A Simulation of the Flight Experience of the ACIS CCDs on the Chandra X-ray Observatory

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ABSTRACT

The energy resolution degradation of the ACIS CCDs on board the Chandra X-ray Observatory (CXO) has been under investigation since the effect was first recognised two months after launch. A series of laboratory CCD irradiations with electrons and protons have taken place, leading to the belief that low energy protons are responsible for the damage. In order to confirm this, an experiment has been devised to represent the flight experience of the ACIS CCDs, and the results to date are shown here.

Keywords: Charge coupled device, X-rays, charge transfer efficiency

1. INTRODUCTION

The Chandra X-ray Observatory (CXO) was launched on 23rd July 1999 on the Space Shuttle Columbia, and deployed into a highly elliptical orbit 140 000/10 000 apogee/perigee. All instruments functioned nominally in the first 20 days during the activation process. The series of doors, which protect the instruments during launch, were opened and 'first light' calibration images were accumulated of the supernova remnant Cassiopeia A (Hughes et al., 2000, Pavlov et al., 2000).

The CXO consists of two instruments (O'dell and Weisskopf, 1998); the Advanced CCD Imaging Spectrometer (ACIS), an imaging array of four front illuminated CCDS and a spectrometer array of six CCDS, four front illuminated and two back illuminated; and the high resolution camera (HRC), which utilises microchannel plate technology. Two sets of transmission gratings can be used in conjunction with the instruments; the high energy transmission gratings (HETG) optimised for the ACIS array and the low energy transmission gratings (LETG) optimised for the HRC. The two instruments are mounted on a translation table, allowing each instrument to be positioned at the focus of the High Resolution Mirror Assembly; four Wolter type 1 mirror shells, yielding a spatial resolution of better than 1 arcsecond.

While at the focus of the mirror assembly the calibration sources are not visible to the ACIS chips, and so it was only when the HRC was translated into the focus, moving ACIS under the calibration sources, that diagnostics showed the energy resolution of the front illuminated CCDs was degraded. A series of operational tests were performed to confirm the degradation was not a result of dysfunctional electronics or telemetry. Radiation damage from traversing through the radiation belts was suspected and so a 'bake-out' was performed to try to anneal the damage to the CCDs. The ACIS CCDs can only be safely heated to +30 C; the camera was warmed from –100 C to +30 C over 2 hours 45 minutes, remained at this temperature for 3 hours and then cooled over 0.5 hours to +20 C, for 4 hours. When ACIS was cooled back down to -100 C, calibration frames showed further degradation to the energy resolution of the front illuminated CCDs. Following the bake-out, the ACIS array has been stored out of the focus of the mirror assembly for all belt passages and no further damage has been observed. This leads to the conclusion that particles in the Earths radiation belt are responsible for the damage.

From analysis of the telescope arrangement, and the fact that only the front illuminated devices have been affected, it has been determined that the most likely explanation for the damage is low energy protons in the Earth's radiation belts being forward scattered off the telescope mirrors and onto the CCD array. Ground experiments using electrons and high energy protons for irradiations have failed to reproduce the effects seen in the flight devices and the temperature dependence of the charge transfer inefficiency (CTI) (Prigozhin et al., 2000) is consistent with the existence of V-V vacancies in the silicon

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lattice, a known effect of proton radiation damage. The increase in CTI from less than 3×10^{-6} before launch to $\sim2\times10^{-4}$, at 5.9 keV, is consistent with a dose of 10 krads of proton exposure.

The structure of the ACIS front illuminated flight CCDs, Lincoln Laboratory CCID17s, consists of a buried channel formed by a layer of n-type silicon implanted in the bulk p-type silicon wafer. The p-n junction creates a positive potential below the surface of the device, which is attractive to electrons, and therefore charge is transferred within this potential well to the output node. The primary function of the buried channel is to keep the charge packets away from the $Si\text{-}SiO_2$ interface, where straggling bonds and interface states can soak up the charge. Radiation damage to the CCD creates a similar effect, where protons create 'charge traps' within the silicon lattice. If these traps are in the bulk of the device the effect is seen as an increase in thermal generated charge or 'dark current'. If the traps are primarily in the buried channel, the effect is to see a decrease in charge transfer efficiency. From looking at the relative increase in these two diagnostics, one can estimate the energy of the incident protons and the region of damage.

Only the front illuminated devices have been affected and the high CTI to dark current ratio suggests the incident proton has the required energy to stop exactly within the buried channel of the device, approximately 1 μm below the oxide and passivation layers. In the case of the back-illuminated devices, the buried channel is 40 μm away from the surface of impingement and therefore the device appears unaffected due to the protons being stopped well before the buried channel. From considering the ranges of protons within silicon it has been deduced that the proton energy is of the order of 100-200 keV. Experiments conducted by MIT (Prigozhin et al., 2000) on warm CCID17 CCDs has confirmed that the required energy to reproduce the kind of effects and traps seen on flight is approximately 100 keV, this is consistent with the high probability of protons of this energy being forward scattered by the telescope mirrors. To confirm that this is indeed the cause of degradation on flight and to provide a basis for performing amelioration techniques, an experiment to represent the flight experience of the ACIS CCDs has been devised and is explained in the following section.

The degradation of the parallel charge transfer efficiency in the front illuminated devices has led to position dependent energy calibration and a significant increase in the full width at half maximum (FWHM) of the X-ray peaks. Techniques in software are being developed to correct for the position dependent gain (Townsley et al., 2000, http://asc.harvard.edu) and for effective loss of quantum efficiency (Townsley et al., 2000), which occurs due to charge trailing into several pixels thus changing the event grades. The ACIS instrument continues to perform spectacular imaging and spectroscopy and it is estimated that 80-90% of the science can still be performed. Nevertheless an improvement in performance would be advantageous.

2. EXPERIMENTAL SET-UP

2.1. The CCD camera operation

A CCID7 was selected for this test, due to the small number of CCID17s remaining. They are made on the same wafers as the CCID17 and therefore should have the same characteristics as the ACIS flight devices. The CCID7 has a single output node, and an array of 420 x 422, 27 μm^2 pixels compared to the CCID17, which has four output nodes and an array of 1024 x 1026, 24μm^2 pixels.

For the simulation of the flight experience, a CCD camera was required to take data with the CCD cold, before and after irradiation and after a room temperature anneal. The PSU[A] laboratory CCD camera had previously been utilised for proton irradiations at the GSFC[B] facility and modified accordingly, and was selected for use on this basis. An ^{55}Fe source was mounted on a paddle inside the camera, allowing it to be rotated in and out of the view of the CCD, for CTI measurements during the experiment. A programmable shutter was also mounted inside the camera to protect the CCD between irradiations. All frames of data were collected by the CCD camera in the following way; the signal was integrated for a user selected time period (frame integration time), the store area was flushed five times and the image transferred into the store area, which is shielded by 4 mm of G10. The readout register was flushed five times with the image still in the store array. A row was transferred into the serial register and read out at a speed of 28.6 μsec/pixel, a total readout time of 5.8 seconds. The data was then saved to disk, with the clock bias voltages off. This took ~10 seconds. Before the next image was integrated the image and store arrays were flushed five times into the serial register. Then the next image was integrated for the frame integration time plus an overhead of 0.40 seconds. This means that the total integration time was the selected value plus 0.72 seconds.

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It was estimated that, in order to measure the changes in CTI with errors less than 10%, approximately 40 000 MnKα events were required. For this experiment CTI is measured via two methods. The first is from fitting the MnKα X-ray peak, from only the centre pixel of each event, with two Gaussians and a constant, for six samples of 50 bins in the parallel direction. From fitting a line to the change in the position of the mean of the primary Gaussian, not the soft shoulder, with respect to y position, the gradient of this line divided by the intercept is defined as the parallel CTI. The second measurement is from plotting a stacked line trace, of centre pixel signal versus y-position. From defining the MnKα line and performing linear regression on the data, the gradient divided by the intercept is defined as the parallel CTI. The second method is thought to be less accurate due to background effects from defining the sloped MnKα line with two horizontal lines. Serial CTI can also be measured by either method by substituting x-position for y-position.

2.2. Pre-irradiation measurements and characterisation

The CCD was cooled and the temperature controlled to +/- 1 C, by an AD590 mounted on the coldfinger and a solenoid to control the liquid nitrogen flow.

At -60 C, fifteen 'dark' frames (frames without X-rays) were taken with three and ten second frame integrations. This provides a dark current measurement corresponding to that measured with the MIT[C] camera allowing cross-correlation between the cameras and also confirms the CCD characteristics are unchanged, immediately prior to the experiment.

400 frames of Mn X-rays were taken to provide a CTI measurement at -60 C. This along with the measurement at -100 C provides a temperature calibration between the two cameras and known characteristics determined at MIT. Rows 320-422 were of higher X-ray intensity, and therefore CTI is measured from row 0-320 where the X-ray flux is uniform. Ten bias frames were taken before and after the X-ray frames to allow for any flat-field variation in signal.

At -100 C, to decrease the statistical error, 500 frames of Mn X-ray data were taken to provide a CTI measurement and ten bias frames were taken before and after. All files were taken with a three second integration (all integration times have a 0.72 second overhead). The readnoise was less than three electrons, dependent on pick-up from the accelerator equipment. The photon flux was 80 X-rays, in the MnKα peak, per frame, in the main part of the CCD; y=0-320.

2.3. Irradiation conditions

The temperature was controlled so that the CCD remained at -100 C +/- 1 C, and the CCD clock lines and biases were switched off. The irradiation was performed using the Van de Graff generator at GSFC, the total proton dose was 4.3×10^{7} protons cm^{-2} at 95 keV. This was achieved by eight irradiations each 100 seconds long, the beam flux was measured for ten seconds between doses by inserting a surface barrier detector into the beam which, in addition to a timed shutter in the camera housing, prevented the proton beam from reaching the CCD in-between irradiations.

2.4. Post-irradiation

The camera temperature was maintained at -100 C, while 500 frames of MnKα data were taken for CTI measurements and for the ten bias frames before and after the CTI data. The bias frames were used to confirm the background noise was low enough for good measurements, and for consistency throughout the experiment when comparing FWHM before and after the irradiation and after the anneal.

The camera was allowed to warm up to room temperature, with the clock lines and biases switched off. It is estimated that it takes 1 hour to reach +20 C. The CCD was at room temperature for 8 hours.

2.5. Post-anneal

The CCD was cooled to –100 C over 45 minutes, without the voltages being applied. After the CCD temperature had stabilised, 500 frames of data were taken with Mn X-rays for CTI measurements, and ten bias frames before and after.

The CCD was allowed to warm up to -60 C, dark frames were taken with three and ten second frame integration, to provide a dark current map of where the proton beam had hit the CCD and to show any variation in proton dose. This measurement will also provide a second diagnostic to compare with measurements made with the flight CCDs in orbit.

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3. RESULTS

3.1. Pre-irradiation

Dark current and CTI measurements at –60 C

All data processed and shown here have been baseline corrected, by subtracting the mean signal in the overclocks (additional pixels which are from clocking extra pixels out of the serial register) from the signal in the image pixels. This allows for any drift in the electronics from frame to frame. The mean frame, deduced from all frames on a per pixel basis where the pixel has no X-ray signal (i.e. below threshold), is also subtracted from each frame of data to allow for pixel-to-pixel differences in signal.

The dark frames were taken with a three second and ten second frame integration. From calculating the difference in the mean level in the field pixels compared to the overclocks, yields a measure of the dark current generated. The camera runs with 30 overclocks in each row, of which only 28 were used for the dark current measurement to allow for boundary effects. Assuming the calibration is 10.94 eV/dn, and it takes 3.65 eV/electron, the results are shown in table 1 (in electrons) below.

Integration Time (seconds) inc. overhead	Mean in the field pixels (e/pix/sec)	Sigma in the field pixels (e/pix/sec)	Readnoise in the field pixels (e)	Mean in the overclocked pixels (e/pix/sec)	Sigma in the overclocked pixels (e/pix/sec)	Readnoise in the overclocked pixels (e)
3.72	0.62	0.53	4.35	0.00	0.25	3.42
10.72	0.55	0.29	4.56	0.00	0.08	3.45

Table 1. Dark current measurements in electrons, after baseline correction

The spectrum can be seen in figure 1.

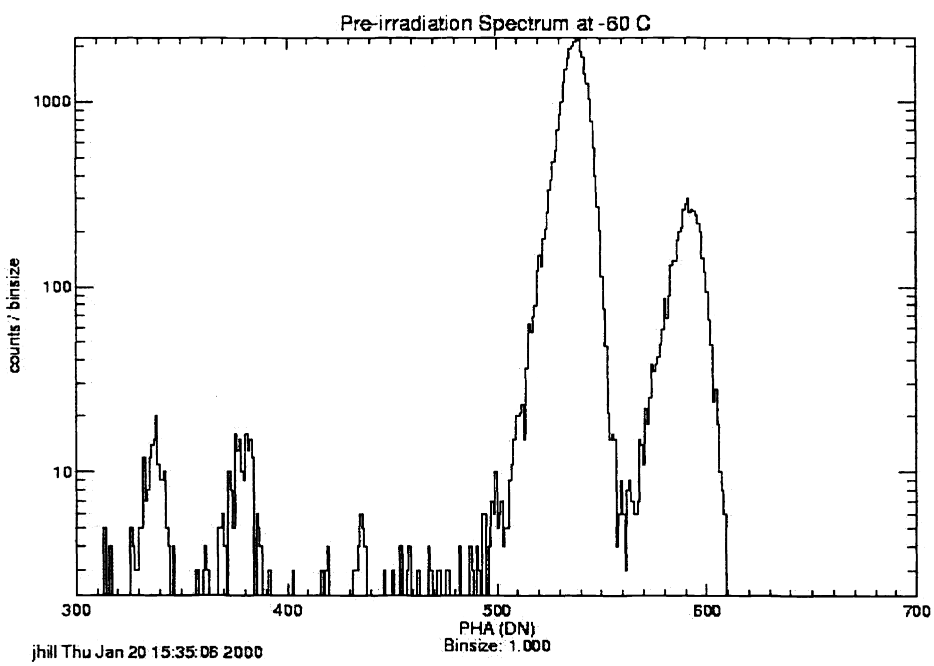

Figure 1. Mn spectrum from CCID7, pre-irradiation at –60C

The MnKα peak can be fitted with two Gaussians and a constant. The fit for ACIS grades 0, 2, 8, 16 and 64 (single pixel events and two pixel horizontally and vertically split) gave the following results;
Gaussian 1; μ =538.7 dn, FWHM=121 eV, area=2.246×10^4 events
Gaussian 2; μ =532.7 dn, FWHM=191 eV, area=8914 events
Background; 10.31
K-S statistic; 0.004462 with a significance of 0.5489
Log Likelihood; 2.270×10^5

Parallel CTI was measured to be ~1.00×10^{-7} +/- 1.00×10^{-7}, serial CTI was of the same order of magnitude, 8.37×10^{-7} +/- 7.35×10^{-7}.

CTI measurements at –100 C pre-irradiation
The comparison of the mean in the field pixels and the mean in the overclocks yields a difference of 0.27 +/- 0.37 e/pix/sec. This is much higher than was measured at MIT and previously at PSU, but the error is large and could be due to electronic pick-up in the CCD array. The readnoise from the electronics was three electrons. Figure 2 shows the Mn spectrum before the proton irradiation, for ACIS grade 0, 2, 8, 16 and 64. It can be seen that there is a gain increase and an improvement in the energy resolution compared to the spectrum at –60 C.

The spectral fit of the MnKα peak for ACIS grades 0, 2, 8, 16 and 64 (see figure 3) gave the following results;
Gaussian 1; μ =542.5 dn, FWHM=122 eV, area=2.273×10^4 events
Gaussian 2; μ =536.0 dn, FWHM=175 eV, area=7497 events
Background; 19.78
K-S statistic; 0.004438 with a significance of 0.5710
Log Likelihood; 2.211×10^5

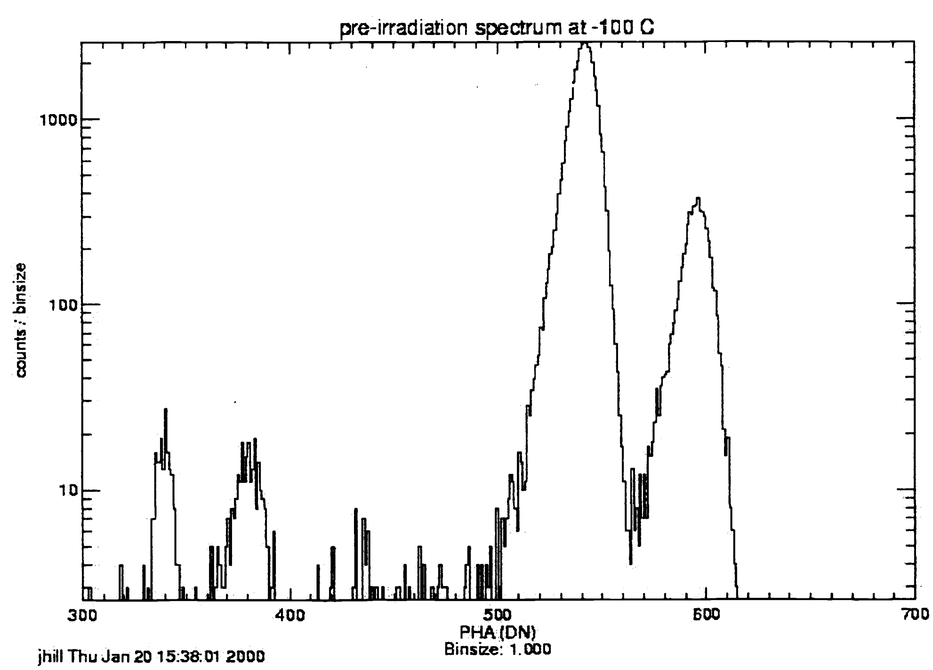

Figure 2. Spectrum from CCID7, pre-irradiation, at -100 C.

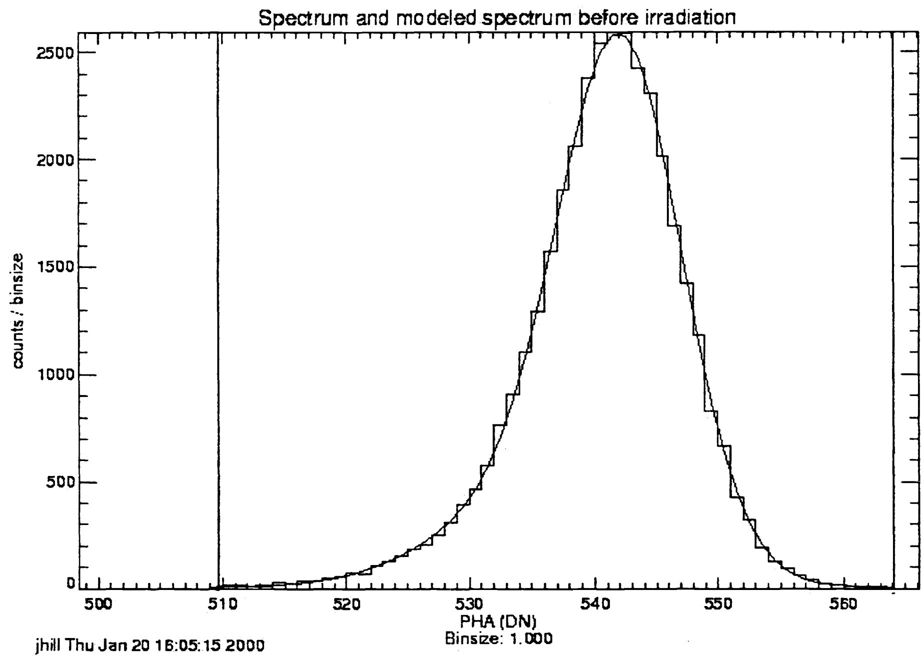

Figure 3. MnKα spectral fit from CCID7 pre-irradiation.

Serial CTI is too small to measure above the error of ~10^{-7} per pixel.
Parallel CTI is of the order of 7.28×10^{-7} +/- 6.98×10^{-7} per pixel, from linear regression on the MnKα line from ACIS grades 0, 2, 8, 16 and 64. From fitting the centre pixel MnKα spectrum with two Gaussians and a constant, for six samples of 50 bins in the parallel direction, the parallel CTI, calculated from the change in the position of the mean of the primary Gaussian with respect to y position, is 8.03×10^{-7} +/- 8.46×10^{-7} per pixel.

CTI measurements at –100 C post-irradiation

The difference between the mean in the field pixels compared to the overclocks yields a difference of 0.26+/-0.36 e/pix/sec. This is the same as the pre-irradiation measurement. This could indicate that the parallel clocks are picking up noise, or that the error is too large to make the measurement significant. The readnoise from the electronics was slightly less than for the pre-irradiation data, 2.83 electrons.

Figure 4 shows the spectrum after proton irradiation of 4.3×10^{7} protons cm^{-2} and before the room temperature anneal, for ACIS grades 0, 2, 8, 16 and 64. The degradation can clearly be seen; there are more events in the soft shoulder relative to the primary peak, and the resolution of both peaks is degraded. The gain is also reduced.

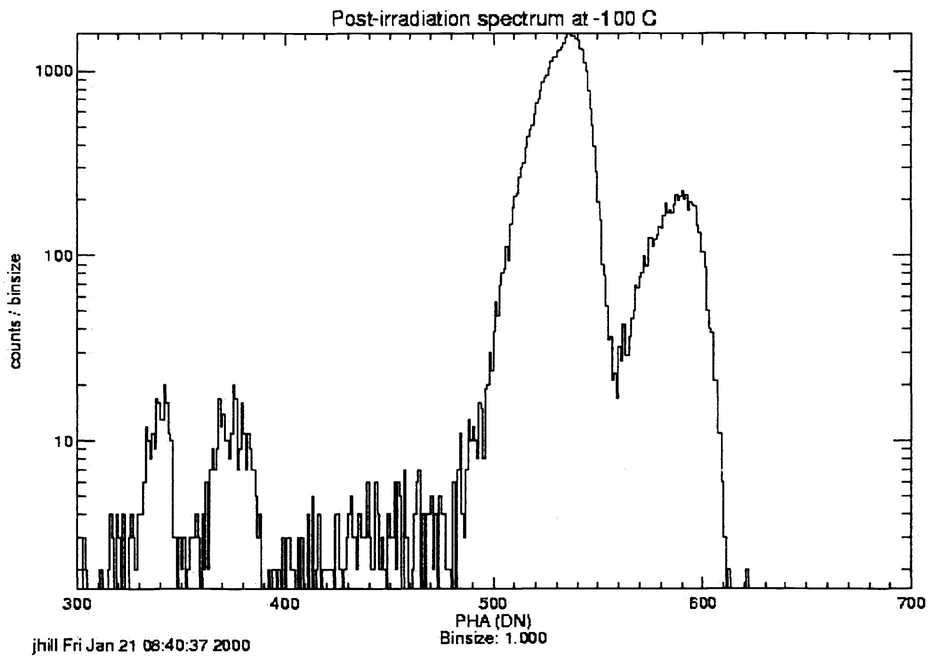

Figure 4. Spectrum from CCID7 post-irradiation.

The spectral fit to the MnKα line from ACIS grades 0, 2, 8, 16 and 64 gave the following results,
Gaussian 1; μ =539.7 dn, FWHM=127 eV, area=1.231×10^{4} events
Gaussian 2; μ =529.7 dn, FWHM=260 eV, area=2.805×10^{4} events
Background; 15.87
K-S statistic; 0.007735 with a significance of 0.01430
Log Likelihood; 2.853×10^{5}

From looking at the MnKα line versus the x-position it is possible to deduce where the irradiation occurred on the CCD. The line appears as a v-shape, and therefore cannot have occurred as a result of an increase in CTI in the serial direction and must be due to change in radiation damage across the CCD. Therefore parallel CTI was measured using columns 100-400 and rows 0-310. From modelling the MnKα peak in the manner described previously, the parallel CTI has increased to 2.05×10^{-5} +/- 3.82×10^{-6} per pixel due to the proton irradiation. This increase in CTI is not as large as expected from previous irradiations, at room temperature, with a CCID17, by MIT. Previous cold irradiations of a CCID10 and CCID17 by PSU, appeared to yield a lower CTI increase than expected, but the experimental procedure has currently not been confirmed.

Performing linear regression on the MnKα peak versus y-position for ACIS grades 0, 2, 8,16 and 64 resulted in an even smaller measure of CTI, $5x10^{-6}$.

CTI measurements at –100 C post-irradiation, post room temperature anneal

The difference between the mean in the field pixels compared to the overclocks yields a difference of 0.07+/-0.22 e/pix/sec. This is lower than both previous measurements, although all noise was significantly lower for these data sets, the readnoise from the electronics was 1.51 electrons. Figure 5 shows the spectrum, for ACIS grades 0, 2, 8, 16, 64 after a proton irradiation of $4.3x10^{7}$ protons cm^{-2} and after the 8-hour room temperature anneal.

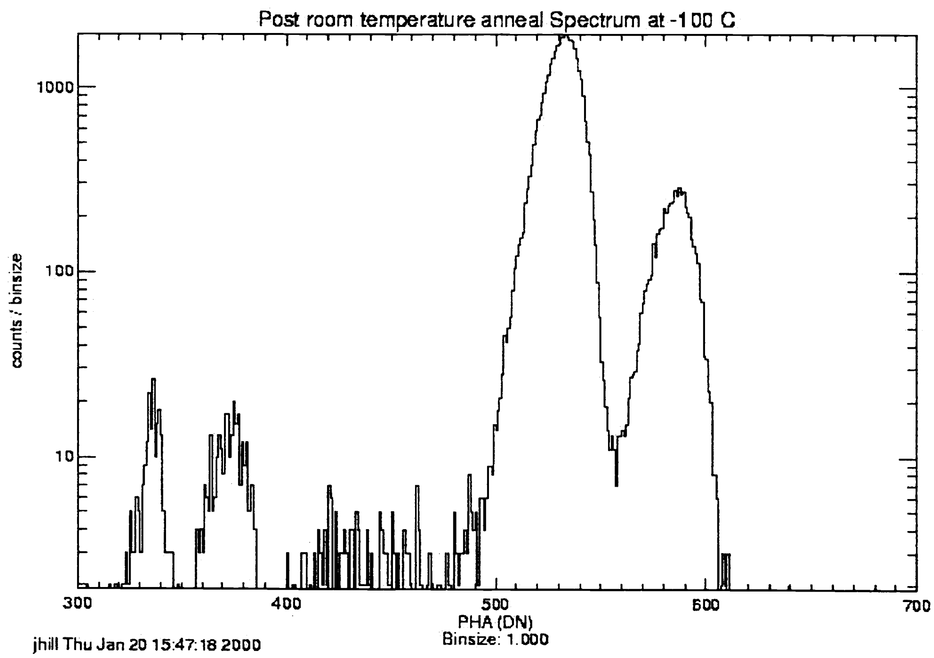

Figure 5. Spectrum from CCID7 post-irradiation, post anneal at –100 C.

The spectral fit to the MnKα line from ACIS grades 0, 2, 8, 16 and 64 gave the following results,
Gaussian 1; μ =535.2 dn, FWHM=138 eV, area=$1.975x10^{4}$ events
Gaussian 2; μ =526.8 dn, FWHM=194 eV, area=$1.685x10^{4}$ events
Background; 19.22
K-S statistic; 0.005506 with a significance of 0.2036
Log Likelihood; $2.655x10^{5}$

From modelling MnKα peak for 6 bins of 50 rows, the parallel CTI appears to have reduced after the room temperature anneal, to $3.43x10^{-6}$+/- $8.97x10^{-6}$. This a marginally significant result. Performing linear regression on the pha versus y-position leads to a CTI of $3.21x10^{-6}$+/-$1.39x10^{-6}$, which is less than the measurement before the room temperature anneal. The gain is further reduced and the resolution of the primary peak has increased, but the soft shoulder FWHM is much reduced thus improving the overall resolution. The escape peaks are separated again and relatively more events are in the primary peak.

4. PRELIMINARY CONCLUSIONS

The figures below demonstrate the changes which occurred in the CCD performance after the irradiation, and after the room temperature anneal. The condition numbers represent the following information; condition 1 is –60 C pre-irradiation, condition 2 is –100 C pre-irradiation, condition 3 is –100 C post-irradiation, condition 4 is –100 C post-anneal.

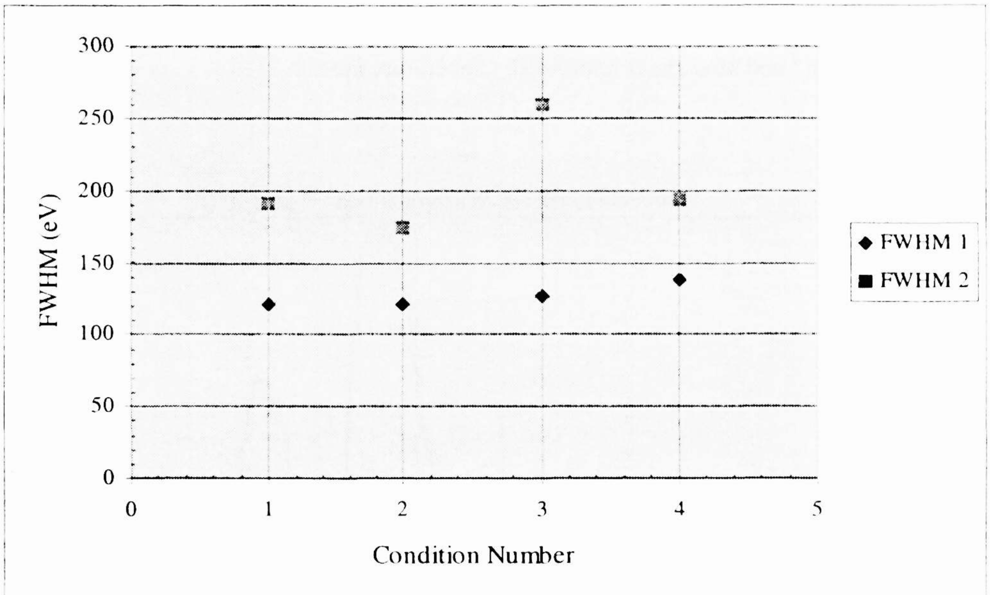

Figure 6. The change in FWHM from fitting the MnKα line with two Gaussians and a constant.

The change in energy resolution can be seen from simply comparing the spectra by eye (figures 2, 4 and 5). This change has been confirmed by modelling the MnKα peak for ACIS grades 0, 2, 8, 16, and 64. Figure 6, shows that spectral resolution is degraded significantly by the irradiation, specifically in the soft shoulder. Also, the average gain for the CCD is reduced by 3 dn. The room temperature anneal improves the spectral resolution overall, although fitting the MnKα peak indicates that the improvement is mostly in the events forming the soft shoulder and the resolution of the central part of the peak is further degraded. The overall gain as measured by the position of the maximum of the MnKα peak decreases by an additional 4.5 dn.

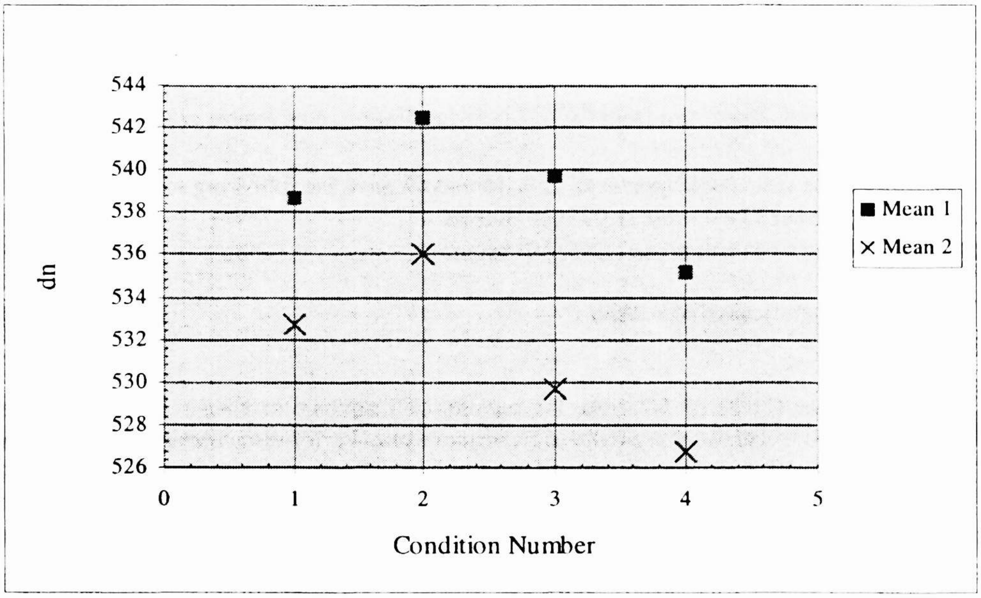

Figure 7. The change in gain from fitting the MnKα line with two Gaussians and a constant.

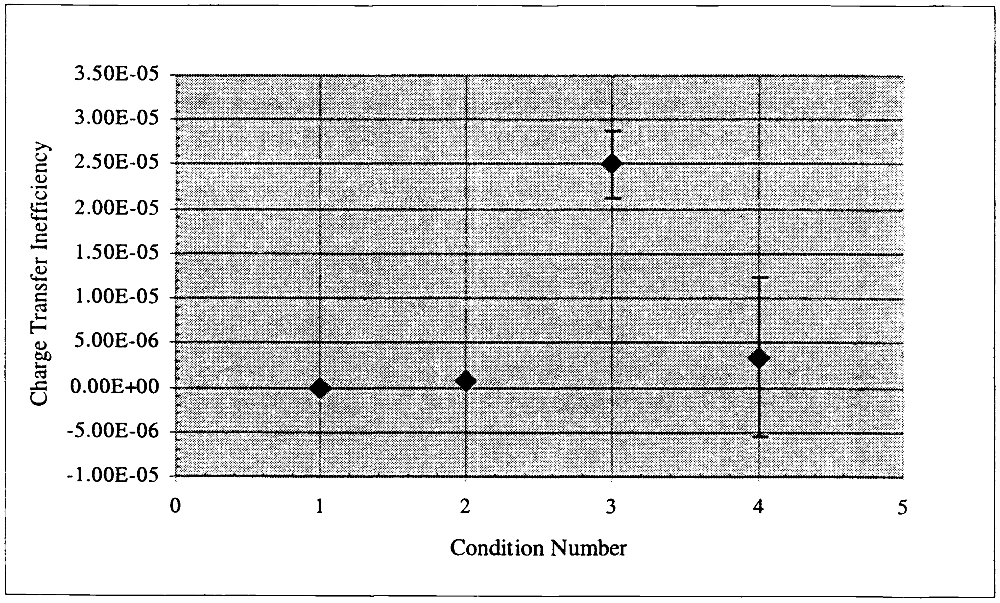

Figure 8. Charge transfer efficiency as a function of CCD condition.

The CTI measurements appear marginal given the statistics, but suggest that there was an improvement after the room temperature anneal.

The results from this experiment indicate that the increase in CTI occurring as a result of proton irradiation at –100 C, operating the CCD with the PSU camera, is less than from room temperature irradiations (Prigozhin et al., 2000). A CTI measurement of $\sim 10^{-4}$ was expected from this dose. The room temperature irradiation of a CCID17 as part of this experiment, indicated a CTI of 4.7×10^{-4} at –110 C, when measured with the MIT camera, after irradiation with the same proton energy and approximately the same proton dose. The CCID17 should actually show less damage than the CCID7 because it has smaller pixels and the charge packets see less silicon per pixel in this CCD. This could imply that the ACIS front illuminated CCDs were subjected to a higher flux than was calculated, if low energy protons are the mechanism by which they were damaged.

No increase in dark current was seen when measured at –60 C by the MIT group.

5. DISCUSSION

MIT see larger CTI in their post-experimental results from the CCID7 than is seen from the data taken with the PSU camera after the room temperature anneal. MIT have also analysed the data taken with the PSU camera and find very little CTI, as shown in section 4. There are three explanations proposed at this stage;

•During the days after the experiment the CTI became worse and therefore further data now needs to be taken with the PSU camera to confirm the 4.5×10^{-5} CTI measured with the MIT camera.

•The illumination pattern seen during the experiment at GSFC is due to only the top 100 rows being illuminated, rows 310-422, and therefore when looking at the events from rows 1-309, the gain is changed but the CTI is constant due to all events arising at the top of the chip and therefore all events loose an equal amount of charge.

•The difference in operation of the two cameras leads to a difference in CTI. The only apparent difference being the full-frame flushes after data saving, the store and readout flushes and a different frame transfer speed.

In previous experiments, the measured CTI after a warm irradiation has not been seen to change in the days following the experiment. There is no reason to suspect that this case is any different beyond the initial anneal at room temperature. The maximum number of lattice defects should have annealed out in the 8 hours at room temperature, and further temperature cycling should have had no affect.

The second theory has been addressed. Assuming only rows 310-422 are illuminated, then the rows below this region (1-309) must have accumulated photons during the transition through the high flux region during the last full frame flush, prior to integration. If this is the case we can compare the time that rows 1-309 spent passing through the suggested illuminated region to the time spent by rows 310-422 during integration. If this theory is correct this ratio should compare to the flux ratios of the two regions.

The row transfer time during the full-frame flush is 76 μs, so the total time spent by rows 1-309 in this region is 8.5 ms. Rows 310-422 spend the integration time plus frame transfer time in to and out of this region. Consider only the integration time for now, as this is row independent, the integration time is 3.72 seconds. The time ratio is then calculated to be 437.6. The flux ratio is 1120/125; 8.96. Therefore it is proposed that this theory is either not complete or incorrect.

Further evidence to dismiss the above theory is provided from experiment. The PSU camera is no longer fully functional, but has enabled data to be taken at –40 C, the size and positioning of the ^{55}Fe source is similar to the set-up at GSFC. If the rows 1-309 only accumulated photons from the transfer through a high flux region at the top of the CCD, then changing the integration time should not change the flux rate in this region. Data were taken with a three second and a ten second integration time. The number of photons/second/frame was 29 for the three second integration and 11 for the ten second integration. In theory the number of X-rays/second/frame should be the same for both integrations, but the difference can be accounted for by the thresholding. At –40 C the dark current is significantly higher for the ten second integration files than for the three second integration files, and therefore more events are lost in the noise.

The illumination pattern can be explained by an alternative theory, but this does not explain the difference in CTI measurements between the two cameras. There is a space of about 1/8'' between the store shield and the store array of the CCD. This means that there is a finite amount of space for photons to illuminate the store array, if the source is close enough. Measurements that were taken prior to the GSFC experiment show a uniform distribution of photons over the CCD. In this case the source was 1 inch in diameter, and approximately 2.5'' away from the image array of the CCD.

At GSFC the source used was much smaller and approximately the same strength. The source was mounted differently because of the set up needed for proton irradiation. From measuring the camera geometry, the source was approximately 5/8'' away from the CCD. From calculations using this geometry, the illumination pattern can be explained in terms of photon illumination under the store shield.

The last suggestion is still under consideration but the theory is as follows. The five full frame flushes before integration will transfer charge collected through the image array 5 times. This charge will fill the traps in both the image and the store array, before the image is collected. If the time constant of the traps is long, which is likely at –100 C, then the traps remain filled and much less signal is lost from the image. The MIT camera was not operated in flush mode and this could explain the difference in CTI measurements between the two cameras.

6. SUMMARY

This experiment has shown that the damage produced by 95 keV protons to a cold CCID7 is less than predicted by warm irradiations of a CCID17. This may be explained by differences in the CCD gate structure, although it is unlikely since both devices are from the same wafer, and therefore should have fundamentally the same structure. The difference in pixel size indicates that the CCID7 should show more CTI than a CCID17 irradiated with the same proton dose.

As was hoped with the orbital bake-out, the damage to the CCID7 in this experiment appears, at this moment, to have been annealed from warming the CCD up to +20 C for eight hours. This, however, is not what occurred on orbit and indicates that the experience of the flight chips differs somewhat from the experiment performed here. It is known that the flight CCDs will not have seen an entirely monochromatic spectrum of protons and therefore the further degradation that was seen after the in-orbit anneal could be due to traps created by a different energy of protons in addition to the 100 keV protons, although recent measurements with the CCID17 which was irradiated warm on the same occasion as this experiment (Prigozhin et al., 2000), shows flight-like traps and behaviour. It is possible that, from the limited flight calibration data it was possible to collect from ACIS, something else occurred during the bake-out that has not yet been accounted for.

The difference in CTI observed by the operation of the two CCD cameras on the same CCD still remains unresolved. Further measurements are being taken with the MIT camera operating in a similar manner to the PSU camera, including the full frame flushes, which will hopefully explain the differences in CTI measurements.

Further experiments need to be performed to ensure that nothing in this experiment remains unaccounted for and that the result is indeed different from that obtained in orbit.

7. ACKNOWLEDGEMENTS

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