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Effects of Stress and Strain on Scintillating and Clear Fibers

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Abstract

Among the improvements planned for the 1997-98 upgrade of the DØ detector at Fermilab are installation of a scintillating-fiber central tracker and a lead-scintillator central preshower counter read out with wave-shifting fibers. Because of space limitations, fibers in both systems may need to undergo bends with fairly small radii, and the resulting stresses and strains may cause light losses. This paper presents results of a study of the effects of deformation on fiber light transmission. Particular emphasis is placed on the new multiclad fibers developed by Kuraray.

I. INTRODUCTION

Tracking detectors based on scintillating-fiber technology are of considerable interest in high-energy physics. For example, a central tracker using some 81 K fibers is being developed for the 1997-98 upgrade of the DØ detector at Fermilab [1]. Generally, such devices employ scintillating fibers located within the detector active volume optically coupled to clear lightguide fibers which transport the light to remote photodetectors. One advantage of fibers, their flexibility, may also present problems since stresses and strains due to bends may affect light transmission.

This issue is also relevant to other detectors that employ flexible fibers, such as calorimeters and preshower detectors in which embedded wave-shifting fibers are used to transport light out of scintillator blocks. Indeed, the upgrade of the DØ detector includes some 6 K channels of a lead-scintillator central preshower counter read out with wave-shifting fibers coupled to clear lightguide fibers that transport the light to distant photodetectors [2].

Because of space limitations in the DØ detector, fibers in the new tracking and preshower systems may need to undergo bends having fairly small radii. The resulting stresses and strains may result in light loss. That is, the light intensity transmitted by a fiber may be reduced by a bend due to 1) local stress-induced changes in the refractive index of core and cladding; 2) deviations from a circular cross-sectional shape resulting from stress; 3) non-adiabatic changes, due to fiber curvature, in the angles between light rays travelling in the core and the corresponding interface; and 4) cracks produced in the cladding if the bend radius is sufficiently small. Such light losses may be important, particularly for the DØ fiber tracker where light intensities are about 30 photons. Results of a study of light losses due to mechanical deformation are described below; earlier results have been presented elsewhere [3].

II. FIBERS TESTED; APPARATUS

The fibers studied are of direct interest for the DØ upgrade and so include clear, wave-shifting, and scintillating types with diameters near 1 mm. Both standard single-clad fibers from Bicron [4] and Kuraray [5], and new, multiclad fibers developed by Kuraray are being studied. These latter fibers are of particular interest because they are brighter [6], have larger attenuation lengths [7,8], and are mechanically more robust, and so are the current candidates for use in the DØ upgrade. The fibers studied are listed in Table I. All have a polystyrene core. The scintillating fibers are doped with p-terphenyl (pT) and 3-hydroxyflavone (3HF), and the wave-shifting fibers with Y11, a proprietary Kuraray dye. The corresponding fiber fluorescence emission peaks are at 535 nm and 505 nm, respectively, both in the green.

Because previous investigations showed that fibers containing 3HF deteriorate under exposure to room-level fluorescent light [9,10], these fibers are handled under illumination from fluorescent lamp fixtures covered by filters that cut off below about 500 nm, which avoids damage [11]. Clear fibers and Y11-doped wave-shifting fibers do not appear to be affected by ambient fluorescent light. Fibers containing 3HF stored in darkness have maintained stable properties over times of at least 3 years.

Light-loss measurements are made by injecting light into one polished end of a fiber sample and measuring the light exiting from the other end with a silicon photodiode. Light loss is defined by $L = (I_0 - I)/I_0$, where I_0 is the photodiode current when the fiber sample is straight and unstressed, and I is the corresponding value when the fiber is deformed in a controlled manner. The apparatus used maintains constant contact between the light source and its fiber end and between the photodiode and its fiber end, thus allowing measurements to be made before, during, and after the deformation without changes in input or output light coupling. The total fiber length remains, of course, essentially constant.

Table I. Fibers studied.

Manufacturer	Type	Cladding	Dopants	Outside Diameter (mm)
Kuraray	clear	single-clad	none	0.830
		multiclad	none	0.830
		multiclad	none	0.965
		multiclad	none	1.000
Kuraray	wave-shifting	multiclad	150 ppm Y11	0.830
		multiclad	250 ppm Y11	0.830
Kuraray	scintillating	single-clad	~ 1% pT + 1000 ppm 3HF	0.830
		multiclad	~ 1% pT + 1500 ppm 3HF	0.830
		multiclad	~ 1% pT + 1500 ppm 3HF	0.925
Bicron	scintillating	single-clad	1% pT + 500 ppm 3HF	0.830

Several different light sources were investigated, including a green light-emitting diode (LED), a red pilot lamp, and a length of pT/3HF-doped scintillating fiber excited either by ultraviolet radiation from a Hg(Ar) lamp or conversion electrons from a ^{207}Bi radioactive source. Initial tests indicated no significant differences in results of measurements made with these sources, confirming a previous finding by CDF [12]. Thus, the green LED was used for most subsequent measurements since it provides green light (as produced by the scintillating and wave-shifting fibers) with the greatest convenience.

III. FIBER BENDING STUDIES

A typical setup for bending studies is shown in Fig. 1. The larger loop has no significant effect on the measurement but allows the bend radius, *r*, to be varied while keeping the total fiber length constant. During the course of the bending measurements, two incidental effects were observed. First, the light loss caused by a loop in a short fiber, say 100 cm in length, is two to four times greater than that produced by the same loop in a longer fiber, say 500 cm long. Also, the light loss caused by a given loop in a fiber of fixed length depends somewhat on the position of the loop. Both of these observed effects may be attributed to the conversion of a fraction of meridional rays to skew rays in the deformed fiber region, and the fact that skew rays have shorter attenuation lengths than meridional rays. For example, skew rays generated when the loop is close to the light source are rapidly attenuated in travelling along the fiber to the photodetector; those produced when the loop is close to the photodetector have but little distance to travel and are hardly attenuated, resulting in a smaller loss. However, these effects are expected to have little influence on the results presented below because moderately long fiber lengths -- between 250 cm and 800 cm -- were used in the measurements, and because the loops were formed at the fibers' centers, as shown in Fig. 1, where effects of position are small.

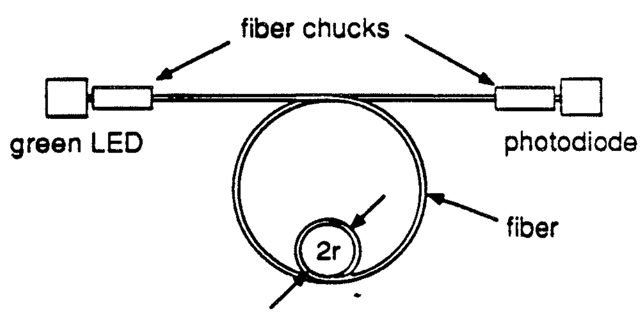

Fig. 1. Schematic drawing of a typical setup used to measure light loss due to a circular loop of radius *r*.

Bending studies began by investigating the influence of radius on light loss using single-turn circular loops, as shown in Fig. 1. As anticipated, light loss increased with decreasing bend radius. The difference in the behavior of Kuraray clear single-clad and multiclad fibers of 0.830 mm diameter is illustrated in Fig. 2. The superiority of the multiclad fiber is obvious: it can be bent into a circle of 1 cm radius before producing a light loss of 3%, while the single-clad fiber can be bent no smaller than 2 cm in radius without exceeding this loss.

Light-loss data for single-turn loops of Kuraray multiclad clear, scintillating, and wave-shifting fibers, all of 0.830 mm diameter, are shown in Fig. 3. As can be seen, dopants in the fiber have little, if any, effect. Also shown in Fig. 3 are data for Kuraray multiclad scintillating fiber of 0.925 mm

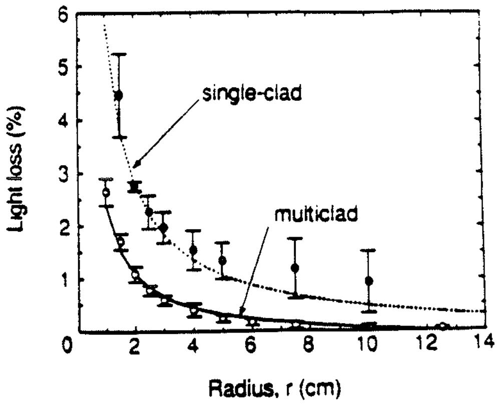

Fig. 2. Light loss as a function of radius for single-turn loops of Kuraray clear single-clad and multiclad fibers of 0.830 mm diameter. Smooth curves have been drawn through the data.

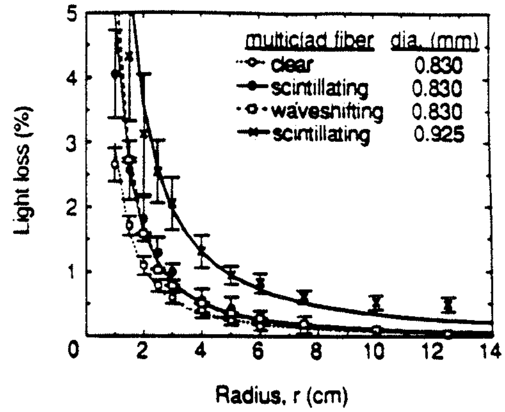

Figure 3. Light loss as a function of radius for single-turn loops of various Kuraray multiclad fibers. Smooth curves have been drawn through the data.

diameter, which appears to exhibit an anomalously high bending loss. The dependence of light loss on fiber diameter was studied using Kuraray clear multiclad fibers having diameters of 1.000 mm, 0.965 mm, and 0.830 mm. Within statistical uncertainties, all yielded the same results, emphasizing the anomaly of the 0.925-mm-dia. scintillating fiber just mentioned.

Bending studies were restricted to radii greater than 1 cm. At smaller radii cracks appeared in the fiber cladding causing large light losses, and the fiber was permanently damaged; this was particularly true for single-clad fibers. Generally, over the range investigated, the light loss of single-turn circular loops of radius r can be parameterized as $L = A/r^n$, where A is a constant and n is near 1.5.

To explore the effects of light loss due to bending in other than circular configurations, a single-turn loop, made of 0.830-mm-dia. Kuraray clear single-clad fiber, was deformed from a circle of 20 cm diameter into an oval form. The resulting additional losses as a function of eccentricity are consistent with those measured for a circular loop whose radius equals the smaller radius of curvature of the oval.

The effect of total bend path length was investigated by measuring light transmission through multiple-turn circular loops of various radii. The results for Kuraray clear 0.830-mm-dia. single-clad fiber are shown in Fig. 4, and those for clear 0.965-mm-dia. multiclad fiber in Fig. 5. These data appear to be reasonably well parameterized by the form $L = A\sqrt{N}/r^n$, where N is the number of turns and A and n are constants, which is a generalization of the single-turn relation. A fit to the multiclad-fiber data in Fig. 5 yields $A = 3.53$, $n = 1.5$, and L is in percent when r is in centimeters. It should be noted that for fractional turns -- e.g., a 90° bend in a fiber -- the loss is quite low even for small radii.

An interesting phenomenon noted in the course of the fiber bending studies is the existence of transient effects -- that is, certain fiber deformations produce changes that require times of the order of minutes before reaching equilibrium. This behavior is not surprising given the plastic nature of the fibers. As an example, a circular one-turn loop one cm in radius was made at time zero and the corresponding light output was measured as a function of time. After

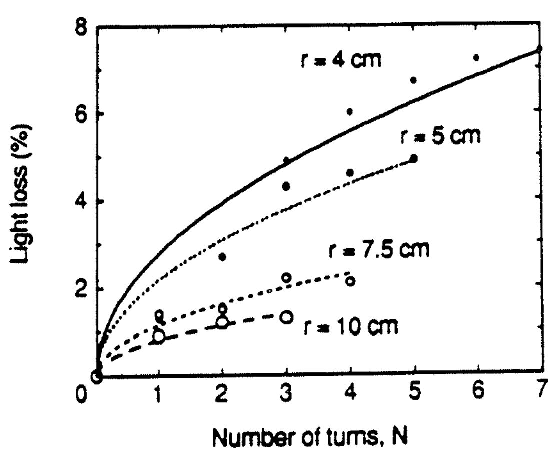

Fig. 4. Light loss as a function of number of turns for circular loops of 0.830-mm-dia. Kuraray clear single-clad fiber of various radii.

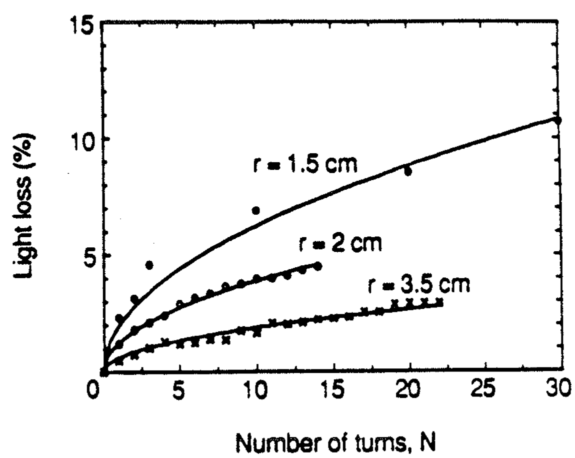

Fig. 5. Light loss as a function of number of turns for circular loops of 0.965-mm-dia. Kuraray clear multiclad fiber of various radii.

10 minutes, the loop was undone and the light measurements continued for 10 minutes more. This experiment was performed using Kuraray clear single-clad and multiclad fibers of 0.830 mm diameter. The transient effect was considerably larger for the single-clad fiber: exhibiting a time constant of about 2 minutes for both situations, creating the loop produced a loss of 55%, while undoing the loop left a permanent loss of 7%, presumably due to observable microcracks that had developed. The multiclad fiber showed almost no delay in reaching a loss of 3%, and then returning to its initial transmission with no visible formation of microcracks. This type of transient was observed only for circular loops smaller than 1 cm and 2 cm in radius, respectively, for multiclad and single-clad fibers, and so does not affect the results of the bending measurements presented above.

The effect of aging on light loss in bent fibers is also being studied. To enhance the likelihood of observing changes, fairly extreme conditions -- two 10-turn loops of Kuraray 0.965-mm-dia. clear multiclad fibers, one of 1.3-cm radius and one of 0.8-cm radius -- have been established, and light transmission is being monitored as a function of time. So far, no significant changes have been observed after an interval of four months.

IV. OTHER FIBER DEFORMATIONS

Although of less direct applicability to the DØ detector upgrade project, other fiber deformations such as tensile elongation, cross-sectional compression, and torsion have also been explored. To study the effect of tension on fiber light transmission, light from a green LED was injected into the polished upper end of a fiber supported by a rigidly fixed chuck. A distance d below, an aluminum tube epoxied to the fiber served as a support for hanging adjustable weights, W, which applied a tensile stress to the fiber. Observation of the position of the tube yielded the corresponding fiber elongation. An unstressed section of the fiber below the tube, about 50 cm in length, transmitted the fiber light to a photodiode.

Weights W between 0 g and 1.3 kg were used. (The rupture strength for 0.965-mm-dia. fibers is about 3.8 kg [13].) Fifty-gram steps were used, and a measurement cycle with increasing then decreasing weights took about 20 minutes. This procedure was applied to a clear Kuraray single-clad fiber 1 mm in diameter having d = 183 cm, and a similar multiclad fiber of 0.830 mm diameter with d = 201 cm. In both cases the fibers obeyed Hooke's law, and the slopes of the stress-strain curves yielded values of Young's modulus consistent with the handbook value of 3.17×10^{10} dyne/cm^2 for polystyrene [14]. While the light losses for both fiber types were quite small -- less than 1% -- their behaviors were distinctly different: the multiclad fiber displayed a linear, single-valued dependence of light loss on tensile force, while the single-clad fiber's light loss exhibited a closed hysteresis loop with losses for increasing tension lower than those for decreasing tension.

The effects of compression were investigated by squeezing single-clad and multiclad fibers in a clamp fitted with 10-cm-long jaws of three possible cross-sectional types: 1) two flat surfaces, 2) one flat surface and one V-groove, or 3) two symmetric V-grooves. Initial investigations made by painting 10-cm fiber sections black or covering them with light-transmitting mineral oil indicated that the light losses observed under compression were not simply caused by the escape of cladding light in the clamp region.

Fiber light output was studied for a total force range between zero and 50 kg (weight) applied over the 10-cm length. While the measured light loss was essentially a linear function of applied force in all cases, the single-clad fibers showed considerably more loss than the multiclad samples. For clear fibers of 0.830 μm dia. compressed between type-2 jaws, the loss was about 0.19% per kg and 0.08% per kg for single-clad and multiclad fibers, respectively. The losses for larger diameter multiclad fibers were even smaller.

Measurements on 0.965-μm-dia. clear multiclad fiber showed that light loss at a given compressional force decreased progressively using type-1, type-2, and type-3 jaws. For example, at 30 kg the loss was 1.7%, 1.3%, and 0.2%, respectively. This result may be interpreted as indicating that compressional light loss is caused predominantly by deformation of the fiber cross-sectional shape away from the original circular profile.

Effects of torsion were briefly investigated using a Kuraray single-clad scintillating fiber of 0.830 mm diameter. With both ends of a 400-cm-long fiber fixed -- one end coupled to a green LED, the other to a photodiode -- the center of the fiber was twisted through an angle of 360°. No change in transmission was noticed.

V. SUMMARY

The 1997-98 upgrade of the DØ detector will include, in addition to other improvements, a scintillating-fiber central tracker and a central preshower counter. The former system will involve some 81 K scintillating and clear lightguide fibers, and the latter some 6 K wave-shifting and clear lightguide fibers. Because of space limitations, fibers in both systems may need to undergo bends of fairly small radius, and the resulting stresses and strains may result in light losses. This issue is being investigated for a number of scintillating, wave-shifting, and clear fibers with diameters near 1 mm, particularly the new, multiclad variety developed by Kuraray. The deformations studied include bending, tensile elongation, compression, and torsion. Generally, except for severe bending or considerable compression, light loss was found to be less than a few percent. The effects of bending were investigated using single-turn and multiple-turn loops of various radii. As expected, light loss increased with decreasing radius. For the fibers studied, little dependence on either core dopants or diameter was observed. Generally, the light loss, L, in an N-turn loop of radius r could be parameterized by the form $L = A\sqrt{N/r^n}$, where A is a constant and n is near 1.5. Considerable difference was found between Kuraray multiclad and single-clad fibers. The former can be bent into single-turn loops with radii as small as 1 cm before the light loss reaches 3%, while the latter produces this loss at a 2-cm radius. An aging study, still in progress, showed no change in light transmission through small 10-turn loops of multiclad fibers after an interval of four months.

The effects of tensile elongation were also explored for Kuraray clear single-clad and multiclad fibers with forces up to 1.3 kg applied to 2-m-long lengths. Over this range, both fiber types obeyed Hooke's law and produced light losses less than 1%. Compressive stress produced more light loss in single-clad than in multiclad fibers: when squeezed between 10-cm-long flat/V-groove jaws, the observed losses were about 0.19%/kg and 0.08%/kg, respectively. Studies using jaws of different cross-sectional shapes indicate that compressional light loss is caused predominantly by deformation of the fiber cross-sectional shape away from the original circular profile. Finally, a single observation of the effects of torsion indicated no change in transmission for a 360° twist at the center of a 400-cm-long Kuraray single-clad scintillating fiber with fixed ends.

The observations made indicate that multiclad fibers produce smaller light losses under deformation than single-clad fibers, and that their use, together with avoidance of bends with radii smaller than a few centimeters, should avoid light loss due to stresses and strains.

VI. ACKNOWLEDGEMENTS

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