Radiation Hardness Evaluation of an Analogue Optical Link for Operation at Cryogenic Temperatures

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Abstract

The effect of neutron radiation on light emitters and optical fibers at cryogenic temperatures (-184° C) has been investigated as part of the development of an analogue optical link, intended for use at future high energy physics experiments. The LED's were also exposed to a gamma radiation dose of 3 Mrad. High radiance GaAs LED's, quantum-well LED's, quantum-well laser diodes and optical fibers have been exposed to neutron radiation reaching fluences of 10^{15} neutrons/cm^2.

I. Introduction

The detectors and front-end electronics at the future Large Hadron Collider[1] (LHC) must operate reliably in a high radiation environment. We have developed a low-cost analogue optical link [1] - consisting of a driver, an emitter, an optical fiber, and a PIN photodiode followed by a transimpedance amplifier (as shown in Fig. 1) - for use in the ATLAS experiment [2]. In the first phase of the project the link was intended to transfer signals from the preshower detector [3] to outside the ATLAS liquid argon (LAr) cryostat. Consequently, the emitting part of the link (driver, emitter and ∼10m of fiber) would operate at LAr temperatures (-184° C) and would need to resist radiation levels of about 10^{14} (1 MeV) neutrons/cm^2 (n/cm^2) and 1 Mrad of gamma radiation accumulated over 10 years [2]. Other requirements for the analogue optical link include: dynamic range$\geq$11 bits, resolution of 8 bits, non-linearity$\leq$2%, and bandwidth$\geq$50 MHz.

We report on a series of irradiation tests carried out for several emitters and fibers, with neutrons at the Grenoble SARA facility [4] and with a ^{60}Co gamma source. A few comparisons with results from tests at room temperature are also presented. The radiation hardness of the current driver needed for most LED's was not studied here but preliminary investigations show that suitable LED drivers are available. Drivers are not needed for quantum-well devices with low threshold current.

[1]Will be situated at CERN, European Laboratory for Particle Physics, Geneva, Switzerland.

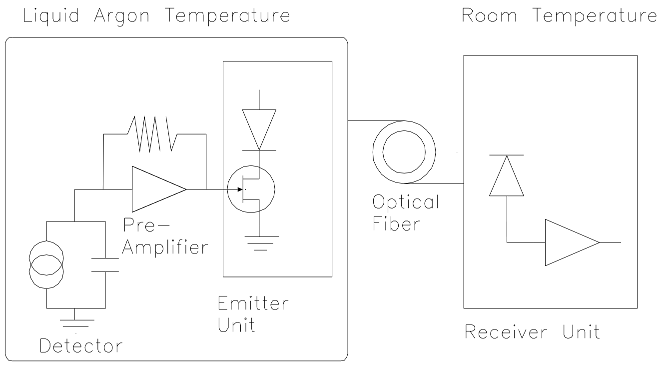

Fig. 1 Schematics of the cold optical link intended for use with the ATLAS liquid argon preshower detector.

II. Experimental Setup

During irradiation the devices were contained in a cryostat and all measurements were performed at LAr temperature unless stated differently. All devices were DC biased: ∼10 mA for the light emitting diodes (LED) and ∼4 mA for the laser diodes (LD). Current pulses were sent to one emitter at a time. The resulting light signals were transferred through optical fibers to remote receivers. The irradiations were performed over a period of 3-4 days. The neutron fluences were measured by the activation of Ni foils [4] and the gamma doses were measured with alanine dosimeters [5]. The total uncertainty for given fluences and doses is 20% in each case. The neutron energy spectrum at the SARA facility peaks at 6 MeV and the kerma displacement factors [6] used to convert the fluence to 1 MeV equivalent are 2.3±0.3 for GaAs [4] and 1.4 for SiO_2 [7].

III. Results: Light Emitting Diodes

The requirement for large dynamic range necessitates the use of high radiance LED's. One candidate was the HFE4050[2] $Al_xGa_{1-x}As$ LED, which give light around 850 nm. Others of this kind, such as the 1A362 [3], were also tested. Both devices are heavily doped and thus have short minority-carrier recombination lifetimes, which usually offers good radiation resistance [8]. The degradation of light output power from emitters is related to an increase in the recombination lifetime [8], τ.

[2]Manufactured by Honeywell, 830 Arapho Rd, Richardson,TX.

[3]Manufactured by ABB HAFO, Box 520, S-175 26 Järfalla.

A. Neutron Irradiation

The candidate LED's were exposed to a neutron beam to measure their radiation tolerance. Fig. 2 shows the relative light output for GaAs LED's during two irradiations together with a quantum well (QW) LED ETX001[4].

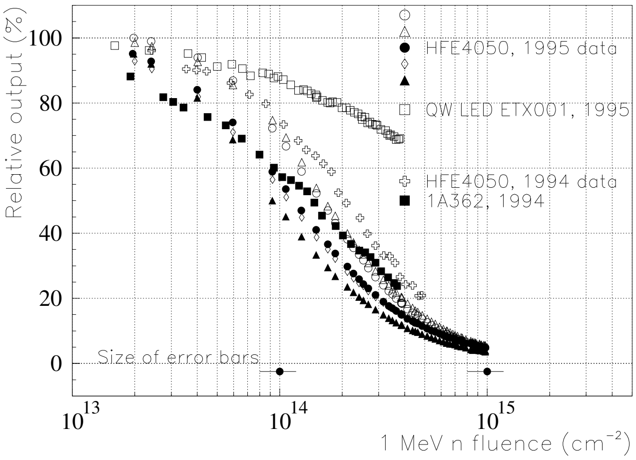

Fig. 2 LED output as function of received neutron fluence.

If one assumes that the radiation damage causes an increase of recombination lifetime one can parameterize the light loss

$$\frac{P}{P_0} = \frac{1}{(1 + \phi\tau K)^{1/\alpha}} \tag{1}$$

of the light output P (normalized to its pre-irradiation value), where ϕ is the neutron fluence, τ the recombination lifetime, K the damage constant and α a parameter depending on the recombination process. $\alpha = 1/3$ indicates space-charge recombinations [9]. Fig. 3 shows data with the fit to the parameterization. The HFE4050 showed damage for which the fit yield a τK which is of the same order as that for the LED's tested in reference [8], while the QW LED is significantly better. For low fluences the parameterization deviates from the data points for the GaAs LED especially, but is still able to predict the approximate performance for fluences above 10^{14} neutrons/cm^2. The HFE4050 LED's were packaged in TO46 cans with protection windows and with ball lenses mounted on the chip. The LED's with and without lenses and/or windows were tested to check for any attenuation effect. No such significant darkening was observed. The 1A362 LED was irradiated both at room and LAr temperatures as shown in Fig. 4. Although the dose rate differed there is no indication that the temperature strongly influences the radiation resistance.

1) Linearity

The light output as a function of the input current is shown in Fig. 5 for different fluences. The differential non-linearity from the fit of the data is displayed in Fig. 6. For signal currents of 10 mA the LED signal is still in the "knee" region of the diode curve. There is an apparent improvement in the

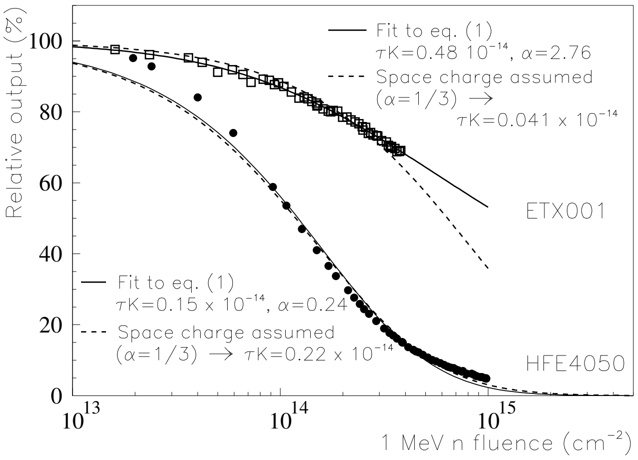

Fig. 3 Parameterization of radiation damage effects to a typical HFE4050 and an ETX001 quantum well LED.

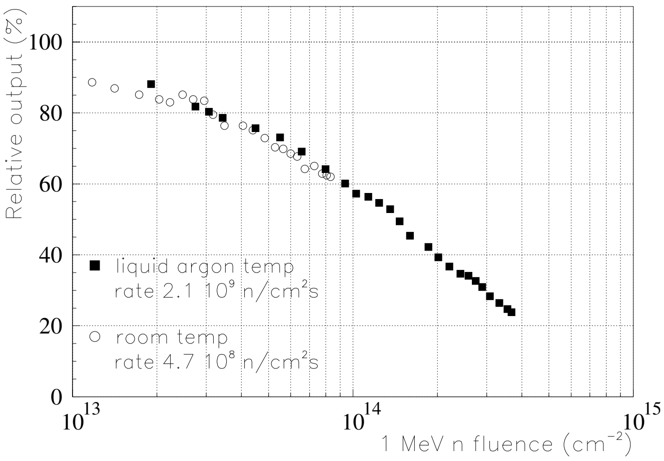

Fig. 4 Radiation tolerance of GaAs (1A362) LED at room temperature and at cryogenic temperature.

linearity due to a decrease in the slope of the light output as function of current. This makes the "knee" of the diode curve less pronounced. There is no degradation in the linearity due to irradiation. For higher order polynomial fits the deviation from a fit is less than 2%. In a high energy physics experiment the readout electronics are continously calibrated and variations in the response of the LED's can be eliminated.

2) Noise and Rise Time

The noise, taken as the RMS of the output signal, from the HFE4050 increased as displayed in Fig. 7. The RMS did not depend on the input current. Also shown is the ratio between the RMS and expected maximum output signal. The ratio reached ~0.4% after 10^{14} n/cm^2, which may limit analogue applications. For the readout of the preshower detector a band pass filter adapted to the specific preshower signals can be applied to reduce the noise. The rise times were measured pre- and post-irradiation in room temperature. In both cases the rise

[4]Manufactured by Sarnoff, CN 5300, Princeton, NJ.

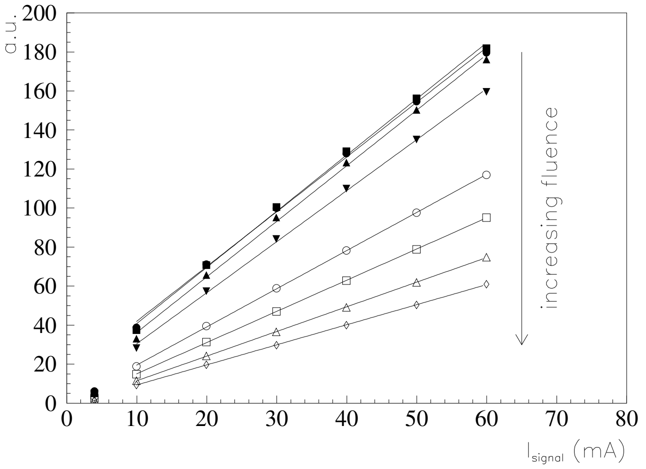

Fig. 5 Light output from a HFE4050 LED during irradiation versus current. The fluences for the different curves are given in Fig. 6.

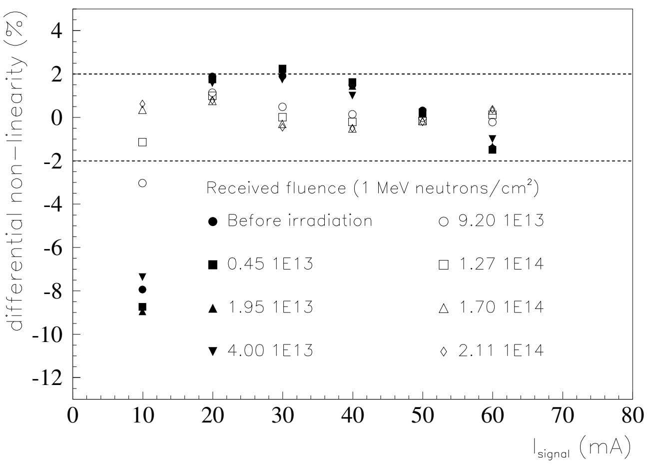

Fig. 6 The differential non-linearity from a linear fit of the data displayed in Fig. 5.

time satisfied < 6 ns in accordance with the specification.

3) Dose Rate and Annealing Effects

It should be noted that the components of the optical link were exposed to the expected LHC dose roughly three orders of magnitude faster than in the real LHC experiments. The more realistic lower dose rates may effect the results presented here. When a high current is applied to the emitter, annealing could be observed. The recovery varied significantly between different devices. The annealing was not permanent and a few devices returned to the pre-annealing output levels after only a few hours. In this work only limited investigations of possible annealing procedures were performed. For full evaluation of annealing, dedicated tests are needed. Such test should also include accelerated life time tests and the radiation damage dependence on dose rate. Such effects are described in [10].

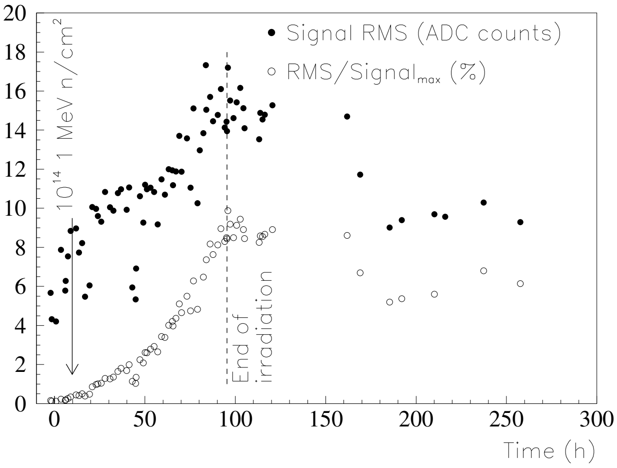

Fig. 7 Noise from a HFE4050 LED during and after an irradiation of 10^{14} n/cm^2.

B. Gamma Irradiation

The HFE4050 and 1A362 GaAs LED's were exposed to gamma radiation from a ^{60}Co source both at room and cryogenic temperatures. Initially the components were exposed to 1.7 Mrad at room temperature. After this dose all of the LED's were degraded less than a few percent, as shown in Fig. 8. The same components were then exposed to an additional dose of 1.4 Mrad at cryogenic temperature (in this case liquid nitrogen at $-196°$ C) and this radiation dose caused an additional degradation of less than 1%. For the total accumulated dose of 3.1 Mrad the degradation of the LED's varied between 2 and 4%.

IV. RESULTS: LASER DIODES

New commercially available QW LDs offer very good light output and low threshold currents. The radiation resistance of indium phosphide (InP) LD, emitting light around 1300 nm, has been investigated. The InP LD STH51007G [5], a QW diode, and QLR3S350-002 [6], a standard LD, were exposed to the neutron beam. The former LD resisted the neutron radiation significantly better. When biased above threshold the light output dropped less than 15% after $2.9 \cdot 10^{14}$ (6 MeV) n/cm^2 when biased above threshold. Our tests indicate that QW LDs can be more radiation tolerant than conventional LDs [9]. Vertical cavity surface-emitting laser diodes (VCSEL) offer excellent performance [11] and when exposed to neutron radiation the HFE 4080[7] showed a 15% loss after 10^{14} (1 MeV) n/cm^2 but no additional damage was observed for fluences up to $8 \cdot 10^{14}$ (1 MeV) n/cm^2. This VCSEL is not optimized for LAr temperature and was biased at 15 mA. VCSEL devices look very promising for future use in high radiation environments.

[5]Manufactured by Siemens Comp., Cupertino, Ca.

[6]Manufactured by Lasertron Inc., Sunrise, Fl.

[7]Manufactured by Honeywell 830 Arapho Rd, Richardson,TX.

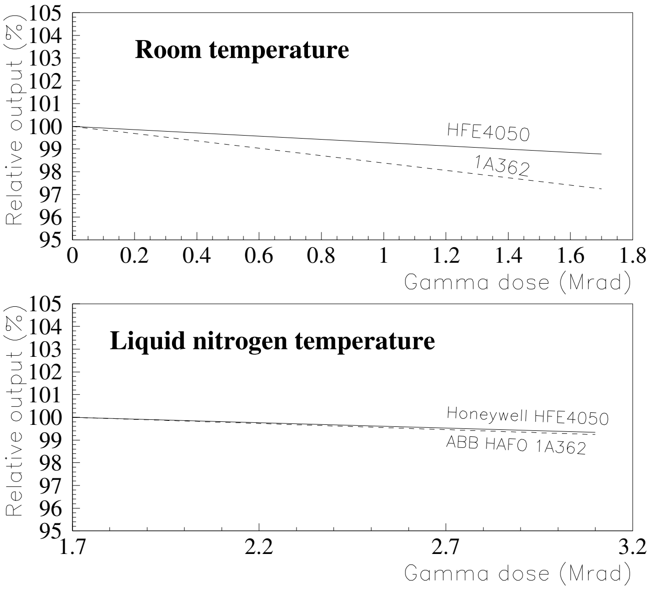

Fig. 8 The relative GaAs LED light output as function of gamma dose from a ^{60}Co source at room temperatures (upper) and cryogenic temperatures (lower). The cold irradiation followed the irradiation at room temperature. The dose on the x-axis is the total accumulated dose.

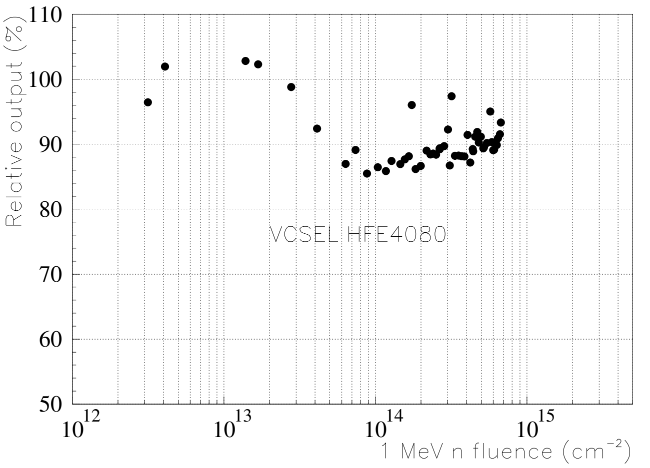

Fig. 9 VCSEL light output in liquid argon as function of received neutron fluence.

1) Threshold Current

One undesirable feature of LDs under radiation is an increase of threshold current due to radiation damage as shown in Fig. 11. In an analogue application it is necessary to always be biased above the threshold. Over a limited range it might be possible to raise the bias current to compensate for an increased threshold current.

2) Linearity and Noise

Above the knee of the diode curve, the linearity of the response of the tested LDs was consistently better than 2%.

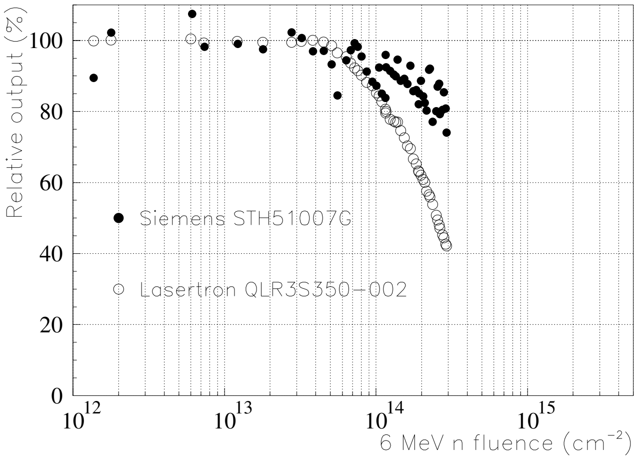

Fig. 10 Quantum well laser diode light output as function of received 6 MeV neutron fluence

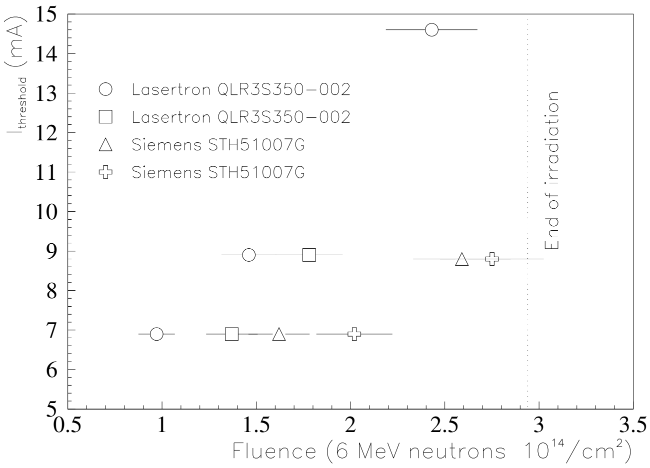

Fig. 11 Quantum well laser diode threshold currents as function of received 6 MeV neutron fluence.

The differential non-linearity is shown in Fig. 12.

The noise, taken as the RMS of the output signal, increased during the irradiation roughly by a factor of three as shown in Fig. 13. However, the light output decreased only slightly, thus the relative ratio of the RMS to the expected maximum signal was below 1 % even for fluences as high as $3 \cdot 10^{14}$ (6 MeV) n/cm^2.

V. Results: Optical Fibers

The radiation resistance of optical fibers has been extensively discussed in the literature [8, 12]. Pure silica core fibers are well-known to be gamma radiation hard. Moreover, improvement of glass purity and reduction of OH-content have improved the radiation hardness of optical fibers over the years. Fig. 14 shows a summary of tested fibers suitable for use in an analogue optical link. Our interest was mainly focused on multi mode large core diameter fiber which couples the maximum amount of light power from the emitters. The high light power is needed to produce the required dynamic range.

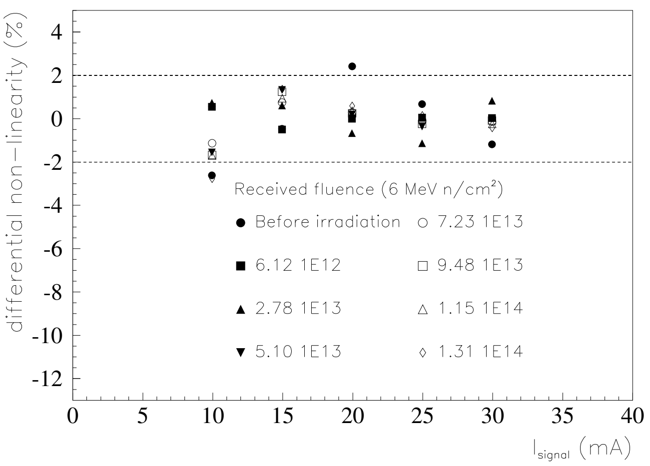

Fig. 12 The differential non-linearity of the Lasertron QW LD, QLR3S350-002.

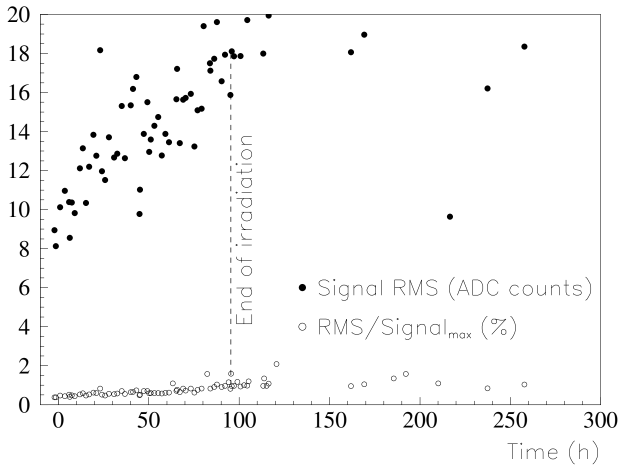

Fig. 13 Noise of the Siemens QW LD, STH51007G, during irradiation. The maximum signal is for an input current of 50 mA.

Our neutron tests at SARA (at LAr temp.) show that, for 10 m of multimode fiber, an attenuation less than 1% is observed using fluorine-doped[8] cladding and of the order of 30% using hard-core polymer cladding[9].

VI. Conclusions

We have shown that commercial GaAs LED's can withstand neutron radiation of 10^{14} (1 MeV) n/cm^2, with a light output degradation of less than 50%. A dose of $\sim$3 Mrad causes a $\sim$3% loss of light output. Quantum well LED's and LDs were shown to be more neutron resistant than the GaAs LED's. The high initial light output and, the low degradation of $<$15% after $\sim$ 10^{14} (1 MeV) n/cm^2 make QW devices suitable for analogue and digital links. A VCSEL device showed good radiation resistance. A VCSEL array under development will

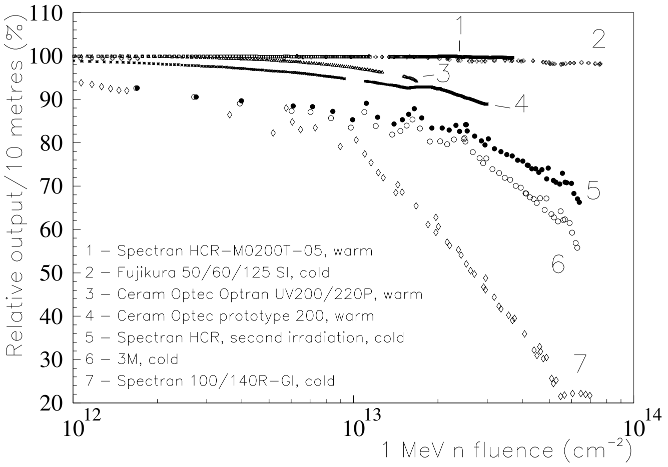

Fig. 14 Relative transmission of optical fibers as function of received neutron fluence.

be subjected to future tests. Several optical fibers met the requirements for radiation hardness for use at LHC.

VII. Acknowledgements

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VIII. References

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[8] From Fujikura,Surrey, England - 50 μm core, 50/60/125.

[9] For example Spectran, Avon, Cn - HCR-MT200-05.