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Scintillating Fiber Tracking Techniques*

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I. INTRODUCTION

Scintillating fiber detectors represent a particularly elegant solution to SSC tracking problems. Capable of being drawn into waveguides of very small cross section and long axial length, these detectors hold promise for providing high resolution tracking information in large volume detectors as well as microvertex devices.

The resurgence of enthusiasm for scintillation imaging, after two decades of malaise, has been kindled by the successful development of new scintillation glasses[1,2] and plastics[1,3,4] which can be clad and drawn into functional waveguides, as well as developments in image intensification and electronic imaging systems.[5] Tracks and interactions have been recorded successfully and with good efficiency in 25μm glass fibers[1,6] of ≤ 2cm length, in 1mm plastic fibers[3,7] of >1m length, and in multifiber bundles of 100μm fibers[4] of ≤ 30cm length, making these detectors potential competitors with silicon microstrips, CCDs and drift chambers.

However, to realize a useful detector based upon scintillating fiber materials will necessitate further R and D. It is the purpose of this paper to indicate the current status of the field and to suggest avenues for further work.

II. SCINTILLATION FIBER DETECTORS

The fundamental structure of a scintillation tracking device is the fiber-optic waveguide. There are many possible forms for such a guide: circular cross section, square cross section, hexagonal cross section, to name but a few. Waveguides are also distinguished by their refractive index profile, two examples of which are indicated in Fig. 1 for a guide of circular cross section. For a particle detector, the guide would consist of a scintillating core material of index n_1, a non-scintillating cladding of index $n_2 < n_1$, and an optional coating called extramural absorber which resides on the external surface of the cladding. To date, all scintillating fibers manufactured for particle physics have been of the "step-index" type, which has a smooth but abrupt transition between core and cladding indices. Typical index differences are $\Delta n = n_1 - n_2 \leq 0.1$. For such values of Δn, typically ≤10% of the scintillation light produced within a given fiber is trapped by internal reflection within that fiber.

Core Material: Candidate core materials may be derived from glass, plastic, or liquid scintillators. Table I presents a list of several recently developed materials, including values of quantum efficiency (QE) and attenuation length (λ) for fibers of a specified diameter. To date plastic scintillators have provided the highest QE and largest values of λ (for fibers of diameter ~1mm), whereas glass and liquid scintillators have provided the highest resolution waveguides (fibers with diameters ~25μm). Values of refractive indices for core and cladding measured at Na(D) are indicated in the table. These indices are in fact somewhat higher at the wavelengths of principal emission (which are in the blue), but because the cladding index is also higher at shorter wavelength, Δn is not changed appreciably.

Cladding material: Cladding material is an additional, indispensible element of a fiber-optic waveguide, and it must be carefully selected to match the core material for several reasons. First, the wave which is propagating in a guide propagates in both the core and the cladding - hence the cladding must be transparent to the scintillation light. Second, the cladding must be thick enough to contain the evanescent wave, yet sufficiently thin that most of the volume of the fiber is active material. A useful rule of thumb is that the cladding should be about four wavelengths thick. Third, the cladding must be matched to the core in terms of thermodynamic properties, so that a high quality interface between core and cladding results during the fiber drawing process. This last requirement could be avoided through the use of soft, silicone cladding materials which have a very low refractive index (n_2=1.35), but the fragility of such coatings makes them unattractive if any handling of the fiber guide is required.

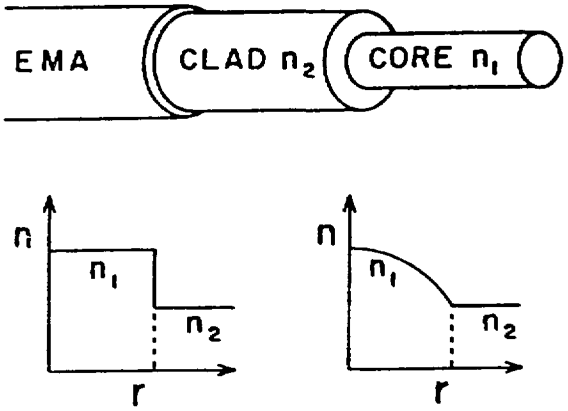

Fig. 1 Schematic of fiber optic waveguides: left, "step-index"; right, "graded index".

Extra-mural Absorber: The use of extramural absorbers (EMA) has been found to be essential to remove the bulk of the scintillation light which is produced but not trapped in the fiber of origin, and which would otherwise propagate freely throughout the volume of the detector. This can be accomplished by several forms of EMA: "super-facial" in which opaque material or an aluminum refective layer resides on the outer surfaces of the cladding as indicated in Fig. 1, by "interstitial" placement of opaque, absorbing fibers within the fiber lattice, or by dark wax or black epoxy fusions if multifiber bundles are employed.

Table 1

Properties of Scintillating Fibers

Material	Scintillation Efficiency	n_1(core)	n_2(clad)	Attenuation Length	Diameter
Polystyrene[a]	10 Photons/keV	1.58	1.50	120 cm	1 mm
Polystyrene[b]	10	1.59	1.46	120	1
Polystyrene[c] (PBD + .02% 3-HF)	12	1.58	1.50	90	1
Glass GS1/SC20[d]	3-4	1.56	1.49	<20 ~ 4	1 0.025
Liquids[e]					
1-Methylnapthalene +BIS/MSB	10	1.62	1.49	> 2.5	0.050
1-Phenylnapthalene +DPH +DPA	10	1.67	1.49	> 2.5	0.050

a) R. Binns, Washington University, St. Louis
b) R. Bourdinaud, SACLAY
c) A. Bross, Fermilab and R. Binns
d) R. Ruchti, Notre Dame, and A. Bross and J. Kirkby, CERN
e) D. Potter, Carnegie Mellon University

Attenuation Length: The attenuation lengths of the materials presented in Table I are in the meter range for plastic fibers of 1mm diameter, and in the 4-5cm range for glass fibers of ~25μm diameter. These values are thought to be dominated by local irregularities in refractive index and in the quality of the interface between core and cladding materials. Additionally, for glasses there is a significant problem associated with self-absorption in the material due to the presence of an undesirable valence state of Cerium (4+) and with devitrification or crystallization of the material on a microscopic scale.[1,2,6] Both of these effects lead to substantial reduction in light propagation.

Radiation Resistance: A noteworthy property of Cerium glass and polystyrene plastic scintillators is their radiation resistance. Cerium glass samples of 4mm thickness can tolerate dosages in excess of 10^7 rads with 20% light transmission loss at peak fluorescence (395nm).[1,6] In fact, Cerium is a common additive to many glasses to enhance radiation resistance. Polystyrene scintillation fibers of the Saclay type, after an exposure of 3×10^6 rads, are found to have a factor of 2 reduction in attenuation length.[3] This is significantly better than current experience with acrylic scintillators.

Fiber Profile: Finally one can question the utility of the "step-index" fiber guide, when more efficient waveguides have been developed by the communications industry with attenuation lengths of many kilometers. The answer is simply that the physical situation is vastly different in the two cases. In the communication problem, there is essentially an infinite amount of input power - e.g. an infrared laser light source - with the light injected directly into a "graded-index" fiber which propagates, at most, one or two modes. In the high energy physics problem, the source of input power is a minimum ionizing particle passing through the fiber medium. Because the level of produced scintillation light is extremely low (by laser standards) and isotropically emitted within the scintillation medium, a much greater bandwidth is essential - hence the use of the "step-index" device. Nevertheless, one would hope that more clever forms of waveguide could be developed through further R and D, which will provide simultaneously good light trapping and very long attenuation length.

III. TRACKING

Among the recent triumphs of scintillation imaging has been the successful recording of tracks and interactions in Cerium glass fiber-optic plates and in plastic fiber detectors. Figs. 2-5 show examples of events recorded by several groups[1,3,4,6] and Table II indicates the relative performance of glass and plastic materials. All the groups utilize multi- stage image intensifiers capable of single photon counting, and film or CCD/CID electronic cameras for data recording. Event clarity and spatial resolution is excellent, particularly for glass fibers. Residual distributions for tracking in glasses[1,6] are shown in Fig. 6.

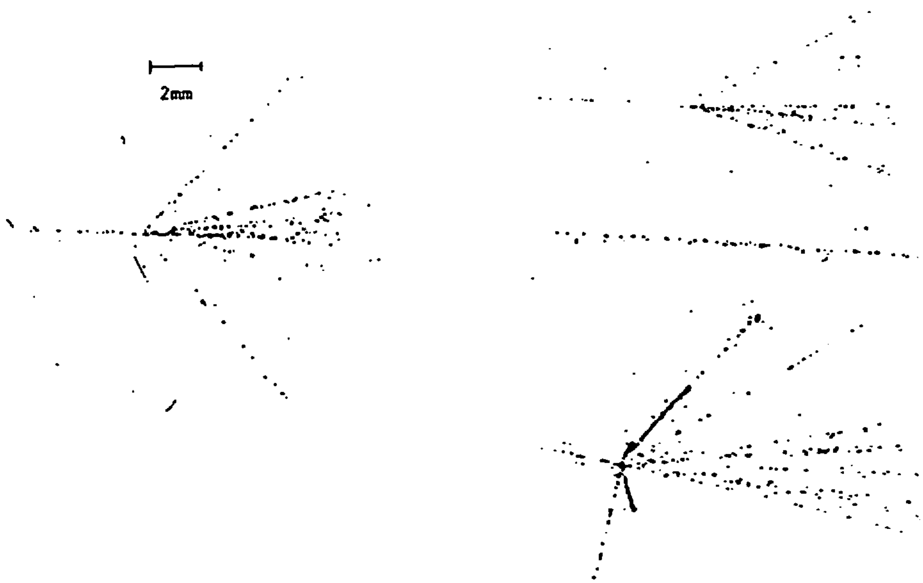

Fig. 2 Tracks and interactions of 50 GeV/c pions recorded in GSI glass using the Fermilab NH beam: left, 40 μm fibers with EMA; right, 25 μm fibers with EMA. (Ref. 1)

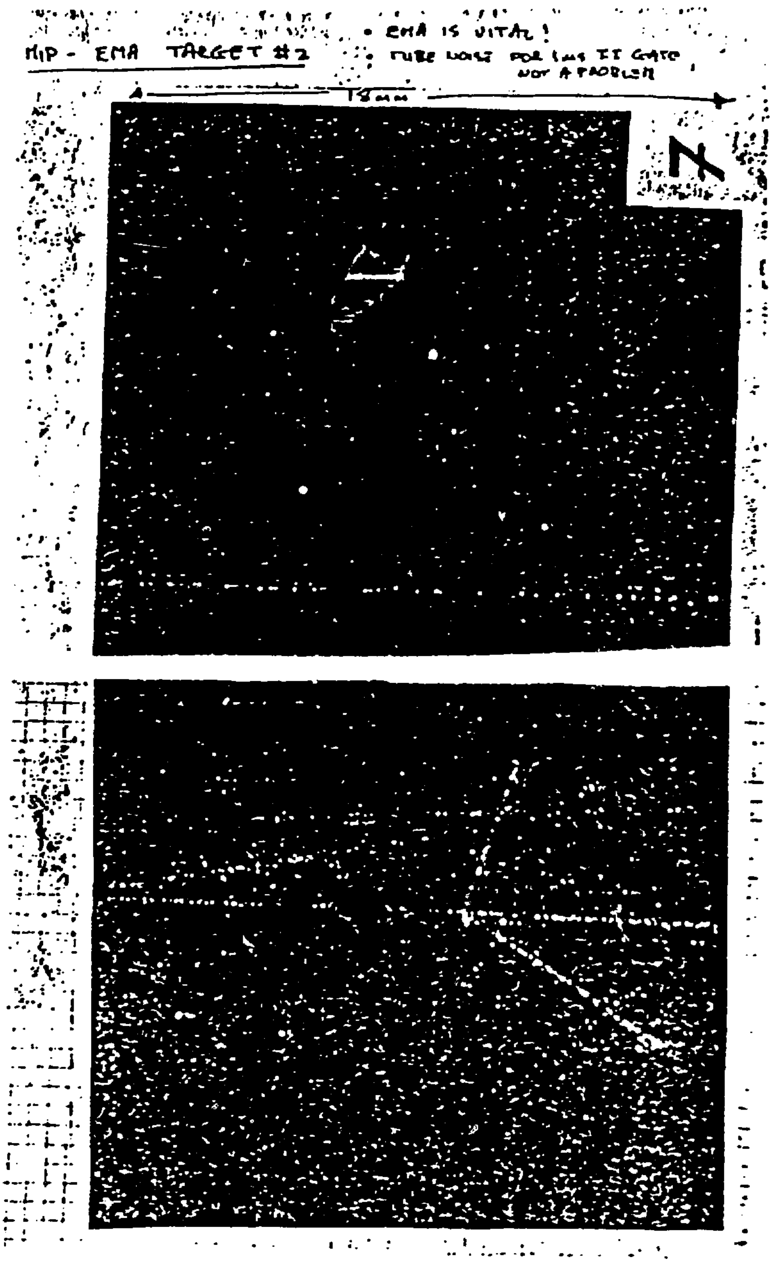

Fig. 3 Tracks and interaction recorded in a GSI target with EMA at CERN/ps test beam (Ref. 6).

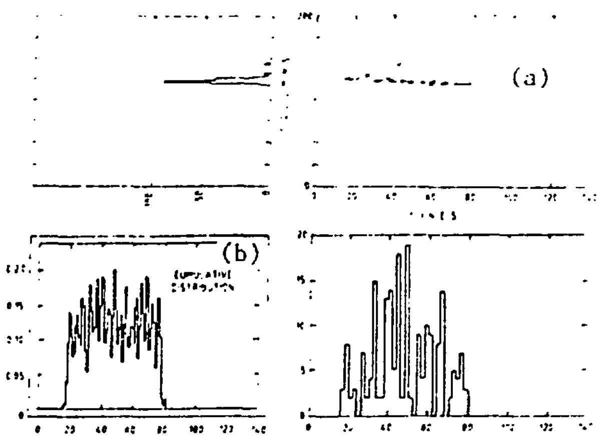

Fig. 4 CCD images of hadron tracks recorded in Saclay type polystyrene fibers of 1 mm diameter. (ref 3)

(a) Display of CCD rows and columns for a hadron track.

(b) Cumulative distribution of the charge per CCD row for ~ 100 hadrons.

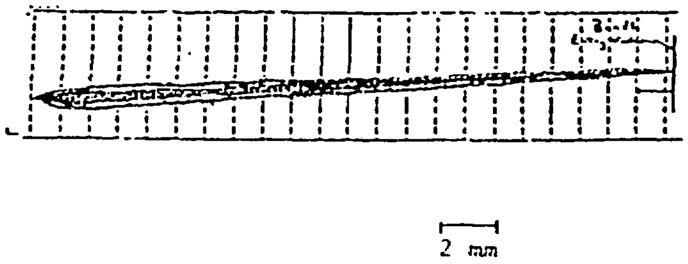

Fig. 5 Stopping Fe fragment in a bundle of polystyrene multifibers of 100 μm diameter. (ref. 4)

Table II

Comparison of Fiber Performance

Property	Glass	Plastic
Information density	6 Hits/mm (in 25 μm fibers)	12 Hits/mm (in 1 mm fibers)
X_0	1%/mm	0.25%/mm
Optical Attenuation Length	≤ 20 cm (bulk) 4-5 cm (25 μm fibers)	120 cm (in 1 mm fibers)
Decay time	50 ns	a few ns
Radiation Hardness	10^6 rad Co^{60} 1 inch length	10^6 rad Co^{60} reduces Att. Len. by factor of 2

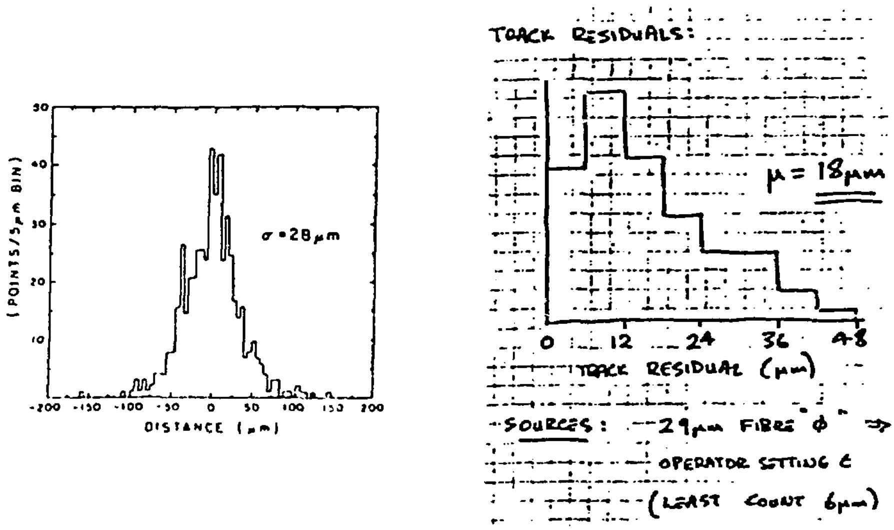

Fig. 6 Track residual distributions for GSi scintillating glass targets: left, 25 μm fibers (Ref. 1); right, 29 μm fibers (Ref. 6).

IV. CURRENT DEVELOPMENTS AND COMMENTS ON FURTHER R AND D

Plastic Fibers: A current effort in plastic scintillator development is directed toward large Stokes shift materials - those with minimal self- absorption. This feature is important for two reasons: first, the fiber diameter might be reduced (hopefully) to dimensions comparable to those of glass fibers ~25μm; second, the attenuation length in the material might be extended to several meters. Several candidate materials have been identified, one of which is 3-Hydroxyflavone (3-HF). A. Bross and W.R. Binns are pursuing this.[2,4] Additionally, efforts are underway by the Saclay group to produce plastic multifibers containing constituent fibers of small cross section with good light transmission properties using conventional materials.[3]

Glass Fibers: New efforts on Cerium glass scintillator development are directed toward the elimination of Cerium (4+) from the glass to provide significant improvement in light transmission (J. Kirkby et al[4]) and in variation of the host glass composition from silicate to germanate and aluminate glasses (R. Ruchti, A. Rogers et al[1]). These groups are attempting to produce significant improvements in attenuation length for Cerium(3+) based glasses. Further efforts are directed toward other scintillation materials including Bismuth and Praesodymium in glass hosts (R. Ruchti, A. Rogers et al[1]).

Liquid Capillaries: An effort is underway to develop efficient, high-index liquid scintillators for use in glass capillary arrays. Such devices are useful for active targets, and if a long attenuation length can be demonstrated, they might also be useful for collider detectors (D. Potter[5]).

General R and D: Once the optimization of the basic scintillators takes place, suitable cladding materials have to be identified, and industrial expertise enlisted to produce high-quality fiber-optic guides. Additionally, extensive development of image intensifiers (including efficient photocathodes and fast phosphor screens) and fast readout CCD cameras should be undertaken in conjunction with industry.

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