Radiation Damage Studies of Optoelectronic Components for the CMS Tracker Optical Links

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Abstract

Optical links are being developed to transfer analogue tracking data and digital timing and control signals in the future Compact Muon Solenoid (CMS) experiment at CERN. The radiation environment inside the CMS tracker will be extreme, with hadron fluences up to ~10^{14}/cm^2 and ionising doses of ~100kGy over the experimental lifetime. Prototype link elements, consisting of commercially available 1310nm multi-quantum-well InGaAsP lasers and InGaAs p-i-n photodiodes, have been irradiated in a fully packaged form with ~6MeV neutrons to 10^{15}n/cm^2, 24GeV protons to 4x10^{14}p/cm^2 and ^{60}Co-gammas to 100kGy. Three types of single-mode optical fiber, two pure-silica core and one Ge-doped core, were irradiated in several stages with ^{60}Co-gammas to a total dose of ~90kGy.

Neutron and proton damage induced large increases in laser threshold and significant decreases in light output efficiency. P-i-n leakage current increased by up to 6-7 orders of magnitude for neutron and proton damage. P-i-n response was relatively unaffected until ~2x10^{14}n/cm^2, or ~4x10^{13}p/cm^2, after which the photocurrent decreased rapidly. Gamma damage after 100kGy was minor in comparison to hadron damage in both the lasers and p-i-n photodiodes. The radiation induced attenuation at 1300nm in the optical fibers was dependent upon the fiber type, with losses of 0.08dB/m for the pure-silica core fiber and 0.12dB/m in the Ge-doped core fiber, after ~90kGy. The annealing in one of the pure-silica core fibers was found to be temporary in nature.

I. INTRODUCTION

The Compact Muon Solenoid experiment (CMS)[1] is one of two large, general purpose experiments to be installed in the CERN Large Hadron Collider (LHC). Analogue signals from 10^7 microstrip detector channels in the CMS tracker will be time- multiplexed (at 256:1) and transmitted at 40Msamples/s along 50000, 100m long, optical links[2]. Several hundred digital optical links will also be used to pass timing and control signals to and from the tracker. Prototype optical links, based on laser transmitters, are currently being tested[3] at CERN, following developments within the RD23 collaboration[4].

The LHC will collide two 7TeV proton beams at the centre of CMS at a rate of 40MHz, with ~20 p-p collisions occurring every 25ns at the highest beam luminosities. Simulations predict that each p-p collision will generate ~180 high energy particles (roughly 70 $\pi^{\pm}$, 10 $p^{\pm}$, 10n, 10 $K^{\pm}$, and 80 γ from π^0 decays)[1]. Significant radiation damage will be caused by these particles (and their decay products, plus lower energy secondary electrons and spallation neutrons), increased by the helical trajectory that charged particles will follow in the 4T magnetic field inside the CMS tracker. The highest particle fluxes will be close to the beam interaction point. For example, at a radius of 20cm from the beam axis (at the innermost layer of silicon microstrip detectors) the fluence over ten years of high luminosity LHC operation will consist of ~10^{14}neutrons/cm^2 (~1MeV) and ~5x10^{14}/cm^2 charged hadrons (typically several hundred MeV in energy)[1,5]. In addition, a total ionising dose of ~100kGy will result from charged particles and gammas. It is expected that the LHC will run for approximately six months per year and the experiments will take data over a period of at least ten years. All of the optical link components situated inside the CMS tracker must therefore be sufficiently reliable and radiation resistant to last the lifetime of the experiment. Maintenance or replacement of components will be very difficult, due to the overall complexity of the apparatus and induced radiation levels.

The motivation for this work was to qualify the radiation hardness of all the prototype optical link components to the level of hadron fluences and ionising doses expected inside the CMS tracker. A representative selection of results is presented here for radiation damage and recovery in lasers, p-i-n diodes and fibers. A separate paper[6] describes the radiation damage studies of candidate connectors for the CMS optical links.

II. RADIATION DAMAGE EFFECTS

Radiation damage occurs when incident particles transfer sufficient energy to a material to displace host atoms or to cause ionisation[7]. In semiconductor lasers and p-i-n diodes, we have found that the effects of displacement damage are more important than ionisation damage for fluences and doses typical of LHC levels. Displacement damage introduces defect states into the band-gap that can act as generation-recombination centres[7]. In semiconductor lasers, recombination at these defects competes with band-to-band

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radiative transitions for the injected carriers, resulting in higher threshold currents[8-13]. Above threshold, the stimulated recombination lifetime is much shorter than the lifetime associated with recombination at defects. The laser slope-efficiency (dL/dI, where L is the output light power at current I) is therefore relatively unaffected[8-11] by displacement damage, until high fluences are reached ($>10^{14}$n/cm^2)[13]. Degradation of integrated components inside a fully packaged laser transmitter, such as lenses, can cause significant attenuation of the output power[12]. The emission spectrum of semiconductor lasers is found to be unaffected by radiation damage[9]. Little data is available on the recovery of the damage in lasers.

In p-i-n detectors, generation of charge at the defects causes an increase in dark current[14-17], raising the minimum power level of detectable optical signals and increasing the noise. A defect, denoted E2, at E_C-0.29eV is reported to be responsible for leakage current increases in 1MeV electron irradiated InGaAs p-i-n diodes[14-16]. Recovery of leakage currents in electron irradiated InGaAs p-i-n diodes proceeds in proportion with log(t/τ), consistent with a distribution of activation energies[16]. Radiation induced defect states in the band gap can also act as trapping/recombination centres for electrons and holes, causing a reduction of the photocurrent[17].

It is well established that irradiation causes increased attenuation in SiO_2 optical fibers (Refs. [18-22] are examples of recent studies). The level of damage depends upon many factors such as the fiber type (composition and impurities, geometry, and drawing conditions), the radiation source (ionisation or displacement damage), and environmental parameters during irradiation and recovery (transmitted light level and wavelength, and temperature). Ionising dose appears to be more important than displacement damage for the doses of interest inside the CMS tracker[21]. The competing rates of creation and annealing (plus activation and de-activation) of absorption centres typically give rise to a dependence on both total dose and dose-rate for which several kinetic models have been proposed[19,23,24]. The effect of a series of irradiations has been reported by Griscom[25] for multi-mode pure silica core and Ge-doped core fibers, where temporary recovery was observed between irradiation stages due to optical bleaching of defects that were rapidly re-activated in the subsequent irradiation step. Temporary recovery of radiation induced attenuation was observed in our earlier gamma irradiation tests on pure-silica core fibers[21] (at 1550nm) and in this paper we investigate the effect of different light levels on this behavior.

III. EXPERIMENT

We tested 1310nm multi-quantum-well lasers based on the double channel planar buried heterostructure (DCPBH)[26] geometry, shown schematically in Fig. 1. The lasers are mounted on silicon sub-mounts, pigtailed with actively aligned, single-mode fiber and hermetically sealed in a ceramic mini-DIL package by Italtel. Naked laser die (mounted inside TO-cans), as well as lasers from other manufacturers, have also been studied[13] but the results will not be reported here. Lasers were tested with both lensed Ge-doped fiber and angle-cleaved pure-silica core fiber pigtails. The initial slope-efficiency (dL/dI) was E~0.2W/A for devices with lensed fiber and E~0.06W/A for cleaved fiber. The laser threshold current before irradiation was typically I_t=8-11mA.

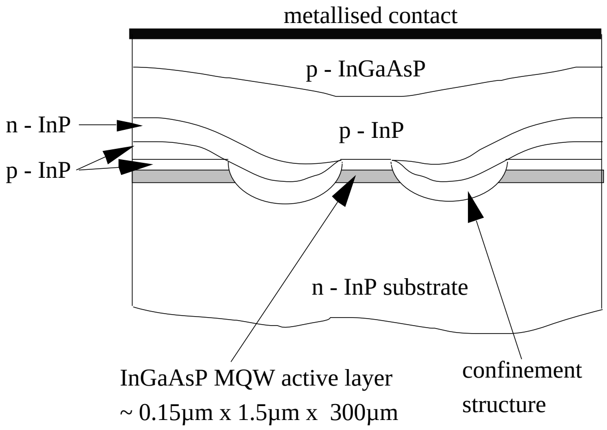

Fig. 1: Schematic cross-section of DCPBH InGaAsP laser.

Laser characteristics were measured periodically during irradiation. The L-I measurement took ~1 minute and was made at intervals of 30 minutes to 1 hour, using an adjustable current window of I_t-10mA<I<I_t+20mA. In the current range above threshold, the lasers operate in a linear region, with no observable roll-off due to heating of the device. The threshold current was measured as the intercept (on the current axis) of a line fitted to the L-I data above 20µW output power, after subtracting any sub-threshold d.c. offset in the output amplifier. The slope-efficiency (E) is the gradient of this fitted line. The effect of electrical bias on the radiation damage (and recovery) was also tested by keeping some devices under bias (5-10mA above threshold), and others unbiased, between the measurement cycles.

The p-i-n detectors tested were 75µm active diameter, back-illuminated, planar InGaAs photodiodes (on a 600µm x 600µm die) manufactured by Epitaxx. A schematic cross section of the devices is shown in Fig. 2[14,27].

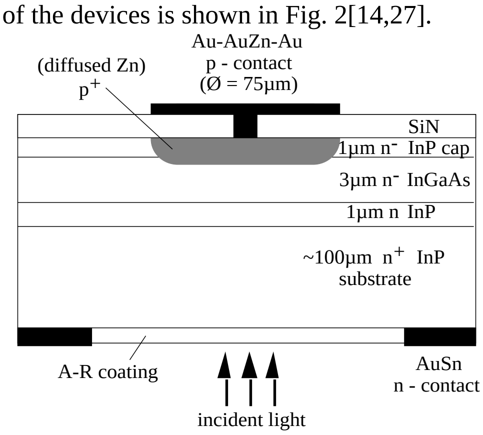

Fig. 2: Schematic cross-section of InGaAs p-i-n photodiode

The photodiodes were supplied by Italtel in a mini-DIL package, pigtailed with single-mode fiber. The fiber is coupled to the diode via a V-groove etched into the silicon sub-mount. The pre-irradiation leakage current was I_{leak}~100pA and the initial responsivity at 1310nm was η~0.9A/W.

The p-i-n leakage current and responsivity were monitored at reverse bias voltages of 0, 2.5, 5, 7.5 and 10V during irradiation. Light from a 1310nm laser situated outside the radiation source was transmitted, via an 8-way optical splitter and 8-way fiber ribbon, to the devices under test. One channel of the splitter was connected to a photodiode (also located outside the source) to monitor any fluctuations in the laser characteristics. Incident power levels at the p-i-n diodes were ramped between 0 and ~250µW (over ~1 minute) at periodic intervals (~30 minutes to 1 hour). In between measurements, the devices were un-illuminated and reverse biased at 5V.

Neutron tests were conducted at the SARA facility[28] at ISN, Grenoble. Neutrons are stripped with an average energy of 6MeV from an 18MeV deuteron beam incident on a beryllium target. A 5µA beam current produced up to ~$2x10^9 n/cm^2/s$. Ni foil dosimeters were used to measure the fluence with an accuracy of ~15%. Proton irradiation was carried out using the 24GeV proton synchrotron (PS) beam at CERN. The fluence was measured with aluminium foils to an accuracy of ~6%. The proton beam consisted of 14s cycles with three 2s-long beam pulses of ~$2x10^{11} p/cm^2$ per pulse. The ^{60}Co source at Imperial College was used for gamma irradiation. The dose rate was ~1.3kGy/hr and the total dose was measured with alanine dosimeters to ~10% accuracy. All the exposures were carried out at room temperature. Table I summarises the number of devices tested, the fluences and doses received, and the duration of the irradiation and monitored recovery period.

Table I
No. of devices irradiated, measurements, fluences and time scales.

Particle type	No. of devices	Measure-ments	Fluence (or dose)	Exposure period	Recovery period
neutron ~6MeV	10 lasers 5 p-i-n's	I_t, E I_{leak}, η	up to $10^{15}/cm^2$	102 hours	up to 2100 hours
proton 24GeV	5 lasers 4 p-i-n's	I_t, E I_{leak}, η	$4x10^{14}$ $/cm^2$	10 hours	660 hours
gamma ^{60}Co	5 lasers 5 p-i-n's	I_t, E I_{leak}, η	100kGy	70 hours	60 hours

Fibers from three different manufacturers were irradiated at the ^{60}Co source at Imperial College. Fibers with pure silica core, F-doped cladding and UV-cured acrylate coating manufactured using a VAD process with 9/125/250µm (core/cladding/coating diameters) geometry were obtained from Sumitomo (fibers A), and FiberWare (fibers B). Fibers C were supplied by Lycom, having the same geometry but with Ge-doped core, pure silica cladding, UV-cured acrylate coating and manufactured by an MCVD process. Table II details the irradiation conditions. Dose rates were measured using a silicon photodiode to be uniform to within 10% over the fiber spool. All fibers were wound onto 45mm diameter spools, and no connectors or splices were present in the irradiation area. The temperature inside the source cell was 19.5±1.0°C during the irradiation and recovery periods.

To investigate the effect of temporary annealing[21,25] the tests were carried out in several stages: typically 24hrs exposure (to ~45kGy), 24hrs of annealing, then a second exposure for 24hrs (also ~45kGy), followed by a longer annealing period of ~72 hours. Two fiber samples from each manufacturer, of equal length, were irradiated together in each test with different light power levels (150nW and 100µW) continuously transmitted in each fiber sample. The radiation-induced attenuation of 1300nm laser light was measured at 1-5 minute intervals during irradiation and recovery. The transmission through a third, unirradiated fiber was used as a reference to track fluctuations of the laser output power during each test.

Table II
Summary of fiber irradiation conditions

Fiber	Test Length	Light Level	Dose Rate	Total Dose
A1	210m	100µW	1.9 kGy/hr	98 kGy
A2	210m	150nW	1.7 kGy/hr	88 kGy
B1	120m	100µW	1.85 kGy/hr	88 kGy
B2	120m	150nW	1.9 kGy/hr	90 kGy
C1	120m	100µW	1.9 kGy/hr	88 kGy
C2	120m	150nW	1.85 kGy/hr	86 kGy

IV. RESULTS

The effect of radiation damage on the laser threshold and efficiency, and the subsequent annealing, is given in Section A. The radiation damage to the p-i-n leakage current and response is then discussed in Section B, and Section C describes the radiation damage effects on fibers.

A) Lasers

An example of the L-I characteristics measured during the proton test (just before irradiation and after $3x10^{14} p/cm^2$) is illustrated in Fig. 3. An increase in threshold current and decrease in efficiency are both clearly visible.

The threshold increases measured during neutron and proton irradiation were much larger than the changes seen during gamma irradiation. For example, neutron damage results are shown in Fig. 4 for 5 devices irradiated at the same time but with different neutron fluxes. The threshold increase is roughly linear with fluence though some annealing of the damage occurred during the irradiation period. Similar effects are seen for proton irradiation, but for a given fluence, 24GeV protons are 4-6 times more damaging than the ~6MeV neutrons. In contrast, a gamma dose of 100kGy caused a threshold shift of only ~1mA.

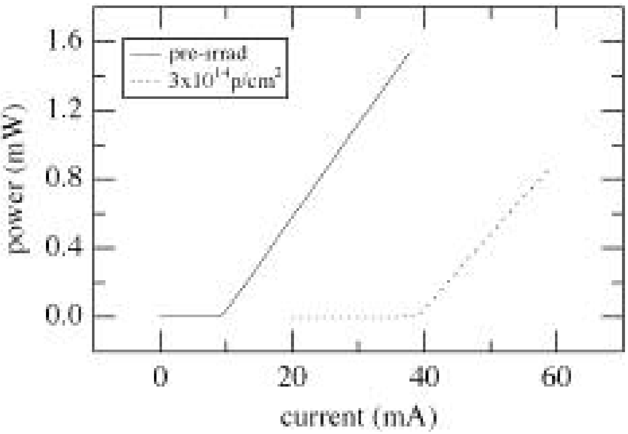

Fig. 3: L-I curves measured during proton irradiation.

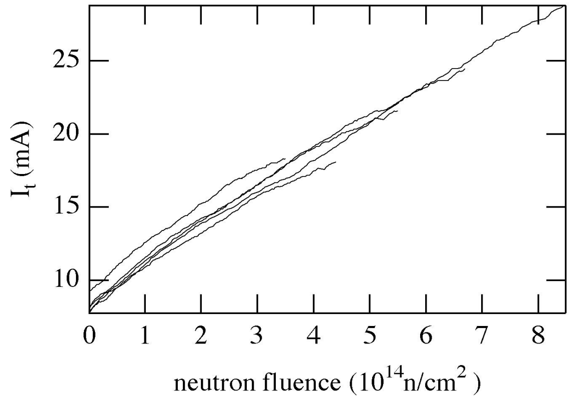

Fig. 4: Threshold current increases during neutron irradiation.

Electrical bias decreases the radiation induced threshold increase, as illustrated in Fig. 5 for data measured (a) during and (b) after proton irradiation, under the bias conditions given in Table III. The devices all received the same fluence (to within 10%) but the damage effects are greater in the unbiased lasers. When the same bias is applied to *all* the lasers during the recovery period (regions IV, V, and VI in Fig. 5(b)), the overall threshold change approaches a similar value for all five lasers. A similar increase in damage in unbiased devices was also measured during neutron irradiation. These results are consistent with the reduction in radiation-induced threshold change for biased lasers reported in ref. [10].

Table III
Bias condition of lasers during proton irradiation and recovery period referring to the results shown in Fig. 5.

Region [Fig.]	Time (hrs)	Group A	Group B
I [5(a)]	2.6 - 8.2	biased at 30mA	unbiased
II [5(a)]	8.2 - 13	biased at 50mA	unbiased
III [5(b)]	13 - 349	biased at I_t+10mA	unbiased
IV [5(b)]	349 - 452	all biased at 60mA	
V [5(b)]	452 - 590	all biased at 80mA	
VI [5(b)]	590 - 663	all biased at 100mA	

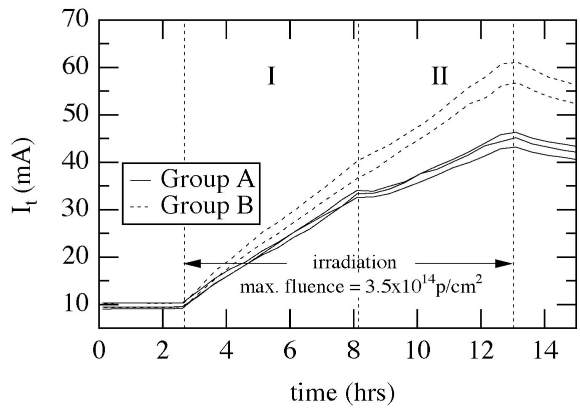

Fig. 5(a): Decreased threshold damage in biased lasers.

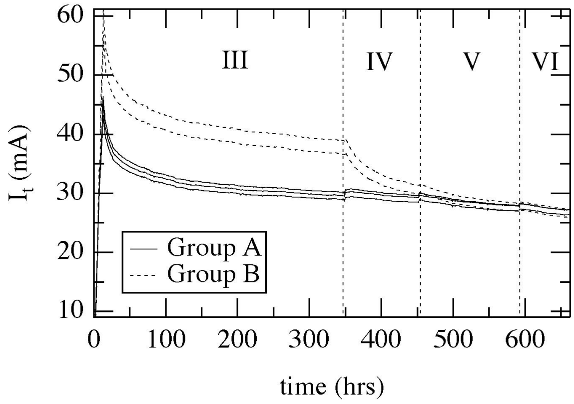

Fig. 5(b): Recovery of threshold damage the showing effect of bias.

As shown in Fig. 6, the recovery of the threshold current after proton irradiation (data taken from region III of Fig. 5(b)), normalised to the damage at the end of irradiation, is linear with log(t) with a drop of ~15% per decade (at 27.5°C). Similar annealing behaviour, seen in leakage current recovery of electron irradiated p-i-n diodes[16], was shown to be consistent with a distribution of thermal activation energies for annealing of particular defect species.

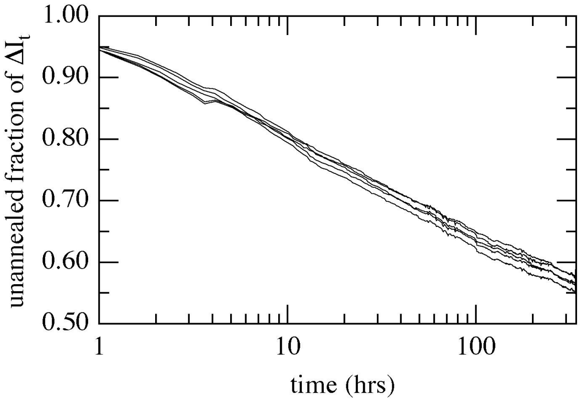

Fig. 6: Linear dependence of threshold recovery with log(time) after proton damage (corresponds to region III in 5(b)).

The similar rate of recovery seen in Fig. 6 for biased and unbiased devices can be explained if the effect of electrical bias is simply to shift the distribution of activation energies to a lower value (assuming that the distribution of defects with different annealing activation energies is uniform). In this case, there will be some extra short term annealing for biased devices, which actually occurred during the irradiation period.

In contrast to other studies[8-11], where the particle fluences were typically lower, significant efficiency loss was also observed, as shown for neutron damaged lasers in Fig. 7. As with the threshold increase, 24GeV protons were a factor of 4-6 more damaging than a similar fluence of ~6MeV neutrons The efficiency loss, like the threshold increase, was roughly linear with fluence.

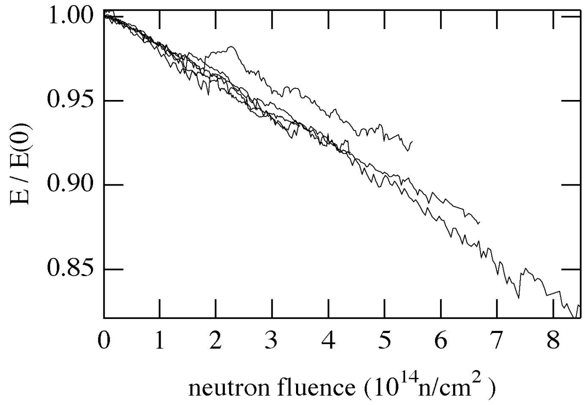

Fig. 7: Efficiency loss for lasers during neutron irradiation.

The results of gamma irradiation were relatively inconclusive in terms of efficiency loss. Three devices had a ~8% loss after 100kGy and two other lasers showed no loss. The data from two devices with no loss were, however, strongly correlated with temperature outside the source where the monitoring photodiodes were located. In general there was some temperature dependence of the light coupling into the monitoring photodiodes in all of the experiments, resulting in the efficiency data being more noisy than the threshold data.

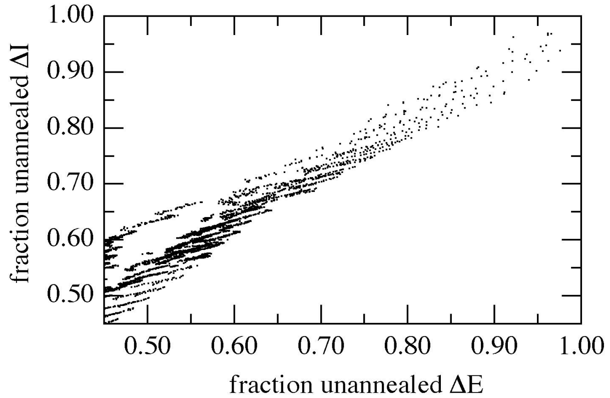

Fig. 8: Correlation between recovery of threshold and efficiency damage following proton irradiation.

For the proton test, where the temperature environment was the most stable, a direct correlation is visible between the recovery of the efficiency loss and threshold change, as shown in Fig. 8. The loss of efficiency is therefore probably related to the threshold increase, which is caused by the decrease in injected carrier lifetimes[8], rather than, for example, radiation-induced degradation of the packaging.

With the combined information of damage and recovery effects it is possible to predict[13] the threshold current and efficiency change for irradiation over an extended period, such as during the lifetime of the CMS experiment. To obtain a more reliable estimate of the damage to the components used inside the CMS tracker, it will be necessary to calculate the non-ionising energy loss (NIEL)[29] in the laser material for the different radiation sources used, as well as for the different particles encountered inside the CMS tracker. The NIEL hypothesis has been extensively demonstrated to relate measured displacement damage effects in different materials to the incident particle type and energy[30]. Work is currently in progress on these calculations.

B) P-i-n photodiodes

The leakage currents measured at 2.5, 5, 7.5 and 10V reverse bias are shown as a function of fluence in Fig. 9 for neutron and proton damaged p-i-n detectors. The radiation induced leakage current increases non-linearly with fluence by up to 6-7 orders of magnitude more than pre-irradiation values. Approximately 10 times more neutrons were required to cause the same increase in dark current as for protons.

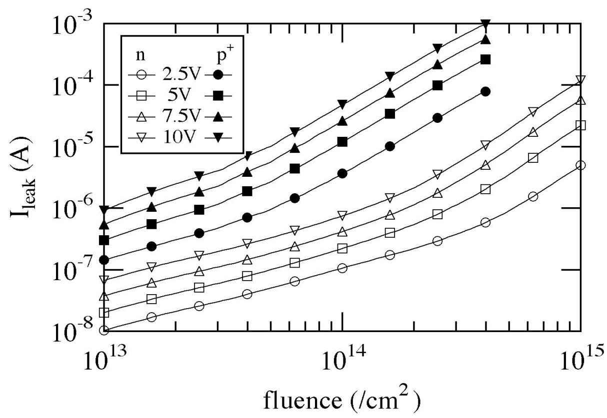

Fig. 9: Leakage current increase in proton irradiated p-i-n detectors.

In contrast to the hadron irradiation results, devices that were irradiated with ^{60}Co gammas to 100kGy showed a much smaller increase in leakage current, of ~3 orders of magnitude[31]. Since the overall increase in leakage current due to an ionising dose of 100kGy is much smaller than that due to typical LHC hadronic fluences, ionising damage will be a minor factor in determining the leakage current in p-i-n diodes used inside the CMS tracker. The relatively low level of leakage current increase due to ionising damage also suggests that the difference in the damage rates of the neutrons and protons is not related to the additional electric charge of the proton, but mainly to the energy difference (and NIEL) of the radiation sources.

Annealing of the leakage current was also measured after each irradiation test. The neutron-irradiated devices were measured for the longest period (3 months), during which time ~20% of the initial damage annealed[31]. For the gamma-irradiated devices no significant recovery was observed in 80 hours following irradiation. Recovery measurements on the proton-irradiated p-i-n diodes were consistent with the neutron damage but the results were less noisy as the temperature in the PS beam area was relatively stable (27.5±0.5°C). Plotting the unannealed fraction of the leakage current damage against time, as in Fig. 10, shows that the leakage current damage has a uniform rate of annealing over log(time), about 10% per decade (at 27.5°C), independent of bias voltage. This behaviour, as with the laser threshold recovery, is consistent with a distribution of activation energies for annealing[16].

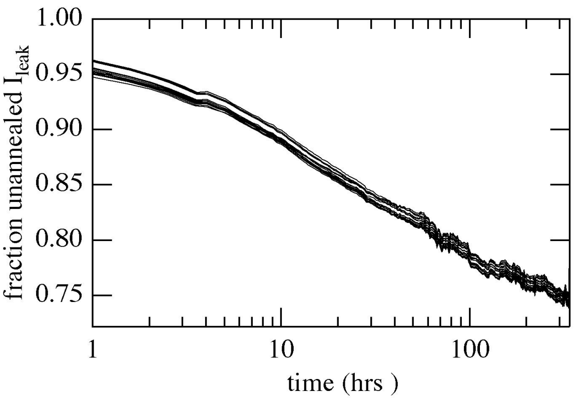

Fig. 10: Log(time) dependence of leakage current annealing in proton damaged p-i-n diodes.

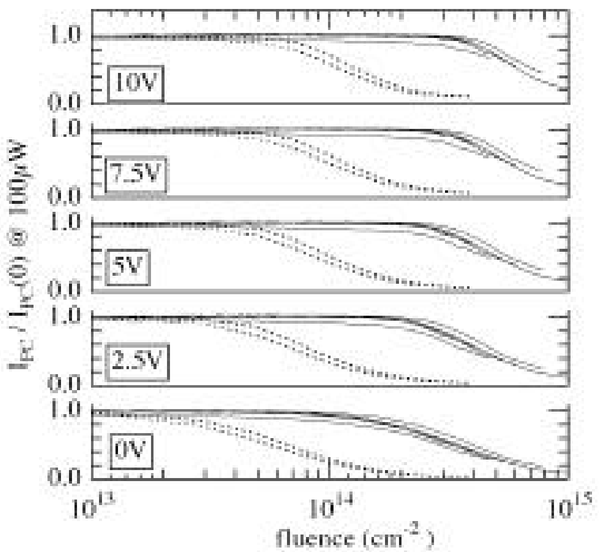

Fig. 11: Decrease in photocurrent I_{PC} for 100µW optical signal during neutron irradiation (solid lines) and proton irradiation (dashed lines) for bias voltages between 0V and 10V.

The effect of neutron and proton irradiation on the p-i-n response is illustrated in Fig. 11, showing the photocurrent for a 100µW d.c. optical signal, normalised to the initial value. There is only a small decrease in photocurrent up to a certain fluence, around 1-4x10^{14}n/cm^2 or 2-8x10^{13}p/cm^2, depending upon the bias voltage. Above this fluence, there is a rapid decrease of the response towards zero.

The results are qualitatively similar for neutron and proton irradiated diodes, but the 24GeV protons are ~5 times more damaging than ~6MeV neutrons in terms of the average fluence required to cause, for example, a 50% drop in photocurrent. For both neutrons and protons there is a roughly linear increase with bias voltage in the fluence required to cause 50% loss of signal. In contrast to neutron and proton damage, there was no significant change in the photocurrent after gamma irradiation to 100kGy[31]. No significant recovery of the damage to the p-i-n responsivity was observed following irradiation with neutrons or protons.

C) Fibers

The time evolution of the induced attenuation during the series of fiber irradiation tests is shown in Fig. 12, with the same results plotted against dose in Fig. 13.

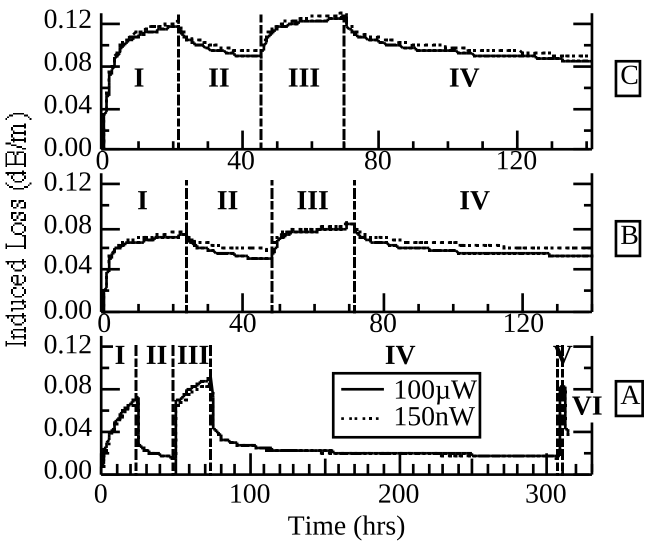

Fig. 12: Time evolution of the induced loss in the three fibers A, B, and C. Regions I, III, and V correspond to periods of irradiation, while regions II, IV, and VI correspond to annealing with the source off. The majority of the recovery in type A fibers appears to be temporary in nature.

The radiation induced losses in the pure-silica core fibers (types A and B) were ~0.08dB/m after 80kGy, compared to ~0.12dB/m in the Ge-doped core fiber. This low level of damage indicates that all three fibers are suitable for use inside the CMS tracker where around 10m of fibre (multiplied by 50000 channels) will be used inside the tracker to transfer signals from the front-end electronics to a patch panel, where connection is made to 90m long fibre ribbons linked to the remote data acquisition hardware. Further tests are underway to measure the dose-rate dependence, though type A fibers have very little dose-rate dependence at 1550nm[21].

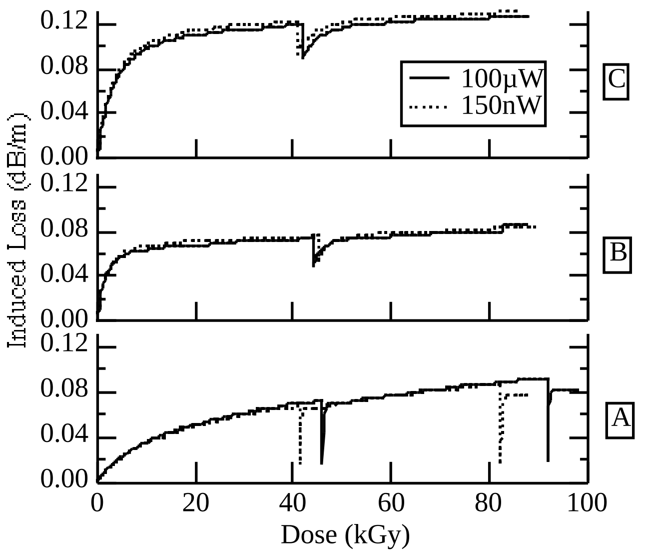

Fig. 13: Induced loss in the fiber samples as a function of dose, illustrating the temporary recovery component for type A fibers.

The recovery of the damage in Fiber A has (at least) two components: one anneals fast, but is temporary, and the other is slower, but permanent in nature. Both the damage and recovery in Fiber A are independent of the transmitted light power, suggesting that the temporary recovery is due to thermal, rather than optical, bleaching of the radiation induced defects. More series of irradiations are planned, using different temperatures, to confirm this hypothesis. In contrast, the recovery of the attenuation in types B and C is permanent in nature and depends, to a small extent, on the level of transmitted optical power.

V. SUMMARY

Commercially available 1310nm MQW DCPBH lasers and $In_{0.47}Ga_{0.53}As$ p-i-n detectors in single-mode fiber pigtailed packages have been irradiated with ~6MeV neutrons up to 10^{15}n/cm^2, 24GeV protons to 4x10^{14}p/cm^2 and ^{60}Co gammas to 100kGy. For the lasers the damage from 24GeV protons was 4-6 times worse than ~6MeV neutron damage and for the p-i-n photodiodes the protons were 5-10 times more damaging. In comparison to hadron damage, the effects of gamma irradiation were much smaller.

Large laser threshold current increases were observed following neutron and proton damage, the worst case being an increase of 50mA for the proton damage, in conjunction with an efficiency loss of ~50%. The damage to the lasers recovered with a log(time) dependence and, as a result of this annealing, the overall damage will be much smaller in our actual application, where the irradiation period is spread out over 10 years. The lasers should therefore be sufficiently radiation resistant for use in the CMS tracker optical links.

The leakage current in p-i-n photodiodes increased (non-linearly) by up to 6-7 orders of magnitude, compared with pre-irradiation values, for the highest neutron and proton fluences. After a fluence of ~5x10^{14}n/cm^2 (or 10^{14}p/cm^2) the photocurrent was reduced by 50% and by 90% for fluences twice as high. The leakage current recovered with a log(time) dependence but no recovery of the photocurrent was observed. If the present prototype p-i-n photodiodes are used in the CMS tracker, it will be necessary to ensure that they are located at a radius ~50cm from the beam, where the hadron fluence is <10^{14}/cm^2[1,5].

A series of gamma irradiations have been carried out (in two stages) on three types of single-mode optical fiber using a dose-rate of ~1.9kGy/hr and a total dose of ~90kGy. The two pure-silica core fibres had a loss of ~0.08dB/m compared to 0.12dB/m in the Ge-doped fiber. It can be concluded that radiation induced losses will not be an important effect if any of these fibers are used inside the CMS tracker. The recovery of one of the pure-silica core fibers was found to be largely temporary in nature and independent of optical power, whereas the other fiber types had permanent annealing with some dependence on the transmitted power. This temporary annealing behaviour should be included, where appropriate, in kinetic models that are used predict the attenuation in fibers in order to avoid large errors.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

[1] The Compact Muon Solenoid Technical Proposal. CERN Report LHCC 94-38 (1994).

[2] G. Hall, "Analogue optical data transfer for the CMS tracker", *Nucl. Inst. and Meths. A*, vol.386, p.138, 1997.

[3] V. Arbet-Engels, G. Cervelli, K. Gill, R. Grabit, C. Mommaert, G. Stefanini and F. Vasey, "Analogue Optical Links for the CMS Tracker Readout System", presented at 7th Pisa Meeting on Advanced Detectors, to be published in Nucl. Instr. and Meth. A.

[4] RD23 Collaboration Status Report, "Optoelectronic Analogue Signal Transfer for LHC Detectors", CERN/LHCC 97-30 (1997). For more information see the RD23 www page: http://www.cern.ch/RD23/

[5] M. Huhtinen, "Radiation Environment Simulations for the CMS Detector", CMS TN/95-198, (available from CMS Secretariat, CERN, CH- 1211, Genève 23, Switzerland)

[6] J. Batten, J. Troska, K. Gill and F. Vasey. Paper in preparation.

[7] J. E. Gover and J. R. Srour., "Basic Radiation Effects in Nuclear Power Electronics Technology", *Sandia Laboratory Report*, SAND85-0776 (1985).

[8] C. E. Barnes and J. J. Wiczer, "Radiation Effects in Optoelectronic Devices", *Sandia Laboratory Report*, SAND84-0771 (1984).

[9] C. Barnes, D. Heflinger and R. Reel, "Effect of Neutron Irradiation on Laser Diode Properties", *Proc. SPIE*, vol.1174, p.233, 1989.

[10] B. D. Evans, H. E. Hager and B. W. Hughlock, "5.5-MeV Proton Irradiation of a Strained Quantum-Well Laser Diode and a Multiple Quantum-Well Broad-Band LED", *IEEE Trans. Nucl. Sci.*, vol.40, p.1645, 1993.

[11] H. Lischka et al., "Radiation Effects in Optoelectronic Devices", *Proc. SPIE*, vol.2425, p.43, 1994.

[12] P. W. Marshall et al., "Space-Radiation Effects on Optoelectronic Materials and Components for a 1300nm Fiber Optic Data Bus", *IEEE Trans. Nucl. Sci.*, vol.39, p.1982, 1992.

[13] K. Gill, V. Arbet-Engels, G. Cervelli, R. Grabit, C. Mommaert, G. Stefanini, J.Troska and F. Vasey, "Effect of Neutron Irradiation of MQW Lasers to 10^{15}n/cm^2", CMS Note 97/044. (available from authors). Paper in preparation.

[14] R. J. Walters, G. J. Shaw, G. P. Summers, E. A. Burke, S. R. Messenger, "Radiation Effects in $Ga_{0.47}In_{0.53}As$ Devices", *IEEE Trans. Nucl. Sci*, vol.39, p.2257, 1992.

[15] G. J. Shaw, S. R. Messenger, R. J. Walters and G. P. Summers, "Radiation-Induced Reverse Dark Currents in InGaAs Photodiodes", *J. Appl. Phys.*, vol.73, p.7244, 1993.

[16] G. J. Shaw, R. J. Walters, S. R. Messenger and G. P. Summers, "Time Dependence of Radiation-Induced Generation Currents in Irradiated InGaAs Photodiodes", *J. Appl. Phys.*, vol.74, p.1629, 1993.

[17] H. Ohyama, J. Vanhellemont, Y. Takami, K. Hayama, T. Kudou, S. Kohiki and H. Sunaga, "Degradation and Recovery of $In_{0.53}Ga_{0.47}As$ Photodiodes by 1-MeV Fast Neutrons", *IEEE Trans. Nucl. Sci.*, vol.43, p.3019, 1996.

[18] E.W.Taylor, E.J.Friebele, H.Henschel, R.H.West, J.A.Krinsky, C.E.Barnes, "Interlaboratory Comparison of Radiation-Induced Attenuation in Optical Fibers. Part II: Steady-State Exposures", *IEEE J.Light.Tech.*, vol.8, pp.967-976, June 1990.

[19] M.Kyoto, Y.Chigusa, M.Ohe, H.Go, M.Watanabe, T.Matsubara, T.Yamamoto, S.Okamoto, "Gamma-Ray Radiation Hardened Properties of Pure Silica Core Single-Mode Fiber and Its Data Link System in Radioactive Environments", *IEEE J. Light. Tech.*, vol.10, pp.289-294, March 1992.

[20] H.Henschel, O.Köhn, H.U.Schmidt, E.Bawirzanski, A.Landers, "Optical Fibres for High Radiation Dose Environments", *IEEE Trans. Nucl. Sci.*, vol.41, pp.510-516, June 1994.

[21] K.Gill, R.Grabit, M.Persello, G.Stefanini, F.Vasey, "Gamma and neutron radiation damage studies of optical fibres", *J.Non-Cryst. Solids* (in print).

[22] H.Henschel, O.Köhn, H.U.Schmidt, "Radiation-induced loss of optical fibres at 1300nm and 1550nm wavelength", *Proc. SPIE* , vol.2811, pp.68-76, 1996.

[23] D.L.Griscom, M.E.Gingerich, E.J.Friebele, "Model for Dose, Dose-Rate and Temperature Dependence of Radiation-Induced Loss in Optical Fibers", *IEEE Trans. Nucl. Sci.*, vol.41, pp.523-527, June 1994.

[24] H.Henschel, E.Baumann, "Effect of Natural Radioactivity on Optical Fibers of Undersea Cables", *IEEE J. Light. Tech.*, vol.14, pp.724-731, .

[25] D.L.Griscom, "Radiation hardening of pure-silica-core optical fibers by ultra-high-dose γ-ray pre-irradiation", *J. Appl. Phys.*, vol.77, pp.5008-5013, May 1995.

[26] G. P. Agrawal and N. K. Dutta, Semiconductor Lasers 2nd Edition, New York: Van Nostrand Reinhold, 1993, p.202.

[27] A. M. Joshi, G. H. Olsen and S. R. Patil, "Reliability of InGaAs Detectors and Arrays", *Proc. SPIE*, vol.1580, p.34, 1991.

[28] J. Collot, P. De Saintignon, P. Gabor, A. Hoummada, G. Mahout, D. Marchand, F. Merchez, E. L. Florian, C. Leroy, P. Jean and B. Merkel, "A Neutron Irradiation Facility Featuring Cryogenic Temperatures and Dedicated to Large Hadron Collider Detector Design", *Nucl. Instr. and Meth. A* , vol.350, p.525, 1994.

[29] G. P. Summers, E. A. Burke, M. A. Xapsos, C. J. Dale, P. W. Marshall and E.L. Petersen, "Displacement Damage in GaAs Structures", *IEEE Trans. Nucl. Sci.*, vol.35, p.1221, 1988.

[30] G. P. Summers, E. A. Burke, P. Shapiro and S. R. Messenger, "Damage Correlations in Semiconductors Exposed to Gamma, Electron and Proton Radiations", *IEEE Trans. Nucl. Sci.*, vol.40, p.1372, 1993 (and refs. therein).

[31] J. Troska, K. Gill, R. Grabit, F. Vasey, " Radiation Damage Studies of InGaAs p-i-n Photodiodes for the CMS Tracker Optical Links", CMS Note (1997). Paper in preparation.