STATE OF ART OF (GREEN) WAVELENGTHSHIFTING FIBERS

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December 19, 1996

Abstract

Comparative studies of the optical properties of polystyrene WLS fibers for High Energy Physics Experiments are presented. The response of fibers to the blue light of a plastic scintillator is compared for fibers with different dopant concentration, with single and multiple cladding, and with several Ultra Violet Absorbers (UVA) with different concentrations. Preliminary results on the mechanical stress of the fibers are shown and a brief summary of the radiation hardness is given.

Contribution to the Sixth Topical Seminar on Experimental Apparatus for Particle Physics and Astrophysics, San Miniato, Tuscany, 21-24 May 1996

1 Introduction

Until the 1980's, WaveLengthShifter (WLS) optical fibers were used only in very special cases but, presently, plastic WLS fibers are part of almost all the HEP detector systems. To this success, the initiative by K. Pretzl was crucial as was the effort of P.Sonderegger for scintillating fiber development.

In this paper we will report on our experience on polystyrene WLS fibers developed for electromagnetic and/or hadronic calorimeters. This work is still in progress and it is essentially developed to optimize the performance of the Barrel Hadronic Calorimeter of ATLAS (TILECAL/ATLAS).

The TILECAL concept (fibers running parallel to the edge of scintillating tiles) was proposed in 1991 [1] and since then several prototypes have been built. This calorimeter is made of iron plates interleaved with Scintillator Tiles read by 1 mm diameter ($\odot$) WLS fibers [2] [3]. Fibers from BICRON, KURARAY and POL.HI.TECH companies are being tested and used to build prototypes and the final ATLAS calorimeter.

Special tests have been also made in order to select 1 mm $\odot$ WLS fibers for the upgrade DELPHI Scintillator Tile and WLS fiber Calorimeter (STIC) [4] [5]. In this calorimeter, the absorber is made of plates of lead interleaved with scintillating tiles and the fibers are placed perpendicular to the tiles (nowadays called "*Shashlik type*"). In both TILECAL and STIC calorimeters the scintillator plastic tiles are produced by injection molding technique at IHEP/Protvino, Russia [6]. The base material is transparent granulated polystyrene doped with 1.5% of PTP and 0.04% of POPOP.

WLS fibers are not used only in calorimeters. They are very useful whenever it is necessary to bring the light signal from a scintillator to a region not close to the photodetector. Such is the case of the VETO detector placed in front of the STIC calorimeter in order to trigger on a single photon. This detector is made of plates of scintillator read laterally by WLS fibers. The signal is brought to the exterior of the DELPHI detector by clear fibers connected to the WLS fibers as it is described in [7]. This is an example of using WLS fibers outside the calorimetry field.

2 General requirements for WaveLengthShifting fibers

The requirements for electromagnetic and hadronic calorimeters are not necessarily the same. Fibers for electromagnetic calorimeters are about 50 cm long (as it is the case when the absorber is lead) and for hadronic calorimeters the typical lengths are of the order of 200 cm. The density of fibers can also change drastically from one calorimeter to another.

General requests are:

Figure 1: Light output $I(x)$ for some typical 200 cm long WLS fibers as a function of distance x to the PMT (left). Light output of WLS fibers normalized to the BCF91A (95) fiber (right).

Figure 2: Light output $I(x)$ for some typical 50 cm long WLS fibers as a function of distance x to the PMT (left). Light output of WLS normalized to the BCF91A (SC) fiber (right).

Table 1: Typical values for lightoutput $I(90cm)$, $I(140cm)$ and attenuation length L_2 (long component), of 200 cm long fibers. 5 fibers of each type were measured and the RMS for L_2 , $I(90)$ and $I(140)$ is less than 5%. $\sigma(I)$ for Kuraray fibers is $\leq 3\%$

Fiber type	L_2	$I(90)$	$I(140)$
BCF91A (94)	222	0.172	0.134
BCF91A (95)	242	0.189	0.150
BCF91A MC (95)	244	0.272	0.220
BCF99-28 No UVA (94)	216	0.220	0.176
BCF99-28A 600 ppm UVA (94)	159	0.182	0.130
Y11(200)MS 30 ppm UVA (94)	262	0.282	0.237
Y11(200) (94)	235	0.205	0.166
Y11(200)MS 600 ppm UVA (95)	270	0.295	0.247
S048-100 N4 (95)	251	0.189	0.167

- Good efficiency in converting blue light from scintillator to a longer wavelength. The wavelength should match the photodetector quantum efficiency.
- The light from the fiber should be transmitted through the fiber with attenuation as low as possible. A compromise between long attenuation length and high light output should be obtained and the solution will depend on the length of the fiber. Typical attenuation lengths of 1 m to 4 m are easily achieved, depending on the type of fiber, and if it is mirror aluminized (or not) at one end, etc. For short fibers (50 cm) the attenuation length is not so critical as it is for long (200 cm) fibers, although this depends essentially on the specific detector requirements.
- Fiber response should be fast enough to avoid pile-up of signals. Fibers with decay times of 10 ns or less are available.
- Fiber to fiber response fluctuation should be small. Homogeneity of the material and uniformity of the diameter should be required. "Good" values for fiber to fiber fluctuation are of the order of 5% or less. Fluctuations of 2% in the diameter are very common.
- Fibers should be flexible and insensitive, as possible, to mechanical stress. In general, flexibility is gained at expenses of shorter attenuation lengths.
- Fibers should be radiation hard. The level of radiation hardness required depend on the radiation environment of the experiment. In general, radiation hardness is in competition with fast decay times and long wavelength. "Blue" fibers are, in general, faster but less radiation hard.

- Fiber response to charged particles should be minimised. This is achieved by doping the fibers with Ultra Violet Absorber (UVA).

Those demands are guiding this work in order to characterize and optimize the response of "green" WLS fibers with spectra matching the quantum efficiency of bi-alkali photomultiplier tubes (PMT).

Table 2: Typical values for light output $I(20cm)$, $I(40cm)$ and attenuation length L between 20 and 40 cm, for 50 cm long fibers. $\sigma(L) \leq 5\%$ and $\sigma(I) \leq 3\%$.

Fiber type	L (cm) [20,40]cm	$I(20)$ (a.u.)	$I(40)$ (a.u.)
Y11(200)MS	100.9	6.08	5.00
Y11(200)MS al.	166.0	8.56	7.76
Y7(250)	76.5	4.13	3.21

3 Experimental results

In this paper we will report on the optimization of the optical fiber properties: light yield, attenuation length, response to charge particles and mechanical flexibility. This work was developed in close collaboration with BICRON, KURARAY and POL.HI.TECH producers. Some of the main results obtained with 1 mm $\odot$ BICRON (BCF91A, BCF99-28 and 28A), KURARAY (Y11(200) and Y11(200)MS ¹) and POL.HI.TECH (S048-100 and S048-100 N3, N4 and N5) fibers are presented. Experimental results for fibers measured as function of several parameters are presented:

- Dopant concentration.
- Fiber cladding.
- UV absorber concentration.
- Mechanical stress.

Fiber response to the blue TILECAL scintillator is measured using a bi-alkali EMI9813KB photomultiplier tube (PMT) and integrating the current $I(x)$ with a digital multimeter [8]. The light in the scintillator is excited by electrons from a ⁹⁰Sr β -source. The same β -source was used to evaluate the WLS fiber response to charged particles. Position of the light (and β) source, movement of the scanning

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¹the number in brackets stands for the dopant concentration, M for multicladding and S means that the fibers are produced to be flexible

Figure 3: Light output for Bicorn fibers, with different UVA concentrations. Fibers illuminated with TILECAL scintillator light (left), and with electrons from ^{90}Sr β -source (right).

Figure 4: Light output for Pol.Hi.Tech. S048-100 fibers. Fibers illuminated with TILECAL scintillator light (left), and with electrons from ^{90}Sr β -source (right).

table and measurement of the current, are computer controlled by a Macintosh equipped with LABVIEW software [9, 10].

For the comparison of the light output of fibers from different producers or with different claddings (single clad vs. double clad), all the fiber light output cone is detected (section 3.2). For the other systematic tests (dopant concentration, UVA concentration, etc.) only about 95% of the cone is detected, and attenuation length is slightly overestimated, but for comparative measurements the conclusions remain valid [8].

In first approximation the fiber light output can be described by the equation:

$$I(x) = I_{0S} \exp\left(-\frac{x}{L_{attS}}\right) + I_{0L} \exp\left(-\frac{x}{L_{attL}}\right) \quad (1)$$

L_{attS} is the short attenuation length, L_{attL} is the long attenuation length and $I_{0T} = I_{0S} + I_{0L}$ is the light yield.

All light output results are presented in arbitrary units. As absolute reference, the number of photoelectrons produced by Minimum Ionizing Particles (muons of 150 GeV) in the center of a 3 mm thick Protvino scintillator tile read laterally by one Y11(200)MS fiber at about 70 cm from a light guide in front of a XP2012 PMT is 1 photoelectron. The fibers are mirror aluminized at the end opposite to the PMT with typical reflectivity values of 0.7.

3.1 Effect of the dopant concentration

Since 1992, fibers with various concentrations have been systematically tested. Optimal concentrations for each of the selected type of fibers were found. Till a certain limit, the light yield increases with increasing dopant concentration. First, the light transmitted through the fiber is not attenuated, but after a certain dopant concentration the increase in light yield is obtained at expenses of decreasing the attenuation length.

In Fig. 1-left are shown the light output $I(x)$ of the several typical fibers tested for the TILECAL calorimeter: Bicon BCF91A and BCF99-28, Y11 from Kuraray and S048-100 from Pol.Hi.Tech.

In Fig. 1-right the same experimental results are shown but with the $I(x)$ values normalised to the correspondent values for the BICRON BCF91A fibers used to instrument the first TILECAL prototype. Note that the S048-100 N4 were the best fibers tested by us in terms of light output and attenuation length. The optical characteristics of those fibers are shown in table 1.

All three producers can offer WLS fibers with light output and attenuation length that are compatible with the minimal requirements of the TILECAL calorimeter. For simplicity we can consider as reference the light output and attenuation length of BCF91A fibers.

BCF99-28 fibers have higher concentration than fibers BCF91A giving more light without degradation of the long attenuation length ($\geq 200\text{cm}$) [8], so they are

Figure 5: Light output for Kuraray fibers with different UVA concentrations. Fibers illuminated with TILECAL scintillator light (black) and with ^{90}Sr β -source (open).

better adequate to the TILECAL calorimeter. Kuraray offers fibers (Y11(200)MS) with better light output and attenuation length. Y11(200) are slightly better than the BCF91A, at least for distances greater than 100 cm. Pol.Hi.Tech produces already fibers (S048-100 N4) with characteristics similar to the BCF91A. However for some of these fibers other parameters need also to be optimized, such as mechanical fragility [8] and radiation hardness [11]. The choice for each application depends on all these parameters.

Fig. 2 shows recent experimental results from studies to optimize the light yield response of short fibers (50 cm long) to instrument the upgrade DELPHI STIC calorimeter. Y11 fibers with 300 ppm can be adequate for this detector increasing the signal/noise, ratio improving the detection of particles depositing little energy in the calorimeter as it is the case of muons. Since the fibers are shorter it is possible to increase the light yield without appreciate deterioration of the effective attenuation length. This value, when measured between 20 cm and 40 cm from the PMT is ~ 100 cm without mirror and about 160 cm with an aluminized mirror (reflectivity of 0.7) at one fiber end.

In Fig. 2 it can be seen the gain in light output, when using (with bi-alkali PMT) Y11 fibres instead of the Y7, not available when the STIC was designed and material commissioned. Typical values for light output and attenuation length are shown in table 2.

Figure 6: Ratio $[I(140) \text{ with UVA}] / [I(140) \text{ no UVA}]$ for Bicron, Kuraray and Pol.Hi.Tech fibers, as function of UV absorber concentrations. The S048-100 UV absorber concentration was not specified. Scintillator (black dots) and electron response (open dots).

3.2 Fiber cladding

Light yield can be critical for calorimeters using small density of WLS fibers, as it is the case of TILECAL. Using multicladding fibers, not only improvement on optics is achieved, but also on the mechanics. Fibers are also better protected by the multicladd.

KURARAY Multicladd scintillating fibers are available since the last few years [12]. Multicladding Y11(200)MS WLS fibers were used to instrument one of the TILECAL prototypes and the TILECAL module 0. In Fig. 1 is shown the optical improvement by using a multicladd instead of a single cladding fiber. When compared with single clad fibers they show an increase of about 40% in light output for distances to the PMT larger than 1.4 m. Note that the multicladd thickness reduces the "active" WLS fiber diameter, although, mechanically, the outside diameter is the same (1 mm).

BICRON and POL.HI.TECH are also developing this technique but the results are not yet satisfactory.

3.3 Fibers with UV absorber

Experimental tests on the first TILECAL prototype [3], have shown that muons or pions impinging on the crack region between scintillators produce an enhancement of the calorimeter signal, leading to appreciable non-uniformities. This effect can be reduced with the addition of small concentrations of UV absorber (UVA) to

Figure 7: Ratio of light output after/before bending as a function of curvature radii. The Y11(100) fiber has one curvature and the others have two curvatures.

the mixture used in the commercial standard fibers.

It is crucial that the response (light yield and attenuation length) of fibers to scintillator light does not change significantly. A compromise among all those effects should be done interactively with tests of the prototypes.

Results of the light output response of several fibers with and without UVA is shown in Fig. 3, 4 and 5. Response of fibers to charged particles (electrons from the ^{90}Sr β -source) and to light of the blue scintillator is compared. Fig. 6 shows the ratio of the light output at 140 cm for fibers doped with and without UVA as function of the UVA concentration.

Instrumentation of the TILECAL calorimeter with Y11(200)MS fibers doped with 600 ppm UVA, improved considerably its uniformity ($< 1\%$ globally) [14].

BICRON fibers with UVA needs some optimization and more systematic studies are necessary. Pol.Hi.Tech S048-UVA fibers (concentration not specified) seem to be adequate to the TILECAL uniformity response.

3.4 Mechanical stress

Flexibility of the WLS fibers for TILECAL calorimeter is mandatory. The fibers are curved to diameters of about 10 cm or less and they should survive during 10 years. Mechanical fragility of fibers can be considerable [8].

Presently, the plasticity of the fibers can be optimized to reach the calorimeter required performance as it shown in Fig. 7. Some of the fibers can be bent to diameters of 5 cm without appreciable degradation of the attenuation length. Further tests are underway.

3.5 Radiation hardness

Comparative tests of different types of fibers were performed at low and high dose rates (from 0.55 Krad/h up to 1.5 Mrad/h). The effect of low γ energy (1.3 MeV) and Compton electrons was compared with the effect of a mixed field of neutrons and gammas from a nuclear reactor. These tests are reported in another contribution to this conference [15] and described in detail in [11].

For reasons of completeness we summarise those results in the following way: i) no dose rate effects were observed, at least in the range of dose rates and conditions of these experiments; ii) degradation of fibers by γ radiation is similar to the degradation by neutrons, as far as the dose is the same and the conversion flux-dose is realistic; iii) Adequate type of UVA with adequate concentration can help on radiation hardness; iv) 2 m long fibers irradiated with uniform field of 140 Krad along 130 cm (the 50 cm near the photodetector are not irradiated) suffer mainly from degradation of the attenuation length. At the distance of 180cm the best tested Kuraray fibers loose about 10 % . The best fibers from Bicron lose about 15% and Pol.Hi.Tech loose about 25 %.

4 Summary

WLS fibers produced by BICRON, KURARAY and POL.HI.TECH present properties to be used in electromagnetic, in hadron calorimetry and in a great variety of plastic scintillating detectors. All three companies offer fibers with reasonable light yield and attenuation length (typically ≥ 200 cm for non-aluminized fibers) and acceptable plasticity to be curved to diameters of the order of 10 cm. WLS dopants and UVA absorber concentration can be tuned to the specific requirements of the calorimeter.

For calorimeters using a small density of WLS fibers, as the case of TILECAL, multiclad fibers with light yield similar to the Y11 KURARAY fibers will improve considerably the calorimeter performance.

The radiation hardness of the fibers is not in general a problem for LEP experiments and can be suitable for some regions of the LHC detectors, such as the barrel hadron region of ATLAS or CMS [11].

5 Acknowledgments

We gratefully acknowledge B. Tomé for commenting this text and helping us with the fibrometer. Special thanks are due to J. Patriarca and M. Stielau for helpful assistance. We thank M. Mishina, B. Miller and J. Huston for helping us with the fiber cutting machine. Our gratitude goes to those that made this work pleasant, although with thousands of fiber measurements. This work was supported by JNICT/Portugal.

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