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A Spiral Fiber Tracker for the J-PARC E36 experiment

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A Spiral Fiber Tracker (SFT) has been developed for use in the E36 experiment at the Japan Proton Accelerator Research Complex (J-PARC). The SFT is designed for conducting high-precision momentum measurement of charge particles from kaon decays and consists of four layers of flat ribbons made of 1 mm diameter plastic scintillating fibers. The ribbons are spirally wound around the kaon stopping target at the center of the detector setup, a single ribbon per layer. A total of 64 fibers are read out by 128 HAMAMATSU MPPCs connected to the scintillating fibers at both ends by clear fiber extensions. The SFT started to collect beam data in the spring of 2015.

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1. Introduction

The TREK/E36 experiment [1] is currently being performed at the Proton Synchrotron of the Japan Proton Accelerator Research Complex (J-PARC) in Tokai, Japan. The primary physics goal of the experiment is the precise measurement of $\Gamma(K^+ \to e^+\nu)/\Gamma(K^+ \to \mu^+\nu)$ using two leptonic decay modes of stopped positive kaons. The Standard Model (SM) prediction for the value of the decay widths ratio is highly precise and a deviation from this value would clearly indicate a violation of lepton universality and the existence of New Physics beyond the SM.

Schematic cross-sectional side and end views of the E36 detector system are shown in Fig. 1. E36 experiment utilizes a 800 MeV/c K^+ beam stopped in an active target made of scintillating

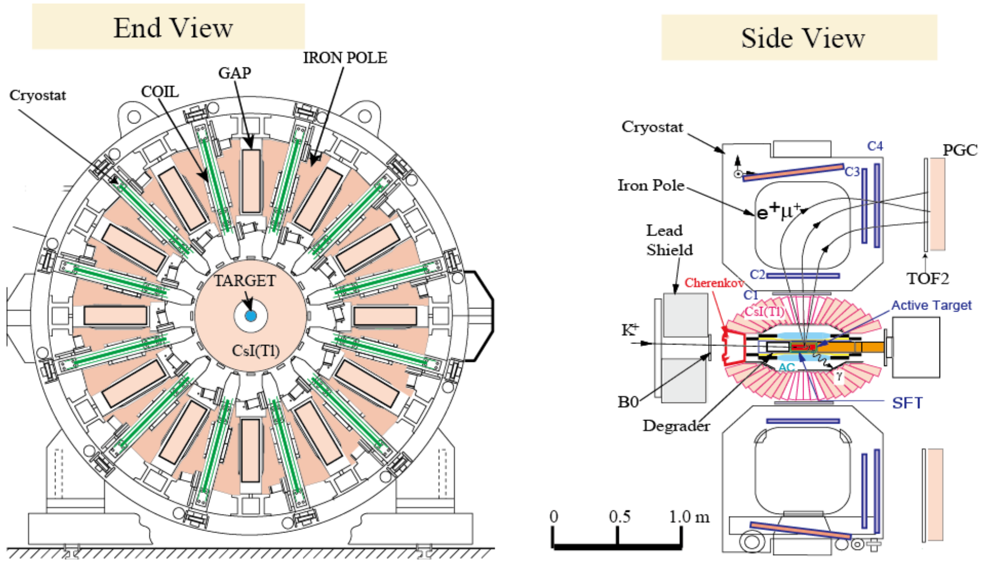

Figure 1: Cross-sectional side and end views of the E36 detector setup.

fibers. A superconducting toroidal magnet and 3 layers of multiwire proportional chambers (C2, C3, C4) in each of 12 toroidal sectors provide precise measurement of the momentum spectra for $K_{\mu 2}$(236 MeV/c) and K_{e2}(247 MeV/c) decay modes of stopped kaons. The precise measurement of the momentum requires at least four-point tracking, which suggests that additional tracking devices must be set close to kaon decay point. The kaon decay point is measured with the scintillating fiber target and the Spiral Fiber Tracker (SFT), which is mounted around the target and defines z-coordinate of the decay point along the target.

The target is made of 256 pieces of rectangular 3.2x3.2 mm^2 scintillating fibers with a length of 20 cm forming a 6 cm diameter cylinder. In each fiber a thin wavelength shifter (WLS) fiber is embedded in a groove and the light through the 1 mm diameter WLS fiber is read by a Hamamatsu multi-pixel photodiode MPPC. As the SFT and the target are made of plastic fibers and mounted in the same place we use the same readout electronics for both detectors.

Particle discrimination (PID) between e^+ and μ^+ is carried out with aerogel Cherenkov counters (AC) and time-of-flight counters (TOF1) mounted around the target, Pb-glass Cherenkov counters (PGC) and time-of-flight counters (TOF2) mounted at the magnet sector exits. The photon detector consists of 768 CsI(Tl) crystals and covers 75% of the total solid angle. The photon detector is for the study of radiative decays and the suppression of backgrounds.

2. Design of the Spiral Fiber Tracker

The SFT is installed in very limited space around the target and must provide both tracking capability with spatial resolution better than 1 mm and detection efficiency higher than 98%. The thickness of the SFT should not exceed 5 mm, minimum active length must be greater than 20 cm to cover the target. An important design consideration was the minimization of the detector cost.

The SFT consists of four fiber ribbons of slightly different size, each forms a single detection layer around the target. A schematic drawing of one of the ribbons is shown in Fig. 2. The 1 mm diameter 11.5 m long individual fiber is a combination of a 5.5 m long active scintillating part, multiclad fiber Kuraray SCSF-78MJ ([2]) spliced with two clear Kuraray fibers at both ends to route the light signals downstream outside the magnet to photosensors, Hamamatsu MPPCs. The scintillating fibers are glued together into a flat ribbon as shown in Fig. 2; elastic epoxy is applied to one side of the ribbon. Since the fiber diameter can deviate ± 10 μm, the alignment gap between neighboring fibers was set by the gluing jig mould to be 50 μm to fix accurate position of a fiber relative to the ribbon edge. The clear fibers are not bound and form a flexible bundle.

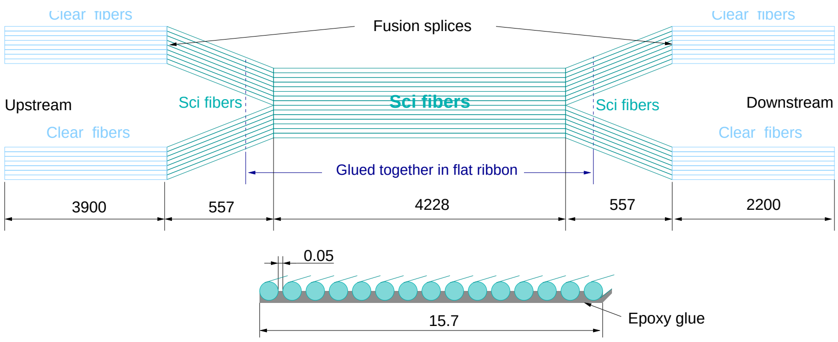

Figure 2: Schematic layout of the ribbon for 1-st layer. All dimensions are in mm.

The four ribbons are spirally wound one-by-one around the active target holder (Al-pipe of 79 mm diameter), one ribbon per layer, two adjacent layers are staggered by a fiber half-diameter (0.5 mm). The two first 15-fiber ribbons are coiled in staggered configuration with one helicity, the two 17-fiber ribbons are coiled in staggered configuration over first ones with the opposite helicity.

The z-coordinate reconstruction is done as follows. Three-point tracking with the wire chambers produces a track which can be traced back to SFT, that defines an area of hit on the SFT surface in a first iteration. Within the area we have a set of 15 or 17 different fibers for a single layer, one of them is identified as a fired one. Thus a hit position is known with the accuracy of fiber positioning, close to 1 mm. Fired fibers from different layers improve the accuracy to 0.5 mm, at least.

Different number of fibers in the ribbons and different helicities allow us to reconstruct independently the hit position (z-coordinate) using the unique pattern of hit fibers from different layers. The fibers in the inner and outer ribbons cross over each other in the projection because of different helicities. Different number of fibers in the inner and outer ribbons (15 vs 17) changes the crossing combination for each coil so that this combination is a function of azimuthal angle and z-coordinate. Azimuthal angle of a track is known roughly from the trigger counters mounted in each of 12 azimuthal gaps of the magnet. The pattern of fired fibers indicates the fired coil, and the position of fired fiber in this coil gives z-coordinate of a track.

The SFT was assembled in April, 2014 at KEK [3]. The scintillating and clear fibers were fused and glued in the ribbons by Moderation-Line Co., Ltd. A rotating dummy pipe with the same diameter as the actual target holder was prepared for SFT assembling. Kapton film of 0.15 mm thickness was wrapped around the pipe as a smooth substrate for sliding the SFT during installation process. To facilitate the removal of the SFT off the pipe, Mylar strips with 0.1 mm thickness were placed along the pipe between the pipe and the Kapton. The fiber ribbons were tightly coiled around the dummy pipe and fixed locally by adhesive tape. Though the fiber ribbons were relatively rigid the visual inspection did not expose any damage in the coiled ribbons. The active part of the SFT at the 4-th layer represents 14 coils of a 17-fiber ribbon, in total 238 fibers along the tracker. The active part of the SFT is about 250 mm, the outer diameter is 86 mm, the SFT thickness is 3.7 mm (less than 4 mm due to staggering). The coiled part of SFT and the extended fiber bundles were shielded from light with black plastic sheet and black heat-shrinkable tubes (non-heated), respectively. After that the clear fiber ends were glued into plastic couplers with colorless epoxy cement EJ-500 (Eljen Technology, USA) and the fiber ends were hand polished. Finally, the SFT was transferred from the dummy pipe to the actual target holder. All fibers were examined with an LED flasher to check for any accidental damage inflicted during assembly.

All assembly procedures were carefully performed to avoid applying extra bending tension to the fiber ribbons and bundles. Fig. 3 shows the SFT views at different assembly stages.

Figure 3: Assembling of the SFT: first two ribbons are coiled around the dummy pipe (*left*); SFT view before gluing of the fibers into couplers (*right*).

3. Photosensors and front-end electronics

A total of 64 fibers are read out by 128 Hamamatsu MPPCs S10362-11-50C ([4]). The MPPCs have an active area of 1x1 mm^2, 400 pixels, the PDE for a blue scintillating light is above 30% after correction for crosstalk and afterpulsing. The MPPCs are inserted in couplers and soldered on boards which are mounted inside a light-tight box cooled by Peltier elements to $5-8°$C. Signals from the MPPCs are sent to VME ADCs over 9.2 m long micro coaxial ribbon cables.

The MPPC readout is implemented with VME-EASIROC 64-ch. boards designed in Tohoku University, Japan[5]. The design is based on ASIC EASIROC (Extended Analogue Sipm Integrated Read-Out Chip) developed by Omega/IN2P3 in France. The board combines amplifier, peak-hold ADC with low and high gain channels, discriminator, multi-hit TDC with 0.8 ns resolution, and bias voltage adjustment for each individual MPPC.

4. Test of scintillating fibers

We tested a few 3 m long Kuraray scintillating multiclad fibers SCSF-78MJ of 1 mm diameter to estimate the basic expected performance of the SFT. The emission peak of the fiber is 450 nm, the decay time is 2.8 ns

Fig. 4 shows the test setup for the light output measurement with a radioactive source. Sr^{90} irradiated through a lead collimator the fiber under test. The trigger signal was produced by a 1x1 cm^2 plastic counter located behind the fiber. The counter was viewed by a small photomultiplier. The fiber readout was performed with a MPPC of the same type used in the SFT. The other fiber end was left open, with no mirror.

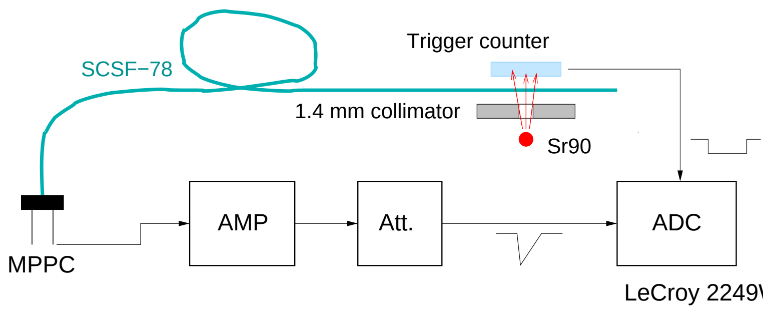

Figure 4: Setup for light output measurement with a β-source Sr^{90}

The light yield was measured to be 12 p.e./MIP at 2 m from MPPC. At far end the light yield dropped to 6 p.e./MIP. No correction for optical crosstalk of MPPC was applied so the result can be overestimated by 20%. A point 3 m from the MPPC (far end) is close to the middle point in the real SFT scintillating fiber. Additional losses of light in the SFT fiber are caused by attenuation in the clear fiber (CF) extention, bending of the fiber in 14 or 17 coils and the junction between CF and scintillating fiber. Splicing of fibers was done by fusion inside a 20 mm long teflon tube. The average loss at the splicing joint was about 12% according to manufacturer measurements. Bending losses can be estimated from Kuraray specification as 10-15% for 8 coils (center of SFT).

The expected light signal in the SFT fiber is estimated to be around 3 p.e. at a single end for central part of SFT.

The light attenuation in the scintillating fiber was measured by illuminating the fiber with an UV LED with a peak emission wavelength of around 365 nm. The LED exited the fiber through a collimator of 0.5 mm diameter at a variable distance to the end coupled to a MPPC. The far end of the fiber was left open. The result is presented in Fig. 5. The measurements were fitted by a sum of

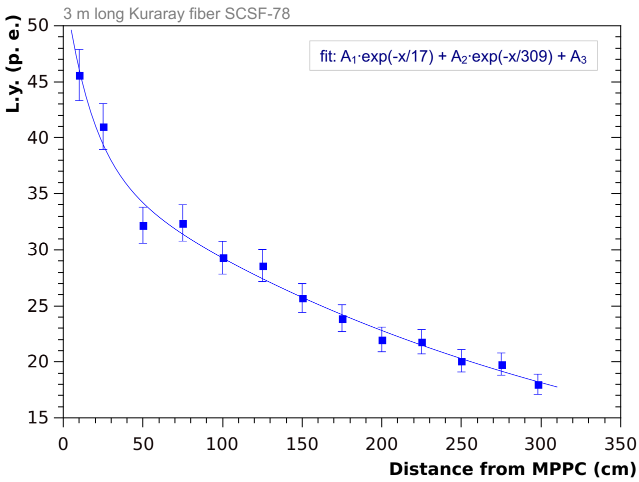

Figure 5: Scintillating fiber attenuation curve. Double exponential function is used to fit the curve.

two exponential functions: $A_1 \cdot exp(-x/\lambda_s) + A_2 \cdot exp(-x/\lambda_l)$, where the short attenuation length λ_s=17 cm and the longer attenuation length λ_l=309 cm. Kuraray datasheet specifies the longer attenuation length for a 3 m long SCSF-78 as >4 m [2].

5. Measurement of the SFT detection efficiency

Cosmic rays tests were performed to measure the SFT detection efficiency. The trigger was arranged with TOF1 and additional trigger counters which limited the hit area to a length of 5 cm along the SFT. Only cosmic muons incident normal to the SFT surface were selected.

Cosmic ray particles cross 4 fiber layers in the upper part of SFT, and 4 fiber layers in the lower part generating two independent events for one trigger. A single event is recorded if the particles hit the same fiber in both upper and lower parts of SFT. This effect can be taken into account by correction of total statistics:
$N_{tot} = N_{trig} + (14/15)N_{trig}$ for the first two layers;
$N_{tot} = N_{trig} + (16/17)N_{trig}$ for 3d and 4th layers,
where N_{tot} and N_{trig} are numbers of events and triggers, respectively.

Contributions from backgrounds and accidentals in the total number of detected events N_{det} were estimated by analyzing the raw TDC spectra. The background before the timing peak was fitted with a horizontal line, then subtracted from the area with cosmic events within the timing peak. Because of the low light signal an event is counted if either of the fiber ends fired, i.e. show a hit within timing peak of TDC spectrum.

The detection efficiency for a layer was calculated as a sum of the efficiencies for all fibers in this layer. The results are listed in Table 1. The measured value for a single fiber layer contains the contribution from geometrical inefficiency caused by 50 μm gap between the scintillating fibers plus inactive fiber cladding of 60 μm thickness, 16% in total. The last coulmn in Table 1 shows the corrected values of the layer detection efficiency with the geometrical inefficiency subtracted. The geometrical inefficiency is suppressed in the SFT by staggering two fiber layers.

Table 1: Detection efficiencies for SFT layers. Last column shows the detection efficiencies after correction for dead space between fibers.

Layer	Det. efficiency, %	Corrected, %
1st	77.14	91.83
2nd	79.09	94.15
3rd	75.32	89.67
4th	80.56	95.90

The calculation of the detection efficiency for two and more layers is problematic because of two factors. Cosmic particles cross 8 fiber layers. Also there is no correct way to make correction for accidentals in two and more layers. We can count the zero events for all 4 layers without any correction, where a zero event means no hits in any of 64 fibers. Measured in such a way the inefficiency is 0.17%.

6. Conclusion

The SFT was designed for conducting high-precision momentum measurement of charge particles from kaon decays and consists of four layers of flat ribbons made of 1 mm diameter plastic scintillating fibers. The ribbons are spirally wound around the kaon stopping target at the center of the detector setup, a single ribbon per layer. A total of 64 fibers are read out by 128 HAMAMATSU MPPCs connected to the scintillating fibers at both ends by clear fiber extensions.

The light yield was estimated to be about 3 p.e./MIP at one end of a fiber for the central part of SFT. Because of the low light yield any of the 2 fiber ends are sufficient to count an event. The detection efficiency for a single layer was measured in the cosmic test to be 78% on average. Main contribution to the inefficiency, 16% out of 22%, is attributed to dead material between the scintillating fibers.

The SFT started to collect beam data in the spring of 2015.

7. Acknowledgments

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