EFFECTS OF RADIATION DAMAGE ON SCINTILLATING FIBRE CALORIMETRY

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Abstract

We report on measurements of radiation hardness of plastic scintillating fibres to be used for scintillating fibre calorimetry. Fibres were irradiated by a ^{60}Co γ -source and the effects on the emission and on the attenuation of scintillation light in a number of different fibre types were studied. Results are given on the changes in the wavelength spectrum induced by ionising radiation. The influence of optical filters, glue and surrounding gas were investigated. A Monte Carlo study is described that simulates radiation damage in a compensating lead-fibre calorimeter and predicts the impact on the performance. By combining the results of the radiation hardness measurements of the fibres and the results of the Monte Carlo, a limit is set on the acceptable dose level. If we define a contribution of 0.8% to the constant term of the electromagnetic energy resolution due to radiation damage as an acceptable performance degradation, we determine, with the best fibres that are presently commercially available, an acceptable dose limit of 7 Mrad.

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1. INTRODUCTION

Detectors operating in future LHC or SSC experiments will encounter a considerable amount of radiation [1,2]. It is therefore of great importance to study the effect of radiation on the performance of such detectors. The origin of the radiation at these future colliders is the pp collisions themselves, the most abundantly produced particles being neutral and charged pions. Since all the energy of electromagnetic showers is deposited in a region of limited depth, most of the effects of radiation damage on the calorimeter performance are due to the production of electromagnetic showers in the calorimeter itself, through the 2γ decay of π^0 's [1].

In the framework of the CERN-LAA project, the SPACAL collaboration has developed prototypes of a scintillating fibre calorimeter intended for the detection of both electromagnetic and hadronic showers in an experiment at a future multi-TeV hadron collider [3]. The detectors contain a large number of 1 mm diameter, 2 m long parallel plastic scintillating fibres embedded in a lead matrix at a volume ratio of 1:4 to achieve compensation [4]. The fibres run almost parallel to the direction of the particles to be detected. A single calorimeter tower contains 1141 fibres, which are read out by a single photomultiplier. In addition to compensation, the advantages of this technique include good energy resolution for electromagnetic and hadronic showers, fast detector response, hermeticity, uniformity of detector response as a function of the impact position and angle independent of the degree of segmentation, low noise and sensitivity to minimum ionising particles [3].

With respect to the radiation sensitivity of this detector two aspects are important. Since the light signal is automatically carried to the outer surface of the calorimeter, there is no need to place electronics in the high radiation areas in the front. Lead/scintillator calorimetry is also advantageous in terms of the calorimeter induced neutron flux in the detector cavity. It is a factor 3.3 smaller than for lead/liquid argon and a factor 2 smaller than for uranium/scintillator calorimetry techniques [1,2].

To achieve the calorimeter properties mentioned above, the scintillating fibres have to fulfil a number of requirements [5]. To first order the production and attenuation of light in a scintillating fibre are described by an exponential function:

$$I(z) = I_0 e^{-z/\lambda_{att}}, \quad (1)$$

where I_0 = the quantity of light produced at a distance z from the light detector,
 λ_{att} = the attenuation length of the fibre,
 $I(z)$ = the quantity of light detected.

The attenuation of light in most of the fibre depends on the wavelength and on the production angle of the light [5,6]. Therefore the transmission of light along the fibre would be

described more correctly if we replaced eq. (1) by a sum of exponential functions. An effective increase of λ_{att} for standard blue fibres can be achieved with an optical filter that cuts off the short wavelength components (< 450 nm) [5].

In order to limit the effects of light attenuation on the hadronic energy resolution to an acceptable level, λ_{att} should be at least 3 m. By then placing a mirror of sputtered aluminium at the far-end of the fibre (with a reflectivity of typically 85%), the effective attenuation length improves from 3 m to the 6-8 m necessary for jets. Fluctuations in I_0 for fibres read out by the same photomultiplier should be smaller than 6% to maintain a good energy resolution for electromagnetic showers, with an energy independent contribution of less than 1%. The stability of the above properties is of major importance, so they should be maintained under the high radiation doses expected [1,2]. Further reports on radiation hardness studies of scintillating fibres can be found in [7,8].

This paper consists of two parts. The first part reports on a series of measurements of the effects of radiation on the fibre performance. It covers sections 2-5. The second part gives the results of a Monte Carlo analysis of the effects of radiation on the calorimeter performance and covers sections 6 and 7.

In section 2 we describe the set up used for fibre irradiation as well as the different set ups used to measure the fibre characteristics before and after irradiation. Section 3 starts with an overview of fibres available on the market when this investigation was started, followed by results on the wavelength spectra before and after irradiation. Section 4 reports on the influence of the surrounding medium on the radiation damage to the fibres. In section 5 a comparative study of the radiation hardness for different types of fibres is presented. Section 6 describes the input parameters used for the Monte Carlo simulations. The results are presented in section 7. Conclusions are given in section 8.

2. EXPERIMENTAL SET UP OF THE IRRADIATION TESTS

Two different ^{60}Co γ -sources were used for the irradiation of fibres of 40 cm length. The dose rate profile of the first source, the "normal intensity" source, is shown in Fig. 1a. Measurements of the light output of the fibres were normally performed on the less irradiated side (left hand side in Fig. 1a). For this source the maximum dose rate of 30 krad/h was reached at 30 cm from the read-out end.

For the second ^{60}Co γ -source, appropriate shielding was set up to simulate better the narrow dose profile of electromagnetic showers in the calorimeter. The profile of this "very high intensity" source is shown in Fig. 1b. It reached a maximum of 1.05 Mrad/h at 27 cm from the read-out end.

Fibre measurements were performed using three different set ups, which we will call Box1, Box2 and Box3. Box1 was used for comparative studies on 2.2 m long fibres, a length appropriate for use in the calorimeter. A single fibre was placed in a tray facing a plexiglass light guide followed by an XP2081B¹ photomultiplier used in current mode. The photomultiplier was equipped with a photocathode whose sensitivity peaks at 450 nm and which is sensitive up to 650 nm. The read-out end of each fibre was polished by hand using fine sandpaper. The opposite end was cut with a knife. A Kodak wratten #3 filter, which cuts off wavelengths below 450 nm, was mounted between the light guide and the photomultiplier. For better reproducibility, all optical contacts were made in air without using optical grease. Above the fibre a small carriage was mounted containing either a 256 nm ultraviolet (UV) light source or a ⁹⁰Sr β -radioactive source. As the carriage moved along the fibre, the signal of the photomultiplier was measured in current mode under computer control. For SCSN38² fibres we checked (using Box3, described below) that the detected wavelength spectrum, and therefore the self-absorption part of the light attenuation in these fibres, was independent of the type of source used. The UV lamp was more convenient for measuring non-irradiated fibres, since the intensity, and therefore the signal to noise ratio, was much higher. The stability of the UV lamp was checked using a photodiode and was found to be better than $\pm 0.2\%$. Nevertheless, for irradiation tests the use of the UV lamp was not appropriate, since the UV light might be absorbed differently in the non-irradiated and in the irradiated cladding material. The effect of irradiation would then be overestimated. Therefore, it was used only for the comparative measurements of non-irradiated fibres (sect. 3).

In Box2, fibres of 40 cm length were tested. In this set up the fibre to be tested was placed between two other fibres, which were used for trigger purposes. The fibre being tested was held directly against the input window of an RCA8850 photomultiplier equipped with a photocathode, which was sensitive up to 600 nm, peaking at 360 nm. The box contained a ⁹⁰Sr β -source that could be moved along the fibres. This set up allowed single-photoelectron counting and was most suitable when absolute scintillation light measurements were desired for a small number of photoelectrons produced at the photocathode. The signal from the fibre under test was stored in a Multi-Channel Analyser³, whose input gate was activated by the coincidence of the trigger fibres. The average number of photoelectrons was essentially given by the average channel number of the MCA spectrum after calibration of the single photoelectron response. The efficiency of the set up was determined from the ratio of the number of coincidences of all three fibres in the set up and the number of coincidences of the trigger fibres only. It was found to be $\approx 98\%$, independent of the position along the non-irradiated test fibre.

¹ Philips, 8-stage.

² Kyowa Gas, now Kuraray Co Ltd, Tokyo, Japan.

³ Canberra 40.

The third set up (Box3) was intended to measure the fibre wavelength spectra. It is described in detail in ref. [5]. In this set up the fibre to be tested was illuminated by a 337 nm nitrogen laser [9], which emitted light pulses of 0.8 ns duration. The light emitted by the fibre was detected by a photodiode. A fraction of the laser beam was directed to a second photodiode for calibration purposes. The advantage of a laser beam is the large amount of light available (0.7 mJ per pulse), which allowed measurements of the wavelength spectra with a monochromator.

The typical reproducibility of the light output measurements in set ups described above was of the order of 5%.

Most of the irradiations and measurements reported in this paper were done using short (40 cm) fibres. Therefore the results may not always be fully representative for the long fibres (2.2 m) used in the fibre calorimeter. A comparison between the results on radiation hardness from long and short fibres will be presented in section 5.3.

3. FIBRE SELECTION AND WAVELENGTH SPECTRA

Companies producing or developing scintillating plastic fibres were requested to supply samples. Over the past few years fibre qualities in terms of attenuation length and radiation hardness have improved continuously. We have been including new products in any new tests that were undertaken, which explains the varying choice of fibre types for the different radiation tests described in this paper.

Box1 was used to test the suitability of the different types of non-irradiated fibres for our calorimeter. Fig. 2 shows an attenuation curve as measured in Box1 for a non-irradiated Kyowa SCSN38 fibre. The curve clearly shows a steep attenuation of light in the first 60 cm from the emission point and a slower decrease at longer distances. This phenomenon comes from the fast absorption of low wavelength components and of the light produced at large angles and reflected on the cladding-air interface [5,6]. In Fig. 2 the first effect was much reduced since we were using a yellow filter which absorbed the short wavelengths (< 450 nm). The dashed line corresponds to the result of a fit to eq. (1) for $z = (60-215)$ m, giving $\lambda_{att} = 4.28$ m.

For comparative studies, the light output measurements of a number of different polystyrene fibre types were fitted to eq. (1) for distances between 60 cm and 215 cm to the PM. A yellow filter was used in these measurements. The average result for I_0 and λ_{att} as well as the σ_{RMS} of these quantities over a sample of 20 fibres are shown in Fig. 3. The experimental results depicted in Fig. 3 refer to fibres received from industry in the first half of 1989. Only fibres with an attenuation length larger than 3 m are suitable for use in the calorimeter.

The prototypes of our fibre calorimeter [3,10,11] contain SCSN38 fibres apart from a single test module that was equipped with polystyrene fibres doped with 3HF+PTP. This choice was mainly dictated by the availability of suitable fibres at the time of the construction.

Fig. 4 shows the wavelength spectra of three types of fibre before and after irradiation with the "very high intensity" dose profile (Fig. 1b). The spectra were measured in Box3 and were corrected for the sensitivity of the photodiode. The laser beam was directed close to the point of maximum damage (9.5 Mrad), at 10 cm from the fibre end. The fibres were read out from the end closest to the damaged region. This means that the curves shown in Fig. 4 represent the emission spectra combined with effects of light transmission over 10 cm of the irradiated fibre. No yellow filter or mirror were used in these measurements.

In Fig. 4a and Fig. 4b the measured spectra of SCSN38 and SCSN81 fibres are shown. The spectrum of the non-irradiated fibres ranges from ≈ 400 nm to ≈ 560 nm (blue fibres). From the spectra of the irradiated fibres, it is seen that the radiation mainly affects the light detected at short wavelengths. As we will see in section 5.2, this is mainly a light transmission effect. In Fig. 4c the spectra are shown for a polystyrene fibre doped with 0.02% 3HF and 0.01% PTP (yellow fibre). For this fibre the non-irradiated spectrum is centered at a longer wavelength (500 nm-650 nm). By comparing Figs. 4a and 4b with Fig. 4c we see that the yellow fibre is more resistant to radiation.

Fig. 5, which is derived from the spectra of Fig. 4, shows the ratio of the pulse heights of the irradiated and non-irradiated fibres as a function of the wavelength. Above 500 nm this ratio is typically 75% for both SCSN81 and 3HF+PTP fibres and 40% for SCSN38 fibres. Below 500 nm the ratio decreases to 30% for SCSN81 fibres and 20% for SCSN38 fibres, at 425 nm.

The use of a yellow optical filter results in an apparent improvement of the radiation hardness of the blue fibres (SCSN38, SCSN81), at the expense of the total amount of light detected (not a critical parameter in our design). This effect is shown in Fig. 6 for SCSN38 fibres irradiated by the "normal intensity" source (Fig. 1a) during 31, 119 and 311 hours. This corresponds to doses at the peak of the profile of 0.9, 3.6 and 9.3 Mrad, respectively. The fibre measurements were carried out in Box2 within 2 hours after the end of the irradiation.

Although the irradiation was not uniform along the fibre, eq. (1) has been used in order to compare the radiation effects on the light transmission in the fibres. The fit was done for the experimental points between 4 cm and 36 cm from the end read out by the photomultiplier. The results are given on the right-hand side of the graphs in Fig. 6. By comparing the extrapolation to $z = 0$ in Figs. 6a and 6b, one sees that the wratten #3 filter cuts away roughly 77% of the emission spectrum. As shown earlier [5], the light at shorter wavelengths is absorbed more

rapidly also in the absence of radiation. In this case the attenuation length improved from 66 cm to 112 cm if a yellow filter was used. For a maximum dose of 0.9 Mrad the fraction of the initial light output ($I(z)$ at $z = 30$ cm) remaining after irradiation was 74% for the data with optical filter and 67% without filter. The effective attenuation length was 64 cm with filter and 35 cm without filter.

4. THE INFLUENCE OF THE MEDIUM SURROUNDING THE FIBRES

The fibre damage due to radiation and in particular its eventual recovery is influenced by environmental effects. In existing lead/scintillating-fibre calorimeters, like the Omega and NA38 calorimeters [12,13], glue (Araldite F) was used to aggregate fibres to preformed lead sheets. As the use of glue may facilitate the construction of calorimeter modules, the influence of glue surrounding the fibres was tested at an early stage. For these tests Optectron S101A⁴ and S101(UA2)⁵ fibres were used. The manufacturer informed us that these two types of fibre differed only in their cladding composition. For these tests, fibres covered with Araldite F glue were compared to fibres without glue. The glue was applied on the central part of 40 cm long fibres, over a distance of 17 cm to 34 cm from the PM. The light output was measured in Box2 outside the region of the glue, at distances of 10 cm and 36 cm from the PM. We observed that the glue did not influence the transmission for non-irradiated fibres.

The fibres were irradiated by the "normal intensity" source (Fig. 1a) for a total of 115 hours, corresponding to a dose of 2.8 Mrad at 36 cm from the end read by the PM. The irradiation was interrupted several times for about 10 minutes to measure the light output. The light output after irradiation was normalized to the light output before irradiation and the relative light yields for excitation at 36 cm from the PM are shown in Figs. 7a,c. No yellow filter was used in the measurements. After irradiation the fibres were left in air and the light output was measured several times. The results for $z = 36$ cm are shown in Figs. 7b and 7d. For the measurement at 10 cm from the PM the two types of fibre did not show any difference in the amount of light detected, as expected.

From Fig. 7 we can conclude that this glue enhanced the damage to the fibres under irradiation. This effect was much more important for S101(UA2) fibres than for S101A fibres. Furthermore, the S101A fibres showed recovery effects, which were absent for the S101(UA2) fibres. We observed that the S101(UA2) fibres covered with glue turned brown under irradiation, whereas the S101A fibres became only a little yellow. This colouring effect did not disappear for the S101(UA2) fibre after the irradiation, while the colouring of the S101A fibre seemed to fade away. As the two fibre types differed only in the cladding material, the observed differences in light transmission along the fibres must be attributed to a difference

⁴ Société Optectron, 91946 Les Ulis, France.

⁵ Name supplied by Optectron. These are not the same fibres as those used for the UA2 Scintillating Fibre Detector.

in interaction with the cladding. These results made us decide to refrain from using glue in the construction of the SPACAL calorimeter.

Further tests on environmental effects concerned the influence of the surrounding gas. For this purpose, S101A fibres were irradiated with the "normal intensity" source (Fig.1a) in either air or a vacuum. The total dose at the maximum of the profile was 3.5 Mrad. The light output at 10 cm (right hand side of Fig. 1a) from the dose maximum was measured in Box2 before and after irradiation as shown in Fig. 8. No yellow filter was used for these measurements. The response of the fibres irradiated in air was measured several times during the first two hours after the irradiation and later again, at intervals of several days. Within the 5% reproducibility of the measurements, those fibres showed no signs of recovery after irradiation, in agreement with Fig. 7b. The average light loss after irradiation was 37% for these fibres.

The fibres irradiated in vacuum initially lost 95% of their response. After 45 minutes of recovery in air, the response increased to 25% of the value before irradiation, and 5 days later to 65%, after which only a very small recovery was observed. The recovery curve in Fig. 8 corresponds to a recovery time constant of 1.5 hours for short (< 1 hour) recovery times. If all the values in Fig. 8 are considered a recovery time constant of several days is extracted.

From these results we conclude that the presence of air during the irradiation inhibits some non-permanent radiation damage that appears in fibres irradiated in vacuum, at least for the dose rate of 30 krad/h used in this test. Within the precision of the measurements the permanent damage to the fibres after recovery is similar in the two cases. More precise and systematic measurements on this subject are in progress.

5. COMPARATIVE STUDIES OF RADIATION HARDNESS

In this section, we present results of a comparative study of the radiation hardness for 5 different types of fibre. The fibres were irradiated according to the "very high intensity" radiation profile (Fig. 1b) with a maximum dose rate of 1.05 Mrad/h at 27 cm from the PM. Peak doses of 1.1, 3.2, 9.5 and 23.0 Mrad were applied. The measurements were carried out in Box1. A yellow filter was used in these measurements. Fig. 9 shows the attenuation curves for the following types of fibre: SCSN38, SCSN81, S101A, 3HF and 3HF+PTP. The curves were normalised at each position to the response for non-irradiated fibres. From Fig. 9 we see that the 3HF+PTP fibres were the least damaged. To quantify the local loss in light emission and light transmission separately for the different types of fibre as a function of the dose, we applied a simple mathematical model which roughly fits the data.

5.1. The model

The model assumes that the scintillation light produced in the fibre decreases with increasing dose. The light emission at the excitation point ($z=0$) is described as:

$$I(0,D) = I_0 e^{-D(z)/\gamma}, \quad (2)$$

where $D(z)$ = the total dose at position z (cm) along the fibre,
 I_0 = the light emission in the absence of radiation,
 γ = a measure of the resistance against a reduction of the light emission as a consequence of ionising radiation, (γ in Mrad).

The local loss in light transmission is parametrised as [14]:

$$k(z) = k_0 + \alpha D(z), \quad (3)$$

where $k(z)$ = $1/\lambda_{att}(z)$,
 k_0 = $1/\lambda_{att}$ in the absence of radiation, as in eq. (1),
 $1/\alpha$ = a measure of the resistance against a reduction of the light transmission as a consequence of ionising radiation, (α in Mrad⁻¹ cm⁻¹).

A high radiation resistance corresponds to a small value of α and a large value of γ .

In eqs. (2) and (3) the wavelength dependence of α and γ for the transmitted and emitted light, respectively, has been neglected. As we have seen from Fig. 4, this is not correct, especially for blue fibres. Since the blue light that is more affected, is cut by the yellow filter, this contribution is partially eliminated. Nevertheless, the wavelength dependence of α and γ is still evident as we will see later (Tables 1,2).

The "very high intensity" dose profile $D(z)$ of Fig. 1b was fitted to a second order polynomial. By combining eqs. (1)-(3) one obtains the following expression, which was used to fit the measured light output in the region of the source ($z > 18$ cm):

$$I(z,D) = I_0 e^{-D(z)/\gamma} e^{-zk_0(z)} e^{-\alpha \int_0^z D(z') dz'} \quad (4)$$

5.2. Results for short fibres

The fitted values of α and γ for all fibres are presented in Table 1. The fits carried out included only data points in the irradiated region ($z > 18$ cm). It turned out that the fibre response was also affected outside the region of the source ($z < 18$ cm). This effect is not yet understood. It does not seem to scale with the applied dose. In a first approach, the curves were normalised to 1 at the point closest to the photomultiplier (Fig. 9). As this overall normalisation clearly influences the results in some cases, the baseline was redefined for a second set of fits as the average ratio of the responses for the irradiated and non-irradiated fibres outside the region of the source ($z < 18$ cm). The results are presented in Table 2.

From Tables 1 and 2 one observes a systematic increase of γ with increasing dose, most likely as a result of the simplified model that does not include wavelength dependence. The parameters α and γ should follow eqs. (2) and (3), respectively, for each wavelength. Since the combined emission and transmission spectra of the blue fibres change when the fibre is irradiated (see Fig. 4), the remaining light will be produced and transmitted more in the yellow region and will therefore have larger values of γ and smaller values of α . For the yellow fibres the emission spectrum is hardly affected when the fibre is irradiated with a peak dose of 9.5 Mrad (see Fig. 5). Nevertheless γ was observed to increase with increasing dose for the 3HF+PTP fibres and also for the blue fibres. This is attributed to transmission effects between the primary and secondary emission of light in the emission process [15]. This hypothesis is supported by the fact that γ does not depend on the dose for doses up to 9.5 Mrad for the 3HF fibres, the only type of fibre used in this study which contains a single dopant.

In this simplified model, the logarithm of the light output scales with the dose profile if the loss in transmission is negligible ($\alpha = 0$). This is illustrated in Fig. 10 for two types of fibre, 3HF and SCSN81, both irradiated by a 3.2 Mrad dose. The 3HF fibre has a small transmission loss and the effects of radiation lead mainly to a loss in light emission. Correspondingly, the fractional signal loss closely follows the irradiation profile $D(z)$. The SCSN81 fibre has a better emission resistance but a worse transmission resistance. The maximum loss in light output (at $z = 32$ cm) occurs well beyond the dose maximum (at $z = 27$ cm). In general we observed that the radiation effects in the yellow fibres (3HF and 3HF+PTP) mainly concerned the emission, whereas the blue fibres (SCSN38, SCSN81 and S101A) lost essentially in transmission.

For each fit, the typical errors on α and γ are in the 5% -10% range. By comparing Tables 1 and 2, one sees that the uncertainty of γ due to the unknown baseline shift is much bigger. The fitted value of α changes very little, but the values of γ are up to a factor 1.8 larger in Table 2. The fit to the measurement of the 3HF+PTP fibre at 3.2 Mrad was ignored in Table 2, since the small pulse height loss observed was not significantly sensitive to the shape of eq. (4).

5.3. Comparison to the results for long fibres

A problem that was not yet addressed in the results shown so far, is the possible contribution of a light component with a short attenuation length. Such a component, which is negligible for the 2.2 m long fibres used in SPACAL, could have played a role for the 40 cm long fibres, for which all the results shown above were obtained. As we saw from Fig. 2, a non-irradiated fibre has a steeper pulse height decrease in the first 0.5 m than in the last 1.5 m, even when a yellow filter is used. This is mainly due to the light that propagates in the cladding [6] and is easily lost in the cladding-air interface. A fit was performed to the curve presented in Fig. 2 (measured with yellow filter) using three exponential components:

$$I(z) = I_1 (e^{-z/\lambda_{\text{core}}} + R e^{(-2L+z)/\lambda_{\text{core}}}) + I_2 (e^{-z/\lambda_{\text{clad}}}), \quad (5)$$

where

- R = the coefficient of reflection for a fibre without mirror (assumed to be 4%),
- λ_{clad} = the attenuation length of light travelling in the cladding,
- λ_{core} = the attenuation length of light travelling in the core,
- L = the length of the fibre (2.2 m).

The values of I_1 , I_2 , λ_{core} , and λ_{clad} calculated from the fit are:

$$\begin{aligned} I_1 &= 81.1 \pm 0.1 \text{ (a.u.)} \\ \lambda_{\text{core}} &= 4.06 \pm 0.02 \text{ m} \\ I_2 &= 34.5 \pm 1.6 \text{ (a.u.)} \\ \lambda_{\text{clad}} &= 0.12 \pm 0.01 \text{ m} \end{aligned}$$

If the cladding term is omitted ($I_2 = 0$) in eq. (5), a fit to the same data yields $\lambda_{\text{att}} = 2.19$ m (for the region $z = 0-60$ cm) and $\lambda_{\text{att}} = 4.07$ m ($z = 60-215$ cm), respectively. We see that $\lambda_{\text{att}} = \lambda_{\text{core}}$ when λ_{att} is taken from the fit in the last 1.5 m of the fibre. The light travelling in the cladding is absorbed after typically 0.2 m. Our measurements show that this component is also less radiation hard.

The last 40 cm of a long (2.2 m) S101A fibre were exposed to the inhomogeneous dose profile of Fig. 1b. The rest of the fibre received a negligible dose. The signal measured in the last 40 cm of the fibre (180-220 cm) normalized to the non-irradiated signal is presented in Fig. 11 (closed circles). The measurement was done in Box1 with a yellow filter and without mirror. The fibre was then cut at 180 cm from the PM and the last 40 cm were remeasured (open circles).

For the long fibre the fitted values of α and γ in the irradiated region are $5.7 \cdot 10^{-3} \text{ Mrad}^{-1} \text{ cm}^{-1}$ and 24.8 Mrad respectively. After cutting the fibre, the values obtained for the remaining 40 cm are $\alpha = 6.5 \cdot 10^{-3} \text{ Mrad}^{-1} \text{ cm}^{-1}$ and $\gamma = 21.3 \text{ Mrad}$. So for the long fibre the

results are typically 15% better. This is due to two effects. In general, light at a short wavelength is absorbed more rapidly than light emitted at a longer wavelength, even for a non-irradiated fibre. We have also seen in section 3 that the short wavelengths are more sensitive to radiation. As the light produced close to the PM has more components with short wavelengths, it is less radiation hard. This effect is partially reduced by the yellow filter. The second effect originates from the light travelling in the cladding. If the cladding becomes more opaque under irradiation, the cladding light will be absorbed more quickly. This effect will mainly be seen for the short fibre.

This study emphasizes the importance of performing radiation damage studies in realistic conditions. For hadronic calorimetry the fibres under study should be about 2 m long. If the S101A fibre is considered a representative example, the results given in Tables 1 and 2 are pessimistic by about 15%.

6. DESCRIPTION OF THE MONTE CARLO SIMULATIONS

In this section a Monte Carlo calculation is described which simulates radiation damage in a fibre calorimeter in order to study the effect on its performance. For a detector placed in an LHC or SSC environment, most of the damage to the calorimeter will originate from the development of electromagnetic showers in the calorimeter itself, as all the energy of these showers will be deposited in a region of limited depth. In particular, the damage will mainly come from the 2γ decay of π^0 s, which are abundantly produced in pp interactions [1,2]. These π^0 s will have average transverse momenta close to 600 MeV/c both at LHC and SSC, so the typical γ energies will vary from ≈ 3 GeV to ≈ 300 MeV for polar angles between 5° and 90° , respectively.

As we have seen in the previous sections, the damage to the fibres consists of a combination of a loss in the light emission and a loss in light transmission. The relative importance and the absolute magnitude of these effects depend strongly on the type of fibre to be used and also on the total radiation dose. Therefore, these effects were left as parameters in the study. For incoming neutral and charged pions, the impact of ionising radiation on the electromagnetic and hadronic energy resolution, respectively, as well as on the π^0/π^+ signal ratio and on the signal linearity, were determined as a function of these parameters.

The longitudinal development of the showers in the calorimeter was simulated following the parametrizations described in [16]. For an electromagnetic shower with energy E between 5 GeV and 92 GeV, the differential energy loss is given by:

$$dE = k_{em} t^{a-1} e^{-bt} dz, \quad (6)$$

where t = the depth inside the calorimeter in radiation lengths ($X_0 = 0.75$ cm in our case),

k_{em} = the overall normalisation constant,

a = $2.284 + 0.7136 \ln(E)$, (E in GeV),

b = $0.5607 + 0.0093 \ln(E)$, (E in GeV),

z = the depth inside the calorimeter (z in cm), unlike before, when z was the distance to the PM.

For $E < 5$ GeV, the values a and b were taken from earlier Monte Carlo work by E. Longo and I. Sestili [17]:

a = $3.0 + 0.43 \ln(E)$, (E in GeV),

b = 0.46.

The Monte Carlo values for a and b describe the longitudinal development regardless of the starting point for each individual shower, whereas the experimental values above 5 GeV [16] model the average longitudinal behaviour with respect to the starting point. The difference is a slightly smoother distribution for the Monte Carlo values [17].

The analytic expression for the hadronic showers [16] contains both an electromagnetic part characterized by the radiation length, and a hadronic part characterized by the interaction length λ_I . It originates from a fit to data from non-compensating calorimeters with a sandwich structure, which yielded for pion showers:

$$dE = k_{had} \{ w t^{c-1} e^{-dt} + (1-w) u^{c-1} e^{-gu} \} dz, \quad (7)$$

where u = the depth inside the calorimeter in units of λ_I , ($\lambda_I = 21$ cm in our case),

k_{had} = normalisation constant,

c = $0.6165 + 0.3183 \ln(E)$, (E in GeV),

d = 0.2198,

g = $0.9099 - 0.0237 \ln(E)$, (E in GeV),

w = 0.4634,

dz = depth in cm.

To simulate compensation, the normalisation constants k_{em} and k_{had} were chosen such that both electromagnetic and hadronic showers deposit E_{inc} into a calorimeter of infinite length. All the parameters were held fixed over the course of several showers, so the simulation did not properly model the variations in the energy deposition. The variations in the starting point s of the showers produced by the incoming particles were chosen from an

exponential probability distribution with mean value X_0 for incoming electrons and $1.5 \cdot \lambda_I$ for charged pions [11]. These variations are the direct cause of the light level variations at the photomultiplier given by this model.

The attenuation $A(z)$ of light in fibres of length L was described by a single exponential and the effect of a mirror with reflectivity R placed at the fibre end opposite to the read-out ($z = 0$), was included:

$$A(z) = e^{-(L-z)/\lambda(z)} + R e^{-(L+z)/\lambda(z)}. \quad (8)$$

We used $R = 0.85$ [3].

The damaging effect to the fibres was approximated by assuming an average shower profile with an energy characteristic for the incident radiation. An electromagnetic shower of energy E_{rad} starting at $z = 0$ and parametrized as in (6) was taken. E_{rad} was left as a free parameter in the calculation. For this purpose the dE/dz profile (6), using the parameter values determined by E. Longo and I. Sestili, was normalised to 1 at the peak of the distribution giving $V_N(z, E_{\text{rad}})$. In this way the loss in light transmission can be described similar to eq. (3):

$$1/\lambda = (1/\lambda_{\min} - 1/\lambda_0) V_N(z, E_{\text{rad}}) + 1/\lambda_0, \quad (9)$$

where λ_0 = the attenuation length before irradiation,
 $\lambda_{\min}$ = the local attenuation length after irradiation at the peak of the damage profile ($V_N(z, E_{\text{rad}}) = 1$).

As an example, Fig. 12a shows the attenuation length λ along the fibre for $\lambda_0 = 4$ m, $\lambda_{\min} = 0.5$ m and $E_{\text{rad}} = 1$ GeV.

For the local loss in light emission, the Monte Carlo study assumed a linear dependence on the dose:

$$I = I_0 (1 - f V_N(z, E_{\text{rad}})), \quad (10)$$

with f = the fractional emission loss at the peak of the damage.

For the f -values that are relevant for the Monte Carlo studies (maximum $f = 20\%$) the difference between a linear and an exponential, eq. (2), behaviour of the emission loss is negligible. For $f = 0.2$ at the peak of the damage the maximum difference in fibre response between the two parametrisations corresponds to 0.7%. The emission along the fibre for $f = 0.2$ and $E_{\text{rad}} = 1$ GeV is illustrated in Fig. 12b.

Taking formulae (6)-(10) together, the light output L at the photomultiplier for an electromagnetic or hadronic shower with energy E and with starting point s in the calorimeter is given by:

$$L = I_0 \int_s^L (1-fV_N(z,E_{\text{rad}})) V(z-s,E) A(z) dz \quad (11)$$

The shower function $V(z-s,E)$ may either describe an electromagnetic or a hadronic shower and was determined by the parameters given in [16], whereas the normalised function $V_N(z,E_{\text{rad}})$ was assumed to be entirely electromagnetic with an energy E_{rad} in general much smaller than E .

This model is approximate in several aspects. Fluctuations in the shower development other than the ones coming from the starting point were ignored. Also, rather than trying to characterize the radiation by a single energy, a better model might incorporate a representative distribution of energies. Moreover, in practice one deals with jets consisting of charged and neutral hadrons with a specific energy spectrum rather than π^0 's only. The charged hadronic contribution to the radiation damage profile was not included in this model.

7. RESULTS OF THE MONTE CARLO SIMULATIONS

In this section we describe the results of the Monte Carlo simulations in which the parameters λ_0 , λ_{min} , f , R , E and E_{rad} were varied. The effect of the radiation damage on the electromagnetic and hadronic energy resolution, on the signal linearity and on the ratio of the π^0/π^+ response were studied. The length L of the calorimeter was chosen to be 2.4 m ($11.4 \lambda_l$) to minimize leakage effects. For each set of these parameters 10^4 showers were generated to simulate the light level at the photomultiplier. Fluctuations in the light level were simulated by fluctuations in the starting position of the showers only. To obtain the real energy resolution of a fibre calorimeter, one should add the signal resolution described here (the effect of a non-uniform fibre response as a function of depth) in quadrature to the inherent energy resolution due to fluctuations in the energy deposition in the calorimeter. The results from the Monte Carlo study given below are in agreement with those reported from an independent study on the same subject for electromagnetic showers [18].

One of the consequences of the finite attenuation length of the fibres is a non-Gaussian response function for hadronic showers. Showers that extend deeper than average inside the calorimeter create a high energy tail in the calorimeter signal distribution, since their scintillation light has less distance to travel to the photomultiplier. This effect has been observed experimentally [11] and depends strongly on the values of λ_0 and R . For the results described

below, λ_0 was fixed at 4 m and R was fixed at 0.85, representative values for the present calorimeter prototypes.

If the fibres are damaged in a particular region, variations in the light level will occur as the shower development fluctuates across it. In practice, this effect is only important for electromagnetic showers since they develop entirely in the region affected by radiation damage. Hadronic showers are much less affected as they usually develop deeper inside the calorimeter. For example, for $E_{\text{rad}} = 1$ GeV and $E = 10$ GeV a 10% drop in the light yield of the fibre at the peak of the damage causes a drop of about 6.6% in the signal for electromagnetic showers, whereas there is on average only a 0.2% drop in the response for hadronic showers.

Fig. 13 shows the π^0/π^+ response ratio as a function of λ_{min} and as a function of the fractional loss f . The energy E of the incoming particle was fixed at 10 GeV and the energy of the damaging showers E_{rad} was fixed at 1 GeV. The results depend mainly on f . The dependence on λ_{min} is very weak, as the local transmission loss is only effective across the small (5-10 cm) depth where the electromagnetic showers caused the damage. The numerical values of the Monte Carlo results are given in Tables 3 and 4 for incoming energies of $E = 10$ GeV and $E = 150$ GeV, respectively. From these tables one sees that, although compensation was forced at the shower level, the π^0 response is smaller by 2.3% in the absence of radiation. This is due to the attenuation of light in the fibres. The 6.6% decrease in the π^0 response at $E = 10$ GeV for $f = 0.1$ does not impose an equally large deterioration of the π^0/jet response ratio, as jets consist on average of about $1/3$ π^0 s. Therefore, the corresponding π^0/jet response ratio will be approximately 0.942. By comparing Tables 3 and 4 one sees that the π^0/π^+ response ratio improves at higher energy ($E = 150$ GeV) from 0.915 to 0.932 for $f = 0.1$.

Fig. 14 shows the contribution of the radiation damage to the electromagnetic energy resolution σ_{RMS}/E for $E = 10$ GeV and $E_{\text{rad}} = 1$ GeV as a function of λ_{min} and f . Again the dependence on λ_{min} is very weak for $\lambda_{\text{min}} > 0.5$ m. A 10% drop in the light yield at the peak of the damage gives a 0.8% contribution to the electromagnetic energy resolution at $E = 10$ GeV. At $E = 150$ GeV this contribution is similar (see Table 4).

The contribution to the energy resolution of single charged pions is shown in Fig. 15 ($E = 10$ GeV, $E_{\text{rad}} = 1$ GeV). From this figure one can see that there is a 2.3% contribution to the hadronic energy resolution in the absence of radiation, ($\lambda_{\text{min}} = \lambda_0$ and $f = 0$). This is due to fluctuations in the starting point of the hadronic shower in combination with the attenuation of light in the fibres ($\lambda_0 = 4$ m). This has been observed experimentally and can be corrected for if the particle's impact point is known and if the calorimeter is tilted by a few degrees with respect to the incoming particle direction [11]. A 10% drop in the light yield at the peak of the damage gives an additional contribution of 0.2% to the energy resolution for hadrons for $\lambda_{\text{min}} > 1$ m. At $E = 150$ GeV these contributions amount to 2.4% and 0.2%, respectively. By comparing

Figs. 14 and 15 one sees that the hadronic energy resolution is more sensitive to transmission losses, whereas the electromagnetic energy resolution is mainly sensitive to emission losses.

The electromagnetic showers of incoming particles with higher energy E develop deeper inside the calorimeter than the showers of lower energy particles. Therefore, the local damage to the fibre response will result in a decreasing average fractional signal loss at increasing energy for $E > E_{\text{rad}}$. Fig. 16 shows the ratio of the average calorimeter response for electrons between 150 GeV and 10 GeV as a function of f and λ_{min} . For $f = 10\%$ and $\lambda_{\text{min}} > 0.5$ m the resulting nonlinearity amounts to 2.5%. For hadronic showers there is almost no nonlinearity effect due to the radiation damage.

To test the dependence of the above results on the energy E_{rad} , the calculations were repeated for $f = 10\%$ and $E_{\text{rad}} = 10$ GeV. In this case the π^0/π^+ signal ratio decreases to 0.91 at $E = 10$ GeV and to 0.92 at $E = 150$ GeV. The contribution to the electromagnetic energy resolution improves to 0.4% at 10 GeV and 0.7% at 150 GeV. For $E = 10$ GeV, the difference in the electromagnetic energy resolution between $E_{\text{rad}} = 10$ GeV and $E_{\text{rad}} = 1$ GeV is understood, because the fibre response curve rises steeply after the peak of the damage before levelling off at the nominal value for an undamaged fibre. So for electromagnetic showers with a higher energy than the ones that caused the damage, the fluctuations are actually bigger than for showers with an energy similar to E_{rad} .

For comparison, the Monte Carlo simulations were repeated for different initial fibre properties, in particular for $\lambda_0 = 7$ m and $R = 0$. The results for electromagnetic showers are essentially the same as the values described above. The hadronic performance, however, is affected differently. For $E = 10$ GeV the contribution to the charged pion energy resolution increases from 2.3% to 4.2% due to the absence of the mirror. A 10% drop in the light yield at the peak of the damage gives an additional 0.2% contribution independent of λ_{min} , so independent of transmission losses, in this case.

By combining the results of the Monte Carlo study and the radiation damage tests described in section 5, one can determine which radiation level can be tolerated while maintaining an acceptable calorimeter performance. Assume we define the fraction $f = 10\%$ as the level of acceptable performance deterioration. Depending on the physics aim of such a calorimeter, the most important degradation will probably consist of the 0.8% contribution to the constant term of the electromagnetic energy resolution (see above).

In terms of the description, eq. (2), of the local emission loss of the fibres (see section 5), this amount of degradation to the electromagnetic energy resolution corresponds to $\text{Dose}_{\text{max}}/\gamma = 0.11$. If we take the emission loss parameter $\gamma = 55.4$ Mrad measured for the SCSN81 fibres (average Table 1 and 2, 9.5 Mrad values), this limit corresponds to a maximum allowed dose of 6.1 Mrad. A similar level of performance degradation due to the transmission

loss of the fibres sets a limit of 0.25 m on $\lambda_{\min}$. Combining this limit with $\alpha = 4.55 \cdot 10^{-3} \text{ Mrad}^{-1} \text{ cm}^{-1}$ measured for SCSN81 fibres, the corresponding maximum allowable dose is 8.2 Mrad (eq. (3) and eq.(9)). For the 3HF+PTP fibre the transmission limit corresponds to a maximum allowable dose of 26.4 Mrad, whereas the emission limit corresponds to 4.0 Mrad. All these limits are probably underestimated by 15% due to the use of short fibres for the radiation tests (see sect. 5.3). There is an estimated $\pm 30\%$ error on the emission limits due to the uncertainties in the baseline shift of the radiation measurements (see section 5). Taking this into account the SCSN81 fibre can presently be considered as the most radiation hard fibre for use in a calorimeter with a maximum dose around 7 Mrad. However, the radiation hardness of the 3HF+PTP fibres is very similar and the choice depends on the limit that is set on the electromagnetic energy resolution. If the criterion is relaxed, then the 3HF+PTP fibres will be preferred because of their better transmission properties.

It is interesting to see with which polar angle a given limit of 7 Mrad corresponds in a possible LHC or SSC experiment. The estimated dose levels in LHC and SSC experiments are based on calculations assuming spherical calorimeter shapes, where forward and backward cones in the high-rapidity region were removed [1,2]. To obtain estimated dose levels at different radii R from the interaction point, we have scaled these estimated values according to $1/R^2$. Assuming a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at the LHC running 10^7 seconds per year and a distance R to the interaction vertex of 4 m, a 7 Mrad limit corresponds to 4 years of running at pseudorapidity $\eta = 2.7$ (polar angle 8°) [2]. In the case of a similar shape detector and the same running time per year at the SSC with a luminosity of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, the 7 Mrad limit corresponds to 4 years of running at $\eta = 3.3$ (polar angle 4.2°) [1]. Going further away from the interaction point at a radius of 10 m, the SSC limit corresponds to $\eta = 3.9$ (polar angle 2.3°) under the same conditions.

To further judge the suitability of the lead-fibre calorimeter technique we calculate a maximum total dose of 2 Mrad in a barrel calorimeter covering $\eta = \pm 1.5$ (polar angle $\pm 25^\circ$) at a radius of 1.3 m over 4 years of LHC running. In terms of the parameters f and $\lambda_{\min}$ of the Monte Carlo simulation for the SCSN81 fibres this means $\lambda_{\min} = 90 \text{ cm}$ and $f = 5\%$ (average of Table 1 and 2, 3.2 Mrad values). These values correspond to a degradation of about 0.4% in the electromagnetic energy resolution.

8. CONCLUSIONS

We have measured the radiation damage in polystyrene based scintillating fibres under a number of different conditions. From these measurements we conclude that the radiation mainly affects the short wavelength components of the light and therefore the effect can be reduced by using a suitable optical filter. The use of Araldite F glue surrounding the fibres

deteriorates the radiation hardness. Fibres irradiated in air show less damage immediately after the irradiation than fibres irradiated in a vacuum.

For 5 different types of fibres the loss in light output after irradiation with doses up to 23 Mrad was measured and tentatively separated into a loss in light transmission and a loss in light emission. The 3HF and 3HF+PTP fibres have the smallest loss in light transmission, whereas the SCSN81 fibres show the smallest loss in light emission. For the use of SCSN81 fibres in a fibre calorimeter we can set the highest limit on the maximum allowable dose at the peak of the damage in a future colliding hadron beam experiment. Defining a maximum allowable degradation of 0.8% of the electromagnetic energy resolution, which corresponds to a degradation of about 0.2% of the hadronic energy resolution, a 2.5% nonlinearity effect on electrons between 10 GeV and 150 GeV and a 6.6% effect on the π^0/π^+ response ratio (determined by a Monte Carlo simulation), the maximum allowable dose is 6.1 Mrad. This limit is probably underestimated by 15% due to the use of short fibres for the radiation tests and has an estimated $\pm 30\%$ error due to the uncertainties in the baseline shift of the radiation measurements. We estimate from these results that lead/fibre calorimetry is feasible at the LHC (luminosity $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, 4 years of running) up to pseudorapidity $\eta = 2.7$ at a distance of 4 m from the interaction vertex. For a barrel calorimeter ($\eta = \pm 1.5$) at a radius of 1.3 m, the corresponding deterioration of the electromagnetic energy resolution would be 0.4%.

Further measurements of the radiation hardness of scintillating fibres under more realistic conditions, in particular inside a calorimeter module and irradiated by electrons of the relevant energies, are foreseen for the near future.

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TABLE CAPTIONS

- 1 Results of the fits to the measurements shown in Fig. 9 as a function of the peak dose. The data were normalised at each position to the response of the non-irradiated fibre, with an overall normalisation fixed to 1 at the position closest to the photomultiplier. The parameters $1/\alpha$ and γ describe the resistance against a reduction of the light transmission and light emission, respectively, as a consequence of ionising radiation. The typical errors on α and γ are in the 5-10% range.
- 2 Results of the fits to the measurements shown in Fig. 9, but with a different overall normalisation, as a function of the peak dose. The data were normalised at each position to the response of the non-irradiated fibre, with an overall normalisation that fixes an average ratio of 1 outside the region of the source. The parameters $1/\alpha$ and γ describe the resistance against a reduction of the light transmission and light emission, respectively, as a consequence of ionising radiation. The typical errors on α and γ are in the 5-10% range.
- 3 Results of the Monte Carlo simulation for damaging radiation with typical energy $E_{\text{rad}} = 1$ GeV and for incoming electrons and charged pions with energy $E = 10$ GeV. The initial attenuation length of the fibres is fixed at $\lambda_{\text{att}} = 4$ m with a mirror reflectivity of 85%. The simulation was repeated for 3 values of the fractional emission loss f and 5 values of the attenuation length λ_{min} at the peak of the damage. Result are given for the electromagnetic pulse height L_{em} , the electromagnetic energy resolution $\sigma_{\text{RMS}}/L_{\text{em}}$, the hadronic pulse height L_{had} , the hadronic energy resolution $\sigma_{\text{RMS}}/L_{\text{had}}$ and for the π^0/π^+ response ratio.
- 4 Results of the Monte Carlo simulation for damaging radiation with typical energy $E_{\text{rad}} = 1$ GeV and for incoming electrons and charged pions with energy $E = 150$ GeV. The initial attenuation length of the fibres is fixed at $\lambda_{\text{att}} = 4$ m with a mirror reflectivity of 85%. The simulation was repeated for 3 values of the fractional emission loss f and 5 values of the attenuation length λ_{min} at the peak of the damage. Result are given for the electromagnetic pulse height L_{em} , the electromagnetic energy resolution $\sigma_{\text{RMS}}/L_{\text{em}}$, the hadronic pulse height L_{had} , the hadronic energy resolution $\sigma_{\text{RMS}}/L_{\text{had}}$ and for the π^0/π^+ response ratio.

FIGURE CAPTIONS

- Fig. 1 Dose rate profiles of the two ^{60}Co - γ sources used for the irradiation tests.
- Fig. 2 Response of an SCSN38 fibre as a function of the distance to the photomultiplier. A yellow filter was inserted between the fibre and the photomultiplier.
- Fig. 3 The average light output I_0 versus the average attenuation length λ_{att} for several types of fibres as obtained from a single exponential fit to the measured pulse heights between 60 cm and 215 cm from the photomultiplier. Each point represents an average of 20 fibres and the error bars give the σ_{RMS} of these quantities. A yellow filter (< 450 nm) was inserted between the fibre and the photomultiplier.
- Fig. 4 Wavelength spectra measured at 10 cm from the photomultiplier, close to the peak of the dose profile, for a) SCSN38, b) SCSN81 and c) 3HF+PTP fibres before and after irradiation with the narrow dose rate profile. The total dose at the profile maximum was 9.5 Mrad (Fig. 1b).
- Fig. 5 The ratio between the pulse heights (Fig. 4) of irradiated and non-irradiated fibres as a function of the wavelength for SCSN38, SCSN81 and 3HF+PTP fibres after an applied dose of 9.5 Mrad at the peak of the dose profile.
- Fig. 6 The average number of photoelectrons detected in a 1 mm SCSN38 fibre as a function of the distance to the photomultiplier, a) using a yellow filter between the fibre and the photomultiplier and b) without yellow filter. The PM was put at 30 cm distance from the peak of the "normal intensity" dose profile. The effective attenuation length λ_{att} resulting from a single exponential fit between 4 cm and 36 cm from the PM is given on the right as a function of the dose at the peak of the profile (Fig. 1a).
- Fig. 7 The effect on light transmission in irradiated fibres with and without glue (Araldite F). The average number of photoelectrons $\langle N \rangle$ was measured at 36 cm from the PM. The peak of the "normal intensity" dose profile was at 30 cm from the PM. The measured value normalised to the value before irradiation is given as a function of the dose (at 36 cm) for two types of fibres, a) S101A and c) S101A(UA2). After 2.6 Mrad (at 36 cm) the fibres were taken away from the source and were remeasured several times, b) S101A and d) S101A(UA2).
- Fig. 8 The effect of the gas surrounding the irradiated fibre. The light output was measured at 10 cm from the PM, at the peak of the "normal intensity" dose profile. The measured value normalised to the value before irradiation is given as a function of the recovery time after a 2.8 Mrad dose for two S101A fibres, one irradiated in air and the other in a vacuum. The recovery took place in air for both fibres.
- Fig. 9 Pulse height as a function of the distance to the light detector for five different types of fibres, a) SCSN38, b) SCSN81, c) S101A, d) 3HF and e) 3HF+PTP. The curves measured after irradiation are normalised at each position to the response of

the non-irradiated fibre. The global normalisation was based on the point closest to the PM. The arrow indicates the peak of the dose profile.

- Fig. 10 Example of two fibres irradiated with a dose of 3.2 Mrad at the peak of the 'very high intensity' profile, a) 3HF losing essentially emission and b) SCSN81 losing essentially transmission. The curves represent the fit to a model describing the decrease in light emission (γ) and in light transmission (α) as a function of the dose.
- Fig. 11 The detected pulse height from the irradiated region of an S101A fibre normalised to the pulse height for the non-irradiated fibre for the case in which the light has to travel over a long distance (min. 180 cm) to the photomultiplier (closed circles) or a short distance (open circles). The last 20 cm of the (same) fibre were irradiated by the 'very high intensity' profile (Fig. 1b), peaking at 9.5 Mrad.
- Fig. 12 Illustration of the radiation damage to an individual fibre in a calorimeter at a hadron collider as parametrized in the Monte Carlo simulation: a) the impact on the light transmission ($\lambda_0 = 4$ m, $\lambda_{\min} = 0.5$ m, $E_{\text{rad}} = 1$ GeV), and b) the impact on the light emission ($f = 0.2$, $E_{\text{rad}} = 1$ GeV).
- Fig. 13 Result of the Monte Carlo calculation. The π^0/π^+ response ratio as a function of $\lambda_{\min}$ for 3 different values of f for $E = 10$ GeV, $E_{\text{rad}} = 1$ GeV and $\lambda_0 = 4$ m.
- Fig. 14 Result of the Monte Carlo calculation. The impact of the fibre radiation damage on the electromagnetic energy resolution σ_{RMS}/E for $E = 10$ GeV and $E_{\text{rad}} = 1$ GeV, as a function of $\lambda_{\min}$ for 3 different values of f .
- Fig. 15 Result of the Monte Carlo calculation. The impact of the fibre radiation damage on the hadronic energy resolution σ_{RMS}/E for $E = 10$ GeV and $E_{\text{rad}} = 1$ GeV, as a function of $\lambda_{\min}$ for 3 different values of f .
- Fig. 16 Result of the Monte Carlo calculation. The ratio of the average calorimeter response for electrons between 150 GeV and 10 GeV as a function of $\lambda_{\min}$ for 3 different values of f and for $E_{\text{rad}} = 1$ GeV.

Table I

	SCSN38		SCSN81		S101A		3HF		3HF+PTP	
Dose _{peak} (Mrad)	α (Mrad ⁻¹ cm ⁻¹)	γ (Mrad)	α (Mrad ⁻¹ cm ⁻¹)	γ (Mrad)	α (Mrad ⁻¹ cm ⁻¹)	γ (Mrad)	α (Mrad ⁻¹ cm ⁻¹)	γ (Mrad)	α (Mrad ⁻¹ cm ⁻¹)	γ (Mrad)
3.2	6.5×10^{-3}	20.0	4.5×10^{-3}	25.1	—	—	2.9×10^{-3}	13.7	1.2×10^{-3}	18.2
9.5	5.1×10^{-3}	28.9	4.6×10^{-3}	39.4	6.5×10^{-3}	21.26	1.8×10^{-3}	14.5	1.4×10^{-3}	27.9
23.0	—	—	—	—	—	—	2.3×10^{-3}	25.8	1.4×10^{-3}	51.9

Table II

	SCSN38		SCSN81		S101A		3HF		3HF+PTP	
Dose _{peak} (Mrad)	α (Mrad ⁻¹ cm ⁻¹)	γ (Mrad)	α (Mrad ⁻¹ cm ⁻¹)	γ (Mrad)	α (Mrad ⁻¹ cm ⁻¹)	γ (Mrad)	α (Mrad ⁻¹ cm ⁻¹)	γ (Mrad)	α (Mrad ⁻¹ cm ⁻¹)	γ (Mrad)
3.2	6.1×10^{-3}	37.4	4.1×10^{-3}	54.7	—	—	2.6×10^{-3}	16.3	—	—
9.5	5.0×10^{-3}	38.5	4.5×10^{-3}	71.4	6.3×10^{-3}	26.5	1.7×10^{-3}	15.7	1.0×10^{-3}	52.4
23.0	—	—	—	—	—	—	2.3×10^{-3}	28.0	1.3×10^{-3}	71.8

Table III
10 GeV

f	$\lambda_{\min}(\text{m})$	$L_{\text{em}} (\text{a.u.})$	$\sigma/L_{\text{em}} (\%)$	$L_{\text{had}} (\text{a.u.})$	$\sigma/L_{\text{had}} (\%)$	$\pi^0/\pi^\pm$
0.0	4.0	10170	0.02	10410	2.33	0.977
	2.0	10030	0.03	10300	2.36	0.974
	1.0	9767	0.06	10080	2.39	0.969
	0.5	9270	0.14	9678	2.79	0.958
	0.25	8387	0.37	8998	3.41	0.932
0.1	4.0	9503	0.83	10390	2.52	0.915
	2.0	9375	0.81	10270	2.48	0.913
	1.0	9130	0.86	10050	2.71	0.908
	0.5	8666	0.93	9655	2.97	0.898
	0.25	7845	1.20	8968	3.78	0.875
0.2	4.0	8839	1.72	10360	2.70	0.853
	2.0	8719	1.72	10250	2.76	0.851
	1.0	8491	1.76	10030	3.54	0.847
	0.5	8065	1.89	9625	3.41	0.838
	0.25	7300	2.08	8958	4.10	0.815

Table IV
150 GeV

f	$\lambda_{\min}(\text{m})$	$L_{\text{em}} (\text{a.u.})$	$\sigma/L_{\text{em}} (\%)$	$L_{\text{had}} (\text{a.u.})$	$\sigma/L_{\text{had}} (\%)$	$\pi^0/\pi^\pm$
0.0	4.0	152600	0.02	156900	2.39	0.973
	2.0	150600	0.03	155200	2.33	0.970
	1.0	146700	0.05	152000	2.52	0.965
	0.5	139600	0.11	146200	2.52	0.955
	0.25	127000	0.29	136200	3.25	0.932
0.1	4.0	145900	0.77	156600	2.43	0.932
	2.0	144000	0.79	154900	2.34	0.930
	1.0	140300	0.81	151600	3.33	0.925
	0.5	133500	0.86	145800	2.89	0.916
	0.25	121500	1.05	136000	3.38	0.893
0.2	4.0	139300	1.63	156200	2.81	0.892
	2.0	137500	1.62	154500	2.78	0.890
	1.0	134000	1.66	151300	3.16	0.886
	0.5	127400	1.69	145600	3.07	0.875
	0.25	116000	1.85	135800	3.52	0.854

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16