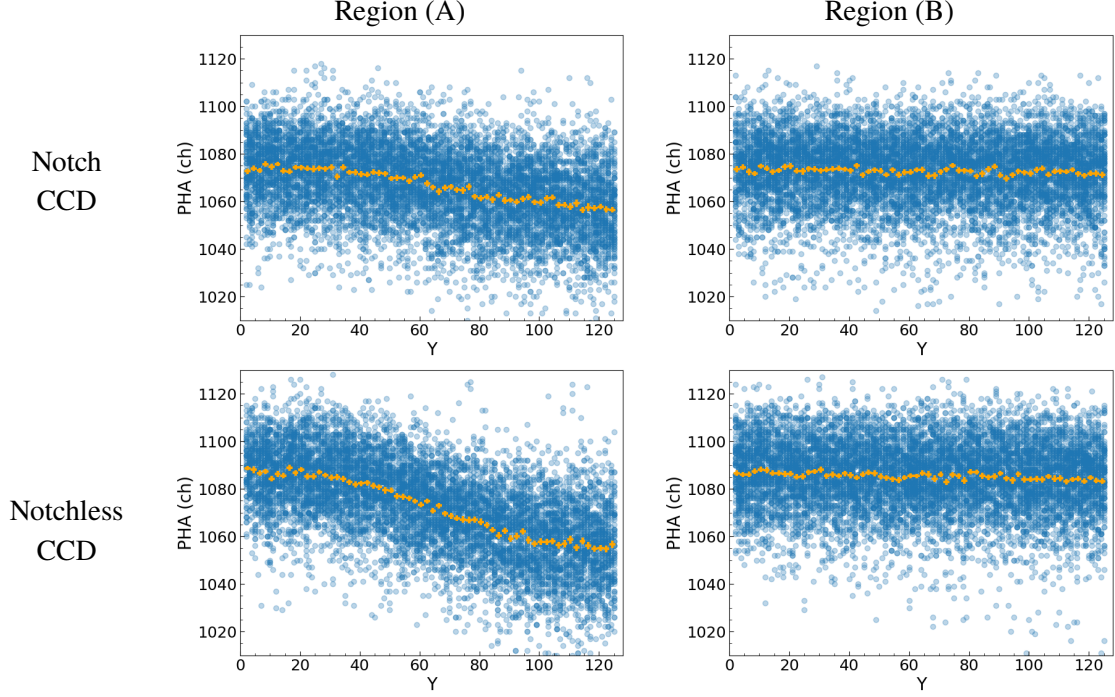


Figure 2. Pulse heights of X-ray event produced by the Mn- $K\alpha$ line from an ^{55}Fe source as a function of the row number of Y. Blue dots show each event and the yellow crosses denote the mean of the pulse height every 2 rows and the standard deviation of the mean. Upper and lower panels show those of the notch and notchless CCDs, and left and right panels show those in region (A) and region (B), respectively.

beam was incident, apparently and non-linearly lost charges as the number of transfers increases. Comparing the notch and notchless CCD results (comparing upper and lower panels), the pulse height reduction of the notch CCD is smaller in spite of the larger total number of the incident protons to the notch CCD. It qualitatively indicates that the CTI degradation of the notch CCD is mitigated by employing the notch structure.

3.1 Measurement of CTI

Defining that CTI_y is the value of the CTI in the charge transfer between the row numbers of y and $y - 1$ in the 2×2 binned format, CTI can be quantitatively evaluated by fitting the pulse heights with the function of the row number as below:

$$\begin{aligned}
 PHA(Y) &= PHA_0 \times (1 - CTI_1)^2 \times (1 - CTI_2)^2 \times \cdots \times (1 - CTI_Y)^2 \\
 &= PHA_0 \times \prod_{y=1}^Y (1 - CTI_y)^2,
 \end{aligned} \tag{3.1}$$

where Y is the row number of a binned pixel at which X-ray is incident, PHA_0 is the pulse height corresponding to the original charge produced by the Mn- $K\alpha$ line, and $PHA(Y)$ is the pulse height observed at the binned pixel with the row number Y . If the CTI_y were constant, the equation (3.1) could be simplified as $PHA(Y) = PHA_0 (1 - CTI_y)^{2Y}$, which well describes the experimental situation

where the radiation damage was uniform across the imaging area [5]. Since the proton fluence differed in each row in this case, the simplified function does not apply. Considering that the beam has a Gaussian-shape profile, we assumed that CTI_y is represented by the following Gaussian function:

$$CTI_y = c \exp \left\{ -\frac{(y - Y_0)^2}{2\sigma^2} \right\} + CTI_{\text{init}}, \quad (3.2)$$

where c is the maximum CTI, Y_0 is the center of the beam axis, σ is the beam width, and CTI_{init} is the initial value of the CTI measured before the experiment.

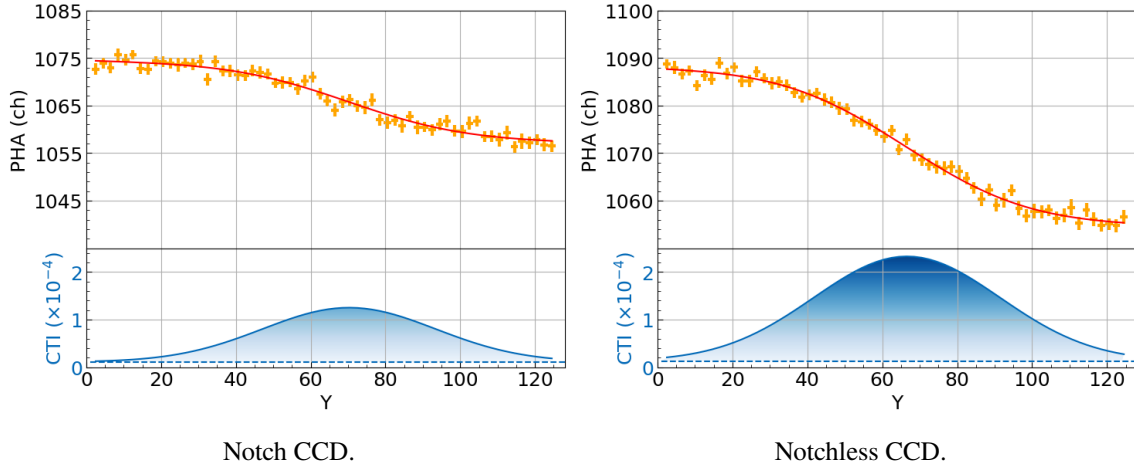


Figure 3. Vertical profile of pulse heights in region (A) (yellow cross) with the best fit function (red line) (upper panel) and the CTI_y (blue solid line) with the initial CTI value (blue dotted line) (lower panel) as a function of the row number of Y . The data of the pulse heights are the same as shown in figure 2.

Figure 3 shows the fit results. All datasets are well described by the composite model consisting of the equations (3.1)–(3.2), and the parameters obtained are reasonable. For example, Y_0 in the notchless CCD case was 66.6 ± 1.1 , which matches the peak of the dark current distribution shown in figure 1 and where the pulse height reduction is the largest. The same applies to the notch CCD case.

3.2 Estimation of the proton fluence in each row

In order to quantify the relation between the CTI and the radiation damage at each row, the proton fluence in each row also needs to be estimated. Since the total number of the incident protons to the imaging area was measured, the proton fluence in the row of y was estimated by integration of the beam distribution:

$$\Phi(y) = n_p \int_{Y=y}^{Y=y+1} \int_{X=40}^{X=80} f(X, Y) dX dY, \quad (3.3)$$

where $\Phi(y)$ is the proton fluence in the row of y , n_p is the total protons incident to the imaging area, and f is a normalized beam distribution. We approximated the beam distribution as a 2D Gaussian function. The value of the vertical width was taken from the CTI model fitting described above while that of the horizontal width was estimated by fitting the horizontal profile of pulse heights with the Gaussian function as shown in figure 4. This horizontal profile was made from the single pixel events in the region of $40 \leq Y \leq 80$ where the damage was the most severe. The vertical and horizontal

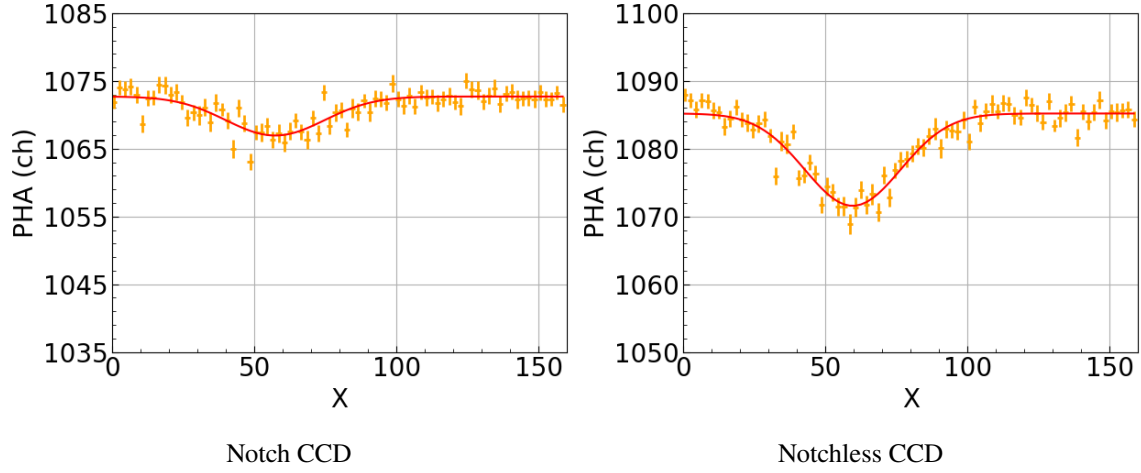


Figure 4. Horizontal profiles of pulse heights (yellow cross) with the best fit function (red line).

widths in the notchless CCD case were 0.81 ± 0.03 mm and 1.19 ± 0.08 mm, respectively. Similar values were obtained in the notch CCD case. These values were consistent with those measured at the beam monitor in the upper stream of our system [10], especially in terms of the ratio of the vertical and horizontal widths. In our estimation, the notch and notchless CCDs were irradiated by up to $\sim 7.9 \times 10^{10}$ protons cm^{-2} and $\sim 4.5 \times 10^{10}$ protons cm^{-2} in the highest fluence area, respectively.

3.3 Evolution of CTI as a function of the equivalent time in orbit

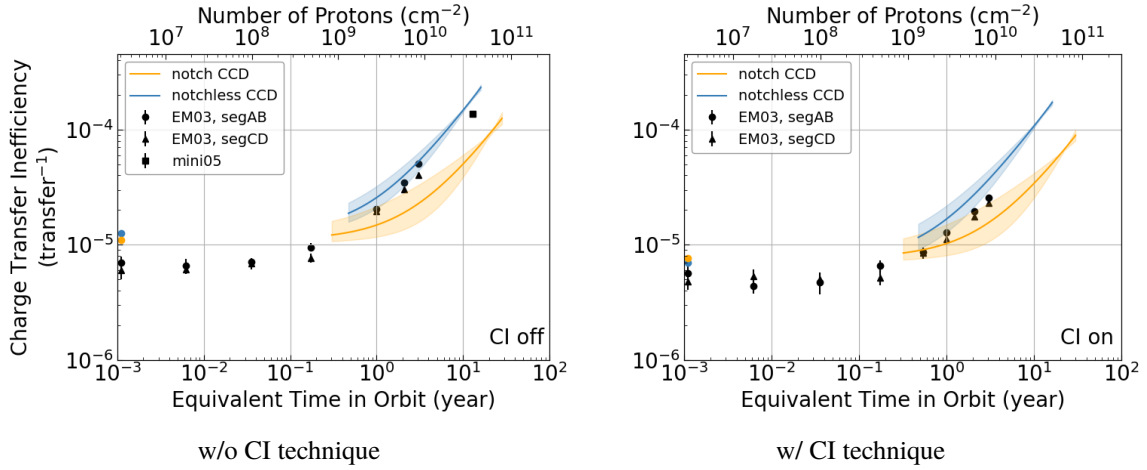


Figure 5. CTI as a function of equivalent time in orbit. The vertical axis is CTI and the horizontal axis on the bottom is the equivalent time in orbit, which is converted from the proton fluence on the top axis [5]. The blue and orange lines show the results of the notchless and notch CCDs, respectively. The blue and orange dots at 10^{-3} years indicate the initial CTI values before the experiments. The black dots show the results of our previous measurement for the Hitomi CCD [5].

Figure 5 shows the CTI as a function of the equivalent time in the low earth orbit where the XRISM satellite is planned to be injected. This figure basically plots CTI_y vs $\Phi(y)$ obtained above,

and $\Phi(y)$ is converted to equivalent time in the XRISM orbit following Mori et al. (2013) [5]. It is clear that the introduction of the notch structure mitigates the increase of CTI by a factor of 2–3 (comparison between blue and orange lines). Comparison with our previous measurement of the notchless Hitomi CCD, which was performed with an ^{55}Fe source at -110°C , also shows the effectiveness of the notch structure (comparison between black dots and the orange line). Since we had already shown that even the notchless CCD adopted for Hitomi was radiation tolerant enough for space use [5], these results suggest that our new notch CCD has a sufficient margin of radiation tolerance for the application to XRISM. We also confirmed that the CI technique effectively works for both types of the CCDs (comparison between left and right figures).

4 Discussion

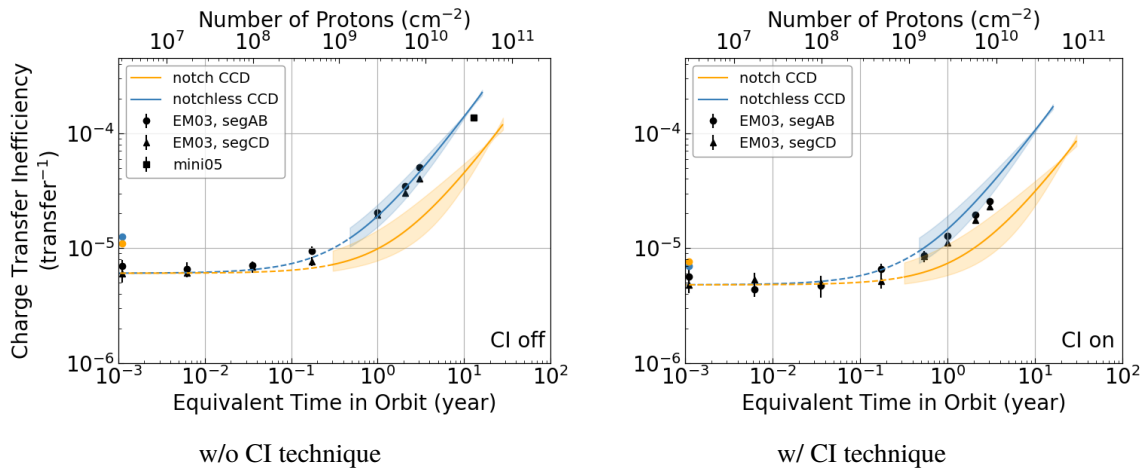


Figure 6. Same as figure 5 but the initial CTI values of the notch and notchless CCDs used in this experiment are hypothetically set to the same value of the Hitomi CCD. The dotted lines are the eye guide to clarify the hypothetical situation.

We performed proton radiation damage experiments on our newly developed notch CCD and previously developed notchless CCD, and verified the effectiveness of the notch structure in this simple control experiment. The introduction of the notch structure improved radiation hardness of our device by a factor of 2–3. Other experiments using different manufacturing p-channel CCDs have also reported a similar degree of improvement from comparisons of their notch and notchless devices [8, 11]. We note that experimental conditions, such as proton beam energy and CCD working temperature, are different among experiments including ours. Although the detailed manufacturing processes regarding the notch implant of each device are not available, this might suggest that the width ratios between the notch implant and the channel are similar to each other.

The notchless CCD is basically the same as that adopted for Hitomi and thus it is expected that their radiation hardness is comparable. However, in figure 5, the CTI degradation of the notchless CCD used in this experiment appears to be greater than or equal to that of the Hitomi CCD (comparison between the blue line and black dots). Figure 6 is the same as figure 5 but the initial CTI values of the notch and notchless CCDs used in this experiment are hypothetically set to

the same value of the Hitomi CCD. Here, we only changed the initial CTI values and the rest of the parameters in the equations (3.1)–(3.2) are fixed to the best fit values. Although the hypothetical notchless CCD curves are yet to correspond completely to the Hitomi CCD data, the initial CTI value differences may be a part of the reasons for the difference between the notchless CCD and the Hitomi CCDs in figure 5.

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