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SMILE Soft X-ray Imager (SXI) CCD370 proton irradiation results

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ABSTRACT

The SMILE mission, a collaborative effort between the European Space Agency and the Chinese Academy of Sciences, seeks to enhance our comprehension of the interplay between solar phenomena and the Earth's magnetosphere-ionosphere system on a global scale. Among its instrumental arsenal is the Soft X-ray Imager (SXI), designed to capture photons generated within the 200 eV to 2000 eV energy spectrum through the solar wind charge exchange process. This imaging tool employs two large CCD370s, each with 4510 x 4510 18 µm pitch pixels, as its focal plane.

SMILE will orbit Earth in an elliptical trajectory, traversing the radiation belts approximately every 52 hours. Over the course of its anticipated 3-year mission, the CCDs onboard will endure progressive deterioration from the persistent presence of trapped and solar protons. To gauge the extent of this damage and its effect on the devices' functionality, a sequence of proton radiation campaigns is underway.

The final cryogenic irradiation campaign has now been completed using a fully functioning engineering model of the SXI CCD370s that will be used in flight and irradiating up to the expected end of life total non-ionising dose. The results show that the measured parallel charge transfer inefficiency (pCTI) varies with temperature both before and after irradiation, however the trend changes from decreasing with temperature to increasing. This is thought to be due to a change in the dominant effective trap species. The impact of multiple charge injection lines and 6x6 binned frame transfer is also assessed and shows that between -130 to -100 °C the pCTI, when both measures are utilized, is independent of temperature. This suggests potential for more flexible thermal controls in future missions that use similar devices.

Keywords: CCD; soft X-ray imager; characterisation; SMILE; cryogenic; proton irradiation; Charge transfer in-efficiency

1. INTRODUCTION

The European Space Agency (ESA) and the Chinese Academy of Sciences (CAS) have collaborated to create the Solar Wind Magnetosphere Ionosphere Link Explorer (SMILE) mission [1]. SMILE aims to enhance our understanding of the connection between the Sun and Earth on a global scale by observing the interaction between the solar wind and the magnetosphere. To accomplish this, SMILE is equipped with a range of instruments including the Soft X-ray Imager (SXI), the Ultra-Violet Imager (UVI), the Light Ion Analyser (LIA), and the Magnetometer (MAG). The SXI, operating within the 0.2 - 2.0 keV energy range, will specifically capture emissions resulting from the solar wind charge exchange (SWCX) process [2][3]. Operating within a highly elliptical polar orbit, SMILE will endure radiation exposure from both trapped and solar protons throughout its 3-year mission [4]. Given the susceptibility of the detectors to radiation because of the direct line of sight through the micro pore optics (MPOs), coupled with the delicate nature of the signals to be detected, it is crucial to monitor the performance of the imagers within the SXI over their operational lifespan to ensure the scientific objectives are met.

Charge-Coupled Devices (CCDs) stand as a well-established choice for focal plane detectors, widely utilized in numerous space missions owing to their capacity to deliver high-quality data with minimal noise and dark current. Nonetheless, the space environment where they operate gradually damages the silicon within the detector. Particularly in missions orbiting Earth like SMILE, high-energy protons cause disruptions in the uniform lattice structure by displacing silicon atoms, forming vacancies. These vacancies traverse the lattice until they stabilize into defects like divacancies or Silicon E-centers, thereby introducing additional energy levels or "traps" between conduction and valence bands. These

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traps can intercept electrons during signal transfer through the device, releasing them later based on each trap's emission time constant, a phenomenon elucidated by the Shockley-Read-Hall theory [5][6]. This effect leads to increased charge transfer inefficiency (CTI), resulting in image degradation due to charge loss or smearing. The emission time constant of each trap varies with temperature. Thus, to accurately predict the impact of traps in an irradiated CCD during its mission, characterization must be conducted under intended operational temperature conditions.

Conventionally, this has been achieved by irradiating at room temperature and subsequently cooling the device under vacuum for testing. However, research demonstrates that devices begin to anneal almost immediately after irradiation, as the traps' activation energy is met by thermal energy from the environment, irreversibly altering the trap landscape and device performance. Consequently, it has become more common to irradiate a device at its operating temperature and maintain that temperature throughout testing to preserve a mission-like landscape and improve result accuracy. This paper, conducted by the Centre for Electronic Imaging at The Open University, examines the performance of a CCD370 post-irradiation by 10 MeV protons at the nominal SMILE SXI operating temperature of -120 °C, to a fluence of 4×10^9 protons/cm^2, as the final part of the SMILE radiation damage studies. It focuses on the temperature dependance across -130 to -100 °C of parallel CTI measured using 3 different low energy X-ray sources which vary from 1.5 keV to 6 keV and the extent to which injecting rows of charge into the image area and 6x6 binning via frame transfer readout helps recover device performance after receiving an end-of-life proton fluence.

2. METHODOLOGY

Device under test

The CCD370 is a large 2 node device and the version used in this test campaign is an engineering model (EM) of the ones that will be used in the SXI during flight with the only difference being cosmetic imperfections on the EM, the specifications are summarized in Table 1.

Table 1. CCD370 design specifications

Specification	Value
Image area size	3791 rows x 4510 columns
Store area size	719 rows x 4510 columns
Pixel size	18 x18 µm
Silicon thickness	16 µm
Serial registers	1
Output nodes	2

Experimental Setup

A bespoke vacuum enclosure facilitated the characterization of the CCD, allowing for cooling between -130 to -100 °C and incorporating a 3 mm aluminum window to enable the protons to enter the chamber from the in-air beamline. X-ray analysis is performed utilizing an Oxford Instruments Jupiter 5000 X-ray tube and the k-alphas of 3 retractable fluorescence targets, Manganese, Calcium and Aluminum which provide X-rays of 5.9, 3.7 and 1.5 keV respectively. Additional information on a comparable configuration can be found in [7]. To create unirradiated areas of the CCD 10 mm thick retractable steel shields were used as in Figure **1**, this enabled serial and parallel CTI measurements to be carried out in insolation and for the device to be irradiated in quadrants. Charge injection images were not taken in the pre-irradiation characterization stage as there will be minimal performance gains, if any, due to the low trap numbers.

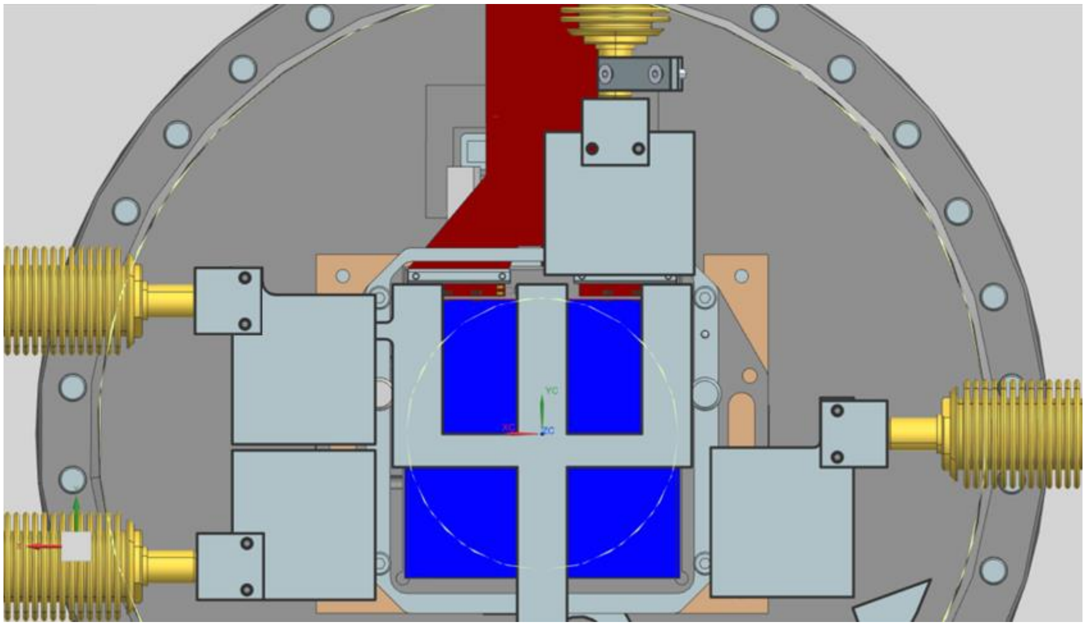

Figure 1. CAD model of CCD370 (in blue) shielding design with the serial readout at the top of the device

Test Facility

The facility used for the irradiation is the MC40 Cyclotron at Birmingham University, England and a flux of approximately 2×10^8 protons.cm^{-2}.s^{-1} with 10 MeV protons is used to provide a total fluence of $4\text{x}10^9$ proton (10 MeV equiv.).cm^{-2} through two irradiations of $2.0\text{x}10^9$ proton (10 MeV equiv.).cm^{-2} on each quadrant, the beamline and device setup are summarised in Table 2.

Table 2. CCD370 proton irradiation characteristics.

Specification	Value
Device temperature during irradiation (°C)	120
CCD Biasing	Running
Proton Energy (MeV)	10
Total 10 MeV proton equivalent fluence (protons.cm^{-2})	$4.0\text{x}10^9$
Flux (protons.cm^{-2}.s^{-1})	$\sim2\text{x}10^8$

Test Conditions

The X-ray CTI has been measured using the stack line trace method [7], the test conditions are summarized in Table 3 and have been chosen to approximate the conditions the CCDs will experience during flight. Measurements both before and after irradiation have been obtained. The performance improvements that can be achieved by injecting rows of charge have been assessed by using varying numbers of injected rows spread evenly though the image/store area and recording the X-ray CTI.

Table 3. X-ray CTI test conditions used throughout the cryogenic CCD370 proton irradiation campaign.

Variable	Setting
Integration Time (s)	10
X-ray density (X-rays.pix^{-1})	~1/3600
Temperature (°C)	-130 to -100
Readout	Full frame and frame transfer (6x6 binned)
Number of images per variable	>60
Native pixel readout speed (kHz)	100
Charge injection signal level (e^-)	~10,000

3. RESULTS

To provide a more complete picture of how the CCDs performance changes due to proton damage a thorough pre-irradiation characterization is carried out. The dashed pCTI results in Figure 2 to Figure 5 show the beginning of life pCTI and that it gradually improves with temperature in both full frame and frame transfer readout modes, this matches the results seen in the flight devices [8]. The results are summarized in Table 4 for the nominal operating temperature of -120 °C.

After irradiation there is a distinct change in the temperature dependence, which can be seen clearly in the full frame data in Figure 2 and Figure 3, where the device warming degrades the CTI. This is due to the numbers of traps present within the CCD silicon drastically increasing and the dominant trap species over -130 to -100 °C changing so that it affects the CTI more as temperature increases. However, as lines of charge injection are added and the readout mode changes to 6x6 binned frame transfer from full frame it gradually lessens across the temperature range assessed. The results in Figure 5 clearly show that with 5 lines of charge injection and frame transfer parallel CTI has been largely decoupled from its temperature dependance. This is due to the presence of the charge injection lines prefilling the traps prior to readout so that many of them will not capture from the X-ray's charge cloud and the 6x6 binning collecting the majority of the remaining trailing charge tail so that it is not disconnected from the X-ray event. All of the post irradiation CTI results shown have been linearly scaled to a fluence of $3.1\text{x}10^9$p.cm^{-2} to match the current 95 % confidence level estimation of the SMILE SXI end of life total non-ionizing dose.

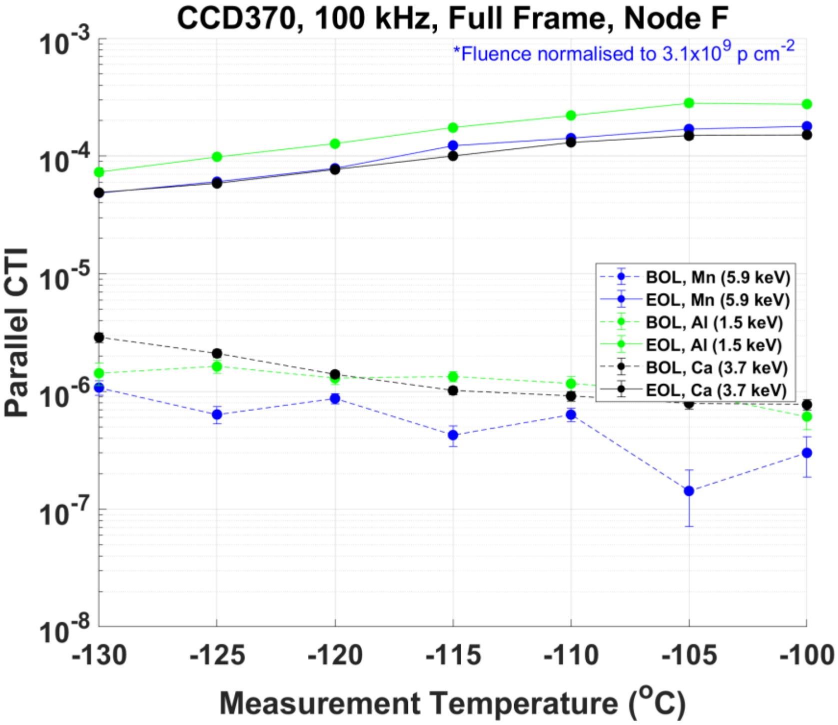

Figure 2: Temperature dependence of full frame parallel CTI at BOL and EOL in a CCD370

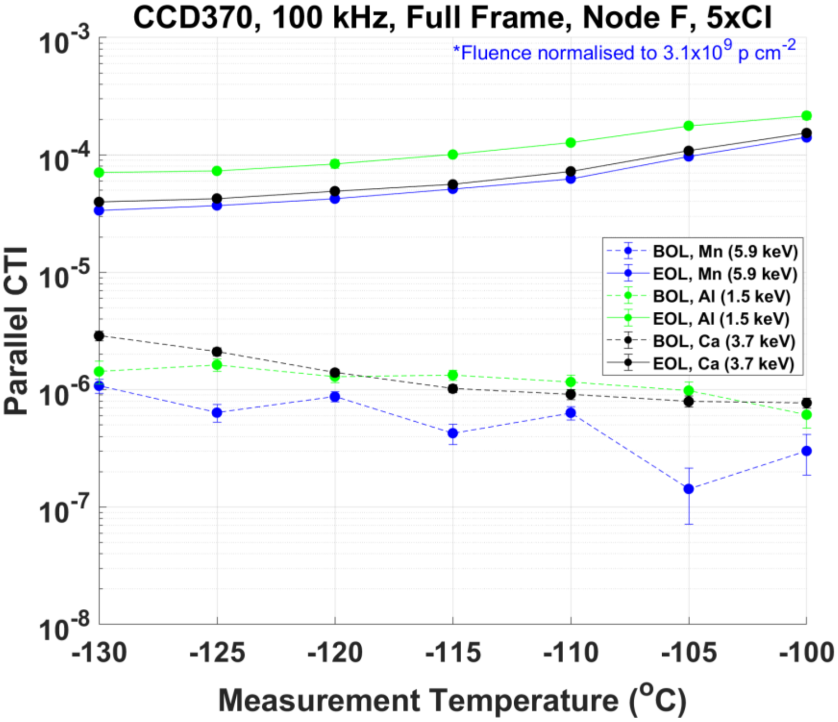

Figure 3: Temperature dependence of full frame parallel CTI at BOL and EOL in a CCD370 with 5 blocks of charge injection spread evenly through the image/store area of the EOL data.

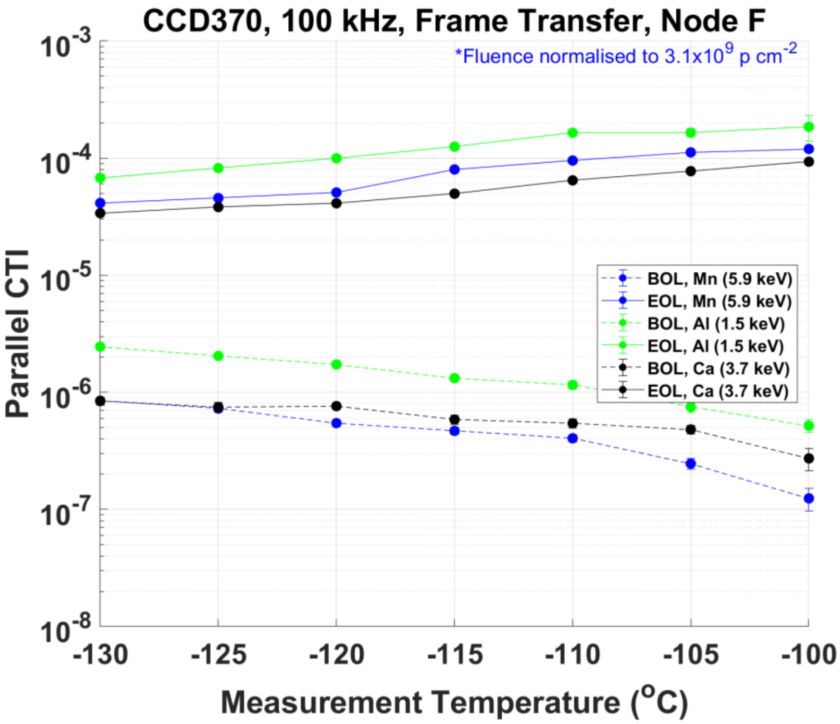

Figure 4: Temperature dependence of 6x6 binned frame transfer parallel CTI at BOL and EOL in a CCD370

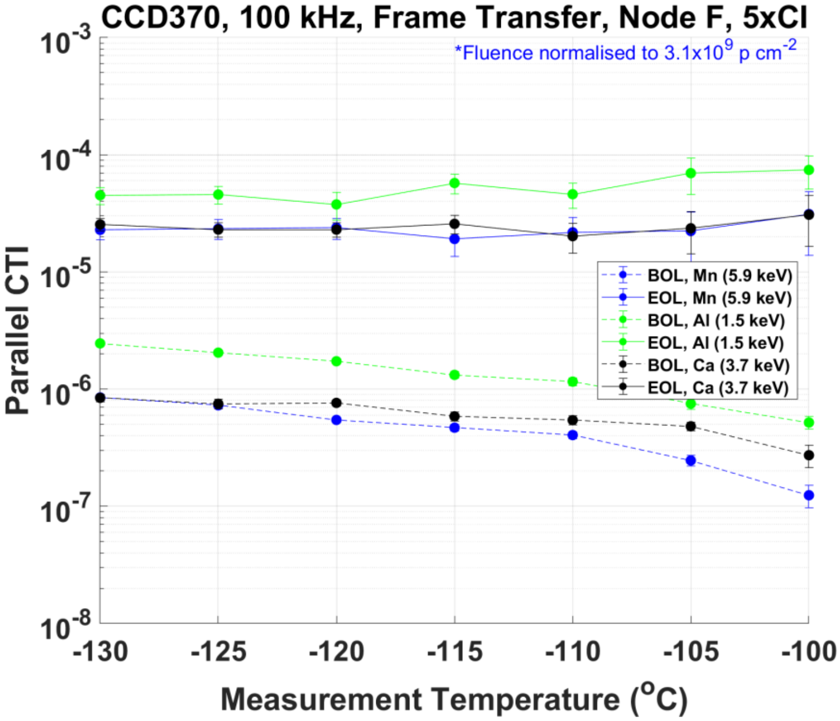

Figure 5: Temperature dependence of 6x6 binned frame transfer parallel CTI at BOL and EOL in a CCD370 with 5 blocks of charge injection spread evenly through the image/store area of the EOL data.

Table 4. Summarized Parallel CTI values at the nominal operating temperature (-120 °C) for full frame and 6x6 binned frame transfer readout modes both with and without charge injection lines at beginning and end of life proton fluences.

	5.9 keV X-ray Parallel CTI			
	Full Frame		**Frame Transfer**	
Mission Stage	**No Charge Injection Lines**	**5 x Charge Injection Lines**	**No Charge Injection Lines**	**5 x Charge Injection Lines**
BOL	1.4×10^{-6}	-	7.6×10^{-7}	-
EOL	7.7×10^{-5}	4.9×10^{-5}	4.1×10^{-5}	2.3×10^{-5}

4. CONCLUSIONS

The results show that pre-irradiation the CTI improves with temperature and post irradiation it degrades, likely due to the dominant effective trap species present changing. The decline in performance due to radiation damage in CCDs is well understood with the charge injection and frame transfer modes built into the SMILE SXI devices to help mitigate its effects [5][6]. The immediate improvement in CTI when both these measures are applied is clear from the results and to be expected, however, the decoupling from temperature dependance is not.

The combined effect of 6x6 binning and transferring charge injection lines through the CCD prior to readout has shown that the parallel CTI post irradiation remains constant within error between -130 to -100 °C. The science behind this behavior is currently being investigated by matching up the trap landscapes with the readout speeds/schemes. However, the higher level impact of this result means that for this metric there is more flexibility on operating temperature to achieve the same performance, which if known early enough in a missions design phase then it can simplify the thermal constraints/control.

ACKNOWLEDGEMENTS

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REFERENCES

[1] W. Raab et al., SMILE: A joint ESA/CAS mission to investigate the interaction between the solar wind and Earth’s magnetosphere, Proc. SPIE 9905 (2016) 990502.
[2] K. Dennerl et al., *Solar system X-rays from charge exchange processes*, Astron. Nachr. 333 (2012) 324.
[3] B. Walsh et al., Wide field-of-view soft X-ray imaging for solar wind magnetosphere interactions, J. Geophys. Res. 121 (2016) 3353.
[4] A. Holland et al., Techniques for minimizing space proton damage in scientific charge coupled devices, IEEE Trans. Nucl. Sci. 38 (1991) 1663.
[5] Shockley, W. & Read, W. T. *Statistics of the Recombinations of Holes and Electrons*. Phys. Rev. 87, 835–842 (1952).
[6] Hall, R. N. *Electron-Hole Recombination in Germanium*. Phys. Rev. 87, 387–387 (1952).
[7] Parsons, S.; Buggey, T.; Holland, A.; Sembay, S.; Randall, G.; Hetherington, O.; Yeoman, D.; Hall, D.; Verhoeve, P. and Soman, M. (2021). Effects of temperature anneal cycling on a cryogenically proton irradiated CCD. Journal of Instrumentation, 16(11), article no. P11005. DOI: https://doi.org/10.1088/1748-0221/16/11/p11005
[8] Parsons, S., Hall, D. J., Hetherington, O., Buggey, T. W., Arnold, T., Hubbard, M. W. J., and Holland, A. (2024). SMILE soft X-ray Imager flight model CCD370 pre-flight device characterisation. Earth Planet. Phys., 8(1), 25–38. DOI: 10.26464/epp2023057