Scintillating Fibre Detector for the Mu3e Experiment

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AN EXPERIMENT SEARCHING FOR THE LEPTON FLAVOUR VIOLATING DECAY

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

$B(\mu \rightarrow eee) < 1.0 \times 10^{-12}$ (SINDRUM, 1988)

Mu3e: find or exclude $\mu \rightarrow eee$ at a $10^{-16}$ level

$BR_{SM} < 10^{-50}$

Any observation is a sign for new physics.

MUONS

- Stopping rate up to $10^8 \mu/s$
- Extent momentum resolution due to recurring tracks
- Double layers
- HV-MAPS (high voltage monolithic active pixel sensor)
- $\sim 50 \mu m$, minimize multiple scattering

TIMING

- Scintillating
- $250 \mu m$ fibres (few 100 ps)
- $1 \text{ cm}^3$ tiles ($\sim 100$ ps)
- Silicon Photomultipliers

REQUIREMENTS

- Combinatorial bg very good vertex/time resolution
- bg: $\mu \rightarrow eee$ very low material budget to get best possible momentum resolution

more details: "Status of the Mu3e detector", D. Wiedner, Tu 28/2.
Timing Detector Motivation

Internal Conversion
\[ \mu \rightarrow eee\nu\nu \]

- coincidence
- same vertex
\[ |\sum P_e| \neq m_\mu^2 \]
- BR = 3.4 \cdot 10^{-5}

Combinatorial BG
\[ 2 \times \mu^+ \rightarrow e^+\nu\nu \]
\[ ? \rightarrow e^- \]

excellent momentum resolution
excellent vertex/timing resolution

Signal
\[ \mu \rightarrow eee \]

- coincidence
- same vertex
\[ |\sum P_e| = m_\mu^2 \]

Mu3e Phase I

Events per 0.2 MeV/c²

- \[ \mu \rightarrow eee\nu\nu \] at 10^{-12}
- \[ \mu \rightarrow eee \] at 10^{-13}
- \[ \mu \rightarrow eee \] at 10^{-14}
- \[ \mu \rightarrow eee \] at 10^{-15}
Timing Detector Motivation

**BG suppression**
Fraction of reconstructed tracks (Michel decay, $\geq 6$ hits) with dominant timing from corresponding detector.

- **suppression**
  - only tiles $\mathcal{O}(10)$
  - only fibres $\mathcal{O}(30)$
  - combination $\mathcal{O}(100)$

**Charge Identification**
Time resolution $\leq 0.5$ ns allows reliable charge identification for recurling ($\geq 8$ hits) tracks.

![Suppression Pie Chart](image)

![Charge Identification](image)
Trigger-Less DAQ

reasonable time $\rightarrow$ high $\mu$ rates required (PSI)
online reconstruction
trigger-less DAQ
Readout Concept

3072 channels

- 2844 Pixel Sensors
- Up to 45 1.25 Gbit/s links

- 3072 Fibre Readout Channels
- 16 Gbit/s link each

- 6272 Tiles

Switching Board

- 16 Gbit/s link each
- 12 10 Gbit/s links per Switching Board
- 8 Inputs each

Gbit Ethernet

GPU PC

PC

PC

Switching Board

Data Collection Server

Mass Storage

Front-end (inside magnet)

86 FPGAs

12 FPGAs

14 FPGAs

max 72 Gbit/s
The Scintillating Fibre Detector

Components
- cylindrical $r \sim 6\,\text{cm}$; $l = 28-30\,\text{cm}$
- 12 ribbons of 3-4 layers of 250 $\mu\text{m}$ fibres
- SiPM column arrays
- mixed mode ASIC: MuTRiG

Requirements
- as thin as possible;
  $\leq 0.5\% \, X/X_0$ (1 mm)
- as efficient as possible; $\sim 100\%$
- time resolution better than 500 ps
- up to 250 kHz/fibre;
The Scintillating Fibre Detector

STiC/MuTRiG

12: 28-30 cm long ribbons of 250 µm fibres

Components

- cylindrical $r \sim 6$ cm; $l = 28-30$ cm
- 12 ribbons of 3-4 layers of 250 µm fibres
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- as thin as possible;
  $\leq 0.5\% \ X/X_0$ (1 mm)
- as efficient as possible; $\sim 100\%$
- time resolution better than 500 ps
- up to 250 kHz/fibre;
bottom line: very limited space
### Expected Number of Photons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{dE}{dx}$</td>
<td>$(160 \text{ MeV } e^-)$</td>
</tr>
<tr>
<td>$d_{\text{fibre}}$</td>
<td>$200 \text{ keV mm}^{-1}$</td>
</tr>
<tr>
<td>Yield</td>
<td>$\sim 8 \text{ ph keV}^{-1}$</td>
</tr>
<tr>
<td>$\varepsilon_{\text{cap}}$</td>
<td>$5.4%$</td>
</tr>
<tr>
<td>$d_{\text{att}}$</td>
<td>$95%$</td>
</tr>
<tr>
<td>$\varepsilon_{\text{detection}}$</td>
<td>$30%$</td>
</tr>
<tr>
<td>Approximation</td>
<td>$\approx 5$</td>
</tr>
</tbody>
</table>
Scintillating Fibre Detector Optimization (Layers)

Implications on Tracking

- invariant mass ($m_{\text{eee}}$) resolution

Impact on Timing

- fibre detector efficiency
- fibre detector time resolution

Relative efficiency for $\mu \rightarrow \text{eee}$

- $\sigma_{\sqrt{t_1 + t_2}} / 2$ [ns]
Prototypes

4 layers, 250 µm fibres, ~ 45 cm long
in lab ($^{90}$Sr), at PSI ($\pi M1$) 115-215 MeV/c e, SP 190 GeV/c protons

Squared Fibres

Saint Gobain BCF-12 ($\tau \approx 3.2$ ns)

additional Al coating

Hamamatsu S13360-1350CS

(1.3 × 1.3 mm$^2$, 50 µm pitch, trenches)

Round Fibres

Kuraray SCSF-81M
($\tau \approx 2.4$ ns, $\gamma_{SCSF-81} < \gamma_{BCF-12}$)

optional TiO$_2$ in glue

Hamamatsu S12571-050P (1 × 1 mm$^2$)

and SiPM column array (same as LHCb)
Results: Single Layer

Squared Fibres ($\varepsilon^{0.5p}_{OR} = 97\%$)

Time Resolution (single layer)

$$\sigma = \frac{t_l - t_r}{2} = 0.7 \text{ ns}$$

Number of Photons (single layer)

Round Fibres ($\varepsilon^{0.5p}_{OR} = 95\%$)

Time Resolution (single layer)

$$\sigma = \frac{t_l - t_r}{2} = 1.0 \text{ ns}$$

Number of Photons (single layer)

Photons per sides. (0.5 phe)

less photons → geometrical → yield → no coating
Results: Multiple Layers

Triple Layer Time Resolution
single fibre (fan-out), pre-amp/digitizer

particle

trigger
offline selection: hits in 3 layers

Time Resolution (triple layer)

\[
\sigma = \frac{t_1 - t_r}{2} = 550 \text{ ps}
\]

\[
\varepsilon_{\text{OR}}^{0.5p} > 99 \%
\]

SiPM column array readout
no fan-out, mixed-mode ASIC: STiC3.1

particle

Time Resolution (column array)

\[
\sigma = \frac{t_1 - t_2}{2} = 0.7 \text{ ns}
\]
Readout Electronics: STiC3.1/MuTRiG

- **mixed mode**, ≈ 50 ps t-stamps
- high impedance, opt. differential

### Timing Threshold

### Energy Threshold

### Timing Trigger

### Energy Trigger

### XOR Output

### Coarse Counter

622 MHz

### Fine Counter

32 x 50 ps Bins

### Hysteresis

Tiles: both Thresholds

Fibres: only Timing-Threshold and Energy-Flag

"time mode"

<table>
<thead>
<tr>
<th></th>
<th>STiC3.1 in use</th>
<th>MuTRiG received end Jan.</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of channels</td>
<td>64</td>
<td>32</td>
</tr>
<tr>
<td>LVDS speed [Mbit/s]</td>
<td>160</td>
<td>1250</td>
</tr>
<tr>
<td>event size [bit]</td>
<td>48</td>
<td>47</td>
</tr>
<tr>
<td>event rate / chip [MHz]</td>
<td>~2.6</td>
<td>~20</td>
</tr>
<tr>
<td>event rate / ch [kHz]</td>
<td>~40</td>
<td>~650</td>
</tr>
<tr>
<td>power per channel [mW]</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>size [mm x mm]</td>
<td>5x5</td>
<td>5x5</td>
</tr>
<tr>
<td>number of PLLs</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>
## Data Rate and Clustering

<table>
<thead>
<tr>
<th></th>
<th>Event Rate [M/s]</th>
<th>Data Rate [Gbit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>at $10^8$ stopped $\mu$/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SciFi detector</td>
<td>274</td>
<td></td>
</tr>
<tr>
<td>Scintilating Fibres (235k/s/fibre)</td>
<td>1083</td>
<td></td>
</tr>
<tr>
<td>SiPM columns signal (420 k/s/column)</td>
<td>1290</td>
<td>36.1</td>
</tr>
<tr>
<td>SiPM columns dark counts (∼300 k/s/column)</td>
<td>922</td>
<td>25.8</td>
</tr>
<tr>
<td>SiPM columns total clustering</td>
<td>2211</td>
<td>61.9</td>
</tr>
</tbody>
</table>

- on FPGA (FE)

- best timing: use tracking
Summary and Outlook

STiC
MuTrIG

12: 28-30 cm long ribbons of 250 µm fibres

SiPM column arrays

3 layers, 32 mm width

- R&D finished (baseline chosen)
- full prototypes expected early 2018
- Mu3e: first beam expected 2019
Appendix
The Fibre Detector: Squared Results

**Time Resolution** (single layer)

\[ \sigma = (t_l - t_r)/2 = 700 \text{ ps} \]

**Number of Photons** (single layer)

Summed photons from both sides. (0.5 phe, AND)

**Efficiency**

<table>
<thead>
<tr>
<th>( \varepsilon_{\text{single}} ) [%]</th>
<th>OR</th>
<th>AND</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 phe</td>
<td>97</td>
<td>71</td>
</tr>
<tr>
<td>1.5 phe</td>
<td>79</td>
<td>34</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( \varepsilon_{\text{triple}} ) [%]</th>
<th>OR</th>
<th>AND</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 phe</td>
<td>&gt;99</td>
<td>95</td>
</tr>
<tr>
<td>1.5 phe</td>
<td>97</td>
<td>67</td>
</tr>
</tbody>
</table>
The Fibre Detector: Round Results

**Time Resolution** (single layer)

\[ \sigma = \frac{(t_l - t_r)}{2} = 1.0 \text{ ns} \]

**Number of Photons** (single layer)

Summed photons from both sides. *(0.5 phe, AND)*

**Efficiency**

<table>
<thead>
<tr>
<th>( \varepsilon_{\text{single}} ) [%]</th>
<th>OR</th>
<th>( \varepsilon_{\text{triple}} ) [%]</th>
<th>OR</th>
<th>AND</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 phe</td>
<td>95±9</td>
<td>0.5 phe</td>
<td>97±1</td>
<td>70*</td>
</tr>
<tr>
<td>1.5 phe</td>
<td></td>
<td>1.5 phe</td>
<td>90*</td>
<td></td>
</tr>
</tbody>
</table>
Crosstalk

**Al coating**
- no additional Al
- significant cross-talk reduction
- ~60 % yield increase (diffuse)

<table>
<thead>
<tr>
<th>Material</th>
<th>n</th>
<th>Light Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>optical cement</td>
<td>1.56</td>
<td>~40 %</td>
</tr>
<tr>
<td>Araldite rapid</td>
<td>~1.5</td>
<td>~30 %</td>
</tr>
<tr>
<td>optical grease</td>
<td>1.465</td>
<td>~20 %</td>
</tr>
</tbody>
</table>

**TiO₂ in glue**
- crosstalk-reduction (ribbon dependent)
- 10-20 % yield increase (diffuse)
- ~10 % cluster size reduction
Radiation Damage

expectations:
- $e^+/e^-$ flux: $0.9/1.7 \text{ MHz mm}^{-2}$
- integrated flux per year: $0.8/1.4 \cdot 10^{10} \text{ e}^+/e^- \text{ mm}^{-2}$
- dose per year: $55/97 \text{ mJ}; 24/42 \text{ Gy}$