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Irradiation Tests of Optoelectronic Components for Atlas SCT Readout.

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Abstract

Two kinds of optical-link technologies have been investigated by the Atlas-SCT collaboration for data readout; one based on LEDs and the other on MQW-Modulators. Presented in this note are the results of irradiating LEDs and MQW-Modulators with neutrons and protons. The devices were biased and the performances of the optical links were monitored throughout the tests. The fluences achieved were $\sim 5 \times 10^{14}$ n cm^{-2} (1MeV-equivalent) and $\sim 6 \times 10^{13}$ p cm^{-2} (24GeV).

1 Introduction

Two kinds of optical-links have been investigated in detail by Atlas-SCT groups for transferring data from the detector front-end to the counting room. One is based on the direct modulation of LEDs [1] and the other is based on the use of Multi-Quantum-Well Modulators (MQWs) [2]. Simple schematic diagrams for these two systems are shown in Figure 1.

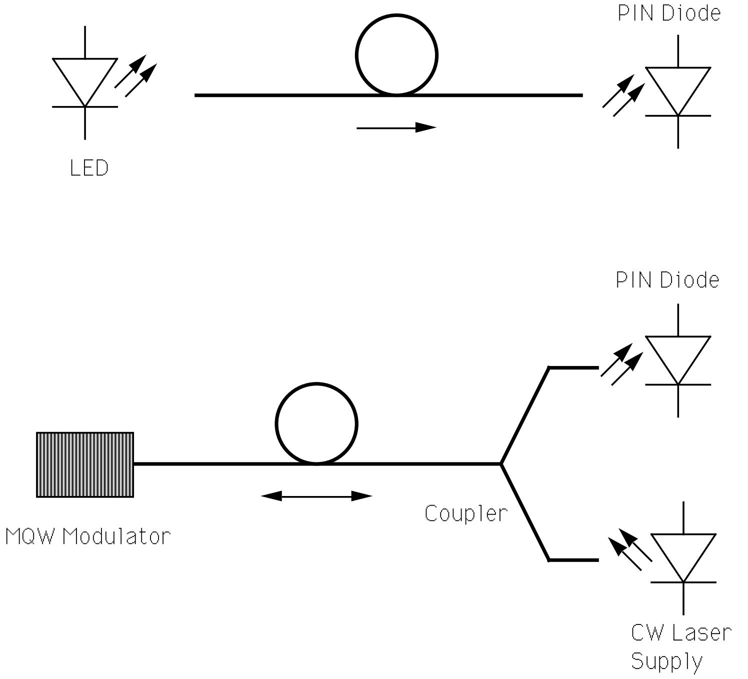

Figure 1: *Schematic diagrams of LED and MQW based optical links.*

The LED based system comprises an LED at the detector front-end and a PIN diode in the counting room, interconnected by multi-mode fibre. Electrical signals from the front-end are used to modulate the light output of the LED and are recovered via the PIN diode. The motivation for pursuing an LED based system is that the technology is considered a mature one, allowing a degree of confidence in the predictions of cost and performance.

The MQW-Modulator based system has been investigated by the RD23 collaboration [3] and comprises an MQW, laser diode, PIN diode and an optical coupler, all interconnected by single-mode fibre. The modulator is a passive electro-optical device that has the characteristic that the amount of light it transmits (or reflects) is dependent on the applied voltage. Light from a laser source ($\lambda = 1550$nm) is reflected from the MQW to the PIN diode via the optical coupler. The reflected light is intensity modulated by front-end signals applied to the MQW. The motivation for developing this technology is the passive nature of the MQW, which results in very little power dissipation together with high expectations for levels of radiation resistance and reliability. It is a new technology, however, requiring much research and development and collaboration with industry.

Crucial to the use of any electronic components in LHC inner-detector regions is an understanding of their performance after irradiation with neutral and charged hadrons and gammas. In the ATLAS SCT, for example, the predicted maximum fluences over a 10 year operational life are $\sim 10^{14}$ neutrons cm^{-2} and $\sim 10^{14}$ charged-hadrons cm^{-2}. The predicted maximum gamma dose is $\sim$ 15 Mrad. The radiation environment for the PIXEL detector is even more hostile.

Presented in this note are the results of irradiating LEDs and MQW-Modulators with neutrons and protons. In both cases, the devices were biased and the link performances monitored. In Section 2, the neutron and proton irradiation facilities are described. Section 3 and Section 4 discuss in detail the irradiation of LEDs and MQWs respectively, and the results obtained. Section 5 summarises these results and Section 6 gives some discussion on future plans.

2 Facilities

The University of Birmingham Dynamitron was used for the neutron tests. Neutrons are extracted via the reaction ^{9}Be(d,n)^{10}B, that is, the stripping of deuterons on a thick Beryllium target. The Dynamitron is a variable energy potential drop machine capable of terminal potentials up to 3MV, and is powered by a radio-frequency oscillator operating at about 130kHz. For the irradiation tests, a deuteron beam energy of 2.6MeV and a current of 200μA was used. This gives a neutron energy centred at around 1MeV with a spread of approximately 2MeV, and a yield of $\sim 10^{11}$n sr^{-1}s^{-1}.

The proton irradiation studies used the CERN PS, in the East Hall. The proton energy is 24GeV and fluences of 10^{14} p cm^{-2} day^{-1} are easily obtainable. (Typically there are bunches of $\sim 10^{11}$ protons every 14 seconds; the spread is dependent on the beam optics but an area 1cm × 1cm is achievable). In these irradiation tests the devices under test were mounted on an x-y stage (designed for the irradiation of silicon detectors) which scans an area of 6cm × 6cm transverse to the beam direction. Consequently, expected fluences are of the order of 10^{13} p cm^{-2} day^{-1}.

2.1 Dosimetry

Activation foils were used to measure the total neutron or proton fluences. Measuring the gamma activity of the foils after irradiation allows the flux to be determined. For the neutron tests, Indium foils were cut to sizes corresponding to the components to be irradiated and positioned nearby. The reaction ^{115}In(n,n$'$)^{115m}In, with its low threshold of 0.339MeV and its product with a 4.486 hour half-life and 0.459 gamma rays per metastable decay was suitable for these tests. After irradiation, the foils were placed in a high precision Germanium detector (cooled to 77K) and the gamma activity measured.

For the proton tests, Aluminium foils were used for an initial calibration run. The fluences obtained, via the reaction ^{27}Al(p,3pn)^{24}Na (producing a 1.368MeV gamma with a $\sim$ 15 hour half-life), were used to calibrate a Secondary Emission Counter. The activity of the Aluminium foils was measured in the same way as for the Indium foils.

3 Irradiation of LEDs

The LEDs irradiated in these tests are manufactured by ABB HAFO [4] (based on a GaAlAs structure), emitting light at a wavelength of 820nm. The devices are micro-packaged with the light-output coupled into 50μm-core radiation hard multi-mode fibre. Typical rise and fall times are $\sim$ 4ns. All the LEDs had been irradiated previously with 1.4×10^{14} neutrons cm^{-2} at the ISIS facility (DRAL-UK). Although degradation of light-output was observed as a result of these irradiations [5], all the devices recovered (within experimental errors) to their original values after applying high (post-test) drive currents. This recovery of the LEDs under forward bias (injection annealing) is thought to be related to recombinations at the radiation induced defect sites [6].

Throughout the Dynamitron and PS irradiation tests, the LEDs were driven with a current of 20mA. At regular intervals, however, the light power output was measured as a function of drive current (in 5mA steps up to 50mA).

3.1 Neutron irradiation of LEDs

Three LEDs were available for irradiating with neutrons. The devices were positioned, close together, $\sim$ 2cm below the Beryllium target. The Indium foils for the dosimetry were placed on top of the LEDs. Measurements were taken (of light-output versus drive current) starting one week prior to the irradiations in order to obtain an estimate of the experimental uncertainties associated with the tests. The Dynamitron was operational for twelve hours during the day and switched off at night. The irradiations were done over two days, resulting in four runs each of approximately five hours duration. Measurements continued for five days after the irradiation to investigate the annealing phenomenon. The ambient temperature in the irradiation zone was 14 ± 1 °C.

Figure 2 shows the light output power versus the drive current for one of the LEDs, before and after irradiation.

Figure 3 shows the light-output powers (at 20mA) versus time relative to the pre-irradiation averages for the three LEDs. The neutron irradiation started on the seventh day and finished at the end of the eighth, as shown in Figure 4. All the devices received fluences greater than 5×10^{14} n cm^{-2}. However, because the LEDs were positioned relatively close to the Beryllium target where the neutron flux is inhomogeneous, each LED received a different fluence.

A definite degradation of all three LED light-outputs can be seen during the irradiation period. The worst case was LED 2 which fell to less than 20% of its original value. At the end of the seventh day, after one day of irradiation, the light-output of all three LEDs recovered slightly from their degraded values, until the irradiation resumed (as indicated by the peaks). These increases, ascribed to the LEDs annealing, correspond to the shutdown of the Dynamitron for the night (and hence no neutron irradiation). The same kind of recovery is observed immediately after the final irradiation period.

On completion of the tests the experimental set-up was dismantled and removed to another experimental area. After reconnection, an increase in light-output of $\sim$ 10% was seen on all three LEDs. The reason for this increase is not clear but is probably due to the cleaning of optical connectors during reassembly of the experimental set-up. Higher drive

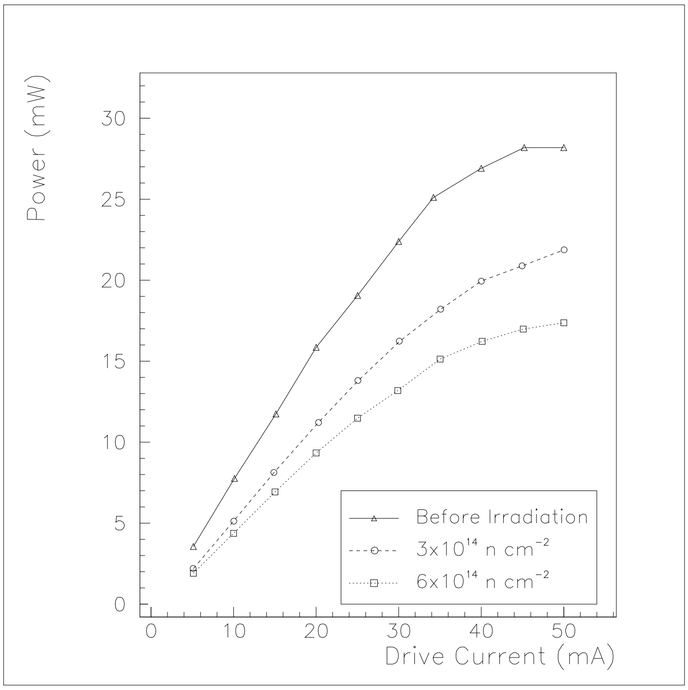

Figure 2: *Power output versus drive current for a typical LED, after two neutron fluences.*

currents were then applied to the LEDs to look for signs of full annealing, (not shown on Figure 3). At 50mA, LED 2 very quickly recovered to its pre-irradiated value but the other two remained at their degraded values. The drive currents were subsequently increased to 100mA upon which LED 3 quickly showed a full recovery. LED 1 showed a slow recovery to about 85% of its original value. However, it should be noted that there is a 10% uncertainty on these measurements due to the removal of the experimental set-up to a different location.

3.2 Proton irradiation of LEDs

A further three ABB HAFO LEDs were irradiated using the CERN PS facility. They were mounted on a board that was attached to the scanning x-y stage (see Section 2), and positioned so that the LEDs were in the centre of the 6cm × 6cm irradiation area. Measurements were taken starting one week prior to the irradiations in order to obtain an estimate of the experimental uncertainties. The irradiation lasted for six days but measurements continued for a further five days. The ambient temperature in the PS irradiation zone was 27 ± 1 °C.

Figure 5 shows the relative light-output power of two of the LEDs (biased at 20mA) with time . Unfortunately a fibre-break during installation meant that only two of the LEDs could be monitored online. Degradation of both LEDs can be seen starting on the seventh day, corresponding to the beginning of the proton irradiation. After six days of irradiation, both LEDs have degraded to approximately 65% of their original values. No sign of annealing is seen in the post-irradiation period. Unfortunately any further study of annealing (eg by increasing drive currents) was not possible due to time constraints. Figure 6 illustrates the proton fluence during these tests.

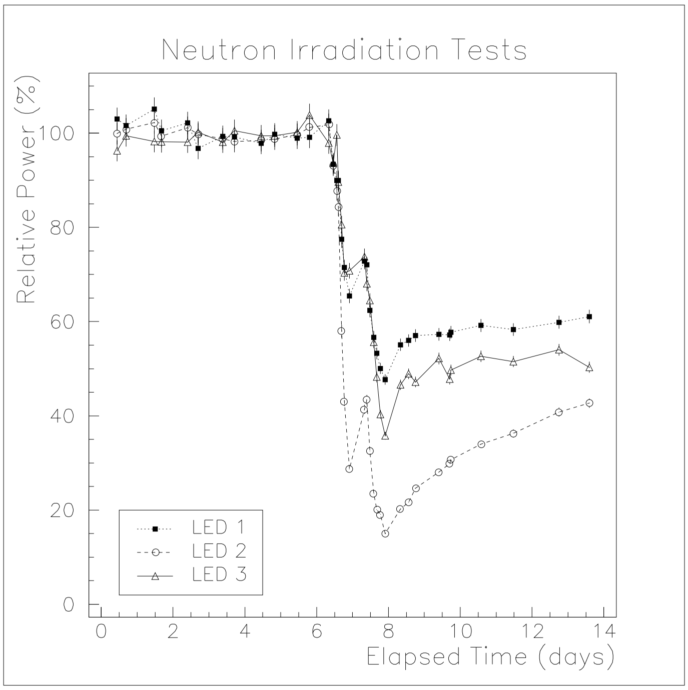

Figure 3: *Relative light power versus time for the three LEDs irradiated with neutrons.*

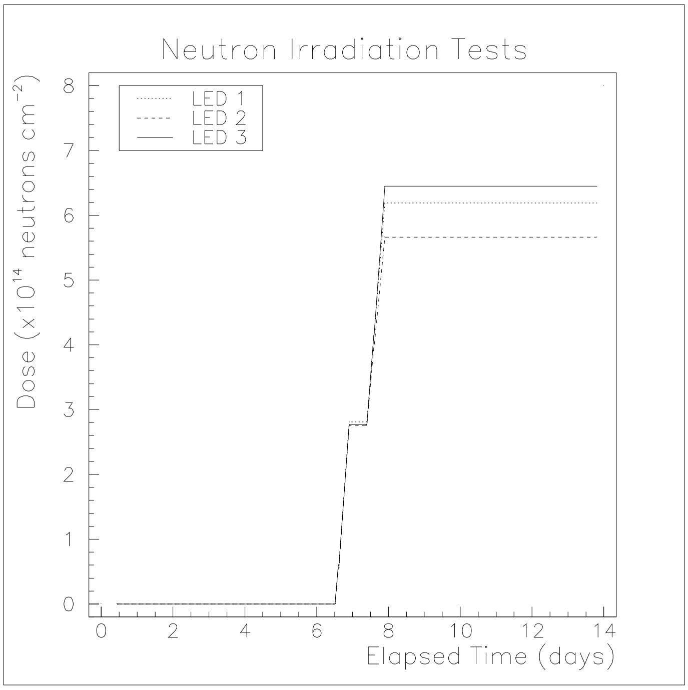

Figure 4: *Neutron fluences for the three irradiated LEDs; the measurement uncertainty is* $\sim$ *20%.*

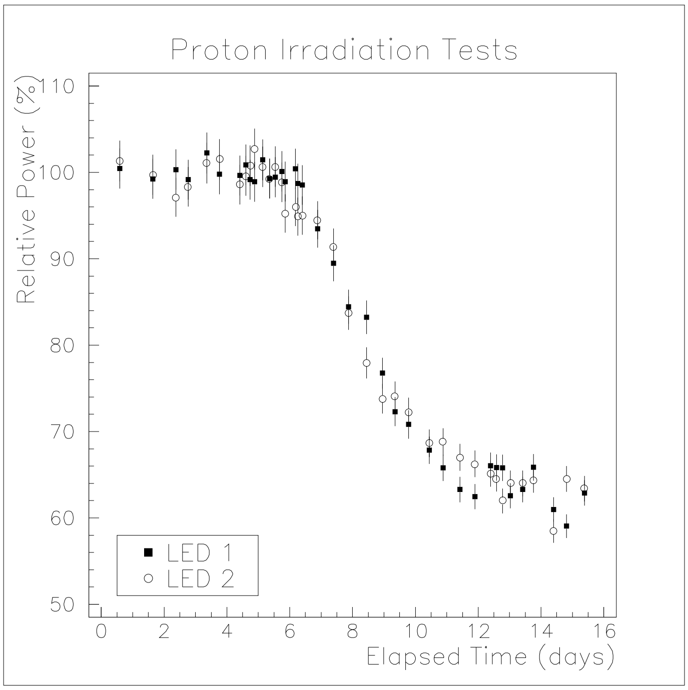

Figure 5: *Relative light power versus time for the two LEDs irradiated with protons.*

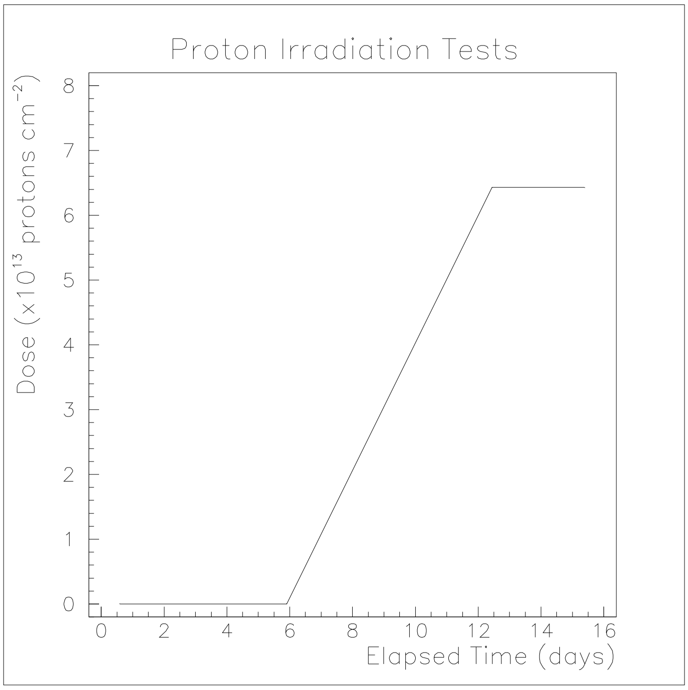

Figure 6: *Proton fluences for the two irradiated LEDs; the measurement uncertainty is* $\sim$ *20%.*

4 Irradiation of MQW-Modulators

The devices tested were 4 channel (phase 2 type) MQW modulators manufactured by GEC Marconi Materials Technology [5]. The RD23 philosophy for the MQW based optical link is to operate some of channels on a device to readout the front-end data while using the remaining channels to receive the clock and control data required by the front-end chips. Three properties have been measured to assess the performance of the link:

- For the readout of data the important property is the link gain, defined as voltage output from the link divided by the voltage input applied to the MQW. This property along with the noise of the link defines the signal to noise ratio for the transmitted data[1].

  In ATLAS readout operation a 40MHz data signal will provide the modulating voltage. For these tests only DC biases were applied to the MQWs. This avoided the problems associated with sending AC electrical signals over long distances to the irradiation area (where electrical equipment could not be used). However, a time varying light signal is required at the receiver PIN diode because the amplifiers are AC coupled. To achieve this the laser source was modulated.

  Measurements were made of the amplitude of the time varying PIN diode signal as the DC bias voltage to the MQW was varied in steps from -7V to -15V. A third order polynomial is fitted to the data and the gradient at the inflection point found. The gradient is defined as the link response. The time varying signal at the PIN diode is proportional to the modulation amplitude of the laser source and the reflectance of the MQW. The link response is therefore proportional to the link gain. The factor of proportionality could not be measured as the signal before reflection from the modulator saturated the amplifier.

- The photo-current is the current due to light incident on the MQW, and is a good indicator of the opto-absorption of the device. It is determined by measuring the voltage across a known resistance, in series with the MQW, at a particular incident light power. By varying the reverse bias voltage in steps from -7V to -15V, the photo-current gradient can be determined in the same way as for the link response.

  The photo-current gradient is proportional to the link gain, because the opto-absorption determines the amplitude of the reflected signal at the PIN diode. However, the photo-current should be a better guide to changes in MQW chip behaviour, mainly because it does not include uncertainties due to the receiver electronics.

- An important property of the MQW when used as a photo-diode is its dark current, which determines the noise of the receiver electronics. The dark current is the current when there is no light incident on the MQW. It was determined by measuring the voltage across a known resistance, with the MQW biased at -10V.

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[1] The link has been primarily developed for the readout of analogue data.

4.1 Neutron irradiation of MQWs

The experimental set-up allowed four modulator channels to be measured. Two packages were irradiated, with two channels from each being monitored. The devices were positioned side by side and $\sim$ 2cm below the Beryllium target. The Dynamitron was operated in the same way as in the LED tests (Section 3.1). Measurements were taken starting a few days before the irradiation to check the stability of the set-up, during the irradiation, and for a few weeks after to look for any recovery of the devices. The neutron fluence received by each MQW is shown in Figure 7d.

The link response for each channel is plotted in Figure 7a. Decreases in link response of $\sim$ 20% can be seen for channels 3 and 4, corresponding to irradiation fluences of $\sim 3.3 \times 10^{14}$ and 6.5×10^{14} n cm^{-2} respectively. Channel 1, however, exhibits no obvious radiation induced degradation (within the experimental uncertainty of $\sim$ 10%). Results are not shown for channel 2 because it was disconnected a number of times to allow monitoring of the light power in the system. This remained constant to within the measurement capabilities of the optical power meter (0.1dBm).

The photo-current gradients are shown in figure 7b. The negative values indicate the increase in photo-currents as the bias becomes more negative. Again only three channels are plotted. Clear degradations can be seen for all three channels of $\sim$ 10%.

The dark current for all four channels is shown in figure 7c. They all increase dramatically during the irradiation period (from several nA to $\sim 1\mu$A). The two channels of S/N 17 exhibit a larger increase in dark current corresponding to the higher received neutron fluence.

4.2 Proton irradiation of MQWs

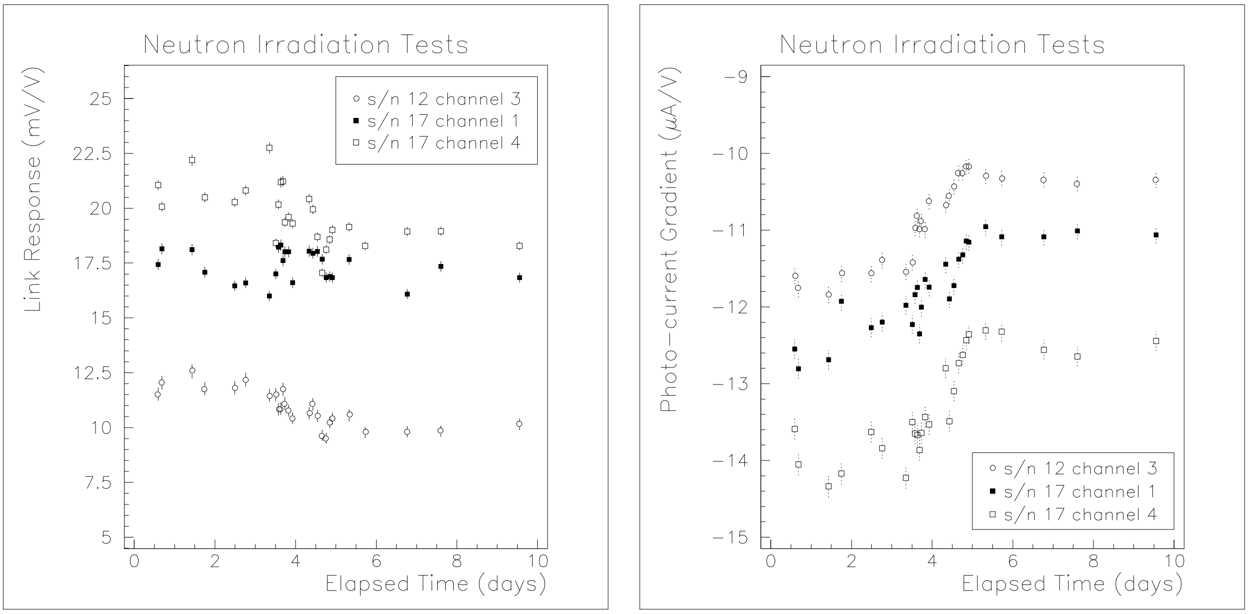
The same experimental setup was transferred to the CERN PS; the same four channels were irradiated and monitored.

The link response is shown in Figure 8a. The measurements taken prior to the irradiation show a spread in their values of typically $\sim$ 5%. This is an estimate of the stability of the link, for the set-up used in these tests. Degradations are observed on all channels as a result of irradiating with $\sim 6.4 \times 10^{13}$ p cm^{-2}. The size of the degradation in the worst case is $\sim$ 30%.

The photo-current gradients are shown in Figure 8b. The two channels of S/N 17 exhibit large degradations that are continuous throughout the test period, although there is no obvious correlation with the irradiation plot of Figure 8d. In the worst case of channel 1 the degradation is $\sim$ 20%. For S/N 12, it is not clear that any degradation has occured within the uncertainties associated with the stability of the link.

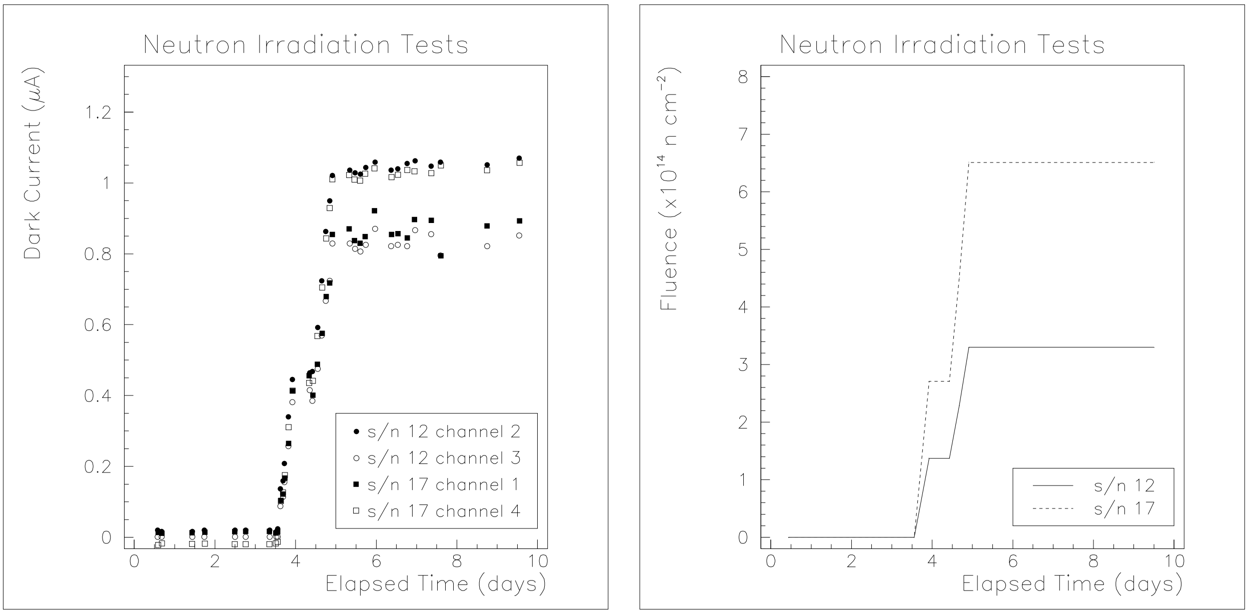
The dark currents for the four channels are shown in Figure 8c and also exhibit different responses for the two different modulators. For device S/N 17 the dark currents are steady during the pre-irradiation period (but at a higher level than at the end of the Dynamitron (neutron) tests due to the higher ambient temperature (27 ± 1°C cf 15 ± 2°C)). An increase in dark currents correlated to the proton irradiation period is observed, from 2μA to 3μA.

The two channels of device S/N 12, however,show a dramatic increase in dark cur-



(a) Link response at inflection point.

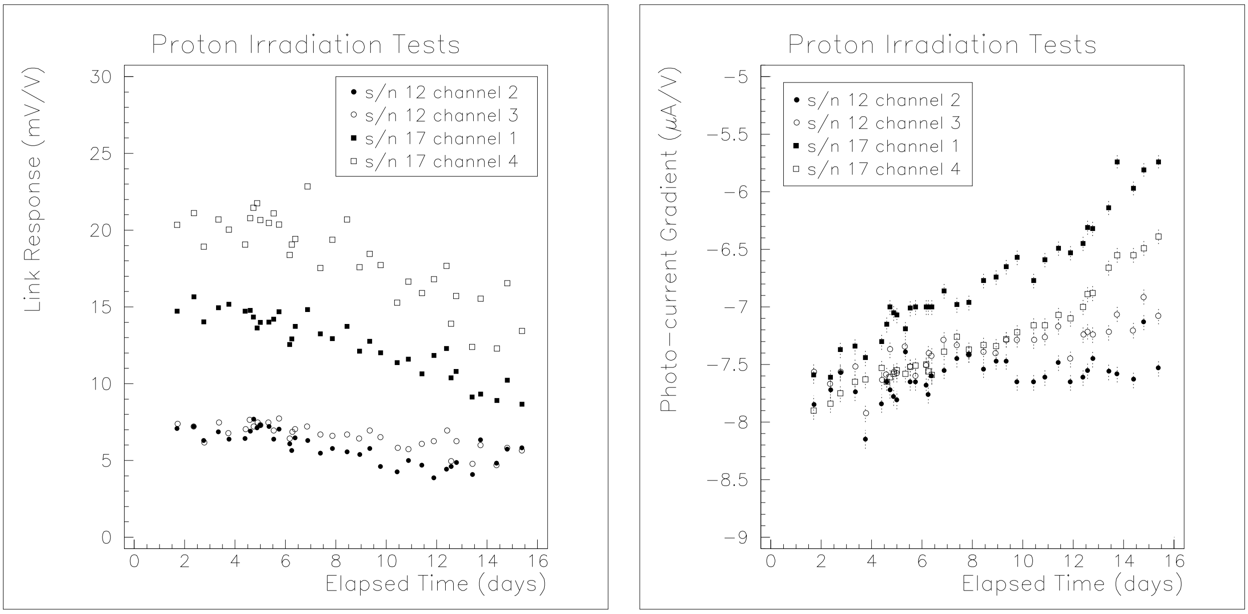
(b) Photo-current gradient at inflection point.



(c) Dark current at -10V.

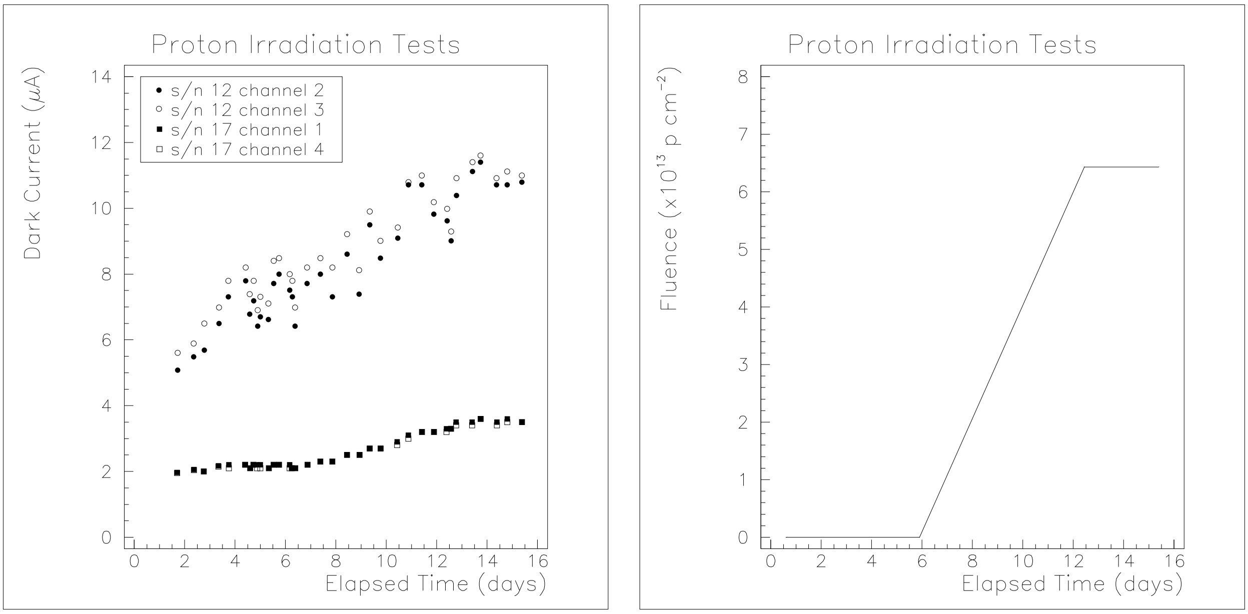
(d) Neutron fluences for the two MQW packages; the measurement uncertainty is $\sim 50\%$.

Figure 7: *Neutron irradiation test results.*



(a) Link response at inflection point.

(b) Photo-current gradient at inflection point.



(c) Dark current at -10V.

(d) Proton fluence for the two MQW packages; the measurement uncertainty is ∼ 20%.

Figure 8: *Proton irradiation test results.*

rents compared to the values measured at the end of the neutron tests. Throughout the proton tests they continued to increase steadily. When measuring the dark currents a time dependence was observed after switching off the light incident on the MQW. This is the reason for the larger statistical spread in the measured values. The cause has not been established, but is thought to be due to passivation problems at the modulator mesa [8].

5 Summary

ABB HAFO LEDs have been irradiated with $\sim 6 \times 10^{14}$ n cm^{-2} and $\sim 6 \times 10^{13}$ p cm^{-2}, while biased at 20mA. A significant decrease in optical power is observed for all the tested LEDs. In the worst case, a LED degradation of $\sim 80\%$ is seen during irradiation with neutrons. This would normally imply that the LED drive currents would have to be increased throughout the operational lifetime of the LHC[2]. However, all the LEDs irradiated with neutrons have exhibited near full recovery as a result of applying higher drive currents (not once but twice). A solution is therefore to design the LED drivers so that they can provide the necessary annealing currents. It should also be noted that the operational lifetime of the LHC is ~ 10 years hence the dose rates will be much lower. The degradations of the LEDs are therefore expected to be smaller than those observed in the irradiation tests, due to continual annealing throughout the LHC lifetime. The annealing of LEDs, and the effects on reliability, has been investigated by other ATLAS-SCT groups [5]. Unfortunately, annealing studies were not possible after irradiating the LEDs with protons. This is to be investigated in future studies.

MQW-Modulators have been irradiated with $\sim 5 \times 10^{14}$ n cm^{-2}, followed by $\sim 6 \times 10^{13}$ p cm^{-2}. Deteriorations of the link gains, due to the neutron irradiation, are less than $\sim 20\%$ for all the channels measured. The corresponding deteriorations in the photo-current gradients are less than $\sim 10\%$. For the proton irradiation, deteriorations of up to $\sim 30\%$ and $\sim 20\%$ are measured in the link gain and photo-current gradient respectively. The lower proton fluence, compared to the neutron fluence, suggests that the 24GeV protons are more damaging than 1MeV-equivalent neutrons.

Dramatic increases in dark currents are observed, on all channels, during both irradiation tests. All the channels exhibited stable behaviour for the neutron tests, but during the interval before the proton tests the channels on one of the MQWs showed a large increase in dark currents and became less stable. This is believed to be due to problems with the passivation of the device.

The results obtained for the MQW in these irradiation tests suggest that a performance margin of up to $\sim 50\%$ may be required at the start of LHC operation, to ensure acceptable data readout throughout the LHC lifetime. Test-beam results [9] indicate that the MQW based link is satisfactory for transmitting analogue data before irradiation damage. One can conclude that even after irradiation damage it will be acceptable for the transmission of binary data and, with adequate care, suitable also for analogue transmission.

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[2] Tests have shown that an optical power of at least 10μW at the PIN diode will be required to give a bit error rate of less than 10^{-9}, thus eliminating the need for error correction schemes.

6 Future

The Birmingham group intends to continue its studies on the performance of irradiated electro-optical components. In particular, a package designed for use in the data transfer of the ATLAS-SCT (manufactured by GEC Marconi Materials Technology) will be investigated. The package contains two LEDs, for the transmission of the binary front-end data, as well as one PIN diode, for the reception of timing and control signals[3]. Emphasis will be placed on investigating the properties of the PIN diode to test the predictions of the manufacturers.

Atlas Inner Detector groups are also looking at Vertical Cavity Surface Emitting Laser diodes (VCSEL) arrays for the readout of data. These devices are interesting for several reasons. Most importantly, perhaps, is a large potential cost saving over the LED based link (the adopted ATLAS baseline link) and MQW based links. VCSELs also appear to be very radiation hard and due to a high power output at only 1mA drive current, may not even require drivers. However, VCSEL arrays are not presently available in suitably packaged forms and have not been adequately tested to prove that the reliability required for ATLAS operation can be achieved.

ATLAS ID groups currently involved in optical link research and development are Bern, Birmingham, CERN, Geneva and Oxford.

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[3] Although ABB HAFO LEDs have shown that they could be used in a high radiation environment, the combined LED/PIN packaging is more suitable for the requirements of the ATLAS-SCT.

7 References

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