Instrumentation for experiments with high-intensity pulsed muon beam
MuSEUM experiment

Sohtaro Kanda /

kanda@post.kek.jp
Production of Muon

- **Proton driver**
  
  Proton → Graphite → Positive pion → Negative pion

- **Parity violating pion decay**
  
  Neutrino → Pion → Muon
  4 MeV at pion rest frame
  Spin polarized
Decay of Muon

- Parity violating muon decay

\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]

- Neutrinos
- Muon
- Positron

- Positron energy spectrum

- Positron angular asymmetry

2016. 10. 13 at J-PARC dsys workshop
Muon Spin Dynamics

- Muon spin rotation and relaxation
  
  In the presence of B-field, muon spin rotates with Larmor frequency
  \[ \omega_\mu = -\frac{q g_\mu}{2m_\mu} B \]
  
  Spin relaxation occurs due to the B-field distribution

- Decay positron time spectrum
  
  Muon is a powerful probe for local magnetic field thanks to its spin dynamics and self-analyzing feature

Pulsed and Continuous Muon Beam

- **Pulsed beam : J-PARC, RAL**
  - Higher event rate
  - Higher S/N
  - Limited timing resolution
  - Pulse synchronized trigger
  - Ensemble average

- **Continuous (DC) beam : PSI, TRIUMF, MuSIC**
  - Less event rate
  - Less S/N
  - High timing resolution
  - Necessity of trigger counter
  - Event-by-event analysis
## Measured muon properties

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Mass Muonium HFS spectroscopy</td>
<td>DC (Chopped)</td>
<td>120 ppb</td>
<td>117 ppb</td>
<td>38 ppb</td>
<td>Liu 1999</td>
</tr>
<tr>
<td>Mean lifetime Decay positron counting</td>
<td>DC (Accumulated)</td>
<td>1 ppm</td>
<td>0.96 ppm</td>
<td>0.32 ppm</td>
<td>Tishchenko 2013</td>
</tr>
<tr>
<td>g-2  Decay positron tracking in storage ring</td>
<td>Pulse</td>
<td>540 ppb</td>
<td>463 ppb</td>
<td>283 ppb</td>
<td>Bennet 2007</td>
</tr>
</tbody>
</table>
### Muon as a probe for new physics search

<table>
<thead>
<tr>
<th>Method</th>
<th>Beam</th>
<th>Limit</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+\rightarrow e^+\gamma$</td>
<td>52.8 MeV $e^+$ and $\gamma$ back to back</td>
<td>$\text{Br}&lt;4.2\times10^{-13}$</td>
<td>PSI MEG 2016</td>
</tr>
<tr>
<td>$\mu^-\rightarrow e^-\bar{\nu}_e$</td>
<td>105 MeV $e^-$</td>
<td>$\text{Br}&lt;7\times10^{-13}$</td>
<td>PSI SINDRUM-II</td>
</tr>
<tr>
<td>$\mu\rightarrow eee$</td>
<td>$e^-$ tracking</td>
<td>$\text{Br}&lt;1.0\times10^{-12}$</td>
<td>PSI SINDRUM-I</td>
</tr>
<tr>
<td>$g-2$</td>
<td>$\mu^+$ in storage ring</td>
<td>$\Delta a_\mu(\text{Exp.-Th.})=289(80)\times10^{-11}$</td>
<td>BNL E821 2006</td>
</tr>
<tr>
<td>EDM</td>
<td>$\mu^+$ in storage ring</td>
<td>$d\mu&lt;1.9 \times 10^{-19}$ e cm</td>
<td>BNL E821 2009</td>
</tr>
<tr>
<td>Lorentz Violation</td>
<td>$\mu^+ e^-$ spectroscopy</td>
<td>$2\times10^{-23}$ GeV</td>
<td>LAMPF 1999</td>
</tr>
<tr>
<td>$\mu^+ e^- - \mu^- e^+$ conversion</td>
<td>$e^+ e^-$ annihilation</td>
<td>$P&lt;8.3\times10^{-11}$</td>
<td>PSI 1999</td>
</tr>
</tbody>
</table>
Towards Higher Precision

- Precision muon physics with continuous muon beam has been limited by statistical uncertainty.
- When statistical precision is improved severalfold, systematic uncertainty limits the measurement precision.
- To explore the new frontier of precision muon physics with high-intensity pulsed muon beam, both
  - High-rate capable detector
  - Precision control and monitoring of environment
    - are of importance
- In this talk, as an example of new generation of muon precision measurement, MuSEUM experiment is introduced.
Muonium Energy Levels

\[
\nu_{12} + \nu_{34} = \delta_{\nu}
\]
\[
\nu_{12} - \nu_{34} \propto \mu_\mu/\mu_p
\]

or
\[
\delta_{\nu} = \left(\frac{16}{3}\alpha^2 R_\infty c g_e g'_\mu\right) (1 + m_e/m_\mu)^{-3} (1 + \delta_{\text{QED}})
\]

- Direct measurement at zero magnetic field (\(\delta_{\nu}\))
- Indirect measurement under a high magnetic field (\(\nu_{12}\) and \(\nu_{34}\))
- Our goal is x10 improvement for both experiments
MuSEUM Experiment

Experimental Procedure:
1. Muonium formation
2. RF spin flip
3. Positron asymmetry

- Upstream Counter
- Muonium
- Polarized muon beam
- RF Tuning Bar
- RF Cavity
- Kr Gas Chamber
- Online Beam Monitor
  - 2D cross-configured fiber hodoscope
- “Zero” or High B-Field
- Positron Counter
  - Segmented scintillation counter

Positron Counter

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MuSEUM Instruments

- **Positron counter**
  - Segmented scintillator+SiPM
  - Positron counting
  - High rate capability is required

- **Online beam profile monitor**
  - Fiber hodoscope
  - Beam monitoring
  - Minimum amount of material is required

- **Offline beam profile monitor**
  - IIF+CCD beam imager
  - 3D muon stopping distribution
  - Beam tuning

- **Background monitor**
  - Lq. scint.+WFD
  - Neutron/Gamma/Positron discrimination
  - Self trigger
DAQ Overview

- Beam Sync. Pulse
- Pulse 25 Hz
- Beam Sync. Pulse
- Hold
- Online Beam Profile Monitor
- Peak Holding ADC
- Common Start
- Positron Counter
- Multi Hit TDC
- Environmental Monitors
  - B-Field
  - Gas Pressure
  - RF Power
  - Temperature
- Event Builder
- Data Writing
- Online Monitor

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Positron Counter

- Scintillator pixel+SiPM+Kalliope (ASD+multi-hit TDC)

- Two layers of segmented scintillation counter
- 10 mm×10 mm×3 mmt unit cell, 240 mm × 240 mm detection area
- High rate capability and tolerance to a high magnetic field

Frontend Electronics

- Kalliope: KEK Advanced Linear and Logic-board Integrated Optical detector for Positrons and Electrons

- 32ch inputs for MPPC
- ASIC implemented amplifier, shaper, discriminator
- FPGA programmed multi-hit TDC (common start)
- SiTCP data transfer

MPPC on PCB

- Eight layered PCB for MPPC mount

PCB with mounted MPPCs

Micro strip line impedance was adjusted to 50 Ohm
White Paper Mask

- White paper mask for light diffused and position marker

Photo detection comparison between black and white paper mask

White paper mask on a PCB as position marker and reflector
Reflector Film

- Thin polymer film with folding for light reflection

Laser cut ESR

ESR ribbons to be inserted

Folded film bands are inserted between sides of scintillators

Positron Detector Assembly
Assembled Positron Detector

Fully assembled scintillator segments

Top cover was placed for scintillator protection

ESR top cover
Installation

- Fiber Beam Profile Monitor
- Positron Counter w/Al Absorber
- Muon Beam
- Kr Gas Chamber (RF Cavity inside)
- Three layers of magnetic shield
- 200 mm
Hit Map on the Detector Plane
Time spectrum of coincidence hit
Instantaneous event rate was 10 MHz at maximum
30 coincidence hit per pulse
5% of pileup loss at the highest event rate
Systematic uncertainty due to the pileup loss is negligible
Fiber Beam Profile Monitor

- Cross-configured fiber hodoscope with SiPM readout
- To be placed in front of the target chamber
- Online monitoring of beam profile and intensity
- Minimum amount of material is required

S. Kanda, RIKEN Accelerator Progress Report Vo. 48 (2015)
Scintillation Fiber Array

Fiber array layer structure

- Resin 25 μ
- Fiber 100 μ
- Polyimide 25 μ

40 fibers are bundled for a ch. and connected to MPPC
Fiber Thickness Uniformity

layer thickness (um)

3% of Uniformity

Total thickness including fibers, resin, and substrate
Assembled Fiber Monitor
Installation

Muon Beam

200 mm

Fiber Beam Profile Monitor

Kr Gas Chamber (RF Cavity inside)

Three layers of magnetic shield

Positron Counter w/Al Absorber
Muon beam profile was measured by fiber beam profile monitor

Correction for light attenuation is to be applied
Beam Intensity Stability

Detailed analysis is in progress

Trigger (25 Hz)
Summary

- Precision muon physics with continuous muon beam has been limited by statistical uncertainty.
- Experiment with high-intensity pulsed beam has great potential to improve precision muon physics.
- To explore a new frontier of precision physics with high-intensity pulsed muon beam,
  - High-rate capable detector and
  - Precision control and monitoring of environment are essential.
- MuSEUM has got underway as a new generation of precision measurement with the highest intensity pulsed muon beam.
Supplements
## Environment Monitors

<table>
<thead>
<tr>
<th>Object</th>
<th>Instrument</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static B-Field</td>
<td>Fluxgate probe</td>
</tr>
<tr>
<td>RF Power</td>
<td>Thermal power sensor</td>
</tr>
<tr>
<td>Gas Pressure</td>
<td>Capacitance gauge</td>
</tr>
<tr>
<td>Gas Purity</td>
<td>Q-Mass</td>
</tr>
<tr>
<td>Temperature</td>
<td>Thermocouple</td>
</tr>
</tbody>
</table>
The progress of hydrogen atom spectroscopy had brought evolution of quantum mechanics.

- 1913: Bohr model
- 1916: Fine structure (FS)
- 1928: Dirac equation
- 1935: Hyperfine structure (HFS)
- 1947: Lamb shift (QED)
Positron Detector
MPPC on PCB