Proton Irradiation of Swept-Charge Devices for the Chandrayaan-1 X-ray Spectrometer (C1XS)

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Abstract

This paper presents work carried out in support of swept-charge device (SCD) characterisation for the Chandrayaan-1 X-ray Spectrometer (C1XS) instrument. A brief overview of the C1XS instrument is presented, followed by a description of SCD structure and operation. The SCD test facility and method of device characterisation using two different drive sequencers to assess leakage current and spectroscopy performance (FWHM and noise at Mn-Kα) are then described. The expected end-of-life (EOL) 10 MeV equivalent proton fluence for the SCDs of C1XS was modelled using Monte Carlo simulation software and used in a subsequent proton irradiation study involving eight SCDs. The irradiation study was carried out at the Kernfysisch Versneller Instituut (KVI) in the Netherlands and characterised the impact of 50 % and 100 % of the expected Chandrayaan-1 EOL proton fluence on the SCD operational characteristics. The radiation environment modelling, irradiation methodology and post-irradiation characterisation of the devices are presented in this paper and recommendations about the planned C1XS operational temperature and shielding are given.

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Key Words: *Chandrayaan-1; C1XS; CCD; swept-charge device; radiation damage; X-ray spectroscopy*

1. Introduction

The Chandrayaan-1 X-ray Spectrometer (C1XS) instrument to be flown on Chandrayaan-1 is the direct descendent of the Demonstration of a Compact Imaging X-ray Spectrometer (D-CIXS) instrument flown onboard the European Space Agency's SMART-1 lunar mission that was launched in 2003 [1, 2]. The C1XS instrument is an X-ray florescence spectrometer, consisting of six modules of four SCDs [3]. The D-CIXS instrument, with its similar arrangement of six

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detector modules is pictured in Figure 1. The Chandrayaan-1 mission is scheduled for launch in early 2008 with a planned mission duration of two years in a 100 km circular orbit around the Moon.

To ensure the C1XS instrument will remain operable for the entire mission lifetime, it is important to understand the space radiation environment that Chandrayaan-1 will be exposed to. For silicon devices operating in space, the main radiation damage components of concern are trapped protons in the Earth's radiation belts and solar protons, which can cause displacement damage in the silicon of the SCDs resulting in bright pixels [4-6] and ionisation damage causing an increase in device leakage current [7]. To obtain estimates of the expected total end-of-life (EOL) proton fluence, modelling of the spacecraft trajectory and the resulting proton fluence was carried out using the European Space Agency (ESA) Space Environment Information System (SPENVIS) software suite [8]. The structure and operation of the SCD devices are described in the next two sections of this paper, followed by a description of the radiation environment modelling. The proton irradiation study is then described in detail and the paper concludes with an overview of the study outcomes.

2. The Swept-Charge Device

The swept-charge device (SCD), or CCD54, uses charge-coupled device (CCD) technology developed by e2v technologies and funded by the Particle Physics and Astronomy Research Council and the Department of Trade and Industry as part of the IMPACT programme, for use as an industrial X-ray spectrometer in the energy range of 0.5-10 keV at close to room temperature [9]. The detector benefits from a large detection area of 1.1 cm^2 and achieves near Fano-limited spectroscopy at -15 ^{o}C, a temperature that is easily achievable using a thermoelectric cooler (TEC). The active area is 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 as dashed lines in the figure, the charge transport channels are indicated by solid lines, the pitch of the channel stops is 25 μm. A three-phase clocking pattern is used to transfer charge through the device, the charge 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. The various clocks and biases required to drive the device are also indicated in the figure.

The SCD 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 device characterisation process discussed in the following section of this paper.

Continuous clocking with V_{ss} held high, also known as “dither mode” clocking, is used to minimise the surface generated leakage current. The avoidance of an image integration period and the high rate periodic charge clocking (approximately 100 $kHz.sample^{-1}$) suppress the surface leakage current by maintaining the silicon surface in inversion. The noise contribution arising from total leakage current can therefore become negligible in comparison to the system read-out noise of 5-10 electrons r.m.s. for temperatures around -10 ^{o}C.

The devices used in the presented study were housed in ceramic modules, each containing four SCDs, a concept developed for the D-CIXS instrument onboard SMART-1 [1]. An example SCD module is shown in Figure 3 which also shows the device numbering scheme within a module. The devices were all operated using the same clock and drive voltages as given in Table 1. A standard read-out from the device produces a line of 575 samples in length. Reading out the device a number of times and displaying the rows of data sequentially allows a 2D ‘image’ to be built-up, each row in the image corresponding to a single read-out of the SCD. A 40 sample $\times$ 40 sample section of such an image is shown in Figure 4, the bright samples in this case being generated by Al-Kα X-rays. The horizontal charge distribution of the X-ray events along a given read-out profile can be seen in the image. For the purposes of X-ray peak full width at half maximum (FWHM) calculations, only isolated X-ray events were considered in the analysis.

3. SCD Characterisation

The two SCD modules used in this study were provided by Rutherford Appleton Laboratory and were characterised using a vacuum chamber test facility at Brunel University. During testing, each SCD module was housed inside the vacuum chamber, clamped to a two stage TEC which was in turn attached to a copper block with internal water cooling. Temperature control to ± 0.1 ^{o}C was provided by a Lakeshore controller (model number 331) and the temperature was measured using a 1000 Ω platinum resistance thermometer attached to the side of the ceramic SCD module package to ensure accurate reading of the SCD package temperature. Data were recorded at temperatures of +10 ^{o}C, 0 ^{o}C, -10 ^{o}C, -20 ^{o}C and -30 ^{o}C, using two different device sequencers in each case (described below). An ^{55}Fe X-ray source was attached to the clamp holding the SCD module, directly above the device being tested, providing sparse illumination with Mn-Kα X-rays of energy 5898 eV. Figure 5 shows a photo of the test facility. Clock and bias voltages (as given in Table 1) were provided by CCD drive electronics from Xcam Ltd. and the data were recorded on a laptop computer.

The first drive sequencer, **Sequencer 1**, was used to read-out the whole device area, resetting the charge packet for each subsequent sample. There was no delay between each successive read-out of the device. A section of a 600 line profile image recorded using Sequencer 1 is shown in Figure 4. Figure 6 shows the average line profiles of images recorded at a number of temperatures. Sequencer 1 was used to analyse the recorded X-ray spectrum, allowing the FWHM and the device noise to be measured. The Mn-Kα all event spectrum (raw spectral data) and isolated event spectrum (X-ray events with charge localised to a single sample) displayed in Figure 7 were obtained from an analysis of line read-outs recorded from SCD 1 of module 2 over a period of 2 hours, operating at a temperature of -30 ^{o}C. The resulting isolated event spectrum has a noise level of 10 electrons r.m.s. with a FWHM of 165 eV at ~6 keV.

The second drive sequencer, **Sequencer 2**, was used to integrate the charge, giving a programmable delay between successive line read-outs (effectively an image integration period), programmable in units of ms between 1 ms to 15 s. This sequencer allowed for the identification of any artefacts in the leakage current profile over the surface of a device. Typically 3 ms – 10 ms was sufficient to enhance the leakage current in a device to produce images like the one shown in Figure 8. Average line profiles from images recorded using Sequencer 2 at different temperatures are shown in Figure 9. The characteristic triangular shape of the SCD leakage current profile (the slope being caused by the changing size of the sample collection area) is clearly visible in the figure, the leakage current decreasing with decreasing operating temperature. These data were again taken from SCD 1 of module 2.

Each of the eight SCDs in the two modules were fully characterised prior to proton irradiation, with data taken using each of the two sequences at various temperatures as described above. Table 2 lists the observed cosmetic defects that were present in each of the 8 SCD devices prior to proton irradiation.

4. The Chandrayaan-1 Radiation Environment

To obtain an estimate of the expected Chandrayaan-1 EOL proton fluence for the duration of the 2 year space mission the European Space Agency (ESA) software suite SPENVIS (Space Environment Information System) was utilised [8]. The software requires the orbital parameters of the spacecraft to be entered for the duration of the mission, after which various radiation models can be used to calculate the total proton fluence received at the spacecraft over the duration of the mission.

The Chandrayaan-1 orbital profile was separated into two sections: a transfer orbit from the Earth to get to the Moon of ~7 days duration, and the 2 year duration circular orbit around the Moon at an altitude of 100 km. The parameters of the transfer orbit were provided by the Indian Space Research Organisation (ISRO), with the launch date set to 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 proton belt is located from around 500 km above the Earth's surface, with protons of energies greater than 10 MeV being confined below an altitude of around 20,000 km. The total proton fluence accumulated during the transfer orbit phase is ~7.3×10^{12} protons.cm^{-2} from 0.1 MeV to 400 MeV, a value calculated using the AP-8 trapped proton model within SPENVIS, under solar maximum conditions.

During the 2 year mission duration at the Moon, Chandrayaan-1 will be exposed to solar protons which provide the largest component of high energy proton exposure for the mission. The modelled JPL-91 solar proton fluence (with a confidence of 95 %) for the duration of the mission gives a total of 5.1×10^{11} protons.cm^{-2} between an energy of 0.1 MeV and 200 MeV, the 2 year lunar orbit following chronologically after the transfer orbit. In this instance, 1.4 years of the mission takes place during a period of maximum solar activity. To consider the worst case, the model was also run with the whole 2 year mission duration at solar maximum giving a calculated EOL solar proton fluence of 7.0×10^{11} protons.cm^{-2}.

Using the Non-Ionising Energy Loss function (NIEL), the total 10 MeV equivalent trapped and solar proton fluences for the Chandrayaan-1 mission duration were calculated and are shown in Figure 10, plotted as a function of aluminium shielding thickness. The use of NIEL scaling in charge-coupled device detectors has been described in detail and allows for the comparison of observed radiation damage effects with other proton irradiation studies [10].

In order to arrive at an estimate of the total 10 MeV equivalent proton fluence expected to be received by the SCDs of C1XS, the following assumptions were made:

i. The 2π solid angle behind the detector is nominally shielded by 3 mm aluminium and 6 mm tantalum, in addition to the collimator and any spacecraft structure. It was therefore assumed that the 2π shielding behind the C1XS SCDs will be (conservatively) equivalent to 28 mm aluminium (given that 6 mm of tantalum is equivalent to ~25 mm of aluminium).

ii. The 2π solid angle in front of the C1XS instrument is 100 % shielded from protons by the Moon. The gyration radius of low energy protons is much larger than the 100 km Chandrayaan-1 lunar orbit altitude and thus these protons will not enter the collimators of the instrument (the gyration radius of a 100 keV proton is ~7500 km extending to much larger radii at higher proton energies).

From the data presented in Figure 10, the total expected 10 MeV proton fluence for the 2 year Chandrayaan-1 mission through 28 mm of aluminium shielding is 1.1×10^9 protons.cm^{-2}, with 1.38 years of the mission occurring at solar maximum. Taking into account the 2π solid angle of shielding provided by the Moon (effectively halving the total fluence received), the total Chandrayaan-1 expected EOL 10 MeV equivalent proton fluence is estimated to be ~5×10^8 protons.cm^{-2}. [It should be noted that when considering the worst case situation, where the full 2 year mission is taken to occur at solar maximum, the total expected proton fluence rises to a value of ~7×10^8 protons.cm^{-2}].

The chosen 10 MeV equivalent proton fluences to be used in the SCD irradiation study were therefore 5.0×10^8 protons.cm^{-2} and 2.5×10^8 protons.cm^{-2}, representing approximately 100 % and 50 % of the 2 year Chandrayaan-1 expected EOL 10 MeV equivalent proton fluence respectively.

5. SCD Proton Irradiation

Proton irradiation of the two SCD modules was carried out at the Kernfysisch Versneller Instituut (KVI) in the Netherlands using the Accelerateur Groningen-ORsay (AGOR) cyclotron. The accelerator beam energy was 45 MeV protons (degraded from 90 MeV) and proton fluences of 7.8×10^8 protons.cm^{-2} and 3.9×10^8 protons.cm^{-2} where given to SCD modules 1 and 2 respectively. Using the NIEL function to scale the beam energy to a 10 MeV equivalent dose, these fluences correspond to 10 MeV equivalent proton fluences of 4.3×10^8 protons.cm^{-2} and 2.1×10^8 protons.cm^{-2} respectively, representing approximately 100 % and 50 % of the 2 year Chandrayaan-1 expected EOL 10 MeV equivalent proton fluence. Dosimetric accuracy was stated by KVI staff to be within 10 %. The time taken for each of the two SCD module irradiations was 100 seconds.

An aluminium shield was used to define the regions of each SCD in a given module that would be irradiated, as illustrated in Figure 11. The same shielding scheme was used for each of the two SCD modules. In each case, device 1 was left un-irradiated as a control device. 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. After irradiation, a comparison of the data taken from each of these two devices allowed the effects of radiation damage in the central channel to be discriminated from radiation damage effects in the charge collection area. The top half of device 4 was irradiated to allow a comparison of the irradiated half with the non-irradiated half of the device, allowing the separation of any radiation damage induced leakage current increase from any decrease in charge transfer efficiency (CTE).

For irradiation, each SCD module was housed in an aluminium holder, with a shaped aluminium shield clamped in front of the devices. The thickness of the shield was 15 mm, enough to prevent 45 MeV protons reaching the SCDs. A system of lasers was used to correctly align the proton beam for each irradiation. The irradiations were carried out with the devices unbiased. After irradiation it was expected that both the number of bright samples and the leakage current in the irradiated areas would increase. Table 3 summarises the proton fluence given to each SCD module and the duration of each irradiation.

6. Post-irradiation SCD Characterisation

Post-irradiation characterisation of the SCDs was carried out using the same test facility as described in Section 3 above. Tests were initially performed on all devices at +20 ^{o}C to ensure that each device was still operational. All the SCDs were found to operate using the same clock and bias voltages as prior to irradiation and exhibited the expected increase in leakage current and bright sample populations associated with radiation damage.

For characterising the spectral resolution of the irradiated devices, an ^{55}Fe X-ray source was used in conjunction with 3 mm thick G10 fibreglass laminate board, which was placed between the X-ray source and the SCD under study to act as a shield, allowing X-ray illumination of the irradiated or un-irradiated areas of each device. Sequencers 1 and 2 were then used to record data at +10 ^{o}C, 0 ^{o}C, -10 ^{o}C, -15 ^{o}C, -20 ^{o}C, -30 ^{o}C and -40 ^{o}C.

Figure 12 shows line profiles recorded using Sequencer 2 at different temperatures after irradiation. Data from SCD 4 of module 1 (irradiated to 4.3×10^{8} protons.cm^{-2}) are shown in the figure. 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 read-out profile and evident in the steeper gradient of the right side of the profile.

Figure 13 shows how the measured resolution at Mn-Kα varies with operational temperature before and after irradiation to 50 % and 100 % of the expected EOL proton fluence. The data are taken from SCD 3 in each module in the two irradiated cases, and from SCD 1 of module 2 in the un-irradiated case. Also indicated in the figure are the approximate upper and lower FWHM limits as measured by D-CIXS at the end of the cruise phase of the SMART-1 mission and data taken from an earlier SCD irradiation study [9]. In the earlier irradiation study, an SCD was irradiated to a 10 MeV equivalent proton fluence of 3.4×10^8 protons.cm^{-2}, the data being comparable to the 4.3×10^8 protons.cm^{-2} data taken from a device in the current study for temperatures below -20 ^{o}C. It is not currently understood why the device from the earlier study exhibits a lower FWHM at temperatures above -20 ^{o}C. The higher FWHM observed by the SCDs of D-CIXS is a result of the significant difference in journey time to the Moon for each of the two lunar missions, the longer SMART-1 travel time resulting in increased radiation damage of the devices before reaching lunar orbit. The SMART-1 spacecraft, using an experimental electric propulsion engine, travelled to the Moon over a period of 14 months, compared with a Chandrayaan-1 planned travel time of ~7 days. Table 4 presents the current study data shown in Figure 13 in numerical form.

7. Conclusions and Future Work

The ESA SPENVIS software suite was used to model the Chandrayaan-1 expected EOL 10 MeV equivalent proton fluence, giving a value of 1.1×10^9 protons.cm^{-2} at the end of the two year mission. Taking into account the originally proposed instrument shielding (equivalent to ~28 mm aluminium) and the assumption that the 2π solid angle in front of the detectors will be shielded from protons by the Moon, the end of mission 10 MeV equivalent proton fluence reaching the C1XS SCD detectors is estimated to be ~5×10^8 protons.cm^{-2}.

Based on the results of the modelling, 10 MeV equivalent proton fleunces of 5×10^8 protons.cm^{-2} and 2.5×10^8 protons.cm^{-2} were selected as target fluences for a proton irradiation study involving two device modules, each featuring four SCDs. These two fluences represent 100 % and 50 % of the total expected EOL proton fluence for the SCDs of C1XS respectively. The 5×10^8 protons.cm^{-2} fluence level is comparable to that predicted for XMM-Newton at EOL, a spacecraft operating in a highly elliptical Earth orbit for a nominal duration of 10 years [11]. The results of the presented SCD irradiation study are therefore directly applicable to possible future SCD based instruments located in orbits where the radiation fluence is dominated by solar protons.

After proton irradiation all SCD devices were found to be operational, exhibiting a moderate, ~10 % – 15 %, increase in leakage current. The recommended operation temperature for the Chandrayaan-1 SCDs was -20 ^{o}C where after irradiation to 2.1 $\times$ 10^{8} protons.cm^{-2} (~50 % of the expected life time fluence) the FWHM at Mn-Kα was found to be ~225 eV, within the 250 eV C1XS resolution specification. The resolution will then degrade further during the course of the second year of the mission to ~260 eV by EOL, when operating at -20 ^{o}C.

Maintaining the resolution of the SCDs within the required 250 eV FWHM specification for the full two year duration of the mission can be achieved by reducing the planned operational temperature of the devices to below -20 ^{o}C or by the inclusion of additional shielding around the devices.

Future work using the irradiated SCDs will include measurement of device resolution at Al-Kα and an investigation into the effects of sample binning on improving the device resolution. It is worth noting that the C1XS instrument has a movable door that could be closed during periods of high solar activity to reduce the soft proton component reaching the detectors.

Acknowledgements

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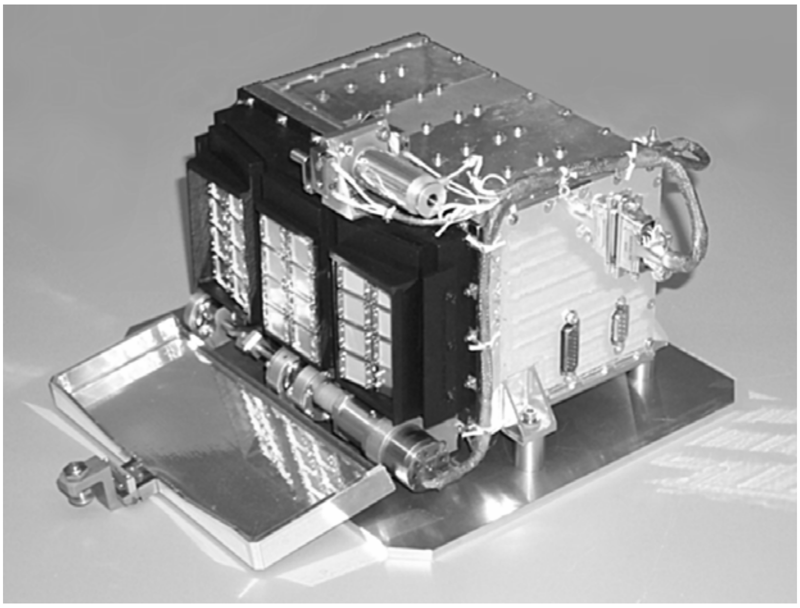


Figure 1

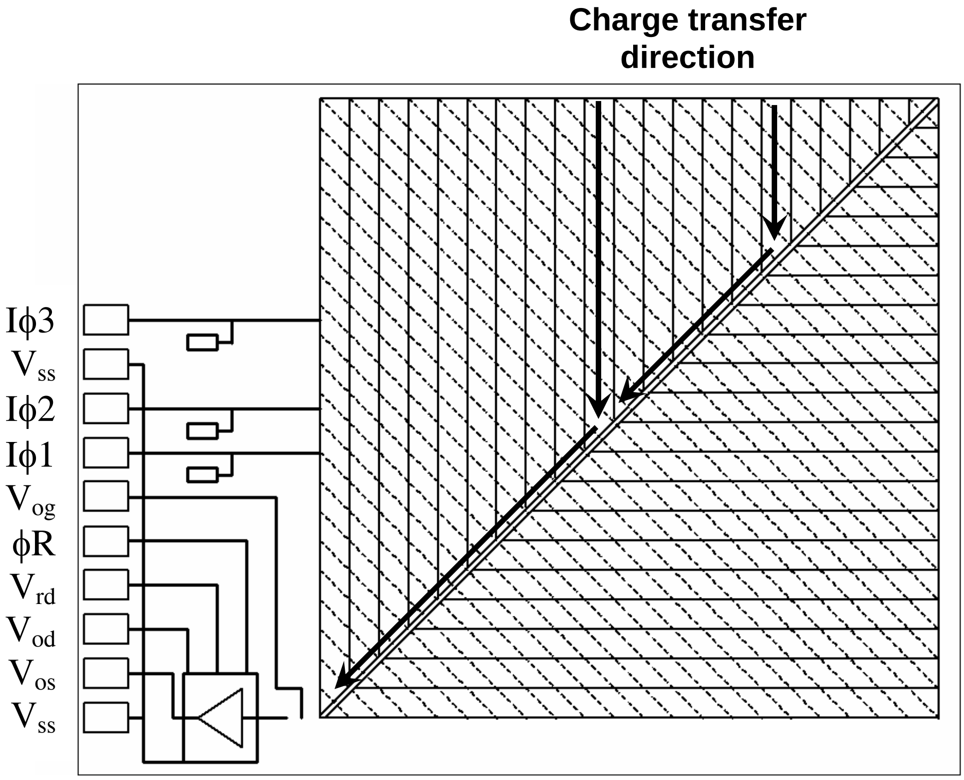

Charge transfer direction
Iϕ3
Vss
Iϕ2
Iϕ1
Vog
ϕR
Vrd
Vod
Vos
Vss

Figure 2

SCD number: 1 2 3 4

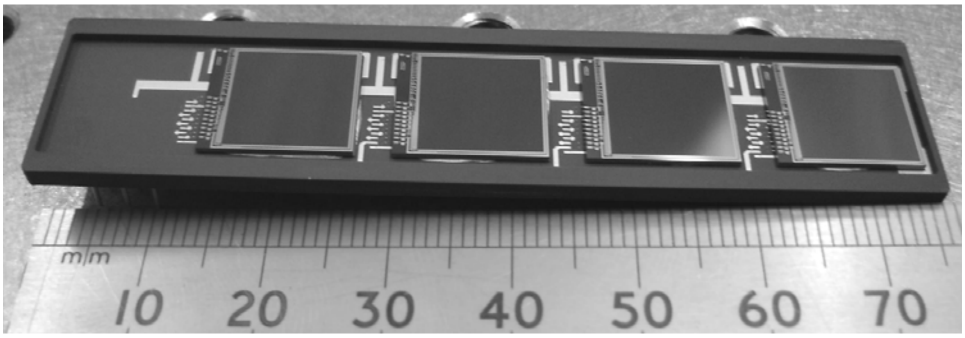


Figure 3

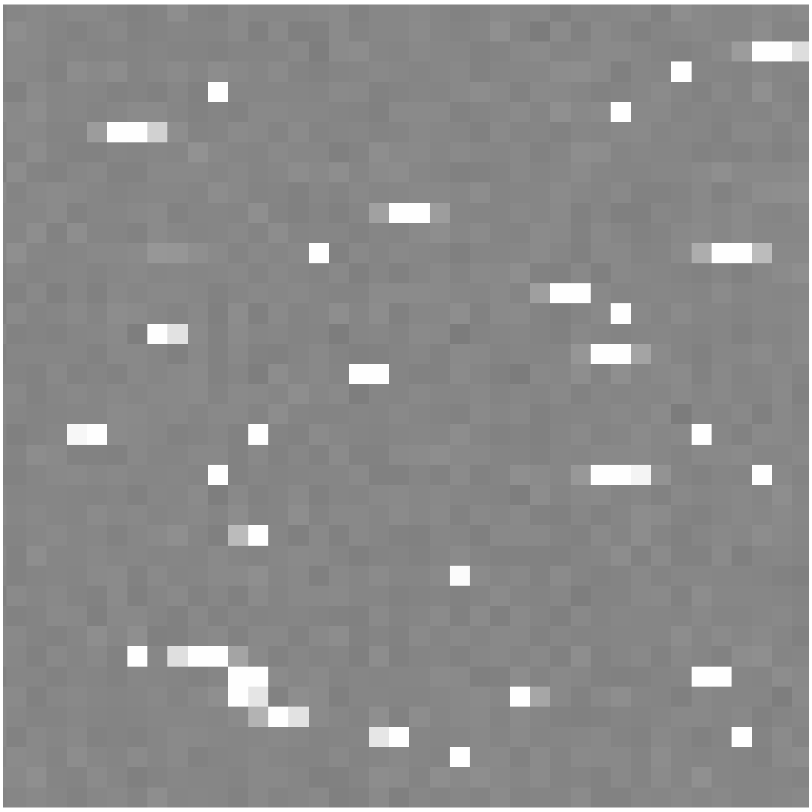


Figure 4

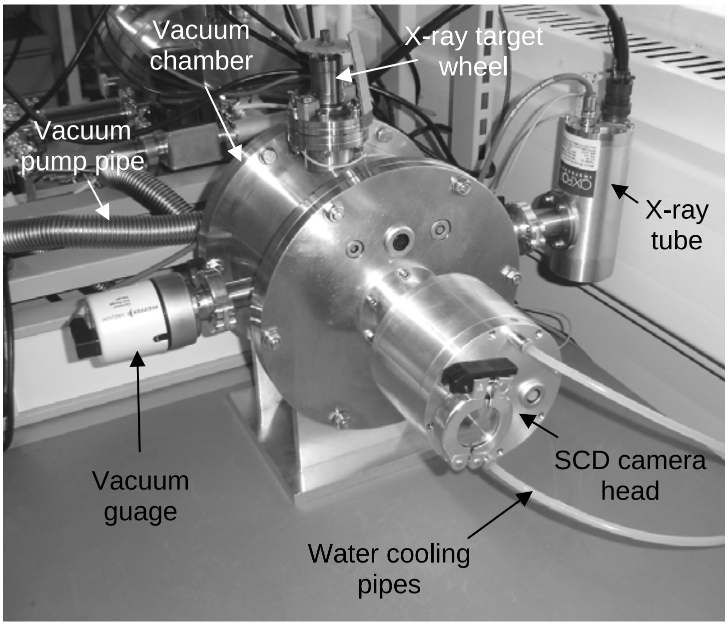
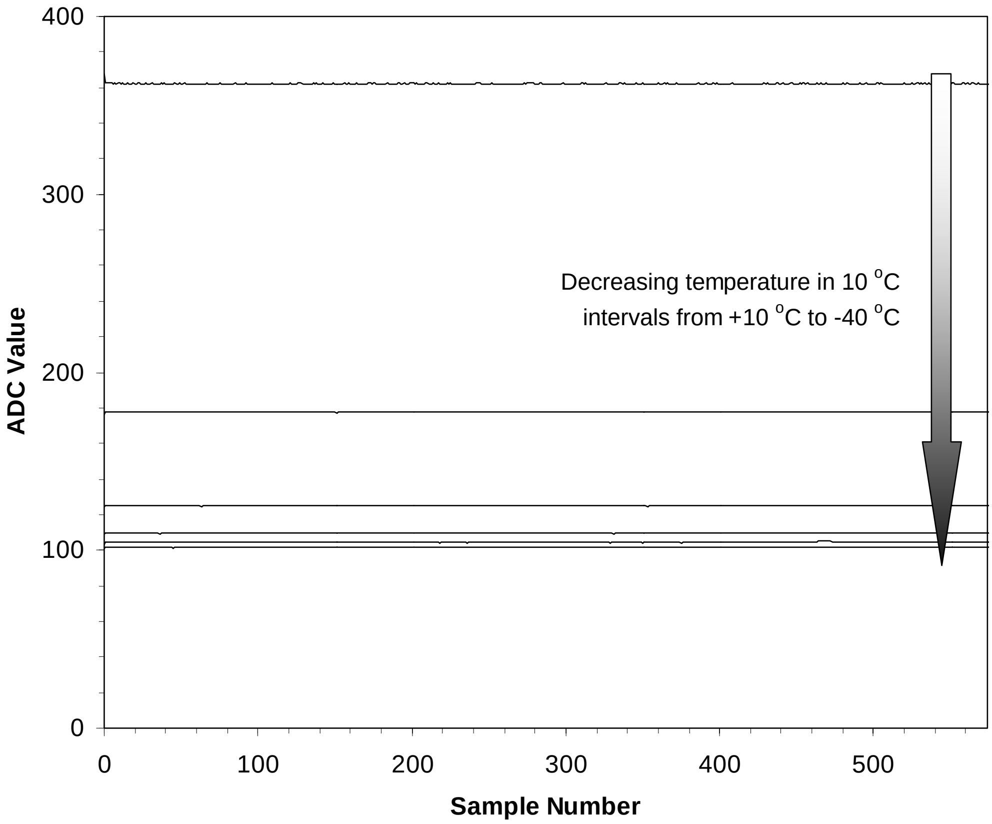

Vacuum
chamber
X-ray target
wheel
Vacuum
pump pipe
X-ray
tube
SCD camera
head
Vacuum
guage
Water cooling
pipes

Figure 5



400
300
200
100
0
ADC Value
0
100
200
300
400
500
Sample Number
Decreasing temperature in 10 °C
intervals from +10 °C to -40 °C

Figure 6

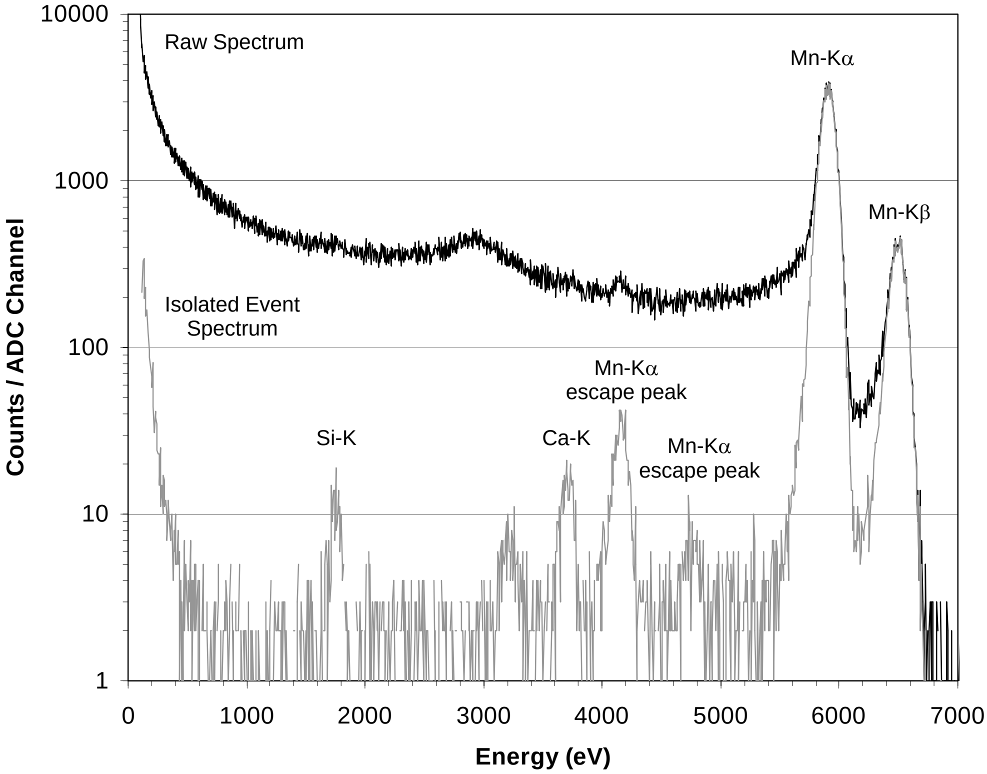

10000
1000
100
10
1
Counts / ADC Channel
Raw Spectrum
Mn-Kα
Mn-Kβ
Isolated Event Spectrum
Mn-Kα escape peak
Si-K
Ca-K
Mn-Kα escape peak
0
1000
2000
3000
4000
5000
6000
7000
Energy (eV)

Figure 7

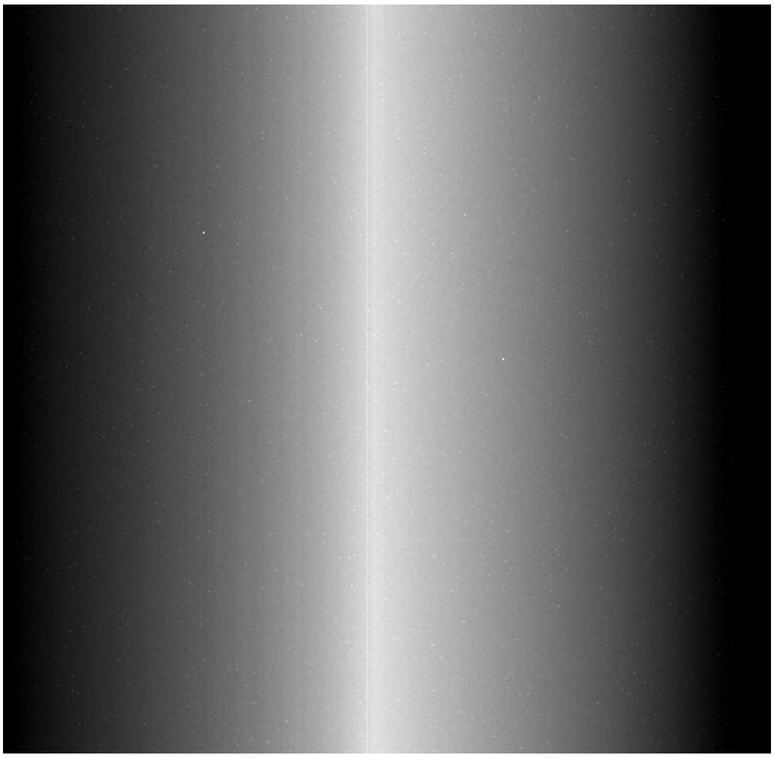
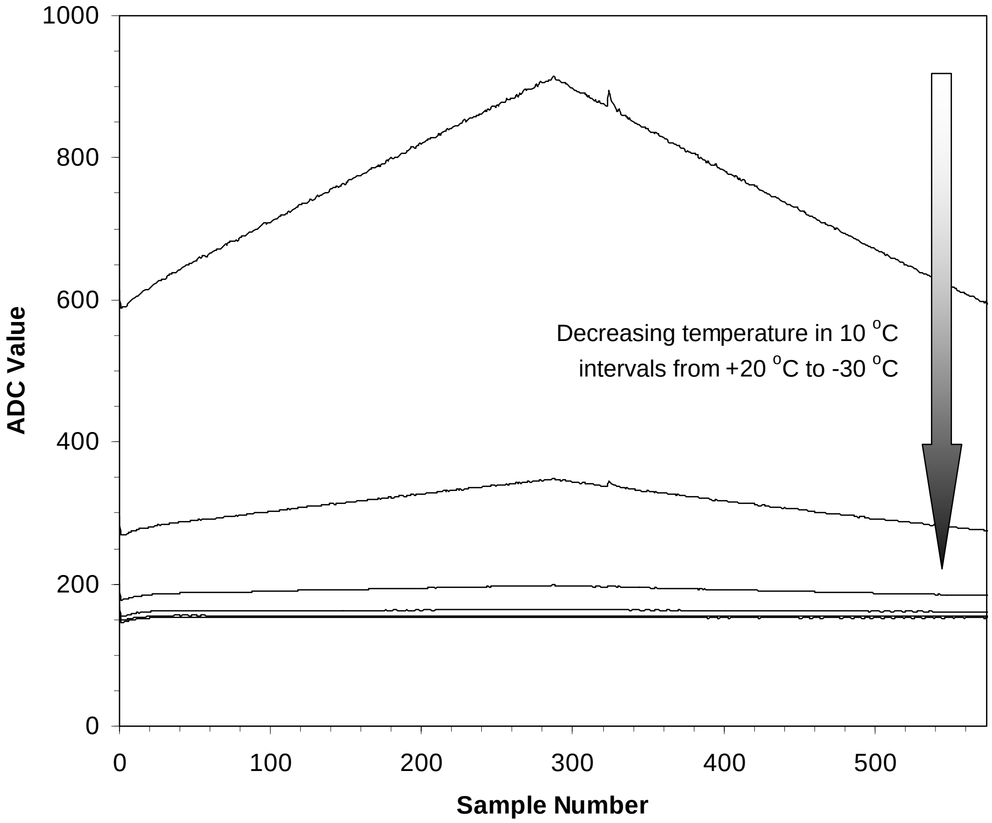
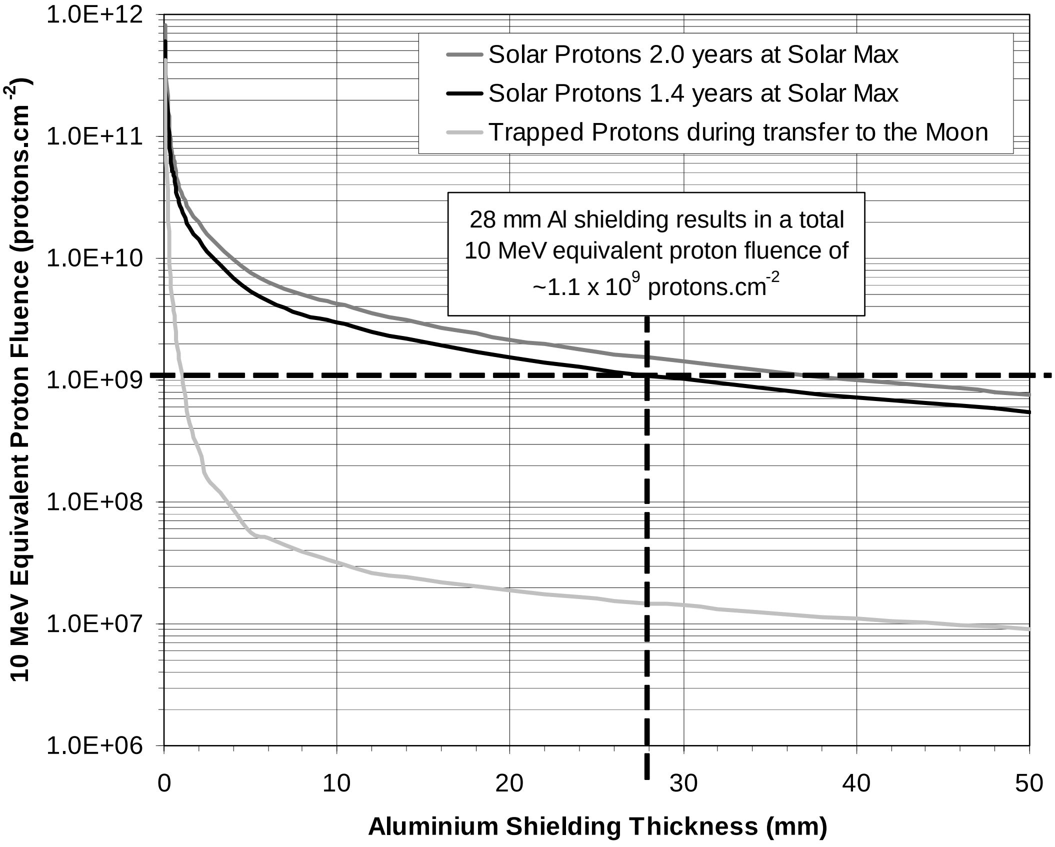


Figure 8



ADC Value
1000
800
600
400
200
0
0
100
200
300
400
500
Sample Number
Decreasing temperature in 10 °C intervals from +20 °C to -30 °C

Figure 9



1.0E+12
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
0
10
20
30
40
50
10 MeV Equivalent Proton Fluence (protons.cm-2)
Aluminium Shielding Thickness (mm)
Solar Protons 2.0 years at Solar Max
Solar Protons 1.4 years at Solar Max
Trapped Protons during transfer to the Moon
28 mm Al shielding results in a total
10 MeV equivalent proton fluence of
~1.1 x 10^9 protons.cm^-2

Figure 10

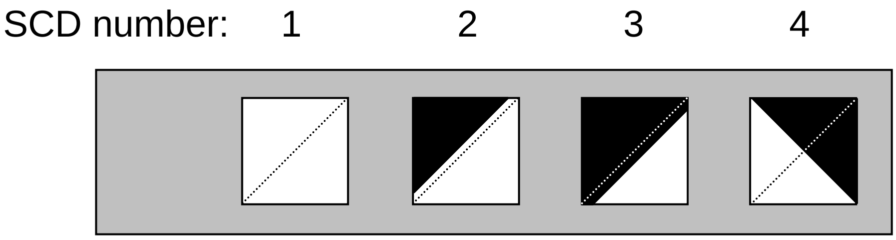
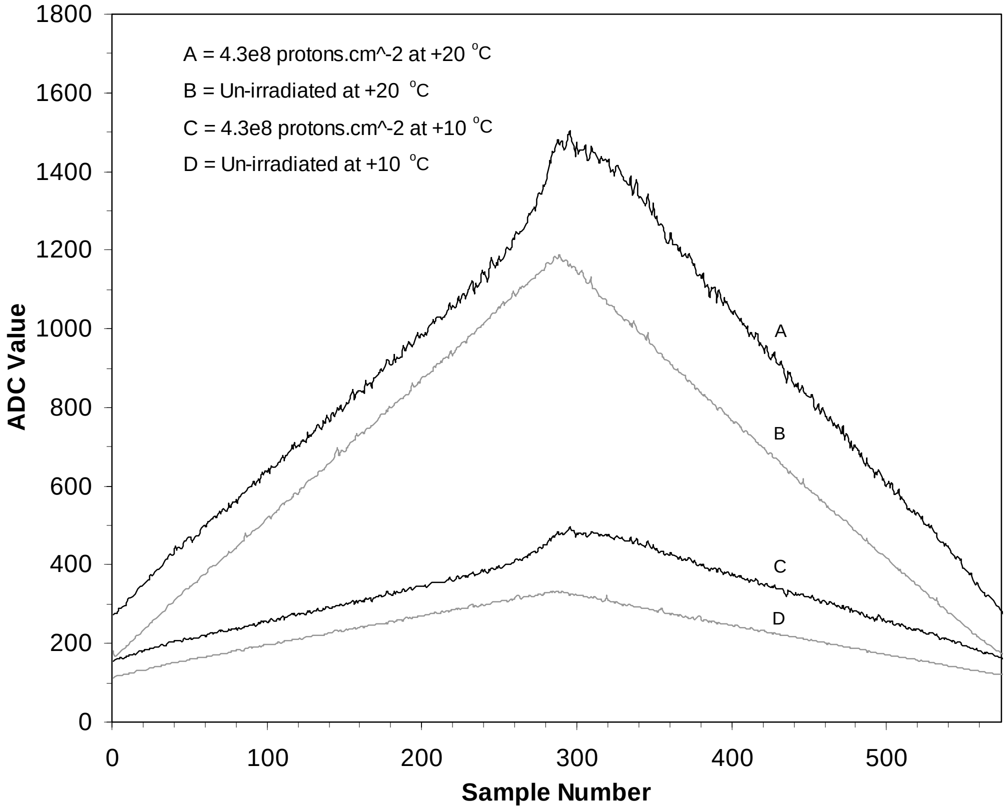


Figure 11



A = 4.3e8 protons.cm^-2 at +20 °C
B = Un-irradiated at +20 °C
C = 4.3e8 protons.cm^-2 at +10 °C
D = Un-irradiated at +10 °C
A
B
C
D
ADC Value
Sample Number
0
200
400
600
800
1000
1200
1400
1600
1800
0
100
200
300
400
500

Figure 12

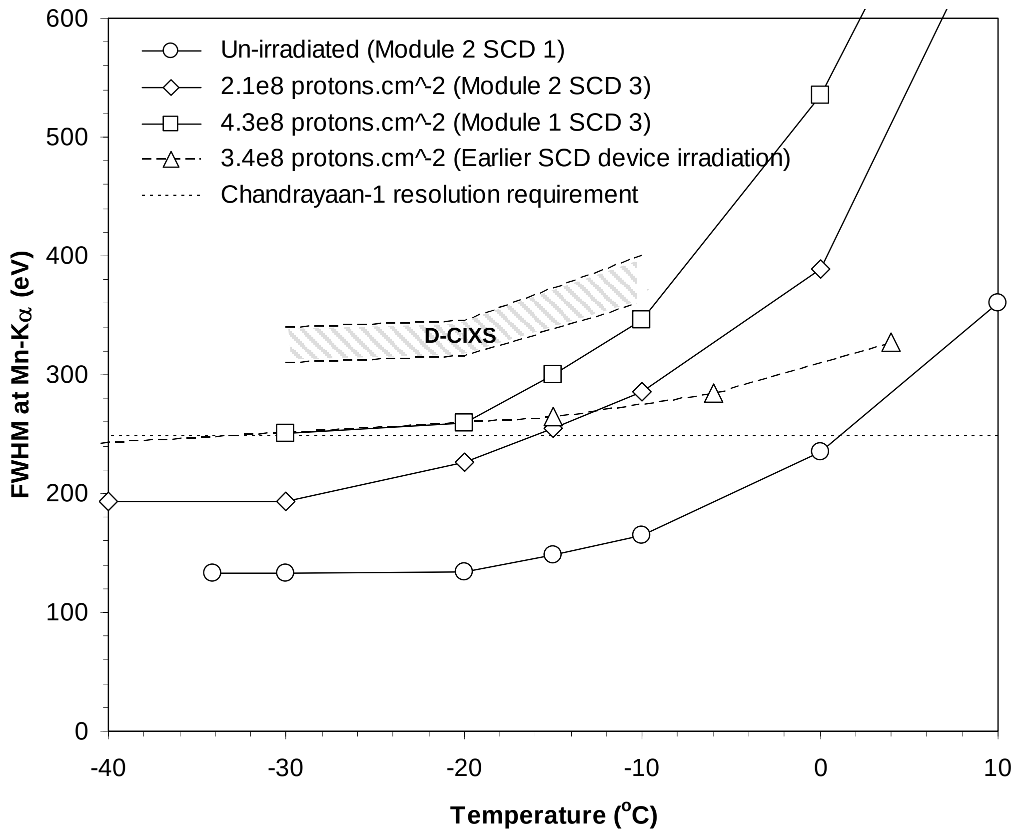

Un-irradiated (Module 2 SCD 1)
2.1e8 protons.cm^-2 (Module 2 SCD 3)
4.3e8 protons.cm^-2 (Module 1 SCD 3)
3.4e8 protons.cm^-2 (Earlier SCD device irradiation)
Chandrayaan-1 resolution requirement
D-CIXS
FWHM at Mn-Kα (eV)
Temperature (°C)
600
500
400
300
200
100
0
-40
-30
-20
-10
0
10

Figure 13

Figure 1. A photograph of the D-CIXS instrument (image used courtesy of Rutherford Appleton Laboratory).

Figure 2. A schematic of the SCD showing the diagonal electrodes (dashed lines) and underlying isolation channels (solid lines) arranged in a herringbone structure. The charge transfer direction during read-out of the device is indicated by the arrows.

Figure 3. A photograph of a single D-CIXS module, consisting of four SCDs.

Figure 4. A 40 sample × 40 sample section of an 'image' of 575 SCD read-out line profiles showing Al-Kα X-rays.

Figure 5. A photograph of the SCD test facility.

Figure 6. Stacked line profiles recorded at different temperatures using Sequencer 1.

Figure 7. Raw spectral data and the corresponding isolated event X-ray spectrum obtained using ^{55}Fe at -30 ^{o}C.

Figure 8. An 'image' of 600 SCD read-out line profiles recorded using Sequencer 2.

Figure 9. The average line profile of images recorded at different temperatures using Sequencer 2, revealing the characteristic triangular leakage current profile of an SCD.

Figure 10. Modelled 10 MeV equivalent proton fluence as a function of shielding thickness.

Figure 11. SCD module irradiation schematic, showing the location of SCDs 1 to 4 and the irradiated area of each device (in black). The central charge transport channel in each device is indicated by the dotted lines.

Figure 12. The characteristic SCD triangular leakage current profile recorded at different temperatures using Sequencer 2. The increase in leakage current as a result of radiation damage of one half of the device is clearly visible in each profile.

Figure 13. SCD FWHM at Mn-Kα as a function of temperature.

Clock/Bias	*Voltage (V)*
$I\phi 1$ high	10.0
$I\phi 2$ high	10.0
$I\phi 3$ high	10.0
ϕR high	6.1
Clock low	0.0
V_{ss}	10.0
V_{og}	3.0
V_{rd}	17.0
V_{od}	29.0

Table 1. SCD clock and bias voltages.

Module	*Device*	*Cosmetic Quality*
1	1	Non-functional
	2	Bright sample at 282
	3	Bright sample at 282
	4	Bright sample at 345
2	1	Bright sample at 324
	2	Bright samples at 128, 273, 460
	3	Bright samples at 174, 232, 259, 284, 313, 368, 385
	4	Bright samples at 174, 232, 259, 284, 313, 368, 385

Table 2. SCD cosmetic quality summary.

Module	*45 MeV Fluence (protons.cm^{-2})*	*10 MeV Equivalent Fluence (protons.cm^{-2})*	*Irradiation Time (s)*
1	7.8×10^{8}	4.3×10^{8}	100
2	3.9×10^{8}	2.1×10^{8}	100

Table 3. Proton irradiation parameters.

	FWHM at Mn-Kα (eV)		
Temperature (^oC)	*Un-irradiated*	*2.1×10^8 protons.cm^{-2}*	*4.3×10^8 protons.cm^{-2}*
10	360.97	696.93	825.00
0	235.37	389.07	535.60
-10	164.90	286.10	346.27
-15	148.13	255.01	300.20
-20	134.37	225.87	259.83
-30	133.13	193.50	250.10
-40	-	192.97	-

Table 4. Measured FWHM at Mn-Kα as a function of temperature for un-irradiated and irradiated SCDs (at approximately 100 kHz read-out speed).