Development, Simulation, and Prototype Performance Measurements of the Mu2e Straw Tracker

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Fermilab Users Meeting
June 20th, 2018

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Outline

1. Brief overview of Mu2e and physics motivation
2. Mu2e straw tracker design
3. Tracker Prototype low level measurements
4. Simulating the tracker
5. Comparing resolution + efficiency from prototype data and simulation

See upcoming talk by Tomonari Miyashita for more details on the experiment!
Charged Lepton Flavor Violation

- Mu2e will search for neutrinoless conversion of a muon to an electron in a nuclear environment:
  \[ \mu^- N \rightarrow e^- N \]

- This would violate **charged lepton flavor**, something that has never been seen before.

- Any detection of charged lepton flavor violation would be an unambiguous sign of new physics! (SM contribution is \(< 10^{-50}\))

- Mu2e goal is a \(10^4\) improvement!
The Mu2e Experiment at Fermilab

- Stop $10^{18}$ muons on Aluminum
- Conversion produces monoenergetic 105 MeV electrons
- Main background is decay-in-orbit electrons
- Only distinguishable by momentum, want high precision measurement that can handle high rate
The Straw Tracker Detector

- Cylindrical straw tracker operating in uniform field
- Tracker is in vacuum
  - Measurement is multiple scattering dominated
  - Entire detector much less than one radiation length of material
Tracker Configuration

- 18 stations, each containing $12 \times 120^\circ$ panels for stereo measurement
- Blind to DIO electron momentum peak and beam flash
- Expected resolution better than 200 keV/c
The Straw Tracker Detector

- ~21,000 low mass straw tubes in vacuum
  - 5mm diameter, 0.5-1.2m long
  - 15µm mylar wall, 25µm tungsten wire
  - 1 atm of 80/20 Ar:CO₂, wire at 1425V
What are we measuring

- Individual threshold crossings digitized in time (TDC)
  - Drift time $\rightarrow$ radial resolution $\sim 200$ $\mu$m
- Straws are instrumented on both sides
  - Time division $\rightarrow$ longitudinal resolution $\sim 4$ cm
- Falling edge digitized for Time over threshold
  - Measure of path length / radius independent of $t_0$
- ADC measures pulse waveform for background rejection
Tracker FPGAs and Firmware

- Most of functionality in FPGAs - highly configurable
  - Have already taken advantage to add new features (Time over threshold)
  - Originally had Altera FPGAs, now using Microsemi SmartFusion2 for radiation tolerance
- 2x Digi FPGAs that digitize 48 channels each
  - Separate TDCs for each end of straw
  - Continuous readout of summed ADC waveform at 50 MHz
- Data buffering, DAQ communication, tracker slow controls in ROC FPGA
Firmware TDC Design

- Need \(\sim 4\text{cm}\) resolution longitudinally along straw
- Near speed of light signal \(\rightarrow <100\text{ps}\) time resolution
- Achieve resolution in firmware while minimizing resource usage
  - Initial design based on wave-union design by Jinyuan Wu
  - Delay chain for sub-clock tick precision
  - Average multiple chains to subdivide large delays
  - Auto calibration of bin widths

1 delay chain

3 delay chains

8 delay chains
Firmware Design

FPGA resource usage for 48 channel design

- Have managed to implement design that fits all 48 channels in a single chip
- Learning process dealing with Microsemi FPGAs
  - Architecture changes from Altera version
  - Much smaller community, support resources
  - Difficulties with timing constraints - manual placement of delay chains and ADC interface
  - Several hour compilation time for full design
- Demonstrated readout chain from digitizing FPGAs through to DAQ computer over SERDES
An 8-straw tracker prototype for testing and performance measurements

- **Portable self-contained setup**
  - Cross talk → proton beam from 88” cyclotron at Berkeley Lab
  - Radiation sensitivity → UC Berkeley High Flux Neutron Source
  - Straw and electronics parameters → radioactive sources
  - Efficiency/resolution → cosmic rays
- Read out over USB serial using custom DAQ
Sources used to measure gain, energy resolution, time division, simulation tuned to results

Mu2e Straw Longitudinal Resolution

\[ \text{55Fe source at } 1.33 \times 10^4 \text{ gain } \quad \nu_{\text{eff}} = 203.0 \pm 0.5 \text{ mm/ns} \]

\[
\begin{array}{l}
z = -175.0 \text{ mm, } \sigma_z = 29.9 \pm 0.7 \text{ mm} \\
z = -87.5 \text{ mm, } \sigma_z = 30.3 \pm 0.6 \text{ mm} \\
z = 0.0 \text{ mm, } \sigma_z = 26.3 \pm 0.5 \text{ mm} \\
z = 87.5 \text{ mm, } \sigma_z = 34.7 \pm 0.9 \text{ mm} \\
z = 175.0 \text{ mm, } \sigma_z = 35.0 \pm 0.9 \text{ mm}
\end{array}
\]

- Gas gain by measuring current with $^{55}\text{Fe}$
- Energy resolution using 5.9 keV x-ray peak

(Tom-Erik Haugen)

(Andrew Edmonds)
Simulation of the straw tracker response

- Detailed Geant4 simulation of full detector
- Custom code takes energy deposition in each straw and models physics and electronics response
Simulation of the straw tracker response

Simulation of waveform threshold crossing at each end of straw

- Each ion cluster modelled individually, including drift, wire propagation, and electronics response
Simulation of the electronics response

Input pulse shape  →  Apply electronics response

(Data from Manolis Kargiantoulakis)

(SPICE sim from Vadim Rusu)

- Use unshaped waveforms from source at different distances to model attenuation, dispersion
- Fit for transfer function describing preamp and integrator response
  - Model includes saturation effects, pulse shape distortion
  - Important for accurately determining proton discrimination, modelling pileup
Reconstructing track position for performance measurements

- Use PMT trigger and ATLAS FEI4 pixel detectors to allow precise reconstruction of cosmic ray tracks
  - MIPs similar to conversion electron signal
  - Allow resolution and efficiency measurements
Reconstructing track position for performance measurements

- ATLAS FEI4 detectors measure track position
  - 2.0x1.9cm chips, 250x50µm pixels
- PMT trigger gives $t_0$ for drift time measurement
  - $\sim$600ps time resolution
- Reconstruct relative position and timing of pixels, PMTs, straws, wires with maximum likelihood fit
Transverse resolution

\[ 0.0 < \text{DOCA} < 0.5 \]

\[ 0.5 < \text{DOCA} < 1.0 \]

\[ 1.0 < \text{DOCA} < 1.5 \]

\[ 1.5 < \text{DOCA} < 2.0 \]

\[ 2.0 < \text{DOCA} < 2.5 \]

- Agrees with simulation tuned to low level parameters
- Model and simulation include full DOCA dependence of resolution
  - gaussian smearing $\times$ exponential with constant $\tau$
  - $\tau$ encodes effect of cluster statistics
Transverse resolution

- Agrees with simulation tuned to low level parameters
- Model and simulation include full DOCA dependence of resolution
  - gaussian smearing \( \times \) exponential with constant \( \tau \)
  - \( \tau \) encodes effect of cluster statistics
• Efficiency measured at many voltages/thresholds to determine optimal running conditions
With just hit time measurement, require $t_0$ estimate from track reconstruction before drift time can be determined
- Time over threshold allows a measure of path length (and thus radial distance) independent of $t_0$
- Implemented in firmware, being added to reconstruction
- Simulation agrees well with data
  - Shows predictive power of detailed model
• Sensitivity studies now include results of simulation tuned to prototype measurements
• Track resolution depends on hit level resolution and efficiency, as well as reconstruction techniques
• Mu2e will search for CLFV with greatly improved sensitivity
• Straw tracker provides a precise momentum measurement, made possible by timing and waveform measurements from the straws
• 8-straw prototype was used to tune detailed simulation of straw physics and electronics
• Hit level performance proven with prototype
• Momentum resolution will allow us to reach our sensitivity goals!