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MONTE CARLO SIMULATIONS OF SCINTILLATING FIBER OPTIC WAVEGUIDES

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ABSTRACT

Preliminary results from model calculations of a single scintillating fiber optic waveguide are discussed.

INTRODUCTION

We have been studying the light transmission properties of single scintillating fiber optics waveguides through detailed Monte Carlo simulation and experimental measurements. In particular, we have been attempting to probe the nature of the single-photon detection problem in this context as part of the effort to develop a scintillating fiber tracking subsystem for use in SSC experiments.

As currently envisioned, a single channel for such a tracking detector will consist of an active scintillating fiber waveguide optically coupled to a passive waveguide and then to a highly efficient photodetector. Refer to Figure 1. From the standard lore one may determine five distinct stages to this single-photon detection problem, each with its own concomitant processes and problems:

(1) passage of an ionizing particle through the scintillating fiber deposits a certain amount of energy, causing a series of excitations, non-radiative and radiative transfers dependent on the detailed bulk composition and molecular structure, and resulting in the emission of a photon;
(2) propagation of light along the fiber with a certain complex light-collection efficiency determined by the geometry of the waveguide, the degree of structural imperfection, and the amount of (self-)absorption of the light by the scintillator material itself;
(3) transmission across a physical discontinuity, a splice from the scintillator waveguide to a non-scintillator ("clear") waveguide for transport of light out of the fiducial volume of the detector;
(4) negotiation of one or several bends in the clear waveguide light-pipe;
(5) conversion of single photons to electronic signals by an optically-coupled photodetector with high quantum efficiency.

The first of these involves development of new efficient bulk scintillators, which is currently under investigation [1,2]. The last of these involves the development of SSPMs and VLPCs [1,3]. Thusfar, the focus of the present effort has been on the second of these items, and herein we shall concentrate on certain preliminary estimates from this study. We stress that it is extremely important to understand in the most precise possible terms the detailed behavior and response of a single waveguide. The systematic study of such a system is our ultimate goal.

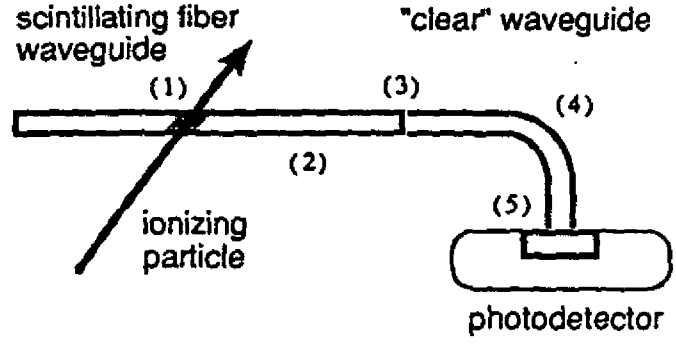

Figure 1. Schematic of a single fiber channel.

The full author list for the Fiber Tracking Group may be found in Reference 1.

SCINTILLATOR PHOTON YIELD

The raw photon yield from a ionizing charged particle passing through the bulk scintillator is dependent on the molecular properties of the material. For our present use, it may be expressed as

$$I_0 = \left(\frac{dE}{dx}\right) \Delta x \frac{Q}{E_\gamma} \qquad (1)$$

where dE/dx is the mean energy loss associated with the ionizing radiation, Δx is the given path length traversed by the particle in the fiber waveguide, Q is the quantum efficiency of the core material, and E_γ is the "effective" energy required to liberate a single photon. Typical numbers for these quantities give $I_0/\Delta x$ = (2 MeV/cm)(0.05)/(4.7eV) = 2000 photons/mm of track length.

Thus we have a nearly-constant number of photons produced per unit track length for such materials. The photodetection problem then becomes one of geometrically determining the appropriate path length of the particle across the fiber, and tracing the propagation of the light produced along this path through the waveguide in order to estimate the number of photons reaching the detector-end of the fiber. In practice, the above-quoted number will be reduced by a factor on the order of 100.

LIGHT PROPAGATION

In principle, the parameters relevant to the detailed understanding of a scintillating fiber waveguide and to the evaluation of its efficiency are quite large in number [4]. In attempting to systematically study this parameter space, we have been developing a detailed waveguide simulation code OPTICKS [5] which has thusfar given good qualitative agreement with observation. Our code adopts an approach that is principally one of geometric optics, with modifications from macroscopic electrodynamics.

Define the *survival fraction* as that fraction of photons produced in the waveguide which propagate without escaping through the clad or being absorbed in the core and thus exit the waveguide at the detector end. What are the major effects involved? They are:

(0) the geometry and sizes of the waveguide (cross-sectional shape, core, clad and coat thicknesses, length);
(1) structural imperfections, specifically due to mechanical imperfections of the interface between the core and clad, producing reflection coefficients less than unity;
(2) self-absorption of the scintillation light by the core material itself, depending on the overlap of the emission and absorption spectra and the wavelength of the propagating light.

Effect (1) yields power-law absorption; whilst effect (2) yields exponential absorption. The combination reduces th initial intensity, Equation (1) by the factor

$$g = R^N \cdot \exp(-D/\lambda_B) \qquad (2)$$

where R is the reflectance, N is the number of times the photon encounters the interface, D is the total path length of the photon in the fiber, and λ_B is the bulk attenuation length of the material (related inversely to the concentration times the molar extinction coefficient).

Efficiency vs. Radial Position of Source

Consider the case of a cylindrical waveguide in which a point-source is placed on the optical axis and then successively moved radially away from the axis. We have calculated the survival fraction as a function of the position of the point-source for the specific configuration of: PS/PMMA core/clad materials, fiber length of 3m, fiber diameter of 500μm, effectively *no* bulk absorption in the core, and 95% absorbing "black" coat exterior to the clad. This simple case is to be seen as almost pure geometry. Refer to Figure 2.

With the point-source on the optical axis, the only modes of the waveguide which are excited involve meridional-rays (i.e. modes for which the propagation vector crosses the optical axis). The survival fraction in this case is ~0.02. As the point-source is moved further away from the optical axis, an increasing number of skew-ray modes are excited (i.e., the nonmeridional-rays or "winding" modes). Many more channels will then open up for light propagation. There is an increasingly-significant sampling of the relative contribution of the skew-ray modes, so that the survival fraction grows quadratically with radial distance to ~0.07.

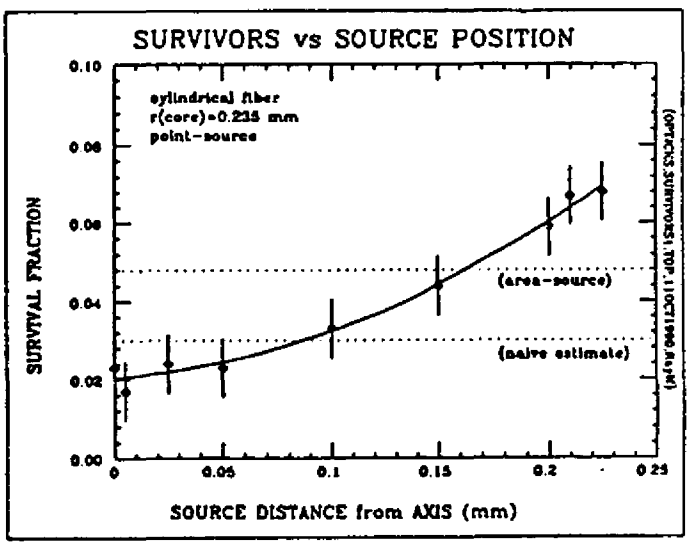

Figure 2. Variation of the survival fraction from a point-source with radial distance from the optical axis.

The naive efficiency estimate for meridional rays *only* is the well-known result $\varepsilon_0 = 0.5\,(1\text{-}n(\text{clad})/n(\text{core})) = 0.03$ and is indicated in Figure 2 by the lower dotted line. Although this estimate is often quoted as the de facto efficiency, it falls short by greater than a factor of two for many modes (in even this simple case). It is clear from this that there is a significant contribution to the light collection efficiency made by skew rays. A more appealing mean behavior may be inferred from a random sampling of the full cross-sectional area of the cylindrical fiber. As is reasonable, the resulting value of 0.048 properly weights the more distant areas. The upper dotted line in Figure 2 indicates the survival fraction so obtained. This is a reliable value for the mean fraction of photons trapped in the direction of the detector.

Forster Transfer Mean Free Path

For these scintillators, there is a mean free path (inversely related to dye concentration) between the sites of ionization energy deposition and scintillation photon emission. Our geometric studies indicate that the survival fraction drops to 80% linearly with this mean free path up to the fiber diameter. This implies that for efficient fiber production, one must maximize the dye concentration in order to minimize the mean free path and increase the geometric efficiency. However, self-absorption effects will compete with this gain.

End-face Distributions

We have investigated the intensity distribution of photons emerging from the end-face of the waveguide for the case of different sources of light. From a point-source on axis (meridional-rays) we obtain an areal distribution peaked in the center of the end-face disk; from a point-source near the core-clad interface (skew-rays) we obtain a distribution which is depleted in the central region but more heavily populated on the periphery; and from an area-source (sampling) we obtain a distribution which is fairly uniform over the end-face disk. Figure 3 shows the skew-ray distribution, which contributes the long time-component of fiber traversal times ("afterglow").

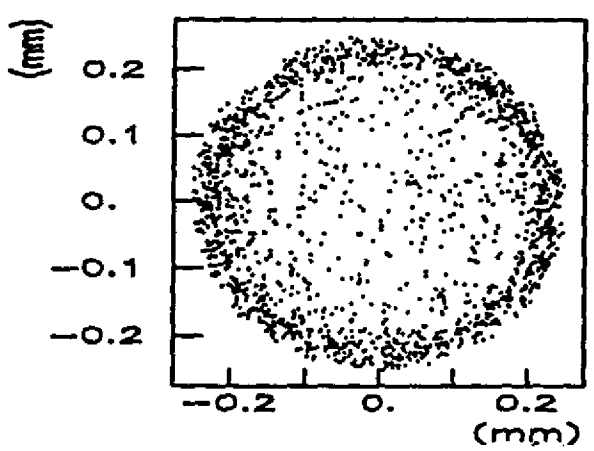

Figure 3. Intensity distribution at end-face of fiber from point-source near interface (mostly skew-rays).

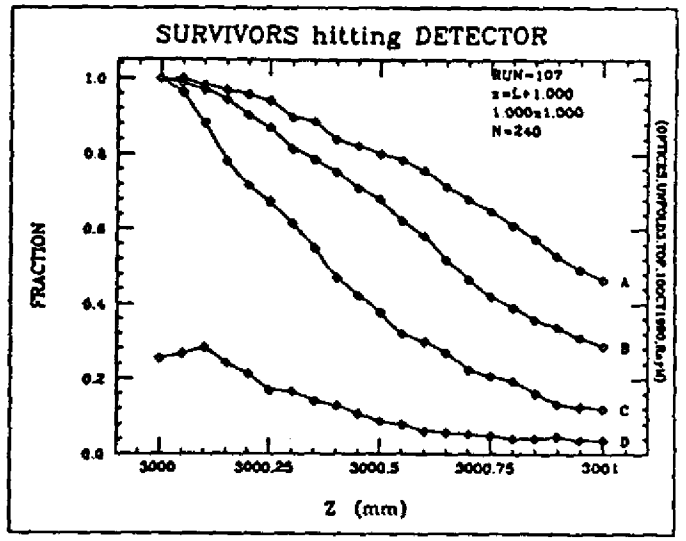

Figure 4. Fraction of photons emerging from the end of the waveguide and accepted by the photodetector.

As for the angular distributions of emergent photons, the general feature is that skew-rays contribute larger angles to the distribution, while meridional-rays tend to contribute more paraxial modes. The mean polar angle is in fact the value given by the numerical aperture. This (and the previous) result is in agreement with intuition and experimental observation of light emerging from the end of a fiber.

Additionally, we have modelled the geometric acceptance of a single-element photodetector by calculating the variation of the collection efficiency of emergent photons with the distance from the end of the fiber to the detector. Perfect quantum efficiency is assumed. Figure 4 shows the results for an area-source of light in the waveguide and for different photosensitive sizes. Detector "A" corresponds to $(1\text{mm})^2$ active area, "B" to $(0.750\text{mm})^2$, "C" to $(0.500\text{mm})^2$, and "D" to $(0.250\text{mm})^2$. Detector "B" is the nominal size of a SSPM active region. Considering the area-source to be a good indicator of average behavior, over 90% efficiency may be maintained out to almost 250μm from the fiber end-face.

CONCLUSIONS

We have begun a systematic study of single scintillating fiber waveguides and have developed a detailed Monte Carlo simulation for this purpose. Preliminary results have been presented. We shall continue the study of bulk absorption effects, time-dispersion, reflective coatings, and bend losses.

REFERENCES

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