Prototype Studies for the Mu3e Scintillating Fiber Detector

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on behalf of the Mu3e Collaboration

PhD Seminar 2015
The Mu3e Experiment

Search for the charged lepton flavor violating decay

$$\mu^+ \rightarrow e^+e^-e^+$$

with an aimed single event sensitivity of $O(10^{-16})$
(staged approach: Phase I SES $10^{-15}$, Phase II SES $<10^{-16}$)

Standard Model: $\text{BR} < O(10^{-50})$

$\Rightarrow \mu \rightarrow e^+e^-e^+$ is sensitive to new physics
Experimental Layout (Phase I)

**Scintillating Fiber Detector**

**Purpose:**
Complement the silicon tracker (unambiguous silicon hit assignment to tracks)

**Requirements:**
- timing resolution < 1 ns
- detection efficiency ~100 %
- as little material as possible (multiple scattering)

**Baseline design:**
~4'500 fibers of 250 μm thickness and ~ 35 cm length arranged in three-layer-ribbons, read out by Silicon Photomultipliers (SiPMs) at both fiber ends
Scintillating Fiber Detector

**Challenge:** Achieve good timing resolutions (< 1 ns) with high detection efficiency using so little (< 1 mm) scintillation material

- expected energy deposit (MIP) ~ 30 keV ≈ O(10) detected photons per fiber

**Measurement goals with PSI prototypes:**
- timing resolution in single- and multi-hit event
- detection efficiency
  for both 250 μm and 500 μm squared fibers

**Tests...**
- in the lab (Sr90 source)
- in PiE5 area @ PSI (28 MeV/c e⁺, older version of the 250 μm prototype)
- in PiM1 area @ PSI (115 MeV/c e⁺, newer version of the 250 μm prototype)
The Prototypes

- Telescope structure
  - 3 layers
  - 14 channels (7 fibers read out at both ends)

Arrangement of the fibers

beam/ source

single fiber used for trigger purposes
The Prototypes

• Telescope structure
  – 3 layers
  – 14 channels (7 fibers read out at both ends)
• Squared 250 μm fibers
  – Saint-Gobain BCF-12 multiclad
  – 25 cm length
  – coated with 100 nm of aluminum to suppress crosstalk between fibers
  – fibers mounted on a plexiglass frame

cross talk between adjacent fibers (Sr90 electrons)

no coating around the fibers

cross talk ~30 %

Aluminum coating around the fibers

cross talk < 1 %
The Prototypes

- Light detection: SiPM coupled at both fiber ends
  - Hamamatsu S12815-050C
  - 50 μm pixel size, sensitive area 1.3 x 1.3 mm²
  - Coupling fiber – SiPM with optical grease
Electronics

• Preamplifiers:
  – MAR-amplifiers developed at PSI (and optimized for small amount of detected photons)

• DAQ: PSI DRS evaluation boards (daisy-chained)
  – Waveform digitization @ 5 GSPS
  – 4 channels per board
  – Max. acquisition rate for one single evaluation board: 500 Acq./sec
The Lab-Setup

- **Sr90 source**
  - Collimator mounted on a moving stage
- **External trigger**:
  - Plastic scintillator (4 x 4 x 20 mm$^3$) coupled to
  - SiPM (Hamamatsu 3 x 3 mm$^2$ active area)
  - Select MIPs ($E_e > 1.5$ MeV)
  - Get rid of thermal noise (no cooling)
Results 250 μm – Source

- Collected light – Sum of both SiPM (readout of both fiber ends) – Threshold 0.5 NPhe

SiPMs in “OR” logic
(at least 1 SiPMs sees a signal)

Mean NPhe = 7.3
efficiency ≈ 92 %
(single fiber)

SiPMs in “AND” logic
(both SiPMs see a signal)

Mean NPhe = 8.3
efficiency ≈ 74 %
(single fiber)
Results 250 μm – Source

• Collected light – Homogeneous response of the detector – Threshold 0.5 NPhe (AND logic)

All fibers see ~ the same amount of light

Mean # of NPhe

Source e⁻

efficiency (OR) ≈ 97 %
efficiency (AND) ≈ 79 %
(fiber layer)
Results 250 μm – Source

- Timing: Custom waveform analysis with offline constant fraction discrimination – Threshold 0.5 NPhe (AND logic)

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Single hit timing resolution

$$\sigma(T) = \sigma((t_1 - t_2)/2)$$

time measured by SiPM 1

time measured by SiPM 2

fibers under consideration

$\sigma(T) \approx 515$ ps
Results 250 μm – Source

- Timing: Custom waveform analysis with offline constant fraction discrimination – Threshold 0.5 NPhe (AND logic)

\[
\sigma(\bar{T}') = \sigma((T_{12}-T_{34})/2) = \sigma(T)/\sqrt{2}
\]

Note:
\[
\sigma(\bar{T}') = \sigma((T_{12}-T_{34})/2) = \sigma((T_{12}+T_{34})/2) = \sigma(\bar{T})
\]

fibers under consideration

\[\sigma(\bar{T}') \approx 410 \text{ ps}\]
Test Beam PiE5

- Test of a previous version of the 250 μm prototype
  - Difference w.r.t. new version: Al coating via sputtering instead of PVD ➔ slightly less performing fibers (mean collected number of photons 7.4 NPhe instead of 8.3 NPhe)

- Beam Momentum: \( p = 28 \text{ MeV/c} \) positrons
Results 250 μm – Test Beam PiE5

- Timing: Custom waveform analysis with offline constant fraction discrimination – Threshold 0.5 NPhe (AND logic)

\[ \sigma(T) \approx 535 \text{ ps} \] (single hit)

\[ \sigma(T') \approx 465 \text{ ps} \] (double hit)
Conclusion

• Prototype studies with a telescopic structure of 250 μm squared multiclad scintillating fibers have shown the following performances:
  – ca. 8 (mean) collected photons per fiber, observed for all fibers of the prototype (homogeneous detector response)
  – cross talk < 1 %
  – single fiber efficiency of 92 % (OR-logic) and 74 % (AND-logic)
  – fiber layer efficiency of 97 % (OR-logic) and 79 % (AND-logic)
  – timing resolution of ca. 515 ps (single hit) and ca. 410 ps (double hit)

• Performances in the lab and test beam are consistent
• Analysis of the PiM1 test beam data underway
  – Time-of-flight measurement
  – Improvements on the timing algorithm
Outlook

• Preparation of a “large prototype” ongoing
  – confirmation of detector performances (collected light, efficiencies, timing resolutions)
  – first “small” 32 fibers, 64 channels module (measure multi-layer efficiency, study clustering algorithms)
  – to be tested in October 2015 in PiM1 @ PSI
Backup
Test Beam - PiM1

- **Momentum:** $p = 115$ MeV/c ($e^+, \mu^+, \pi^+$)
- **Beam size:** $(\sigma_x, \sigma_y) = (6.6 \text{ mm, } 9.4 \text{ mm})$
- **Total rate:** $\sim 5.8 \times 10^5$ particles/s @ 2.2 mA proton current
- Particle separation by time-of-flight
Results – Test Beam PiM1

• Time-of-flight measurement

# events scaled by a factor 10 for $\pi^+$, $\mu^+$
Results 250 μm – Source

- Collected light (NPhe) – Single SiPM (readout of one fiber end) – Threshold 0.5 NPhe
Results 250 µm – Source

- Timing: Custom waveform analysis with offline constant fraction discrimination – Threshold 0.5 Nphe (AND logic)

Single Gaussian Fit

\[ \sigma(T) \approx 555 \text{ ps} \]

\[ \sigma(T') \approx 400 \text{ ps} \]

\[ \sqrt{2} \]