Development of scintillating fiber detector technology for high rate particle tracking

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Abstract

The performance of a scintillating fiber detector prototype for tracking under high rate conditions is investigated. A spatial resolution of about 100 \( \mu \text{m} \) is aimed for the detector. Further demands are low occupancy and radiation hardness up to 1 Mrad/year. Fibers with different radii and different wavelengths of the scintillation light from different producers have been extensively tested concerning light output, attenuation length and radiation hardness, with and without coupling them to light guides of different length and diameter.

In a test run at a 3 GeV electron beam the space dependent efficiency and spatial resolution of fiber bundles were measured by means of two external reference detectors with a precision of 50 \( \mu \text{m} \). The light output profile across fiber roads has been determined with the same accuracy.

Different technologies were adopted for the construction of tracker modules consisting of 14 layers of 0.5 mm fibers and 0.7 mm pitch. A winding technology provides reliable results to produce later fiber modules of about 25\( \times \)25 cm\(^2\) area.

We conclude that on the basis of these results a fiber tracker for high rate conditions can be built.

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1 Introduction

The use of scintillating fiber detectors has some advantages compared to other detector principles in terms of spatial and time resolution, robustness of the detector, match to different shapes, radiation hardness, etc. [1]. Examples for the advantageous use of fiber detectors under very different conditions are the D0 experiment, CHORUS [2] and the H1 Forward Proton Spectrometer [3].

The fiber detector under discussion is aimed to be a tracking device, with time characteristics according to the bunch crossing time of the accelerator of 96 ns. The spatial resolution is required to be about 100 µm. The fiber detector should be of such a granularity, that an occupancy of a few percent is reached. The structure and readout of the detector has to be constructed in such a way, that up to four events per bunch crossing can be registered with an overall charged particles multiplicity of more than 100. The scintillating fibers should not change their characteristics significantly after an irradiation of 1÷2 Mrad. All these demands and the solutions presented below match to a possible application of the fiber detector as the inner tracker in the HERA-B project at DESY [4]. The fiber detector would consist of 48 one-dimensional detector planes, some of them operating in a magnetic field of about 0.8 T. A plane consists of four quadrants of 25×25 cm² each. The available space and the magnetic field conditions demand the light collection from the scintillating fibers by means of light guides of a length of about 2÷3 m. The readout of the scintillating fiber detector is assumed to be realized by multichannel photomultipliers (PSPM) of Hamamatsu® type R5900-00-M64 with 64 pixels per device. This photomultiplier is still under development, only a few prototype examples exist. The characteristics are similar to the 16 pixel devices used for our investigations. The test and characteristics of this PSPM are not more subject of this paper.

In chapter 2 the optical properties (light yield, attenuation length and coupling efficiency) and radiation hardness of various fiber materials are discussed.
In chapter 3 the results obtained for fiber detector prototypes in a test run at a 3 GeV electron-beam are presented. For different fiber bundels efficiency and spatial resolution were determined by means of reference detectors.
The development of the technology for the large scale production of fiber detectors is described in chapter 4.

2 Choice of fiber material

2.1 Optical characteristics

Method

All measurements were performed with standardized fiber samples of 30 cm length and a cross section of 2×2 mm² independent of the fiber diameter, which varies between 0.25 mm

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5Hamamatsu Photonics K.K., Electron Tube Division, 314-5, Shimokanzo, Toyooka Village, Iwata-gun, Shizuoka-ken, Japan
and 0.50 mm. Fibers of three producers (BICRON, KURARAY, Pol.Hi.Tech) were investigated, whereby the wavelength of the emitted scintillation light covered the blue and green spectral regions. All investigated fibers have a double cladding, which leads to an increased light trapping efficiency. The sample was connected to two Philips photomultipliers (PMS) XP2020, S1 and S2. Below the fiber sample a scintillator (5 mm thick and 10 mm width) was installed. It was read out by two PMs Philips XP1911, T1 and T2, from each side. The sample was exposed to a $^{106}$Ru source. A collimator with variable slit width was mounted between source and fiber sample. The amplitude spectra were measured by an ADC, if a trigger signal occurred, derived from a coincidence between S2, T1 and T2. The setup was calibrated so that the number of photo-electrons (pe) could be estimated. The results are related to the bialkaline photo-cathode of the PM XP2020 which is similar to the bialkaline photo-cathode of the multi-channel PM forseen for later application.

**Light yield**

The results for a sub-sample of fiber materials of 0.5 mm diameter are shown in Fig.1. Generally, it is seen that the light yield decreases with increasing scintillator emission wavelength because the PM’s sensitivity curve is not unfolded. There is no remarkable difference between the best materials of the three producers and the light yield is typically 4.5 pe per 1 mm scintillator.

| Producer    | Material          |
|-------------|-------------------|
| BICRON      | BCF 12            |
| KURARAY     | SCSF-78M          |
| Pol.Hi.Tech | POLIFI 1242A and B|

The application of a mirror on one side of the fiber sample increases the light yield by a factor of 1.7. The light yield decreases with decreasing fiber diameter by 10÷40 percent for diameters of 0.5 mm compared to 0.25 mm.

**Attenuation in clear fibers**

The measurement of the attenuation length of clear fibers is done with the setup previously described. A scintillating fiber sample of known light yield is used. The clear fiber is coupled to the fiber sample by a standardized coupling mask. The measurements were performed for clear fibers of different diameters (1.0 mm...1.7 mm) from the three producers. The results are shown in Fig.2. No strong dependence on fiber diameter and wavelength is seen. The fibers from KURARAY show the best attenuation length for all diameters.

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6BICRON, 12345 Kinsman Road, Newbury, Ohio, USA
7KURARAY Co. LTD., Nikonbashi, Chuo-ku, Tokyo 103, Japan
8Pol.Hi.Tech., s.r.l., S.P.Turanense, 67061 Carsoli(AQ), Italy
9Philips Photonique, Av. Roger Roncier, B.P.520, 19106 Brive, France
Coupling of scintillating fibers and clear fibers

Several tests were performed to couple scintillating and light guide fibers. After an optimization of the coupling pieces the coupling efficiency became better than 95% independent on the medium between both fibers (air, glue, optical grease).

2.2 Radiation hardness

Radiation hardness tests were performed depositing doses of about 1 Mrad on scintillating fiber samples in a few minutes. The fiber samples are similar to those described above (see chapter 2.1).

Irradiations were performed in a 70 MeV energy proton beam at the VICKSY accelerator of the Hahn-Meitner Institute, Berlin. The beam leaves the beam tube through a scatter foil, passes a 380 mm air gap and two diaphragms of 30 mm and 50 mm thick PMMA shaping a radiation field of 2 mm × 10 mm on the fiber sample. The accumulated dose is measured by an ionization chamber behind the sample.

Different scintillating fiber materials of the three producers mentioned above were irradiated. The influence of using glue in the sample production on the radiation hardness was also studied. The scintillating fiber samples were irradiated as follows:

- Spot-like irradiation.

The scintillating fiber samples were irradiated at two places along the fiber, 10 cm
Figure 2: Attenuation length for clear fibers (diameters: 1.0 mm, 1.5 mm, 1.7 mm) produced by KURARAY, Pol.Hi.Tech. and BICRON.

from the fiber ends. The accumulated doses have been 1÷1.4 Mrad and 0.2÷0.4 Mrad at the two positions, respectively.

- Profile-like irradiation.
  Along the scintillating fiber sample the accumulated radiation dose was decreased from 1 Mrad to 0.2 Mrad.

The light output was measured before and after the irradiation (for several weeks) at different points of the irradiated sample so that the influence of high and low dose could be distinguished. Also the measurement positions are chosen such, that the damage of scintillator efficiency and/or plastic matrix (light transmission) can be disentangled.

**Results**

The results are given in table [I]. For most of the materials the scintillator efficiency decreases by 20÷80 percent just after the irradiation; the decrease in light transmission varied from 20 to 70 percent compared to the initial value.
For four materials from Pol.Hi.Tech. only transmission is damaged. For nearly all materials a strong recovery process is seen. It takes from 80 to 600 hours to recover the light yield and transmission to a level of at least 90%. No significant influence of the glue on damage and recovery is observed. Fig. 3 shows the behaviour of two samples for several hundred hours after irradiation.

![Graph showing the evolution of light output](image)

Figure 3: Evolution in time of the light output for point-like irradiated KURARAY SCSF scintillating fibers. The solid, dashed and dotted curves correspond to measurements with the source placed at 10, 20 and 25 cm with respect to S1, respectively.

### 3 Results of test run in an electron-beam

Small-scale fiber detector prototypes were exposed in an 3 GeV e-beam at DESY in order to measure:

- the efficiency and resolution
- the light output across the fibers.

Here, a detector geometry is defined which is the basis for all further investigations. The fiber detectors are assumed to be constructed of 14 layers of 0.5 mm scintillating fibers.
The fibers are arranged with a pitch of $700 \mu m$ in the layers. The layers are staggered to each other by $350 \mu m$. The seven scintillating fibers with the same coordinate form a "road" and are coupled to one light guide fiber of $1.7 mm$ diameter.

The fiber samples used in the test run are based on this geometry defined for the final detector. Fig.4 shows a schematic cross section through the fiber bundle exposed in the test beam. It consists of 8 roads with 7 fibers per road. The diameter of fibers is $0.5 mm$. The nominal pitch in one layer amounts to $700 \mu m$.

![Figure 4: Schematic cross section of the exposed fiber bundle](image)

Figure 4: Schematic cross section of the exposed fiber bundle

The setup of the beam tests is sketched in fig.5. A similar setup was described in more detail in [5]. It consists of a trigger system, two external reference detectors and the fiber sample itself. The scintillation light is collected via $3 m$ long light guide fibers.

![Figure 5: Setup of the test-beam exposure; T1...T4: Trigger counters, T5...T6: Planes of the fiber reference detector included in the trigger, P1...P4: Planes of the Si-strip telescope, TS: Fiber sample under test](image)

Figure 5: Setup of the test-beam exposure; T1...T4: Trigger counters, T5...T6: Planes of the fiber reference detector included in the trigger, P1...P4: Planes of the Si-strip telescope, TS: Fiber sample under test
The reference detectors are a scintillating fiber detector consisting of two planes (T5,T6) giving an accuracy of 170 $\mu$m for through-going tracks and a Silicon micro-strip telescope (P1÷P4). For the Si-telescope a track residual of 52 $\mu$m was measured as shown in Fig.6.

![Figure 6: Track residual of the Si-strip telescope](image)

**Results**

The mean light output for roads of 7 fibers readout via 3 m long light guide fibers was measured to be 6.2 photo-electrons.

The "light profile", i.e. the light output across the fiber road is shown in Fig.7. It follows the expected dE/dx behaviour for the realized fiber geometry.

The efficiency for all roads plotted in Fig.8 shows a flat distribution with a mean value of 98 percent.

The spatial resolution was measured to be 121 $\mu$m (Fig.8) by the reference detectors unfolding the accuracy of 52 $\mu$m of the Si-telescope.

4 Development of fiber detector technology

Different technologies are tested to find the best way to produce the fiber detector modules:

- A winding technology as it was used for the production of the CHORUS tracker [6].
- A mounting technology of single layers based on a proposal from the Heidelberg University [7]. A prototype is produced by GMS[10].

[10]GMS - Gesellschaft für Meß-und Systemtechnik mbH, Rudower Chaussee 5, 12489 Berlin, Germany
• A technology developed by KURARAY were also a prototype is produced.

Using these methods several prototypes are partially still under construction and could not be investigated up to now in detail. This will be done however in a forthcoming testrun at DESY.

The winding technology was investigated in more detail in our lab. A construction setup was manufactured and tested. The principle of the winding technology is based on a layer-by-layer increase of the mechanical tension of the fiber to receive a flat detector after removing the ribbon from the winding drum. The results are encouraging; flat ribbons with a good accuracy can be produced.

5 Conclusions

Based on the investigations presented above we conclude, that a radiation hard fiber detector for high rate conditions fulfilling the demands on efficiency, time and spatial resolutions can be realized.

Extensive investigations resulted in a material choice, which gives a light yield of 4.5 pe/mm and radiation hardness of at least 1 Mrad for the material SCSF-78M.

In the exposure of test detector samples to an electron beam a spatial resolution of 121 µm is measured. The efficiency is constant across the detector and amounts to about 98%.

The time delay and jitter resulting from the effects of light collection in fibers and readout via multi-channel PMs are of the order of a few nanoseconds not considering readout electronics.
Different technologies for the production of the fiber modules are tested. The comparison of the technologies is still going on. We conclude, that the construction of fiber detectors for high rate conditions on the basis of these investigations seems to be possible.

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Figure 9: Efficiency distribution of the fiber sample

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| Material   | $\lambda$(SF) | Specialties | Irradiation | Dose at 10 - 20 cm | Damage (%) at 10 - 20 - 25 cm | Recovery to 90 % | Result                  |
|------------|---------------|-------------|-------------|-------------------|-------------------------------|------------------|------------------------|
| BCF-12     | 430           | glue        | spot        | 0.4 / 1.4 Mrad    | 72 - 82 - 60                  | 600 h            | T and S damaged        |
| BCF-12     | 430           | no glue     | spot        | 0.4 / 1.4 Mrad    | 62 - 62 - 68                  | 600 h            | T and S damaged        |
| BCF-60     | 530           | glue        | spot        | 0.4 / 1.4 Mrad    | 58 - 76 - 60                  | 600 h            | T and S damaged        |
| BCF-60     | 530           | no glue     | spot        | 0.4 / 1.4 Mrad    | 63 - 45 - 49                  | > 600 h          | T and S damaged        |
| BCF-12     | 430           | glue        | profile     | 0.2 - 1.0 Mrad    | 82 - 77 - 82                  | 160 h            | T and S slightly damaged |
| BCF-60     | 530           | glue        | profile     | 0.2 - 1.0 Mrad    | 95 - 89 - 89                  | 160 h            | T and S slightly damaged |
| 0042-2-0975| 430           | glue        | spot        | 0.4 / 1.4 Mrad    | 79 - 89 - 89                  | 400 h            | T and S slightly damaged |
| 0042-2-0975| 430           | no glue     | spot        | 0.4 / 1.4 Mrad    | 70 - 100 - 85                 | 400 h            | T and S slightly damaged |
| 1242 A     | 420           | glue        | spot        | 0.2 / 1.4 Mrad    | 99 - 73 - 62                  | > 180 h          | mainly T damaged       |
| 0246 B     | 460           | glue        | spot        | 0.2 / 1.4 Mrad    | 100 - 99 - 94                 | 0 h              | no damage at all       |
| 0248 C     | 480           | glue        | spot        | 0.2 / 1.4 Mrad    | 100 - 93 - 89                 | 150 h            | mainly T damaged       |
| 1242 B     | 420           | glue        | profile     | 0.2 - 1.2 Mrad    | 100 - 52 - 27                 | > 160 h 100 - 48 - 47 | mainly T damaged     |
| 1246 B     | 460           | glue        | profile     | 0.2 - 1.2 Mrad    | 100 - 99 - 83                 | 160 h            | mainly T damaged       |
| SCSF-81M   | 430           | glue        | spot        | 0.4 / 1.4 Mrad    | 70 - 83 - 77                  | 600 h            | T and S damaged        |
| SCSF-81M   | 430           | no glue     | spot        | 0.4 / 1.4 Mrad    | 80 - 78 - 100                 | 400 h            | S damaged              |
| SCSF-78M   | 430           | glue        | spot        | 0.2 / 1.4 Mrad    | 72 - 33 - 74                  | 80 h             | T and S damaged        |
| PMP-450    | 450           | glue        | spot        | 0.2 / 1.4 Mrad    | 100 - 100 - 100               | 0 h              | no damage at all       |
| 3HF        | 530           | glue        | spot        | 0.2 / 1.4 Mrad    | 100 - 100 - 100               | 0 h              | no damage at all       |
| SCSF-78M   | 430           | glue        | profile     | 0.2 - 1.2 Mrad    | 94 - 89 - 84                  | 180 h            | T and S damaged        |
| PMP-450    | 450           | glue        | profile     | 0.2 - 1.2 Mrad    | 95 - 79 - 76                  | 180 h            | T and S damaged        |
| 3HF        | 530           | glue        | profile     | 0.2 - 1.2 Mrad    | 100 - 100 - 100               | 0 h              | no damage at all       |

Table 1: Results on the proton irradiation damage to the different scintillating fiber materials.