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Characterisation of Swept-Charge Devices for the Chandrayaan-1 X-ray Spectrometer (C1XS) instrument

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ABSTRACT

The Indian Space Research Organisation (ISRO) Chandrayaan-1 mission is India's first lunar spacecraft, containing a suite of instruments to carry out high-resolution remote sensing of the Moon at visible, near infrared and X-ray wavelengths. Due for launch in early 2008, the spacecraft will carry out its two year mission in a polar orbit around the Moon at an altitude of 100 km. One of the eleven instruments in the spacecraft payload is the Chandrayaan-1 X-ray Spectrometer (C1XS), a descendant of the successful D-CIXS instrument that flew on the European Space Agency SMART-1 lunar mission launched in 2003. C1XS consists of 24 swept-charge device (SCD) silicon X-ray detectors arranged in 6 modules that will carry out high quality X-ray spectroscopic mapping of the Moon using the technique of X-ray fluorescence. This paper presents an overview of the Chandrayaan-1 mission and specifically the C1XS instrument and describes the development of an SCD test facility, proton irradiation characterisation and screening of candidate SCD devices for the mission.

Keywords: Chandrayaan-1, Swept Charge Device, SCD, C1XS, SMART-1, D-CIXS, Moon

1. INTRODUCTION

The work presented in this paper has been carried out in support of the Chandrayaan-1 X-ray Spectrometer (C1XS) instrument development. C1XS, shown in Figure 1, is the descendant of the Demonstration of a Compact Imaging X-ray Spectrometer (D-CIXS) instrument flown onboard SMART-1 launched in 2003 [1,2]. Designed to primarily test an ion propulsion engine, SMART-1 spent around 15 months in the Earth's radiation belts while traveling to the moon causing significant damage to the swept-charge device (SCD) modules onboard. Chandrayaan-1 is scheduled for launch in early 2008 with a mission duration of two years in a 100 km circular orbit around the Moon. The C1XS primary mission objective is to map the lunar surface for distribution of elements such as magnesium, aluminium, silicon, calcium, iron and titanium to gain further information about the lunar crust.

Fig. 1. CAD image of the C1XS instrument, highlighting the 14° field of view (image courtesy of RAL)

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The SCD, or CCD 54, was developed by e2v technologies to perform as an industrial X-ray spectrometer detector in the energy range 0.5-10 keV and achieves near Fano-limited spectroscopy at -10°C . The detector benefits from a large detection area of 1.1 cm^2 covered with 1725 diagonal electrodes with the isolation channels in the underlying silicon arranged in a herringbone structure, as shown in Figure 2. The electrodes are depicted by the dashed lines in the figure, the charge transport channels are indicated by the solid lines, the pitch of the channel stops being $25\text{ }\mu\text{m}$. A three-phase clocking pattern is used to transfer charge through the device, the charge collected in each diagonal element having to move through the same number of clock cycles to reach the read-out node located in the bottom left of the figure.

Fig. 2. Schematic of the SCD, indicating the various clocks and biases required

The device is read out in a similar manner to a conventional CCD, requiring 575 clock triplets to read out the whole device area. The charge packets can either be reset per sample, or can be accumulated and progressively sampled using a “reset on demand” or reset every n samples. These two methods of operation form the basis of the two drive sequencers used in the characterisation of the devices. Continuous clocking, with the silicon under low level clocking being inverted is much like dither mode clocking and is used to minimise the surface generated leakage current. The avoidance of an image integration period and the high rate periodic charge clocking ($\sim 100\text{ kHz.sample}^{-1}$) suppress the surface leakage current by allowing insufficient time for interface states to become active in the short periods in which the silicon surface is not in inversion. The noise contribution arising from total leakage current is negligible in comparison to the system read out noise of 5 - 10 electrons r.m.s. for temperatures around -10°C .

Thus far the work conducted can be divided into three studies, the first for voltage and clock optimisation to select the most suitable settings to be used during testing. The second, a proton damage characterisation to ensure that C1XS would have an energy resolution of at least 250 eV at Mn-K α throughout the mission lifetime, making recommendations for improved shielding and operational conditions. The third study was the full characterisation of fourteen modules available for flight to enable the selection of six modules for the flight instrument, testing the cosmetic quality, dark current, FWHM and noise measurements of each module.

2. EXPERIMENTAL ARRANGEMENT

Each SCD module was housed inside a vacuum test facility shown in Figure 3, clamped to a ceramic cold finger, resting on a two stage TEC. Temperature control to $\pm 0.1^{\circ}\text{C}$ was provided by an ILX Lightwave controller (model number LDT-5525) and the temperature was measured using a $1000\text{ }\Omega$ platinum resistance thermometer attached to the ceramic cold finger. SCD drive electronics were provided by Xcam Ltd. and the data were recorded on a laptop computer. An Oxford instruments XTF5011/75 TH X-ray tube with a Tungsten filament was used to fluoresce target materials and a ^{55}Fe

source held in front of the SCD being tested was used to expose it to Mn-K α X-rays. A Pfeiffer vacuum pump was used to evacuate the air in the SCD camera head with testing occurring at a pressure of $< 10^{-4}$ mbar. Figure 4 shows a photo of an SCD module and indicates the numbering order of the four devices within a given module.

Fig. 3. A photograph of the SCD test facility

Fig. 4. SCD module showing the device identification number

The two drive sequencers used for testing were called Sequencer 1 and Sequencer 2 respectively. Sequencer 1 was used to read out the whole device area, resetting the charge packet for each subsequent sample, allowing the FWHM of various characteristic X-rays and the device noise to be measured (only isolated events were used in the analysis presented in this paper). The second sequencer, Sequencer 2, was used to integrate the charge, giving a programmable delay between successive line readouts (effectively an image integration period), programmable in units of ms between 1 ms to 15 ms (data was acquired using 10 ms). The image produced using Sequencer 1 is similar to that produced by a CCD, with each row corresponding to one readout of the SCD. An image produced using Sequencer 2 is displayed in Figure 5. The leakage current decreasing with decreasing operating temperature is clearly visible in Figure 6 which shows average line profiles of images recorded at different operating temperatures. The waveform shown results from device structure, in which the magnitude of the dark charge relates to the length of electrode under which it was integrated.

Fig. 5. An image of 150 linear SCD readouts recorded using Sequencer 2

Fig. 6. The characteristic triangular leakage current profile on an SCD

2.1 Voltage and timing optimisation

Tests were performed using an ^{55}Fe source to illuminate the SCD with $\text{Mn-K}\alpha$ X-rays at -20°C . The operational clock/bias voltages (V_{Image} , V_{Reset} , V_{od} , V_{rd} , V_{og} , V_{ss}) and clock delay/integration (Int^+ delay, Int^- delay, Int time and clock pulse width delay) other than the specific variable being tested were fixed at the values selected under initial testing of the SCD. The timings of the Int^+ , Int^- and Int parameters are related to the dual-slope integration method of correlated double sampling used and are indicated in the cartoon clocking trace shown in Figure 7. The FWHM, device noise measurements and the number of ADC channels between the noise peak and X-ray peak were recorded to observe the effects on device performance and gain allowing the optimal settings to be selected.

Fig. 7. A cartoon showing the dual slope integration timings Int^+ , Int^- and Int

2.2 Proton irradiation characterisation

The European Space Agency space environment information system (SPENVIS) [3] software was utilised to obtain an estimate of the expected Chandrayaan-1 end of life (EOL) proton fluence for the duration of the 2 year mission. Using orbital parameters provided by ISRO the mission was split into two stages, the ~ 7 days transfer orbit and the 2 years in circular orbit around the moon at an altitude of 100 km, with the launch date set to the 29th of February 2008.

During the transfer orbit, Chandrayaan-1 passes through the Earth's radiation belts, providing a trapped proton component to the total proton fluence. The total proton fluence accumulated during the transfer orbit phase is $\sim 7.3 \times 10^{12}$ protons.cm⁻² from 0.1 MeV to 400 MeV. The data were calculated using the AP-8 trapped proton model under solar maximum conditions and are shown in Figure 8. The largest component of high energy proton exposure for the mission is as a result of solar protons. Data were calculated using the JPL-91 solar proton fluence model (with a confidence of 95%) to give a total of 5.1×10^{11} protons.cm⁻² between the energy of 0.1 MeV and 200 MeV, this data is also shown in Figure 8.

Using the Non-Ionising Energy Loss function (NIEL) [4] the total 10 MeV equivalent proton fluence for the Chandrayaan-1 mission duration was calculated and is shown in Figure 9 plotted as a function of aluminium shielding thickness. In addition to the modeled 10 MeV equivalent proton fluence vs. aluminium shielding thickness the following assumptions for the Chandrayaan-1 radiation study were made:

1. The 2π solid angle behind the detector is shielded by 3 mm of aluminium and 6 mm tantalum, plus the collimator and any spacecraft structure. It is assumed that the 2π solid angle of shielding behind the SCDs is therefore (conservatively) equivalent to 28 mm aluminium (given that 6 mm tantalum is equivalent to ~ 25 mm aluminium).
2. The 2π solid angle in front of C1XS is 100 % shielded by the Moon, the gyration radius of low energy protons being much larger than the 100 km orbital altitude and thus these protons will not enter the collimators of the instrument.

As shown in Figure 9 the total 10 MeV proton fluence through 28 mm of aluminium shielding is 1.1×10^9 protons.cm⁻², taking into account the 2π solid angle of shielding provided by the moon the total Chandrayaan-1 expected EOL 10 MeV equivalent proton fluence is estimated to be $\sim 5 \times 10^8$ protons.cm⁻². The chosen 10 MeV equivalent proton fluences used in the SCD irradiation study were therefore 5.0×10^8 protons.cm⁻² and 2.5×10^8 protons.cm⁻², corresponding to 100 % and 50 % of EOL proton fluence respectively.

Fig. 8. Proton fluence for the Chandrayaan-1 mission

Fig. 9. 10 MeV equivalent proton fluence as a function of aluminium shielding thickness

The irradiations were carried out at the Kernfysisch Versneller Instituut (KVI) in the Netherlands using the Accelerator Groningen-Orsay (AGOR) cyclotron. The accelerator beam energy was 45 MeV (degraded from 90 MeV) and proton fluences of 7.8×10^8 protons.cm⁻² and 3.9×10^8 protons.cm⁻², equivalent to 10 MeV fluences of 4.3×10^8 protons.cm⁻² and 2.1×10^8 protons.cm⁻², were given to SCD modules 1 and 2 respectively. Dosimetric accuracy was stated by KVI staff to be within 10 %. Time taken for each module irradiation was ~2 minutes.

During the irradiation each module was placed in an aluminium holder, with a 15 mm thick aluminium shield clamped in front. The irradiated areas of each module are highlighted in Figure 10. Device 1 was left un-irradiated as a control. The area to one side of the central charge transport channel in device 2 was irradiated and in device 3 the same area was irradiated with the inclusion of the central transfer channel. This will allow the effects of radiation damage in the central channel to be discriminated from the radiation damage effects in the charge collection area. The back half of device 4 was irradiated to investigate the resulting increase in leakage current.

Fig. 10. SCD module irradiation showing device identification and highlighting the irradiated areas in black

Post-irradiation characterisation of the SCDs was carried out using the test facility described above. FWHM and noise measurements were recorded to demonstrate the effects of the irradiation on device performance, using Mn-K α and Al-K α X-rays. A 6 mm thick sheet of Tufnol 10G was placed between the X-ray source and the SCD under study to only allow X-ray illumination of the area highlighted on device 2 in Figure 10 when testing with devices 2 and 3. This removes unwanted signal from the un-irradiated sides of the device which would affect the results. Sequencers 1 and 2 were then used to record data at 10, 0, -10, -15, -20, -30 and -40 °C.

2.3 Screening of C1XS flight SCD modules

C1XS will use 6 SCD modules which will be selected from 14 modules supplied by the Rutherford Appleton Laboratory. The aim of this study was to recommend modules for flight selection and flight spares, selecting modules on a point scoring scheme to select the modules with best performance that would work well together. Modules received negative scores for bright defects and high leakage current profiles and positive scores for being within one or two standard deviations for noise and FWHM with a maximum of 8 points per module per temperature (1 point for noise, 1 point for FWHM for each of the four devices on a module).

The SCD module under test was held inside a camera head as shown in Figure 3. Handling of SCD modules was conducted inside a Lamar Flow bench to prevent dust and any other contaminants entering the chamber. The initial stage of testing was that of functionality and cosmetic quality. This was conducted using Sequencer 2 at 20 °C. The module was then cooled to -10 °C. Energy calibration was carried out using Cu-K α X-rays, followed by measurements of device FWHM and noise using Cu-K α and Al-K α X-rays with Sequencer 1. The variance in the Cu-L α line was recorded to provide information about the linearity and the calibration in eV per channel was recorded to provide information about the gain. This process was repeated at -20 °C, -30 °C and -40 °C for each device in each module.

3. RESULTS AND DISCUSSIONS

3.1 Voltage and timing optimisation

The optimal voltages were selected based on the FWHM, noise, gain and total counts in the Mn-K α peak to provide the best performance and stability, allowing for slight changes in voltage during operation. The optimised operational voltages are given in Table 1, and the timing parameters in Table 2.

Table 1. SCD operational voltages.

<i>Clock/Bias</i>	<i>Voltage (V)</i>
Image	10
Reset	6.1
V _{od}	29
V _{rd}	17
V _{og}	3
V _{ss}	10

Table 2. SCD timing parameters.

<i>Parameter</i>	<i>Time (μs)</i>
Int+ delay	2.11
Int- delay	0.53
Int time	3.51
Clock pulse width delay	4.53

3.2 Proton irradiation characterisation

Recorded line profiles at 20 °C and 10 °C for device 4 of module 1 are shown in Figure 11. There is a modest increase in leakage current as a result of radiation damage to the top half of the device, visible as a bulge in the centre of the readout profile and evident in the steeper gradient of the right side of the profile. Figure 11 also shows recorded line profiles from the module before irradiation. The reason for the difference on the un-irradiated side is due to a temperature difference caused by the thermal contact between the ceramic module package and the cold finger after replacement inside the chamber. The test method was changed at a later date so that the module is held onto the cold finger using a set number of bolt turns which ensures similar thermal contact is achieved thus reducing this effect.

Fig. 11. The characteristic triangular leakage current profile recorded using device 4 of module 1

Figure 12 shows the variation in the measured resolution of the Mn-K α peak with operational temperature before and after irradiation to 50 % and 100 % of the expected EOL proton fluence. The data taken from device 3 of modules 1 and 2, and from device 2 of module 1 in the un-irradiated case. The approximate upper and lower limits of the resolution of D-CIXS at its arrival at the Moon for Mn-K α X-rays are also displayed for comparison. These results are in agreement with an earlier SCD proton irradiation study [5].

Fig. 12. Device FWHM at Mn-K α vs. temperature

The final set of tests performed were on the radiation effects on the central channel, Figure 13 shows the variation in the measured resolution of the Al-K α peak with operational temperature before and after irradiation to 100 % of the expected EOL proton fluence. The data were taken from the irradiated side of device 2 module 1 and the un-irradiated side of device 3 of module 1 after being irradiated with 4.3×10^8 protons.cm⁻² and device 2 of module 2 in the un-irradiated case. Figure 13 shows that damage to the central transfer channel has a far greater effect to the energy resolution of the SCD than specific damage to the charge collection area, operating on average at 63% or 12% worse energy resolution than an un-irradiated device respectively.

Fig. 13. Device FWHM at Al-K α vs. temperature

3.3 Screening of C1XS flight SCD modules

The 14 modules studied were referred to as modules 1 through 14, and should not be confused with module 1 and 2 discussed in the previous sections. The functionality and cosmetic quality tests showed that module 4 was not operational. The total number of bright defects in the four devices of each module is given in Table 3.

Table 3. The number of bright defects on each of the 14 modules tested

Module	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Bright Defects	6	6	18	Fail	38	47	8	12	12	16	9	12	10	13

The data was processed into a set of summary spreadsheets of FWHM, noise, variance in Cu-L α and eV/Ch. The later two were found to vary little for each module. The FWHM of Cu-K α and Al-K α are displayed in Figure 14 and Figure 15 respectively with the noise calibrated using the Al-K α data shown in Figure 16. Module 1 was rejected due to the failure of device 2 to provide isolated events and modules 3 and 7 were rejected due to the poor performance of all devices within the respective modules. The outcome of the screening tests was the recommendation of 6 modules for flight with four flight spares.

Fig. 14. Module comparison of FWHM for Cu-K α vs. temperature

Fig. 15. Module comparison of FWHM for Al-K α vs. temperature

Fig. 16. Module comparison of noise for Al-K α vs. temperature

4. CONCLUSIONS

After the proton irradiation, all SCD modules were found to be operational, exhibiting a moderate $\sim 10\%$ - 15% , increase in leakage current. To maintain the target resolution of 250 eV at 5.898 keV for the full mission duration the importance of the shielding provided and the temperature of operation are clearly highlighted in Figure 12 with the comparison to D-CIXS. Based on this the 3 mm of aluminium and 6 mm of tantalum used as a basis for the irradiation study were recommended as the minimum shielding required for C1XS. The shielding around C1XS in the latest instrument design will now consist of a 4 mm thick aluminum electronics box, 6 mm of tantalum behind the SCD modules and a 3mm copper cold finger, an increase of 3 mm of tantalum over that used on D-CIXS. The operational temperature of C1XS was initially variable around -17°C . Following the proton irradiation study, it was recommended that the temperature should be reduced to at least -20°C . Mission temperature will now be less than -17°C for $\sim 90\%$ of the mission reaching as low as -70°C after the position of C1XS onboard Chandrayaan-1 was changed.

The susceptibility to increased CTI over increased leakage current is shown in Figure 13, with the loss of resolution at -20°C from 129 eV to 221 eV at 1.487 keV after 4.3×10^8 protons. cm^{-2} being mainly as a result of damage to the central transfer channel and not to that of the charge collection area which gave a FWHM of 153 eV at 1.487 keV after irradiation. This suggests that around 26 % of the loss in resolution is a result of damage to the charge collection area and increased leakage current, with the remaining 74 % being due to damage along the central transport channel and the increased CTI. This is explained by the charge transport geometry in the SCD, all charge packets travel through some length of the central transport channel, while each charge packet only flows through a given transport channel in the charge collection region.

The line profiles recorded during the proton irradiation study showed that the intensity of the bright defects already present increased as a result of proton damage. However, no new bright defects were generated as a result of radiation damage. An increase in leakage current gradient was a clear indication of lower device performance. This was also true for the flight screening, as summarised in Table 4 which lists the leakage current gradient, the number of bright defects and resolution at Cu-K α and Al-K α for some of the 14 modules that underwent testing. Although modules 5 and 6 had a

high number of bright defects their overall leakage current was lower than that of modules 7 and 3 which had far fewer defects.

Table 4. A selection of the modules giving the gradient of the leakage current profile, defects and FWHM at -30°C

Module	Leakage current gradient	Defects	FWHM at 8.047 keV	FWHM at 1.487 keV
11	1.54	9	151	82
5	1.64	38	152	85
13	1.68	10	153	90
10	1.79	16	153	87
6	1.99	47	153	94
14	2.01	13	160	93
7	2.62	8	173	118
3	3.55	18	254	216

The module screening provided lots of data for un-irradiated modules, giving at the lower -20 °C temperature of C1XS a FWHM of 168 eV for Cu-K α , 109 eV for Al-K α and 10 electrons r.m.s. noise (including leakage current). At -40 °C the FWHM is 148 eV for Cu-K α and 80 eV for Al-K α and 6 electrons r.m.s. total noise. Testing to -50 °C shows that there is little improvement with further cooling. The lower -70 °C temperature of C1XS will provide benefits as the radiation dose builds up. The linearity of each device was typically good, with most values for the Cu-L α line within ± 5 eV of the expected energy. The following modules were recommended for flight selection 2, 5, 8, 10, 12 and 13.

Future work will include testing the quantum efficiency of the devices before and after irradiation, fluorescing targets over the entire energy detection range of the SCD, and modifying the 3 phase clocking sequence for further device optimisation.

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