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Proton irradiation of the CIS115 for the JUICE mission

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ABSTRACT

The CIS115 is one of the latest CMOS Imaging Sensors designed by e2v technologies, with 1504x2000 pixels on a 7 μm pitch. Each pixel in the array is a pinned photodiode with a 4T architecture, achieving an average dark current of 22 electrons $\text{pixel}^{-1} \text{s}^{-1}$ at 21°C measured in a front-faced device. The sensor aims for high optical sensitivity by utilising e2v's back-thinning and processing capabilities, providing a sensitive silicon thickness approximately 9 μm to 12 μm thick with a tuned anti-reflective coating.

The sensor operates in a rolling shutter mode incorporating reset level subtraction resulting in a mean pixel readout noise of 4.25 electrons rms. The full well has been measured to be 34000 electrons in a previous study, resulting in a dynamic range of up to 8000. These performance characteristics have led to the CIS115 being chosen for JANUS, the high-resolution and wide-angle optical camera on the JUPITER ICy moon Explorer (JUICE).

The three year science phase of JUICE is in the harsh radiation environment of the Jovian magnetosphere, primarily studying Jupiter and its icy moons. Analysis of the expected radiation environment and shielding levels from the spacecraft and instrument design predict the End Of Life (EOL) displacement and ionising damage for the CIS115 to be equivalent to 10^{10} 10 MeV protons cm^{-2} and 100 krad(Si) respectively. Dark current and image lag characterisation results following initial proton irradiations are presented, detailing the initial phase of space qualification of the CIS115. Results are compared to the pre-irradiation performance and the instrument specifications and further qualification plans are outlined.

Keywords: CMOS APS, JANUS, CIS115, Dark current, displacement damage.

1. INTRODUCTION

JUICE is a spacecraft destined for Jupiter, with an expected cruise phase of 8 years and a science observation lifetime in the Jovian environment of 3 years [1]. One instrument on JUICE is an optical camera called JANUS with a field of view (FOV) of 1.72x1.29 degrees and resolution up to 15 $\mu\text{rad pixel}^{-1}$ [2]. When JUICE becomes the first spacecraft to orbit the moon of a gas giant, JANUS will undertake a detailed survey of Ganymede. In other observation stages of its mission, JANUS will map the surfaces of Europa and Callisto, observe the occurrence of lightning and cloud structures in Jupiter's atmosphere and perform photometry of other satellites in the Jovian system.

The JANUS camera uses a three-mirror anastigmat optical design [3] coupled with a Complementary Metal-Oxide-Semiconductor (CMOS) Active Pixel Sensor (APS), to achieve a FOV equivalent to $3.00 \times 2.25 \text{ m}^2$ and a resolution equivalent to 1.5 mm pixel^{-1} from an observation distance of 100 m. At the closest approaches during its orbit of Ganymede (500 km), this resolution is equivalent to approximately 7.5 m pixel^{-1} , which is suitable for targeted observations of selected surface features. During higher orbits the ground sampling distance will be increased, and the trade-off of coverage with data volume and downlink rate capabilities is expected to require the use of pixel-binning for the majority of mapping that will inherently degrade the resolution.

The CMOS APS selected for JANUS is the CIS115, which was designed by e2v technologies plc following proton and gamma irradiation campaigns of a test-chip with similar architecture, the CIS107. The readout architecture and a Beginning Of Life (BOL) electro-optic performance study of a front-faced sensor has been reported previously [4], including readout noise and iron-55 calibration. A back-thinned CIS115 with e2v's multi-layer astronomy anti-reflection coating has been specified for the flight sensor in JANUS' focal plane to improve quantum efficiency in the range of 400 nm to 900 nm. A selection of the first characterisation results from a back-illuminated CIS115, the CIS115-14901-4-13E (#4-13E from here-on) are presented here. During its exposure to the space environment in cruise and observation

phases the CIS115 on JANUS's focal plane will be bombarded by the local environment of cosmic and solar rays and particles trapped in the Jovian magnetosphere. To qualify the sensor and characterise its expected performance throughout the mission, an in-depth characterisation campaign for CIS115s is planned. A proton irradiation campaign has been conducted on a single CIS115 (#4-13E) to help prepare for the future campaigns as a commissioning step for characterisation tests and equipment, and to give an early indicator of performance or possible problems.

2. PROTON IRRADIATION OF THE CIS115

#4-13E was irradiated at the Proton Irradiation Facility [5] (PIF) at the Paul Scherrer Institute in Switzerland in April 2015. 2.09×10^{10} 74 MeV protons cm^{-2} were directly incident on the sensor from the PIF, at an average flux of 2.15×10^7 protons $\text{cm}^{-2} \text{s}^{-1}$ (taking 972 seconds). The fluence was selected to be the Non-Ionising Energy Loss equivalent to 1×10^{10} 10 MeV protons cm^{-2} , which is the expected End of Life (EOL) proton fluence for the JANUS sensor after the environment and shielding is taken into account. For the irradiation, the #4-13E was held at room temperature and pressure with its connection pins shorted in anti-static conductive foam (Figure 1).

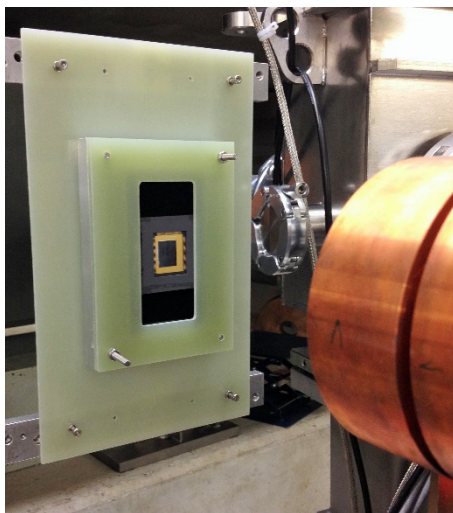


Figure 1. The CIS115-14901-4-13E held in its mounting jig in the PIF with its temporary cover glass removed. When the beam is on, the protons are incident onto the detector from the foreground on the right-hand side, where the copper attenuators are currently seen (proton beam is off).

3. DISPLACEMENT DAMAGE EFFECTS MEASURED IN THE CIS115

3.1 Experimental setup

A CMOS characterisation test bench has been set up at the Centre for Electronic Imaging to test the CIS115s before and after irradiations. The CIS115 is driven by a CMOS Camera System supplied by XCAM Ltd. [6]. The CIS115 is situated in a stack of PCBs where clock and bias signals are generated and 16-bit analogue to digital conversion of the output signals occurs. Communication with the PCB stack occurs via fibre optic cable to a control box, which also supplies power to the stack.

For testing, the CIS115 is held in vacuum and is cooled using a PCC Cryotiger via a copper cold finger applied to the reverse of the sensor ceramic package. The temperature of the ceramic package is stabilised with a resistive heating element to a range between -55°C and -45°C when the Cryotiger is running, and from 30°C to above 40°C when the vacuum chamber is at room temperature. A window on the chamber allows *ex vacuo* optics to generate a flat field on the sensor; the illumination from a red LED is used for the lag measurements in Section 3.3.

3.2 Dark current

High energy protons incident on the silicon detector are expected to cause displacement damage in the form of lattice defects that can act as traps for electrons mid-way between the conduction and valence bands, leading to increased dark signal generation. Dark current has been measured by exposing the detector to darkness for integration times between

0.1 s and 60 s. Sufficient statistics are obtained by recording 10 images at each integration time, where the integration times are in a random order. The signal of each pixel is averaged across the 10 images and the dark current is calculated from the gradient of a linear fit of the signal versus integration time relationship on a pixel by pixel basis.

The pixel-by-pixel dark current map for 30°C is shown in Figure 2, where are pattern due to the rastering of the annealing laser used during back surface passivation can be observed. Cosmetic defects with extremely high dark current (defined here as >1000 electrons s^{-1} at 20°C) appear as blobs covering in the order of 100 pixels in the map since the signal from the defect blooms into adjacent pixels in #4-13E, affecting their measurement. Later revisions of the CIS115 have an anti-blooming property, limiting the image area affected by either a pixel with high dark current or high-flux sources within the FOV.

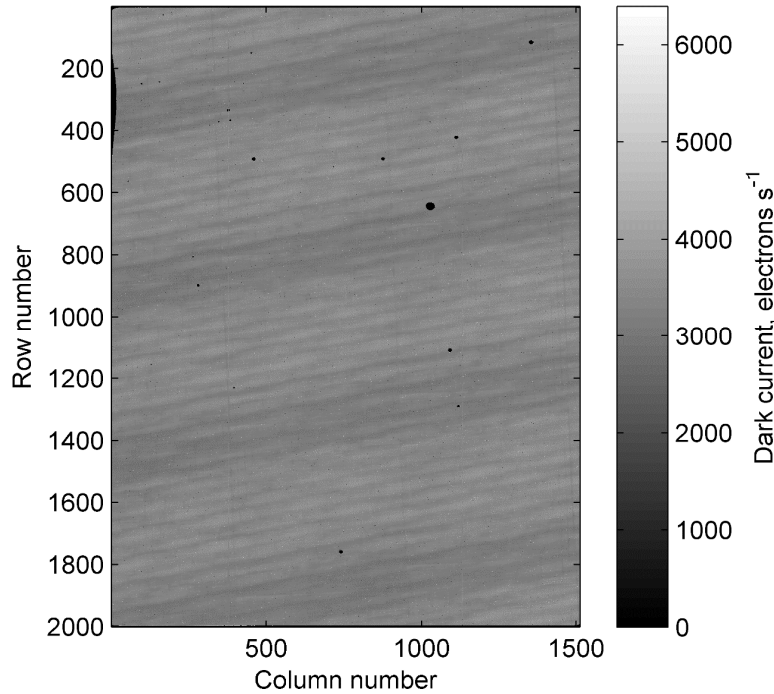


Figure 2. A diagonal non-uniformity is shown in the pixel-by-pixel map of the dark current across the CIS115 at 30°C, caused by manufacturing processes on the sensor's back surface. Black spots indicate regions of extremely high dark current, each caused by a single pixel blooming into adjacent pixels.

The distribution of dark current across the array for a range of temperatures above room temperature, before and after irradiation is displayed in Figure 3. Most pixels measured a similar background dark current generation at BOL, shown by the tall and narrow peak at each temperature. A small proportion of pixels measured a dark signal level higher than background – when the dark signal of each pixel is extrapolated down to 20°C, 0.47% of pixels are defined as cosmetic defects with > 1000 electrons s^{-1} . The generation of lattice defects from proton interactions is understood to be the cause of increased dark current in most pixels post-irradiation. The dark current spectrum is wider and a greater number of pixels measured up to 10^4 electrons s^{-1} . The fall-off at signal levels above this is due to limitations in the experimental method – shorter integration times must be used to accurately measure pixels with extremely high dark current.

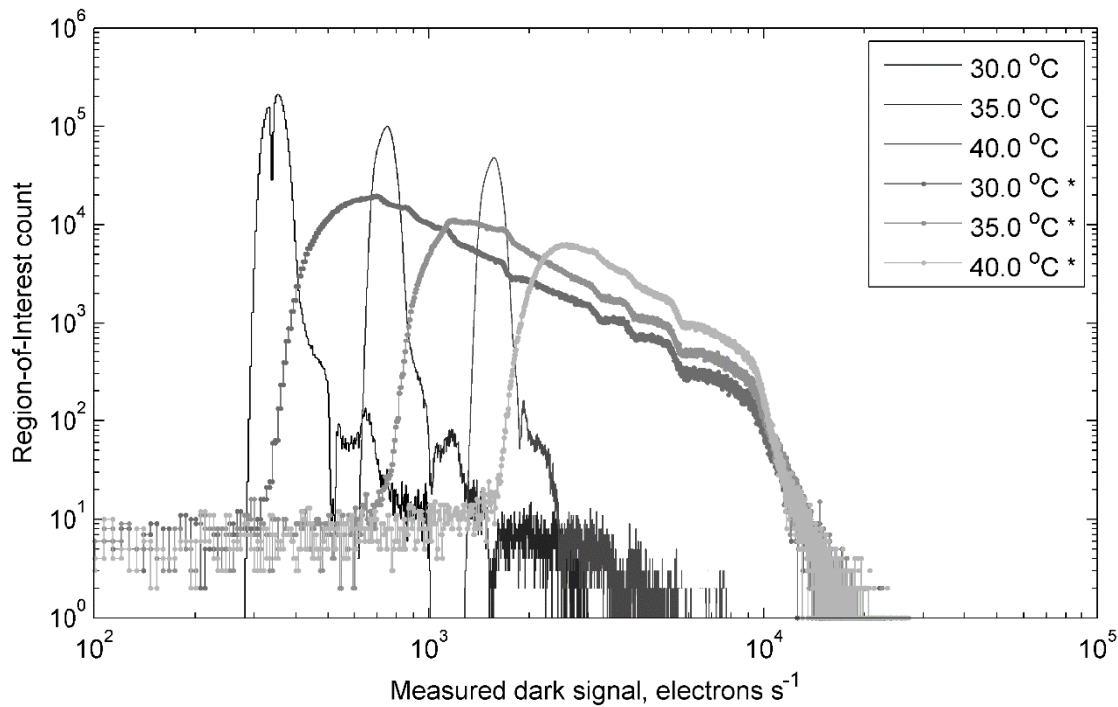


Figure 3. Histogram of the pixel by pixel dark current generation for the CIS115-14901-4-13E pre and post irradiation at a range of warm temperatures. Post-irradiation distributions (marked with a * in the legend) shows a general trend of increased dark current, as expected.

The readout noise should be less than 8 electrons rms. for the majority of pixels in the CIS115 in JANUS, and the dark current should not contribute a significant amount to the overall noise of the pixel. Therefore, the dark current shot noise should be less than this 8 electrons rms. (a magnitude of 64 electrons pixel⁻¹), as an absolute maximum to limit any degradation to the image signal to noise. Integration times during the mission will be in the range of approximately 1 ms for close fly-by observations to 10 s for photometry measurements of Jovian objects. The longer integration time allows a dark current limit (DC limit) to be set at less than 6.4 electrons pixel⁻¹ s⁻¹. More detailed instrument performance analysis will be applied in the future, but this first-case DC limit allows initial bounds on the sensor to be set.

The DC limit is shown relative to the behavior of the sensor dark current with temperature in Figure 4. The exponential trend of the dark current is indicated by linear fits in the log scale. The dark current of the median pixel is below the DC limit at the planned operating regime of the CIS115 in JANUS (-50±5°C), both before and following EOL proton irradiation, demonstrating that the dark current will be sufficiently suppressed during operation. In the JANUS specification, bright pixel defects are defined as exhibiting a dark current greater than 1000 electrons pixel⁻¹ s⁻¹ at 20°C. Using the post-irradiation trend line, such a pixel will have a dark current of 0.269 electrons pixel⁻¹ s⁻¹ at the warmest expected operational temperature of -45°C, which is significantly below the DC limit. Working back from the DC limit, a bright pixel defect with greater than 7300 electrons pixel⁻¹ s⁻¹ at 20°C is expected to exhibit a dark current greater than the DC limit at -45°C.

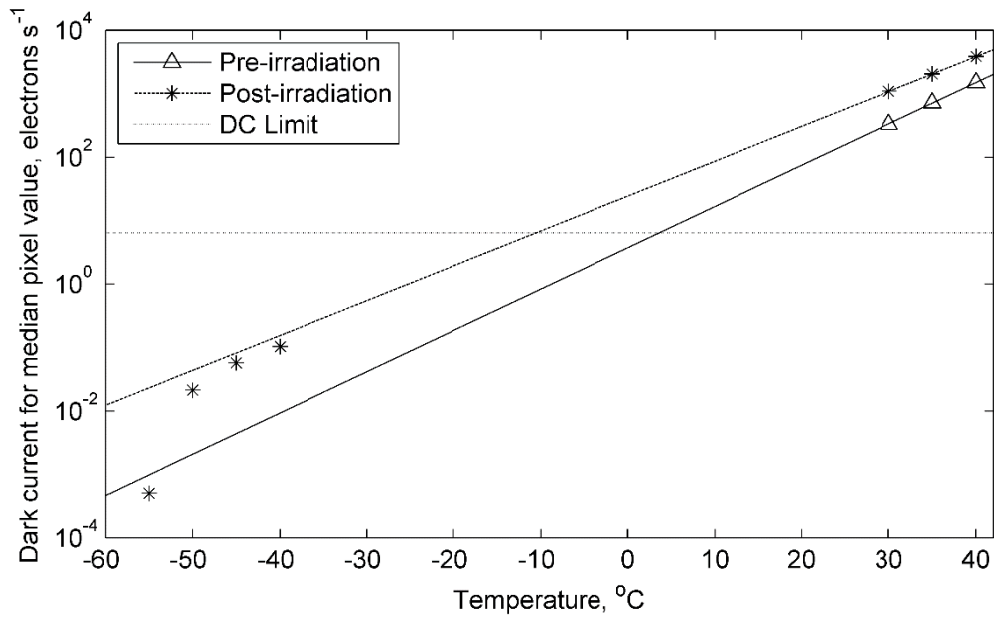


Figure 4. The relationship of the median pixel dark current with temperature shows the expected exponential decrease at colder temperatures. At temperatures below -40°C the average dark current is not measurable with the applied integration times but it increases to measurable levels following irradiation. The point at which the dark current is well suppressed for JANUS, the DC limit, is shown by the horizontal dotted line.

3.3 Image lag

Image lag is where some signal generated during the period of one integration time is not completely read out during the next readout sequence, but 'lags' behind to be read out in a subsequent frame. Image lag can introduce ghosting artefacts, where bright features from previous exposures appear in a later image, possibly masking features in the latest images, reducing the signal to noise and complicating interpretation of images.

The following test procedure has been implemented to measure the lag performance of the CIS115. Ten consecutive images are captured with the sensor, where each image is preceded with an integration time. During the first five integration times, the sensor is illuminated by a flat field and the illumination is switched off during the last five integration times (Figure 5). The integration time is varied to adjust the signal level, which is measured using the first five images. The image lag is measured by averaging the signal in the sixth image: whilst a small amount of image lag may be present in the subsequent images, this method improves the signal to noise of the measurement.

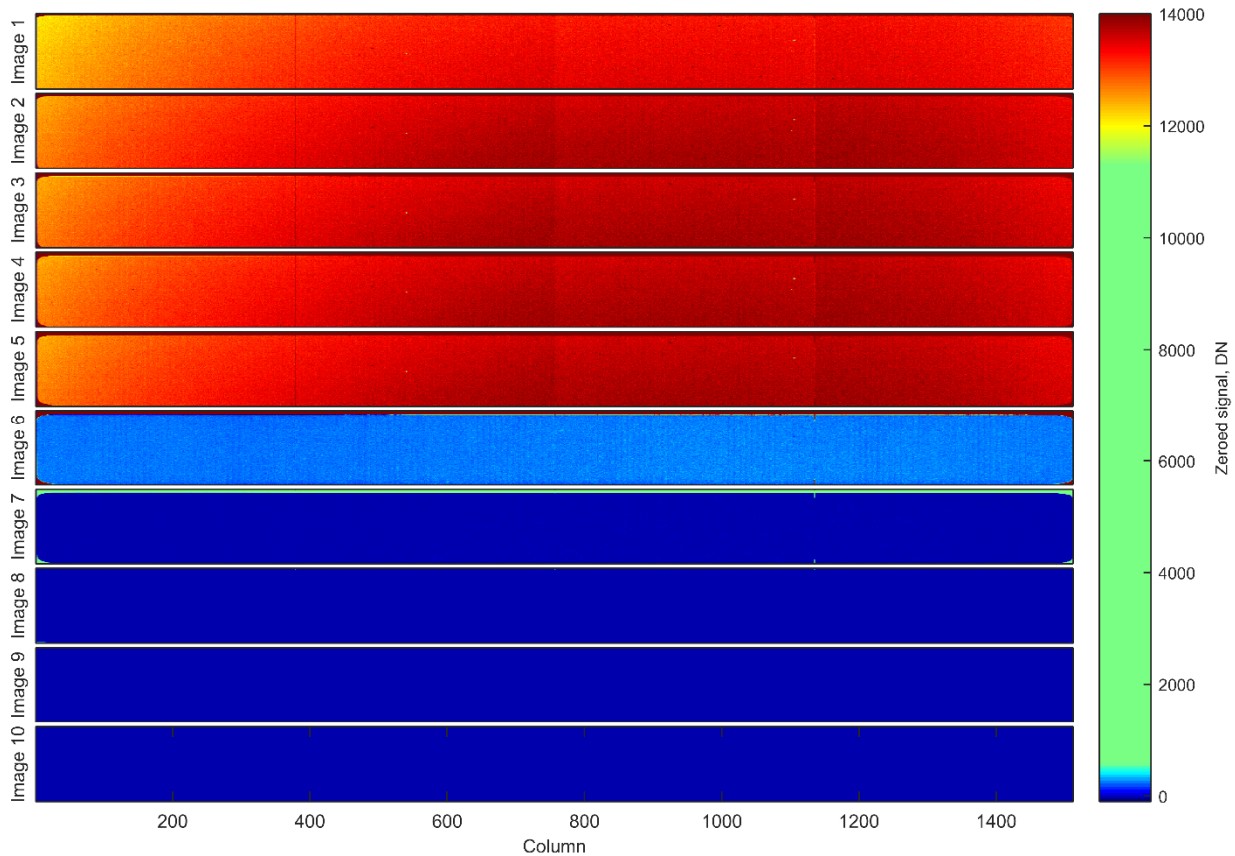


Figure 5. An example set of 10 images recorded as part of the lag testing procedure are all shown at the same colour scale. Image lag is visibly present in image 6, where charge from the previous image is not completely read out.

In 4T CMOS APS, the cause of image lag is incomplete transfer of charge from the photodiode into the sensing node [reference]. One method of varying the transfer efficiency is to adjust the duration that the transfer gate is held at a high potential, τ_{TG} . Figure 6 displays the lag performance versus signal level for a range of τ_{TG} , which shows that the image lag is degraded following EOL proton irradiation but the image lag remains well below 2.5% for most of the signal range measured.

Two regimes of lag behavior are observed, separated by a 'knee-point' at a signal level of approximately 10000 electrons. The position of the knee-point was hypothesized to vary with the high voltage applied to the transfer gate, VTRA, and therefore the lag testing was repeated for a range of VTRA. Figure 7 shows the position of the knee-point shifting to a higher signal level as VTRA is decreased, improving the performance overall. However at VTRA below 3 V, the transfer efficiency degrades significantly across the signal range. EOL proton irradiation appears to degrade the lag performance for VTRA above 3 V, and slightly improve the performance at VTRA below 3 V.

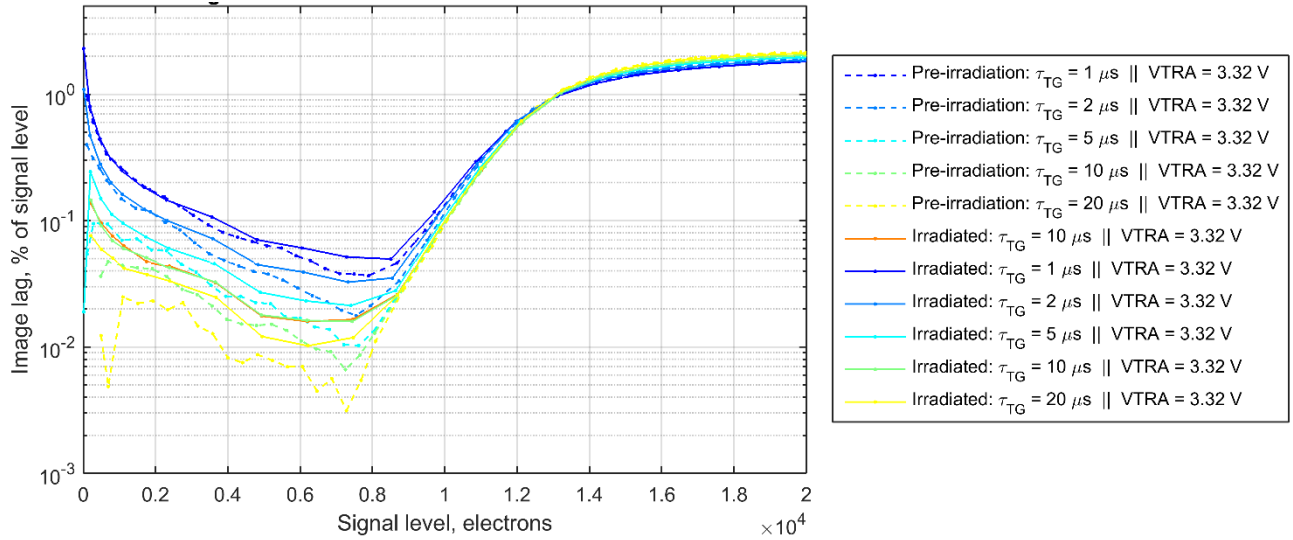


Figure 6. Image lag performance is degraded in the low signal levels at shorter transfer gate pulse durations (τ_{TG}) and also appears to worsen following irradiation. In the higher signal regime above approximately 10000 electrons, the behavior with τ_{TG} reverses, where longer pulses result in worse image lag.

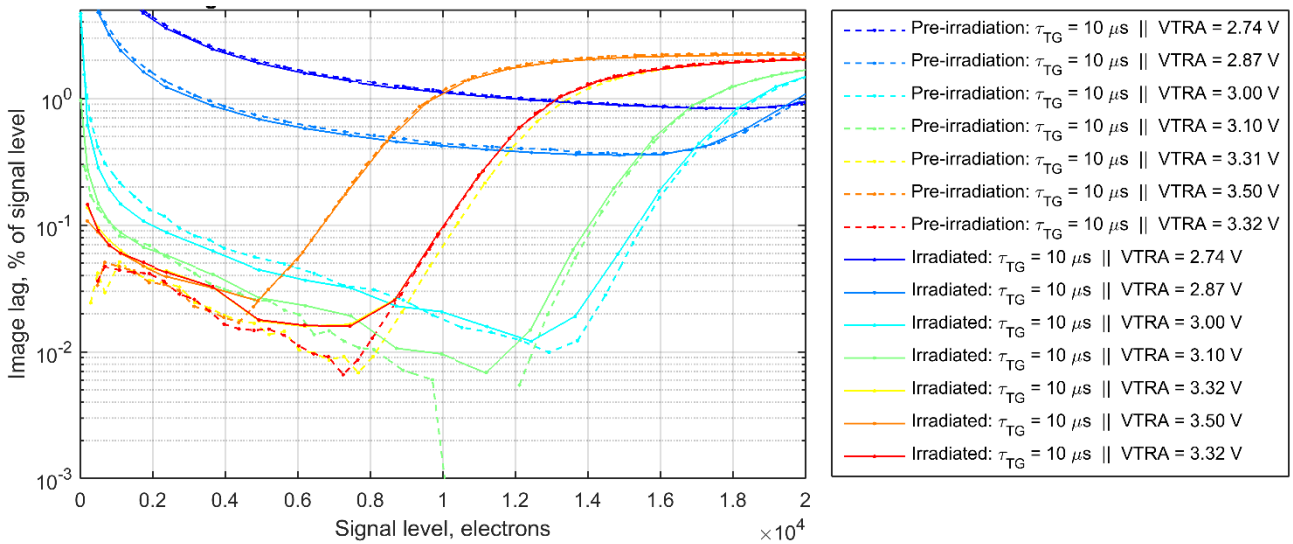


Figure 7. The image lag performance varies significantly with the applied transfer gate voltage (VTRA), including the position of the knee-point (above which the image lag significantly degrades). Current standard operating voltage is VTRA = 3.32 V.

As the transfer gate is switched on, a potential gradient is formed encouraging electrons to flow from the photodiode, across the transfer gate and to the sense node. If the signal packet is large, the potential well at the sense node may be insufficient to contain all the charge, and some may spill back under the transfer gate. The signal threshold at which this occurs will be lower with a larger VTRA because the difference between the sense node empty potential and the transfer gate channel potential will be smaller. Any charge stored in the transfer gate channel may be returned to the photodiode when the transfer gate is set to its low voltage (0 V), rather than completing its transfer into the output node, explaining the shifting of the knee-point with VTRA observed.

For current testing, values of VTRA = 3.32 V and $\tau_{TG} = 10 \mu\text{s}$ have been recommended to achieve optimum lag performance across the signal range. However, further analysis of the entire instrument performance may indicate that a

lower setting of VTRA, such as 3.1 V results in improved performance without any detrimental effects in other characteristics. Other methods of potentially improving the transfer gate performance, such as varying the transfer gate clock edges, may be investigated with the goal of improving JANUS' overall instrument performance.

4. CONCLUSIONS AND FUTURE WORK

A CMOS APS that has been selected for JANUS has been irradiated to its expected EOL 10 MeV equivalent proton fluence of 1×10^{10} protons cm^{-2} . The measured dark current spectrum and temperature relationship have demonstrated an increase in the number of bright pixel defects in the sensor following irradiation, and an overall increase in dark current across the sensor. However, the results have compared to the DC limit required for good performance in the JANUS instrument, and the average dark current is suppressed to be comfortably within the limit at the warmest expected operational temperature (-45°C). The lag performance has been characterised as a function of signal level and transfer gate high voltage and duration before irradiation and after the expected EOL proton fluence. Image lag has been shown to degrade significantly at signal levels above a knee-point, which depends on VTRA, but is better than 2.5% across the measured range, and better than 1% at signal levels between 1000 electrons and 10000 electrons when using $VTRA = 3.31 \text{ V}$ and $\tau_{TG} = 10 \mu\text{s}$.

Since this study, device #4-13E has been irradiated a second time at the Proton Irradiation Facility at PSI, to bring its total fluence up to twice the expected EOL fluence. A full characterisation test is being undertaken on this sensor to measure any further change in performance. Additionally, as part of the JANUS sensor qualification programme, two more CIS115s have been irradiated to EOL and twice EOL fluences. These sensors will act as further test vehicles for investigating any effects observed due to displacement damage.

The Total Ionising Dose (TID) expected for the JANUS sensor is 100 krad(Si) at EOL. CIS115s will undergo testing up to twice this dose using a Co-60 cell as a gamma irradiation source. The lag performance is expected to be affected [7], and other changes in performance will be measured. Furthermore, a complete and detailed space qualification process is planned for the CIS115s, including further proton and gamma testing as well as exposure to heavy ions to study for single event effects and an electron irradiation to study the combination of TID and displacement damage.

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