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Neutron Irradiation of Optical Link Components.

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Abstract

Results from a study of the radiation hardness of components intended for use in optical links at LHC are presented. Neutron irradiations of light emitting diodes and optical fibres from a few different suppliers have been carried out at the SARA facility in Grenoble. The loss of optical output power and transmission are studied up to doses of the order of 10^{14} neutrons/cm^2 (LHC-equivalent 1 MeV neutrons). The behaviour under radiation of a link used to read out the liquid argon presampler in ATLAS is discussed.

1 Introduction

The study of radiation damage of optical links is motivated by the increasing interest in these links for signal transfer from the front-end electronics in LHC experiments. The obtained results are also of interest for other applications of optoelectronic components in radiation environments. We here report on neutron irradiations of Light Emitting Diodes (LED) and optical fibres.

Our goal is to develop an analogue optical link for the readout of the ATLAS liquid argon (LAr) presampler. This subdetector will have a large number of channels and an analogue optical link offers a compact readout solution. The optical link, described in [1], consists of a current driver, a LED, an optical fibre and a PIN diode, as receiver, which is connected to a transimpedance amplifier. The emitting part of the link will operate in LAr, which holds a temperature of 89 K. Only the emitting part of the link (driver, LED, and a few metres of fibre) are exposed to radiation. Therefor there is a need to study these components under radiation. Typical radiation doses that the link will have to withstand during 10 years of LHC operation are of the order of 10^{14} neutrons/cm^2 (LHC-equivalent 1 MeV neutrons) and 1 Mrad gamma dose.

For the time being there exist only prototypes of the drivers not yet optimised for radiation hardness. Consequently, no radiation tests of drivers have been carried out so far. The other devices, of the emitting part of the link, were irradiated in a LAr cryostat, but one irradiation has also been done at room temperature to study the temperature dependence of the damage. The study has been carried out for several GaAs LEDs (see table 1), from different manufacturers, emitting light around 850 nm, at both LAr and room temperature, and on one type of InP LED (see table 1) emitting light around 1300 nm.

Two Multi Mode (MM) fibres (see table 6) were irradiated , one with a pure Silica core and one that was Germanium doped. The latter fibre was known not to be neutron radiation hard but was included to verify earlier measurements.In order to maximise the optical output from the link we intend to use 200 μm core fibres. At the time of the tests no radiation hard fibre with 200 micron core was available to us, so the tests were performed on a 50 μm core fibre with the same structure as we intend to use for the fibres in the final link.

The transmitted light power should be as high as possible to achieve the required signal-to-noise ratio and dynamic range for an analogue link, as explained in [1]. Our measurements were concentrated on the loss of light output but also covered the electrical properties of LEDs under radiation.

2 Neutron irradiation and dosimetry

The irradiations took place at the SARA irradiation facility in Grenoble [2]. Neutrons are generated at SARA through the process ($^9Be(d,n)^{10}B$) by impinging 20 MeV deuterons onto a Beryllium target. An intense neutron beam with an energy centred around 6 MeV is thus produced. The neutron yield and energy spectrum have been thoroughly investigated by Collot et al. [2]. All neutron sources contain a component of gammas. For the SARA facility the beam was found to contain 22% of gammas equivalent to a dose of 0.18 Mrad for 10^{14} neutrons/cm^2.

The given doses in specific positions are measured by the Grenoble group with Nickel activation foils. This measurement scheme gives an error of 10% for the total dose.

An alternative way to measure the dose is to look at the charge that is deposited on the Be-target, since this target is electrically insulated. The integrated target charge is therefore directly proportional to the total dose of neutrons at the target. If the distances to the devices are known one can calculate the total dose received by them. However, one has to take into account the absorption of neutrons by the LAr and the walls of the cryostat. Due to detector problems when analysing the Ni-foils this alternative procedure to calculate the doses was used. The resulting estimated error is of the order of 20%.

The damage caused by neutrons depend on their energy. The neutron energy spectrum at LHC is centred around 1 MeV [3] causing less damage than the SARA neutrons. Consequently a 6 Mev neutron dose has to be converted to obtain the corresponding dose at LHC causing equivalent damage. Conversion factors have been extracted using the kerma displacement cross section [4, 5]. The factors used are 2.8 for GaAs and 3.0 for Si. For InP we have not yet found any data on the kerma displacement cross section and the doses are therefore given for 6 MeV neutrons.

3 Experimental setup

The LEDs were soldered onto two different motherboards which were placed, one after the other, along the beam axis in the 10 l LAr cryostat. A third motherboard was placed outside the cryostat to be irradiated at room temperature. The electrical signals were sent to the LEDs on a 50 Ω AXON[1] ribbon cable. Impedance matching was done with 47 Ω resistors in series with the LEDs.

The LEDs were biased with 8 mA during the whole irradiation (4 days, effective beam time 69 h). For measurements, 2 μs long pulses with 10% duty cycle and an amplitude of 10 – 60 mA from a current pulse generator[2] were used. The pulses were sent to one LED at the time. For two of the diodes (IRE 331-005 and HBFR 1404-05) a different scheme was used. These LEDs were given a bias voltage of 2 V, equivalent to 40 mA, only during the measurements (a few times per day) and pulses from a voltage pulse generator were used.

All the LEDs were optically connected to 62.5 micron fibres[3], put together into ribbons each containing four fibres. Two fibres in one of the ribbons were connected to each other, thus forming a fibre loop identical to two read out fibres. The light transmission of through this loop was monitored to see the attenuation caused by the irradiation of the fibres in

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[1] Manufactured by AXON, Montmirail, France

[2] ILX LDP3811

[3] Ericsson fibre SK6000954 SE

the ribbons. The loss was about 10% for the full dose and the LED results have been compensated for this. PIN diodes connected to transimpedance amplifiers[4] were used to detect the optical signals. The amplified signals were then read out on an oscilloscope. The whole setup was controlled by a personal computer.

About 100 m of the fibres to be irradiated were wound onto 70 mm diameter coils that were placed in the cryostat. During the irradiation the fibres were fed with 850 nm light[5] with an optical power of approximately 20 μW and the outputs from the fibres were monitored with light power metres[6].

4 Results

4.1 Neutron damage of LEDs

4.1.1 Optical output

Table 1 lists the irradiated devices.

LED	*Manufacturer*	*Type*	*Irradiation temp.*	*Remarks*
HFE 4050[7]	Honeywell	GaAlAs	LAr T	
1A362[8]	ABB HAFO	GaAlAs	LAr, room T	
HBFR 1404[9]	Hewlett Packard	GaAlAs	LAr, room T	
IRE 331-005[9]	Laser Diode Corp.	GaAlAs	LAr T	
1A341[8]	ABB HAFO	GaAlAs	room T	Does not work in LAr
1A365[8]	ABB HAFO	InP	LAr, room T	6 MeV n dose used

Table 1: *Irradiated LEDs.*

The decrease in light output for GaAs LEDs in LAr is depicted in figure 1 as a function of the dose. Note that the abscissa start at 10^{13} n/cm^2. All plots are made for one typical LED of each kind. The LEDs output dropped between 5 and 10% in the very beginning of the irradiation, i.e. for a dose below $2 \cdot 10^{12}$ n/cm^2. After this first phase of the irradiation, all the GaAs LEDs show a similar behaviour except for the IRE 331-005 which in the end gave very little light power.

A radiation hard LED is generally heavily doped. The LEDs that were irradiated are probably doped to levels around 10^{18} - 10^{19} dopants/cm^3 and the impurity content are usually magnitudes lower. The exact composition of the LEDs are kept secret by the manufacturers so the dependence on these parameters could not be studied.

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[4] Honeywell receiver HFD 3038, combined PIN and amplifier

[5] ABB HAFO: 1A194

[6] Anritsu ML910B and Rifocs 575L

[7] In ST-housing

[8] In HAFO pigtail3-housing

[9] In SMA-housing

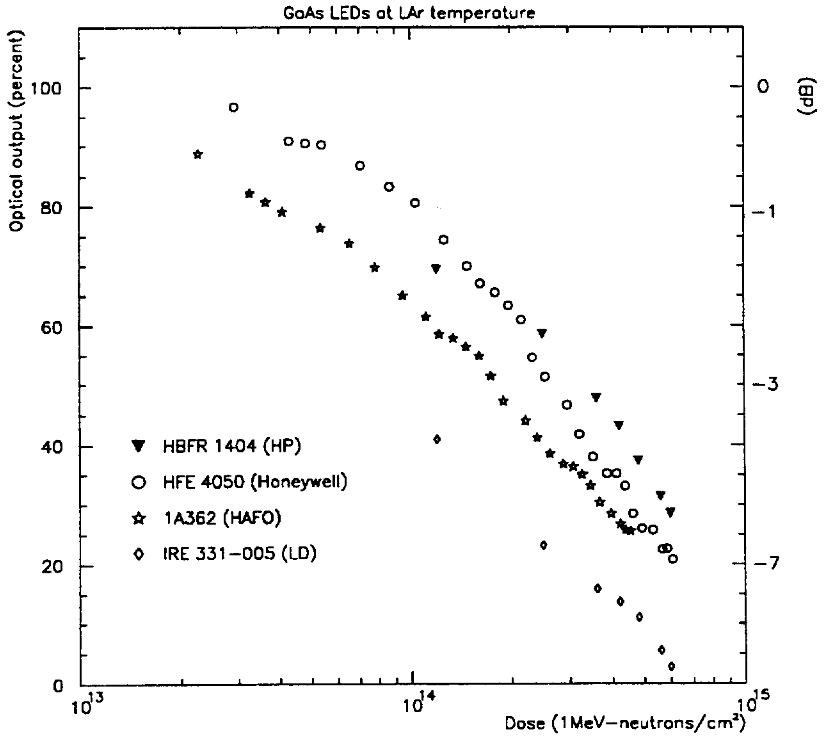

Figure 1: *Light Power of GaAs LEDs during irradiation in LAr*

Two different types of GaAs LEDs have been irradiated at room temperature: 1A362 and 1A341. The results are plotted in figure 2.

Their responses to neutron irradiation are quite similar. The important difference is that 1A341 does not work at LAr temperature. (This is due to its high level of Al content in the $Ga_xAl_{1-x}As$ crystal which, at low temperatures, gives rise to so called DX donor states in the bandgap reducing the light output [6].)

The HFE 4050 drops the least for a dose of up to $2 \cdot 10^{14}$ n/cm^2. For higher doses the HBFR 1404 is slightly better. However, the IRE and HBFR LEDs had a different bias current, 40 mA during the measurements only, instead of 8 mA during the whole irradiation, so the comparison is not completely fair. The light power losses are summarised in table 2.

The results of the InP LEDs that were irradiated are shown in figure 3, with the dose given for 6 MeV neutrons since the kerma displacement cross section for InP is not know to us at present.

The advantage of InP LEDs is that they emit light at 1300 nm where the optical fibres are generally believed to be less sensitive to radiation damage. The one LED that we looked at was more sensitive to radiation damage than the GaAs LEDs, as can be seen in figure 4. (Note, again, that the comparison can only be done for a dose of 6 MeV neutrons). What is not shown in the figure is that the InP LEDs have a much smaller (down to 50%) optical output power than GaAs LEDs and cannot give the required optical output for the presampler analogue optical link. The interest in InP LEDs are for fast digital applications.

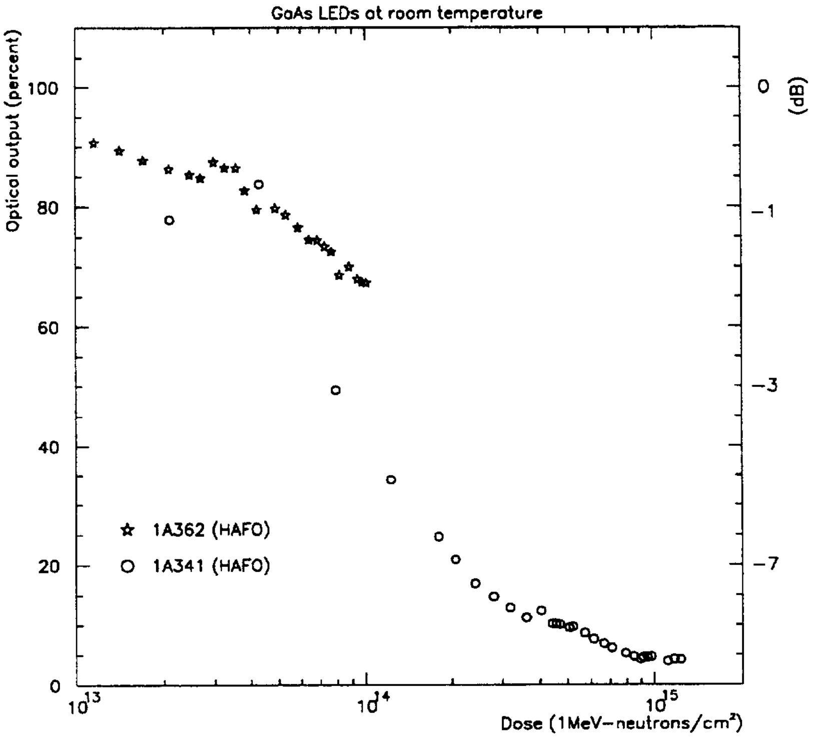

Figure 2: *Light Power of GaAs LED during irradiation at Room T*

LED	*Total dose* n/cm^2	*Dose rate* n/cm$^2 \cdot s$	*Output drop for* 10^{14} *n/cm*^{2}
HFE 4050	$6.0 \cdot 10^{14}$	$2.8 \cdot 10^{9}$	20%
1A362, room	$1.0 \cdot 10^{14}$	$4.7 \cdot 10^{8}$	33%
1A362, LAr	$4.5 \cdot 10^{14}$	$2.1 \cdot 10^{9}$	36%
HBFR 1404	$6.0 \cdot 10^{14}$	$2.8 \cdot 10^{9}$	22%
IRE 331-005	$6.0 \cdot 10^{14}$	$2.8 \cdot 10^{9}$	54%
1A341, room	$1.8 \cdot 10^{15}$	$8.8 \cdot 10^{9}$	58%
1A365, room	$3.5 \cdot 10^{13}$ 6 MeV n	$1.6 \cdot 10^{8}$ 6 MeV n	-
1A365, LAr	$1.6 \cdot 10^{14}$ 6 MeV n	$7.5 \cdot 10^{8}$ 6 MeV n	-

Table 2: *Summary of dose (1 MeV neutrons) and attenuation for irradiated LEDs.*

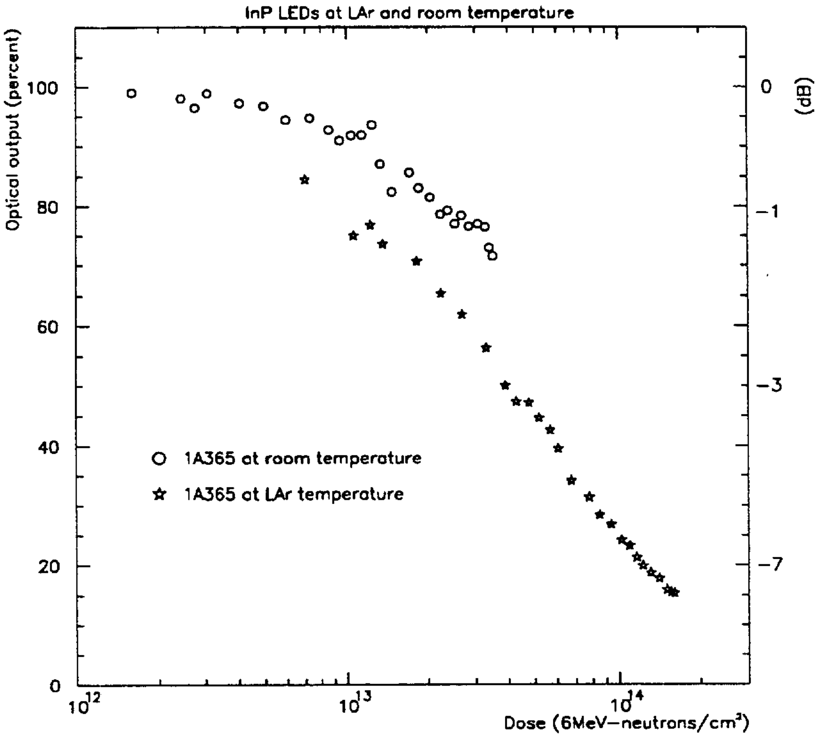

Figure 3: *Light Power of InP LED during irradiation at LAr and Room T*

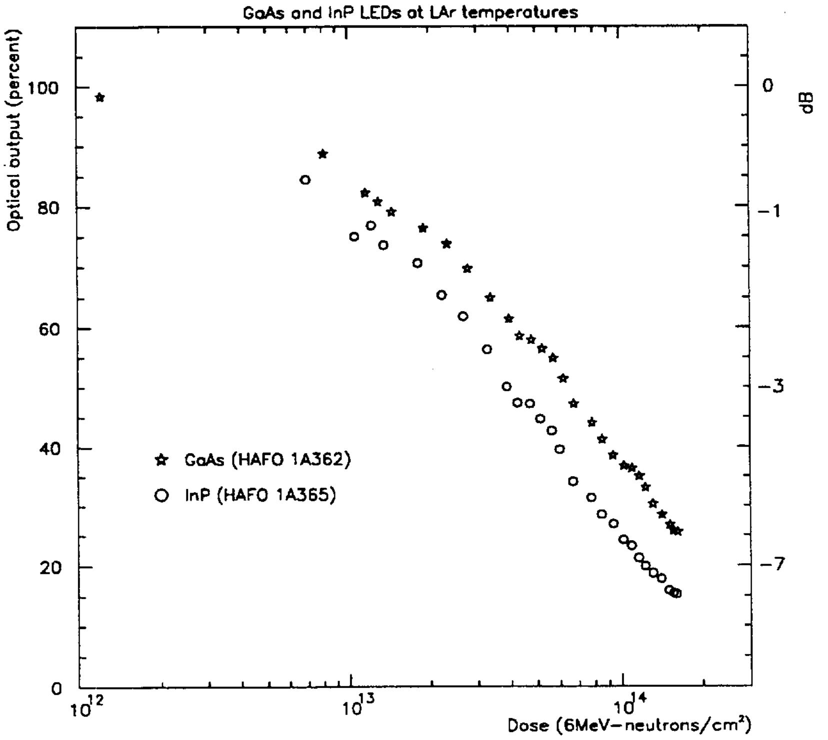

Figure 4: *Light Power of GaAs and InP LED during irradiation at LAr T*

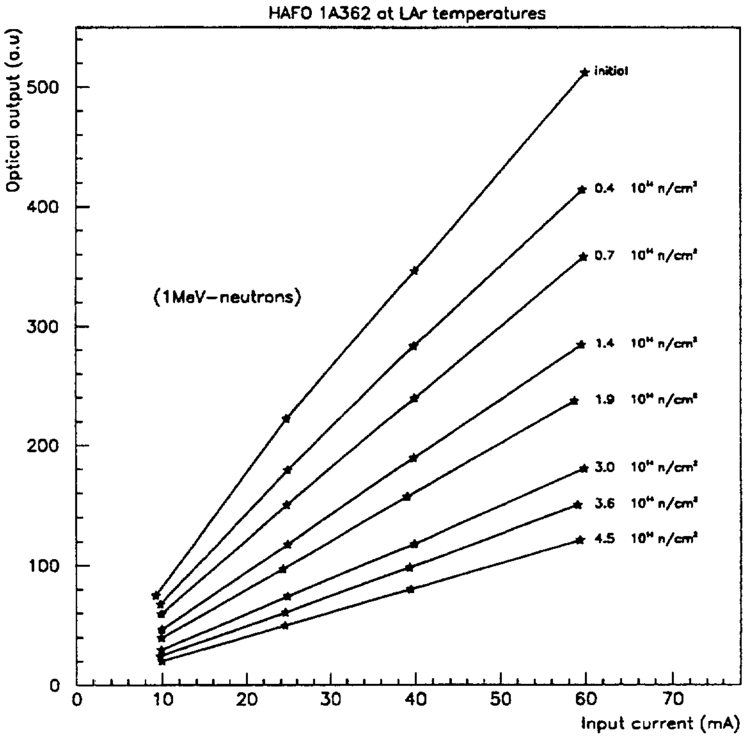

Figure 5: *Light Power vs I for GaAs LED 1A362 during irradiation in LAr. At higher light power the linearity was limited by the receivers.*

The output power versus input current for different doses is shown in figure 5 for one of the 1A362 LEDs. As can be seen the linearity of the output power did not deteriorate during the irradiation, which were true for all tested devices.

The electrical properties were measured before and after irradiation in both ambient temperature and in the cold. No significant changes were found, as shown in tables 3, 4 and 5.

LED	*C @ 1Mhz*	*R* measured DC	ΔR irrad. & non irrad.	BW/t_{rise} specification
HFE 4050	70 pF	4 Ω	<0.5%	85 MHz
1A362	200 pF	7 Ω	<1.0%	<5 ns
HFBR 1404	55 pF	4 Ω	-	3 ns
IRE 331-005	-	4 Ω	-	12 ns
1A341	-	-	-	-
1A365	-	10 Ω	2.5%	-

Table 3: *Electrical properties of LEDs in room temperature.*

LED	t_{rise} room T irrad. & non irrad.	t_{rise} LAr irrad. & non irrad.
1A362	< 6 ns	< 6 ns
1A365	< 8 ns	< 8 ns

Table 4: *Measured rise time (the measurements are limited by the amplifiers). No change due to radiation damage was observed.*

LED	*Temp.*	*Leakage current for 3 V reverse voltage*
1A362	room T	<1 μA
1A362	LAr T	<1 μA
1A365	room T	1 μA / 295 μA
1A365	LAr T	<1 μA

Table 5: *Leakage currents of LEDs before and after irradiation.*

It is not yet understood why one InP LED showed a large leakage current, a problem that none of the other twelve irradiated LEDs suffered from.

4.1.2 Dependence on dose rate and temperature

One GaAs LED, the 1A362, was, apart from being tested at LAr, also tested at room temperature but at a lower dose rate, so the total dose given there was smaller. A comparison between the two different conditions is shown in figure 6, where it can be seen that there are no major differences between the damage caused at room or at cryogenic temperature, and that there is no evidence of a drastic dependence on dose rate. Future tests will have to show the effect of lower dose rates, closer to the true conditions at LHC.

4.1.3 Annealing of GaAs LEDs

The possibility to anneal damaged LEDs have not been investigated in detail, but for two GaAs devices a simple annealing procedure was tried, see figure 7. It was found for the 1A341 that no annealing was visible until the DC current sent through the LED reached around 100 mA. After applying 100 mA DC current to the 1A341, around 20% or more of the light power lost could be recovered.

The threshold for the annealing can be explained by assuming that the recovery of damage is photon assisted. This implies that there has to be excess energy supplied for the process to take place and this energy must be larger than the thermal energy at room temperature. Otherwise we would have seen a spontaneous annealing of the LEDs irradiated at room temperature. As observed for 1A341 the annealing process could be successfully repeated during irradiation at least up to the reached dose of $1.8 \cdot 10^{15}$ n/cm^2. Without annealing this dose corresponds to a drop in light power of 80% for the 1A341.

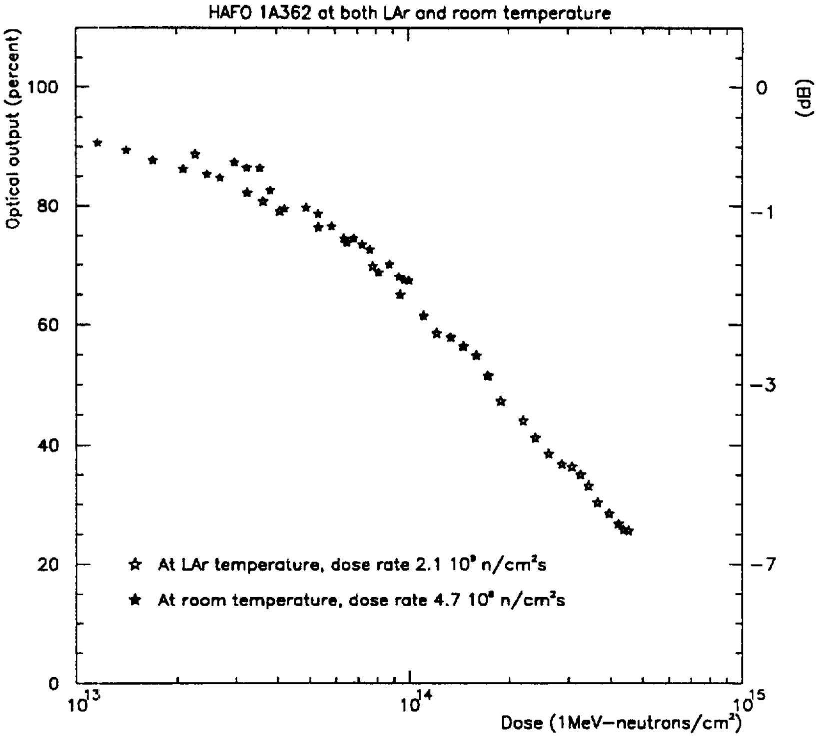

Figure 6: *Light Power of GaAS LED during irradiation at LAr and Room T*

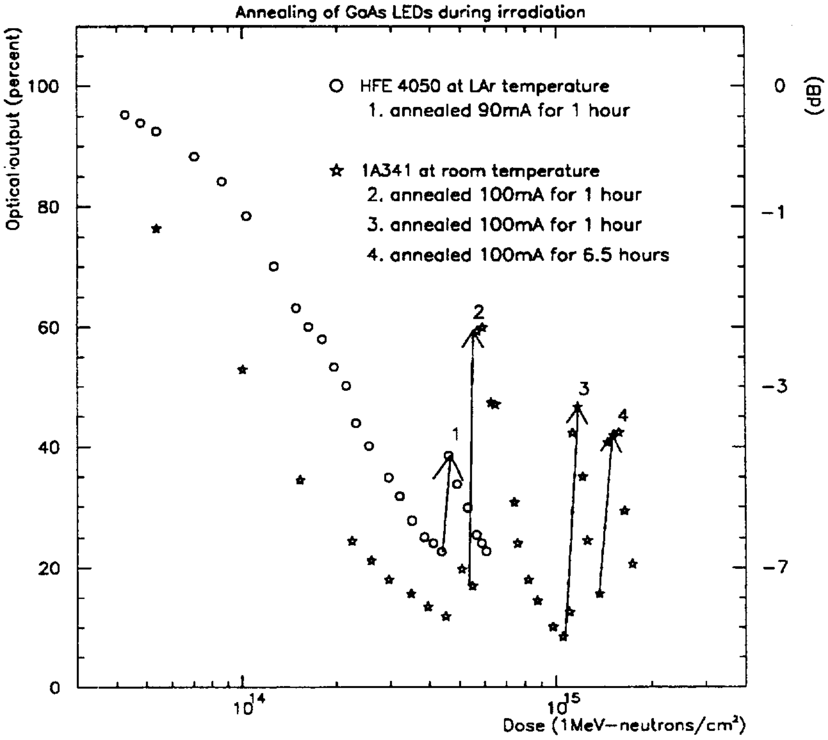

Figure 7: *Annealing of two GaAs LEDs*

4.2 Neutron damage of optical fibres

The irradiated fibres are listed in table 6 and some of their properties in table 7 and 8.

Fibre	*Manufacturer*	ϕ_{core}	*Irradiation*	*Remarks*
50/60/125	Fujikura	50 μm	LAr T	
100/140R-GI	Spectran	100 μm	LAr T	γ Rad Hard

Table 6: *Irradiated fibres.*

Fibre	*Type*	*Dopant*	*OH content*	*Coating*
50/60/125	Pure Silica, Step index	F 5.6 wt%	> 100 ppm	Acrylate
100/140R-GI	Doped, Graded Index	Ge	?	Acrylate

Table 7: *Structure of fibres.*

Fibre	*Total dose*	*Dose rate*	*Attenuation for* 10^{14} n/cm^2
50/60/125	$2.0 \cdot 10^{14}$	$9.4 \cdot 10^{8}$	19%/100 m
100/140R-GI	$2.0 \cdot 10^{14}$	$9.4 \cdot 10^{8}$	No transmission for 100 m

Table 8: *Attenuation in irradiated fibres.*

Results of the two multimode fibres irradiated in LAr are shown in figure 8.

The 50/60/125 pure Silica fibre shows good resistance to neutron radiation also for doses above 10^{15} n/cm^2. The 100/140 fibre with Germanium doped core shows a large attenuation already for doses below $2 \cdot 10^{12}$ n/cm^2. This clearly shows that no dopants should be used to obtain a neutron radiation resistant fibre. The 50/60/125 fibre has a pure Silica core and a cladding where only the five first microns of the cladding are doped with Fluorine and the rest of the fibre outside the cladding is pure Silica.

Although from the point of view of the fibres it would be more favourable to work at 1300 nm it is shown that neutron radiation only marginally degrades the optical transmission even when working at 850 nm, provided the fibres are non-doped.

Since less than 10 metres of the fibre will be exposed to irradiation the contribution from the fibre to the link degradation will be practically negligible. The energy required to anneal the damage in fibres can be provided simply by sending light through the fibre. As shown in figure 9 it is possible to decrease the radiation-induced attenuation in this way. Transmitting about 20 μW of light for 24 hours after irradiation reduced the attenuation of the Fujikura fibre by half or more.

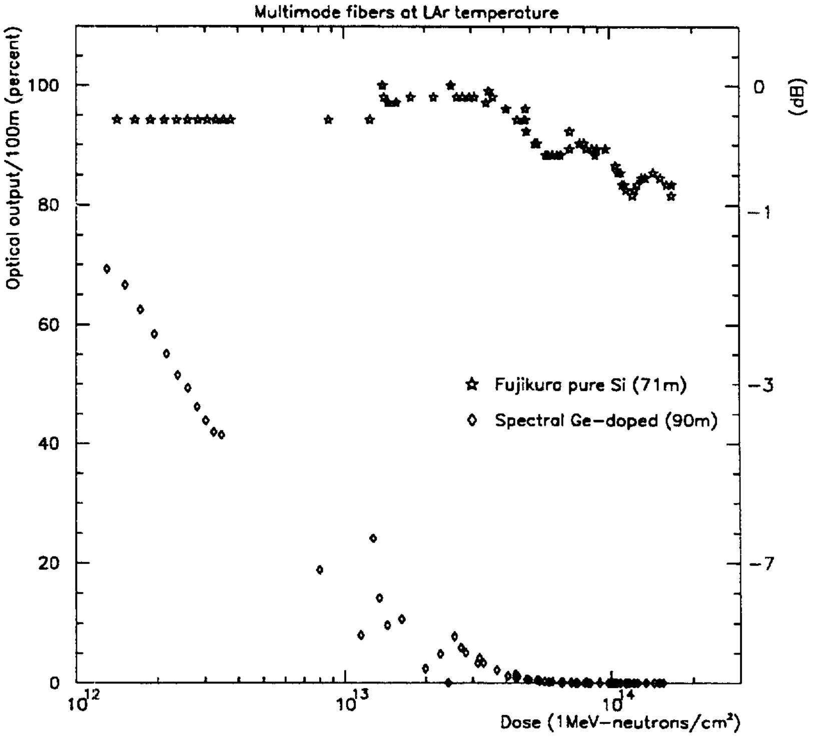

Figure 8: *Transmitted light in multimode fibres during neutron irradiation in LAr.*

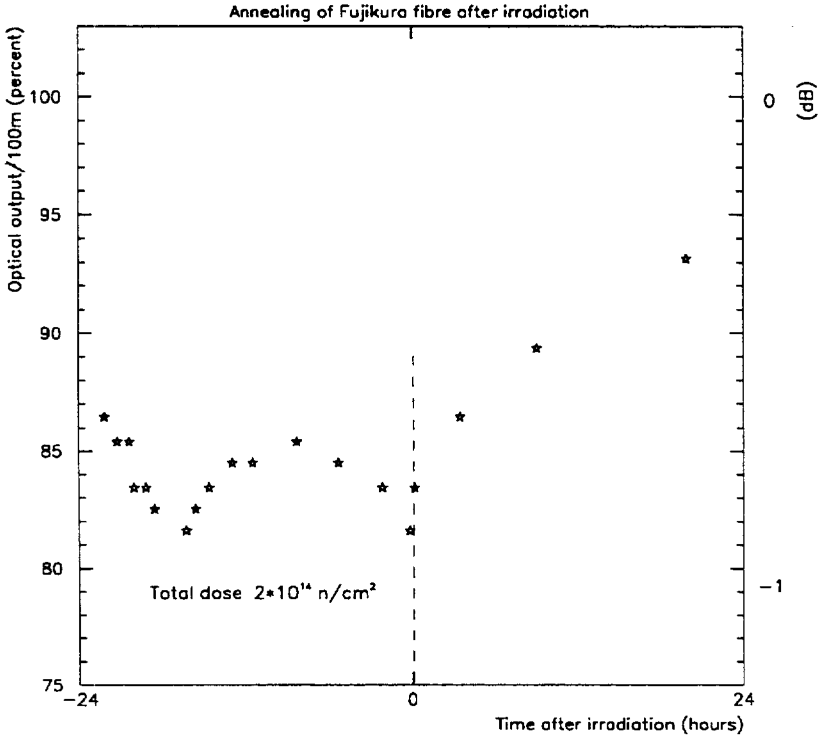

Figure 9: *Annealing of Fujikura MM fibre after end of neutron irradiation.*

5 Gamma radiation resistance

Gamma radiation damage on LEDs and fibres is somewhat different from what applies in the neutron case [7]. Since LHC is expected to give 0.5 to 1 Mrad of gamma dose in the region where our optical link will operate, it is important to study how the devices behave when exposed also to this kind of radiation. The present measurements include only part of the gamma dose to be expected at LHC.

Gamma radiation resistant optical fibres, such as the ones used in our study, can be purchased from several manufacturers [8]. Experiments on gamma radiation hardness of LEDs will take place during the autumn of 1994.

6 Summary and conclusions

We have studied the damage caused by neutrons to GaAs (and InP) LEDs and optical fibres, which are part of an analogue optical link intended for use at LHC.

It is shown that the LED is the weakest part concerning neutron-induced radiation damage. Still, without the use of annealing, the loss of light caused by neutrons is less than 3% per year, i.e. approximately a light reduction by 25% for a dose equivalent of 10 LHC-years of neutrons at the level of the calorimeter (approximately 10^{14} n/cm^2) [3]. It is also shown that the electrical properties of the LEDs are not affected by neutron irradiation.

InP LEDs have not proven to be superior to GaAs LEDs, regarding radiation hardness. They also have the disadvantage of having a poor initial optical output. We therefore see no reason to use InP for the LEDs. Consequently, for our application, 850 nm is a better wavelength than 1300 nm for the link to operate at.

Pure Silica optical fibres meet the presampler requirement of radiation hardness. An optical fibre of pure Silica causes no problem since less than 10 metres of the fibre will be exposed to radiation, so the neutron induced attenuation will only be a few percent after 10 LHC-years. Doped fibres, on the other hand, are once again confirmed not to be neutron radiation hard.

The neutron doses in our measurements were above those expected at LHC and the dose rates were almost three orders of magnitude higher than in a LHC-experiment. However, since LEDs are bulk devices, we expect a similar damage even for lower dose rates. The effect of very low dose rates has to be studied, but already with our present results, we may conclude that an analogue optical link can withstand neutron radiation in LAr up to LHC doses.

Care has to be taken so that no region in the calorimeter has much higher neutron radiation levels than estimated, since the safety margin for perfect operation of the optical link is restricted.

An evaluation of gamma damage on GaAs LEDs is presently going on and results will be reported in a further technical note.

Acknowledgements

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