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RADIATION DAMAGE IN TILE-FIBER CALORIMETER MODULES

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Abstract

A program of measurements has been carried out to determine the radiation hardness of the SDC central calorimeter at the SSC. First, commercially available plastic scintillator plates and fibers were irradiated with a ^{60}Co source to identify the materials best suited for operation in a high radiation field. Then, electromagnetic calorimeter modules were built with these materials and exposed to a 1 GeV electron beam. The behavior of the modules was studied for doses up to 2 Mrad in two different gas environments.

1 Introduction

The main area of concern for the tile-fiber SDC central calorimetry is the radiation hardness of plastic scintillator placed in the region of electromagnetic shower maximum. We have conducted a program aimed at investigating how EM calorimeter modules will survive in the radiation field of the SSC.

In the first part of the program, commercially available scintillator plates and wave length shifting (WLS) fibers were measured after irradiation by a ^{60}Co source. These measurements are described in Ref. [1] and summarized in section 3 of the present note. They were used to select the material for the construction at Fermilab and Purdue Univ. of electromagnetic test modules to be tested in electron beams in France, Japan and China. We report here results obtained by the Saclay group with two such modules exposed to a 1 GeV electron beam at Orsay. We try to answer the question: will the SDC barrel calorimeter survive 10 years at 10 times the nominal luminosity of the SSC ?

2 Doses and Dose Rates

The total doses expected at Shower Maximum (SM) in the SDC calorimeter are given in Ref. [2]. For 10 years at 10 times the nominal luminosity ($L_{nom} = 10^{33}\text{cm}^{-2}\ \text{s}^{-1}$) the end of the barrel ($\eta = 1.4$) will receive $\sim$ 0.6 Mrad whereas the end cap will receive $\sim$ 60 Mrad at $\eta = 3$. These total doses can easily be reached in exposures of detectors to cobalt sources or to intense electron beams.

The exposures must necessarily be done in a relatively short time to yield useful information for the construction of the detectors. The dose rates at these test sites are therefore much larger (by a factor $\sim$ 100 to 1000) than the actual SSC dose rates[1].

[1] At shower maximum of the SDC EM calorimeter the dose rate is $\simeq$ 7 rad/h at the end of the barrel at nominal luminosity.

3 Component tests with ^{60}Co

Samples of scintillator plates, scintillating fibers, WLS and clear fibers were exposed to a ^{60}Co source. Irradiation and annealing were done in air at room temperature. The absorbed doses were calculated from the known activity of the source and measured with analine dosimeters and radiochromic film. The dosimetries agree within 10 %.

3.1 Scintillator plates

The light yield of scintillating plates was measured with small samples $\sim$ 3 mm thick in a way which eliminates the effect of attenuation in the plate. Pulse height analysis of signals produced by electrons from a ^{106}Ru source was performed on samples of 8 different scintillators, before and after irradiation. Figure 1 shows that if one considers blue scintillators, two products stand out:

- RH-5 from BICRON, which shows a large initial light yield, a 30 % drop after 2 Mrad and an almost complete recovery after 3 days of annealing in air. A dose of 6 Mrad results in a 50 % light loss and no recovery after one month.
- SCSN-81 from KURURAY, which yields only 60 % of the light compared to RH-5 but shows no loss up to a dose of 6 Mrad.

The attenuation length in scintillator was obtained independently from the light yield measurement by the optical measurement of light transmission through scintillator bars using a spectrophotometer. The results are shown in Fig. 2 for two blue scintillators. SCSN-81 shows a significant decrease of the attenuation length for two Mrad, even after one month of annealing in air. RH-5 has an even larger drop of the attenuation length.

3.2 Fibers

The attenuation lengths of different scintillating fibers were measured before and after irradiation. Figure 3 shows the signal measured by a PMT at one end as a β source is moved along the 2 m long, 1 mm diameter fibers.

$L(d)$ represents the light yield when the source is at a distance d from the PMT. The straight lines are lines of equal attenuation length. After irradiation (1.6 and 2.7 Mrad) the light yield and attenuation length are reduced significantly. These measurements verify that fibers emiting in the green (b) suffer less radiation damage than fibers emitting in the blue (a).

For the construction of the EMC modules, blue scintillator plates (SCSN-81 from KURURAY) and green WLS fibers (BCF-91A from BICRON) were chosen. The WLS fibers have the same plastic base and secundary emitters as the green scintillating fibers discussed above. From our measurements, we conclude that the loss of light in a tile-fiber assembly irradiated to $\sim$ 1 Mrad will come mainly from the reduced attenuation length in the plate (not from intrinsic light yield) and from the damage to the WLS fiber.

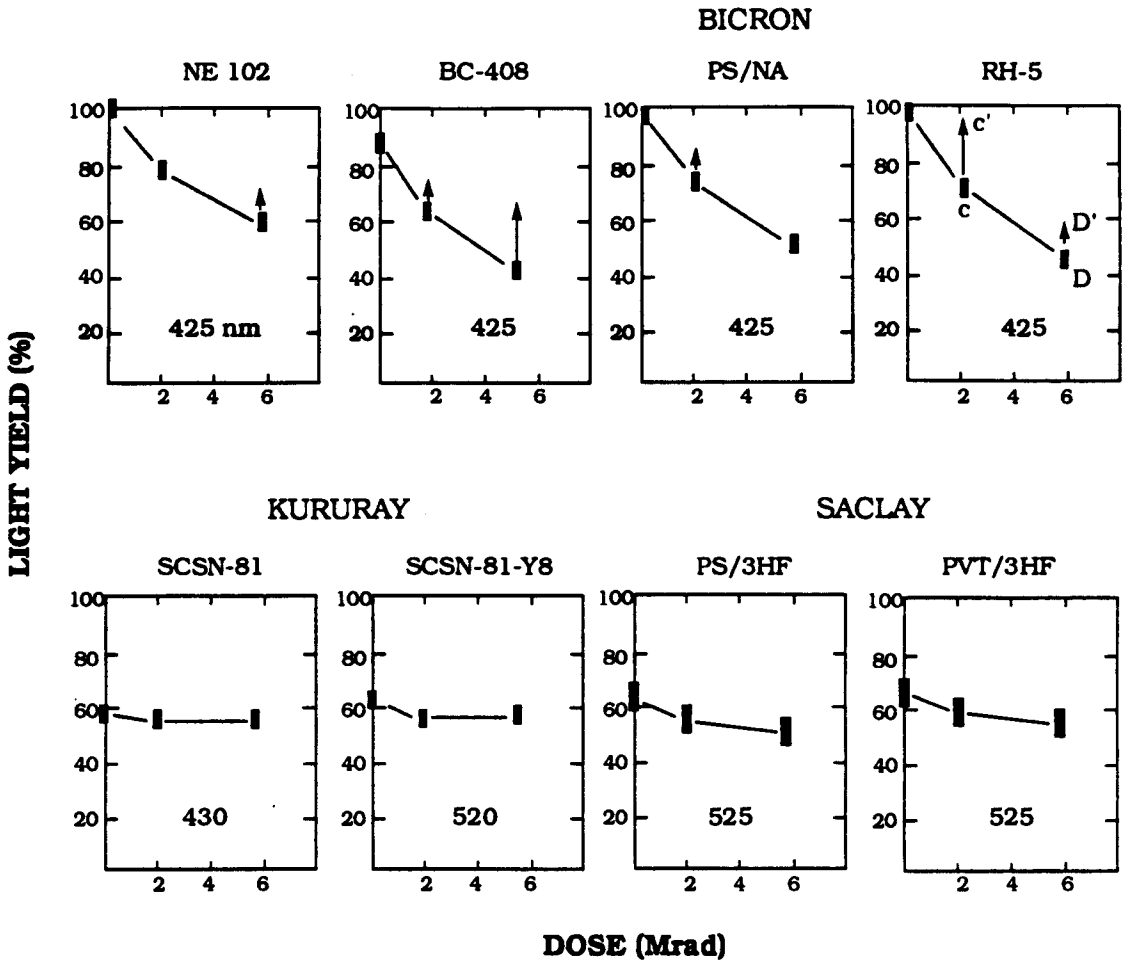

Figure 1: Relative light yield as a function of absorbed radiation dose for 8 types of scintillator plates. Light yields are normalized to NE102=100%. A) before irradiation; C) 2 Mrad at 9 krad/hr; C') 2 Mrad + 3 days of annealing in air; D) 5.7 Mrad at 9 krad/hr; D') 5.7 Mrad + 29 days of annealing in air. The wave length at peak emission is shown for each sample.

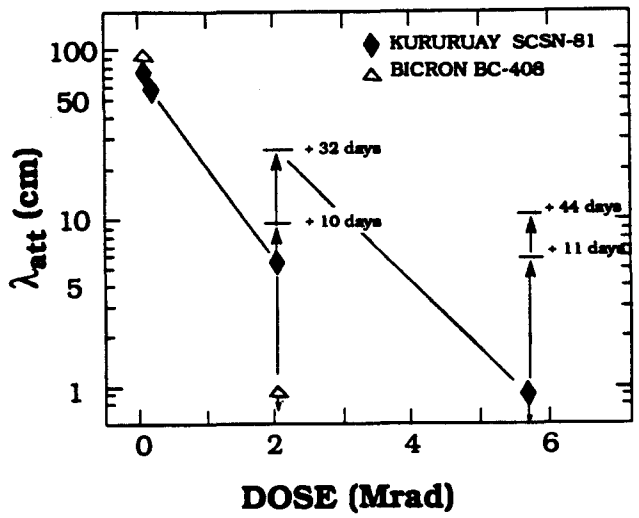

Figure 2: Attenuation length (λ_{att}) of two types of scintillator calculated from the measurement of light transmission along the axis of 25 cm long scintillator bars. The variation with absorbed dose and after annealing in air is shown.

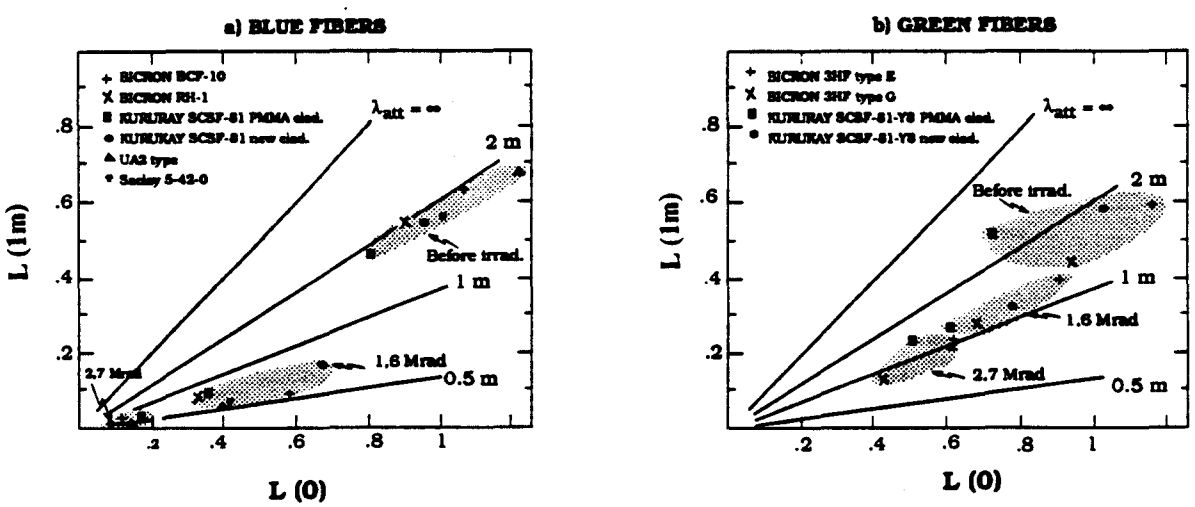

Figure 3: Relative light yield ($L(d)$) and attenuation length (λ_{att}) of fibers after various doses of irradiation. a) Blue bibers. L=1 corresponds to an absolute value of 7.7 photoelectrons. b) Green fibers. The absolute scale for L is not determined.

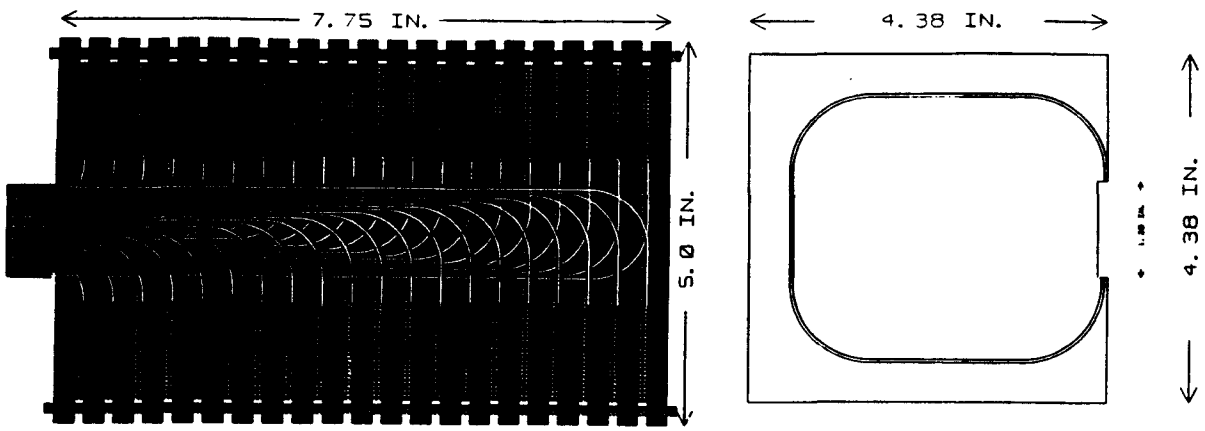

Figure 4: Lay out of the EMC module. The right hand side shows a tile with the groove holding the WLS fiber. The assembled module is shown on the left with the fiber path on top of the module.

4 System Test in an Electron Beam

4.1 Module Description

The modules (Fig. 4) are made of 20 scintillator tiles stacked between $\sim$ 6.4 mm thick lead plates ($\simeq 1.1X_0$). The total depth is $\sim$ 20 cm and represents 22 radiation lengths. The tiles are made of 3 mm thick SCSN-81 scintillator plates of area 12 cm x 12 cm. A machined groove holds a 1 mm diameter green WLS fiber (BCF-91A). The WLS fibers run on top of the module to the rear where they are connected to the PMT. No clear fibers are used to transmit the light. Each module is enclosed in an aluminum container and can be flushed with gas.

4.2 Irradiation

Two modules were exposed to an electron beam at the LURE[2] in Orsay. The experiment took place in July 1991. The 1 GeV electron beam had a 30 ns spill with a 12.5, 25, or 50 Hz repetition rate. The intensity could be varied from 10^9 to 10^{10} electrons per spill. Since the beam size was small ($\sim$1 cm^2) compared with the module dimensions, we used a remote controlled table [3] to move the modules across the beam during the 10 minute long exposures. The first 12 exposures were $\sim$ 20 krad each, and the last four $\sim$ 400 krad each. The time between exposures was $\sim$ 30 hours so that the "average dose rate" was 0.7 and 13 krad/hour respectively.

4.3 Dosimetry

We used three different dosimeter techniques during these beam tests:

- Alanine plastics, which develop free radicals under irradiation. The concentration of free radicals is proportional to the absorbed dose. Alanine dosimeters cover a large dose range: 10 krad to 10 Mrad.

[2] Laboratoire pour l'Utilisation du Rayonnement Electromagnétique

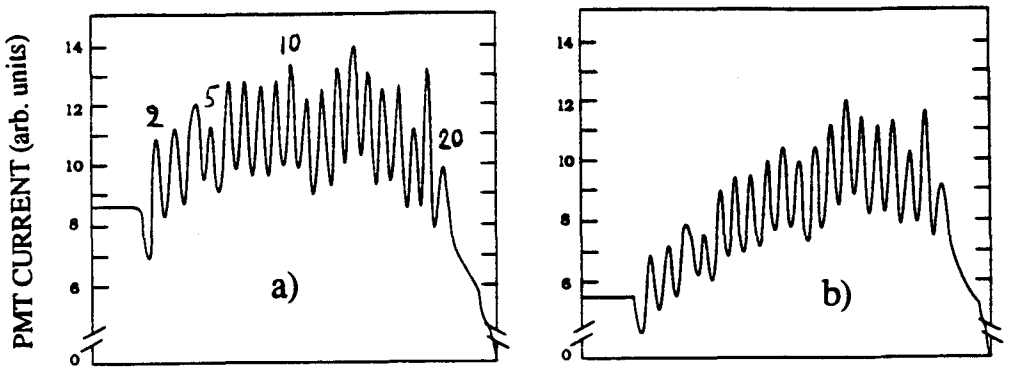

Figure 5: Measured PMT current induced by a ^{137}Cs source moving along a lontitudinal tube in the module before (a) and after (b) irradiation. The first tile seen by the beam is on the left. The vertical scale is arbitrary.

- Radiochromic dye films, 50 μm thick from FWT [4]. These films change their optical density as a result of irradiation. They are sensitive in the range 0.1 to 50 Mrad.
- Radiochromic dye films 125 μm thick from FUJI [5]. They cover the range 0.5 to 30 Mrad.

We used arrays of all three kinds of dosimeters in front of the modules and at shower maximum. The dosimeters were left in place for several irradiations and the beam current monitor was used to determine the dose for each run. More than 160 dosimeters were measured during the experiment. The results obtained with the three methods agree and show a relative spread of 5%. We estimate the absolute uncertainty in the dose to be $\simeq$ 10%. The ratio of the dose measured at shower maximum and that measured in front of the modules is about 9, in agreement with the expectation from 1 GeV electron shower development. The irradiation was uniform across the modules with at most a $\simeq$ 10% drop at the edges.

4.4 Measurements

The response of the EMC modules was measured with a radioactive source before every irradiation. In this way there was always a $\sim$ 30 hour annealing period which is taken into account for determining the average dose rate. The modules are equipped with transverse and longitudinal tubes. A radioactive source of ^{137}Cs located at the end of a wire can be moved through these tubes by using an automated source driver [6].

All tiles are connected to the same PMT, so the movement of the source in a longitudinal tube results in a peak-valley pattern of the PMT current. Figure 5 shows the signals before (a) and after (b) irradiation.

In the longitudinal scan, the peak at any given tile number is due to the signal from that tile and from its neighbors, because the γ rays from the source are penetrating. The closest neighboring tiles see $\sim$ 15% of the signal [7]. The unfolding necessary to obtain the intrinsic response of each tile has not been done, but the main results of this study should not be strongly affected.

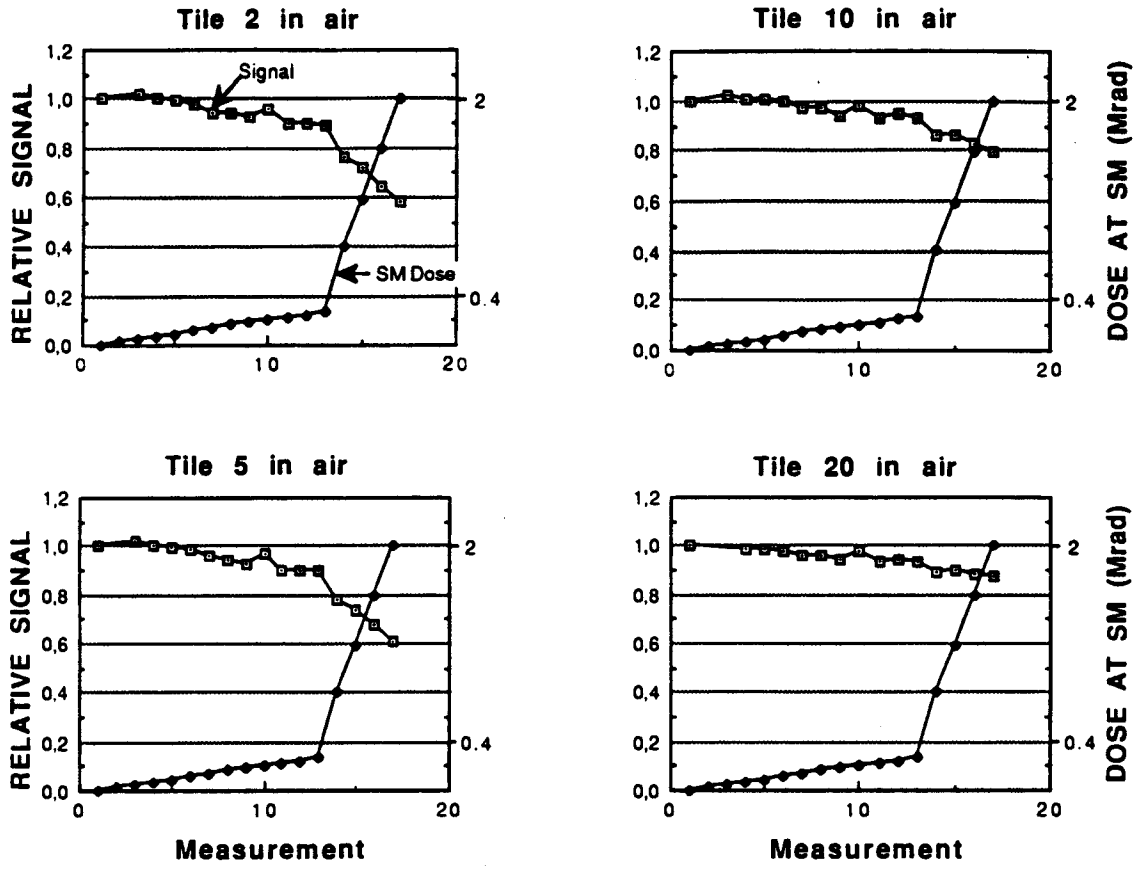

Figure 6: Relative signals as a function of the dose received at shower maximum for tiles # 2, 5, 10, and 20. Values are normalized to the measurements before irradiation.

5 Results of Beam Irradiation

The signals of all 20 tiles have been normalized to the first measurement made before irradiation. Figure 6 shows this relative signal for tiles # 2,5,10, and 20. The total dose accumulated at shower maximum at the time of each measurement is shown on the right hand scale. It is apparent that the damage is worst in tiles # 2 and 5, which are near the shower maximum.

5.1 Damage Profile

Tile # 20 shows a 10% drop of signal after 2 Mrad. According to the shower profile (Fig. 7a), this tile should see very little radiation from the showers. The 10% loss could be due to a drift of the PMT's, which are not equiped for monitoring. However, we believe that this interpretation is unlikely; the PMT high voltage was applied at least 20 minutes before each measurement, and it was monitored very closely. Furthermore, we used other scintillator counters in this experiment, and their PMT's, which were monitored with LED's, showed no drift in gain. We therefore interpret the loss in tile # 20 as the result of direct irradiation, by the electron beam, of the WLS fibers which run on top of the module. Figure 7b shows the

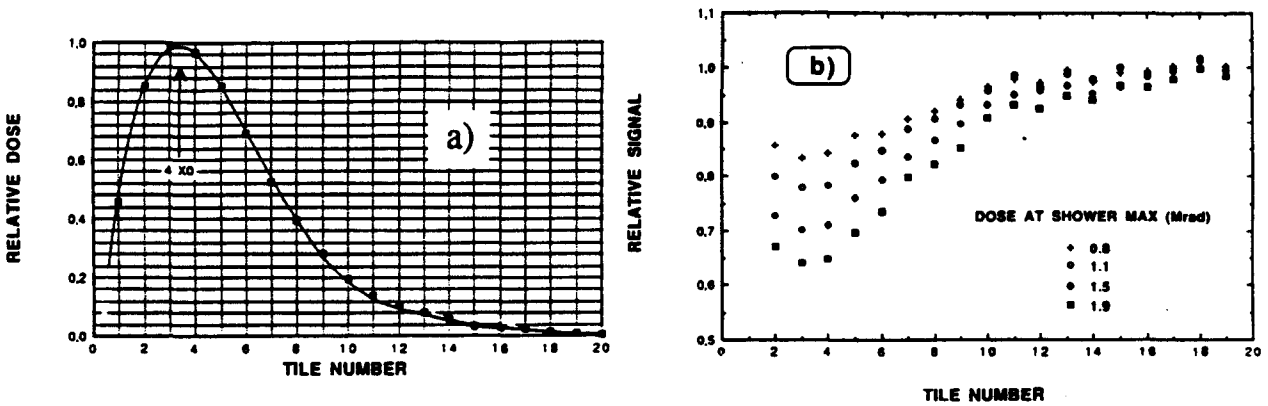

Figure 7: a) Simulated shower profile for 1 GeV electrons as a function of the tile number of the module. b) Damage profile as a function of the tile number for various doses.

damage profile measured after various doses absorbed at shower maximum. In this figure, the signals have been normalized to tile # 20 to take out the effect of direct irradiation of the fibers. The damage profile reproduces the shower development profile.

5.2 Damage vs. Dose

Let S_i be the measured relative signal of tile i (normalized to tile # 20) after irradiation j. The dose for each data point is calculated according to $D_{ij} = D_{SM(j)}.P_i$ where $D_{SM(j)}$ is the measured integrated dose at shower maximum and P_i the ordinate of the normalized shower profile for tile i. Figure 8 shows the relative decrease of the signal as a function of dose.

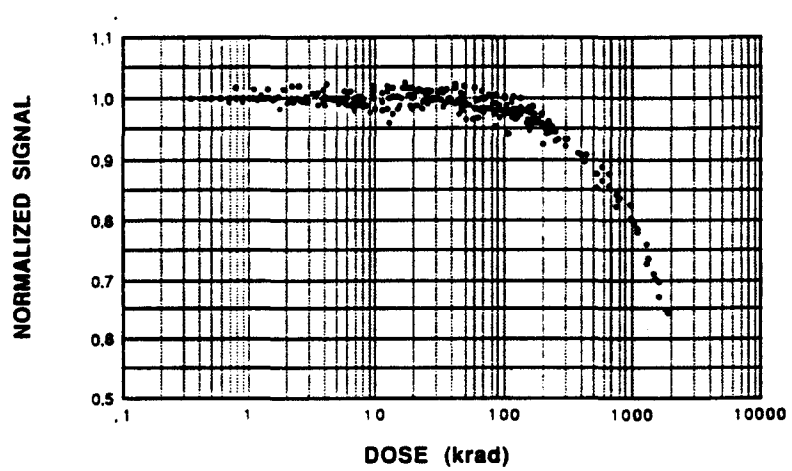

Figure 8: Relative signal, normalized to tile # 20 (see text), as a function of the dose received.

In a real calorimeter assembly, the readout fibers will be damaged by direct irradiation. Therefore, we take a conservative approach and use the measured relative signals before renormalization to tile # 20 to estimate the expected loss of light. We conclude that the light output of the tile-fiber elements of an EMC module decreases by $\simeq$20% for a total dose of 0.6 Mrad. This corresponds to the dose absorbed at the end of the barrel at shower

maximum after 10 years at a luminosity of 10^{34} $cm^{-2}s^{-1}$ (ten times the design luminosity).

5.3 Effect of Nitrogen and annealing

All the above results were obtained for an EMC module in air. A second, identical module was flushed with nitrogen during the duration of the experiment. Results from these two modules are compared in Fig. 9 for tiles # 5, near shower maximum.

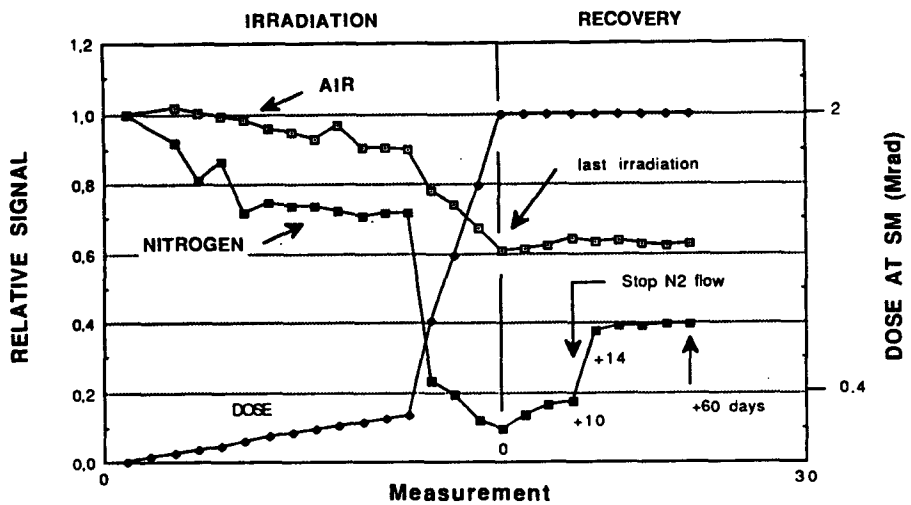

Figure 9: Relative signal of tile # 5, near shower maximum, for a module in air and a module in nitrogen. The recovery after the last irradiation is shown on the right. The dose at shower maximum is indicated on the right hand scale.

- After 2 Mrad, the signal in tile # 5 drops to 60 % of its initial value for the module in air. There is no annealing in this module, even after 60 days.
- The module in nitrogen deteriorates much more quickly: after 2 Mrad the signal from tile # 5 is only 10 % of its initial value. The recovery of this module is very slow in the nitrogen atmosphere. When the nitrogen flow is stopped and the module is exposed to air, the signal recovers to 40% of its initial value. Nonetheless, even after 50 days of exposure to air, the module irradiated in nitrogen does not recover to the level of the module which was kept in air at all times.

6 Conclusion

We have performed radiation damage tests with a cobalt source on samples of plastic scintillators and fibers. Among the commercially available material, we have selected blue SCSN-81 from KURURAY for the plates and green BCF-91 from BICRON for the WLS fibers. We have found that there was no loss in the light yield of SCSN-81 after several Mrad. However, the attenuation length in the plate decreases by a factor ~ 3 after 2 Mrad and 1 month of annealing in air.

We have tested the radiation resistance of two electromagnetic calorimeter test modules built at Fermilab with these materials. The modules were exposed to a 1 GeV electron beam at the Orsay LINAC and their response to a radioactive source was measured before and after irradiations. We found the following results:

- A tile-fiber element in an EMC module irradiated in air loses $\simeq 20\%$ of its light output after having received a dose of 0.6 Mrad. This dose corresponds to the dose absorbed at shower maximum at the end of the SDC barrel EM calorimeter (η=1.4) during 10 years at 10 times the nominal luminosity.

- After 60 days, there is no noticable recovery of the module irradiated and annealed in air. A module irradiated in nitrogen suffers much higher damage; this module does anneal in air, but it does not recover to the level of the module which was kept in air at all times.

According to a study of the effect of radiation damage on detector performance [8], the resolution of the calorimeter is not significantly degraded if the loss at shower maximum is $< 30\%$. For higher damage, good resolution can still be obtained by correcting for the loss of light using in-situ calibration. For this purpose, calibrations with radioactive sources should be performed periodically to monitor the radiation damage in the EM calorimeter and in the Shower Maximum Detector.

We conclude that the barrel calorimeter should survive for the duration of the SDC experimental program with presently-available scintillator and fibers. We do not expect this conclusion to be challenged unless studies now under way [9] show that low dose rates expected at the SSC are much more harmful than the much higher dose rates used in the present study.

In the end cap, for $\eta > 2$, new scintillator and fibers which are much more radiation hard are needed if they must last for 10 years at 10 times nominal luminosity. If presently-available commercial scintillators and fibers are used in this region, they will have to be replaced periodically.

Acknowledgements

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References

[1] SDC-91-00011 and DPhPE Saclay Preprint 91-03.

[2] Letter of Intent, SDC 90-00151, Fig. 4.

[3] On loan from Fermilab.

[4] FWT-60-00 films were obtained from Far West Technology, 330 D S. Kellog, Goletta, Ca 93117, USA. K. Johnson (FSU) suggested their use to us.

[5] FUJI films were provided by K. Takikawa and K. Yasuoka.

[6] V. Barnes provided us with one of his source drivers.

[7] Private communication from V. Barnes.

[8] D. Green and A. Para, Fermilab-FN-565, May, 1991.

[9] M. Contreras and N.D. Giokaris in proc. First Int. Conf. on Calorimetry in H.E.P., 1990 Fermilab. C. Zorn et al. reported by K. Johnson, 2nd Int. Conf. on Calorimetry in H.E.P., 14-18 October, 1991 Capri.