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

J. Gow*[a], D. R. Smith[a], A. D. Holland[b], B. Maddison[c], C. Howe[c], M. Grande[d], P. Sreekumar[e], J. Huovelin[f],
[a]Imaging for Space and Terrestrial Applications Group, School of Engineering and Design, Brunel University, Uxbridge, Middlesex, UB8 3PH, UK
[b]Planetary and Space Sciences Research Institute, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK
[c]STFC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, UK
[d]Institute of Mathematical and Physical Sciences, University of Wales, Aberystwyth, Wales
[e]Space Astronomy & Instrument Division, Indian Space Research Organisation, Bangalore, India
[f]Observatory, P.O. Box 14, FI-00014 University of Helsinki, Finland

ABSTRACT

The Chandrayaan-1 X-ray Spectrometer (C1XS) will be launched as part of the Indian Space Research Organisation (ISRO) Chandrayaan-1 payload in September 2008, arriving at the Moon within 7 days to begin a two year mission in lunar orbit conducting mineralogical surface mapping over the range of 1 – 10 keV. The detector plane of the instrument consists of twenty four e2v technologies CCD54 swept-charge devices (SCDs). Such devices were first flown in the Demonstration of a Compact Imaging X-ray Spectrometer (D-CIXS) instrument onboard SMART-1 [4, 5]. The detector plane in each case provides a total X-ray collection area of 26.4 cm^2. The SCD is capable of providing near Fano-limited spectroscopy at -10°C, and at -20°C, near the Chandrayaan-1 mission average temperature, it achieves a total system noise of 6.2 electrons r.m.s. and a FWHM of 134 eV at Mn-Kα. This paper presents a brief overview of the C1XS mission and a detailed study of the effects of proton irradiation on SCD operational performance.

Keywords: Radiation damage, swept-charge device, SCD, C1XS, Chandrayaan-1, D-CIXS, Moon, X-ray

1. INTRODUCTION

The work presented in this paper has been carried out in support of the Chandrayaan-1 X-ray Spectrometer (C1XS) instrument development, shown in Figure 1. The paper presents the results from the second SCD proton irradiation study carried out at Birmingham University in the UK on the 2nd May 2008. This second study was required to investigate the effects of a revised end-of-life (EOL) expected proton fluence resulting from a change in the expected Chandrayaan-1 launch window and modifications made to the structure surrounding the SCDs following the first proton irradiation study results [1, 2].

Two SCD devices were irradiated to fluences of 3.0×10^8 protons.cm^{-2} and 7.5×10^8 protons.cm^{-2}, corresponding to 40 % and 100 % of the revised EOL dose. When combined with the original proton irradiation levels of 2.1×10^8 protons.cm^{-2} and 4.3×10^8 protons.cm^{-2}, corresponding to 28 % and 58 % of the revised EOL dose, the four investigated dose levels provide a good overview of the SCD radiation damage effects expected over the 2 year mission duration.

Chandrayaan-1 is currently scheduled for launch in late 2008 with a mission duration of two years in a polar 100 km circular orbit around the Moon. The space craft carries eleven scientific instruments, including among others, an imager, an impact probe, a radiation dose monitor and C1XS. 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. The target resolution for the mission set by the scientific team was 250 eV at Mn-Kα. A detailed description of the SCD can be found in [1].

*jason.gow@brunel.ac.uk; phone +44 (0) 1895 266 520; fax +44 (0) 1895 269 773; **www.brunel.ac.uk**

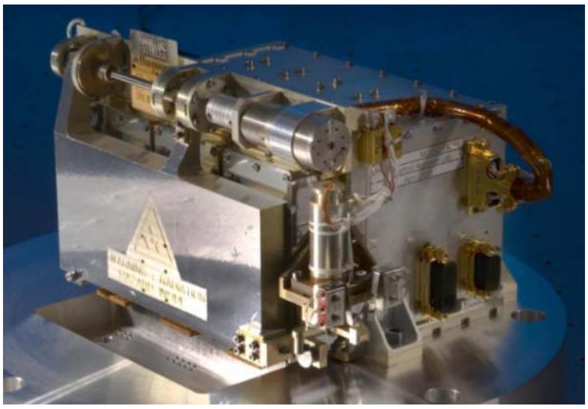

Fig. 1. The C1XS flight instrument (image courtesy of RAL)

1.1 C1XS space radiation environment

The space radiation environment was modeled using the European Space Agency Space Environment Information System (SPENVIS) [6]. The orbital parameters remained the same as those used in the first radiation study but the launch date was changed to 30th September 2008. Figure 2 shows the EOL 10 MeV equivalent proton fluence as a function of aluminium shielding thickness experienced by the SCD modules onboard C1XS over the 2 year mission duration. The following assumptions were made in calculating the proton fluences used in the presented study:

1. 2π solid angle behind the detector is shielded by 4 mm of aluminium (a 1 mm increase when compared to the first SCD irradiation study calculation [1]) and 6 mm tantalum. It is assumed that the 2π solid angle of shielding behind the SCDs is therefore (conservatively) equivalent to 29 mm aluminium (given that 6 mm tantalum is equivalent to ~25 mm aluminium).
2. The 2π in front of the CIXS instrument is 100 % shielded by the moon, the gyration radius of low energy protons being 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).

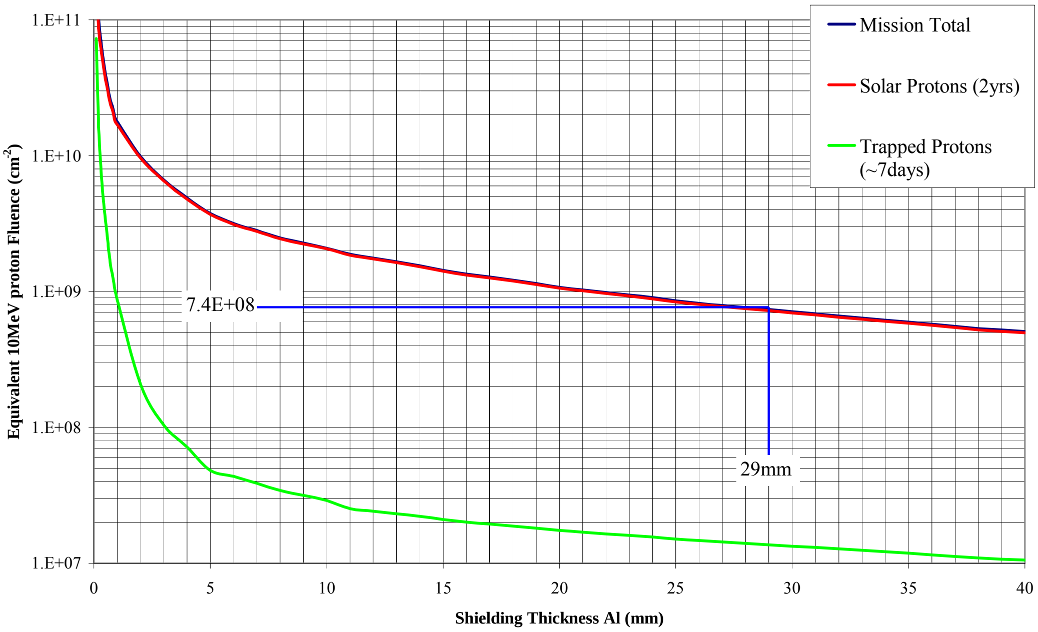

Fig. 2. 10 MeV equivalent proton fluence as a function of shielding thickness experienced by the SCD modules

It should be noted that the 3 mm copper cold finger behind each SCD module and any additional shielding provided by other spacecraft structures have not been taken into account. Occlusion of the Sun by the Moon during the Chandrayaan-1 orbit will also provide a shielding component for a fraction of the mission time. Taking these factors into consideration, the calculated EOL proton fluence used in the SCD irradiation study presented in this paper should be considered worst case.

The chosen 10 MeV equivalent proton fluences to be used in the second SCD irradiation study were therefore 7.5×10^8 protons.cm^{-2} and 3.0×10^8 protons.cm^{-2}, representing approximately 100 % and 40 % of the 2 year Chandrayaan-1 expected EOL 10 MeV equivalent proton fluence respectively.

2. EXPERIMENTAL ARRANGEMENT

The SCD module tested was housed in the test facility shown in Figure 3, featuring the inclusion of a collimator to allow the exposure of a target to a measurable X-ray fluorescence. The SCD module is mounted on a shapal (aluminium nitride ceramic) cold finger attached to a thermo-electric cooler (TEC). The TEC is in-turn mounted on a copper block through which chilled water flows removing the heat from the back of the TEC. This arrangement allows the SCDs to be operated at low temperatures, down to around -40°C to an accuracy of ± 0.2°C. Temperatures inside the chamber are monitored by two platinum resistance thermometers; one mounted on the cold finger, the other located on the ceramic next to device number 4 as shown in Figure 3, allowing the temperature of the device currently being tested to be monitored. All temperatures stated in this paper are measured device operating temperatures.

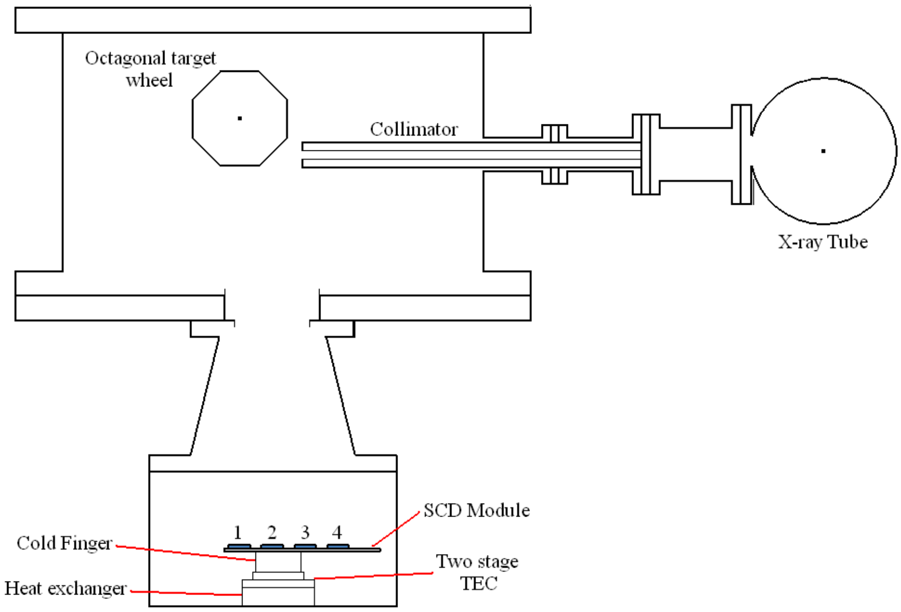

Fig. 3. Schematic of the SCD test facility

Two drive sequencers were used to characterise the SCDs prior to irradiation, called Sequencer 1 and Sequencer 2. 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 report, unless stated otherwise. 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), allowing the characteristic SCD triangular leakage current profile to be obtained.

Each device was tested with the cold finger held at the following temperatures: 20.0°C, 10.0°C, 0.0°C, -10.0°C, -20.0°C, -30.0°C, -40.0°C, and -47.0°C (all ± 0.2°C). The X-ray source used was an Oxford Instruments Tungsten filament with a tube potential of 15 kV and a tube current of 0.15 mA. Previous testing has shown the resulting X-ray beam flux to be stable to within 3 %.

Data was acquired using three sets of 600 readouts with Sequencer 2 and three sets of 4762 readouts with Sequencer 1 (equivalent to 60 seconds live time for each target). The targets used were selected to focus on the important magnesium, aluminium and silicon peaks (Target 1), provide information over the important energy detection range of the SCD (Target 3), demonstrate the expected response from the lunar surface (Target 5) and provide Manganese as a reference target (Target 7). The four targets used for testing were:

1: Magnesium, Aluminium, Silicon (solid samples)

3: Aluminium, Calcium, Copper (solid samples)

5: Magnesium, Aluminium, Silicon, Potassium, Calcium, Titanium, Iron (Lunar regolith simulant, JSC-1A)

7: Silicon, Calcium, Manganese (Rhodonite)

All data analysis was carried out using version 8 of the Xcam ltd. drive electronics software. The analysis included a re-evaluation of the results taken in the original radiation damage study that had used an earlier version of the analysis code and a different SCD headboard. A bespoke Matlab code was used to analyse the data taken using Sequencer 2.

The SCD module used for this study was designated Module 16 (based on a numbering scheme devised for the testing of numerous modules during the development of C1XS). Leakage current profiles obtained for each of the three SCDs under study were obtained using Sequencer 2 and are shown in Figure 4, normalised to the base leakage current. The cosmetic quality of each device is summarised in Table 1 (an investigation into the failure of device 1 is ongoing).

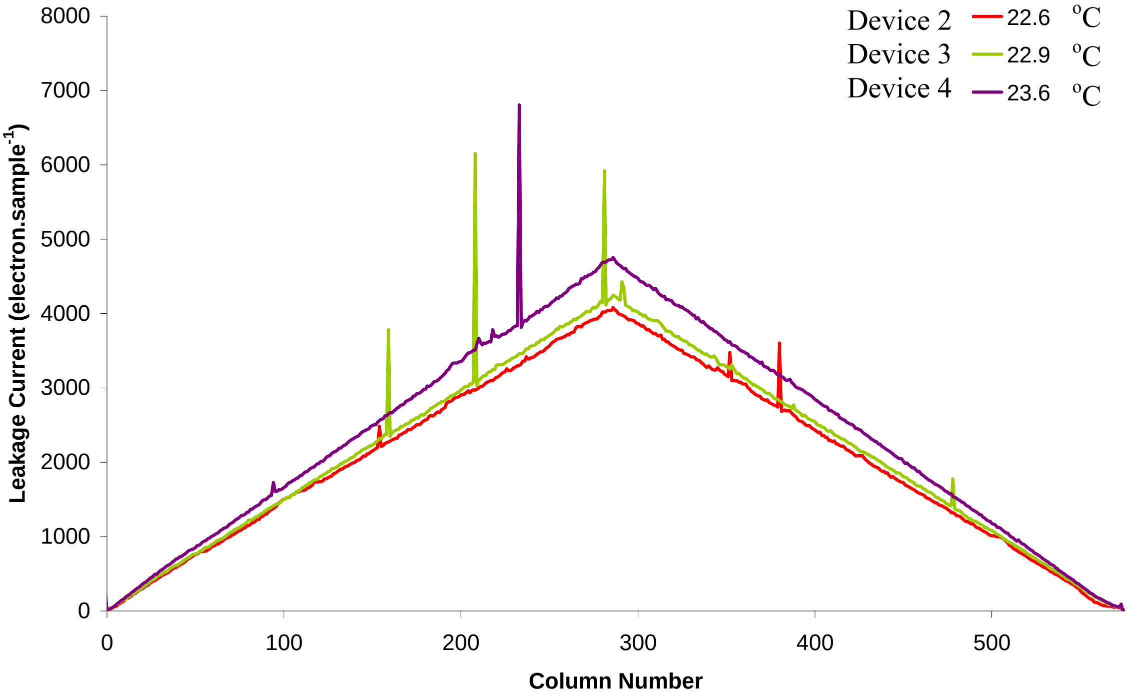

Fig. 4. Triangular leakage current profile of device 2, 3 and 4 of Module 16 before irradiation

Table 1. Cosmetic quality of Module 16

SCD	***Cosmetic Quality***
1	Device failed during pre-irradiation testing
2	Bright defects at 154, 352, 380
3	Bright defects at 159, 208, 281, 291, 478
4	Bright defects at 94, 210, 218, 232

Figure 5 shows the FWHM of Mn-Kα (5898 eV) for the two modules involved in the proton irradiation testing. Module 1 was from the original study and Module 16 was used for this study. This demonstrates that the change in drive electronics and headboard had little effect on the performance of the SCD devices.

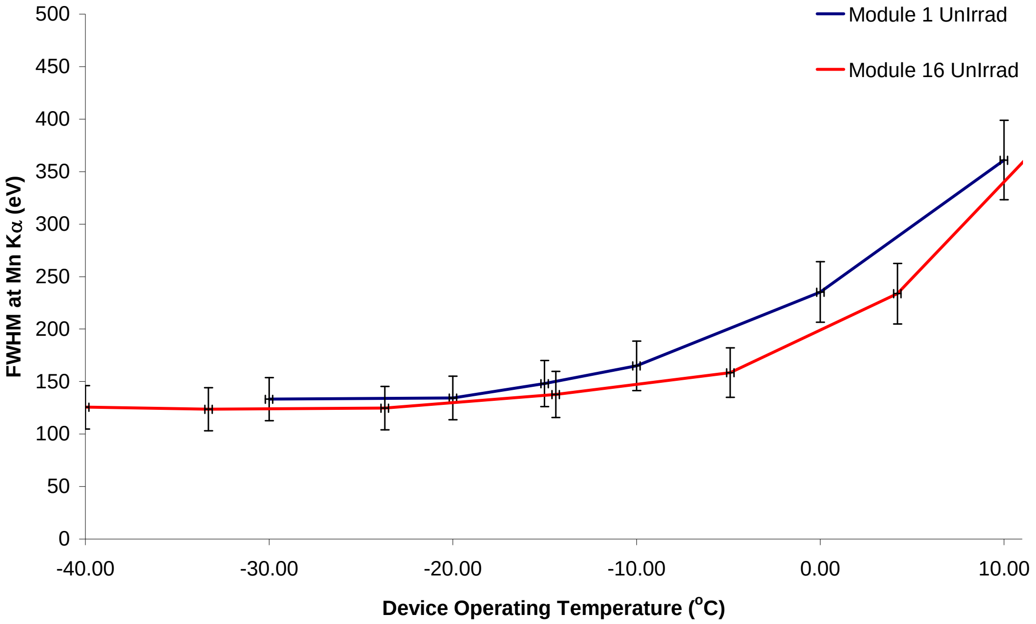

Fig. 5. FWHM of Mn-Kα from un-irradiated devices from Modules 1 and 16

2.1 SCD proton Irradiation

The proton irradiations were carried out at Birmingham University using the MC40 cyclotron. The 15 MeV protons emitted were attenuated by a 30 µm havar window (allowing the beam to exit into air), a 100 µm tungsten scattering foil (to make the beam flux more uniform over the target area), the air between the beam exit and the target SCD and the presence of Gafchromic film (positioned in front of the target SCD to measure the proton fluence received). The SCDs being positioned in an aluminium holder at a distance from the beam exit corresponding to an attenuated proton energy of 10 MeV incident at the surface of the SCD. The irradiation setup is displayed in Figure 6, showing the beam exit with the tungsten scattering foil attached, and the aluminium holder which held the SCD module.

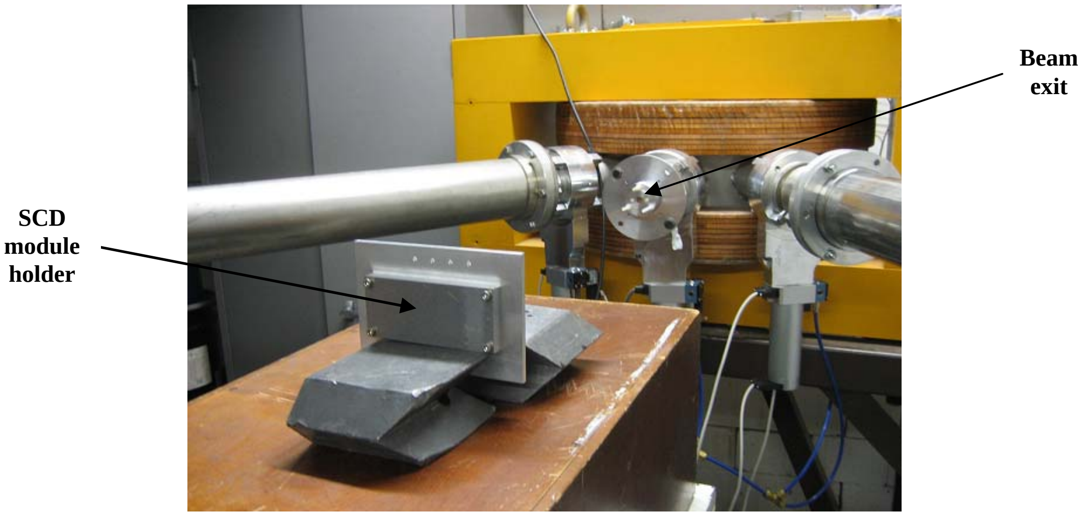

Fig. 6. Irradiation setup at Birmingham University

The beam flux rate at the target distance was calibrated prior to each irradiation using Gafchromic film, allowing the calculation of the time required to reach the target fluences. Gafchromic film was also positioned in front of the target SCD during each irradiation to provide a direct measurement of the total proton fluence received in each case. Beam flux uniformity was found to be within 10 % across the SCD target area. The irradiations were carried out in air with the SCDs un-biased. The whole detector area was irradiated for each target device. Device 2 was left un-irradiated as a control. Device 3 was irradiated with 7.5×10^8 protons.cm^{-2} over ~15 minutes and device 4 with 3.0×10^8 protons.cm^{-2} over ~7.5 minutes. A 10 mm thick aluminium shield covered those devices not being irradiated.

3. RESULTS AND DISCUSSIONS

The SCD characterisation described in Section 2 was repeated following irradiation. The increase in leakage current resulting from each of the two different proton fluences can be seen in Figure 7 which shows data taken using Sequencer 2 after irradiation. The intensity of the bright pixels and the leakage current variation across each device has increased in proportion to the dose given, in line with the results taken in the first irradiation study (it should be noted that the leakage current using Sequencer 1 to provide pulse height analysis is much lower). The profiles from the irradiated devices are symmetrical, demonstrating a uniform proton irradiation in each case.

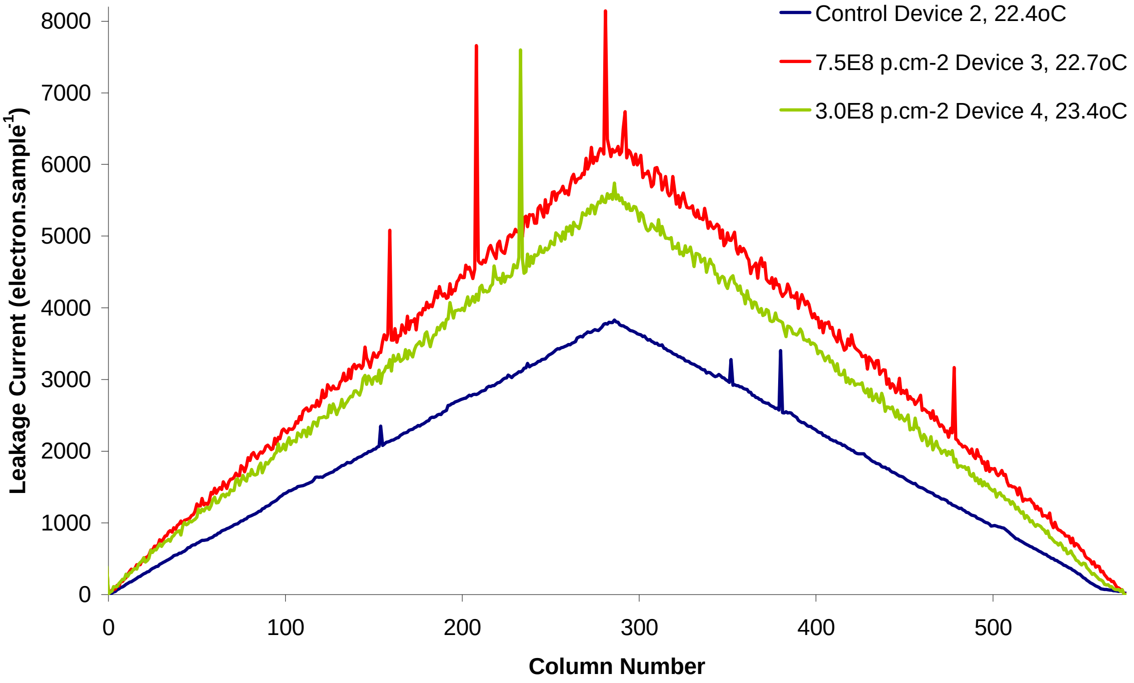

Fig. 7. Triangular leakage current profile of devices 2, 3 and 4 of Module 16 after irradiation

The effect of proton irradiation on the leakage current while using Sequencer 1 can be observed in Figure 8. This figure shows the leakage current profile of device 3 before and after irradiation with 7.5×10^8 protons.cm^{-2} while Figure 9 shows the leakage current profile of device 4 before and after irradiation with 3.0×10^8 protons.cm^{-2}.

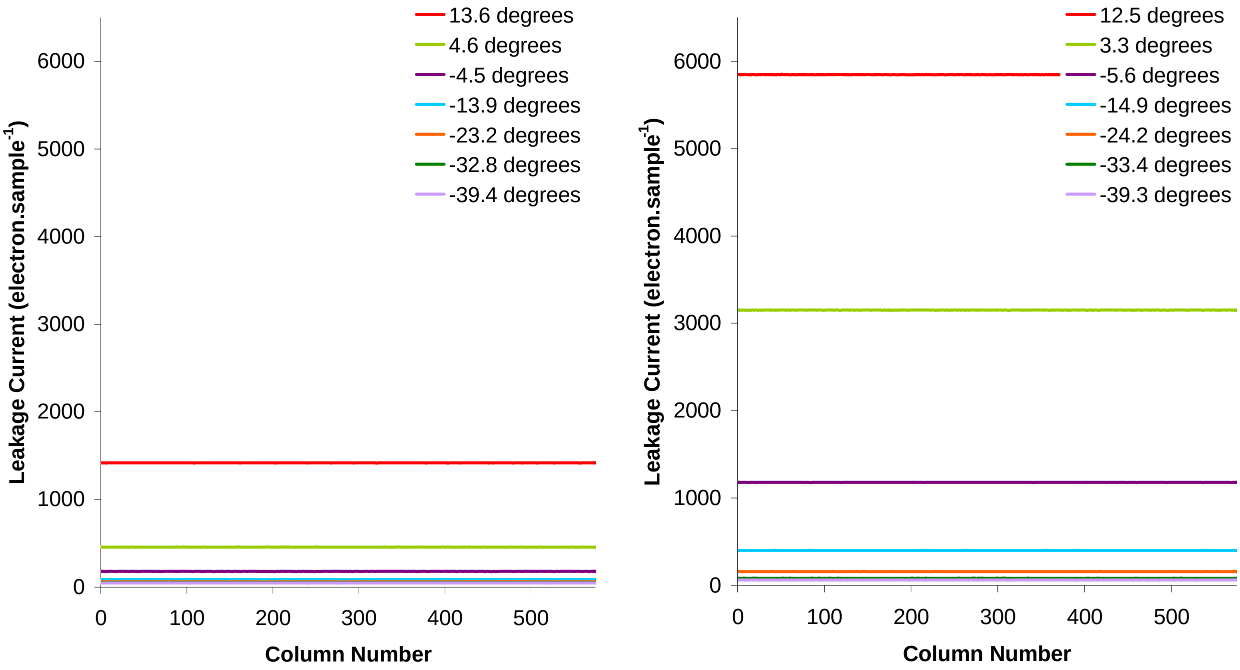

Fig. 8. Leakage current profile of device 3 using Sequencer 1 before and after irradiation to 7.5 × 10^8 protons.cm^{-2}

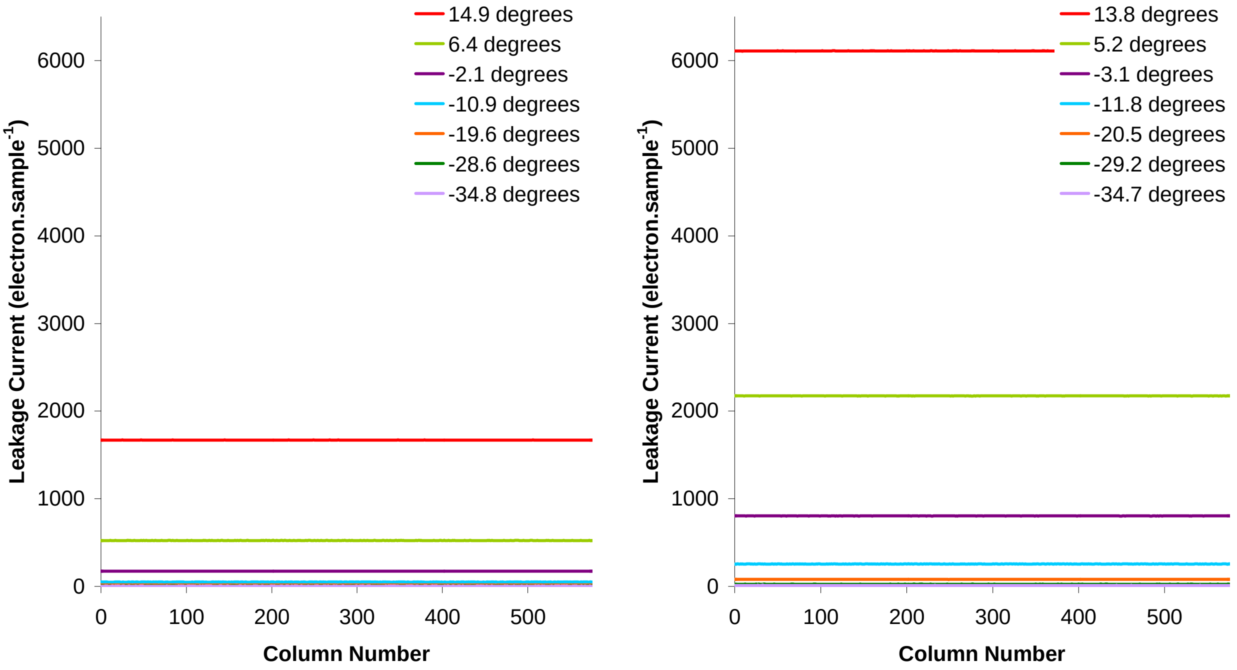

Fig. 9. Leakage current profile of device 3 using Sequencer 1 before and after irradiation to 3.0 × 10^8 protons.cm^{-2}

Figure 10 shows the recorded FWHM at Mn-Kα for the Module 1devices from the first irradiation study (unirradiated, 2.1 × 10^8 protons.cm^{-2} and 4.3 × 10^8 protons.cm^{-2}) and Module 16 from the current study (unirradiated, 7.5 × 10^8 protons.cm^{-2} and 3.0 × 10^8 protons.cm^{-2}). The error bars arise from the differing number of counts, slight variations in the number of electron volts per channel from module to module, and the accuracy in the temperature measurement. The change in FWHM with increasing proton fluence is approximately linear, the FWHM increasing with increasing fluence.

Figure 11 compares the proton fluence with the measured FWHM of Mn-Kα X-rays at -20°C including a linear fit to the experimental data.

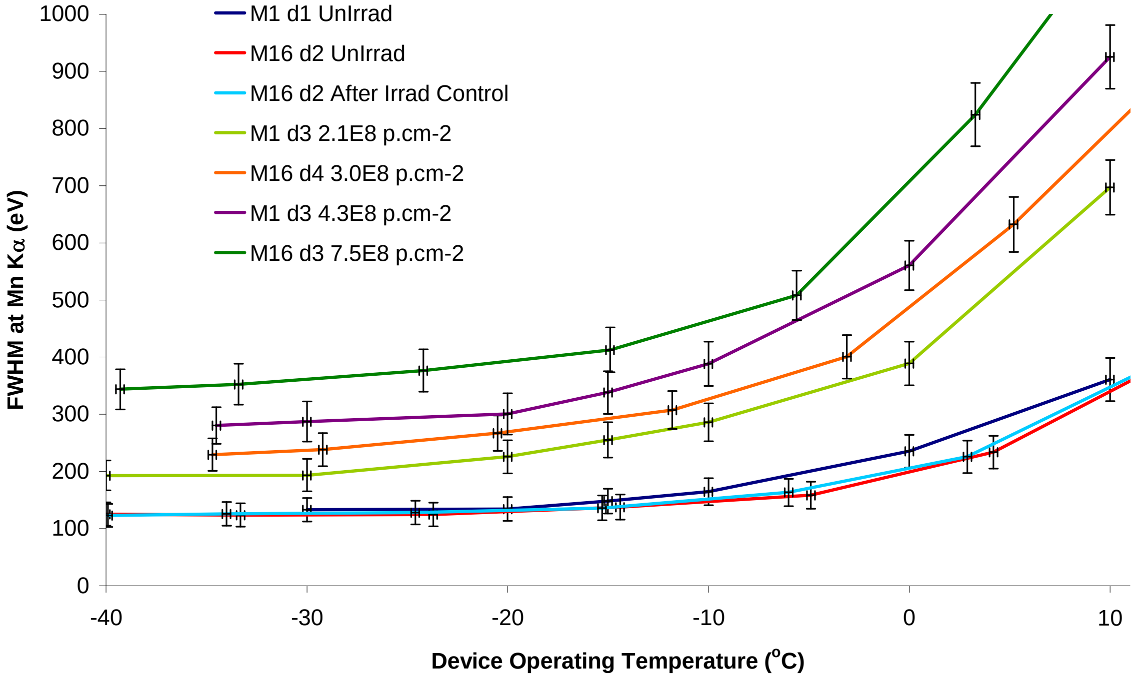

Fig. 10. FWHM of Mn-Kα at different operating temperatures after irradiation

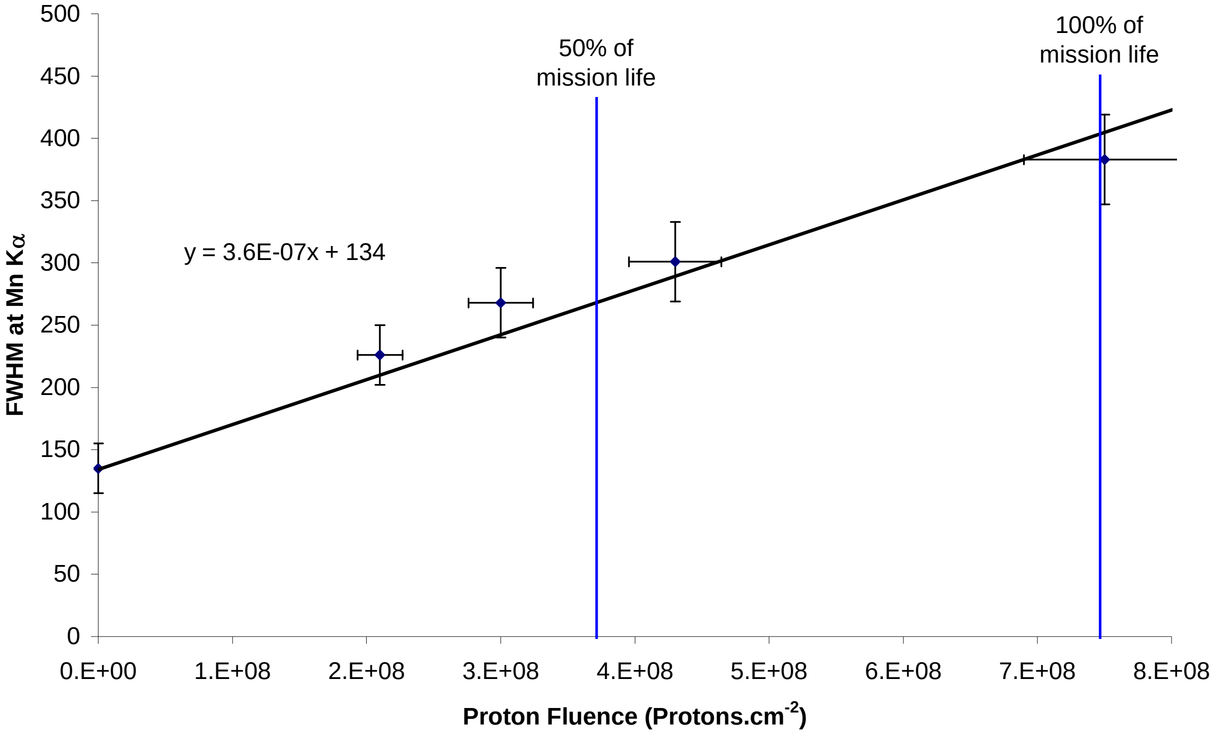

Fig. 11. Proton Fluence versus the FWHM of Mn-Kα at -20°C

On comparison with the measured total noise vs. temperature, shown in Figure 12, the increase in leakage current resulting from irradiation is not enough to account for the decreased noise performance shown in Figures 13 and 14 which compare the Fano limited FWHM of Al-Kα and Cu-Kα with the measured results. The remaining loss in noise performance is as a result of decreased charge transfer efficiency (CTE), highlighted by the greater increase in FWHM at the higher energies which are strongly affected by decreased CTE. Un-irradiated, the SCD becomes near Fano limited at around 9 e^- r.m.s. (4.5 e^- r.m.s. system noise), which corresponds to an operating temperature at or below -10°C.

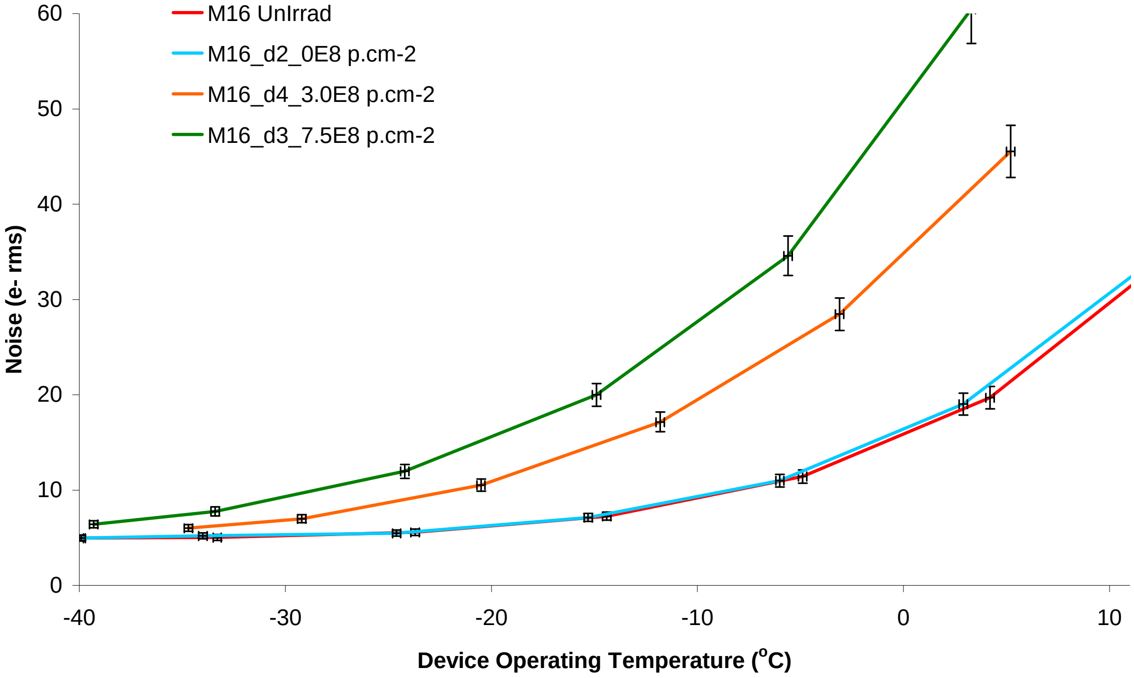

Fig. 12. Device operating temperature versus total noise

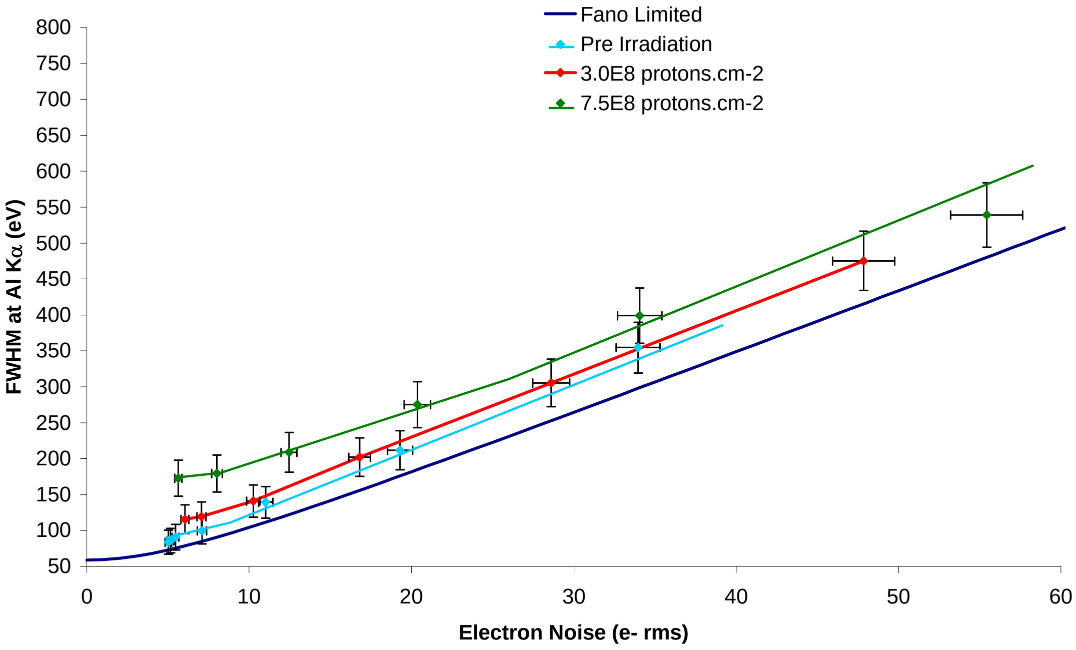

Fig. 13. Fano limited FWHM at Al-Kα compared with measured results

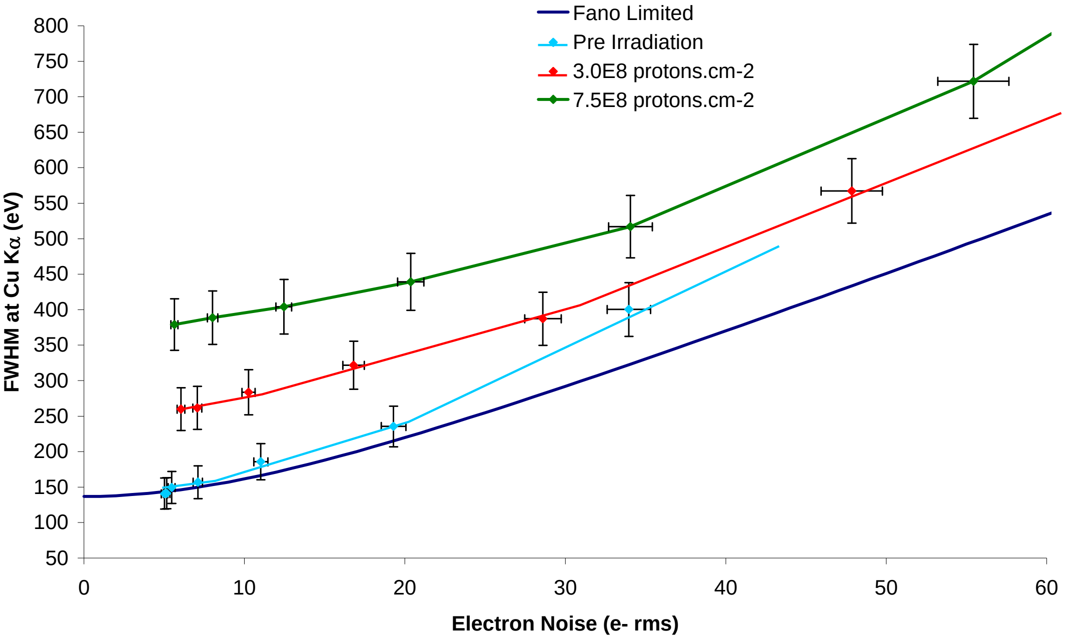

Fig. 14. Fano limited FWHM at Cu-Kα compared with measured results

Spectra from the Lunar regolith simulant are shown before irradiation, after 3.0 × 10^8 protons.cm^{-2}, and after 7.5 × 10^8 protons.cm^{-2} at near mission operating temperature of -20°C in Figure 15. Half way through the mission duration it will be hard to distinguish between Mg, Al, and Si unless the device operating temperature is lower than -20°C, while towards the end of the mission the temperature will need to be as low as -25°C to clearly distinguish the three elements. X-rays of an energy close to Ca at 3691 eV and Fe at 6403 eV, for example K and Mn, will be lost due to increased spreading of the signal as the radiation damage increases. It is therefore essential that K, Mn and the Mg, Al and Si lines are investigated as much as possible in the first year of the mission.

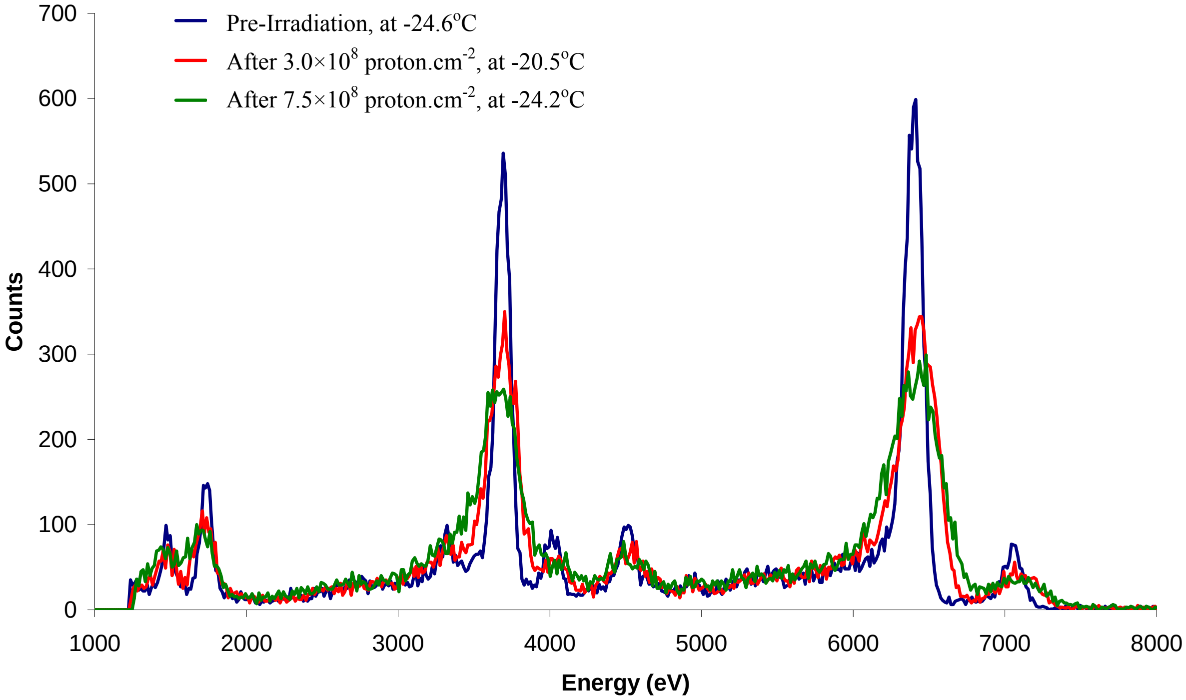

Fig. 15. X-ray spectra of Lunar regolith simulant at near mission operating temperature of -20°C

4. CONCLUSIONS

After proton irradiation to the latest expected Chandrayaan-1 EOL proton fluence all SCD devices were found to be operational, exhibiting an increase of ~70 % in leakage current at 3.0 × 10^8 protons.cm^{-2} and an increase of ~140 % at 7.5 × 10^8 protons.cm^{-2} when operating at -20 °C. The target resolution of 250 eV FWHM at Mn-Kα will be achievable up to around 1 year into the mission with the SCDs operating at -20 °C. Beyond the mid-point of the mission, additional cooling will be required to maintain target resolution. It is vital that the operational temperature of the SCDs used in C1XS is accurately modeled to provide confidence that the instrument will perform well over the entire 2 year mission duration. Maintaining temperature stability is also vital because as the radiation dose increases, device operation above -15 °C becomes very sensitive to temperature fluctuations. At the time of writing this report, it has been stated that the target operating temperature of -20 °C is maintained for greater than 95 % of orbital configurations [3].

The 10 MeV equivalent proton flux that the devices will be exposed to during the mission is around 9.9 × 10^5 protons.cm^{-2}.day^{-1} from solar protons and 2.9 × 10^6 protons.cm^{-2}.day^{-1} from trapped protons during the initial 7 day transfer orbit. This demonstrates the importance of spending as little time as possible within the Earth's radiation belts, both to limit the amount of radiation damage to the SCDs and also to limit any possible damage to the SCD drive electronics.

This study has shown that CTE degradation as a result of radiation damage is the dominant component in the loss of instrument performance during the mission, making the use of isolated events in the analysis of the data essential. Combining split events in the analysis can be used to increase the X-ray detection efficiency, but at the cost of an increased FWHM. Using only isolated events, the measured FWHM of four different elements at -20°C is summarised in Table 2, showing the decrease in performance as a result of the various proton fluencies studied.

Table 2: FWHM at -20°C for different elements over the predicted Chandrayaan-1 mission lifetime

10 MeV equivalent fluence (protons.cm^{-2})	*Elapsed mission time (%)*	*FWHM at 1487 eV (eV) Aluminium*	*FWHM at 3691 eV (eV) Calcium*	*FWHM at 5898 eV (eV) Manganese*	*FWHM at 8047 eV (eV) Copper*
0	0	95	122	134	153
2.1 × 10^8	28			226	
3.0 × 10^8	41	142	200	268	286
4.3 × 10^8	58			300	
7.5 × 10^8	101	238	350	390	420

The eV per channel calibration after the irradiation increased as a result of the formation of new traps sites within the silicon, the un-irradiated value is 13.9 ± 0.1 eV per channel. Lower energy X-rays produce fewer electron hole pairs than higher energy X-rays and are thus more susceptible to electron loss. This resulted in an increase in calibration of 2.9% and 1.7% after 3.0 × 10^8 protons.cm^{-2} and an increase of 7.8% and 3.8% after 7.5 × 10^8 protons.cm^{-2} for Al-Kα and Cu-Kα X-rays respectively. The slight shift in calibration with will have little effect of data analysis as the increase in relation to dose is negligible, a shift of ~0.01% per day for Al-Kα X-rays.

The results of this study and the first SCD irradiation study will allow the performance of the SCDs to be predicted throughout the Chandrayaan-1 mission lifetime and have demonstrated that C1XS will be able to successfully complete its mission to conduct mineralogical mapping over the surface of the moon. Further work will be to continue to analyse the data taken after the irradiation, investigate the points raised in this paper, and to compare these results with the observed radiation damage effects as the Chandrayaan-1 mission progresses.

Acknowledgments

The authors would like to thank Steve Watts from Manchester University for his assistance with the dosimetry during the second irradiation study, David Parker from Birmingham University for the use of the cyclotron, Shoshana Weider from Birkbeck College London for providing the Lunar regolith simulant, and Chris Howe, Barry Kellet, and Brian Maddison from RAL and Christian Erd at ESA for their continued assistance and feedback concerning the calibration of the C1XS instrument.

REFERENCES

1. J. Gow, D. R. Smith, A. D. Holland, B. Maddison, C. Howe, P. Sreekumar, J. Huovelin, M. Grande, "Characterisation of Swept-Charge Devices for the Chandrayaan-1 X-ray Spectrometer (C1XS) instrument", *Proc. SPIE*, vol. **6686**, (2007).
2. D. R. Smith, J. Gow, A. D. Holland, "Proton Irradiation of Swept-Charge Devices for the Chandrayaan-1 X-ray Spectrometer (C1XS)", *Nuc. Inst. Meth*., vol. **A583**, pp. 270-77, (2007).
3. C. J. Howe, D. Parker, B Maddison, R. Edeson, D. Drummond, B. Kellett, J. Spencer, P. Sreekumar, S. Narendranath, A. Shrivastava, L. d'Uston, O. Gasnault, M. Grande, D. Smith, J. Gow, J. Huovelin, "Chandrayaan-1 X-ray Spectrometer (C1XS) – Instrument Design & Technical Details", To be submitted to Planetary and Space Science, (2008).
4. M. Grande et al., "The D-CIXS X-ray mapping spectrometer on SMART-1", Planetary and Space Science, vol. 51, pp. 427-433, (2003).
5. M. Grande et al., "The D-CIXS X-ray spectrometer on the SMART-1 mission to the Moon – First results", Planetary and Space Science, vol. 55, pp. 494-502, (2007).
6. D. Heynderickx, B. Quaghebeur, E. Speelman, E. J. Daly, "ESA's Space ENVironment Information System (SPENVIS): A WWW Interface to Models of the Space Environment and its Effects", Proc. AIAA, vol.0371, (2000).