Electro-optic and radiation damage performance of the CIS115, an imaging sensor for the JANUS optical camera on-board JUICE

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ABSTRACT

The Jupiter Icy Moon Explorer (JUICE) has been officially adopted as the next Large-class mission by the European Space Agency, with a launch date of 2022. The science payload includes an optical camera, JANUS, which will perform imaging and mapping observations of Jupiter, its moons and icy rings. A 13 slot filter wheel will be used to provide spectral information in order for the JANUS experiment to study the geology and physical properties of Ganymede, Europa and Io, and to investigate processes and structures in the atmosphere of Jupiter.
The sensor selected for JANUS is the back-thinned CIS115, a 3 MPixel CMOS Image Sensor from e2v technologies. The CIS115 has a 4-Transistor pixel design with a pinned photodiode to improve signal to noise performance by reducing dark current and allowing for reset level subtraction. The JUICE mission will consist of an 8 year cruise phase followed by a 3 year science phase in the Jovian system. Models of the radiation environment throughout the JUICE mission predict that the End of Life (EOL) non-ionising damage will be equivalent to 10^{10} protons cm^{-2} (10 MeV) and the EOL ionising dose will be 100 krad(Si), once the shielding from the spacecraft and instrument design is taken into account. An extensive radiation campaign is therefore being carried out to qualify and characterise the CIS115 for JANUS, as well as other space and terrestrial applications.
Radiation testing to take the CIS115 to twice the ionising dose and displacement damage levels was completed in 2015 and the change in sensor performance has been characterised. Good sensor performance has been observed following irradiation and a summary of the key results from the campaign using gamma irradiation (ionising dose) will be presented here, including its soft X-ray detection capabilities, flat-band voltage shift and readout noise. In 2016, further radiation campaigns on flight-representative CIS115s will be undertaken and their results will be disseminated in future publications.
Keywords: CMOS APS, JANUS, CIS115, ionising damage, 4T, displacement damage.

1. THE CIS115 IN THE JANUS INSTRUMENT

The CIS115 is the detector (Figure 1) baselined for the imager on the Jupiter Icy Moon Explorer (JUICE) mission [1]. The optical camera, called JANUS (Jovis, Amorum ac Natorum Undique Scrutator), is designed to provide both wide-field and high-resolution images to contribute to the study of the surfaces of the Jovian moons and the upper layers of Jupiter's atmosphere [2]. The telescope optical design has evolved into a Modified Ritchey-Chrétien format [3], with the 7 µm square pixels of the CIS115 [4] providing 15 µrads $pixel^{-1}$ instantaneous field of view, which is expected to result in resolutions equivalent to 10 m $pixel^{-1}$ on the surface of Ganymede whilst observing during close orbital mission phases. The CIS115 has an image area of 2000 rows and 1504 columns giving a field of view of 1.72° × 1.29°.

A filter-wheel with 13 slots will provide narrow and broadband filters ranging from 350 nm to 1060 nm in order for spectral observations to be made, and a front cover module will provide protection to the internals of the telescope until deployment. Power, communication and control are achieved through a proximity electronics unit situated in the camera unit, and a main electronics unit (power supply and data processing) in the central radiation vault of the spacecraft.

The radiation environment of Jupiter leads to a hazardous operating and survival environment for the JUICE spacecraft and instruments. The large number of high energy electrons and protons trapped in the Jovian magnetosphere make up significant contributions to the expected End of Life (EOL) total ionising dose (100 krad(Si)) and non-ionising equivalent fluence (10^{10} 10 MeV protons cm^{-2}) of the CIS115 sensor in the JANUS camera. The CIS115 is undergoing radiation qualification to identify and quantify any changes in performance parameters that can be expected during the mission lifetime and confirm that it meets specifications for camera performance throughout the mission. A study on displacement damage in the CIS115 has been reported [5] showing good device performance following exposure to an EOL equivalent fluence of protons. An ionising radiation damage campaign has been undertaken which will be presented here.

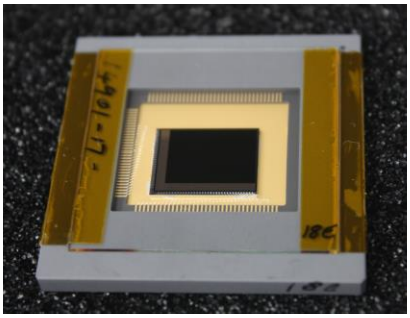

Figure 1. A back illuminated CIS115 is shown here, with a temporary cover glass fixed to provide protection during handling.

2. TOTAL IONISING DOSE TESTING OF THE CIS115

A Cobalt-60 cell at Brunel University London (UK) was used to irradiate two CIS115s at a dose rate of 6.5 krad(Si) $hour^{-1}$ whilst the devices were being clocked and biased with images being recorded throughout the irradiation. The detectors were at room temperature and pressure and positioned 20 cm from the source (Figure 2), allowing for adequate lead shielding to protect the readout electronics that are used for laboratory characterization of the sensor. Each sensor was irradiated separately, and driven using a control box and PC that were located outside the irradiation hutch. Power and fibre optic connections were made to a PCB stack that contains a socket for the CIS115 and is where clocks and biases are generated and outputs are digitized. Testing before and after irradiation showed no change to the camera electronics performance from shielded exposure to the Co-60 source.

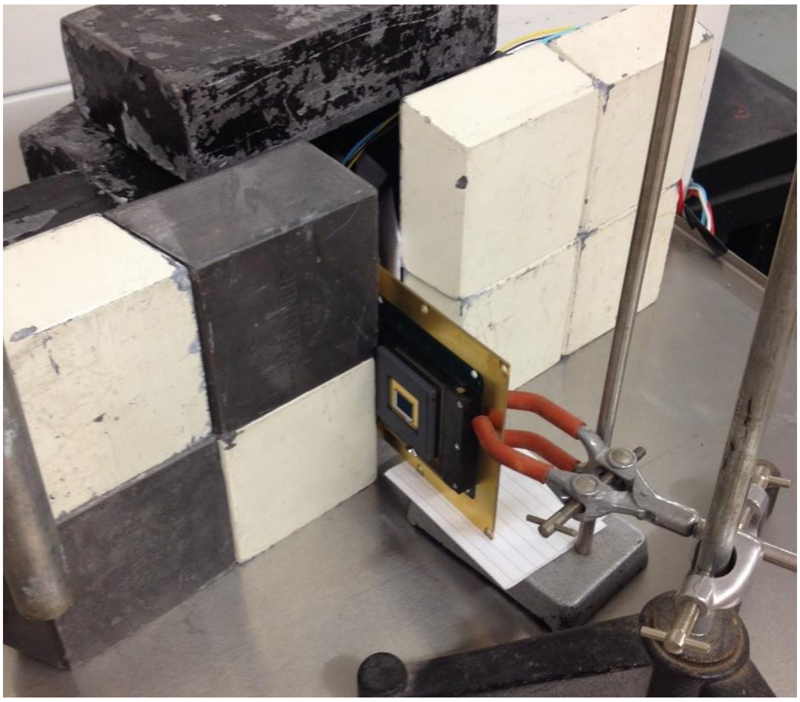

Figure 2. During irradiation, the Cobalt-60 source is extruded from its storage location down the metal pipe seen in the left of this photograph. The sensor is 20 cm from the source, in a zero insertion force socket that provides connection to the camera electronics. Lead shielding (white and grey blocks) is used to protect the active electronic components of the drive and readout electronics from the dose of gamma rays and secondary particles.

Table 1. Ionising dose levels of the two CIS115s studied.

Device serial #	Exposure duration, hours	Accumulated dose, krad(Si)
CIS115-14901-17-15E	15.4	100
CIS115-14901-17-19E	30.8	200

3. IONISING DOSE INDUCED EFFECTS OBSERVED IN THE CIS115

3.1 Observations during irradiation

Irradiations were begun on 18 August 2015, when the two CIS115s were irradiated to EOL and twice EOL total ionising dose levels (Table 1). Data capture was successful with images recorded throughout both the irradiations, confirming that the devices were biased and clocked. The images were captured during irradiation with the device operating in a rolling shutter mode with an effective integration time of 0.18 s, recording a frame every 10 s. The signal from a 100 × 100 pixel region of interest has been plotted in Figure 3, for the last 14.4 hours of irradiation of the 100 krad(Si) device. The linear fit in Figure 3 shows the signal level from gamma ray ionisation reducing by 37.9 DN hour^{-1} or 5.8 DN krad^{-1}, whilst the background level is observed to have reduced by 420 DN, or 4.5 DN krad^{-1} from before to after the exposure. The effect is linear during the irradiation and is therefore believed to be radiation-induced. It is unlikely to be due to temperature variations due to its strict linear behaviour throughout the 14.4 hour period (overnight).

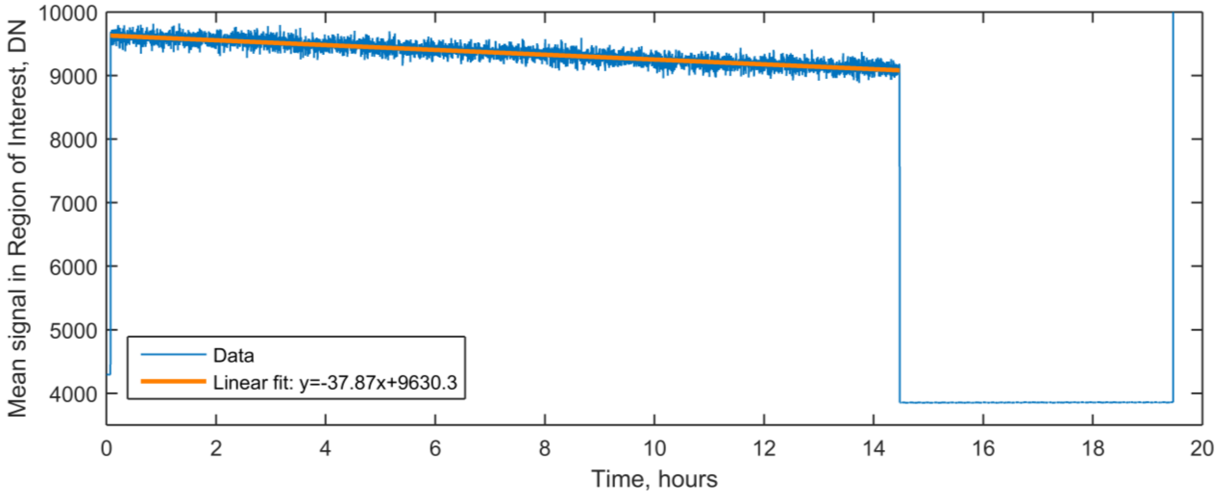

Figure 3. The signal observed during irradiation of a CIS115 begins at a dark level (4300 DN) and increases to 9650 DN as the sensor is exposed to the gamma cell during the first hour. After 14.4 hours, the Cobalt-60 source was retracted into its storage location, reducing the signal observed, and the signal returned to a background level of 3900 DN. After 19 hours, the signal level was saturated (~50000 DN) when the hutch lights were switched on and the recording was halted.

3.2 Characterisation after irradiation

Following irradiation, the devices were returned to the laboratory for characterisation, to compare their performance with data taken before irradiation. Tests included responsivity, dark current, readout noise, electrical transfer function, reset transistor characterisation and image lag measurements.

Calibration measurements were performed using the characteristic soft X-ray spectrum from an Iron-55 source. Signal charge from X-rays is either split across multiple pixels due to diffusion in the field-free region of the back illuminated sensor (split events), or all collected in a single pixel when the X-ray interaction occurs within the depleted region of the photodiode (isolated event). Example split and isolated events are shown in Figure 4.

Isolated events have been selected by identifying pixels that contain greater than 300 eV signal, with nearest neighbours containing less than a threshold of 50 eV of signal (Figure 5). A best fit of the expected manganese K_{α} and K_{β} spectral features leads to a measured energy resolution of 183.5 eV, which shows promise for the CIS115 technology in future soft X-ray applications since this sensor has been designed as an optical imager. This spectrum is also greatly improved from the raw X-ray spectrum recorded with a front-illuminated sensor at room temperature published previously [4].

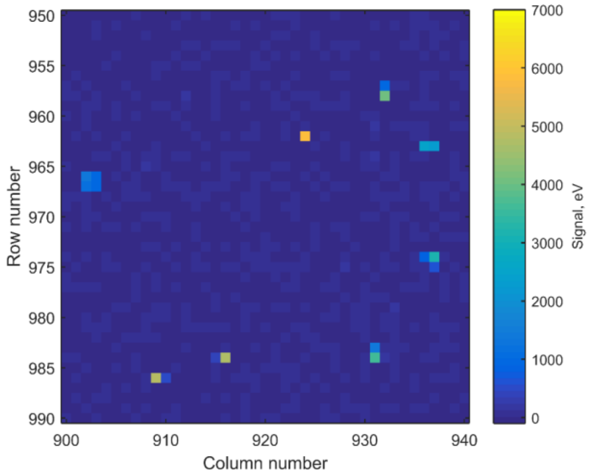

Figure 4. Example X-ray events are observed above the noise floor in this unirradiated CIS115, at -40 ˚C. Charge is often split between multiple pixels. Pixels are 7 µm square and the silicon is thinned to approximately 10 µm, but not fully depleted.

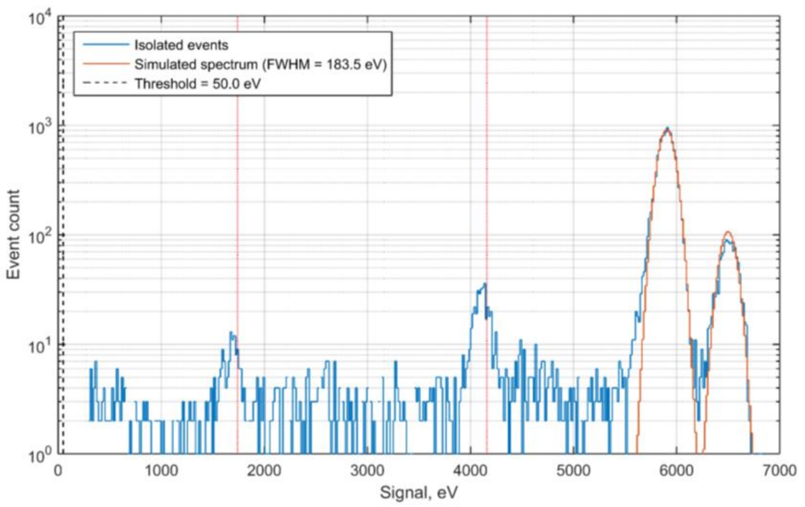

Figure 5. A characteristic X-ray spectrum from an Iron-55 source has been generated from isolated events observed in the CIS115. Manganese K_{α} and K_{β} spectral features are observed at 5898 eV and 6490 eV, whilst silicon-K fluorescence and escape peaks are observed at approximately 1740 eV and 4160 eV respectively.

Following irradiation, the sensor Charge to Voltage Factor (CVF) obtained from Iron-55 spectra is observed to reduce by less than 1% per 100 krad(Si). This change is also detected using the mean-variance technique [6] and observed in a shift of the Electrical Transfer Function (ETF) measurement, where a known signal level is injected and then read out.

3.3 Flat band voltage shift

The small changes in responsivity, saturation voltage and linear drift observed during irradiation are likely due to a flat band voltage shift, investigated through studying the behaviour of the reset transistors in one row of pixels before and after irradiation. The reset transistors were probed by determining the gate to drain voltage at which the reset transistor began conducting, using the timing sequence shown in Figure 6. The charge injected across the reset transistor from the reset drain at a range of drain voltages was measured. In unirradiated sensors, the onset of charge injection has been observed when the difference between drain and gate voltage is 0.31 V. Following ionising irradiation, injection occurs at a more positive reset drain voltage accounting for an effective gate voltage increase due to trapped positive charge in the gate dielectric. The change in the reset drain voltage at which injection begins is an indication of the flat band voltage shift occurring under the reset gate.

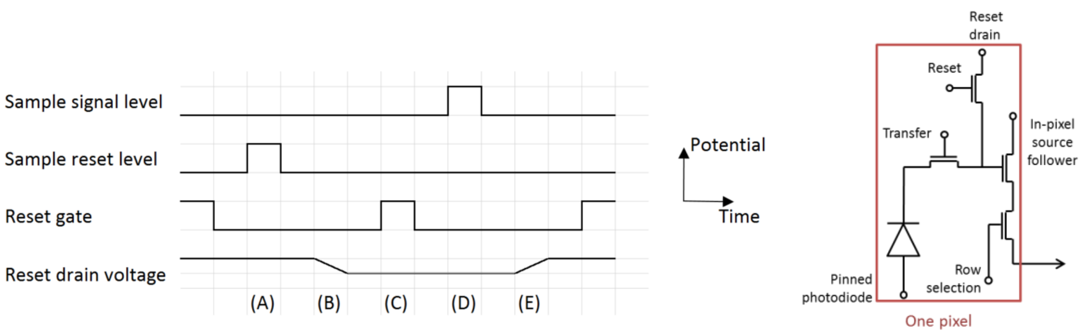

Figure 6. Left: The reset transistor behaviour was tested using the timing sequence shown in this schematic. To begin, the pixel sense node potential was reset and the reset level sampled (A). The reset drain voltage was then changed to a test level (B) before the reset gate was pulsed (C). The any signal injected into the sense node by the new reset drain voltage is then recorded by sampling the signal level (D). The reset drain voltage is then returned to a normal level for normal reset (E). Right: The schematic of the CIS115's 4 transistor CMOS pixel is shown for reference.

The flat band voltage shift is shown in Figure 7 for the two gamma irradiated detectors, and two CIS115 devices that have undergone proton irradiation, as a function of total ionising dose. The effect appears to be saturating as the dose is increased and the shift is 1.6 mV krad^{-1} at 100 krad(Si), or 1.1 mV krad^{-1} at 200 krad(Si).

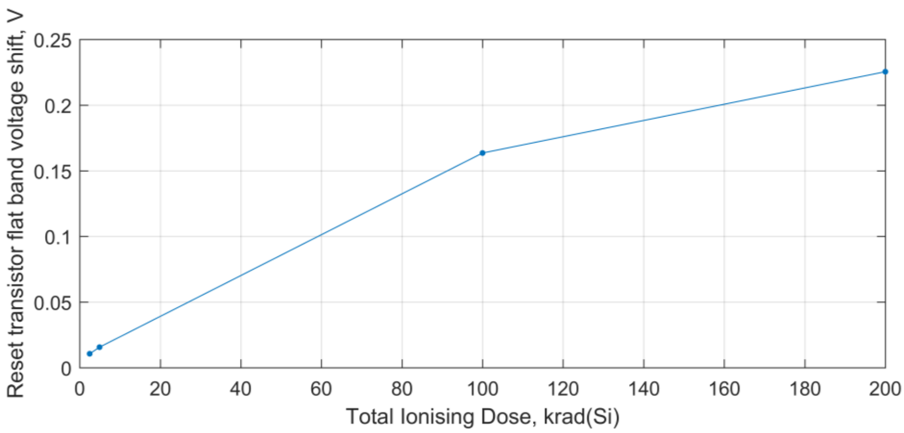

Figure 7. The flat band voltage shift measured on the reset transistors shows a saturating behaviour up to 200 krad.

3.4 Readout noise

The readout noise has been measured on a pixel by pixel basis for the detectors before and after irradiation. Measurements have been taken at -50 ˚C and photodiodes were reset immediately before readout in order to eliminate contributions from dark current and other background signal.

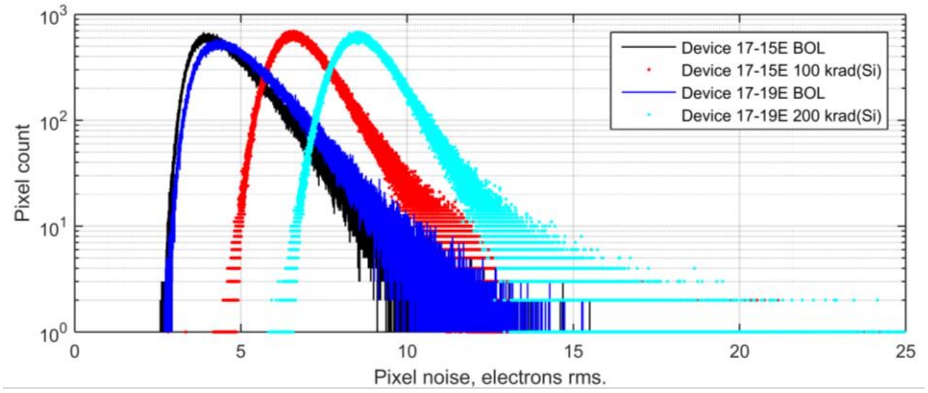

Figure 8. Pixel read noise distributions for the CIS115s at Beginning of Life (BOL) and after ionising doses.

Average pixel readout noise was less than 5 electrons rms for the CIS115s before irradiation. Following irradiation, the readout noise was observed to degrade slightly with increasing ionising dose, and a temperature dependence was observed that was not present before exposure to ionising radiation (Figure 9). The additional noise component does not exhibit an exponential behaviour as expected from the Arrhenius equation, and therefore has not been attributed to dark current. No clear random telegraph signal (RTS) behaviour has been observed during visible inspection of the data and a similar noise increase has not been observed in proton irradiated CIS115s, where large amplitude RTS was more prevalent. The temperature (T) dependence loosely followed a $T^{½}$ behaviour suggesting additional white noise in the analogue chain may be the cause, but further investigation is required to identify the origin of this minor degradation in readout noise and identify methods to mitigate any impact of this effect.

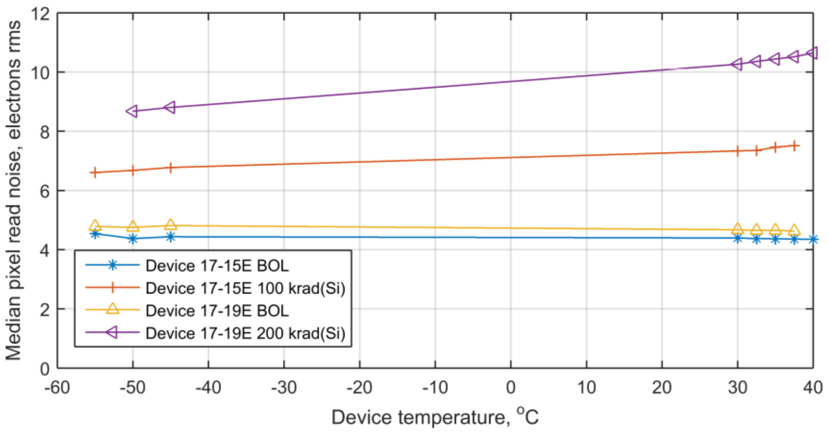

Figure 9. Readout noise has been measured in the detectors operating at temperatures above room temperature (30 ˚C to 40 ˚C) and with the detector cooled cryogenically to the proposed mission operating temperature for JANUS (-55 ˚C to -45 ˚C). A temperature-dependent effect is observed following ionising dose.

3.5 Dark current

The overall dark current measured in the CIS115s increased following ionising irradiation, as shown in Figure 10. The dark current degrades by a factor of approximately 2.5 in both the detectors, suggesting that the degradation is not dependent on total ionising dose at these dose levels. Further testing will include a device radiated to 50 krad(Si) which may help probe the region before the dark current generation mechanism is saturated. For JANUS, the detector is expected to be operated at temperatures below -30 ˚C, allowing the thermally generated dark signal to be suppressed to levels where other noise sources dominate.

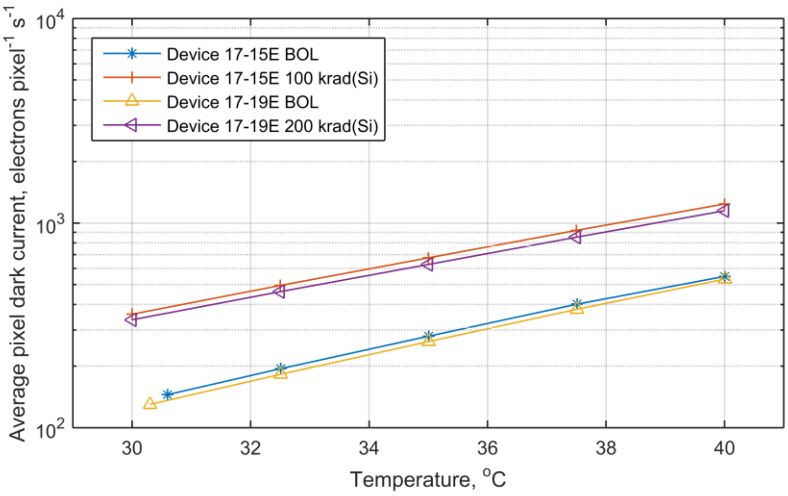

Figure 10. Dark current measurements above room temperature show an approximate 2.5 increase in dark current following both irradiations, compared to Beginning of Life (BOL). For reference, 100 electrons pixel^{-1} s^{-1} is equivalent to 32.7 pA cm^{-2}.

4. SUMMARY AND FUTURE WORK

The CIS115 has been selected as the sensor for the JANUS camera to play an integral part in the scientific study of Jupiter's atmosphere and moons during the JUICE mission. Radiation characterisation and qualification of the CIS115 is ongoing, and a preliminary gamma irradiation of two CIS115s has been undertaken with the initial results presented here. The CIS115s were irradiated at room temperature and were clocked and biased.

One effect of ionising dose on the CIS115 reported here is a flat band voltage shift of 1.6 mV krad^{-1}, at 100 krad(Si) or 1.1 mV krad^{-1} at 200 krad(Si). A shift was also observed during the irradiation in the average signal level being read out by the sensor. The detector responsivity has been determined using a characteristic Iron-55 spectrum, and an example spectrum produced by isolated events has been produced (Figure 5). The responsivity reduced by less than 2% following 200 krad(Si). An additional noise contribution is observed in the readout noise measurement following the ionising dose which roughly follows a $T^{½}$ dependence but must be studied further to understand its source. The dark current has also increased following irradiation as expected, and this will be mitigated in JANUS by operation at a lower device temperature (less than -30 ˚C).

A future radiation campaign is being planned on Lot Acceptance Tested CIS115s as part of their qualification for space applications. Further studies of the effects reported here will be undertaken in order to understand them further. Additional radiation campaigns with protons, heavy ions and high energy electrons will also be carried out, enabling the performance of the CIS115 following exposure to harsh radiation environments to be well characterized. The testing to date shows the CIS115 performs well within the JANUS specifications, and is a promising detector for other applications in the future [7].

REFERENCES

[1] Grasset, O., Dougherty, M.K., Coustenis, A., Bunce, E.J., Erd, C., Titov, D., Blanc, M., Coates, A., Drossart, P., Fletcher, L.N., Hussmann, H., Jaumann, R., Krupp, N., Lebreton, J.-P., Prieto-Ballesteros, O., Tortora, P., Tosi, F., Van Hoolst, T., "JUpiter ICy moons Explorer (JUICE): An ESA mission to orbit Ganymede and to characterise the Jupiter system," Planetary and Space Science 78, 1-21 (2013).

[2] Della Corte, V., Schmitz, N., Zusi, M., Castro, J.M., Leese, M., Debei, S., Magrin, D., Michalik, H., Palumbo, P., Jaumann, R., Cremonese, G., Hoffmann, H., Holland, A., Lara, L. M., Fiethe, B., Friso, E., Greggio, D., Herranz, M., Koncz, A., Lichopoj, A., Martinez-Navajas, I., Mazzotta Epifani, E., Michaelis, H., Ragazzoni, R., Roatsch, T., Rodrigo, J., Rodriguez, E., Schipani, P., Soman, M., Zaccariotto, M., & the International JANUS team, "The JANUS camera onboard JUICE mission for Jupiter system optical imaging," Proc. SPIE 9143, Space Telescopes and Instrumentation: Optical, Infrared, and Millimeter Wave, 914331 (2014).

[3] Greggio, D., Magrin, D., Munari, M., Paolinetti, R., Turella, A., Zusi, M., Cremonese, G., Debei, S., Della Corte, V., Friso, E., Hoffmann, H., Jaumann, R., Michaelis, H., Mugnuolo, R., Olivieri, A., Palumbo, P., Ragazzoni, R., Schmitz, N. "Trade-off between TMA and RC configurations for JANUS camera", this conference (2016).

[4] Soman, M., Holland, A. D., Stefanov, K. D., Gow, J. P., Leese, M., Pratlong, J., Turner, P., "Design and characterisation of the new CIS115 sensor for JANUS, the high resolution camera on JUICE," Proc. SPIE 9154, High Energy, Optical, and Infrared Detectors for Astronomy VI, 915407 (2014).

[5] Soman, M. R., Allanwood, E. A. H., Holland, A. D., Winstone, G. P., Gow, J. P. D., Stefanov, K., Leese, M. "Proton irradiation of the CIS115 for the JUICE mission," Proc. SPIE 9602, UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts VII, 96020O (2015).

[6] Soman, M., Stefanov, K. D., Weatherill, D., Holland, A., Gow, J., Leese, M., "Non-linear responsivity characterisation of a CMOS Active Pixel Sensor for high resolution imaging of the Jovian system," JINST 10, C02012 (2015).

[7] Horton, A., Spitler, L., Mathers, N., Pektovic, M., Griffin, D., Barraclough, S., Benson, C., Dimitrijevic, I., Lambert, A., Previte, A., Bowene, J., Westerman, S., Puig-Suari, J., Reisenfeld, S., Lawrence, J., Zhelem, R., Colless, M., Boyce, R., "The Australian Space Eye: studying the history of galaxy formation with a CubeSat", this conference (2016).