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Radiation damage testing status of the CCDs for the SMILE SXI

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ABSTRACT

The joint European Space Agency and Chinese Academy of Sciences Solar wind Magnetosphere Ionosphere Link Explorer mission (SMILE) aims to develop a global scale understanding of the interaction between the solar weather and the Earth's magnetosphere-ionosphere. The soft X-ray imager (SXI) is one of the instruments on board and will observe photons emitted in the 200 eV to 2000 eV energy range from the solar wind charge exchange process using two large 4510 x 4510 pixel CCD370s as a focal plane. The CCD370s take their design and qualification heritage from similar sensors being used in the PLATO mission, with specific modifications to optimize their performance in this soft X-ray energy range.

SMILE will orbit Earth in a highly elliptical orbit and will pass through the radiation belts every 52 hours. The trapped and solar protons present will gradually damage the CCDs throughout the 3-year mission and degrade their performance. To understand the impact the damage has on the devices a series of proton radiation campaigns are being undertaken. These campaigns are being performed with flight-like SMILE CCDs, and functionally similar PLATO devices, with follow-up characterization across from -130 to -85 °C.

The most recent irradiation campaign has been completed using a PLATO CCD280 kept below -85 °C for irradiation and characterization, and the results show that the measured parallel charge transfer inefficiency varies with temperature between 1×10^{-4} and 4×10^{-4} in unbinned full-frame readout mode. The effect of temperature annealing up to -85 °C on the parallel charge transfer inefficiency has also been assessed and shows that no temperature-dependent annealing of the radiation-induced damage has been observed. A similar behavior is expected to be seen in the SMILE devices, albeit with an anticipated improvement by a factor 3-4 due to the modifications made to the design. Thus, results indicate the SMILE CCD370s will meet the performance requirements of the SMILE SXI instrument.

Keywords: CCD, temperature annealing, radiation damage, X-ray detectors, SMILE

1. INTRODUCTION

The Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) is a joint mission between the European Space Agency (ESA) and the Chinese Academy of Sciences (CAS) [1]. The aim of SMILE is to develop the understanding of the Sun-Earth connection, for the first time on a global scale, by observing the solar wind interacting with the magnetosphere. This will be achieved with a suite of instruments consisting of the Soft X-ray Imager (SXI), the Ultra-Violet Imager (UVI), the Light Ion Analyser (LIA) and the Magnetometer (MAG). The SXI will observe emission from the solar wind charge exchange (SWCX) process which generates low energy X-rays in the 0.2 - 2.0 keV energy range [2][3]. SMILE will have a highly elliptical polar orbit and throughout its 3-year mission will receive radiation damage from trapped and solar protons [5], which combined with the small signals to be detected and the direct path for any radiation through the micro pore optics (MPOs) means that understanding how the performance of the CCD370s within the SXI changes through their lifetime is essential for assessing whether the science goals will be achieved.

The SMILE SXI will have two large CCD370s as its focal plane array which have been adapted from the CCD270s used on the optical imaging PLATO mission to maximize its efficiency for low flux, low energy signals [4]. The improvement in charge transfer inefficiency (CTI) has been achieved by the inclusion of a supplementary buried channel (SBC) which reduces the number of lattice defects encountered by a charge cloud during parallel transfer by shrinking it into a smaller volume [6]. Similarly, radiation tolerance of the serial transfer process has been improved by narrowing the channel of the serial register. Finally, the responsivity of the two outputs in the device have been increased from ~ 2 to ~ 7 $\mu\text{V}/\text{electron}$ by boosting the gain of the output amplifier to reduce the readout noise, which is particularly important at these soft X-ray energies where the smallest signals must be detected above the noise floor.

The work presented in this manuscript has been carried out by the Centre for Electronic Imaging at The Open University to investigate the performance of a PLATO test device (the CCD280) after being irradiated by 7.4 MeV protons at the nominal operating temperature of -120 $^{\circ}\text{C}$ to predicted end of life (EOL) fluence in two $\frac{1}{2}$ EOL steps as part of the SMILE radiation damage study. This work is being performed to prepare for later cryo irradiations on the SMILE devices (CCD380/370), for early readout optimization work, and to provide information for the SMILE modelling activities. The focus of this paper will be on the X-ray parallel CTI results gathered at beginning of life (BOL) and EOL.

2. METHODOLOGY

2.1 Devices Under Test

Throughout the SMILE SXI radiation damage campaigns there are two different device types used: the PLATO CCD280/270s and the SMILE CCD380/370s. Each type has a full-size flight-like device (CCD 270/370s) and smaller test vehicles (CCD 280/380s) which are cut from the same wafers and are functionally the same as the flight-like devices but have 1552×1280 pixels and one readout rather than the 4510×4510 pixels and two outputs of the larger devices. All devices have a store area which covers half of the device with the exception of the CCD370 which covers $\frac{1}{7}$ th of the pixels to enable 6×6 binning, all devices can be run in full frame and frame transfer mode. The results presented in this paper are from a CCD280 run in unbinned full frame mode.

2.2 Irradiation Schedule

The SMILE SXI radiation damage test schedule is split into the four separate campaigns illustrated in Table 1 and begins with irradiations of Plato CCD280s at room temperature (RT) and the nominal -120 $^{\circ}\text{C}$ operating temperature to firstly establish test procedures for the irradiation and characterization, and secondly to measure realistic trap effects at a temperature similar to that found during flight. The CCD280s are optimized for the PLATO mission however they are functionally very similar to the SMILE devices and so are the ideal test device to study whilst CCD380/370s are being manufactured [7].

As part of the preliminary studies in 2016 for SMILE, a room temperature irradiated PLATO CCD270 (serial number 11363-20-01) was characterised whilst using the predicted SMILE-SXI operating conditions (100 kHz line speed and between -125 and -80 $^{\circ}\text{C}$) by ESTEC. This data was subsequently used to form the basis of the performance predictions for the SMILE CCDs and provides a useful comparison for the more recent CCD280 irradiations.

Excluding the SMILE RT campaign, each device is planned to be irradiated in two equal steps up to the EOL fluence predicted using modelling of the radiation environment throughout the mission. Each CCD goes through a pre-irradiation characterization phase where the dark current (and bright defects), charge injection uniformity, radiation-induced trap landscape, and CTI are measured across the -130 to -85 $^{\circ}\text{C}$ temperature range. After the first half EOL cryogenic irradiation the device is briefly characterized at the nominal operating temperature and the device is then irradiated up to EOL. In the schedule in Figure 1 a characterization stage occurs at each horizontal section and it shows that after irradiating the CCD temperature is lowered to -130 $^{\circ}\text{C}$ and characterized before gradually increasing up to -85 $^{\circ}\text{C}$ in 5 $^{\circ}\text{C}$ steps. After each warming stage the device is then re-characterized at -120 $^{\circ}\text{C}$ to assess the impact of any annealing that has taken place.

Table 1: SMILE SXI proton irradiation damage schedule, grey shading indicates completed campaigns.

Device No.	Irradiation step	Temperature during irradiation (°C)	10 MeV proton equivalent fluence (protons.cm ⁻²)	Comment
280 (small PLATO)	1	RT	3.43×10 ⁹ (EOL)	Establish procedures, compare results with ESTEC CCD270.
280 (small PLATO)	1	-120	2.06×10 ⁹ (½ EOL)	Realistic trap effects from cryo irradiation, on a CCD280
	2	-120	0.82×10 ⁹ (additional 20% EOL)	
380 (small SMILE)	1	-120	½ EOL	SMILE device irradiation at operating temperature
	2	-120	EOL	
370 (full SMILE)	1	-120	½ EOL	Any delta effects from large scale device and frame transfer architecture
	2	-120	EOL

Figure 1. Radiation damage campaign characterisation schedule. Measurements are taken at each horizontal section.

2.3 Experimental Setup

The equipment setup used is shown in Figure 2, where the device is mounted inside the vacuum chamber by clamping the CCD onto a copper cold bench which is connected to a CryoTiger® refrigeration system (PT-30), as in Figure 3a. The thermal control is provided through using a resistive heater in thermal contact with the cold bench, allowing an operating temperature range of -135 to -80 °C before overloading the cooling capacity of the CryoTiger®. Temperature control is provided to within 0.1 °C using a feedback system, composed of a Lakeshore 325 temperature controller, the heater, and a 1 k Ω platinum resistance thermometer in the CCD package. A removeable Fe55 source is used to provide a known signal (5898 eV) for calibration and CTI measurements and optical illumination is provided using a 660 nm LED mounted at the rear of the chamber. Clocking and biasing are provided by an XCAM Ltd USB2REM1 camera drive box in conjunction with custom drive software designed to operate using MATLAB.

The system relies on shields which are placed in front of the CCD with a 2 mm gap between the detector surface and the shield. The region to be shielded in the CCD280 is shown in Figure 3b and uses a 1 cm thick steel shield to protect the image area around the readout electronics, this enables the post irradiation parallel CTI to be measured without including any serial CTI. During the irradiation and subsequent testing, the system is powered continuously and has been designed to have sufficient thermal mass of copper and steel to limit the impact of any short-term power loss on the temperature of the device.

Figure 2. The portable test setup for the SMILE CCD cryogenic radiation damage campaign at the test facility

Figure 3. CCD280 A) Mounted onto copper cold bench prior to loading into vacuum chamber B) Shielding layout during proton irradiation

2.4 Test facility

The facility used for the irradiation is the Synergy Health 5MV Tandem accelerator at the Harwell Campus, England and a flux of approximately 1.84×10^7 protons. $\text{cm}^{-2}.\text{s}^{-1}$ with 7.4 MeV protons is used to provide a total of 70% EOL fluence through one $\frac{1}{2}$ EOL 2.06×10^9 proton (10 MeV equiv.). cm^{-2} fluence and in this irradiation one additional 20% EOL 0.76×10^9 proton (10 MeV equiv.). cm^{-2} fluence.

2.5 Test Conditions

The focus of this paper are the parallel CTI results as they are most important in terms of assessing the expected degradation in performance of the SXI CCDs in the SMILE case. This is due to the large number of parallel transfers the average X-ray charge packet will go through. The serial register of the CCD370 is split with an output at each end, halving the average number of serial transfers a charge packet will go through, and the presence of additional shielding above the store area in the flight instrument design will greatly reduce the dose the serial register will receive. CTI has been measured using stack line trace methods with Fe-55 X-ray photons, as this mode is most representative of the SMILE SXI science operations. The test conditions used to capture these images are summarized in Table 2. An example image recorded during testing is shown in Figure 4. To analyse the images, all X-rays are identified, and then the X-rays where signal is split across multiple pixels from charge diffusion are discarded. A further down-selection process is used to select the single-pixel X-rays that have an energy within the characteristic Fe55 $\text{K}\alpha$ spectral line. X-rays are grouped by location (e.g. row number) and their energy spectrum is produced (such as in Figure 5). The photopeak energy in that area of the device is identified via a Gaussian fit. The position of the photopeak and its position in the image are then combined to generate Figure 7 which shows how the measured X-ray signal decreases the further a charge packet has to travel through the device.

The CTI is calculated by fitting to this plot, ideally using the non-linear Equation 1.

$$\text{Charge Remaining} = \text{signal} * \text{CTE}^n \quad (1)$$

$\text{CTE} = \text{Charge Transfer Efficiency}$, $n = \text{number of transfers}$

However as shown by the dashed overlaid traces in Figure 7 a good fit is not possible at higher values of n which indicates that another mechanism is affecting the CTI which is not accounted for in Equation 1. The same initial non-linear feature for low numbers of transfers has been seen previously in testing for CCDs on the Euclid VIS instrument at longer integration times and is shown in Figure 8 [8]. This effect is thought to be caused by the signal electrons in that region seeing a lower number of longer-emission-time (slow) traps due to travelling through fewer unfilled slow traps; in general, the X-ray signal will travel through the number of slow traps between X-ray events (as once filled they can no longer trap charge). As a fit using all the parallel transfers will give an inaccurate measurement, the CTI in this study is therefore calculated with the first 400 rows nearest the readout excluded. This means that the X-ray CTI values quoted only assess the charge lost from the fast traps due to the fit ignoring the initial step change and the actual charge loss is potentially worse, however, as the SXI will be operating with a 7s integration time it is expected that the impact of slow traps will be minimised.

The CTI is reported using two methods to measure the signal of the X-ray events. The first method uses only the signal from the main pixel in the X-ray event (Figure 6A). The other method, called “summed CTI smear”, gives an initial indication of simple CTI recovery by summing the central pixel and the first pixel in the parallel and serial tails (i.e. gives an indication of signal that will be able to be directly recombined into an X-ray energy by the ground data pipeline). The pixels whose signals are summed in the “summed CTI smear” method are indicated in Figure 6B.

The SMILE CCD incorporates a charge injection structure at the top of the image array that can be used to inject a fixed level of charge to be transferred through the pixel array with the aim of filling the slowest traps and hence improve the CTI. In the images testing the impact of charge injection, 2 rows are injected and transferred through the array to be held just before the readout register before and throughout the integration time.

Table 2: X-ray CTI test conditions used throughout the cryogenic CCD280 proton irradiation campaign

Variable	Setting
Integration Time (s)	300
X-ray density (X-rays.pix ⁻¹)	1/2500
Charge Injection Level (e ⁻)	~8500
Temperature (°C)	-130 to -85
Readout	Full frame
Number of Images per variable	50
Background Illumination signal level (e ⁻)	5

Figure 4: Section of an X-ray CTI image with 1x2 rows of ~8500e⁻ charge injection visible at top, close to the serial register.

Figure 5: Gaussian fit to Fe55 ka events in a section of the irradiated area of the CCD280 at -100 °C

Figure 6: The average pixel values of observed X-ray events used to calculate CTI in A) Central Pixel and B) Summed Smear results

Figure 7: -100 °C X-ray parallel CTI with overlaid linear and non-linear fits showing how the inclusion of the first ~400 parallel transfers can generate poor fits when slow traps are present

Figure 8: Example Euclid X-ray CTI on an irradiated device showing how the impact of slow traps increases with integration time [8]

3. RESULTS

3.1 X-Ray Parallel CTI Characterisation

The parallel CTI (pCTI) values are plotted against temperature in Figure 9 to Figure 12, results are shown for calculations using the central pixel and when summing the CTI smear in the surrounding pixels.

The BOL parallel CTI is calculated when the CCD is unirradiated, the result in Figure 9 shows that it stays approximately constant within error at $\sim 3\text{e-}6$. The post irradiation cryogenic CCD280 results show that at 70% EOL the parallel CTI has degraded by a factor of ~ 100 which appears to be worst at $\sim -110^\circ\text{C}$, which is thought to be due to different trap species beginning to dominate.

The RT parallel CTI results in Figure 9 are, as expected, better than the cryo due to more traps annealing whilst the CCD is at RT. However, the significantly higher X-ray density used within the CCD280 RT campaign (1 X-ray per 110 pixels) will also improve the CTI due to more X-ray signal charge clouds being transferred through the trap sites causing some of them to capture but release before the next cloud arrives. Therefore, this should be kept in mind when comparing the results.

Figure 9: Cryogenic X-ray parallel CTI without any lines of charge injection for BOL and 70% EOL, compared against EOL RT irradiation and ESTEC CCD270 data

Figure 10: X-ray parallel CTI with and without 1 line of ~ 8500 e^- charge injection from the irradiated area of the CCD280, compared against PVH irradiated CCD270 data

The results in Figure 10 show how parallel CTI is impacted by transferring 2 lines of ~ 8500 e^- charge injection through the image first. There is a 10-20 % improvement in CTI when charge injection is used between -130 to -110 °C due to the traps being prefilled by the injected charge. The improvement is less significant at higher temperatures because the traps emit captured charge injection electrons more quickly and hence the charge injection has a more limited impact.

Across both charge injection and no charge injection cryogenic datasets the measured CTI is worse than that seen by ESTEC in an RT irradiated CCD270 and in the CCD280 RT data. This is mainly due to the lack of temperature induced trap annealing however the clocking scheme used is also different between the ESTEC and OU.

As expected, summing pixels surrounding an X-ray to recover the smeared charge improves the CTI. This improvement will be harnessed by the on-chip 6×6 pixel binning planned for the in-flight SMILE device operation. Recombination of smeared X-ray charge will also be investigated to be applied in the radiation correction algorithm of the ground software pipeline, but at this stage the recombination does not assist with identifying the lowest energy X-rays above the detector noise floor and results in degradation of instrument energy resolution.

After taking the instrument optical baffle and optical blocking filter applied to the micro-pore optics into account, the focal plane is expected to observe a background optical/UV signal in the order of 5 electrons/bin pixel. This background signal is expected to vary throughout the year, with the moon's location, and with the astronomical background. To simulate this a 660 nm LED is flashed at the beginning of the integration to provide 5 electrons/native pixel which is the upper limit for the diffuse straylight in orbit. The results in Figure 11 and Figure 12 show that the background illumination improves the parallel CTI by $\sim 15\%$ at -120°C without and $\sim 10\%$ with a charge injection line

passed through the image first. The reduction in impact of the background illumination is expected when combined with charge injection as the number of unfilled traps is reduced. Above -100°C the illumination has a lower impact and becomes difficult to quantify due to the error on the CTI measurement.

Figure 11: X-ray parallel CTI with and without $5e^-$ background illumination

Figure 12: X-ray parallel CTI with and without $5e^-$ background illumination and charge injection

3.2 X-ray Parallel CTI Annealing

For the SMILE mission the CCDs non-operating temperature requirement is between -130 to -85 °C and it is expected to vary within that range due to the changing solar cycle. This will impact the trap population present within the proton damaged CCDs as traps are susceptible to temperature annealing and their concentration can change very quickly [9]. It is therefore important to assess how this impacts the CTI by carrying out the temperature cycling described in Figure 1. Simulations carried out by Space Acoustics under contract of Swiss organization FHNW is demonstrating thermal control for operations to be well within the instrument requirement limits and the worst case is expected to be between -125 to -106 °C [10].

The results in Figure 13 clearly show that warming the CCD280 from -120 °C to -85 °C before measuring again at the nominal operating temperature has no measurable impact on the parallel CTI. This remains the case with a charge injection line included and with a 25 day anneal at -120 °C after warming to -100 °C. From the experience of the Euclid keep-cold campaign, it is understood that the lack of impact of annealing on the CTI is due to the number of traps in the trap landscape only reducing slightly with a portion of those only moving from the continuum and into the divacancy peak where their emission time constant is not different enough to change the amount they affect the CTI. The presence of the traps within the trap landscape has previously been studied through trap-pumping [11][12][13][14][15][16][17] and it has been shown that the CTI is directly related to the traps found through these methods [18].

Figure 13: Impact of temperature annealing on X-ray parallel CTI with and without one line of 8500 e⁻ charge injection. Plot also shows the parallel CTI after a 25 day anneal at -120 °C, after warming up to -100 °C

4. CONCLUSIONS

Throughout the course of the SMILE mission the SXI CCDs will be damaged by radiation which over time causes a degradation in their performance. In order to understand the impact of the damage and hence be able to prepare for countering its effects four proton irradiation campaigns have been planned, which start with a room temperature

irradiation of a PLATO CCD280 for developing tests procedures and culminate in a cryogenic irradiation of a SMILE CCD370.

The majority of this paper focusses on the X-ray parallel CTI results from the cryogenic CCD280 campaign which varies with temperature between 1×10^{-4} and 4×10^{-4} in unbinned full frame readout mode and has a factor of one hundred degradation from the BOL performance to the 70% EOL and an approximate factor of ten difference between the room temperature and cryo results due to the temperature annealing. The prefilling of traps through optical loading shows an 10-15% improvement in parallel CTI and including one line of 8500 e^- charge injection in the image can improve it by a further 10 – 20 % at temperatures below -110 °C. The largest part of the testing comprises of the temperature cycling between -130 to -85 °C. This assesses whether incrementally increasing the temperature changes the performance of the CCD due to the traps created in the irradiation annealing and no longer impacting the parallel CTI. The results however show that warming up to -85 °C has no detectable impact on the parallel CTI in the CCD280 and it is thought to be because that whilst the trap landscape will change with the anneal the majority of changes will not have a significant enough effect on the emission time constant of the traps to change how they degrade the parallel CTI.

In terms of the SMILE mission the consistency of the parallel CTI across the tested temperature range shown here is a good indicator that a similar behavior will be seen in the CCD370s. This is beneficial since any correction of the images to counter the effect of CTI will not have to take the thermal history of the focal plane into account.

Analysis of this irradiated device performance is continuing, by investigating the operational parameter space for optimizing the read-out scheme to improve the CTI performance from the baseline reported here, and to study the device performance during in a frame transfer clocking mode more representative of SMILE SXI's in-flight operation. With the last of the CCD280 campaigns complete, the preparation for the first SMILE CCD irradiation is underway and scheduled for early 2021.

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