A high-resolution scintillating fiber tracker with SiPM array readout for cosmic-ray research

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Abstract. **A modular high-resolution scintillating fiber tracker with silicon photomultiplier (SiPM) array readout has been developed in Aachen. Next generation balloon- and space-borne cosmic-ray experiments like PEBS [1] will require measurements at high energies. Due to the low flux of e.g. positrons or antiprotons large area spectrometers are needed to gain a large acceptance. Above ground the area is mainly limited by power consumption and weight issues. Both are addressed by the tracker's light-weight compact design with an expected single point resolution of 50 µm. Extensive tests of the fibers and SiPM arrays have been performed. Additionally, a fiber module prototype has been exposed to a 10 GeV proton beam at CERN in summer 2008. Results of this testbeam and predictions for the achievable spatial resolution from Monte Carlo simulations are presented.**

Keywords**: fiber tracker, silicon photomultiplier**

I. INTRODUCTION

Several experiments like HEAT [2], [3], AMS01 [4] and recently PAMELA [5] show an unexpected rise in their cosmic-ray positron fraction data above 10 GeV. Possible explanations for this excess are a nearby pulsar or an even more exotic process – positrons could be created in the annihilation of dark matter particles. A list of references can be found in [6].
A preferred neuralino mass in the TeV [6] range calls for a measurement providing charge separation up to 2 TeV and a high acceptance of $3000\,\mathrm{cm^2 sr}$ to deal with the steep falling spectrum of cosmic-ray positrons. This is addressed by the PEBS-2 experiment [1].

The PEBS-2 spectrometer (Fig. 1) will consist of two superconducting Helmholtz-like coils providing a mean magnetic field of 0.8 T inside the magnet volume of roughly $90 \times 90 \times 100\,\mathrm{cm^3}$. Three silicon strip detector double layers will be placed at the top, middle and bottom of the inner volume with a single point resolution of $10\,\mathrm{\mu m}$ in the bending plane. Additionally, a double layer scintillating fiber (Sci/Fi) tracker with a single point resolution of $50\,\mathrm{\mu m}$ per layer is planned above the volume. In this configuration the angle of deflection can be calculated and thus the momentum. The layer is 1.2 m away from the inner part to gain resolution with lever arm. A momentum resolution of $\sigma_p/p = 1.8\,\%$ at

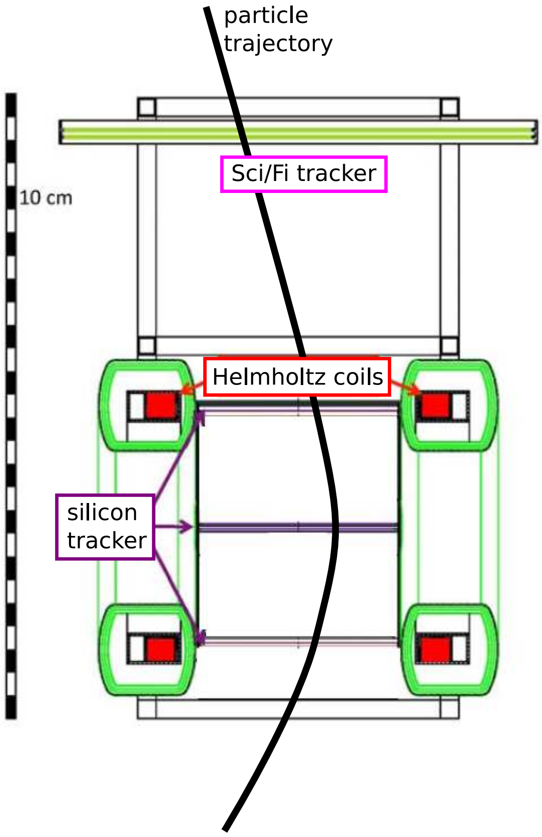

Fig. 1. Drawing of the PEBS-2 spectrometer.

100 GeV can be achieved and meets the requirements mentioned.

II. SCI/FI TRACKER DESIGN

The outer Sci/Fi tracker layer has to have a dimension of $2 \times 2\,\mathrm{m^2}$ to match the acceptance of the inner detector components. It is made up from 2 m long modules such that the whole area is sensitive.

A fiber module (Fig. 2) consists of a carbon fiber/Rohacell foam structure sandwiched between two super layers of fibers, each being 35 mm and 128 fibers wide. Each super layer is constructed from 5 fiber layers of round, scintillating fibers of $250\,\mathrm{\mu m}$ diameter glued together in the tightest arrangement. Linear arrays containing 32 silicon photomultiplier columns each are located at alternating ends of the fiber bundles. A reflective coating to increase the light yield by a factor

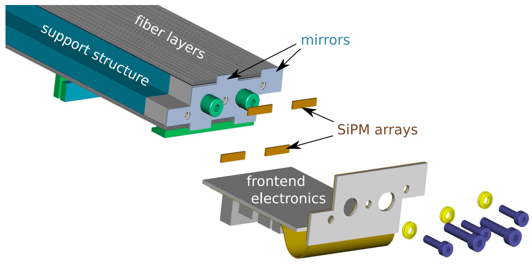

Fig. 2. Exploded drawing of a Sci/Fi tracker module.

of roughly 1.6 covers the opposite end of each fiber. Five fibers in one column are then optically connected to one SiPM column. The weighted cluster mean from amplitudes in adjacent SiPM columns is calculated to pinpoint the intersection of a trajectory with a fiber module.

The fiber layers are produced by winding the fibers on a drum with a helix-shaped groove and a diameter of the fiber module length. Before the production the diameter of the fiber has been measured to be $(250 \pm 10_{\mathrm{rms}})\,\mu\mathrm{m}$. Each cycle the groove has an advance of $275\,\mu\mathrm{m}$. Thus, the fibers are placed in this distance with a mean glue gap of 25 µm. After the first layer is wounded the other layers are wounded on top successively adding glue. After the glue has hardened, the fibers are cut perpendicular to the fibers resulting in a flat fiber bundle which is glued to the support structure. With this procedure the fibers are placed with an accuracy of $20\,\mu\mathrm{m}$, confirmed by optical measurements.

III. SiPM ARRAYS

SiPMs have the virtue of being compact and insensitive to magnetic fields. This allows them to be used inside a particle spectrometer. SiPMs are parallel connected avalanche photo diodes operated above their breakdown voltage arranged in pixels. A photon hitting the surface of an SiPM can cause a pixel to discharge in an avalanche process. The number of pixels fired is approximately proportional to the number of incoming photons with the photon detection efficiency (PDE) as proportionality factor. High photon fluxes compared to the number of available pixels lead to saturation effects and thus a deviation from the proportionality. Additionally, photons produced in the avalanche process can cause neighboring pixels to fire (crosstalk). A more detailed explanation of the operation principles and properties of SiPMs can be found in [8].

In a space- and balloon-borne experiment the temperature of the SiPMs will vary. This causes the breakdown voltage U_0 to change according to

$$U_0(T) = \frac{\mathrm{d}U_0}{\mathrm{d}T}(T - T_0) + U_0(T_0),$$

where T denotes the temperature and T_0 is some reference temperature. Correcting for these variations maintaining a constant overvoltage $\Delta U = U - U_0$ the gain, photon detection efficiency and crosstalk probability were found to be constant.

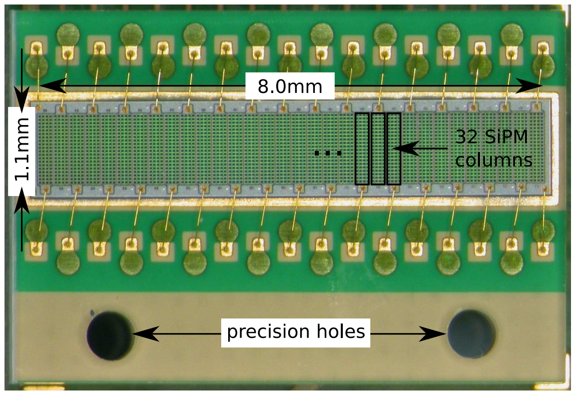

Fig. 3. Microscope picture of a 32 channel Hamamatsu MPPC 5883.

Hamamatsu MPPC 5883 devices (Fig. 3) were specially developed for the readout of the fiber tracker modules. They consist of 32 independent 250 µm wide and 1.1 mm high SiPM channels with a peak sensitivity at 450 nm meeting the peak emission wavelength of the Kuraray SCSF-81M scintillating fibers used. Each channel consists of 4×20 pixels with a size of $50 \times 50\,\mu\mathrm{m}^2$. They have precision holes that allow the sensitive area of the array to be mounted to the fiber module with an accuracy of $\pm 20\,\mu\mathrm{m}$. The 80 pixels guarantee for enough dynamic range for singly charged particles. The devices are equipped with an 250 µm thick epoxy layer to protect the silicon.

48 devices have been tested showing a high homogeneity of their key properties breakdown voltage, gain, photon-detection efficiency, crosstalk and noise over their 32 channels.

The gain is approximately linear with the applied voltage U. Measuring the gain as a function of the bias voltage, the breakdown voltage U_0 of the SiPM channels is determined extrapolating the gain down to 0 ADC counts. The RMS of U_0 over an array is typically 0.03 V. In the 48 device sample, the mean breakdown voltages $\bar{U_0}$ have a value of roughly 69 V with a tolerance of ± 1 V. Thus, every SiPM array has to be biased with an individual voltage, but all 32 array channels can be provided with the same voltage, which greatly simplifies the electronics.

In Fig. 4 the homogeneous response of the SiPM array channels is demonstrated. An array is illuminated with short LED pulses. The resulting spectra are plotted on the x- and z-axis for each channel (y-axis). Additionally, the center of gravity of the photoelectron peaks are marked with black triangles showing the homogeneous response with a gain variation of 1 %.

The photondetection efficiency measured comparing the response of a calibrated photomultiplier tube to that of the MPPC 5883 reaches a value of $\sim 40\,\%$ at 440 nm, comparable to the specification from Hamamatsu.

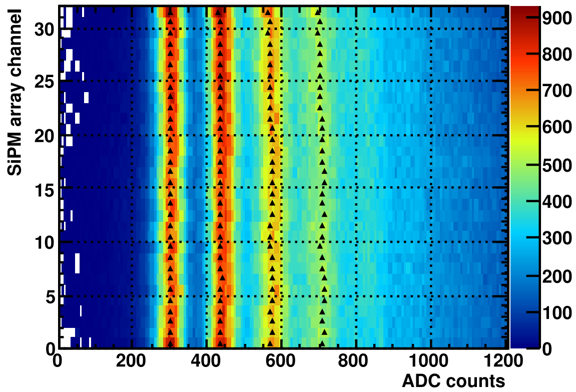

Fig. 4. LED spectra of a 32 channel Hamamatsu MPPC 5883. The center of gravity of the first photoelectron peaks is marked with black triangles.

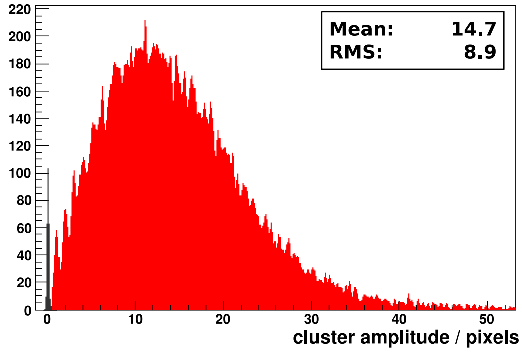

Fig. 5. Stacked signal distribution of an SiPM array exposed to minimally ionizing particles.

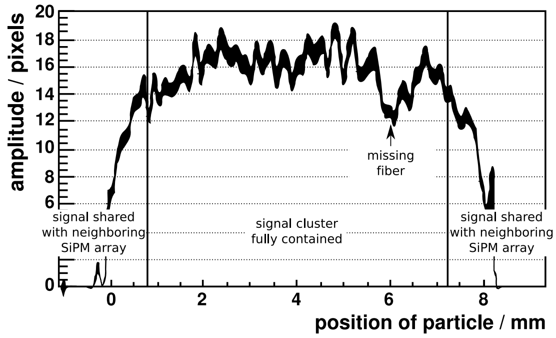

Fig. 6. Light yield along an SiPM array.

IV. TESTBEAM MEASUREMENTS

A 10 GeV proton beam provided by the T9 beamline at CERN was used to test a fiber module prototype similar to the design in Fig. 2 in summer 2008. Two trigger scintillators, a veto scintillator and two AMS02 silicon ladders serving as a beam telescope were mounted to an aluminum frame. The tested Sci/Fi tracker module was held inside the beam telescope which had a spatial resolution of 30 µm perpendicular to the fiber direction at the module position. The intrinsic resolution of the AMS02 silicon detector is 10 µm [9]. Due to multiple scattering and the limited mounting accuracy in the testbeam the effective resolution is here only 30 µm.The whole setup was hermetically closed on all sides to remove any ambient light.

A frontend electronics board based on VA_32/75 chips produced by IDEAS [10], Norway, has been developed to read out the SiPM array channels. Both the beam telescope and the SiPM frontend electronics were read out by AMS02 tracker electronics.

The particle position at the fiber module is calculated from the beam telescope such that it is known which fibers on the tracker module were hit. The signal of the corresponding SiPM array channels is summed and histogrammed to determine the signal distribution.

In Fig. 5 all those 32 spectra are stacked. A mean light yield of 14.7 fired pixels is measured. This number is enhanced by pixel crosstalk effects. Correcting for these effects leads to a value of 10 photoelectrons per minimally ionizing particle.

In Fig. 6 the mean number of pixels fired is plotted versus the fiber position. The response is quite homogeneous except for the edges, where light leaves the fibers with no SiPM array channels to detect. Also around 6 mm less light is detected. In a later visual inspection it was found that a fiber was missing in the fiber bundle at the corresponding position.

The track residuals calculated from the beam telescope and weighted cluster mean taken from the SiPM responses are histogrammed in Fig. 7. The resulting cluster residual histogram shows a Gaussian center with a width of 80 µm and small non-Gaussian tails. Quadratically subtracting the resolution of the beam telescope results in a spatial resolution of 73 µm at a tracking efficiency above 99 %.

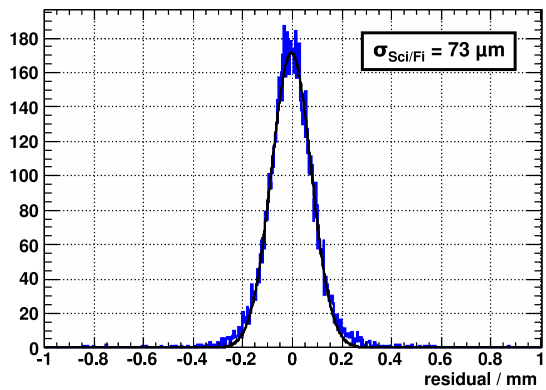

Fig. 7. Spatial resolution of the tested tracker module at 99 % efficiency.

This resolution includes events with a cluster width above three strips due to crosstalk between array columns which appears at very high overvoltages. This can be seen in Fig. 8 where the spatial resolution is plotted versus the cluster length.

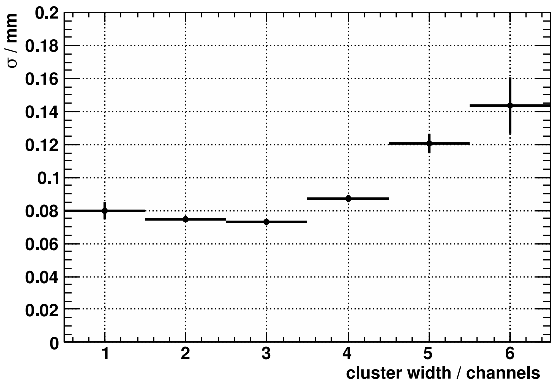

Fig. 8. Spatial resolution as a function of the cluster width.

In a detailed simulation of all relevant parameters of the testbeam setup, including the fiber misplacement measured beforehand, the scintillation process, the SiPM crosstalk, noise, pulse shapes and the whole digitization the results could be reproduced. Especially parameters like the PDE and crosstalk depend on the applied overvoltage and influence the spatial resolution. All those parameters are parametrized according to the characterization measurements outlined above and fed into the simulation. From this the optimal operation overvoltage is calculated to be $\sim$ 1.7 V (Fig. 9). Unfortunately, the SiPM array was operated at too high an overvoltage of 2.7 V during the testbeam which resulted in high crosstalk probabilities between array strips and thus larger cluster widths.

Due to the epoxy layer on the SiPM array the fibers are 250 µm away from the actual detector. This causes the light cone leaving the fibers to overlap several SiPM columns and additionally worsens the spatial resolution. The thickness of the epoxy layer can be varied in the simulation and it is found that reducing the thickness the cluster widths of the signals can be reduced. For the next production Hamamatsu will reduce the epoxy layer thickness to 100 µm, which will lead to a spatial resolution of $\sim 50\,\mu\mathrm{m}$ according to the simulation at the optimal operation voltage (Fig. 9). An additional increase in light yield by 40 % is expected due to an optimized mirror on one end of the fiber module and the use of Kuraray SCSF 78M scintillating fibers. All means together should allow a reliable operation with an average resolution $\leq 50\,\mu\mathrm{m}$.

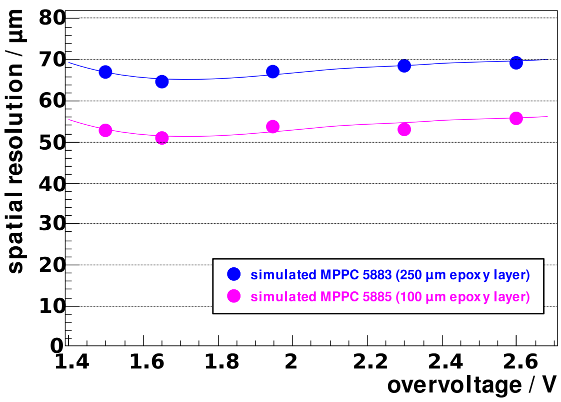

Fig. 9. Expected spatial resolution as a function of the overvoltage for a Hamamatsu MPPC 5883 and for a planned device with a reduced epoxy layer thickness.

V. CONCLUSION

A scintillating fiber tracker with silicon photomultiplier readout can be used in large dimension spectrometers for future cosmic-ray experiments like PEBS. In a testbeam in 2008, a single point resolution of 70 µm at more than 99 % efficiency has already been reached. A resolution of 50 µm is feasible with small improvements of the SiPM readout devices and the fiber module construction. In a testbeam in November 2009, six complete modules will be tested with those modifications.

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