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Ionising radiation damage of optical fibre data link components in the CMS Inner Tracker

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Abstract

Results are presented from cobalt-60 photon irradiations of multi-quantum well (MQW) modulators (to ~20Mrad) and optical fibres (to ~30Mrad). These components form part of the optical data-link for transfer of signals from the silicon microstrip and MSGC elements in CMS. Measurements of the reflectivity of the modulators at different bias voltages were made before and after irradiation showing no significant change. The modulators were irradiated under bias with the dark current in the devices continuously monitored during and for several days after the irradiation. Increases in the dark current were observed due to radiation damage though the devices were fully annealed after several days. The results suggest that the modulators are sufficiently resistant to ionising radiation for use in CMS, though further tests are required. The transmission of the fibres was monitored throughout the irradiation and for part the recovery period after irradiation. The radiation induced attenuation losses in the fibres was fitted with a model describing the time and dose dependence of different defect states. The data obtained here for the fibres could therefore be projected over a ten year lifetime at LHC, resulting in only small transmission losses in fibres used in CMS.

Introduction

Optical fibre data-links for the transfer of data from the front-end electronics of detectors in LHC experiments are currently under development by the RD23 collaboration[1]. These links are the baseline method of data transfer from the MSGC and silicon microstrip detectors in the CMS Inner Tracker[2]. As with all the materials used in the tracking region, the radiation hardness of the modulators and fibres must be demonstrated to be capable of withstanding the large radiation doses that will be accumulated during the running periods of the LHC.

MQW modulators and optical fibres have previously been irradiated with neutrons by RD23[1]. The modulators were unaffected in terms of their reflectance. The leakage current, which does not affect their performance, increased from ~5nA to ~100nA. Of the fibres that were irradiated, pure silica core fibres were found to be more radiation hard than Ge-doped fibre. This result was expected as the induced losses in the fibres are believed to be related to the defects introduced by dopants such as germanium. The dose rates used were around two orders of magnitude greater than those expected at LHC. Therefore, taking fibre annealing into consideration, the pure silica core fibres are sufficiently resistant to *non-ionising* radiation damage for LHC use.

In this investigation we aimed to measure any changes in the properties of MQW modulators and different types of optical fibre as a result of exposure to *ionising* radiation to a high dose (in our case ~1MeV gammas to $\gtrsim$ 20Mrad). It was found that the MQW device performance was unaffected by gamma irradiation, the reflectance was unchanged and increases in dark currents annealed within several days of the irradiation. Radiation induced losses of around 100-120dB/km were observed in the fibres, which received varying doses. The attenuation could be fitted with a ‘kinetic model’[4] which describes a build up of several defect states linearly with dose, combined with exponential decay of these states with different lifetimes for the different states. Knowing the ionising dose rate profile at LHC, this model allowed us to predict the evolution of the induced losses in fibres used in CMS. It was found, for the fibres tested, that one could expect losses of between 2-5dB/100m in a ten year span of high luminosity operation of LHC.

1) MQW modulator radiation damage

The modulators are based on III-V semiconductor electro-absorptive multi quantum well structures grown between asymmetric Fabry-Perot mirrors. The electro-absorption in the devices tested was tuned to obtain a maximum modulation depth at a wavelength of 1.54µm. Reflectivity of the device is modulated by varying the applied electric field across the quantum wells. The devices tested here were configured as a linear array of 8 channels, with active MQW areas of 30µm diameter at 125µm pitch.

Two 8-channel MQW modulators were irradiated with gammas using the experimental arrangement shown in figure 1. The devices were irradiated at room temperature to a total dose of ~20Mrad at a dose rate of 205krad/hr. A 20-channel data acquisition unit was used to monitor the modulators as well as to store the data on disk until it could be analysed.

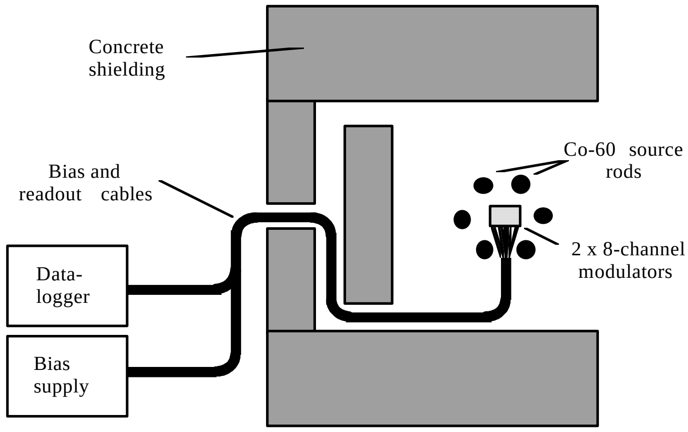


Figure 1: Schematic arrangement of apparatus for MQW modulator irradiation

The modulators were reverse biased at -7V during the irradiation, and for the subsequent three days, in order to monitor any annealing of the leakage current which was measured and recorded every 60 seconds. Figures 2 and 3 show the leakage current data from the devices during irradiation and the three days after irradiation. Radiation damage caused the leakage current in most of the channels to increase to about 100nA. In comparison, the photocurrent generated by the modulator under normal operating conditions is in the range of 10 to 100μA. In most cases the leakage current was fully annealed in the three days after irradiation. The channels which had not annealed in this time were remeasured later and the leakage current was found to have decreased to pre-irradiation levels. The increases in the leakage current are thought to be associated with radiation induced charging of the polyimide layer used to isolate neighbouring MQW structures[5]. This hypothesis may be confirmed by future tests on similar devices without polyimide.

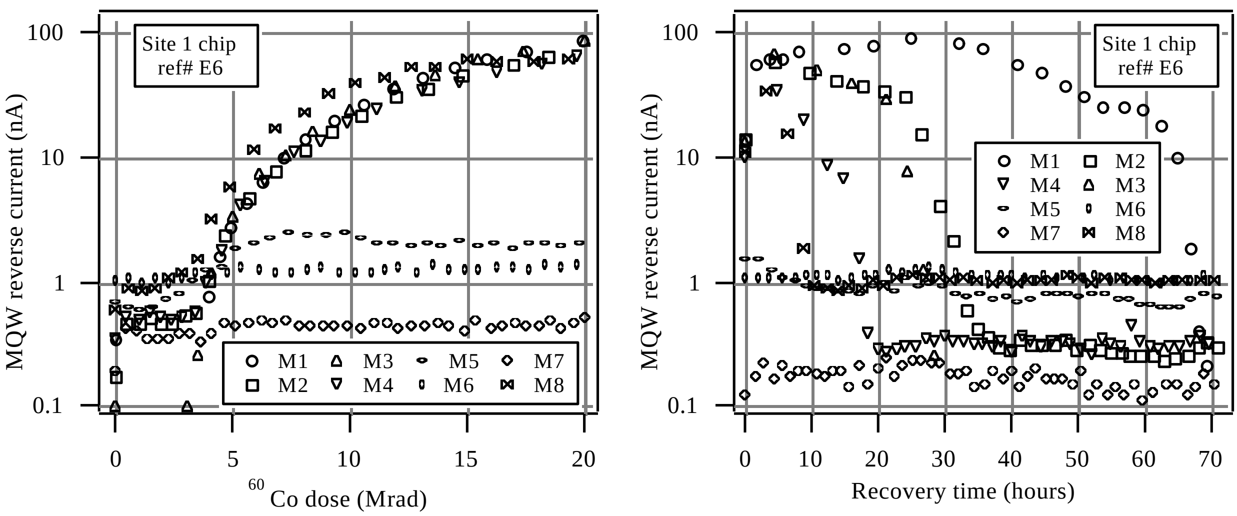
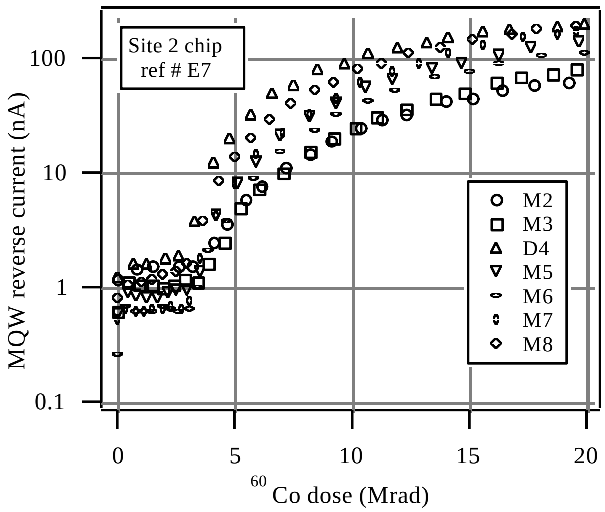


Figure 2: Leakage current results for modulator E6



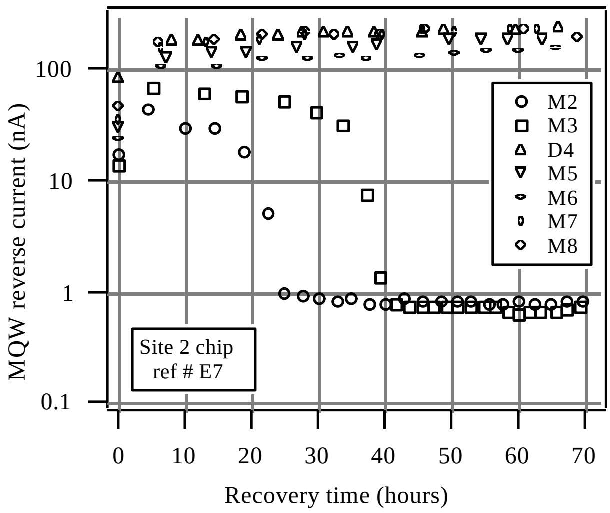


Figure 3: Leakage current results for modulator E7

The reflectance spectra were measured before and after the irradiation (and recovery period), with the results[3] shown in figures 4 and 5. It can be seen that the reflectance spectra were not significantly changed by the irradiation, or that any radiation induced changes had completely recovered by the time the second measurement was made. Further tests are therefore required to determine whether the optical properties are affected during irradiation. The small deviations observed were attributed to differences in measurement conditions.

2) Fibre radiation damage

We aimed to measure, in situ, the radiation induced attenuation characteristics of three different optical fibres; Lycom MCSM (Match Clad - Single Mode), Lycom PSCF (Pure Silica Core Fibre) and Sumitomo PSCF (Pure Silica Core Fibre). From the results we were able to extract parameters describing the evolution of the radiation induced attenuation, using the kinetic model of Kyoto et al[4], detailed in Appendix I, which enabled predictions to be made of the attenuation expected during operation in an LHC experiment.

Figure 6 shows a schematic diagram of the arrangement of the apparatus. The laser light was split four ways and transmitted along the four fibres to four photodetector/amplifier units, where the output voltage was measured every 60 seconds with the data acquisition unit (also used to monitor the modulators). Typically, the optical power level in each fibre was 60µW. The laser and monitoring equipment were situated in the control room and the three fibres under investigation were threaded through access pipes into the source cell. An 88 metre length of each fibre had been wound on a spool, which was placed in the centre of the source to obtain the highest dose rate available. The dose rate at each fibre position was measured using a calibrated photodiode, estimated to be accurate to better than 10% from earlier studies. The fourth fibre was not irradiated and was used to monitor fluctuations in the laser output.

Figure 4(a): Reflectance results before irradiation for modulator E6

Figure 4(b): Reflectance results after irradiation for modulator E6

Figure 5(a): Reflectance results before irradiation for modulator E7

Figure 5(b): Reflectance results after irradiation for modulator E7

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The three fibres were then irradiated for six days, such that the accumulated doses were: 29Mrad for the Lycom MC-SM, 24Mrad for the Lycom PSCF and 36Mrad for the Sumitomo PSCF fibre. After the irradiation, measurements were made for a further 32 hours to investigate the annealing behaviour of the fibres.

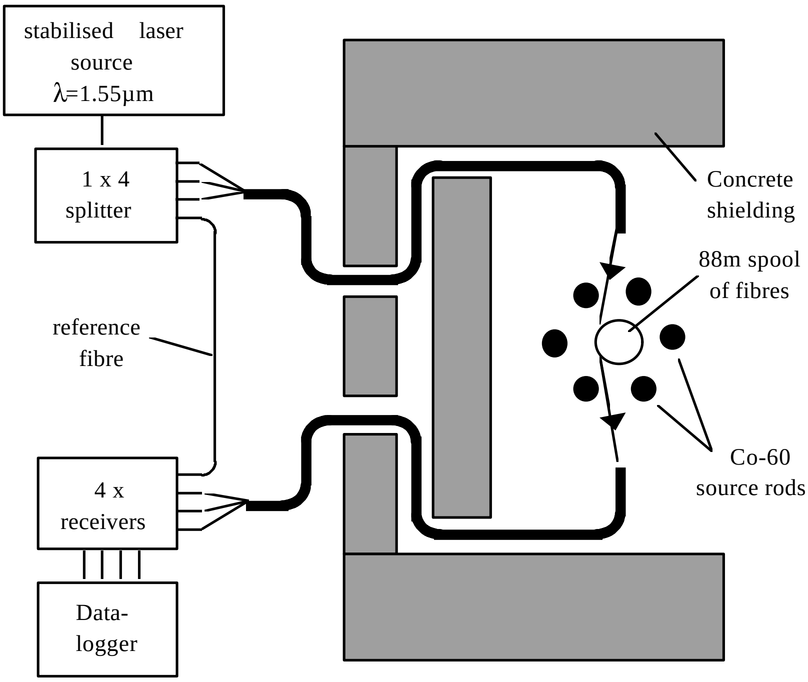
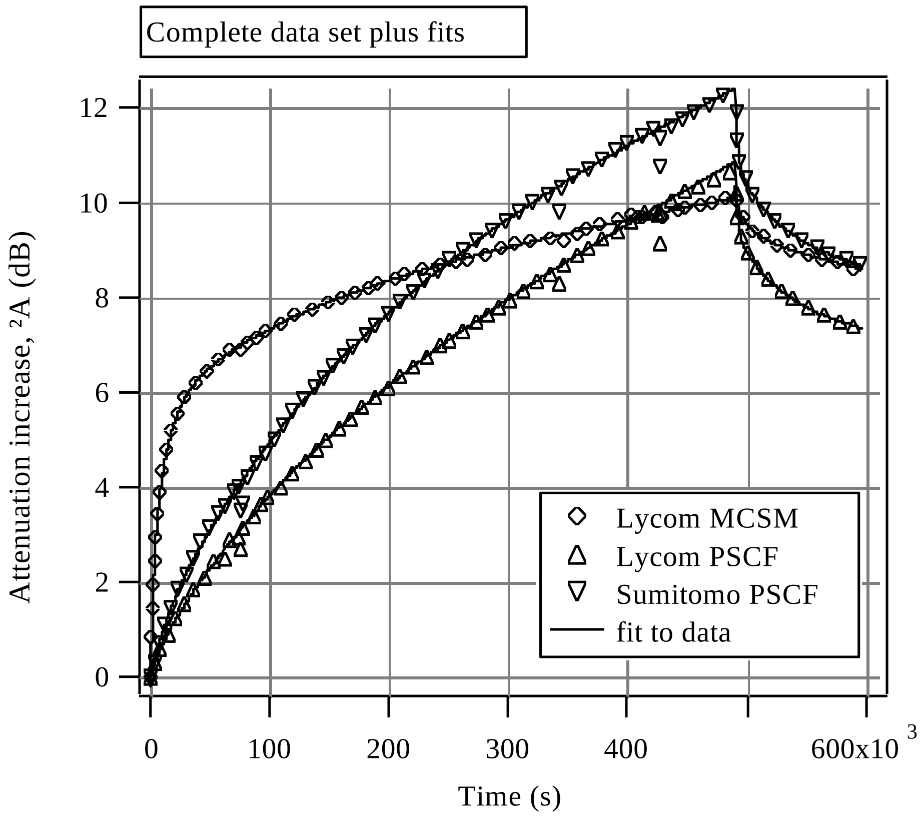


Figure 6: Schematic arrangement of apparatus for fibre irradiation

The following is a brief summary of the extracted parameters (refer to Appendix I for details of the fitted expressions). Figure 7 shows a plot of the full data set and fitted curves for the fibres, along with tabulated results for K_i and τ_i extracted from the fits to the data. Some points lie below the fit, corresponding to intervals when the source was turned off for access. The dose rates for the different fibres are given below in Table 1. These are used, with the K_i and τ_i values to extract the damage constants a_i as shown in Table 2.

Fibre	Dose rate (krad/hr)	Dose rate (Mrad/s)
Lycom MCSM	211±6	(5.46±0.13) x 10^{-5}
Lycom PSCF	175±3	(4.46±0.08) x 10^{-5}
Sumitomo PSCF	268±9	(7.44±0.23) x 10^{-5}

Table 1: Dose rates received by fibres



Damage fit coefficients

	Lycom MCSM	Lycom PSCF	Sumitomo PSCF
K_1	2.12088	0.445405	0.892772
τ_1	2371.88	11546.8	14813.6
K_2	3.36718	4.38787	7.66822
τ_2	11571.8	153728	187074
K_3	2.21623	1.25587e-05	8.84335e-06
τ_3	104372		
K_4	4.99607e-06		

Recovery fit coefficients

	Lycom MCSM	Lycom PSCF	Sumitomo PSCF
$^{2}A_{1}$	0.119247	0.826166	0.987891
τ_2	732.94	447.331	453.812
$^{2}A_{2}$	0.696947	0.73679	0.791014
τ_3	12261.6	3991.87	4993.6
$^{2}A_{3}$	4.36148	2.21663	2.37148
τ_4	567383	56682.2	61798.4
$^{2}A_{4}$	4.97875	7.02453	8.25695

Figure 7: Full data set and fit parameters for fibre irradiation and recovery

Fibre	Lycom MCSM	Lycom PSCF	Sumitomo PSCF
a_1 (dB/Mrad) τ_1 (s)	15±1 2400±100	0.8±0.2 11500±1300	0.8±0.1 15000±1000
a_2 (dB/Mrad) τ_2 (s)	5.0±0.2 11500±300	0.6±0.1 (1.5±0.1) x 10^5	0.55±0.03 (1.9±0.1) x 10^5
a_3 (dB/Mrad) τ_3 (s)	0.36±0.01 (1.1±0.1) x 10^5	0.21±0.04 ∞	0.13±0.01 ∞
a_4 (dB/Mrad) τ_4 (s)	0.08±0.005 ∞		

Table 2: Damage constants and time constants extracted from the irradiation period

Predictions for LHC applications

We take each year at LHC to be an annual cycle of:

(i) Six months (1.58x10^7s) of irradiation with a dose rate of 500rad/hr (1.39x10^{-7}Mrad/s)

(ii) Six months of annealing

It should be emphasised that the evolution of the defects on these long timescales is dominated by the purely dose dependent linear contribution to the induced attenuation. The contribution from the other terms is very small due to their dose rate dependence, plus their induced attenuation recovers quickly in the six month recovery period. Estimates of the increase in the induced attenuation, ÆA, at LHC, based on the dose dependent damage constant for each fibre, are shown in the following table. The conversion from dB to dB/km was made assuming the irradiated length of the fibres to be 88m.

Fibre	ÆA (dB/km) after 1 year	ÆA (dB/km) after 10 years
Lycom MCSM	2.0	20
Lycom PSCF	5.3	53
Sumitomo PSCF	3.4	34

Table 3: Estimates of induced attenuation during LHC operation

These values therefore represent the worst case that could be deduced from our results, where the damage is dominated by the linear, dose dependent contribution, where the induced attenuation does not recover. For comparison, Kyoto et al predict an estimated induced attenuation of 22dB/km for a pure silica fibre irradiated at 100rad/hr for 40 years (which is equivalent to 14dB/km after 10 years at LHC).

One should note that the results from our irradiation could have been equally well fitted with an expression that had no linear contribution, but instead had a dose rate dependent contribution with a very long time constant (~10^6-10^7s). If this is indeed the true parameterisation, it would have implications for LHC operation as the induced attenuation would be decreased overall due to the eventual saturation of the dominant dose rate dependent contribution. However, the results in [4] strongly support the existence of a dose dependent linear term in the kinetic model.

Summary and Conclusions

Two multi-quantum well modulators were irradiated to around 20Mrad. The reflectance of the devices was unchanged and increases observed in the leakage currents were fully annealed within several days following irradiation. These results suggest that the modulators tested are sufficiently radiation resistant for use in the optical data link in the CMS Inner Tracker. Further tests will be undertaken to confirm this conclusion.

Measurements of fibre attenuation were made during irradiation and the subsequent recovery period of several days. The results could be fitted with the kinematic model of Kyoto et al[4] and the extraction of the linear dose dependent contribution (i.e. no annealing) was found to be the most important point for predicting the radiation induced losses in fibres used in CMS, where the longer recovery timescales and much lower dose rate dilute the effect of the dose rate dependent contributions.

The results presented here suggest that standard telecommunication fibres such as the Lycom MCSM are more resistant to low ionising dose rates than pure silica core fibres; a 10m length of Lycom MCSM fibre will have an induced attenuation of only 0.2dB after 10 years in CMS, whereas a similar length of pure silica core fibre will have an attenuation of around 0.4 to 0.6dB. However, pure silica core fibres have been shown to be more resistant to non-ionising radiation loss (e.g. from neutron damage) than standard telecommunications fibre (e.g. Lycom MCSM)[1]. Pure silica core fibres would also be more resistant to high dose rate ionising radiation damage, such as in accidental beam losses in CMS, than the standard telecommunications fibre. To summarise, the radiation induced losses in the fibres used for readout of the front end electronics in the CMS Inner Tracker are expected to be small, around 0.4-0.6dB after 10 years, for the ~10m lengths of pure silica core fibre that will be used in the highest radiation region.

Acknowledgements

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Appendix I

Theory and Kinetic Model

(a) Attenuation and radiation damage

The attenuation, A, in a fibre, length l is given by:-

$$A(l) = \frac{signal_{out}}{signal_{in}} = \exp(-\frac{l}{L}) \qquad (1)$$

where L is the attenuation length.

If the attenuation is assumed to be caused by presence of n species of defect state, with population N_1, N_2...N_n, each defect type gives rise to different characteristic attenuation length L_1, L_2,...L_n inversely proportional to the linear concentration of defects N_i:

$$L_i \, \alpha \, \frac{1}{N_i} \qquad (2)$$

The fibre can be considered as a composite structure with the attenuation, A, given by:

$$A(l) = \exp(-l \; [\frac{1}{L_1} + \frac{1}{L_2} + ... + \frac{1}{L_n}]\,) \qquad (3)$$

$$A(l) = \prod_{i=1}^{n} \exp[-l \, c_i \, N_i] \;\; = \prod_{i=1}^{n} \exp[-c_i \, N_i] \qquad (4)$$

where c_i is a constant.

If the fibre is then irradiated to some ionising dose, Φ, the population of each defect type changes, modifying the fibre attenuation:

$$A(l, \Phi) = \prod_{i=1}^{n} \exp[-c_i \, N_i \, (\Phi)] \qquad (5)$$

Compared to before irradiation:

$$\frac{A(l, \Phi)}{A(l, 0)} = \prod_{i=1}^{n} - \exp[c_i \, \{ N_i \, (\Phi) - N_i \, (0) \}] \qquad (6)$$

$$\frac{A(l, \Phi)}{A(l, 0)} = \prod_{i=1}^{n} - \exp[c_i \, ÆN_i \, (\Phi)] \qquad (7)$$

where $ÆN_i$ is change in the i^{th} defect population.

In dB units:

$$A(dB) = 10 \times \log_{10} \left[\frac{signal_{out}}{signal_{in}} \right] \qquad (8)$$

The magnitude of the radiation induced attenuation is given by the summation:

$$\text{Æ}A\ (dB) = \sum_{i=1}^{n} c_i\ \text{Æ}N_i\ (\Phi) \quad \log e \qquad (9)$$

(b) The Kinetic Model [4]

According to Kyoto et al, the data taken during irradiation can be fitted with the following formula:-

$$\text{Æ}A\ (t) = \sum_{i=1}^{n-1} [\quad K_i\ (1-\exp(-t/\tau_i))\ ] + K_n\ t \qquad (10)$$

The constants $K_{1,2...n-1}$ therefore correspond to the saturation values of the different contributions to the induced attenuation. The terms containing $K_{1,2...n-1}$ are dose rate dependent, whereas the linear term $K_n t$ is only dependent upon the total dose received. The linear term can be included in the summation with $\tau_n = \infty$.

For the period (time t') after irradiation, equation (11) is used to parameterise the recovery of the induced attenuation:

$$\text{Æ}A\ (t') = \sum_{j=1}^{m-1} [\quad \text{Æ}A_j\ \exp(-t'/\tau_j)\ ] \qquad (11)$$

Expressions (10) and (11) can be derived based on two assumptions:

(i) The change in the number of each defect type ÆN_i, without allowing for annealing, increases linearly with dose, Φ:

$$d(\text{Æ}N_i) = \alpha_i\ \Phi\ dt \qquad (12)$$

where α_i is the damage constant.

(ii) The defects anneal according to a first order reaction,

$$d(\text{Æ}N_i) = -\frac{N_i}{\tau_i}\ dt \qquad (13)$$

It can then be shown that for a constant dose rate, such that

$$\Phi = \frac{d\Phi}{dt}\ t \qquad (14)$$

the evolution of the defect population is given by:

$$\text{Æ}N_i(t) = \alpha_i \frac{d\Phi}{dt}\ \tau_i\ [\ 1 - \exp(-t/\tau_i)\ ] \qquad (15)$$

hence:

$$\text{Æ}N(t) = \sum_{i=1}^{n} \text{Æ}N_i(t) = \sum_{i=1}^{n} \left[\alpha_i \frac{d\Phi}{dt} \tau_i \left(1 - \exp(-t/\tau_i) \right) \right] \qquad (16)$$

substituting this expression into (9) gives the induced attenuation:

$$\text{Æ}A\ (\text{dB}) = \sum_{i=1}^{n} \left[c_i \alpha_i \frac{d\Phi}{dt} \tau_i \left(1 - \exp(-t/\tau_i) \right) \right] \log e$$

$$= \sum_{i=1}^{n} \left[a_i \frac{d\Phi}{dt} \tau_i \left(1 - \exp(-t/\tau_i) \right) \right] \qquad (17)$$

where a_i is the damage constant in units of dB/Mrad, if the dose rate units are Mrad/s and the time constants are all in seconds.

The kinetic model for fitting the data during irradiation, expression (10) can therefore be obtained by making the substitution:

$$K_i = a_i \tau_i \frac{d\Phi}{dt} \qquad (18)$$

(c) Predicting the induced attenuation for other irradiation conditions

The a_i and τ_i values can therefore be extracted from the fit of equation (10) to the data from the irradiation period. These values can then be used to predict the induced attenuation during any other ionising radiation exposure where the dose rate profile is known.

Note that the time constant values may also be determined from a fit to the recovery period; however the results from Kyoto et al do not suggest that these time constants should correspond exactly to those of the irradiation period. This is indeed the case in our results and the cause of this apparent discrepancy is unknown.