Proton Irradiation of EMCCDs

David R. Smith, Richard Ingley, and Andrew D. Holland

***Abstract*—This paper describes the irradiation of 95 electron multiplication charge coupled devices (EMCCDs) at the Paul Scherrer Institut (PSI) in Switzerland, to investigate the effects of proton irradiation on the operational characteristics of CCDs featuring electron multiplication technology for space use. This work was carried out in support of the CCD development for the radial velocity spectrometer (RVS) instrument of the European Space Agency's cornerstone Gaia mission. Previous proton irradiations of EMCCDs, have shown the technology to be radiation hard to $\sim$10$\times$ the required six-year Gaia lifetime proton fluence, with no device failures or unexpected operational changes. The purpose of the study described in this paper was to further investigate the statistical probability of device failure as a result of radiation damage, the large number of devices and high proton fluence used, making the study equivalent to testing $\sim$50 complete RVS CCD focal planes to the expected end of life proton dose. An outline of the earlier EMCCD proton irradiations is given, followed by a detailed description of the proton irradiation and characterization of the 95 devices used in this latest study.**

***Index Terms*—Charge coupled devices (CCD), electron multiplication charge coupled devices (EMCCDs), Gaia, proton irradiation, radiation damage, radial velocity spectrometer (RVS).**

I. Introduction

An initial investigation into the effects of proton irradiation on the operational characteristics of e2v technologies CCDs featuring L3Vision electron multiplication technology was carried out in 2003 to assess the potential for using devices featuring electron multiplication technology in space applications, in particular for possible application in the CCDs of the planned radial velocity spectrometer (RVS) instrument of the European Space Agency's cornerstone Gaia mission [1]. Two EMCCDs were irradiated to 10 MeV equivalent fluences of 5×10^8 protons $\cdot$cm^{-2} and 2×10^9 protons$\cdot$cm^{-2} respectively and found to be fully functional post-irradiation, exhibiting increased dark current and radiation damage-induced bright pixel numbers comparable to those found in regular CCDs after similar irradiations. The behavior of the gain register was not altered significantly and any bright pixels generated in the gain registers of the devices were found to increase in amplitude in the same way as the standard readout register pixels, showing no evidence of extraneous field enhancement effects. It was assumed therefore, that the observed bright defects generated were not located in the vicinity of a high field avalanche region [2], [3]. A further study on an increased number of EMCCDs was then undertaken to quantify further the probability of device failure due to radiation damage of the gain register.

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The second study involved the irradiation of 20 EMCCD devices, the proton fluence given this time being increased slightly to 2.5×10^9 protons$\cdot$cm^{-2} for each device. This level of fluence was equivalent to $\sim 4\times$ the lifetime proton fluence expected by the CCDs of the EPIC cameras of XMM-Newton and was approximately the lifetime fluence expected for Gaia RVS CCDs [4]. The devices all functioned after irradiation, showing expected operational changes resulting from radiation damage [5].

From the batch of 20 irradiated CCDs, eight were irradiated a second time, increasing the total fluence given to each device to 2×10^{10} protons$\cdot$cm^{-2}, a factor $\sim 10\times$ the expected six-year Gaia RVS mission fluence. Again all devices functioned as expected after irradiation, indicating that the risk of catastrophic failure of any of the devices of the RVS instrument during its operational lifetime is low. Most of the pixels in the devices contained bright defects after this high level of irradiation. Bright pixels were generated in the readout and gain registers of the devices, the bright pixel amplitude being unaffected by fluence while the dark current scales with fluence. The increase in dark current after the first proton irradiation and the subsequent irradiation was comparable from device to device [5].

Having irradiated a total of 22 EMCCD devices, some to a level of 2×10^{10} protons$\cdot$cm^{-2}, with no device failures occurring and all devices operating within expected parameters after irradiation, the next study needed to improve on the statistics of probable device failure still further. The irradiation of 95 EMCCD devices to the high fluence level of 2×10^{10} protons$\cdot$cm^{-2} was then planned and is the subject of this paper.

II. EMCCD

The EMCCD uses a novel method of charge readout that is capable of an equivalent output noise of less than one electron at pixel rates of over 11 MHz [6], [7]. The CCD is an inverted mode operation, frame transfer device that has a standard readout register followed by a "gain" register that multiplies the signal charge before it is converted to a voltage. The image and store sections of the CCD are each 512 pixels $\times$ 512 pixels, while the readout and gain registers are each 536 pixels in length plus a few reference pixels. Fig. 1 shows a photograph of the device and Fig. 2 shows the device geometry. The pixels in the image, store, readout register and gain register of the device measure 16×16 μm. The device parameters are summarized in Table I.

Gain occurs in the pixels of an additional "multiplication register" following the standard CCD readout register. One electrode in each of the pixels in the gain register ϕHV is clocked with a much higher voltage than is needed to simply transfer the charge. An additional electrode held at $\sim$2 V dc is included immediately before the high voltage electrode which is typically held at $\sim$40 to 50 V. The large electric field between the high voltage electrode and the dc electrode causes the charge carriers

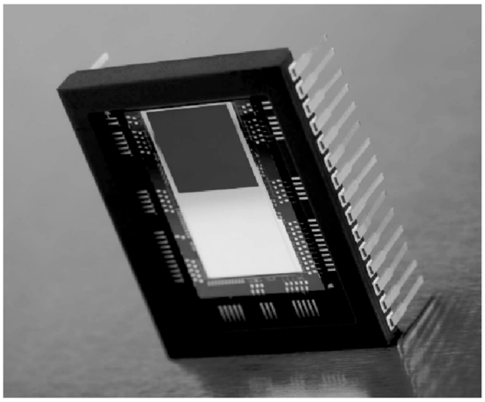

Fig. 1. Studied EMCCD.

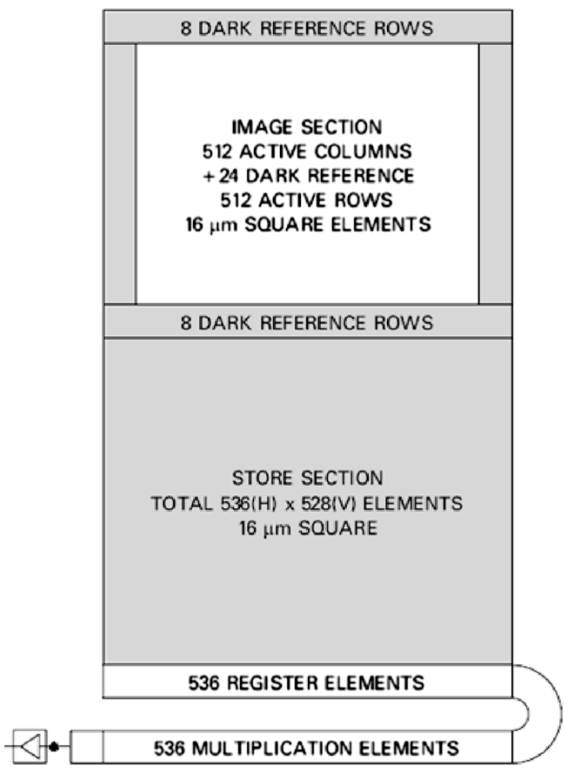

Fig. 2. Geometry of the EMCCD.

TABLE I
EMCCD DEVICE PARAMETERS

Parameter	Value
Operation	Frame Transfer
Active image area	8.192 mm × 8.192 mm
Image section	512 pixels × 512 pixels
Store section	536 pixels × 528 pixels
Pixel size	16 μm × 16 μm

to be accelerated to a high enough velocity to generate more charge carriers through the process of impact ionization. The average gain per pixel transfer through the gain register is generally small, but on passing through the full 536 gain register elements the total gain approaches a few hundred, greatly improving the signal to noise.

This technology is being considered for application in the CCDs being developed for the RVS instrument on the planned European Space Agency Gaia mission. The effects of proton irradiation on the operational characteristics of EMCCD technology therefore needs to be studied in detail, with large numbers of devices being irradiated to obtain reliable statistics on the probability of possible device failure.

III. Device Characterization

The 100 EMCCDs used in this study were all of "reject" grade. Of the 100 devices, 95 were characterized prior to undergoing a proton irradiation, the remaining five devices being held as controls.

The CCDs were each tested prior to irradiation to ensure they worked correctly and exhibited no unusual operating characteristics. Testing was carried out in an un-pumped vacuum chamber operating at $+15$ °C using a Peltier cooling system. This allowed the devices to be operating in the dark at a temperature slightly below room temperature, to suppress some of the dark current and increase the signal to noise while investigating the gain of the device. The temperature stability was ± 0.1 °C. The same set of clock voltages and delays were used for each device. A standard frame transfer sequencer was used to characterize the gain of a given device.

For 75 of the devices selected for irradiation, images were recorded using potentials of 10, 20, 30, 35, 40, 41, and 42 V applied to the high voltage electrode, ϕHV. This covered the range from no gain occurring at all, up to a gain of $\sim$10 at 40 V. The remaining 20 devices characterized prior to proton irradiation only had images recorded with ϕHV at 10 and 40 V to keep the time the devices were switched on, and the time spent with a large potential applied to ϕHV, at a minimum. These devices were operated for $<$2 min, with ϕHV held at 40 V for $<$20 s. This was so the devices could be part of an EMCCD "life testing" programme after post-irradiation characterization. Fig. 3 shows full frame images taken from one of the 95 characterized CCDs with applied ϕHV voltages of 10 and 40 V. The greyscale used in each image is the same making the increase in signal charge clearly apparent in the change from ϕHV of 10 to 40 V. Also labeled in the figure are the underscan and overscan regions, the slightly lower signal around the edge of the device (caused by the aluminum surround as seen in Fig. 1) and a dark column.

For each device, the gain at a given ϕHV was calculated by dividing the average background subtracted image intensity by that at a ϕHV of 10 V (a gain of 1). The maximum gain attained by each device was determined by the onset of signal charge saturating and spreading into the overscan region of the image at a given ϕHV voltage. Of the 95 devices, one was found not to operate at all, while 12 of the devices operated with slightly higher or lower gain than expected at a given applied ϕHV voltage due to serial charge transfer efficiency (CTE) problems causing image smear. Fig. 4 shows the variation in gain with applied ϕHV for the 82 nominally functioning devices.

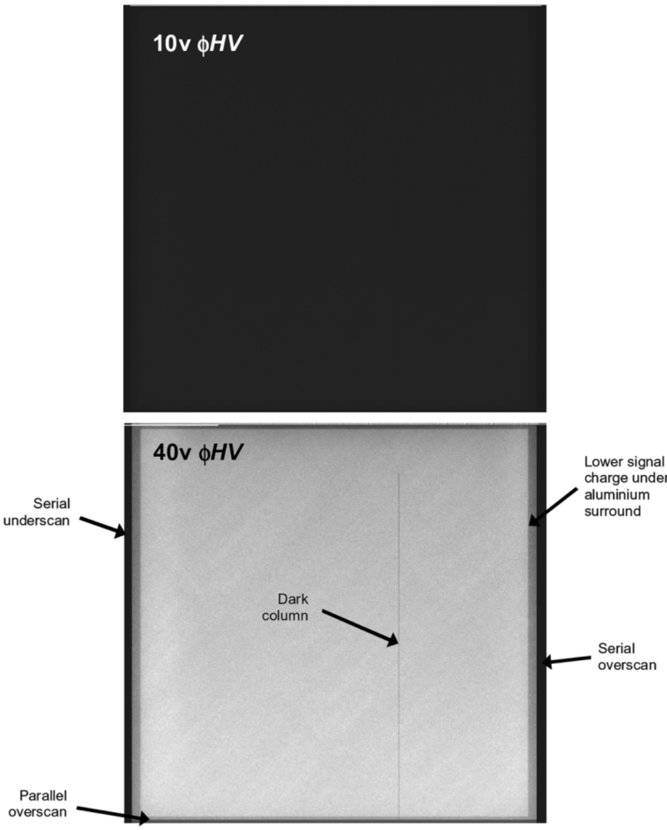

Fig. 3. Full frame preirradiation with ϕHV at (top) 10 and (bottom) 40 V. The same greyscale is used in each image to emphasize the effect of increasing gain.

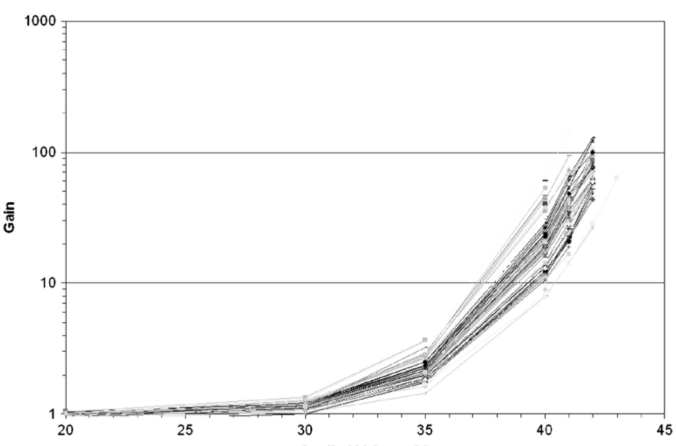

Fig. 4. Gain variation with ϕHV for 82 nominally functioning EMCCDs in the dark at $+15\,^{\circ}$C.

An additional device was found to exhibit significantly higher gain at low ϕHV voltages in the preirradiation testing while behaving in the expected manner after irradiation. This particular erroneous data set was the result of an error in the data taking prior to irradiation and has been excluded from the presented plots. Fig. 5 shows the average gain variation with ϕHV for the 61 correctly functioning, fully characterized devices.

It is interesting to note that the devices featuring low serial CTE were all members of 3 particular manufacturing batches: 3 devices from batch 03 484-7, five devices from batch 03 272-8 and 4 devices from batch 03 272-3. In the case of

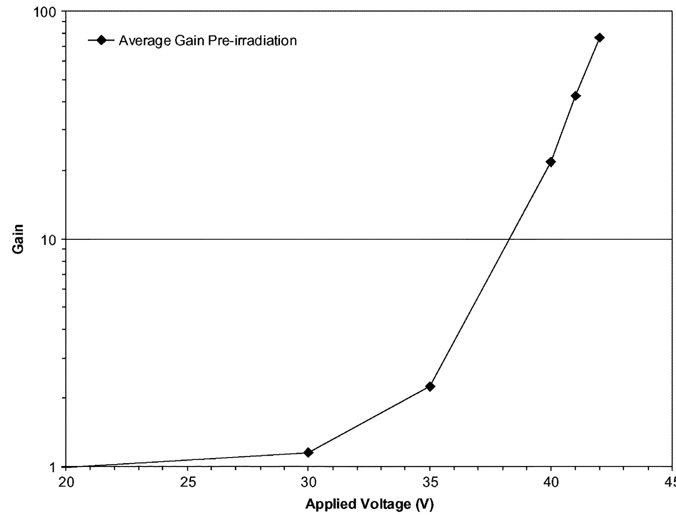

Fig. 5. Average gain variation with ϕHV for 61 EMCCDs.

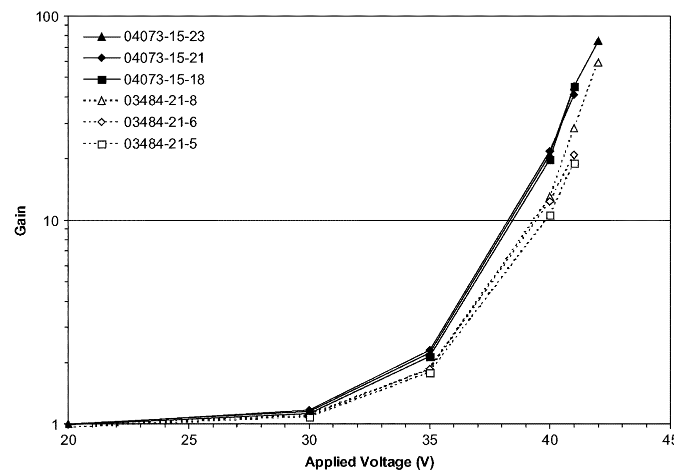

Fig. 6. Differentiation in gain characteristics with CCD batch number.

batches 03 272-8 and 03 272-3, all devices with these batch numbers were found to be erroneous. Within the spread of gain curves from the nominal functioning devices, grouping of given device characteristics into their respective batches can also be extracted from the data. This clearly shows that slight changes in the manufacturing process and material properties can be differentiated from batch to batch when using the characterization parameters chosen for this study. An example of batch differentiation is shown in Fig. 6 which shows the measured gain variation with ϕHV for devices from batch numbers 04 073-15 and 03 484-21.

IV. Irradiation Methodology

The 95 CCD97 devices were irradiated using the proton accelerator facility at the Paul Scherrer Institut (PSI) in Switzerland in April 2005. The devices were each irradiated to a 10-MeV equivalent proton fluence of 2×10^{10} protons$\cdot$cm^{-2}. The mean energy of the proton beam was 9.65 MeV, the non-ionizing energy loss function being used to scale the proton fluence required at 10 MeV to that at 9.65 MeV (a factor 0.04% decrease). The beam fluence uniformity was described by PSI staff to be stable to 10% across the beam diameter of

TABLE II
IRRADIATION PARAMETERS

Parameter	Value
Number of CCDs	95
Beam energy	9.65 MeV
Target 10 MeV Equivalent Fluence	2×10^{10} protons.cm^{-2}
Beam diameter	9 cm
Beam uniformity	10 %

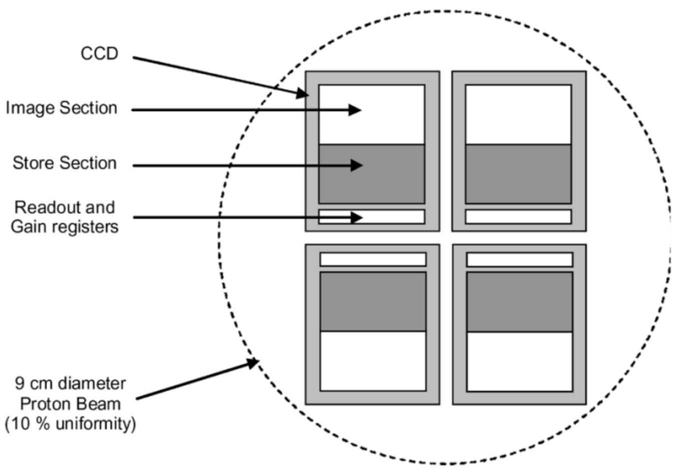

Fig. 7. Irradiation geometry of a single batch of four EMCCDs.

9 cm, centerd on the target. The irradiation parameters are given in Table II. The CCDs were irradiated in batches of four, arranged as shown in Fig. 7. The readout/gain registers of each device were positioned across the center of the beam profile. The devices were mounted in front of the beam by pushing them into a foam card in the arrangement shown, the foam then being clamped in a jig and positioned in the center of the beam profile. It was not necessary to shield any parts of the CCD as it was the irradiation of the readout/gain registers of the devices that was of interest for this study. The beam flux was calibrated such that an irradiation up to the required 10 MeV equivalent fluence of 2×10^{10} protons·cm^{-2} could be carried out in only few minutes. The turnaround time for each batch was of order 20 min allowing for entry and exit from the beam room, the reboxing of CCDs and the set up of the next batch for irradiation. The average time taken for each irradiation was 130 s.

V. Post-Irradiation Device Characterization

After proton irradiation to a 10 MeV equivalent fluence of 2×10^{10} protons·cm^{-2} the CCDs were each tested using the same equipment and testing method as prior to irradiation. Characterization was again carried out in an un-pumped vacuum chamber in the dark operating at $+15$ °C using a Peltier cooling system. The same clock voltages, delays and sequencer used prior to irradiation were used for the post-irradiation testing.

With the exception of the one device that did not function correctly prior to irradiation, all irradiated devices were fully operational after irradiation, all devices exhibiting the expected increase in dark current and generation of bright pixels as a result of radiation damage [8], [9]. The 12 devices found to have low serial CTE in preirradiation testing still exhibited this property post-irradiation.

For the 75 devices fully investigated before irradiation, images were recorded with potentials of 10, 20, 30, 35, 36, 37, 38, and 39 V applied to the high voltage electrode, ϕHV. The slightly lower range of voltages investigated was due to the increased dark current as a result of radiation damage reducing the level of gain that could be reached before the onset of image saturation.

The 20 devices that had previously only been characterized with ϕHV at 10 and 40 V were again only "lightly" tested to keep the amount of time the devices were running and the amount of time spent with high voltage applied to ϕHV to a minimum. Post-irradiation however, the voltages used were 10 and 36 V, the slightly lower high voltage being required to reduce the gain to a level where signal saturation did not prevent useful image data being taken. These devices were operated for <2 min, with ϕHV held at 36 V for <20 s. Fig. 8 shows full frame images from one device, with ϕHV at 10 and 36 V. Surface plots of the two images are also shown in the figure to emphasis the change in dark current level and generation of bright pixels resulting from radiation damage. The mean dark current level of all devices after irradiation with ϕHV at 10 V (a gain of 1) was a factor 2 higher than that prior to irradiation, the standard deviation in the dark current level also increasing by a factor 2.

The gain variation with ϕHV for each of the 82 nominally functioning EMCCDs after irradiation is shown in Fig. 9. The data for a single device are shown in Fig. 10, data taken before irradiation at $+15$ °C are included for comparison. This figure also includes post-irradiation data taken at -50 °C and -100 °C, showing that the level of gain reached at $+15$ °C prior to irradiation can be easily achieved when radiation induced dark current, and therefore the signal saturation level, is reduced by cooling. These additional data were taken using a pumped vacuum chamber and CryoTiger system with temperature control to ± 0.1°C. An LED was switched on inside the vacuum chamber to provide some signal with which to calibrate the gain variation with ϕHV. Due to time constraints prior to the irradiation of the test devices, data could not be obtained at -50 °C and -100 °C for the unirradiated case. However, data recorded at -50 °C and -100 °C are shown in Fig. 10 for one of the five unirradiated control devices. This particular control device has a slightly lower gain at a given voltage than the irradiated device, but the overall gain curve is well within the spread observed in Fig. 4. The increase in gain at a given voltage with decreasing temperature is a result of the lower operational temperature increasing the number of electrons generated by the impact ionization process.

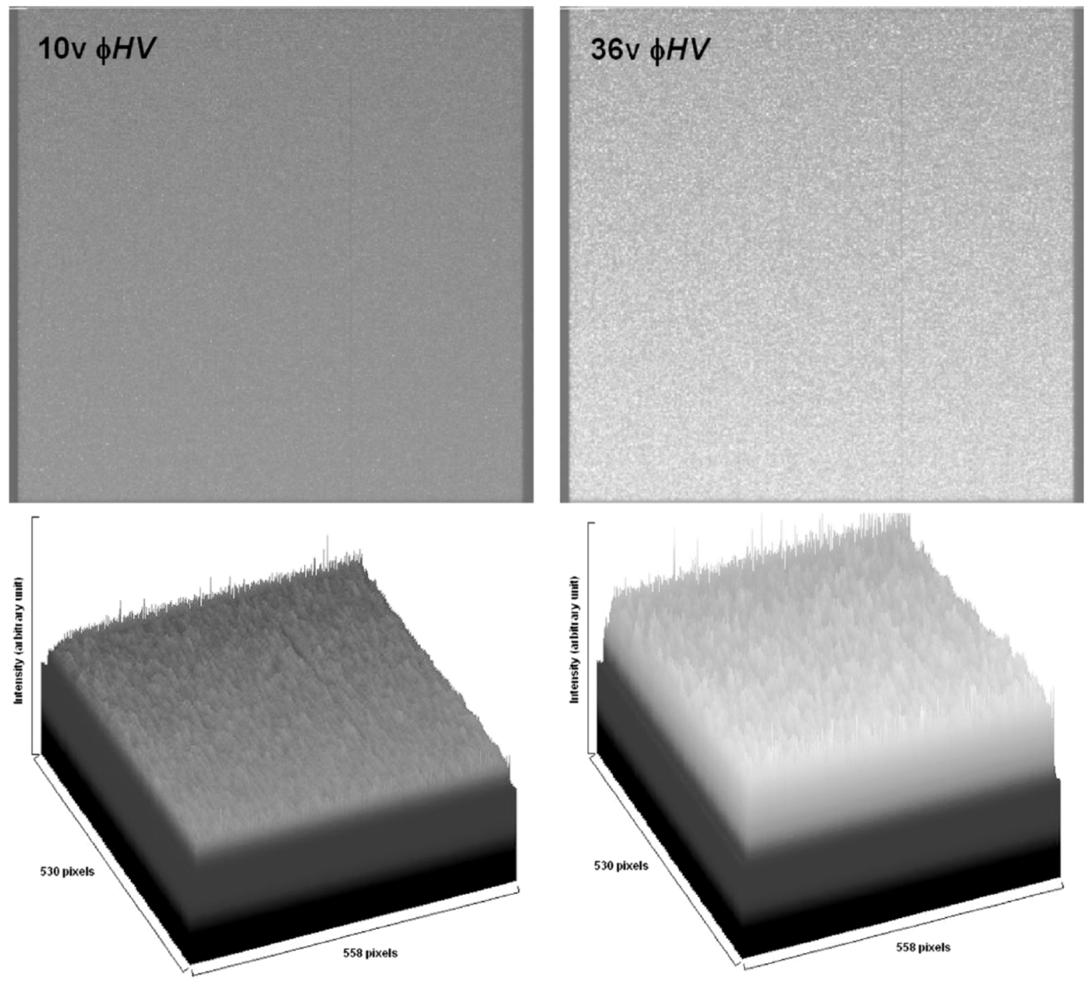

Fig. 8. Full frame preirradiation images taken with ϕHV at 10 (top left) and 36 V (top right). Surface plots of each image are also shown to emphasize the dark current increase and generation of bright pixel by radiation damage.

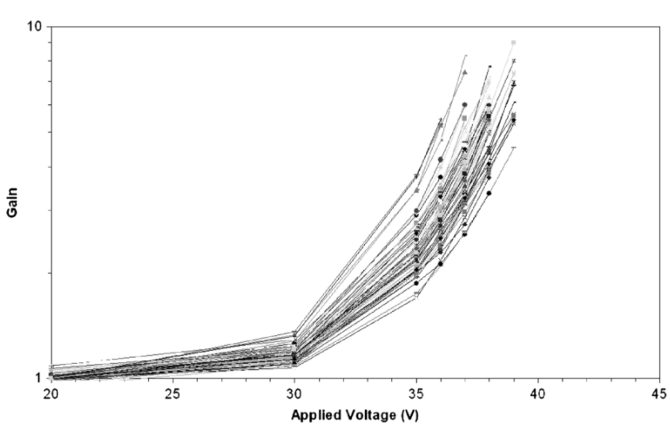

Fig. 9. Gain variation with ϕHV for 82 nominally functioning EMCCDs in the dark at $+15$ °C after irradiation to 2×10^{10} protons·cm^{-2}.

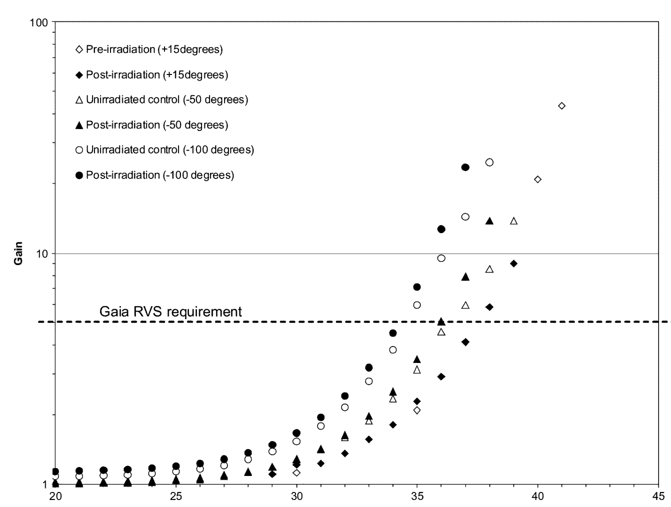

Fig. 10. Gain variation with ϕHV for one EMCCD both before and after irradiation to 2×10^{10} protons·cm^{-2} at $+15$ °C and after irradiation at -50 °C and -100 °C. Data from an unirradiated control device are shown for comparison at -50 °C and -100 °C.

The average gain variation with ϕHV at $+15$ °C for all 82 devices is shown in Fig. 11 which also includes the preirradiation average data for comparison. Although the gain curve does not extend as far after irradiation while operating at $+15$ °C, the shape of the gain curve is comparable to that before irradiation, indicating that the gain structure and gain process have not been significantly affected by irradiation to 2×10^{10} protons·cm^{-2}. The large number of devices and high proton fluence used make this study equivalent to testing ~50 complete RVS focal planes to the expected six-year Gaia RVS mission proton fluence. Even

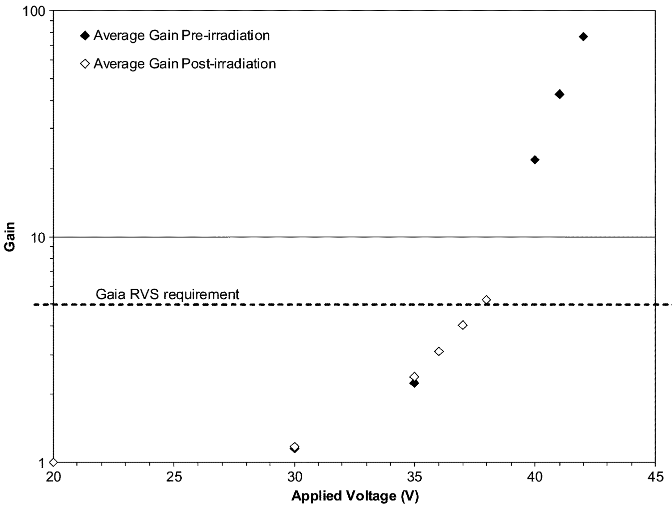

Fig. 11. Average gain variation with ϕHV for 61 EMCCDs, both before and after irradiation to 2×10^{10} protons $\cdot$ cm^{-2}.

operating at $+15$ °C, all devices meet the planned RVS gain requirement after irradiation to 2×10^{10} protons·cm^{-2}.

VI. Conclusion

The main conclusions of this paper are summarized in the following points.

- All 94 irradiated e2v technologies L3Vision CCDs were fully functional after irradiation with a 10-MeV equivalent fluence of 2×10^{10} protons·cm^{-2}, a level equivalent to testing $\sim$50 complete RVS focal planes to the expected end of life Gaia mission fluence.
- No catastrophic device failures occurred as a result irradiation to 2×10^{10} protons·cm^{-2}.
- All devices exhibited the expected increase in dark current and bright pixel population as a result of radiation damage. The 12 devices with low serial CTE prior to irradiation showed the same characteristic after irradiation.
- The increase in dark current as a result of radiation damage reduced the level of gain that could be reached before the onset of image saturation. Operating at $+15$ °C this corresponded to a reduction in gain from $\sim$60 to $\sim$6 (a reduction of $\sim$3 V in the maximum ϕHV that could be applied).
- Cooling a device after irradiation reduces the level of dark current present and allows higher gain to be achieved before image saturation occurs. Operating at lower temperature also increases the gain at a given ϕHV due to the temperature dependence of the impact ionization process. Cooling from $+15$ °C to -100 °C results in a $\times$ 3 gain increase at an ϕHV of 35 V.
- The targeted Gaia RVS gain of $\sim$5 is easily achievable after irradiation to 2×10^{10} protons·cm^{-2}, even operating at $+15$ °C.
- The increase in dark current level and resulting decrease in maximum gain after irradiation were comparable from device to device.
- There is no significant change in the observed gain curve after irradiation up to a gain of $\sim$100.
- Although the maximum gain of each device was reduced after irradiation, the shape of the gain curve is comparable to that before irradiation, indicating that the gain structure and gain process have not been significantly affected by irradiation to 2×10^{10} protons·cm^{-2}.

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References

[1] A. D. Holland *et al.*, "CCDs for the radial velocity spectrometer on gaia," *Proc. SPIE*, vol. 5251, pp. 253–60, 2004.
[2] D. R. Smith, A. D. Holland, and M. S. Robbins, "The effect of protons on e2v technologies L3Vision CCDs," *Nuc. Inst. Meth.*, vol. A513, pp. 296–99, 2003.
[3] D. R. Smith, "Radiation damage in charge coupled devices," Ph.D. dissertation, Univ. Leicester, Sep. 2003.
[4] H. Evans. (2003) Gaia radiation analysis: Cornerstone launch in 2010, 6 yr extended mission. ESA report. [Online]Available: esa/estec/ema/he/GAIA/3b
[5] D. Smith and A. D. Holland, "Proton irradiation of e2v technologies L3Vision devices," *Nucl. Inst. Meth.*, vol. A546, pp. 544–52, 2005.
[6] P. Jerram *et al.*, "The LLLCCD: Low light imaging without the need for an intensifier," *Proc. SPIE*, vol. 4306, 2001.
[7] C. D. Mackay, R. N. Tubbs, R. Bell, D. Burt, P. Jerram, and I. Moody, "Sub-electron read noise at MHz pixel rates," *Proc. SPIE*, vol. 4306, pp. 289–98, 2001.
[8] D. R. Smith, A. D. Holland, M. S. Robbins, R. M. Ambrosi, and I. B. Hutchinson, "Proton induced leakage current in CCDs," *Proc. SPIE*, vol. 4851, pp. 842–48, 2003.
[9] D. R. Smith, A. D. Holland, and I. B. Hutchinson, "Random telegraph signals in charge coupled devices," *Nucl. Inst. Meth.*, vol. A530, pp. 521–35, 2004.

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He has continued to do research in the field of radiation damage effects in CCDs and is currently a Research Associate at Brunel University, Middlesex, U.K. He has published a number of papers on the effects of proton damage on CCD operation, in particular the generation and characteristics of bright pixels exhibiting random telegraph signal behavior, and the effects of radiation damage on the operational characteristics of electron multiplying CCDs.

Richard Ingley, photograph and biography not available at the time of publication.

Andrew D. Holland, photograph and biography not available at the time of publication.