CAN A Pb/SCIFI CALORIMETER SURVIVE THE SSC?

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ABSTRACT

A scintillating fiber based electromagnetic calorimeter module built from radiation-hard materials has been tested in a beam capable of delivering both low and high currents of monoenergetic electrons. Energy resolution and light output measurements were made following high-dose exposures. The procedure was repeated until the resolution of the detector decreased from an initial value of $6.9\%/\sqrt{E}$ to $14.0\%/\sqrt{E}$ and the pulse height dropped by a factor of 11. After four weeks, the detector was retested. Partial recovery was observed in the light output which returned to approximately 52% of its original value. The resolution recovered to a value of $8.8\%/\sqrt{E}$. The tests are described.

1. Introduction

The use of plastic scintillating fibers embedded in a high-Z passive material such as lead is projected to result in a high-resolution, compensating calorimeter appropriate for a new generation of high-energy physics experiments [1]. The resolution is achieved by minimizing the sampling fluctuations. This is realized by the replacement of traditional scintillation plates with small-diameter fibers. Equalization of light output from the electromagnetic and hadronic portions of a hadronically-induced shower (compensation) occurs if the ratio of active to passive material is properly tuned. Several programs are underway [2] to develop such a device. In the interim, great success has already been attained with the development of similar, but smaller, electromagnetic calorimeters [3,4]. These have been found to produce the excellent resolution typically found in lead glass. For both hadronic and electromagnetic fiber-based calorimeters, radiation hardness is an attractive and possibly necessary feature for their widespread inclusion in detectors of the

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future. This parameter is coupled directly, but not limited, to the survival of the root plastic scintillator.

Inherent to the success and utility of such detectors is the quality and performance of the scintillating fibers. Our direct experience is with a 300-element, fiber calorimeter array built using hundreds of kilometers of fibers [4]. The performance of this array greatly depends on the module-to-module uniformity and on the long-term stability of the light output and attenuation length of the fibers. These features are difficult to monitor in a large-scale module production process. Furthermore, they may degrade in a field of high-radiation in a manner which is not easily accounted for in the data analysis. The situation is more complex for the 2 m deep, dual-purpose electromagnetic / hadronic units proposed for the SSC or LHC environments [2]. The highest radiation doses will be localized to the electromagnetic compartment of the calorimeter. Since the fibers in such a calorimeter point toward the interaction region and extend, in part, from inside to outside, the ends nearest to the beam experience a much greater dose of radiation than the ends far away. If the light output of the scintillator slowly decreases due to radiation damage, the response of the front portion of the detector will differ from that of the rear portion for equal depositions of energy per unit volume. The calorimeter may be expected to demonstrate non-linear behavior and worsening of the energy resolution from such an effect.

Scintillating fibers produced to date have been made from a polystyrene core which is intrinsically more radiation resistant than other traditional materials such as acrylic. In part, this has prompted the label "radiation hard" as a characteristic of fiber calorimeters [3,5]. Additionally, both commercial and academic centers are intensely involved in the development of new plastics and fluors which are better suited for stability in the environment of high-radiation fields. Development of such plastics will extend the utility of plastic scintillator in all detector designs. For the moment, we must address the very important question, *"Can a present-day scintillating-fiber calorimeter survive the SSC?"*

The radiation field of the SSC, presented in the model of Groom [6], indicates a wide range in needed survivability versus pseudorapidity (η). With the assumption of ten years of operation at an optimistic luminosity of 10^{34} cm^{-2} sec^{-1}, the expected integrated dose in the electromagnetic compartment of a typical detector ranges from 0.25 megarad (Mr) in the central region at $\eta = 0$ to 50 Mr in the forward region at $\eta = 3.0$. This field is considerably higher than that of current generation, comparable experiments and stimulates new thinking for all detector components which are to be a part of any SSC detector.

We have tested the radiation hardness of a lead / scintillating fiber (Pb/SCIFI) calorimeter module made from state-of-the-art fibers and adhesives. This test was intended as a "proof-of-principle" that a highly radiation resistant instrument utilizing the techniques developed could be built. The spirit of the exercise is to alternately measure, irradiate and remeasure a detector using the same source. The cycle is repeated until the performance of the detector has greatly deteriorated. The source is a 93 MeV monoenergetic electron beam at the University of Illinois Nuclear Physics Laboratory. The beam may be tuned to deliver alternately a narrow, low-intensity beam for resolution and light output measurements or a high-intensity, artificially diffused beam for the irradiations. Some evidence exists indicating nearly total recovery of the light output and attenuation length of some types of scintillating fibers when exposed to air after irradiations [7]. The calorimeter module we built was made from a particularly radiation-resistant fiber of this type. Since access to air was considered essential for rapid recovery, the module was constructed to permit air diffusion to the fibers. The test area was prepared carefully in order to make meaningful retests periodically after the initial runs.

Our program is largely complimentary to the dedicated fiber tests which have been reported at this workshop [8]. While a large variety of fibers can be tested using the "fiber only" methods, the motivation here is to compare results when a real detector is fabricated from a particular fiber and used in an environment which more closely simulates that of its eventual use. If this detector deteriorates at a radiation level below the dedicated "fiber-only" tests, then the question "Who or what do we blame?" must be addressed.

The tests described below show a rapid deterioration of the calorimeter performance with dose. Partial recovery of the pre-irradiation characteristics of the detector are observed after a period of four weeks from the initial irradiation runs. We are continuing to monitor this detector and are planning an additional test with a module made from a new type of "radiation-resistant" fiber.

2. Design Considerations

The Pb/SCIFI calorimeter blocks consist of a matrix of 1 mm diameter scintillating fibers embedded in a lead alloy, Fig. 1. The fiber chosen was a Kyowa, PTP/3-HF (green emitting) polystyrene fiber with an acrylic cladding which we had shown to recover in air to its original attenuation length after a dose of 10 Mr [6]. All fibers are aligned in parallel in the grooves of the plates shown in Fig. 1. They are surrounded by an adhesive which bonds the fibers and the plates in a "lasagne-like" structure. Since constructing a full hadronic calorimeter is impractical, we chose to make our tests with a smaller module optimized for its electromagnetic shower characteristics. This module is based on a well-understood design which has proven successful for us in the past [4].

The volume ratio of fiber-to-lead affects both the energy resolution and the equality of response to electromagnetic- or hadronic-induced showers (e/π ratio). These responses cannot be simultaneously optimized. While energy resolution improves with increasing fiber content, an e/π

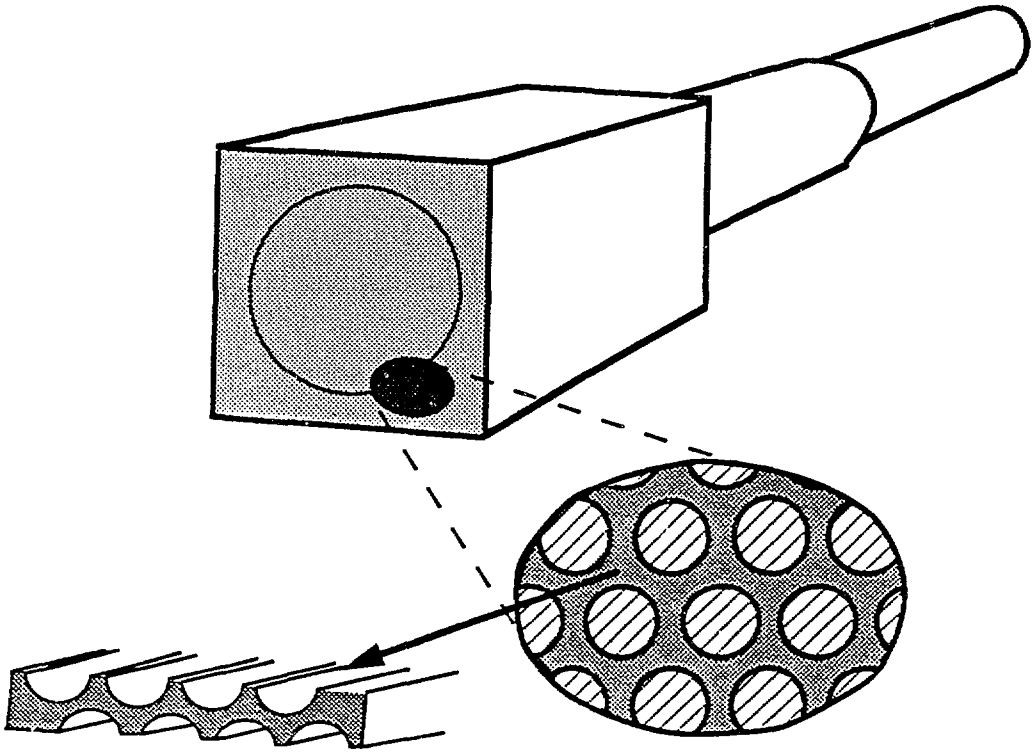


Figure 1
A Pb/SCIFI module is shown with the circle indicating the size of the lightguide which was attached to the downstream end. The enlargement shows the relative matrix of fibers, the construction of which is facilitated by use of a stack of profiled plates interwoven with scintillating fibers. See Ref. 4 for further details.

response of unity is expected when the ratio of fiber-to-lead is approximately 1:4 [1]. The ratio of fiber-to-lead in our (electromagnetic) design is 50 : 35, leaving 15% volume for filling around the fibers with an adhesive. The density of a finished block is found to be $\rho_{Pb/SCIFI} = 4.58 \ \mathrm{gm/cm^3}$ leading to a radiation length of $X_0 = 1.61$ cm. The fibers are placed exactly on the corners of equilateral triangles with a fiber-to-fiber spacing of 1.35 mm, see Fig. 1. The test detector measured 9 x 9 x 22 cm^3 ($\approx 14 X_0$) which is sufficiently long to contain the shower initiated by a 93 MeV electron.

The material used to fabricate the plates is an alloy of pure lead containing 6% antimony by weight. This has far superior mechanical properties compared to pure lead. Inside the grooves of each plate, the fiber is not in direct contact with air, but with the adhesive used to hold the plates together. To optimize the radiation-hardness of the detector, we found that standard optical epoxy cements were unsuitable. Instead, we used Petrach Systems PS-273 encapsulant, a polymer of the polysiloxane family, which was chosen because

1) it remains clear up to 100 Mr,
2) its properties, such as adhesive ability and chemical inertness, are not significantly affected by radiation, and
3) it is highly permeable to air, allowing air to diffuse into the module to enhance recovery.

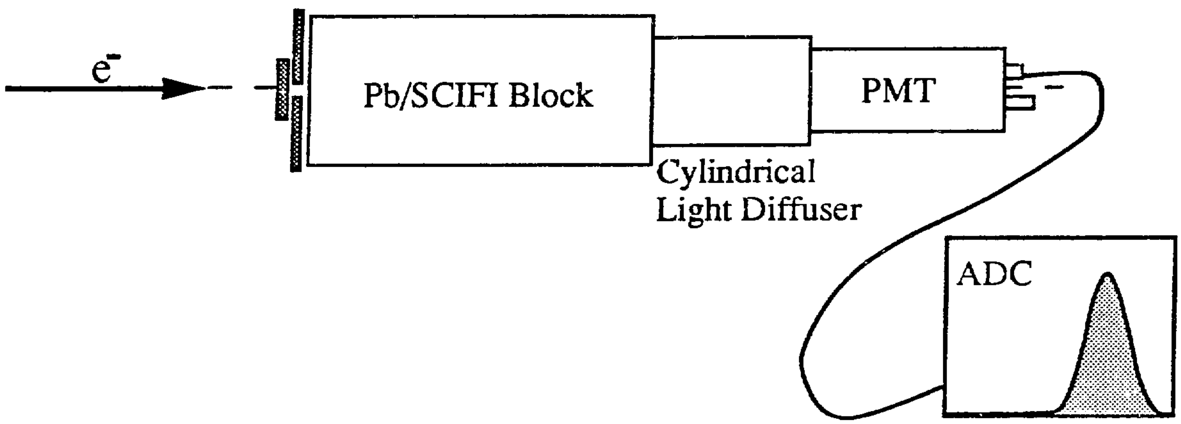
The detector was wrapped in aluminium foil to which several strips of copper tape were attached providing an electrical connection for current integration. If the block had been insulated, it would have accumulated electric charge and become charged to a high voltage. To avoid this, it was discharged to ground through a ballistic galvanometer. This allowed us to measure the total intercepted beam and, from that, to compute the deposited dose. The conversion to a dose scale is discussed below.

A 6.5 cm diameter by 10 cm long cylindrical Plexiglass lightguide was attached to the center of the rear face of the detector and a RCA 8850A photomultiplier tube viewed this lightguide. The light collection was designed to view only the central portion *within a* 6.5 cm diameter region of the module which we intended to damage. During resolution and light output tests, the current from this photomultiplier tube was digitized for each event. An event was defined by a pair of trigger scintillators; one of which had a 0.6 cm hole in the center and was used as a veto.

3. Test Runs and Results

The calorimeter was held in a mechanical cradle and was positioned 1 m downstream of the last vacuum pipe in the electron-scattering hall. The beam profile on the front face of the calorimeter was approximately 5 mm in diameter. This configuration was used for the resolution and light output runs, Fig. 2a. During irradiations, a lead foil diffuser was positioned at the downstream vacuum window of the last vacuum pipe to ensure that the beam was distributed uniformly over the face of the module. The diffused beam incident on the front face of the calorimeter was constrained to a 6.1 cm diameter circle by a lead collimator, Fig. 2b. The uniformity and alignment were checked by positioning a "placebo" calorimeter, an uninstrumented assembly of lead and acrylic scintillator sheets, where the module was to be irradiated. The placebo was irradiated and the scintillator sheets were darkened, providing a record of the beam uniformity and longitudinal shower profile. The beam was quite uniform across the 6.1 cm target circle.

a) Resolution and light output configuration



b) Irradiation configuration

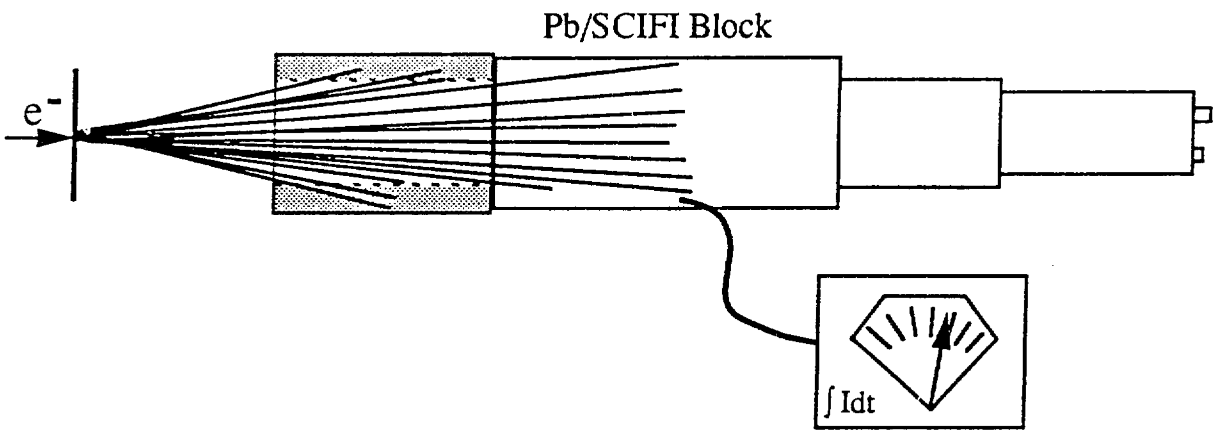


Figure 2

a) The basic setup used for the resolution and light output tests in which a well-focused monoenergetic electron beam is incident on the center of the front face of a Pb/SCIFI module. A histogram of the pulse height for each electron is formed using the trigger scintillators to gate an ADC. b) During irradiation runs, a beam diffuser is inserted upstream of the module and a collimator matched with the cylindrical lightguide is placed in front of the module to produce a uniform irradiation over the front face of the module. The current is integrated to calculate the accumulated dose.

The test calorimeter was then positioned and the electron beam was reduced in intensity to a rate of approximately (10-100) kHz. The resolution and light output were measured, where the absolute light output was determined by the use of a photomultiplier tube calibrated in photoelectrons (pe) per ADC channel. The typical light output for the undamaged detector was approximately 2700 pe / GeV. A pedestal-subtracted ADC spectrum for this run is shown in Fig. 3a. The mean of the peak is at channel 766 and the full width at half maximum (FWHM) corresponds to 405 channels. This represents a resolution of $6.9\%/\sqrt{E}$ with E in GeV when quoted in the format typical for sampling calorimeters. Our previous measurements with similar Pb/SCIFI detectors [4] demonstrate that a $1/\sqrt{E}$ scaling of the energy resolution is valid to very low energies.

Next, the trigger scintillators were removed, a lead collimator was inserted directly upstream of the module and an electro-mechanical table upon which the entire assembly was supported was remotely moved away from the beam line. The electron beam current was then slowly raised to a current of approximately 20 nA. Once stable, the table was repositioned in its original location and the irradiation was begun. The Pb/SCIFI detector was used as a Faraday cup to integrate the total charge. After approximately 15 minutes, the beam stop was inserted and the module was allowed to "cool" for an additional 15 minutes. The setup was then reconfigured for the resolution and light output measurements as described above.

This cycle of measurements was repeated until a total charge of nearly 400 μC was accumulated in the detector. The entire set of measurements was performed in a 36 hour period. In Fig. 3b, the pulse height spectrum from the last measurement is shown in which a greatly distorted peak is evident with a centroid at channel 71 and a FWHM of 77 channels. If the spectrum had a Gaussian form, this would correspond to a resolution of $14.0\%/\sqrt{E}$. The light output here dropped by a factor of 11 compared to that of the original undamaged detector. A plot of the resolution, expressed in "%"$/\sqrt{E}$ (left ordinate) and pulse height of the peak centroid (right ordinate) versus integrated dose in μC for all of the measurements is shown in Fig. 4. To determine the resolution parameter from the data, the FWHM was extracted by hand and was converted to an effective σ as if the detector maintained a Gaussian response. A true Gaussian response was only realized for the undamaged detector. The trend of both the resolution and light output is clear from the data in Fig. 4. Both parameters fall steadily up to an integrated dose of 200 μC. After that, the detector is so heavily damaged that the response changes more slowly. We attribute this to a near saturation of the damage in the portion of the detector where the shower is concentrated. After 200 μC, only the energy deposition in the tail of the shower is observed, presumably, in a portion of the detector with much less damage.

After four weeks, the detector was retested in the same configuration with no changes to the electronics system or beam configuration. The retested detector once again exhibited a near

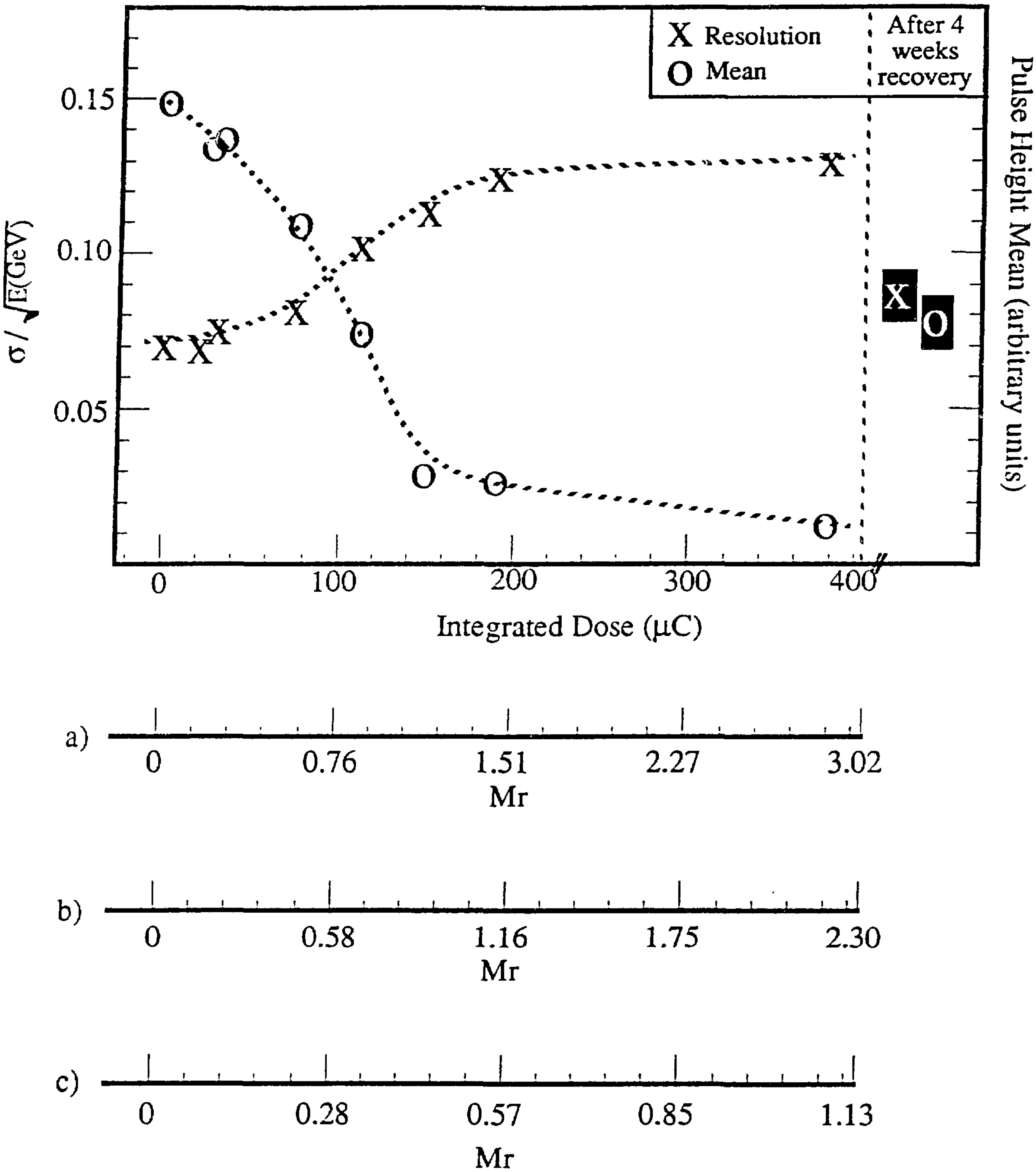


Figure 4

Resolution and pulse height mean versus integrated dose. The dashed lines are to guide the eye only. The separate scales represent calculations of the integrated dose in the regions a) ± 0.5 radiation lengths of shower maximum b) ± 1.0 radiation lengths of shower maximum and c) for the whole detector. The measurement at the right of the plot was made four weeks after the original irradiation and indicates partial recovery of the light output and substantial recovery of the resolution.

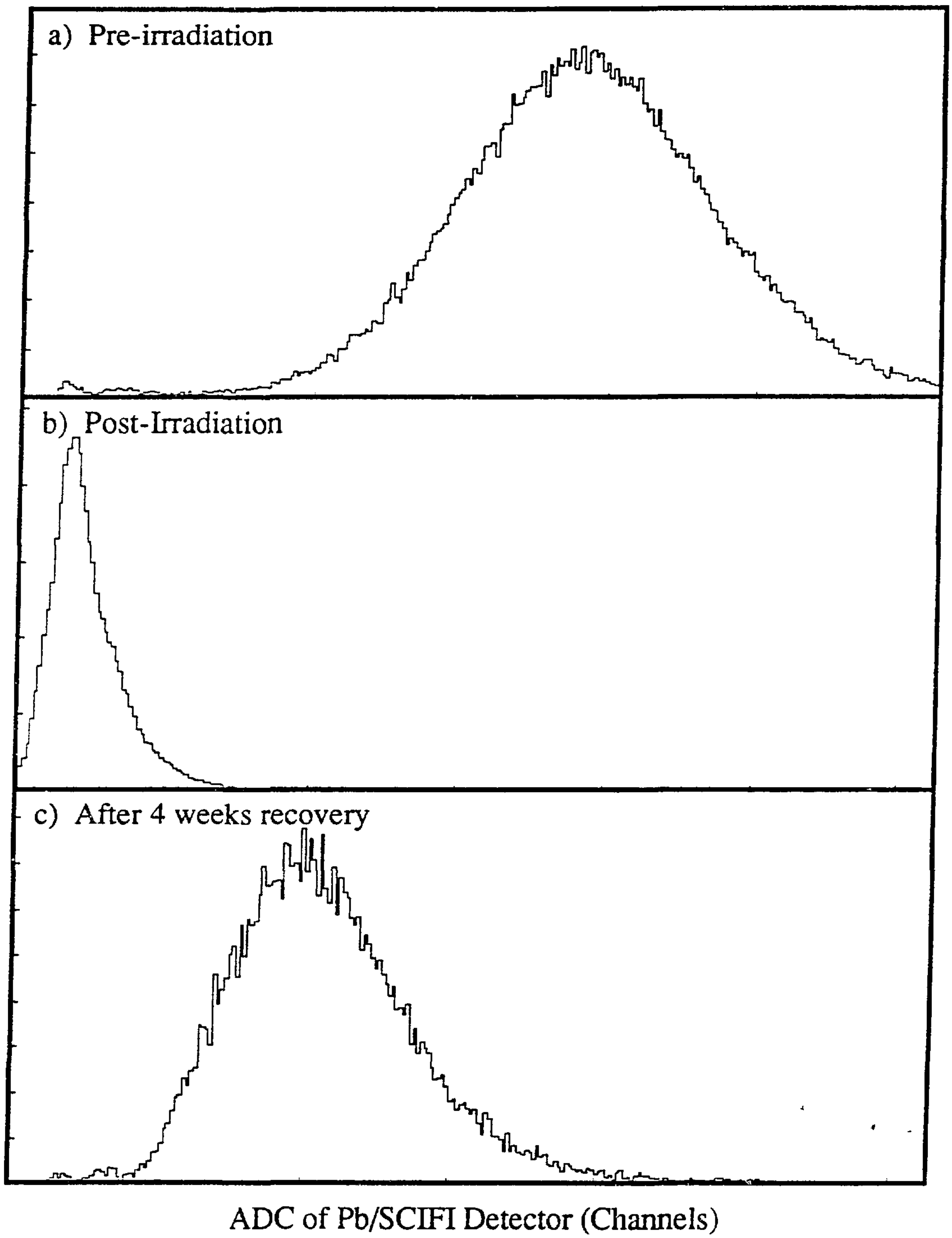


Figure 3
Detector response to 93 MeV incident electron beam before irradiation (a), after an accumulated charge of 400 μC (b), and after four weeks recovery time (c). The centroid of the peak represents the average light output which decreased by a factor of 11 during the irradiation period and recovered to 52% of its original value four weeks later. Similarly, the resolution deteriorated by a factor of 2 during the irradiation and recovered to 80% of its original value, see text.

Gaussian response with a mean of 400 channels corresponding to 52% of the original light output, Fig. 4c. The resolution was measured as $8.8\%/\sqrt{E}$ which is nearly equal to that of the original undamaged detector. These points are indicated at the right in Fig. 4 and are labelled "After 4 weeks recovery".

The Rad is defined as an energy deposition per unit mass, namely; $1\ \text{Rad} = 6.24 \times 10^{10} \text{MeV} / \text{kg}$. Therefore, the abscissa scale conversion in Fig. 4 from μC to Mr involves a calculation of how much energy is deposited in a specific volume. The GEANT simulation program [9] with a full description of the detector geometry, including fiber, cladding, and adhesive, was used to determine the longitudinal energy deposition for an incident, monochromatic 93 MeV electron beam distributed uniformly over a 6.1 cm diameter circle on the front face and viewed by a 6.5 cm diameter lightguide on the downstream face. The integrated energy deposition in three regions about shower maximum was determined. The first region includes only the energy deposited in a band $\pm 0.5\ X_0$ around the shower maximum, resulting in a deposited energy of 18.5 MeV per incident 93 MeV electron. This occurs in a mass of 0.245 kg. We make the simple assumption that the energy deposition is uniform in a material of density $\rho = 4.58\ \text{gm}/\text{cm}^3$ and do not make additional corrections for relative deposition of energy in the lead or fiber. A 20 μC irradiation implies a deposition of 0.151 Mr in this band. The second band is $\pm 1.0\ X_0$ around shower maximum and leads to a deposition of 28.5 MeV per electron. The final region considered is the entire detector with a deposited energy of 86.2 MeV per electron. Since the longitudinal deposition is highly non-uniform, the latter calculation greatly underestimates the damage at the peak of the shower.

4. Conclusion

The three dose scales discussed above are displayed beneath the data in Fig. 4 and indicate that severe performance degradation had occurred after a short-term dose of 0.75 Mr. This would seem to be in contradiction to the tests on free fibers reported in reference [7], in which full recovery of attenuation length and approximately 90% recovery of light output were observed after 10 Mr. The recovery in the latter case was, however, for fibers in unrestricted contact with gaseous air for 10 days. In the present case, we have fibers in contact with a substance (the polysiloxane adhesive) in which the oxygen mobility, although two order of magnitude greater than standard epoxy-based optical cements, is still many orders of magnitude less than free air. A much retarded recovery in the present case can be expected. Still, the detector shows a dramatic recovery after four weeks annealing time. The level of light output, 52%, did not reach 90%, the recovery measured on free fibers, which we may take as an indication that the recovery process was not complete. We intend to retest the detector again in the near future.

The difference between our measurements and those performed on the individual fibers may lie only in the diffusion time of the air into the fibers. A direct comparison of the recovery time should be made between bare and embedded fibers in future "fiber-only" tests. As long as the annealing time can be kept short compared to the time over which the damage is accumulated, Pb/SCIFI calorimeters can be expected to remain fairly stable.

Returning to the question of survival at the SSC, it should be noted that any detector with stability up to 1 Mr will suffice for an η up to 2.0 ($\approx 30^o$) [6]. The tests reported here do not quite demonstrate that benchmark. However, they are not finished. Another post-irradiation measurement is planned. Our hope is to find a combination of materials that will result in a Pb/SCIFI calorimeter stable to 10 Mr.

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