

Neutron and Gamma Irradiation Studies of Candidate Components for LArg Front-end Optical Links

Johan Lundquist, Mark Pearce

*KTH Physics Department Frescati
Frescativägen 24, 10405 Stockholm, Sweden*

Marie-Laure Andrieux, Adrien Patti

*Institut des Sciences Nucléaires,
53 Avenue des Matyrs, 38026 Grenoble, France*

Bernard Dinkespiler, Olivier Martin

*Centre de Physique des Particules de Marseille,
163 Avenue de Luminy, Case 907, 13288 Marseille, France*

Abstract

In this note neutron and gamma irradiations of candidate components for the front-end data links of the ATLAS liquid argon calorimeter (LArg) are described. Three components were tested : VCSEL laser diodes, manufactured by Honeywell (HFE4080) and Mitel (1A440); gigabit serialiser chips (HDMP-1012 - 'G-Link'), manufactured by Hewlett Packard; and, a 10 m length of graded-index multimode 8-way fibre-ribbon, manufactured by Acome. All of the components were tested in isolation.

During the irradiations, the VCSEL's were biased above threshold with a steady DC current. The light output was monitored as a function of bias current at regular intervals during the irradiations. The fibres were coupled to 850 nm laser sources and the attenuation in the fibres was measured during the irradiation. Some annealing studies were also performed for these components. The phase locked loop functionality of the G-Link chips was tested through-out the irradiations.

This note is available as a PostScript file from :
<http://atlasinfo.cern.ch/Atlas/GROUPS/notes.html>

1 Introduction

The baseline read-out solution [1] for the liquid argon (LArg) calorimeter specifies that approximately 1620 Gigabit/s (Gb/s) fibre-optic links will be used to transfer data from front-end electronics boards mounted on-detector to read-out drivers situated approximately 70 m away^a. The unidirectional links have emitters on the front-end boards and receivers in the read-out drivers. The front-end boards are grouped into crates attached to the cryostat flange, situated in the crack between the barrel and endcap calorimeters. The components at the emitting end of the link will be exposed to high levels of both neutron and ionizing (gamma) radiation. It is essential that the behaviour of these components is well understood under such conditions as access is severely limited once the endcap is rolled into place and therefore repairs will require a lengthy intervention. Integrated over 10 years of LHC running (and assuming a machine luminosity of 10^{34} cm² s⁻¹), the expected doses are : 800 Gy, ionizing; and 1.7×10^{13} n cm⁻² 1 MeV (equivalent in silicon) neutrons [2]. Note that these values incorporate safety factors of 4 (ionising) and 3 (neutrons), as advised in the reference^b. The receiving part of the link, located off-detector, is not exposed to significant levels of radiation. Candidate optical link components were exposed to levels of neutron and gamma radiation compatible with 10 years of LHC running. The neutron and gamma doses were administered at separate facilities. During the irradiations, electrical components were biased and monitored although Gb/s data-flows were not present. Some studies were performed of the recovery ('annealing') of damaged components after the irradiation period.

The final architecture of the front-end link is still under consideration but VCSEL (Vertical Cavity Surface Emitting Laser) laser diodes are a strong candidate for use at the emitting end of the link. VCSEL's have a number of desirable properties such as high output power (1 mW at 10 mA bias, typically), low threshold currents (typically, a few mA), compatibility with Gb/s data rates, easy and efficient coupling to multimode fibres and low cost. Moreover, it is generally accepted that VCSEL's offer superior radiation tolerance compared to light emitting diodes (LED's), mainly due to the smaller junction size. This has been illustrated by several VCSEL irradiation studies performed by groups involved in the LArg [3] and SCT [4] projects. It should be noted that in all of these studies, prototype (and unpackaged in the case of [4]) components were used. All of the VCSEL studies detailed in this note use 'off the shelf' packaged single element VCSEL's from Honeywell [5] and Mitel [6]. In both cases, the VCSEL's were equipped with optical fibres with industry standard ST connectors and monitored through-out the irradiations.

Another key component of the emitting end of a link is the serialiser, which takes data words and converts them into a serial stream of bits which can be fed into a VCSEL, for example. If a serial link architecture is adopted for the read-out of the LArg calorimeter, then the 'G-Link' chip-set from Hewlett Packard [7] is a promising serialiser candidate. Four such chips were irradiated. Note that the chips were tested in isolation from the VCSEL's with purely electrical connections.

^aThis distance will be more like 200 m if the read-out drivers are positioned in the control room rather than the level-1 cavern.

^bFor bipolar electronics, additional safety factors of 5 (ionising) and 1.5 (neutron) are advised to take into account the uncertainty on the electronics behaviour due to low dose rate effects.

An 8-way graded-index multimode fibre-ribbon supplied by Acome [8] was also irradiated. This product was previously selected to evaluate a demonstrator analogue optical link project [9] and was not expected to be radiation tolerant but still provides useful information about the radiation resistance of standard germanium doped multimode fibres.

This note is organised as follows. The next section introduces the components that were tested in more detail. Section 3 briefly describes the irradiation facilities. An overview of the experimental set-ups and procedures is given in section 4 and this is followed in section 5 with details of the total doses and the dose rate received by each component under test. Results are described in section 6 and there is a summary and discussion in section 7.

2 Components Tested

2.1 VCSEL's

Nine Honeywell HFE4080-321 VCSEL's and nine Mitel 1A440 VCSEL's were irradiated with neutrons. For technical reasons, only eight of each type were irradiated with gammas. All the VCSEL's were housed in TO-46 style packages. The Honeywell VCSEL's were equipped with a plastic lens to enable efficient coupling into an optical fibre. The Mitel VCSEL's had a flat window in place of a lens. The TO-46 package was mounted inside a metal ST package to allow easy connection to optical fibres. The emission wavelength of the VCSEL's is 850 nm. The active VCSEL chip is approximately cubic, with sides of approximate length 500 μm .

2.2 G-Link Chips

Four Hewlett Packard 'G-Link' transmitter (HDMP-1012) chips were irradiated with neutrons and gammas. Each chip was mounted on an evaluation board with some resistors and decoupling/filtering capacitors. The chips were of the ECL type and came from a 1995 batch.

When configured for use in the LArg read-out scheme, a 2×16 bit (multiplexed) parallel data stream plus a clock is fed to the input of the chip. Four control bits are added and the parallel data stream is transformed into a serial one with a frequency 40 times the input frequency^c. Encoding takes place such that the data and high frequency clock are merged into a single composite signal.

This high frequency synthesis is performed with a phase locked loop (PLL). The operation of the PLL is described more fully in appendix A.

2.3 Multimode Fibre-ribbon

A ten metre length of graded-index multimode 'Oslo' fibre-ribbon provided by Acome was irradiated with neutrons and gammas. The ribbon consisted of eight germanium-doped silica core fibres (each of diameter 50 μm) with an epoxy-acrylate primary coating (of diameter 125 μm). The fibres were encapsulated into a ribbon with polymerisable

^cIn the so-called 'double-frame' mode.

acrylate-urethane resin. The ribbon was supplied with a PVC outer sheathing with Kevlar strands wrapped around the ribbon to provide mechanical strength.

3 The Irradiation Facilities

The components described above were first irradiated with neutrons at one facility and then with gammas at another facility. In this section each facility is described in some detail.

3.1 Neutron Irradiation

Only a brief description of the neutron facility installed at SARA [10] (ISN, Grenoble) is given here. A more detailed description can be found elsewhere [11]. A beryllium target, 3.5 cm in diameter, is located at the end of one of the SARA beam lines. It is bombarded with a $5 \mu\text{A}$ beam of 20 MeV deuterons. A high neutron flux is produced via a stripping reaction. The mean neutron energy is 6 MeV. The gamma contamination after $2 \times 10^{14} \text{ n cm}^{-2}$, measured at the target, is 3.6 kGy [11]. Since the gammas come from nuclear interactions in the target, their energy spectrum is rather broad. The components under test were placed 30 cm after the beryllium target, behind the rear wall of a 10 l liquid argon cryostat^d. The neutron beam has a diameter of approximately 8 cm at this position and is attenuated by a factor of around two due to the presence of the cryostat. A data acquisition system was installed on the roof of the facility. In a typical 48 hour irradiation, objects placed behind the cryostat in this way receive a dose of $\mathcal{O}(10^{13}) \text{ n cm}^{-2}$.

3.2 Gamma Irradiation

The gamma irradiation was performed at Karolinska Hospital in Stockholm. An Alsyttron CGR ^{60}Co based treatment facility, normally used to treat cancer patients was made available over the weekend. As the source decays it emits two gamma rays at energies of 1.17 MeV and 1.33 MeV. The source is housed in a motorised arm that can rotate around a fixed table. Usually, the patient is positioned on the table and the source rotated to perform several short irradiation of the area under treatment. For the irradiations described in this note, the source was fixed at the ‘12 o’clock’ position to look down onto the table which held the test components. The top-most components were placed 30 cm from the aperture of the source. The components could be aligned with the source very accurately using a laser-sighting system and an illuminated ‘mask’ projected from the source housing. An on-line dose monitoring system was provided by a diode detector. A data acquisition system was positioned in an adjoining room. The cobalt source allows an area of approximately $20 \text{ cm} \times 20 \text{ cm}$ to be irradiated at a rate of around 1.3 Gy min^{-1} . The gamma intensity at the edge of this area is approximately 50 % of that in the centre. As the beam is well collimated the relative intensity drops to around 1 % at 1 cm from the edge.

^dMaterials are placed in the cryostat to test for radiation induced liquid argon pollution.

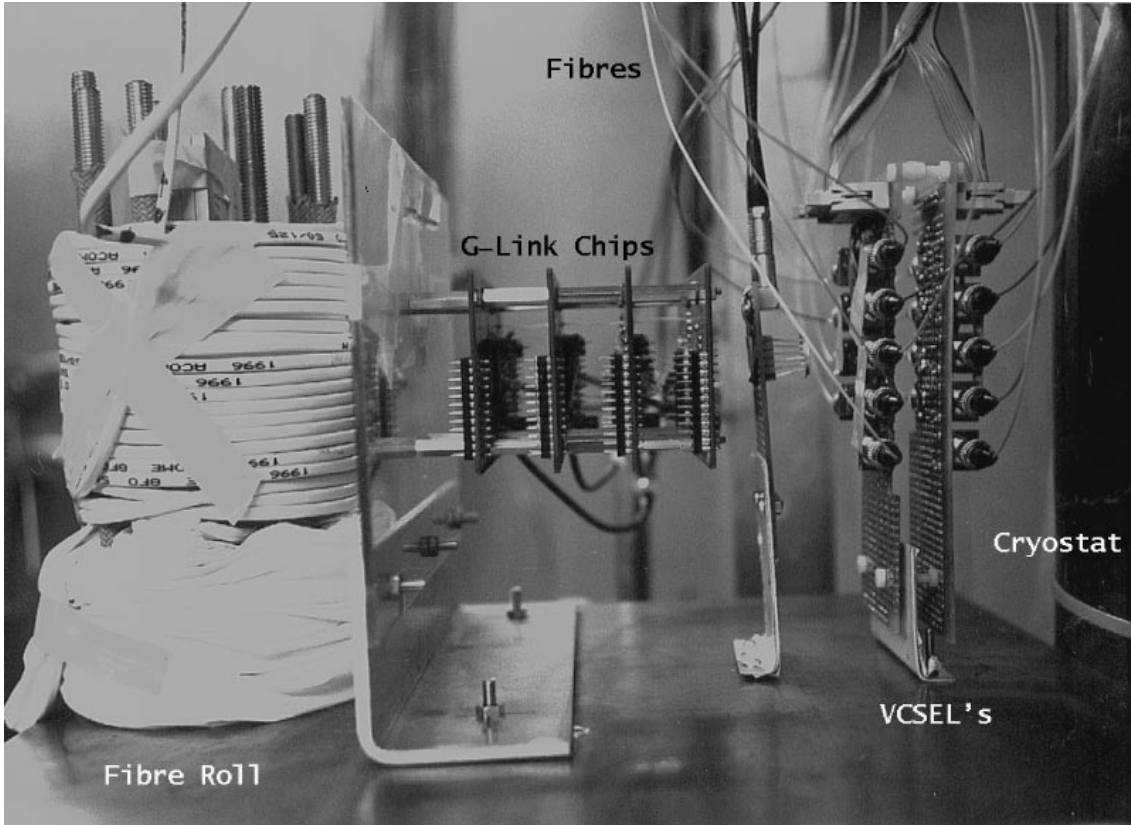


Figure 1: The layout of the components during the neutron irradiation. The unlabeled component mounted directly after the VCSEL's is a prototype VCSEL array from Honeywell. It is not discussed further in this note. The neutron beam arrives from the right, passing through the cryostat and is centred on the components under test.

4 Experimental Set-up and Procedure

The layout of the components during the neutron irradiation is shown in figure 1. Figure 2 shows the layout during the gamma irradiation. The neutron (gamma) irradiation took place more or less continuously over a 35 (70) hour period. In the neutron tests, there were a few short breaks to allow cryostat-based tests to be completed. The next sections describe the test procedures followed for each component in more detail.

4.1 VCSEL's

The VCSEL's were mounted on two FR4 motherboards, separated by 1.8 cm. The common centre of the motherboards was aligned with the nominal centre of the radiation beam. Each motherboard held nine VCSEL's arranged in lines separated by 3 cm according to manufacturer. The Honeywell VCSEL's will be referred to as H1–H9 and the Mitel VCSEL's as M1–M9. The distance between adjacent VCSEL's in a line was 1.5 cm. The lines of VCSEL's were staggered between motherboards to minimise the amount of material between a given VCSEL and the radiation beam. During the neutron irradiation, the front-most VCSEL board was mounted 4.5 cm from the cryostat rear wall. In the gamma irradiation the VCSEL boards were located 33 cm from the source aperture.

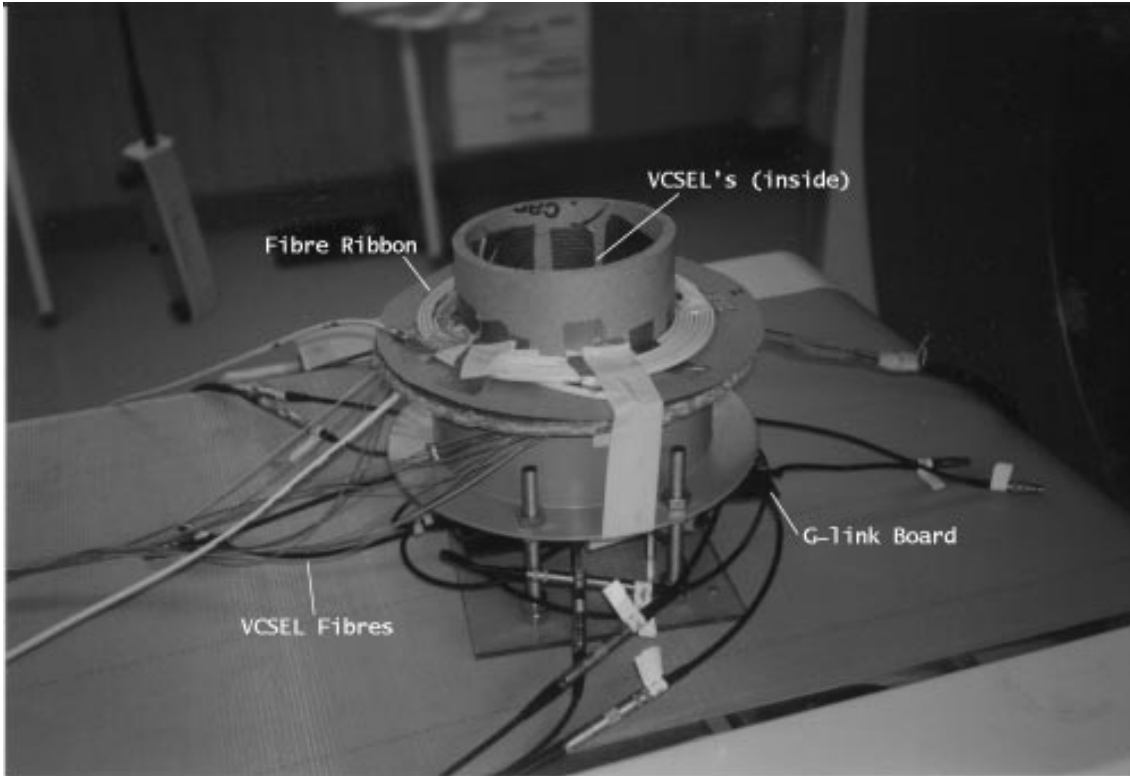


Figure 2: The layout of the components during the gamma irradiation. The gamma beam is centred on the components and arrives from the top. The VCSEL's are mounted on the same board as shown in figure 1 and are placed horizontally into the aperture indicated. The upper VCSEL board is at approximately the same height as the roll of fibre-ribbon.

Measurements were carried out to determine how the DC characteristics of the VCSEL's were affected by the radiation. A constant current source was connected through a demultiplexer (box of relays) to each VCSEL, the cathodes of which were connected to a common ground. Each VCSEL was connected via an ST connector to an optical fibre. The fibres were supplied by Acome^e in 8-way ribbons. In the counting rooms, the other ends of the fibre-ribbons were connected to PIN-diode arrays (via MT connectors^f) mounted in the receiver boxes described in [12]. The receiver box outputs were connected through a multiplexer to a 12 bit ADC mounted inside a PC. The current source, multiplexer, demultiplexer and ADC were under the control of the PC which ran LabView software to enable automated testing.

The fibres connected to the VCSEL's were routed away from the radiation beams by as shorter path as possible to minimise possible radiation-induced attenuation in the fibres. The design of the neutron irradiation chamber meant that the fibres had to be routed approximately 5 m in a cable tray mounted just under the ceiling (approximately 2 m off the floor and 1.5 m from the nominal centre of the neutron beam) until they could be fed into the tube connected to the counting room. In the gamma case the fibres could be run radially away from the beam. In both cases, the effect of radiation on the fibres is

^eSame type as the roll under test.

^fThe MT connector is an industry standard for fibre-ribbon connectors.

assumed to be negligible.

At the start of a data taking run, a VCSEL is selected and biased between 0–10 mA in 20 equally spaced steps. For each step, the current is applied for 1 s and the ADC read-out immediately before the next current step is chosen. Each ADC measurement is composed of 100 samples at 1 kHz. When not involved in this stepping, each VCSEL is connected to a constant bias current. The nominal bias values are 7 mA for H1–H5, 8 mA for H6–H9, 5 mA for M1–M5 and 6 mA for M6–M9. All these bias currents are above lasing thresholds for a particular brand of VCSEL. Note that two different bias currents were chosen within a particular VCSEL brand. This stepping procedure was initiated every half an hour during the gamma irradiation, but only every hour during the neutron irradiation due to a technical problem. The stepping procedure for all VCSEL's took approximately 10 minutes. After the radiation beams were stopped this procedure continued to check for possible annealing effects. After the neutron irradiation, the components were left *in-situ* for 84 hours during these tests. This was not possible after the gamma irradiation and the tests were resumed after a few hours for a period of 90 hours.

4.2 G-Link Chips

The four G-Link chips (2 cm × 1.4 cm) were mounted on separate evaluation boards. During the neutron irradiation, the four boards were stacked with a 2 cm spacing and the chip centres were aligned with the nominal centre of the neutron beam. The first chip was mounted 12 cm from the cryostat rear wall.

The profile of the gamma beam meant that it was best to split the boards into two pairs separated by 1.5 cm. The centres of the board-pairs were aligned with the centre of the gamma beam. The top-most board was mounted 37 cm from the source aperture.

The only function of the G-Link chips monitored during irradiation was the PLL. The input data word was kept constant through-out the test. The clock inputs of the G-Link chips were each supplied with a 5 MHz square wave signal of 50% duty cycle. The chips were configured to raise the input frequency by a factor of 40 ('double frame mode'). The 'PLL locked' outputs from the chips were connected to LED indicators. A schematic of the test set-up is shown in figure 3.

Two tests were carried out on each G-Link chip to check that the PLL was functioning as expected. The first test (possible during both types of irradiation) simply involved checking that the PLL locked indicator was set (absent) when the 5 MHz input signal was present (missing). In the second test (only possible during the neutron irradiation due to equipment availability), the spectrum of the output frequency given by the PLL was examined to check it was centred on 200 MHz. Also, the input frequency was moved by approximately 10 kHz either side of the central frequency and it was verified that the input and output tracked each-other. The amplitude of the output frequency spectrum was also monitored.

4.3 Fibre-ribbon

During the neutron tests, a 10 m length of the fibre-ribbon which was wound around eight support pins. The resulting roll had a diameter of 7.5 cm and a height of 10 cm. The centre of the roll was aligned with the nominal centre of the neutron beam. At 250 cm, the fibre roll was the furthest component from the rear wall of the cryostat.

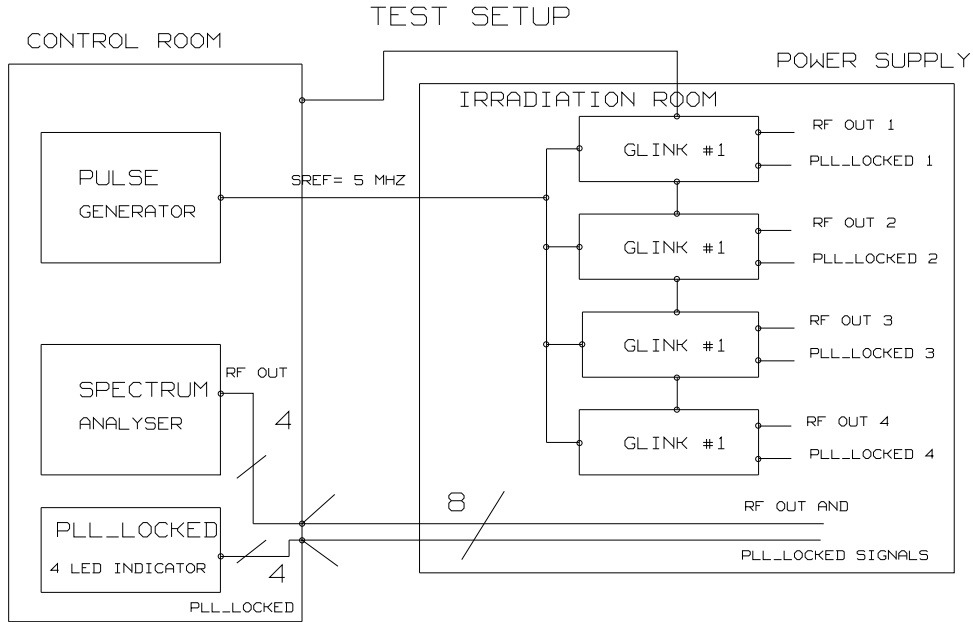


Figure 3: A schematic of the set-up used to test the G-Link chips.

For the gamma tests, the fibre was wrapped in two layers around a tube which formed the aperture for the VCSEL's - see figure 2. The inner diameter of the roll was 9.5 cm and the outer diameter 16.5 cm. The distance from the fibre to the source aperture was approximately 30 cm.

The fibre-ribbon roll was equipped with 8 ST connectors on one end and a single MT connector at the other. Both connectorised ends were located in the counting room with the ST end connected to VCSEL emitters and the MT end connected to a receiver box. The fibre-ribbon was tested by biasing the VCSEL's above the lasing threshold and measuring the received light power at the MT connected end with a receiver box [12]. Due to technical problems during the neutron irradiation, only two of the eight fibres were tested. A continuous light level of approximately 0.8 mW (0.4 mW) was launched into fibre F1 (F2) through-out the irradiation. Four fibres were tested during the gamma irradiation. Two of the fibres (1 and 2) had a continuous light level of approximately 0.9 mW and 0.5 mW, respectively launched into them through-out the irradiation. The VCSEL's connected to the other two fibres (3 and 4) were only biased during measurements. Approximately 0.7 mW was launched into these fibres.

5 Dose Calculations

5.1 Neutron Irradiation

The activation of nickel foils, placed on the components under test, was used to determine the absolute neutron fluence. The foils were circular with a diameter of 0.4 cm and a thickness of 125 μm . Neutron fluences can be measured with an accuracy of 15 % using an activation method based on the charge exchange reaction, $^{58}\text{Ni}(n,p)^{58}\text{Co}$. The ^{58}Co

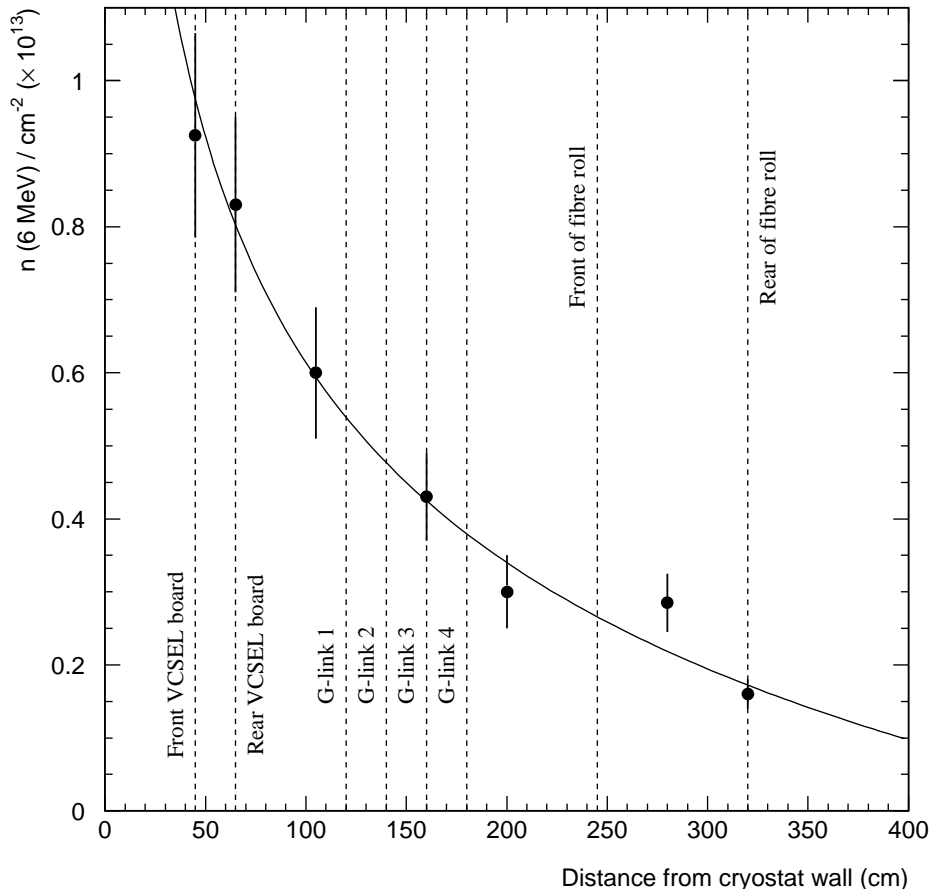


Figure 4: Neutron fluence deduced from the activation of nickel foils shown as a function of distance from the rear wall of the cryostat.

activities are measured using a calibrated germanium detector. The measured activities are converted to neutron fluences using the mean activation cross section of 377 mb for the SARA neutron spectrum at 0° . A more detailed description of the method is given in reference [11]. In figure 4 the results from the nickel foil analyses are shown. The calculated neutron fluence is plotted against the distance from the rear wall of the cryostat. The positions of the devices under test are clearly indicated. The results shown in this figure are for neutrons of mean energy 6 MeV, as produced from the target. To convert into 1 MeV neutron equivalent doses, the method described in [11] is followed. Conversion factors [11, 13] of 2.3 ± 0.3 , for GaAs (VCSEL's); 1.5 ± 0.2 , for Si (G-Link chips and fibres) are used. Strictly speaking the fibres are composed of SiO_2 , however, there appear to be no published conversion factors for this material^g. The corrected fluences are shown in table 1.

The maximum fluence delivered is therefore compatible with that expected after 10 years of LHC running. However, it should be noted that the peak dose rate delivered was much in excess of that expected at ATLAS. Bearing in mind that the LHC will only run for 6 months of the year, the expected ATLAS (1 MeV) neutron dose rate is

^gThe conversion factor of 1.3 ± 0.3 used in [3] is now known to be incorrect [14].

Device	Material	$n(1 \text{ MeV}) \text{ cm}^{-2} (\times 10^{13})$
Front VCSEL board	GaAs	2.25 ± 0.45
Rear VCSEL board	GaAs	1.84 ± 0.37
G-Link 1	Si	0.81 ± 0.16
G-Link 2	Si	0.72 ± 0.14
G-Link 3	Si	0.65 ± 0.13
G-Link 4	Si	0.57 ± 0.12
Front of fibre roll	'Si'	0.41 ± 0.08
Rear of fibre roll	'Si'	0.26 ± 0.08

Table 1: The neutron fluences received by the components converted to 1 MeV equivalents using the factors described in the text.

$390 \times 10^6 \text{ n cm}^{-2} \text{ hr}^{-1}$, whereas approximately $530 \times 10^9 \text{ n cm}^{-2} \text{ hr}^{-1}$ was delivered – around 1400 times that expected.

5.2 Gamma Irradiation

Polymer-alanine dosimeters (2 cm × 3 mm) attached to the components were used to measure the gamma ray doses received by the components. Irradiation of the alanine powder held in a polymeric binder results in the formation of stable paramagnetic centres which are detected using an electron spin resonance technique. The number of paramagnetic centres scales with the absorbed dose, which can be deduced with an accuracy of 4 % using this technique.

The total doses derived from the dosimeters are shown in table 2. As a cross-check,

Device	Gamma Dose (kGy)
Fibre roll	5.33 ± 0.21
Upper VCSEL board	5.81 ± 0.23
Lower VCSEL board	4.40 ± 0.18
G-Link chips	4.32 ± 0.17

Table 2: The total gamma doses, derived from alanine dosimeters, for each of the components under test.

the dose given to the fibre roll was verified using a diode-based detector. During a one minute exposure, the diode indicates a dose rate of $(1.37 \pm 0.01) \text{ Gy min}^{-1}$. From table 2 the alanine dosimeter results indicate that the dose rate over the 70 hour irradiation period was $(1.27 \pm 0.05) \text{ Gy min}^{-1}$, which agrees well with the diode result.

Note that the maximum dose delivered is approximately 6.6 times that expected after 10 years of LHC running. The expected ATLAS dose rate is approximately 18 mGy hr^{-1} . A peak dose rate of 76 Gy hr^{-1} was delivered – around 4000 times that expected.

6 Results

6.1 VCSEL's

Figure 5 (6) shows the output power of typical Honeywell and Mitel VCSEL's measured at the receiver box, plotted against bias current during neutron (gamma) irradiation. In each figure, data recorded at four different times during the irradiation test are shown. The times correspond to : before the irradiation started (filled circles), 24 hours later (filled squares), the last measurement before the irradiation was completed (filled triangles) and the last measurement at end of annealing period (filled inverted triangle). The

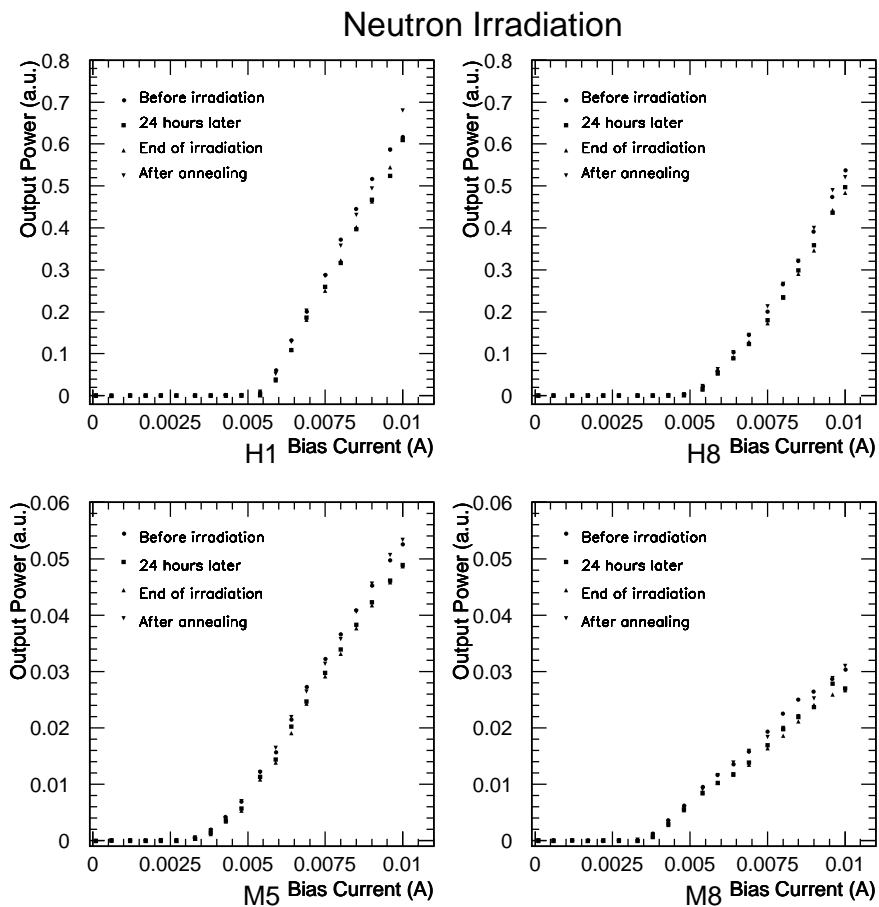


Figure 5: The output power (in arbitrary units) of Honeywell and Mitel VCSEL's plotted against bias current during the neutron irradiation. In all cases the threshold current does not move. The radiation levels received by the components are equivalent to 10 years of LHC running.

received power for the Mitel VCSEL is approximately 10 times smaller than that for the Honeywell VCSEL due to the absence of a coupling lens. The radiation-induced decrease in output power and subsequent recovery during annealing is clearly seen in the figure. For either VCSEL type the threshold current does not move significantly during irradiation or annealing. There is no evidence for any effects due to the different bias currents (H1

Gamma Irradiation

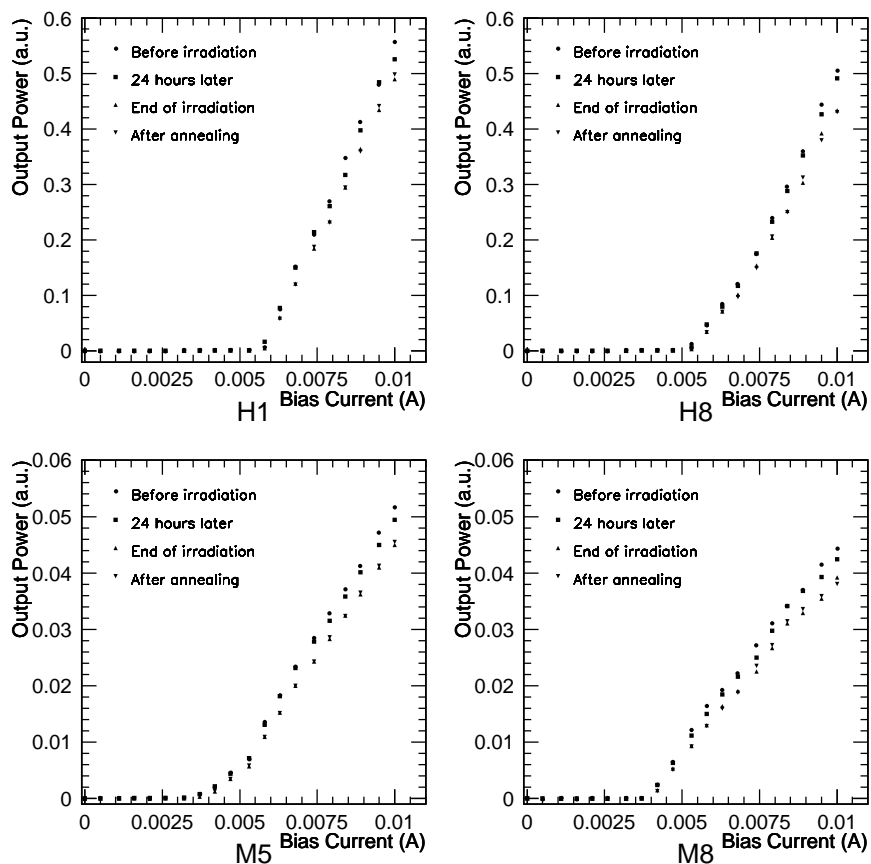


Figure 6: The output power (in arbitrary units) of Honeywell and Mitel VCSEL's plotted against bias current during the gamma irradiation. In all cases the threshold current does not move. The radiation levels received by the components are equivalent to 66 years of LHC running.

$\Rightarrow 7$ mA, H9 $\Rightarrow 8$ mA, M5 $\Rightarrow 5$ mA and M7 $\Rightarrow 6$ mA) applied outside of the 'stepping' measurements (as described in section 4.1).

In order to more fully quantify the decrease in VCSEL output power, the output power (in arbitrary units) measured for a bias current of 7.5 mA is plotted as a function of time in figure 7 (8) for the neutron (gamma) irradiation of Honeywell and Mitel VCSEL's. On these figures, the left- (right-) most vertical line denotes the start (end) of the irradiation period. Note that the scatter of the points for the Mitel VCSEL's appears smaller than for the Honeywell VCSEL's due to the resolution of the ADC (recall that the received power for the Mitel VCSEL's is approximately 10 times smaller than that for the Honeywell VCSEL's due to the absence of a coupling lens).

The attenuation of the light output for both types of VCSEL exposed to neutron radiation exhibits the same overall characteristics. Within the timing resolution of the experiment, there is an immediate attenuation of approximately 5-10 % at the start of the irradiation. This is followed by a slight increase in attenuation during the course of the irradiation. At the end of the irradiation, the attenuation level is maintained for

approximately 12 hours, after which time an annealing process returns the light output to better than 95 % of the pre-irradiation level. Within a given VCSEL brand, there is no evidence for a change in the attenuation due to different bias currents.

The attenuation characteristics for VCSEL's exposed to gamma radiation are noticeably different. The attenuation of the light output is proportional to the accumulated dose. The dotted line on the figures indicates the dose expected after 10 years of LHC running and shows an attenuation of ≤ 5 % which is similar to that seen in the neutron irradiation data. After the irradiation, there is no evidence for any significant annealing in any of the VCSEL's.

6.2 G-Link Chips

Through-out the irradiations, all the tests described towards the end of section 4.2 produced the expected results. There was no evidence in any abnormal operation due to either type of radiation.

After irradiations, the set-up illustrated in figure 3 was recreated in the laboratory. The same tests as indicated in section 4.2 were performed except that an input frequency of 40 MHz was used, giving an output frequency of 1.6 GHz. Each of the chips passed the tests without incident, indicating that after irradiation the PLL's function at Gb/s speeds, as designed.

An additional test was also carried out where the framing of unchanging test data was checked. Tests could only be carried out on output frequencies of 200 MHz due to equipment limitations. This test showed that data was correctly framed and this indicates that the data path of the G-Link was not affected by the either types of radiation.

6.3 Fibre-ribbon

The radiation-induced attenuation for the two fibres exposed to neutrons is shown in the upper part of figure 9. The left- (right-) most vertical line denotes the start (end) of the irradiation period.

The fibres exposed to neutron radiation exhibit an attenuation that scales approximately logarithmically with time (neutron fluence). For both fibres the final attenuation is approximately 20 %. Note that both curves exhibit a 'knee' after approximately 20 hours. An extrapolation from the data indicates a total attenuation of approximately 35 % after 10 years of LHC running (indicated by the dotted vertical line). After irradiation, the attenuation continues to increase for approximately 10 hours and thereafter around 20 % of the radiation induced damage is recovered. These results are for a 10 m length of fibre-ribbon. Using an attenuation coefficient extrapolated from a fluence equivalent to 10 years of LHC running, figure 10 shows how the relative attenuation varies as the length of the fibre under irradiation is shortened.

Four fibres were tested with gamma radiation and the resulting attenuation is shown in the lower part of figure 9. The four fibres exhibit very different characteristics to that seen in the neutron data. The attenuation dependence on time (dose) is exponential. After a 10 year equivalent dose, all four fibres suffer an attenuation of approximately 90 %. There is no evidence for any annealing after the irradiation period (equivalent to 66 years of LHC running !). Once again, these results are for a 10 m length of fibre-ribbon. Figure 11

shows how the relative attenuation varies as the length of the fibre under irradiation is shortened. The effect is more pronounced than that observed in the neutron data.

7 Summary and Discussion

Neutron and gamma irradiations have been performed on several components that are being evaluated for use in a serial Gb/s front-end optical data-link for the LArg calorimeter. The components would be used in the transmitting part of the link mounted on-detector and consist of packaged VCSEL laser diodes^h, manufactured by Honeywell (HFE4080-321) and Mitel (1A440) and ‘G-Link’ serialiser chips (HDMP-1012), manufactured by Hewlett Packard. A 10 m length of 8-way graded-index multimode fibre-ribbon, manufactured by Acome was also irradiated.

During the irradiations, the VCSEL’s were biased above threshold with a steady DC current. The phase locked loop functionality of the G-Link chips was evaluated. The fibres were coupled to 850 nm laser sources and the attenuation was determined. Each component was tested in isolation and there was no Gb/s data-flow.

The light output attenuation for either brand of VCSEL after a 10 year LHC equivalent dose of neutrons or gammas was comparable at between 5 % and 10 % after either type of radiation. During both irradiations, none of the VCSEL’s exhibited a change in threshold current. The light output attenuation observed for the Honeywell VCSEL is consistent with that seen in earlier neutron irradiation studies [3] of a prototype version of this device tested at cryogenic temperatures.

After the neutron irradiation the VCSEL’s were kept biased and the pre-irradiation light levels were recovered after about 12 hours - no such annealing effect was observed for gamma irradiated VCSEL’s biased in a similar manner. The attenuation in the light output of the VCSEL’s is small and will not present a problem for the optical power budgets envisaged for LArg read-out links. Future tests will need to concentrate on the affects of radiation of the dynamic characteristics of VCSEL’s, such as noise and single event effects.

For both types of radiation, no adverse effects were observed during the tests of the phase locked loop functionality of the G-Link chips. The maximum (minimum) neutron fluence received by the chips was a factor 2 (3)ⁱ less than the expected 10 year LHC dose. The gamma dose was equivalent to 66 years of LHC operation^j. Although not designed to be radiation resistant, the G-Link is based on a masked ‘sea of gates’ architecture with 25 GHz (ie: small feature size) bipolar transistors, which may help to explain the apparent radiation tolerance. Tests with Gb/s data flows are currently in preparation and will enable single event effects and the data-way of the G-Link to be thoroughly checked. It should be noted that although ECL G-Links were irradiated, TTL versions will be used in LArg data-links. However, both G-Link versions employ the same processing techniques and no adverse effect on the radiation resistance is therefore expected.

A 10 m length of fibre-ribbon suffered an attenuation of ~ 20 % after a mean fluence which was five times lower than that expected after 10 years of LHC running. After

^hRecall that the Honeywell packaging incorporates a plastic lens.

ⁱIf an additional bipolar electronics safety factor [2] is applied this factor increases to 3 (4.5).

^jThis dose exceeds the dose limit required if an additional bipolar electronics safety factor [2] is applied.

irradiation, approximately half the damage to the fibre was recovered. Assuming that the rate of attenuation remains constant, an attenuation of approximately 35 % can be estimated for 10 years of LHC running. This result is compatible with the results presented in [3] for a graded-index multimode fibre from Spectran^k

During a 10 year LHC equivalent gamma irradiation, the same fibre-ribbon suffered an attenuation of ~ 90 % and no post-irradiation annealing was observed. The amount of attenuation varies strongly as a function of length for the gamma irradiated fibre. In order to judge whether such fibre can be safely used in ATLAS, more information is needed on possible installation scenarios and radiation levels away from the crack region (especially for neutrons which fill the cavern like an isotropic gas).

These results are a promising start to a series of thorough irradiation studies planned for 1998. In forthcoming tests a demonstrator link, consisting of a G-Link coupled to a VCSEL, running with Gb/s data-flows will be studied under irradiation. Also, the effects of repeated irradiations on the same components and delivering vastly elevated dose rates to the components need to be studied.

8 Acknowledgments

The authors would like to thank Jan Isaksson at Honeywell (Malmö) and Richard Arbus at Mitel (Järfälla) for organising the efficient delivery of VCSEL samples. We would also like to thank the SARA cyclotron operation crew for giving us excellent beam conditions and Abderrahmane Benabed from ISN for analysing the nickel foil dosimeters. Bengt-Inge Ruden from Karolinska Sjukhuset is thanked for his help in arranging the gamma irradiation tests and for donating his free-time so generously. Finally, thanks to Anne Fontaine from the CERN dosimetry service for analysing the alanine dosimeters.

^kIn this test the fibre was held at cryogenic temperatures whilst under irradiation.

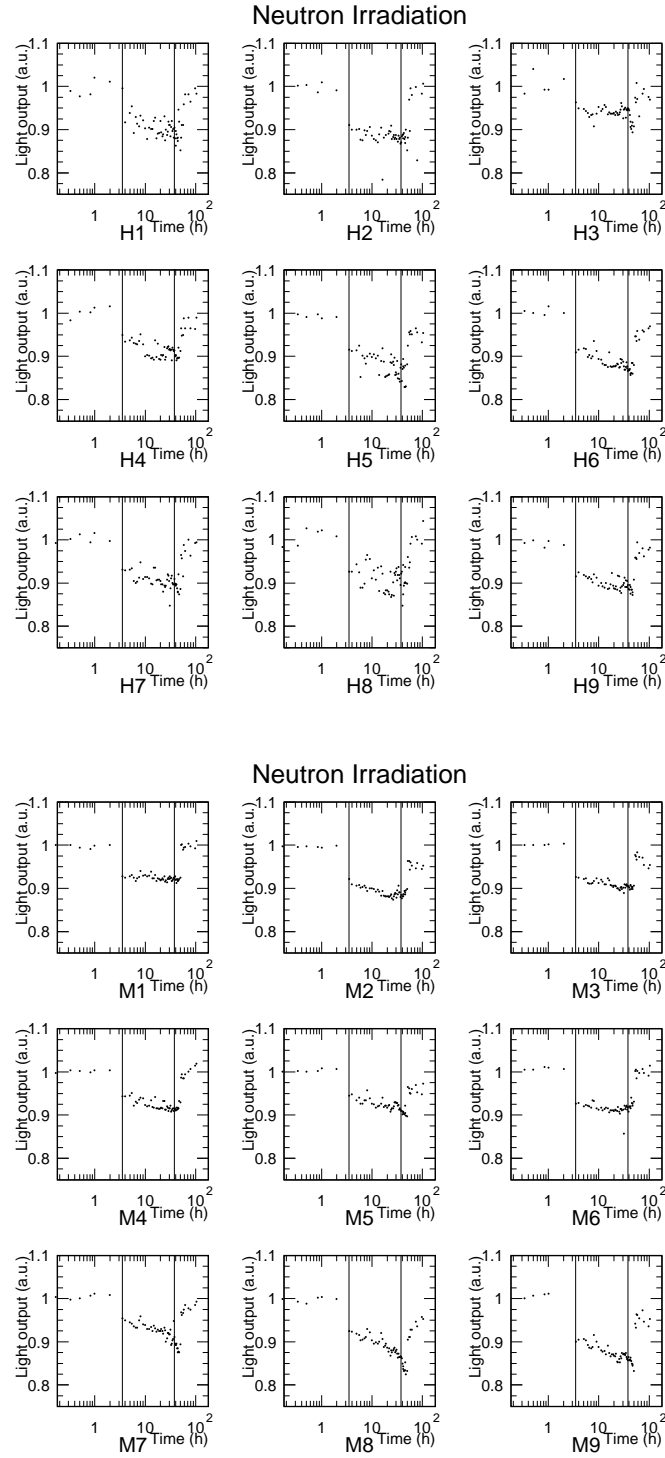


Figure 7: The output power (in arbitrary units) plotted as a function of time during neutron irradiation for Honeywell (upper plots) and Mitel (lower plots) VCSEL's. The left- (right-) most vertical line denotes the start (end) of the irradiation period. The neutron fluence received by the components is equivalent to 10 years of LHC running.

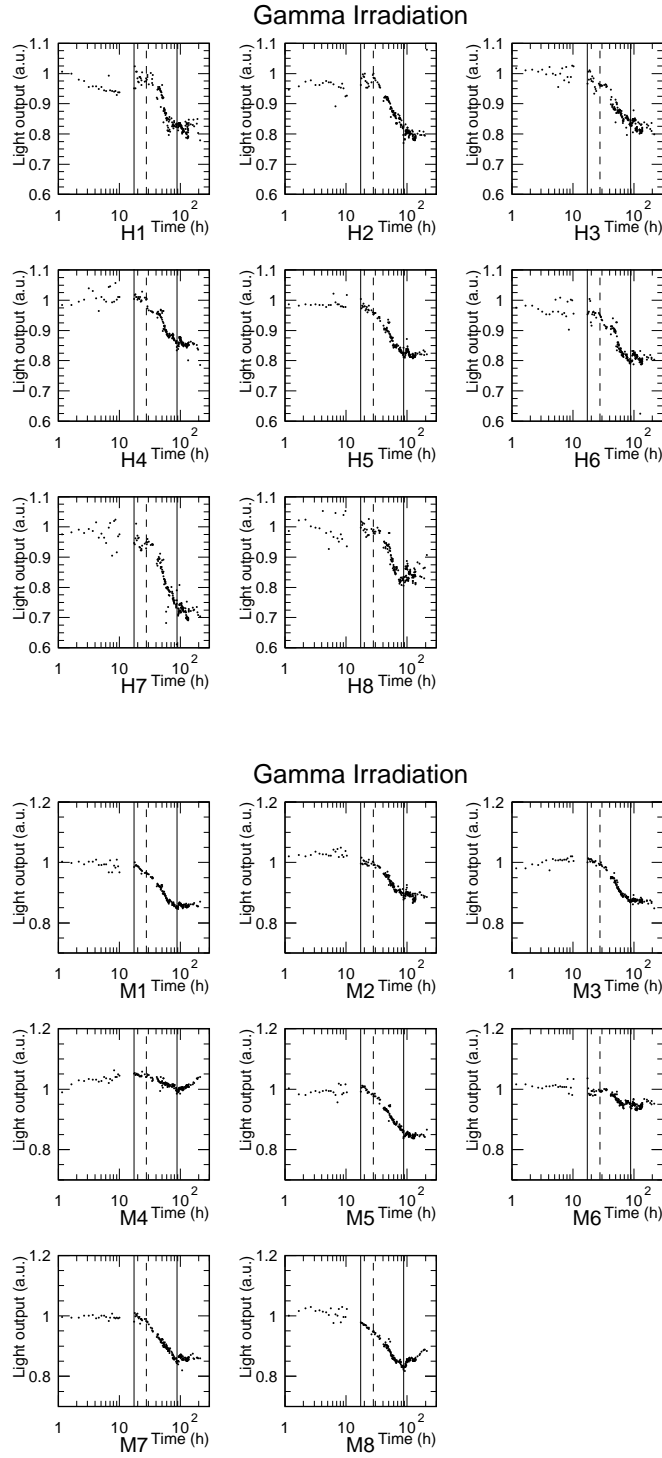


Figure 8: The output power (in arbitrary units) plotted as a function of time during gamma irradiation for Honeywell (upper plots) and Mitel (lower plots) VCSEL's. The left- (right-) most vertical line denotes the start (end) of the irradiation period. The dotted line indicates a dose equivalent to 10 years of LHC operation.

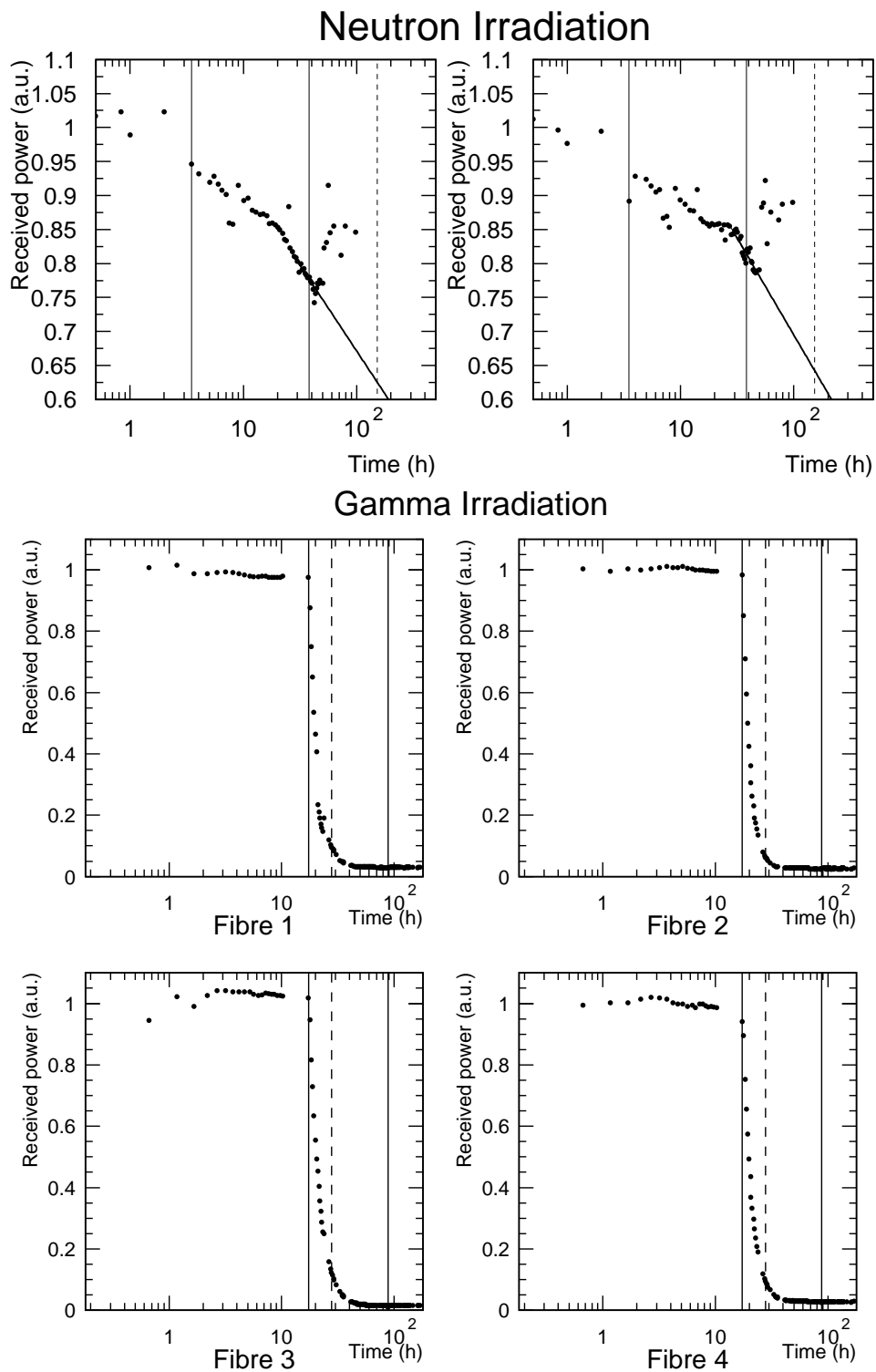


Figure 9: The upper (lower) set of plots shows the attenuation in fibres exposed to neutron (gamma) radiation. The left- (right-) most vertical line denotes the start (end) of the irradiation period. In both types of plot, the dotted line indicates a dose equivalent to 10 years of LHC operation. Note that for the neutron data this requires an extrapolation from the data.

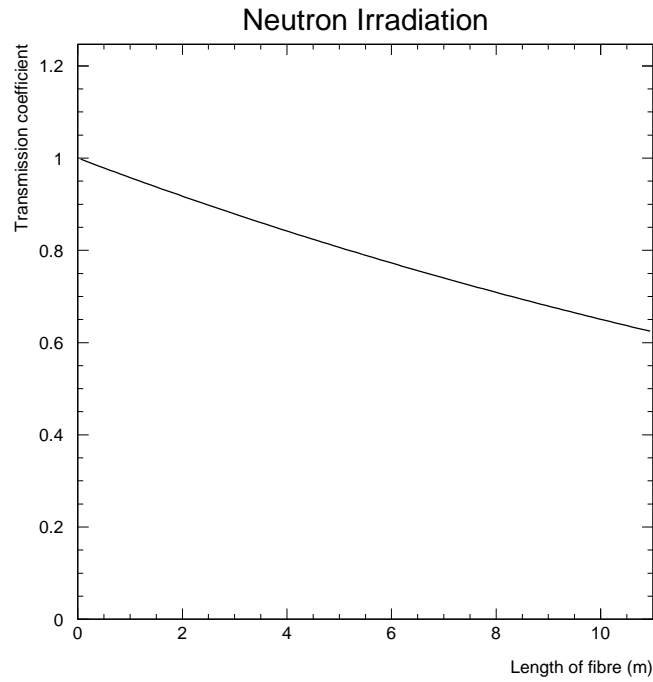


Figure 10: The relative attenuation in the neutron irradiated fibre as a function of the fibre length. A 10 m length was irradiated in the tests described in this note. Note that the neutron fluence delivered to the fibre has been extrapolated to 10 years of LHC running.

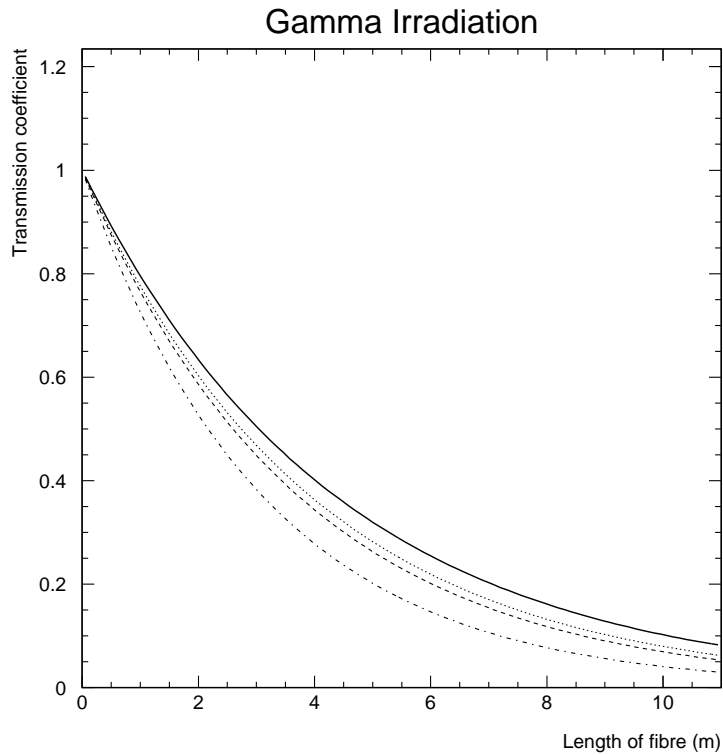


Figure 11: The relative attenuation in the gamma irradiated fibre as a function of the fibre length. A 10 m length was irradiated in the tests described in this note. The four curves correspond to the four fibres tested.

References

- [1] The ATLAS Collaboration, Liquid Argon Calorimeter Technical Design Report, CERN/LHCC/96-41, December 1996.
- [2] ATLAS Policy on Radiation Tolerant Electronics. *Draft 2*.
Available from <http://www.cern.ch/Atlas/GROUPS/FRONTEND/WWW/radto12.ps>
- [3] J. Söderqvist *et al.*, 'Radiation Hardness Evaluation of an Analogue Optical Link for Operation at Cryogenic Temperatures', IEEE Trans. Nucl. Sci. **44** (1997) 861.
- [4] J. Beringer *et al.*, 'Radiation Hardness and Life Time Studies of LEDs and VCSELs for the Optical Readout of the ATLAS SCT', Atlas Internal Note INDET-NO-183, June 1997.
- [5] More details on Honeywell VCSEL's can be found by following the appropriate links from : <http://www.honeywell.com/sensing/prodinfo/fiberoptic/>
- [6] More details on Mitel VCSEL's can be found by following the appropriate links from : <http://www.mitel.com/>
- [7] More details on the Hewlett Packard 'G-Link' chip-set can be obtained by following the appropriate links from : <http://www.hp.com/HP-COMP/fiber/>
- [8] Acome, Departement VDI, Secteur Europe, 52 rue du Montparnasse, 75014 Paris, France.
- [9] B. Dinkespiler *et al.*, 'Analogue Optical Links for the Front-end Read-out of the ATLAS Liquid Argon Calorimeter', Proceedings of the Third Workshop on Electronics for LHC Experiments, London, September 1997.
- [10] R. Jean, J. Aucouturier and H. Leboutet, Annales de Radioélectricité 21 (1966) 122; M. Lieuvain, 9th International Conference on Cyclotrons and their Applications, Les Ulis (1981).
- [11] J. Collot *et al.*, Nucl. Instr. and Meth. **A350**, 525 (1994).
- [12] L-O. Eek *et al.*, 'Development and Performance of a Receiver for an Analogue Optical Link', ATLAS Internal Note LARG-NO-79, September 1997.
- [13] A.M. Ougouag *et al.*, IEEE Trans. Nucl. Sci. **NS-37** (1990), 2219.
- [14] *Private communication* from C. Leroy, Université de Montréal.

Appendix A

A Phase Locked Loop (PLL) in the G-Link Chip

The PLL implemented in the G-Link chip is used as a frequency multiplier. A phase comparator, integrator, voltage controlled oscillator (VCO) and a digital frequency divider (of factor N) are arranged in a loop as shown in figure 12.

A reference signal, S_{ref} , of frequency, F_{in}^1 , is applied to one of the two inputs of the phase comparator. The loop system is said to be locked when the two frequencies at the input of the phase comparator (F_{in}^1 and F_{in}^2) are equal. When this is the case, the frequency of the VCO, F_{out} , is equal to $N \times F_{in}^1$, indicating that the frequency multiplication is complete.

When a phase difference appears between the two input frequencies, it is detected by the phase comparator. The voltage output from the phase comparator (proportional to the phase difference) is integrated and provides an ‘error’ signal at the VCO input. This signal induces a frequency modification at the VCO output with the aim of nullifying the error signal and restoring the locked condition.

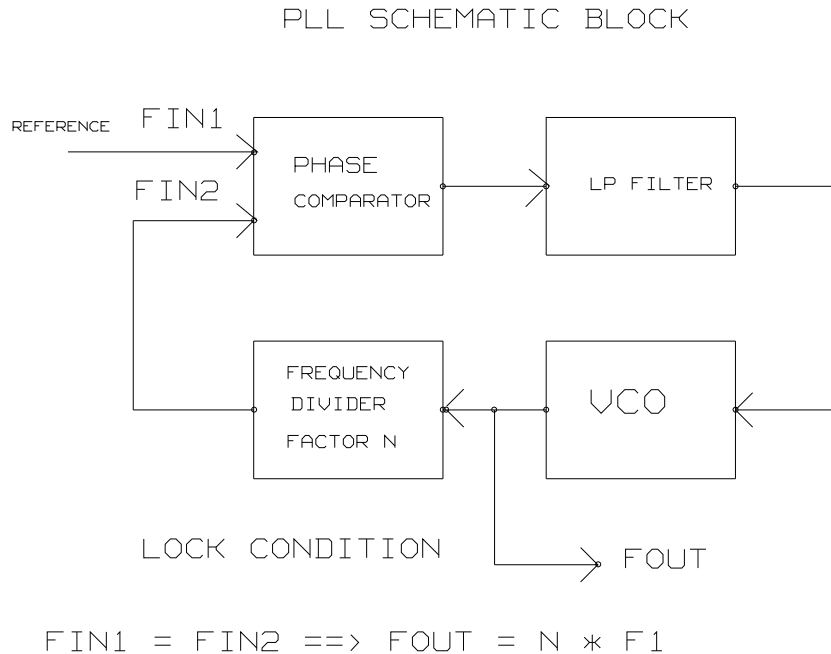


Figure 12: A schematic of the PLL function of the G-Link chip.