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A high-resolution scintillating fiber tracker with silicon photomultiplier array readout

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ABSTRACT

We present prototype modules for a tracking detector consisting of multiple layers of 0.25 mm diameter scintillating fibers that are read out by linear arrays of silicon photomultipliers. The module production process is described and measurements of the key properties for both the fibers and the readout devices are shown. Five modules have been subjected to a 12 GeV/*c* proton/pion testbeam at CERN. A spatial resolution of 50 μm and light yields exceeding 20 detected photons per minimum ionizing particle have been achieved, at a tracking efficiency of more than 98.5%. Possible techniques for further improvement of the spatial resolution are discussed.

1. Introduction

Scintillating fiber trackers [1] have been realized for a number of experiments such as UA2 [2], DØ [3], MICE [4], CHORUS [5] and K2K [6]. Of these, the DØ Central Fiber Tracker has achieved the best resolution of about 0.1 mm using double layers of 0.835 mm thin fibers read out by Visible Light Photon Counters (VLPCs) [7]. VLPCs offer single-photon resolution due to a high internal gain of about 10^4 and are linear up to hundreds of photons. The main drawback of VLPCs is that they have to be operated at cryogenic temperatures which introduces a significant overhead into the operation of scintillating fiber trackers as used in the DØ and MICE experiments. The CHORUS fiber tracker achieves a spatial resolution of 0.185 mm for a single ribbon of seven layers of 0.5 mm thin scintillating fibers and uses CCD cameras instead of VLPCs for readout, as does the K2K scintillating fiber tracker. CCD cameras require image intensifiers to detect the few tens of photons that thin scintillating fibers emit for a minimum ionizing particle. Image intensifiers and photomultipliers are sensitive to magnetic fields and require operating voltages of a few thousand volts.

A new type of scintillating fiber tracker has become possible with the advent of silicon photomultipliers [8–13] (SiPMs) as a viable alternative for the commonly used photon detectors. SiPMs like VLPCs have a high intrinsic gain of 10^5–10^6 but can be operated at room temperature. Furthermore, they are insensitive to magnetic fields and are operated at voltages of 20–80 V. Another key feature of SiPMs are their compact dimensions. This allows the design of detector modules that have almost no dead area if integrated SiPMs are used as photon detectors.

In this article, we describe the design of a new tracking device aiming at the detection of charged particles with an efficiency above 98.5% and a spatial resolution of 0.05 mm. It consists of modules made of ribbons of 0.25 mm diameter scintillating fibers that are read out by silicon photomultiplier arrays. After an overview of the tracker and module design, the process of module production as well as the optical hybrid used for readout are described in Section 2. Sections 3 and 4 deal with the scintillating fibers and silicon photomultiplier arrays employed, respectively. Finally, the performance of several prototype modules as determined in a testbeam at CERN is evaluated in Section 5. Possible future improvements are discussed in Section 6.

2. Tracker layout

2.1. Tracker and module design

The tracker described here is being developed for use in the PEBS [14] balloon-borne detector. It consists of layers made up from modules like the one depicted in Fig. 1. Charged particles traversing the module deposit energy in two ribbons of scintillating fibers that are located at the top and bottom of the

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module, creating scintillation photons. A small fraction of the scintillation light is then guided by total internal reflection to the fiber ends where it is detected by silicon photomultiplier arrays. Each module thus allows two independent measurements of the intersection point of a trajectory. The modules are Z-shaped which allows for them to be placed closely next to each other, so that there are no gaps in a tracker layer. The overlap between the modules allows for internal alignment with tracks within one layer. Each module consists of a mechanical support made up from low-density (50 kg/m^3) Rohacell foam between two thin (0.1 mm) carbon fiber skins. It carries scintillating fiber ribbons that are 32 mm wide and up to 2 m long on both sides. A fiber ribbon consists of five layers of 0.25 mm thin scintillating fibers, glued together in the tightest arrangement. Each module end holds two precision pins for a controlled mounting of optical hybrids carrying four SiPM arrays each. The SiPM arrays have a 8 mm wide and 1 mm high active area and are segmented into 32 individual SiPMs with 80 pixels each, with a readout pitch of 0.25 mm, matching the diameter of the fibers. Groups of 32 fiber columns are read out by an SiPM array at alternating ends of the module. Due to the mounting of the SiPM arrays, sensors cannot be placed next to each other without a dead area of 0.25 mm between them. To minimize this dead zone, a mirror covers the space between the SiPMs in order to increase the light collection on the opposite fiber end.

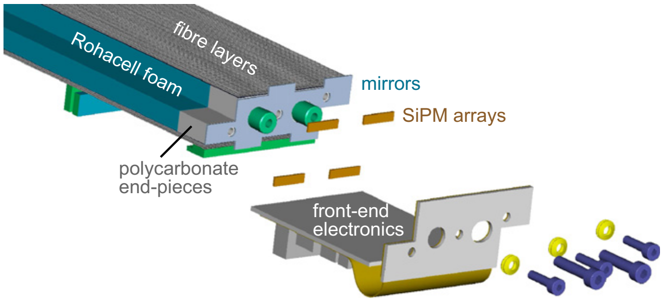

Fig. 1. Exploded view of a tracker module. Two ribbons of scintillating fibers located at the top and bottom are carried by Rohacell foam with polycarbonate end-pieces at the ends. Optical hybrids equipped with silicon photomultiplier arrays and mirrors are screwed to the sides of the module. A corresponding hybrid is mounted to the far side of the module, so that each fiber is covered by a SiPM channel on one side and a mirror on the other. The large screws will be used to mount the module to the tracker walls.

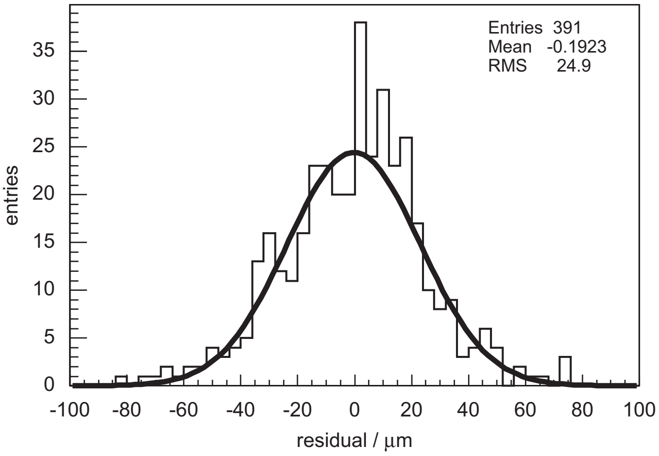

Fig. 2. Distribution of the deviation of the fiber centers from a uniform lattice with a pitch of 0.275 mm, shown here for the fibers included in the picture of Fig. 3. The black line is a Gaussian fit to the data, plotted here for illustrative purposes.

2.2. Module production

Tracker modules have been made from both Kuraray SCSF-81MJ and SCSF-78MJ fibers [15] (Section 3) with a diameter of 0.25 mm each. Ribbons of five layers of 128 fibers each are produced in a winding process similar to the one used to produce the fiber trackers for the CHORUS and K2K experiments. The scintillating fiber arrives uncut on a spool from the manufacturer. A helical groove with a pitch of 0.275 mm, to accommodate small variations in the fiber thickness, is cut into an aluminum drum on a winding machine. The diameter of the drum is a free parameter and can be adapted to the required module length. A release agent is applied to the drum prior to the ribbon production. One layer of scintillating fiber is then wound on top of the drum, with its position precisely fixed by the helical groove, using a controlled tension of 20 g and EpoTek 301M is applied as an adhesive. The fiber end is fixed with a fast curing adhesive and cut. The next fiber layer is wound on top of the first layer, so that the fiber lies in the gap between fibers of the previous layer maintaining a constant fiber pitch over the layers. This process is repeated applying an adhesive to the fibers after each completed layer until five layers of fibers have been wound on top of the drum. After the last fiber layer has been completed, two aluminum end-pieces are screwed next to each other onto the drum to ease the handling of the fiber ribbon. The drum continues to rotate at a constant speed for a few hours until the adhesive is cured. The ambient temperature for the whole process is kept at 22 °C. The fiber ribbon is then cut between the end-pieces, taken off the drum and placed in a Teflon bed that is filled up with glue and then covered by a glass plate. After the glue has fully cured, the setup with the fiber ribbon is placed in an oven heated to approximately 50 °C to allow the fiber ribbon to straighten out.

The precision of the fiber placement in the ribbons is determined by scanning the cross-section in the end-pieces to be better than 0.025 mm for a ribbon consisting of five layers of about 128 fibers each (Fig. 2). A photograph of the front of a completed ribbon, illuminated from above, is shown in Fig. 3.

Two fiber ribbons are glued to the top and bottom of a mechanical support made from a 10 mm thick Rohacell foam layer contained between two 0.1 mm thin carbon fiber skins. Polycarbonate end-pieces are embedded in the support structure to allow the mounting of the optical hybrid. The module ends are then polished to achieve a good optical coupling between the fibers and the SiPMs. Finally, optical readout hybrids carrying the SiPMs (Section 2.3) on a PCB board including the mirrors are screwed directly to the polished fiber ends on both sides of the module.

2.3. Optical hybrid and data acquisition

The fiber modules are read out by SiPM arrays of type Hamamatsu MPPC 5883 (Fig. 4). Each array consists of 32 independent SiPMs

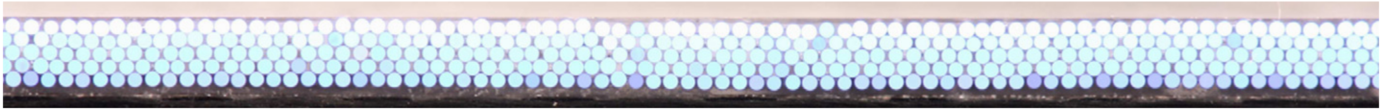

Fig. 3. Close-up photograph of a completed fiber ribbon made of Kuraray SCSF-81MJ fibers of 0.25 mm diameter. The nominal gap in the horizontal direction is 0.025 mm. Five layers of fibers are placed in the tightest arrangement. The supporting carbon fiber skin is seen at the bottom of the picture.