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Radiation effects in commercial off-the-shelf single-mode optical fibres

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ABSTRACT

Several types of commercially available single-mode optical fibres have been irradiated in both gamma and neutron radiation fields to determine the suitability of their use in the readout systems of future particle physics detectors. A comparative survey of the effect of ^{60}Co gammas and neutrons ($<E_n> \sim 6$MeV) on different fibre types, including standard germanium doped and pure silica core fibres, has been carried out. Selected fibres were further exposed to gamma radiation at four different dose rates to assess dose rate effects. Results are presented for the dose and fluence levels of interest (100kGy and 1×10^{14}n/cm^2), showing induced losses at 1300nm to be below 0.1dB/m for both types of field. It has been seen that the damage mechanism is the same for both fields. We conclude that many modern Ge-doped fibres will be suitable for use in future particle physics applications, which gives greater freedom of choice to system designers, and greater immunity from the problems associated with single suppliers of specific fibres.

Keywords: optical fibre, optical fiber, radiation effects, single-mode, COTS, high energy physics

1. INTRODUCTION

Experiments such as the Compact Muon Solenoid (CMS)[1] are being designed to take advantage of the new physics possibilities of the Large Hadron Collider (LHC)[2] which is to be completed at CERN in 2005. The use of optical fibres in the readout system of the central particle tracking detectors[3] of the CMS experiment is desirable because of their low mass, high speed and immunity to electromagnetic interference and crosstalk. The analogue readout scheme chosen for the CMS tracker[4] has resulted in the development of an analogue optical readout link making use of commercially available components wherever possible. An important aspect of using commercial off-the-shelf components in the LHC environment is assessment of their behaviour after irradiation. The optical link design for the CMS tracker readout consists of a laser driver to be realised in a radiation-hard technology, a 1300nm laser diode, optical fibre ribbon cable, multi-way connectors, and photodiode and receiving electronics in the remote counting room. The final system will consist of ~50000 such links, each spanning a distance of ~100m.

The radiation environment[3] in which these optical links must operate over the nominal ten-year operational lifetime will be severe. The ionising dose is expected to reach 100kGy in the central regions of the CMS tracker, while charged and neutral particle fluences in the same region will reach 1.8×10^{14}/cm^2 and 1×10^{14}/cm^2 respectively. Charged particle energies are expected to be mainly in the hundreds of MeV range, while neutral particles will be mainly neutrons with an average energy of 1MeV. The dose rate, assuming a nominal LHC operational schedule, will be a maximum of ~ 4.7Gy/hr in the central most tracking regions. Using the same assumption, the maximum particle flux will be ~4×10^6 /cm^2/s for charged and neutral particles. Of the 100m total length of optical fibre to be deployed in each optical readout channel, approximately only the first 10m will be subject to total doses above 1kGy and fluences above 10^{13}n/cm^2.

In previous irradiation studies on both Ge-doped and pure silica core single mode fibres at 1550nm[5], large differences in the response of these two fibre types to gamma and neutron irradiation were found. Both fibre types remained suitable candidates for use in the CMS tracker readout system after gamma-induced losses, showing similar losses of ~0.1dB/m after 100kGy. Neutron irradiation, however, caused negligible damage in the pure silica core fibres, whereas larger losses were observed in the Ge-doped fibre after fluences of ~5×10^{13}n/cm^2. These findings led to the specification of pure silica core fibre for general use in the high radiation first 10m of the CMS tracker optical readout. A change in the specified operating wavelength of the readout link to 1300nm now requires a re-evaluation of radiation-induced losses at this wavelength. With the aim of assessing which modern single-mode fibres would be suitable for use in the optical readout system of CMS, a survey of single-mode fibres currently available commercially has been carried out at 1300nm as detailed below. The main

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motivation was to gain confidence in any final choice of optical fibre for use in the CMS tracker readout. Ideally, one would hope to be able to choose between different commercially available fibres freely, and perhaps to make use of fibres from several different manufacturers in the final system. This would provide some measure of protection against any single fibre type becoming unavailable during the construction phase of CMS and compromising the commissioning of the final system.

2. EXPERIMENTAL

2.1 Samples tested

Single-mode fibres from a total of seven different manufacturers were included in the survey. Fibres were selected according to their commercial availability, as nothing was known about the radiation sensitivity of most of these fibres. A major aim of the study was to compare the radiation-response of the different types of Ge-doped fibre. For one fibre type (Optical Fibres), three spools were made available to us, each containing fibre from a different preform to assess any batch-to-batch variation in radiation sensitivity. A further cross-check was available to us in testing fibre from Corning, Siecor, and Optical Fibres, who all use the same Corning-patented Outside Vapour Deposition (OVD) fibre production process. The Sumitomo pure silica core (PSC) fibre was included to provide a comparison with the previous test[5].

More detailed information obtained from the manufacturers about their fibres is shown in Table 2.1. The full survey of fibres from all seven manufacturers was carried out at a gamma dose rate of 720Gy/hr, while the range of neutron fluxes achieved was dictated by the layout of the irradiation facility. The Optical Fibres and Sumitomo fibres were also studied at three further dose rates as given in Table 2.2.

Table 2.1: Details of fibre types, as provided by manufacturers. (VAD – Vapour Axial Deposition, PCVD – Plasma Chemical Vapour Deposition)

Manufacturer & type	Process	Core dopants	Cladding dopants	Cut-off Wavelength	Coating
Corning SMF-28™	OVD	Ge	none	≤1260nm (spec.)	Dual layer UV-cured acrylate (CPC6)
Fujikura SM.10/125.04.UV	VAD	Ge	none	1240nm (meas.)	Dual layer UV-cured acrylate
Lycom TrueWave™	N/A	Ge	none	≤1150nm (spec.)	Dual layer UV-cured acrylate (D-LUX 100)
Optical Fibres SM–03-E	OVD	Ge	none	<1250nm (spec.)	Dual layer UV-cured acrylate (CPC6)
Plasma MCSM 267E	PCVD	Ge, F	F	1188nm (meas.)	Dual layer UV-cured acrylate, (DLPC7)
Siecor SMF 1528	OVD	Ge	none	1170 – 1330nm (spec.)	Dual layer UV-cured acrylate (CPC6)
Sumitomo PSC	VAD	none	F	1400nm (meas.)	Acrylate

Table 2.2: Details of samples prepared for the different irradiation tests summarised in this paper.

Fibre Type	Sample parameters for gamma irradiation Spool diameter: 45mm				Sample parameters for neutron irradiation Spool diameter: 75mm			
	Nominal length (m)	Launch power (μW)	Dose rate (Gy/hr)	Total Dose (kGy)	Nominal length (m)	Launch power (μW)	Flux (n/cm^2/s)	Fluence (n/cm^2)
Corning	100	100	720	116	100	60	7.0×10^{8}	2.4×10^{14}
Fujikura	100	100	720	116	100	60	7.4×10^{8}	2.6×10^{14}
Lycom TrueWave	100	100	720	34				
Optical Fibres (spool 1)	200	100	4.8	0.66				
	100	100	38.7	12.9				
	100	100	720	51				
	100	100	1900	46				
Optical Fibres (spool 2)	100	100	720	116	100	60	1.6×10^{9}	5.6×10^{14}
					100		6.1×10^{8}	2.1×10^{14}
Optical Fibres (spool 3)	100	100	720	51				
Plasma	100	100	720	116	100	60	7.8×10^{8}	2.7×10^{14}
Siecor	100	100	720	34	100	60	1.5×10^{9}	5.2×10^{14}
Sumitomo	200	100	4.8	0.66	200	60	1.7×10^{9}	5.9×10^{14}
	100	100	38.7	12.9				
	100	100	720	34				
	200	100	1900	46				

2.2 Irradiation test set-up

All measurements of fibre loss were carried out in situ, using the transmission loss method. A 1300nm laser diode was used to supply light to the fibres under test via an optical splitter. Light returning from the samples was recorded via a photodiode and pre-amplifier on a standalone datalogger. One datalogger channel was reserved for a monitoring function to measure fluctuations in the laser power via one of the splitter channels. Temperature during the test was also recorded inside the irradiation area as well as in the measurement area. For the gamma tests care was taken not to irradiate any splices or connectors. During the neutron test splices were shielded inside a polyethylene box.

The ^{60}Co irradiation cell at Imperial College was used for gamma irradiations in this test. It consisted of four ^{60}Co rods which could be lowered into the centre of a room measuring approximately 3m x 3m. Because of the large area available, it was possible to position the samples to receive different dose rates as required. In this way we were able to achieve dose rates between 4.8 Gy/hr and 1900 Gy/hr. Dosimetry was carried out using a silicon diode of known dimensions to measure the gamma-induced photo-current. The values thus obtained were cross checked using a RadFET provided by NMRC[6]. The two measurements agreed within the 10% measurement uncertainty.

Neutron irradiation was carried out at the S.A.R.A. facility in Grenoble, France[7]. The S.A.R.A. accelerator produces a beam of deuterons with an energy of 18MeV which strike a thick Beryllium target to produce a beam of neutrons with an average energy of 6MeV via the ^{9}Be(d,n)^{10}B stripping reaction. Dosimetry was done using nickel foils, which are only sensitive to neutrons above an energy of ~100keV. Accuracy of the fluence measurement is limited to ~15%, due mainly to uncertainty in the knowledge of the activation cross-sections.

All irradiations were carried out at ambient temperature, which varied with the cycle of day and night. During the gamma tests, temperatures inside the source cell were stable at 19.5±0.5°C, while the temperature in the control area was 20.0±1.5°C. During the neutron test, the irradiation cell temperature was stable at 20.0±0.5°C, while the control area temperature was 25.0±3.5°C. This compares with a projected operational temperature in the inner part of the CMS tracker of –10°C, and in the outer part of 18°C.

3. RESULTS AND DISCUSSION

3.1 Gamma radiation effects

The results of gamma irradiation of all fibres from the seven different manufacturers at a dose rate of ~720 Gy/hr are shown in Figure 3.1. All fibres show very similar loss levels of between 0.04 and 0.06 dB/m after 100kGy, which is very encouraging for their potential use in CMS as this corresponds to a loss of only ~0.5dB for the first 10m of fibre in the high radiation region. This loss is comparable to the reconnection variation[8] in the insertion loss of MT array connectors foreseen for the CMS tracker readout link.

Encouragingly, batch-to-batch variations in the radiation-hardness loss characteristics of the three Optical Fibres samples are very small, since the three curves overlap very well in Figure 3.1. In fact all five fibres which use the Corning process exhibit very similar loss characteristics as shown by the curves ‘a’ in Figure 3.1. The other Ge-doped fibre types show qualitatively similar behaviour, with very similar losses, lending weight to the argument that all Ge-doped samples tested could be used in the final CMS tracker readout system.

While the behaviour of the Ge-doped samples is very similar for all the samples tested, the behaviour of the pure silica core fibre is very different. This difference between Ge-doped and pure silica core fibre is consistent with our own previous results[5], and those of other groups[9]. It appears to be beneficial, in terms of lower loss, to use pure silica core fibre for doses up to 5-20 kGy. Once this dose is reached the loss in Ge-doped fibres is the same or lower than in the pure silica core fibre. At a dose of 100kGy, the dose expected within the central tracking detectors of CMS, there seems to be little advantage in preferring pure silica core to Ge-doped fibre, based on the gamma-induced loss alone.

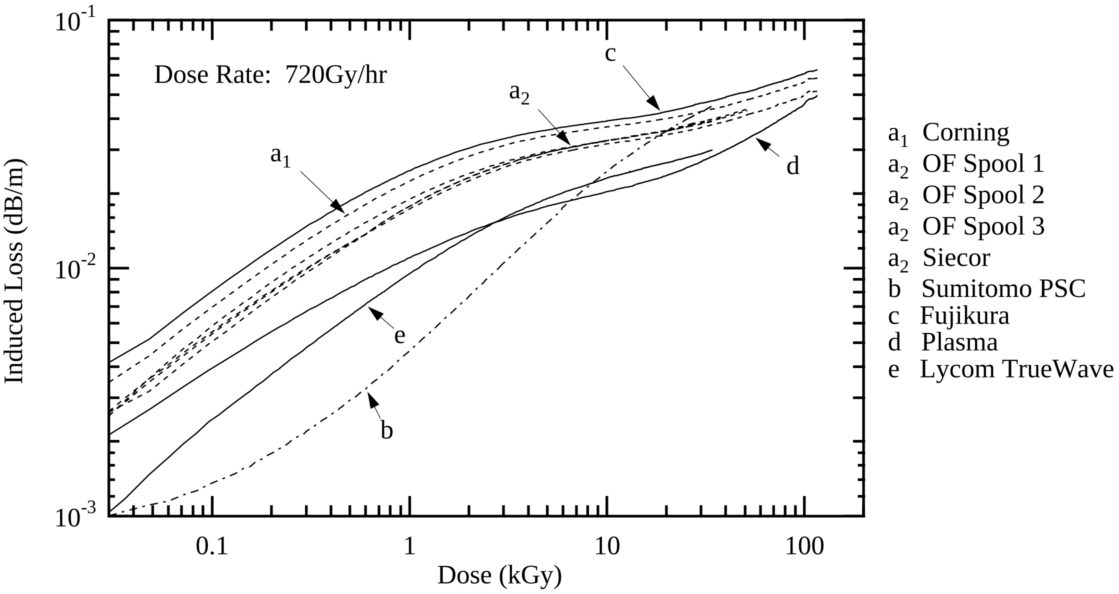

Figure 3.1: Gamma-induced loss in fibres surveyed at ~ 720 Gy/hr. Launch optical power was ~100µW at 1300nm.

The recovery characteristics of fibres in this survey are shown in Figure 3.2. All fibres apart from the Sumitomo pure silica core fibre have very similar characteristics. The Sumitomo fibre recovers faster and to a greater extent than all other fibres. Previous results[10], however, show that annealing in the Sumitomo fibre may only be temporary in nature. When making comparisons with the final application, the fact that many of the optical readout channels will be operating at -10°C for the first 10m inside the central tracking volume of the CMS experiment must be taken into account. The amount of recovery will be diminished[11] in this lower temperature section of the final system.

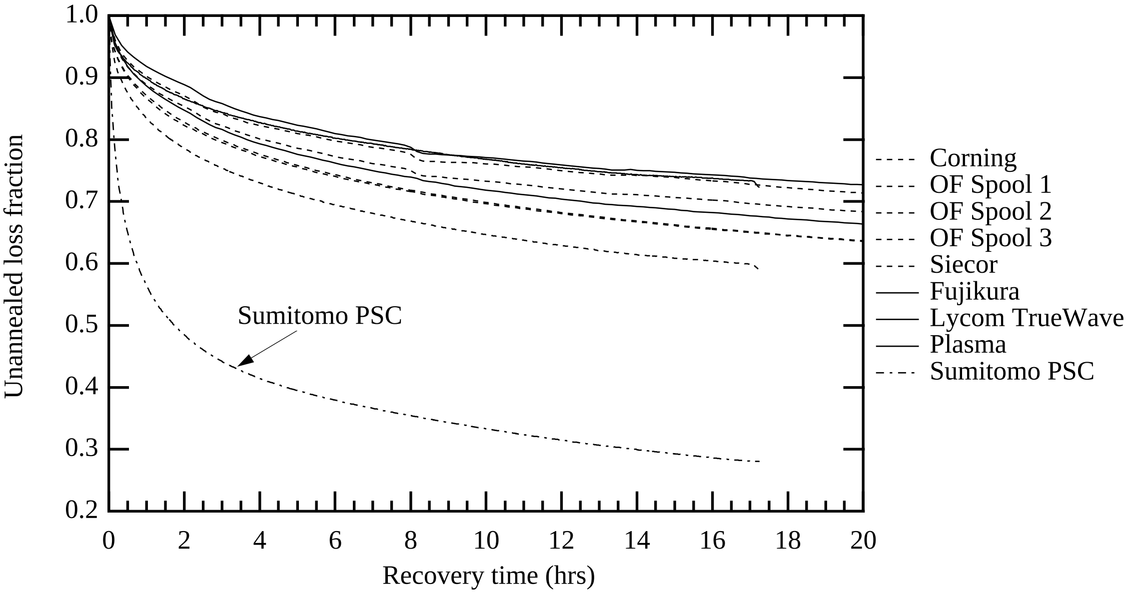

Figure 3.2: Room temperature recovery of gamma-induced loss for fibres exposed at a dose rate of 720Gy/hr.

3.2 Neutron radiation effects

The induced loss due to neutrons from the S.A.R.A. source is shown in Figure 3.3 for the six fibre types included in the neutron test. The six fibres were chosen for their good performance in the earlier gamma tests. Two Optical Fibres samples were included at different distances from the beryllium target to observe the effect of differing fluxes on the neutron-induced loss. This effect can be seen in Figure 3.3, where the low flux sample (a_3) shows an induced loss a factor of 1.8 lower than the high flux sample (a_2) at 10^{14}n/cm^2. The flux in the two samples differed by a factor of 2.6 in this test.

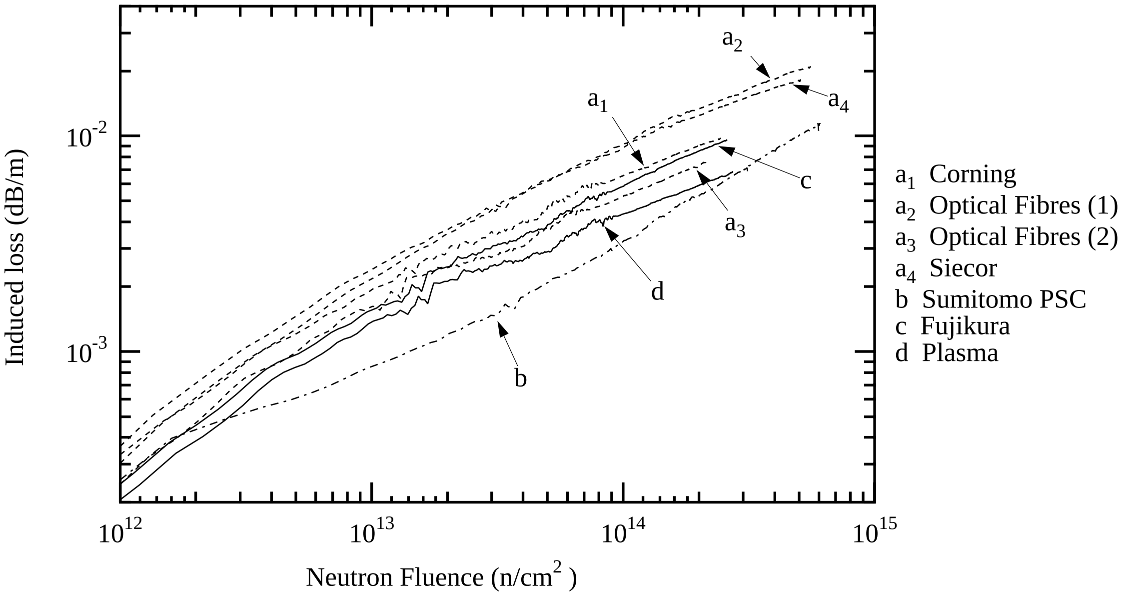

Figure 3.3: Neutron induced loss measured with a launch power of ~60µW at 1300nm. Total irradiation time was 97 hours for all fibre samples.

As in the gamma test, the loss for all fibres after neutron irradiation is below the level of 0.05dB/m, showing the suitability of all fibres tested for use within the CMS experiment. All Ge-doped fibres show the same form in their loss curves under neutron irradiation as was observed under gamma irradiation. Strong similarities between the loss curves are masked slightly by the different fluxes experienced by the different samples. The same difference in the loss curves between the pure silica core fibre and the Ge-doped fibres is also present after neutron irradiation. In the neutron test, however, the absolute difference in loss between the pure silica core fibre and the Ge-doped fibres is only a factor of 2-3 at most, compared to a factor of 5 in the gamma test. This difference is likely to be due to the flux variation over the different samples.

The room temperature annealing behaviour in our neutron-irradiated samples is shown in Figure 3.4. The observed annealing of neutron-induced loss indicates that this test represents an upper limit on the loss that will be encountered in CMS, where the flux will be two orders of magnitude lower. Once again, the Sumitomo pure silica core fibre shows the fastest and greatest amount of annealing. The other fibres all show similar rates and amounts of annealing, which must be taken as maximum amounts when comparing to the final system where in some parts the temperature could be ~30°C lower.

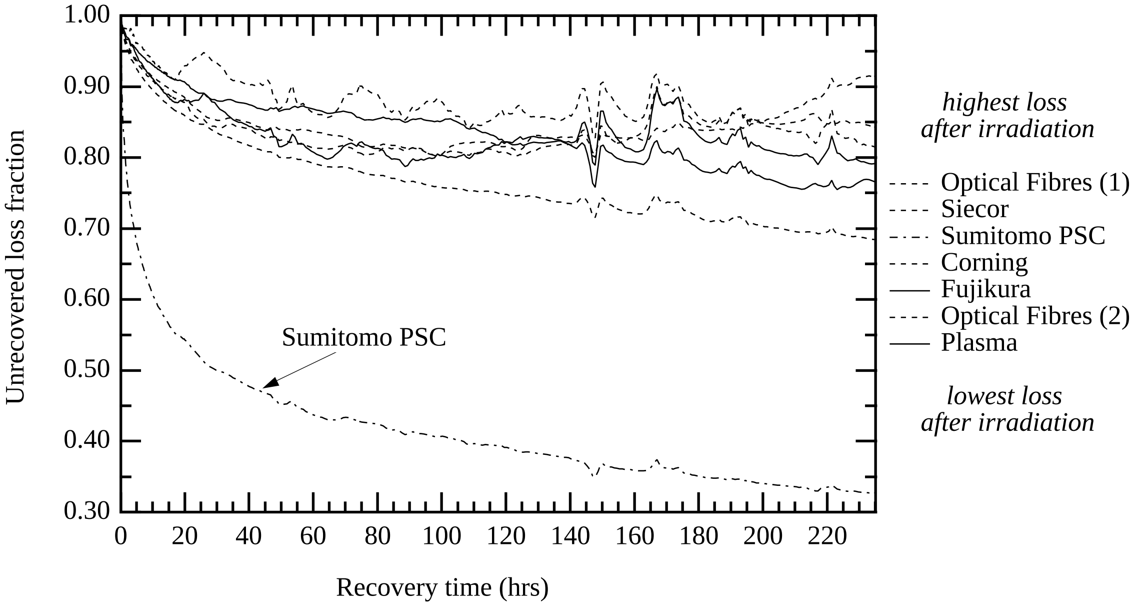

Figure 3.4: Recovery of neutron-induced loss. Data are noisy due to large fluctuations in the control area temperature during this period.

3.3 Comparison of Gamma and Neutron effects

By comparing loss induced versus time for gamma irradiations at different dose rates with the results of neutron irradiation, as shown in Figure 3.5, it is clear that the two types of irradiation are qualitatively very similar. This is important because it suggests that the same mechanism is responsible for the loss induced by both neutron and gamma irradiation. The fact that the curves do not overlay each other is due to different effective dose rates being used in the different irradiations. The dose rate during the neutron irradiation of the Sumitomo and Optical Fibres samples can be estimated by interpolation on Figure 3.5. Using this method, the dose rates received by the fibre samples in the neutron test are estimated to be 20-90Gy/hr. Since the loss mechanism appears to be the same, further qualification of fibres for use within the CMS experiment can now be carried out using gamma sources alone.

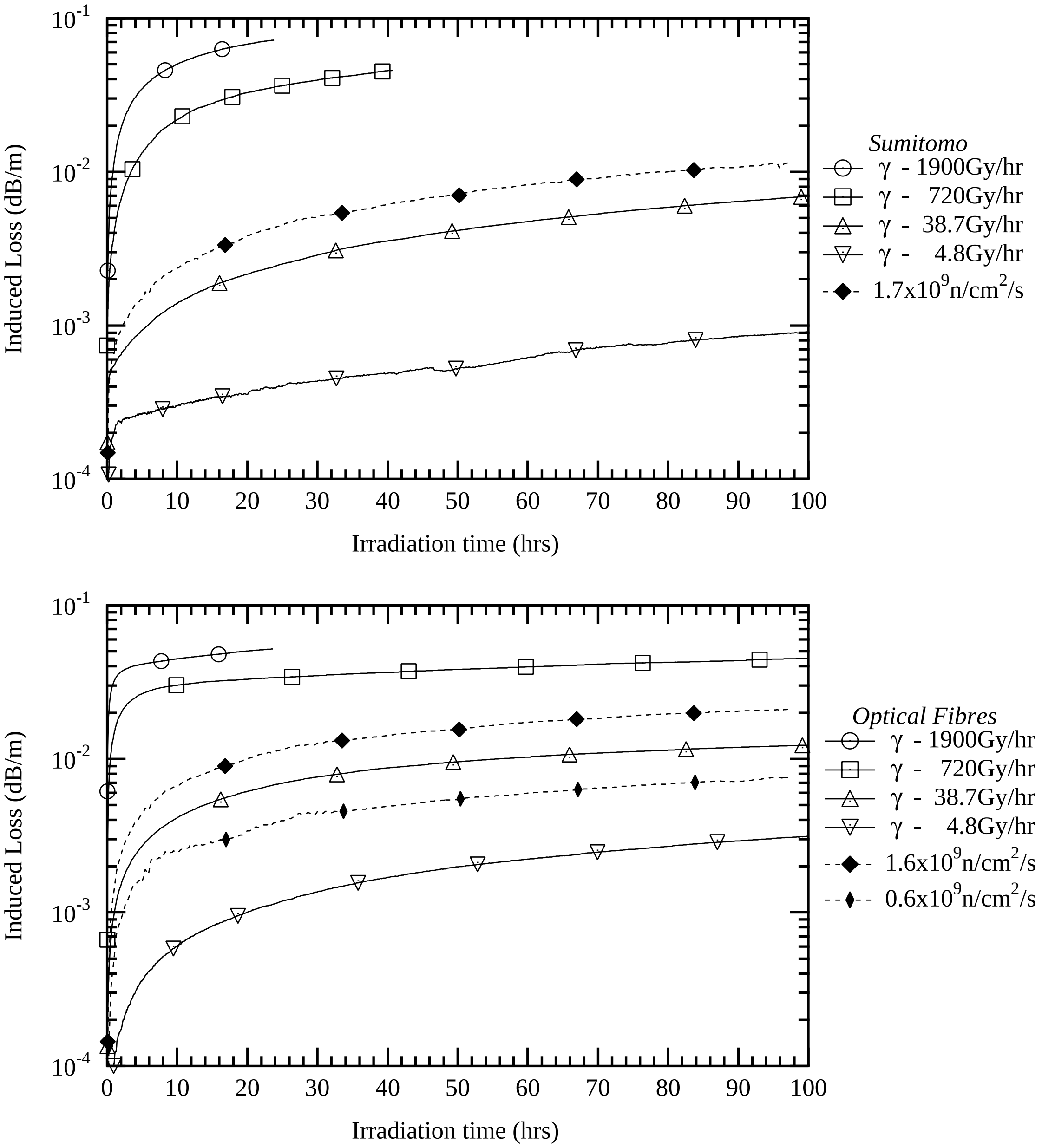

Figure 3.5: Comparison of damage due to different gamma dose rates and neutrons.

4. CONCLUSIONS

All seven single-mode optical fibres types tested show induced losses, measured at 1300nm, of only 0.04-0.06 dB/m after irradiation to 100kGy at a dose rate of ~720Gy/hr. After neutron fluences of 10^{14}n/cm^2 (at a flux of 0.6-1.7×10^9n/cm^2/s), the loss was found to be even lower, reaching values between 0.003 and 0.009dB/m. In the final readout system of the CMS tracker, the dose rate and flux will be lower than these values, indicating that the loss will be lower than the values measured due to annealing occurring during irradiation. Encouragingly, the upper bound set by these measurements is below 1dB total loss for the 10m fibre portion in the high radiation zone, which is acceptable in the current power budget of the CMS tracker optical readout link.

A comparison of the two types of irradiation suggests that the damage mechanism is the same, so that only gamma irradiation of candidate fibres will be required for future qualification purposes. Further irradiations of candidate fibres at lower temperatures are required to better simulate the operating temperature of –10°C in the central parts of the CMS tracking system.

Moreover, six modern Ge-doped fibres from different manufacturers are equally radiation resistant as pure silica core fibres for doses greater than 20kGy. This is the regime of interest for their use within future particle physics experiments where the dose is expected to reach 100kGy over a period of ten years. The specification of pure silica core fibre for use in the CMS tracker optical readout can now be relaxed to include Ge-doped fibres such as those tested in this survey.

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