ATLAS Internal Note

Irradiation of the TC255P CCD by Fast Neutrons Part 2

Kevan S Hashemi and James R Bensinger

Brandeis University

26 July 1999

Abstract: The first time we irradiated TC255Ps with fast neutrons was in April, 1998, at the University of Massachusetts facility in Lowell, USA. In MUON-No-253 we reported that the dark current in all four CCDs increased linearly with 1-MeV equivalent dose. In September, 1998, we sent eight TC255P CCDs to the ATLAS-wide fast neutron test at the PROSPERO reactor in France. When the organizers of the test returned the CCDs to us two months later, we found that their dark currents after irradiation agreed with the model we had proposed on the basis of our first test. We analyzed RASNIK and BCAM images taken with all eight CCDs, including two that received eleven times the estimated worst-case ATLAS end-cap neutron dose. We conclude that we understand the progress of neutron damage in the TC255P, and that the CCD will perform well for the duration of the ATLAS experiment.

Introduction

The first time we irradiated TC255Ps with fast neutrons was in April, 1998, at the University of Massachusetts facility in Lowell, USA. In MUON-No-253 [1], we reported that the dark current in all four CCDs increased linearly with 1-MeV equivalent dose.

In September, 1998, we sent four metal boxes to the ATLAS-wide fast neutron radiation test at the PROSPERO reactor in France. Each box contained two TC255P CCDs as well as one GAL16V8B generic array logic chip, and one DG411DJ analog switch. Upon each box we wrote in green ink the distance from the reactor center we would like the box to be placed, and whether or not the box should be removed during the break. When the organizers of the test returned our boxes, we saw a neutron dose written upon each box in red ink. The dose was expressed in 1-MeV eq. n/cm^2. For the rest of this note, we will use the abbreviation ‘Tn’ for 10^{12} 1-MeV eq. n/cm^2.

Results

Figure 1 is an image we captured from CCD N°8. The box containing this CCD took 9.1 Tn. It was 1.5 m from the reactor center for the entire experiment. You can see a rasnik pattern in the image, lying on top of the vertical intensity gradient that is associated with fast neutron damage [1]. We exposed the CCD for 2 ms, during which time we illuminated the rasnik pattern, and then read out the image, which took approximately 52 ms.

Figure 1: An image captured from a CCD that took 9.1 Tn. The exposure time was 2 ms. The pattern is the shadow cast by a rasnik mask held up against the CCD. The squares are 170 µm wide.

Figure 2 is an image we captured from the same CCD with the same 2-ms exposure and 52-ms readout, except that we did not illuminate the rasnik mask during the exposure. The image shows the dark current that accumulates in damaged pixels while they are waiting to be transferred out of the CCD [1]. We know how long it takes to transfer each line of the image, so we can convert the vertical intensity gradient in the image into a measure of the dark current. This measure has units of ADC counts per millisecond (counts/ms).

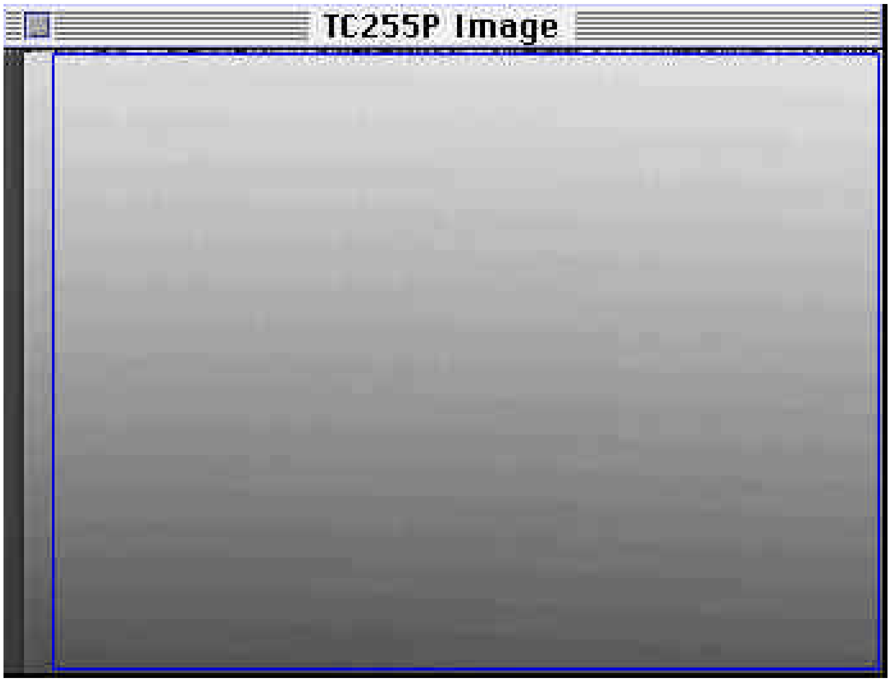

Figure 2: A 2-ms exposure with the light source turned off. The vertical gradient of intensity is caused by dark current accumulating in the pixels during the image readout.

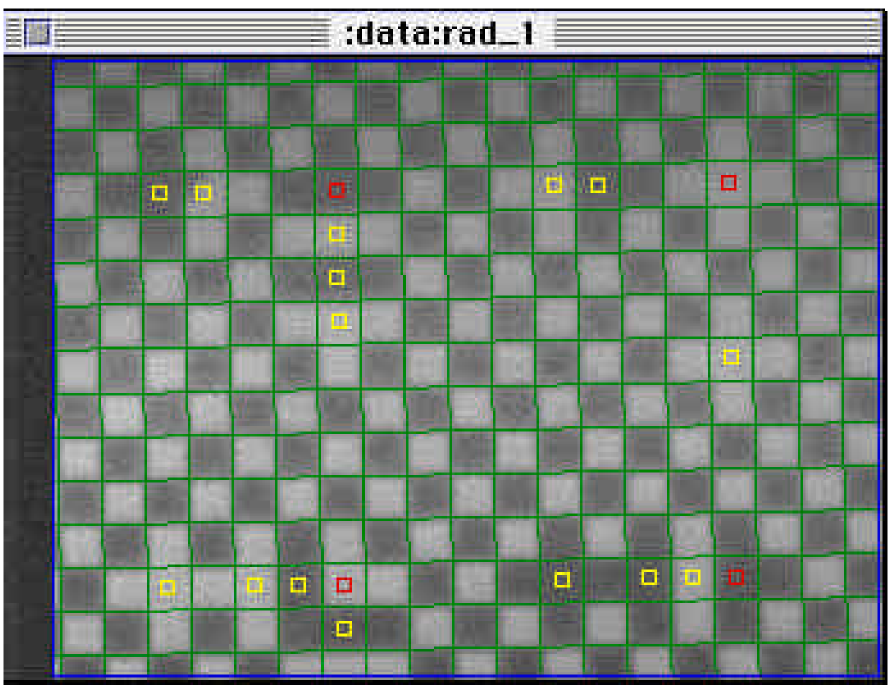

Figure 3: The difference between Figures 1 and 2. That is, a 2-ms exposure with its dark current content subtracted. The results of rasnik image analysis are superimposed in color.

We obtained Figure 3 by subtracting Figure 2 from Figure 1. We intensified the display of Figure 3 to show the image contrast and noise. Our software has superimposed the results of its rasnik analysis in the form of green lines and yellow and red squares. The standard deviation of rasnik measurements we obtained in this manner from CCD Nºs 7 and 8 was less than 1 μm.

CCD	Measured Background Slope (counts/line)	Measured Readout Time (ms/line)	Estimated Neutron Dose (Tn)	Measured Dark Current (counts/ms)	Predicted Dark Current (counts/ms)	Measured Minus Predicted (%)
Prospero 1	0.1905	0.197	2.30	0.967	0.913	5.9
Prospero 2	0.1775	0.197	2.30	0.901	0.913	-1.3
Prospero 3	0.0506	0.197	0.71	0.257	0.282	-8.8
Prospero 4	0.0433	0.197	0.71	0.220	0.282	-22.0
Prospero 5	0.4437	0.197	5.50	2.252	2.183	3.2
Prospero 6	0.4312	0.197	5.50	2.189	2.183	0.3
Prospero 7	0.6234	0.197	9.10	3.164	3.611	-12.4
Prospero 8	0.6455	0.197	9.10	3.277	3.611	-9.3
Lowell 1	0.6433	0.788	3.00	0.816	1.191	-31.4
Lowell 2	2.0567	0.788	7.70	2.610	3.056	-14.6
Lowell 3	0.7957	0.788	2.70	1.010	1.071	-5.8
					average	-8.7
dark currents measured at		24.1	°C			
Lowell 4 not included because it had been annealed						

Table 1: Measured and predicted dark currents for the CCDs that were irradiated at PROSPERO and Lowell.

Table 1 gives the vertical derivative of intensity for images we captured from each of the eight CCDs we sent to PROSPERO, and for three of the CCDs we irradiated at Lowell. We captured all the images within the same fifteen minutes of one another. The temperature in the laboratory was stable at 24.1 °C. In MUON-No-253 [1], we proposed relationship between dark current, ambient temperature, and 1-MeV equivalent fast neutron dose. Table 1 gives the dark current predicted by this model for each CCD, and compares this to the measured dark current. As you can see, the dark current predicted by the model is, on average, ten percent higher than the observed dark current.

We obtained the estimated neutron doses in the fifth column of Table 1 from various sources. For the Lowell test CCDs, we used the estimates provided by the Lowell facility. For PROSPERO test CCDs Nº3 to Nº8, we used the dose written on the boxes in red ink. But for PROSPERO test CCDs Nº1 and Nº2, we used our own estimate. We wrote upon the box containing these CCDs saying that the box should be left 3 m from the reactor center for the entire experiment. It would then receive one quarter the dose received by the box containing CCDs N^{0}7 and N^{o}8, which spent the entire experiment 1.5 m from the reactor center. Upon its return to us, however, we found that the box had written upon it in red ink '1.8 x 10^{11}' and 'Was removed during the break'. But the dark current in CCDs N^{o}1 and N^{o}2 is twelve times higher than the value predicted by our model for a dose of 0.18 Tn. Either the box was left in for the entire experiment, in accordance with our instructions, or we have two CCDs in the same box that behaved dramatically differently from the ten others we have irradiated (four at Lowell and six at PROSPERO). We deem the former hypothesis to be more likely. That is, the box containing the CCDs was incorrectly marked in red ink, and was in fact left in the radiation hall at a range of 3 m for the entire experiment. Because CCDs N^{0}7 and N^{o}8 received 9.1 Tn at a range of 1.5 m, we estimate that CCDs N^{o}1 and N^{o}2 received 2.3 Tn.

Alongside the TC255Ps in each box were two other chips we use in our prototype version of the Pixel CCD Data Acquisition System. One was an E^{2}CMOS generic array logic chip from Lattice Semiconductor called the GAL16V8B. The programs in all four irradiated GAL16V8Bs were intact. The other integrated circuit was an analog switch from Siliconix called the DG411DJ. All four irradiated DG411DJs functioned without any signs of damage when we used them to switch analog image data.

Expected ATLAS Dose

The highest dose received by our CCDs at PROSPERO was 9.1 Tn. A table by A. Ferrari et al [2, Table 1] quotes worst-case doses both in n/cm^2/yr and 1-MeV eq. n/cm^2/yr based upon simulation TP36. These doses are equal to those predicted by the simulation multiplied by a 'systematic safety factor'. This factor is 4 for both the end-cap and the barrel. When the table says 2.9×10^{11} 1-MeV n/cm^2/yr worst-case dose in the end-cap, this means the simulation predicts a ten-year worst-case dose of 0.73 Tn. When we looked at the 1-MeV eq. n/cm^2/yr plot from TP36, we estimated that the dose at the inner edge of the inner chambers in the end-cap was 0.8 Tn. We estimated that the dose on the inner edge of the inner chambers in the barrel, where a radiation plume rises from the inner detector, was 0.5 Tn.

Figure 4 is a section of the neutron fluence map from the more recent TP43 simulation. The units are kHz/cm^2. All neutrons are counted equally.

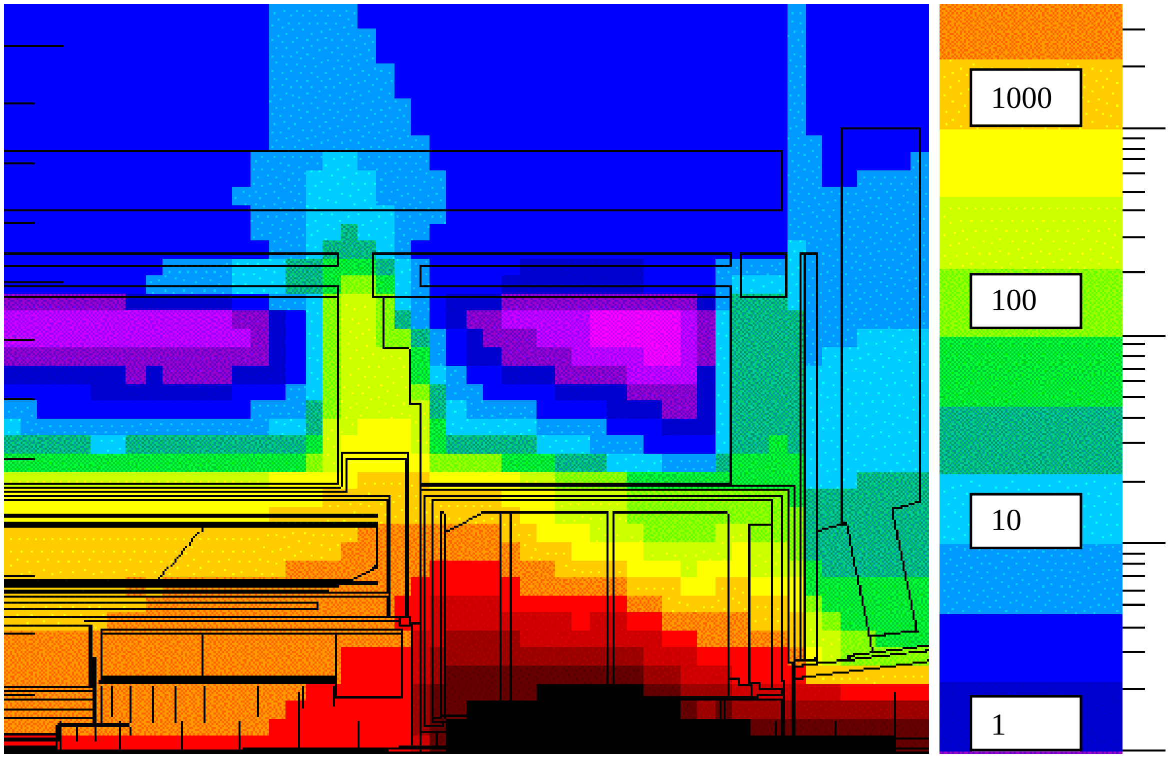

Figure 4: **Detail from TP43 neutron fluence map. The units are kHz/cm^2. We obtained the zipped post script file from the atlas.cern.ch site, in user directory ferraria/public/tp43, file name muhlpnw3.ps-gz.**

From Table 1 in [2], we conclude that the energy-spectrum of the neutrons in the inner parts of the muon detector is such that we can take the fluence in kHz/cm^2 and divide by forty to get the dose on Tn (10^{12} 1-MeV eq n/cm^2) for the ten-year experiment. With this assumption, we obtain from Figure 4 a dose of roughly 0.8 Tn at the transition between the EI and CSC chambers (lower right) and 0.5 Tn in where a plume of higher-fluence crosses the inner barrel chambers (upper left).

Room-Temperature Annealing

The dark current in the CCDs that we irradiated at Lowell fell by up to 50% during the first few weeks after the irradiation. We received the CCDs irradiated at Prospero several weeks after the irradiation, so we were unable to observe the initial drop in dark current by room-temperature annealing. Ten months after the test, however, we repeated the measurements of Table 1, and found that the dark currents in the CCDs were on average 10% lower than they were one month after the test.

Conclusion

We can analyze rasnik images captured from all the CCDs irradiated at the PROSPERO facility. The standard deviation of rasnik measurements we obtained from these CCDs is less than one micrometer in every case. The dark current of each CCD is within twenty percent of the value predicted by our pre-existing model [1]. Consequently, we feel assured that we have a working model of neutron damage in the TC255P. There has been confusion about the neutron dose we can expect in the muon detector, and about what multiple of this dose our electronics should be able to tolerate. At present, it appears to us that the worst case in the barrel is about 0.5 Tn, and in the end-cap is 0.8 Tn. We have demonstrated that the TC255P and our existing data acquisition system can tolerate 9.1 Tn. We have a proven safety factor of eleven. With modifications to the data acquisition system, such as accelerated readout of lower-resolution images, we can increase its tolerance to 37 Tn [1], which would give us a safety factor of forty-six.

References

[1] Hashemi et al, *Irradiation of the TC255P by Fast Neutrons*, ATLAS note MUON-No-253.

[2] Ferrari, *ATLAS Policy on Radiation-Tolerant Electronics Draft Two*, simulation TP36.