The MUSE experiment
Technical Overview

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MUSE is not your garden variety scattering experiment

Low beam flux
  Large angle, non-magnetic detectors.

Secondary beam (large emittance)
  Tracking of beam particles to target.

Mixed beam
  Identification of beam particle in trigger.
Experiment Overview

PSI πM1 channel
≈115, 153, 210 MeV/c mixed beams of e±, μ± and π±

θ ≈ 20° - 100°

Q² ≈ 0.002 - 0.07 GeV²

About 5 MHz total beam flux, ≈2-15% μ's, 10-98% e's, 0-80% π's

Beam monitored with SciFi, beam Cerenkov, GEMs

Scattered particles detected with straw chambers and scintillators

Not run like a normal cross section experiment - 7-8 orders of magnitude lower luminosity.
But there are some benefits: count every beam particle, no beam heating of target, low rates in detectors, ...
Experiment Overview

\[ \theta \approx 20^\circ - 100^\circ \]
\[ Q^2 \approx 0.0015 - 0.08 \text{ GeV}^2 \]
\[ \varepsilon \approx 0.256 - 0.94 \]

Essentially same coverage for all beam particles.
PSI πM1 Channel Characteristics

\(\approx 100 - 500 \text{ MeV/c} \) mixed beam of μ's + e's + π's

Dispersion at IFP: 7cm/%

Momentum acceptance: 3% resolution: 0.1%

Beam spot (nominal): 1.5 cm X x 1 cm Y, 35 mr X' x 75 mr Y'

Spots from 0.7x0.9 cm² up to 16x10 cm², \(\Delta p/p\) from 0.1-3.0%, used previously.

\[ N [\text{mA}^{-1} \text{s}^{-1}] \]

\[ p [\text{MeV/c}] \]
MUSE Design Choices

- Minimal R&D.
- Use existing designs as much as possible.
- Reuse equipment whenever possible.
- Maximal cost reduction.
- Modular construction (can run dress rehearsal with fewer components).

Performance Requirements

- Angle reconstruction to few mr (limited by multiple scattering).
- Reduce multiple scattering as much as possible.
- Mostly timing used for PID – O(50ps) time resolution.
- 99% or better online π rejection.
Beamline Detectors

Scattered Particle Scintillators

Beam Scint.

Straw Chambers

Target Chamber

Target SciFi

Beam Cerenkov

GEMs

Veto Scintillator
Detectors - beam Cerenkov

- Improve timing at target.
- Muon decay event rejection.
- 140ps achieved with cosmics (~110ps from geometrical).
- Estimate 25-50ps resolution can be reached.
- Crystals placed at Cerenkov angle -> better timing from prompt photons.
- Fast MCP-PMT photon detection.
- Likely to use Sapphire/Plastic.

![Cosmic Test: Scintillator MT - Beam Cerenkov Time Difference](image)

<table>
<thead>
<tr>
<th>res</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
<th>( \chi^2 ) / ndf</th>
<th>Constant</th>
<th>Mean</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>439</td>
<td>-35.64</td>
<td>0.1464</td>
<td>21.59 / 10</td>
<td>122.2 ± 7.9</td>
<td>-35.64 ± 0.01</td>
<td>0.1363 ± 0.0058</td>
</tr>
</tbody>
</table>

MCP-PMT  
Quartz Bars  
Sapphire Bars
Detectors - SciFis

- One scintillating fiber array near target
- Precise timing at target, less precise than Cerenkov, but with higher segmentation and rate capability
- RF to target TOF for beam PID
- Provide GEM trigger, spatial info for multi-hit / multi-track selection, to identify triggering track
- 3 SciFi planes + walk correction gives ~300ps timing resolution.

- YUV plane arrangement
- 40 2mm circular fibers / plane
- Double sided readout with maPMT
- Multiplexed to reduce channel cross-talk
Detectors - SciFis

Prototyping at Tel Aviv
Detectors - GEMs

• Determine trajectory for scattering angle and $Q^2$.
• 70um Spatial resolution.
• Third GEM rejects ghost tracks.
• Existing detector repurposed from OLYMPUS experiment @ DESY.

GEMs installed @ PSI
Detectors – Veto

- 8 Segment annular detector around target entrance window.
- Discriminate against muon decay events.

Detectors – Beam line Scintillators

- Beam flux normalization.
- Veto to remove Møller electrons.
Scattered Particle Scintillators

Target

Beam Scint.

Straw Chambers

Target Chamber

Target SciFi

Beam Cerenkov

GEMs

Veto Scintillator

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Target

LH$_2$ target cell
- Thin windows to limit backgrounds
- Small enough to limit multiple scattering
- Big enough so all but tails of beam go through cryogen, not side walls.
- Current plan - 4 cm wide x 8 cm high x 4 cm long.

Low power system
- LN$_2$ baffles reduce heating.
- Snow prevention using baffles + extra space.
Scattered Particle Detectors

- Scattered Particle Scintillators
- Beam Scint.
- Scintillator
- Veto Scintillator

- Straw Chambers
- Target SciFi
- Beam Cerenkov
- GEMs
- Veto Chamber

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Straw Tube Tracker
PANDA STT

- Based on ~1.5m long straws (1cm diameter).
- Close packed straws, w/ minimal gaps.
- ~30um thick straws -> low material budget.
- Mechanical stability provided by overpressuring straws to ~2bar - allows significantly lower material budget.

<table>
<thead>
<tr>
<th>Element</th>
<th>Material</th>
<th>X[mm]</th>
<th>X₀ [cm]</th>
<th>X/X₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Film Tube</td>
<td>Mylar, 27 μm</td>
<td>0.085</td>
<td>28.7</td>
<td>3.0×10⁻⁴</td>
</tr>
<tr>
<td>Coating</td>
<td>Al, 2×0.03 μm</td>
<td>2×10⁻⁴</td>
<td>8.9</td>
<td>2.2×10⁻⁶</td>
</tr>
<tr>
<td>Gas</td>
<td>Ar/CO₂(10 %)</td>
<td>7.85</td>
<td>6131</td>
<td>1.3×10⁻⁴</td>
</tr>
<tr>
<td>Wire</td>
<td>W/Re, 20 μm</td>
<td>3×10⁻⁵</td>
<td>0.35</td>
<td>8.6×10⁻⁶</td>
</tr>
</tbody>
</table>

\[ \sum_{\text{straw}} 4.4\times10^{-4} \]
Gas Mixture

Table 2.2: Properties of different gases and gas mixtures. Z and A are charge and atomic weight, for molecules the total number has to be taken, \( N_p \) and \( N_t \) are the number of primary and total electrons per cm, respectively, \( E_x \) and \( E_i \) are the excitation and ionization energy, respectively, \( W_i \) is the average energy required to produce one electron-ion pair in the gas, \((dE/dx)_{min}\) is the most probable energy-loss by a minimum ionizing particle and \( X_0 \) is the radiation length. For gas mixtures, the weighted average value has been taken.

<table>
<thead>
<tr>
<th>Gas or gas mixture</th>
<th>Z</th>
<th>A</th>
<th>( E_x ) [eV]</th>
<th>( E_i ) [eV]</th>
<th>( W_i ) [keV/cm]</th>
<th>( dE/dx ) [keV/cm]</th>
<th>( N_p ) [cm(^{-1})]</th>
<th>( N_t ) [cm(^{-1})]</th>
<th>( X_0 ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>2</td>
<td>4</td>
<td>19.8</td>
<td>24.5</td>
<td>41</td>
<td>0.32</td>
<td>4.2</td>
<td>8</td>
<td>5299</td>
</tr>
<tr>
<td>Ar</td>
<td>18</td>
<td>40</td>
<td>11.6</td>
<td>15.7</td>
<td>26</td>
<td>2.44</td>
<td>23</td>
<td>94</td>
<td>110</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>22</td>
<td>44</td>
<td>5.2</td>
<td>13.7</td>
<td>33</td>
<td>3.01</td>
<td>35.5</td>
<td>91</td>
<td>183</td>
</tr>
<tr>
<td>i-C(<em>4)H(</em>{10})</td>
<td>34</td>
<td>58</td>
<td>6.5</td>
<td>10.6</td>
<td>23</td>
<td>5.93</td>
<td>84</td>
<td>195</td>
<td>169</td>
</tr>
<tr>
<td>Ar+10% CO(_2)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>26.7</td>
<td>2.5</td>
<td>24.6</td>
<td>93</td>
<td>117</td>
</tr>
<tr>
<td>He+10% i-C(<em>4)H(</em>{10})</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>39.2</td>
<td>0.88</td>
<td>12.7</td>
<td>26.7</td>
<td>1313</td>
</tr>
<tr>
<td>He+20% i-C(<em>4)H(</em>{10})</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>37.4</td>
<td>1.44</td>
<td>20.6</td>
<td>45.4</td>
<td>749</td>
</tr>
</tbody>
</table>

- Ar (90%)/CO\(_2\)(10%) mixture selected – achieves design goals.
- Non toxic/non flammable – easy to deal with.
- Achieved \(\sim\)150um resolution and better than 8kHz/cm.
Construction Procedure

- **Wires:**
  - Straws cut to length.
  - End caps glued and 1 wire end crimped.
  - 12h glue hardening.
  - Wire stretched w/ 50g weight and pressure raised (2bar).
  - 2nd wire end crimped.

- **Straw planes:**
  - Straws placed on jig.
  - Each monolayer glued @ predefined points.
  - Additional layers stacked on first layer.
  - Final arrangement clamped in place.

**Procedure designed to allow straws/wires to be positioned at the 25um level.**
Gas distribution

- Mixture/Pressure controlled by pressure controllers/gas flow controllers from Bronkhorst inc.
- Gas distribution to individual chambers from single mixing chamber.
MUSE Electronics

- Straws provide low charge signal, suitable for discrimination with front end PADIWA board.
- MUSE will use the standard PADIWA->TRB3 setup that is planned for all timing detectors.
- HV distribution / readout card for the straw chambers will be designed and prototyped @ HUJI e-shop.
MUSE Design

- The tracker design has been modified to accommodate the MUSE requirements.
- Design calls for 2 chambers on each side of the detector.
- 5X/5Y planes per chamber.
- X-planes likely closer to target to allow for better resolution in scattering angle.
- ~3000 straws total.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Distance (cm)</th>
<th>Active Area (cm²)</th>
<th>Number of Straws per chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front</td>
<td>30</td>
<td>60 × 55</td>
<td>575</td>
</tr>
<tr>
<td>Back</td>
<td>45</td>
<td>90 × 80</td>
<td>850</td>
</tr>
</tbody>
</table>
Scintillators
Scintillator Overview

- Produced by USC based on design for CLAS12 upgrade.
- State-of-the-art production lab @ USC already set up.
- Expect at least 6 bars/week production rate once design is finalized.
The CLAS12 Scintillator Detector

**Scintillators:**
BC-404; 6 cm x 6 cm x (50 - 200) cm

**PMT:** Hamamatsu R9779, d = 51 mm.

1. Corners masked with black tape
2. No light guides; PMT directly glued to SC; gluing procedure in batches of 6 bars in ‘windmill’ type setup
3. Scintillator wrapped in Aluminized Mylar
4. Light tight DuPont Tedlar encases entire counter
Achieved Time Resolutions

- Time resolution after calibration, event selection, time-walk correction:
  - $\sigma_{avg} = 51$ ps for 203-cm bar
  - $\sigma_{avg} = 34$ ps for 69-cm bar

[Graph showing time resolution vs. position for two types of scintillators: Scintillator 6 cm x 6 cm x 203 cm and Scintillator 6 cm x 6 cm x 69 cm.]
**Scintillator Overview**

- Vertically oriented bars, covering the full acceptance (20–100 deg) – in 2 walls.
- Back wall increased in size to account for multiple scattering.
## Scintillator Overview

<table>
<thead>
<tr>
<th></th>
<th>Front wall</th>
<th>Back wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of scintillator bars</td>
<td>17</td>
<td>27</td>
</tr>
<tr>
<td>Scintillator cross section</td>
<td>6 cm x 2 cm</td>
<td>6 cm x 6 cm</td>
</tr>
<tr>
<td>Scintillator length</td>
<td>103 cm</td>
<td>163 cm</td>
</tr>
<tr>
<td>Target to front-face distance</td>
<td>50 cm</td>
<td>73 cm</td>
</tr>
<tr>
<td>Gap between scintillator bars</td>
<td>0.02 cm</td>
<td>0.02 cm</td>
</tr>
<tr>
<td>Scintillation material</td>
<td>BC-404</td>
<td>BC-404</td>
</tr>
<tr>
<td>Photomultiplier</td>
<td>Hamamatsu R9779</td>
<td>Hamamatsu R9979</td>
</tr>
</tbody>
</table>

![Diagram of scintillator setup](image)
Scintillator Readout

- R9779 PMTs with double output last dynode + anode.
- Dynode (slower) output readout into QDC.
- Anode (fast) readout fed directly into PADIWA for discrimination and TDC.
- Time-walk correction based on QDC.
- **Scintillator efficiency better than 99%.**
Triggering and Data Acquisition

Scattered Particle Scintillators

Beam Scint.

Straw Chambers

Target Chamber

Target SciFi

Beam Cerenkov

GEMs

Veto Scintillator

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• GSI designed Time-to-Digital converters (25ps resolution).
• FPGAs as front end discriminator/amplifier.
• High channel density (256ch/board).
• ADC signals into standard CAEN architecture (v792).
• Custom designed signal splitters where needed.
• Triggering implemented on same architecture.

TRB3 Timing
@ least as good as
CAEN V1290
Data Acquisition

- Data Acquisition based on standard PSI DAQ software (MIDAS).
- Trivial integration with PSI slow controls.
- Distributed frontend allow for high event rate (not limited by software/DAQ).
- Test runs carried out with individual modules of each type of component needed for the DAQ.
# New Equipment Summary

<table>
<thead>
<tr>
<th>Detector</th>
<th>Who</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam SciFi</td>
<td>Tel Aviv</td>
<td>conventional</td>
</tr>
<tr>
<td>GEMs</td>
<td>Hampton</td>
<td>detector exists</td>
</tr>
<tr>
<td>Sapphire Cerenkov</td>
<td>Rutgers</td>
<td>prototyped (Albrow et al)</td>
</tr>
<tr>
<td>Trigger</td>
<td>Rutgers</td>
<td>TRB3 based</td>
</tr>
<tr>
<td>Target</td>
<td>George Washington</td>
<td>conventional - very low power</td>
</tr>
<tr>
<td>Straw Tube Tracker</td>
<td>Hebrew U</td>
<td>copy existing system (PANDA)</td>
</tr>
<tr>
<td>Scintillators (including beam and veto)</td>
<td>South Carolina</td>
<td>copy existing system</td>
</tr>
<tr>
<td>DAQ</td>
<td>George Washington</td>
<td>conventional, except TRB3</td>
</tr>
</tbody>
</table>