Irradiation of nSW Upgrade Components by Fast Neutrons

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Introduction

This document details the results of three experiments in which components to be used in new Small Wheel alignment electronics were subjected to neutron irradiation at the University of Massachusetts at Lowell. The first experiment, on August 5th, 2014, was completed with UMass' Van de Graaff accelerator. The maximum dose achieved in this experiment was estimated at 1.8×10^{12} 1-MeV equivalent neutrons. The latter two experiments, on December 22nd, 2014, and February 6th, 2015, were completed at the Fast Neutron Irradiation facility at the 1-MW research reactor on the Lowell campus, to levels of 2.2×10^{12} and 13.8×10^{12} 1-MeV equivalent neutrons, respectively. Neutron doses in this document will be abbreviated with the nonstandard unit Tn, where 1 Tn = 1×10^{12} 1-MeV equivalent neutrons.

Included in each experiment were Sony ICX424AL charge-coupled device (CCD) image sensors, Philips LumiLEDs "Luxeon Z" light emitting diodes, and one or two types of optical fiber: "Draka Comteq" with 62-μm core, installed in the BEE upgrade alignment electronics, and "CeramOptec WF100" with 100-μm core, which is the current candidate for installation in the new Small Wheel. The CeramOptec fiber was not included in the August test.

To establish radiation tolerance, we imagine the following, worst-case optical line: image sensor exposed for 10 ms, light source 3 m from BCAM, ten-year estimated neutron dose of 5.5 Tn and ambient temperature 20°C. It is noteworthy that no line in the new Small Wheel will have both a 3 m source distance and an accumulated dose of 5.5 Tn. We establish the figure of 5.5 Tn from internal calculations which corroborate doses cited in Edgar et al., who cite a worst-case ten-year neutron dose of 4.8 Tn at luminosity 5×10^{34} cm^{-2}, energy 14 TeV, radius 2.2 m, 10^7 s/year for 10 years.[1]

ICX424AL CCD

To read out the ICX424AL, we expose its image area for a variable amount of time. (In the nSW, we will not need to expose any image sensors for longer than 10 ms.) We then clock the exposed pixels into a second, parallel set of transfer pixels, where the image is then read out one pixel every 500 ns. The ICX424AL has 520 rows and 700 columns, for a readout time of approximately 180 ms. The ICX424AL also supports pixel binning, so with the updated drivers in the new Small Wheel, we will have the capacity to read out the image sensor in 45 ms.

The readout is digitized to eight bits and stored as a Long Wire Data Acquisition system (LWDAQ) image, where each pixel has a value between 0 and 255 "counts." A threshold of approximately 35 counts exists on a blank, unirradiated image. We have previously established that we can take a successful BCAM image with 10% of the sensor's dynamic range, so we claim we can take images with 200 counts of dark current accumulating on the most damaged row of the sensor.

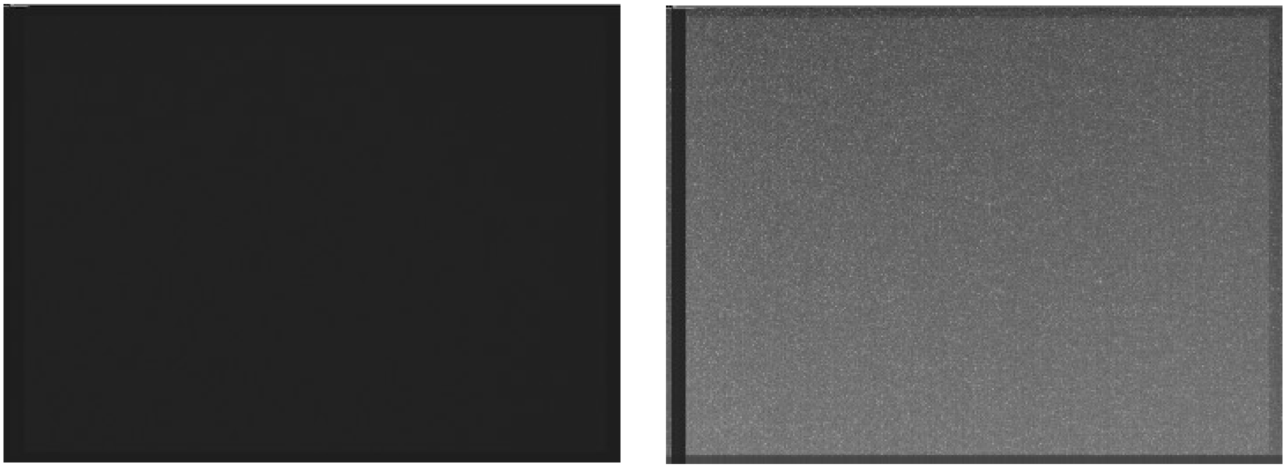


Figure: 100 ms exposure before (left) and after (right) 2.15 Tn of neutron exposure (Dec 22nd).

Neutron damage manifests in CCD image sensors as an increase in dark current.[2] Dislocations in the crystal lattice function as a current source when the image is read out. Since these dislocations are static, we see the same damage every time we take an image with the same sensor. We can observe and quantify this dark current independently in both the image area and the transfer area.

Image Area

To observe the image area dark current, we take dark images of two different lengths and subtract their difference in average pixel intensity counts. We divide this difference by the difference in milliseconds and obtain the dark current in counts/ms. We then account for accumulated dose and obtain the dark current in counts/(ms*Tn).

In the August 5th irradiation at the Van de Graaff accelerator, we were able to take real time data by irradiating four image sensors inside two active H-BCAMs. The four CCDs were exposed to doses of 1.8, 0.9, 0.4, and 0.3 Tn. We took images of 100ms and 10ms exposure regularly throughout the irradiation and track the difference in their intensities. From this we plot a graph of image area dark current vs. accumulated dose:

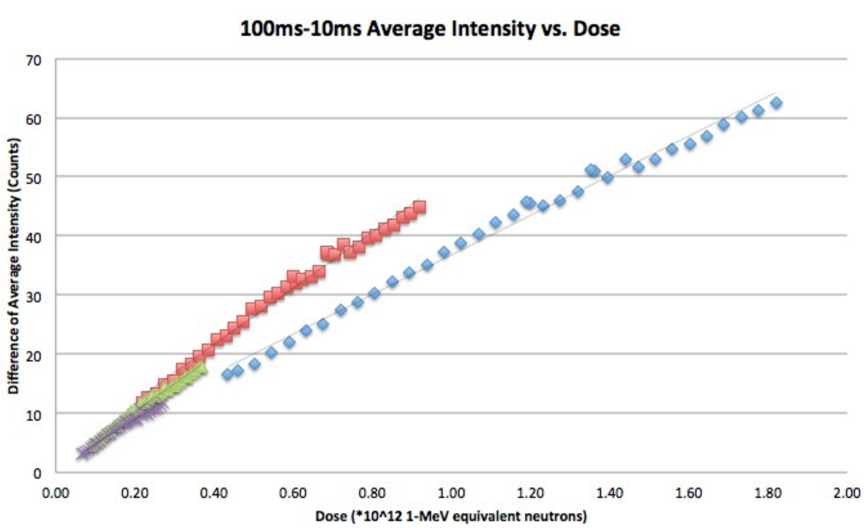


Figure: Image Area Dark Current, Aug. 5th. our ICX424AL sensors

We take the average of the four image sensors and measure image area dark current to be 0.441 counts/(ms*Tn). In 1999[3], we recorded a decrease in dark current after a few weeks of storage at room temperature, which we attributed to thermal annealing of dislocation damage to the silicon lattice. After leaving the ICX424s for six weeks, we take the same images again. The image area dark current is 0.280 counts/(ms*Tn).

We use the same readout to examine the four image sensors irradiated on December 22nd. Because of the nature of the irradiation enclosure we cannot take real time data during this test. We receive our samples back after two weeks, and the average image area damage is 0.324 counts/(ms*Tn). After nine weeks it is 0.328 counts/(ms*Tn). The majority of room temperature annealing seems to happen in the first few days after damage.

The 13.8 Tn irradiation has damaged the image sensor to the point that it is unusable at regular readout speed. We alter the readout board to reduce the gain of the output amplifiers to 40% of original; this is the gain that is used in the new Small Wheel Bar Head (Brandeis device #A2082). The dynamic range of the sensor is increased, but the sensor now saturates at 202 counts. We measure the dark current of the image area, and find that it is 0.124 counts/(ms*Tn).

Transfer Area

The transfer area is exposed for the same amount of time in each image (not including pixel binning), so we measure transfer area dark current as the slope of image intensity across a dark image in units of counts/row. Each 700-pixel row is read out in 350 μs, so we divide the slope by 0.350 to obtain the dark current in counts/ms. We similarly account for radiation dose and plot the dark current in units of counts/(ms*Tn).

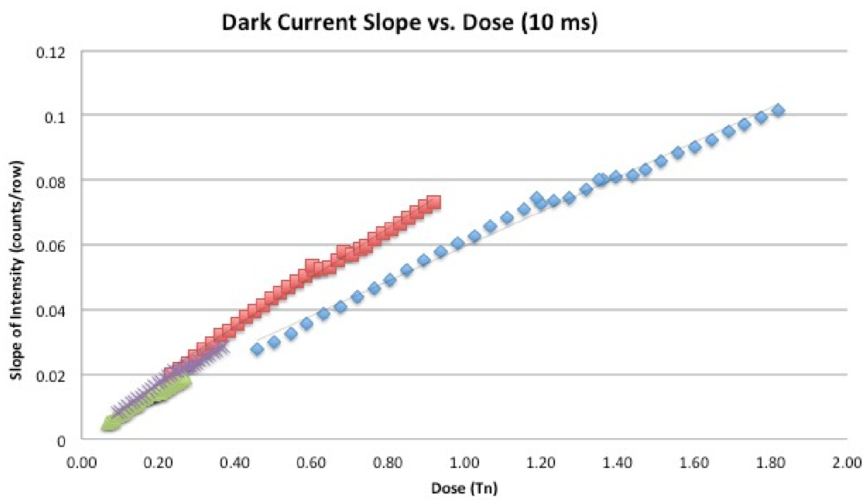


Figure: Transfer Area Dark Current, Aug. 5th.

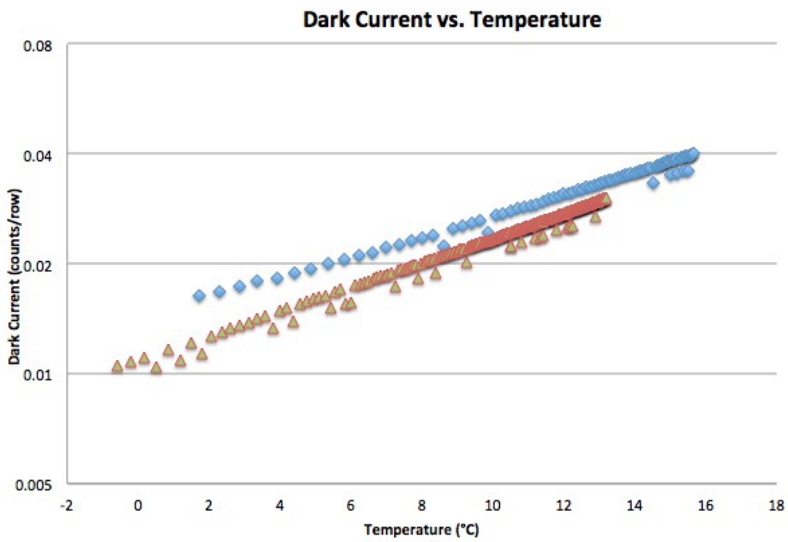
The average dark current on August 5th is .193 counts/(ms*Tn). After six weeks it has dropped to .139 counts/(ms*Tn).

We perform the same tests on images produced two weeks after the Dec. 22nd irradiation. The transfer area dark current is 0.139 counts/(ms*Tn). Five weeks after the irradiation it is 0.128 counts/(ms*Tn). Nine weeks after the irradiation it is 0.113 counts/(ms*Tn).

The images from the February 6th irradiation are similarly too damaged to measure the slope of transfer area dark current. We use the reduced gain board and measure the transfer area dark current to be 0.057 counts/(ms*Tn) after two weeks, and 0.058 counts/(ms*Tn) after four weeks. This is approximately proportional to the original dark current times the change in gain, which we would expect.

Dark Current vs. Temperature

We tested the transfer area dark current of an irradiated ICX424AL as a function of temperature by attaching a resistance-temperature device (Brandeis device #A2053) to the surface of the image sensor inside an HBCAM. We completed this experiment from 0ºC to 20ºC and obtained the following plots:



The dark current in the transfer area doubles with every increase of ~10ºC. All measurements of dark current in terms of counts/(ms*Tn) in this document are normalized to 20ºC using this factor.

Luxeon-Z LEDs

We observed in 2003[4] that our HDSL-4400 infrared light emitting diodes suffered a 90% reduction in output after 10 Tn. We placed 8 448-nm "Royal Blue" Luxeon-Z LEDs in our August 6th irradiation and noticed no reduction in output. Our work on the effects of the damage ionizing radiation causes in optical fibers has subsequently shown that shorter wavelengths of light are more strongly attenuated in a darkened fiber; in December, we included four each of 448 nm, 530 nm ("Green"), 620 nm ("Red") and 655 nm ("Deep Red") Luxeon-Z LEDs. We observed a 5% drop in Deep Red, but that was within the margin of error on the measurement.

We placed the same 16 LEDs in the Feb 6th irradiation and find the following light output:

Deep Red	25.3%
Red	18.4%
Green	100.5%
Royal Blue	104.4%

Table: Relative Light Output of Luxeon-Z LEDs after 16 Tn exposure. LED current 40 mA.

Obtaining consistent light power measurements is surprisingly difficult, but we place the LED directly against a SD445 photodiode and move it until we reach a maximum measurement. We wait three seconds to allow the measurement to settle. Doing so, we can replicate our optical power measurements to within a couple of percent. The new Small Wheel Bar Head (A2082) will contain Blue LEDs and no optical fibers. We may use Red LEDs where we have a sufficient safety margin.

Optical Fibers

We measure the transmission of an optical fiber by injecting light into it with an unirradiated Luxeon-Z LED. This is done by placing the tip of the fiber (in a zirconium ferrule) against the LED using a bespoke aluminum ferrule housing. We place the other end of the fiber injector chain in an iris clamp and observe it with a BCAM at distance of just over one meter.

We have observed that optical fibers are damaged by ionizing radiation. We place 2 62-μm "Draka Comteq" optical fibers in the August test, but we have significant problems estimating the dose due to the placement of the fiber. No damage is measured, but we disregard this test.

We then place four Draka fibers and two Optran 100-μm fibers in the December test. We still note no damage. We place the same 6 fibers in the February 6th test and record the following transmissions.

	Dosimeter sum intensity		BCAM peak intensity	
λ (μm)	Draka 62 μm	Optran 100 μm	Draka 62 μm	Optran 100 μm
448	80%	87%	85%	92%
530	86%	98%	89%	103%
620	95%	101%	95%	104%
655	94%	105%	97%	106%

Table: Optical Fiber Transmission in Length 1m. Exposure 16 Tn. LED current 150 mA.
Measurements relative to omission of fiber from injector chain.

Some of the fibers show greater than 100% transmission, likely because a change of a few degrees in the way the iris clamp holds the ferrule can cause the spot intensity to change by a couple of counts. Still, we see a consistent reduction in transmission with blue light as compared to red. This is not observed with unirradiated fiber. We put an upper bound of 20% reduction after 16 Tn. Because we have a large safety factor with respect to light produced, we do not investigate this any further.

Laser Diodes

We include a HBCAM in the February 6th irradiation and test the output of its laser diodes. There is no reduction in laser intensity after 13.8 Tn.

Tolerance Estimate

We split the tolerance calculation into two parts: light production and image readout.

Light Production

We have shown in ATLAS that a 1 mW light source can create an analyzable image at one meter in one microsecond. We extend this to 10 μs to account for our longest beam lines. We design our LED light sources to output 100 μW continuous power at the tip of the fiber ferrule.

Criterion for image analysis = (1 mW)(10 μs) = 10 nJ

Fiber output = (100 μW)(10 ms) = 1 μJ
Red LED power loss = 25%
Red fiber output = 250 nJ
Blue fiber power loss = 80%
Blue fiber output = 800 nJ

We have a safety factor of 25 with respect to production of red light and a safety factor of 80 with respect to production of blue light. Since we have observed blue light attenuated in optical fibers exposed to ionizing radiation, we will plan to use red light in situations involving optical fiber and blue light in situations without optical fiber.

The new Small Wheel Bar Head will use 448 nm Royal Blue LEDs, which are so far impervious to neutron damage.

Image Sensor

Using existing single pixel readout, we see 145 counts of damage after 5.5 Tn.

Image Area Damage = (.323 counts/[ms*Tn])(10 ms)(5.5 Tn) = 18 counts
Transfer Area Damage = (.129 counts/[ms*Tn])(10 ms)(5.5 Tn) = 127 counts
Regular Readout Total Damage = 145 counts

We reduce the gain to .4 of the original configuration:

Image Area Damage = (.115 counts/[ms*Tn])(10 ms)(5.5 Tn) = 6 counts
Transfer Area Damage = (.058 counts/[ms*Tn])(180 ms)(5.5 Tn) = 57 counts
Low Gain Readout Damage = 63 counts

Since we can tolerate 200 counts of damage, we have a safety factor of 3.5 if we are forced to use regular speed readout, without pixel binning. This may reduce our light output safety factor to 10, but we are comfortable with that outcome.

Our goal for new Small Wheel electronics is a safety factor of five with respect to radiation damage, so we will decrease the amount of time pixels spend in the transfer area to reduce the effects of dark current. We have methods to do this which do not require any changes to BCAM or new Small Wheel Bar Head electronics.

We can use quadruple pixel readout of the BCAM to reduce the amount of time the image spends in the transfer array. This intensifies both light per pixel and image area dark current. However, since transfer area dark current is the dominant term, this increases our radiation tolerance. To account for this, we reduce image area exposure to 2.5 ms to account for the increase in light intensity per pixel. In our existing quadruple-speed pixel readout, image area dark current in low-gain (40%) images is measured at .538 counts/(Tn*ms). Transfer area dark current is measured at .088 counts/row.

If we encounter technical problems with quadruple speed readout after neutron damage, we have the capability to readout half the image at a time, and splicing multiple images together. This will complicate our readout procedure and require changes to existing software, but will not affect the design of Bar Head or BCAM electronics. For example, by reducing the time spent in the transfer array from 180 ms to 90 ms, we can increase our safety factor at 20ºC from 3.5 to 6.

References

[1] Edgar et al., *New Small Wheel Radiation and Magnetic Field Environment.* 15-Jan-2015.

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

[3] Hashemi et al., *Radiation Tolerance of End Cap Alignment Electronics*, Talk at Harvard University 27-Jan-2003.