The Mu2e Calorimeter
Design, status and test results

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1 The full Mu2e Collaboration is listed at http://mu2e.fnal.gov/collaboration.shtml.

David Hitlin  The Mu2e Calorimeter  ICHEP 2016  August 4, 2016
Mu2e is a search for $\mu \rightarrow e$ conversion on Al

- Mu2e will provide the most sensitive search for charged lepton flavor violation
  - Sensitivity improvement of four orders of magnitude
- The conversion signal is an electron with a momentum corresponding to
  $$m_\mu - E_{\text{binding}} - E_{\text{recoil}} \ (104.97 \ \text{MeV/c})$$
  - The electron momentum is measured by a low mass straw tube tracker in a solenoidal magnetic field
- The calorimeter provides confirmation (require $E/p = 1$) (at lower precision) and several other crucial functions:
  - Shower cluster-based seeding of the track-finding algorithm improves efficiency
  - Online software trigger capability
- The calorimeter is also crucial for background rejection:
  - $\mu$ decay in orbit (DIO)
  - Radiative capture (RPC): $\pi N \rightarrow \gamma N'$, $\gamma \rightarrow e^+ e^-$ and $\pi N \rightarrow e^+ e^-' N'$
  - Pions produced by slow antiprotons in the target
  - $\pi/\mu$ decay in flight
  - Electrons in the beam
  - Cosmic rays
The sensitivity goal demands a total of $\sim 6 \times 10^{17}$ stopped muons in a 3 year run of $\sim 6 \times 10^7$ sec. This requires a muon stopping rate of $10^{10}$/sec, placing demands on the detector technologies.

Resulting calorimeter requirements:

- Energy resolution $\sigma_E/E \sim O(5\%)$ at 105 MeV
- Time resolution $\sigma(t) < 500$ ps
- Position resolution $< 1$ cm
- Adequate rate capability
- Operate in 1T magnetic field in a $10^{-4}$ Torr vacuum
- Reliability through redundant photosensors and DAQ
- Survive in the neutron ($10^{12}$ n/cm$^2$) and gamma (100 krad) radiation environment of Mu2e (includes a safety factor of 3)
- Provide close to full acceptance for conversion electron at 105 MeV
A microbunch event

- Simulations encompass a full $\sim 1\mu$s, including all the background overlays from the beam flash, $\mu$ capture products, neutrons, etc. and properly account for contributions from previous bunches.

Use of pulsed proton beam and a delayed live gate allows suppression of prompt backgrounds by many orders of magnitude.

Proton pulses must be narrow.

Out-of-time protons must be suppressed by $\mathcal{O}(10^{10})$. 
Calorimeter design

- The central hole region in the tracker and calorimeter allows us to be largely insensitive to DIO and beam flash backgrounds.
- The calorimeter consists of two identical annuli, spaced apart by 700 mm (½ \( \lambda \) of the helical trajectory of the conversion electron)
  - \( r_{\text{inner}} = 374 \text{ mm} \)
  - \( r_{\text{outer}} = 660 \text{ mm} \)
  - depth = 10 \( X_0 \) (200 mm)
- Each annulus contains 674 square CsI crystals with dimensions 34x34x200 mm\(^3\)
- Each crystal is read out by two large area (14x20 mm\(^2\)) six element UV-extended SiPMs
  - The analog front end electronics is directly mounted on the SiPM
- The digital electronics and voltage regulators are located in electronics crates mounted on the periphery
- Calibration and monitoring are provided by a 6 MeV radioactive source and a laser system
Measured CsI crystal properties

\[ \text{EWLT} = \frac{\int L(\lambda)E(\lambda)d\lambda}{\int E(\lambda)d\lambda} \]

- CsI Kharkov 1 29x29x230 mm³
- CsI Kharkov 3 29x29x230 mm³

Normalized EWLT

- CsI SIC2013 50-50x300 mm³
- CsI Kharkov 1 29x29x230 mm³
- CsI Kharkov 5 20x20x120 mm³
- CsI Kharkov 11 20x20x120 mm³

Transmittance (%) vs. Wavelength (nm)

- Measured transmittance
- Emission line
- EWLT: 47.8%

Graphs showing transmittance and light output metrics for CsI crystals, including light output as a function of distance from the end coupled to the PMT and light output over time.
The radiation environment

- The calorimeter radiation dose is driven by the beam flash (the interaction of the proton beam on target).
- The dose from muon capture is 10x smaller.
- Dose is mainly to the inner radius (up to 400 mm).
- Highest dose/year ~ 10 krad.
- Highest $n$ flux/year on crys. ~ $2 \times 10^{11} \text{n/cm}^2$.
- Highest dose/year on SIPM ~ $6 \times 10^{10} \text{n}_{\text{1MeV}} \text{eq/cm}^2$.

- Qualify crystals up to 100 krad, $10^{12} \text{n/cm}^2$.
- Qualify photo-sensors up to $3 \times 10^{11} \text{n}_{\text{1MeV}} \text{eq/cm}^2$.

Includes a safety factor of 3 for a 3 year run.
Extended response SiPMs match CsI spectrum

- Six 6x6mm cells in a 2x3 array
- 50 mm pixels
- Biased in series/parallel
Energy resolution

- Achieving best possible energy resolution requires efficient shower clustering algorithm with detached cluster recovery and pile-up rejection
  - Cluster algorithm with and without detached cluster recovery

- Pile-up rejection using waveform digitization
Spatial, time resolution

Spatial resolution
Compare predicted and Monte Carlo positions with signal events
\[ \sigma_x = 6.3 \pm 0.2 \text{ mm} \]
\[ \sigma_y = 5.8 \pm 0.2 \text{ mm} \]

Time resolution
Cluster time defined using the energy-weighted crystal times
\[ \sigma_t = 109 \pm 1 \text{ ps} \]
Test beam results: CsI + SiPM

- Test beam with 70-115 MeV electrons @ LNF
- 3x3 array of 30x30x200 mm³ CsI crystals
- Readout: SPL MPPCs
- Results
- Energy resolution $\sigma_E/E = 7\%$ dominated by shower leakage and beam energy spread
- Time resolution $\sigma(t) = 110$ ps.

Energy Resolution [%]

<table>
<thead>
<tr>
<th>Energy [MeV]</th>
<th>Events [10,000 MeV]</th>
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<tbody>
<tr>
<td>70</td>
<td>80</td>
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<tr>
<td>90</td>
<td>100</td>
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<tr>
<td>100</td>
<td>110</td>
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</tbody>
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$\frac{a}{\sqrt{E[GeV]}} \oplus c$
PID: $e/\mu$ separation by TOF, $E/p$

CRV studies show that with a CRV inefficiency of $10^{-4}$, an additional rejection factor of ~200 is needed in order to have < 0.1 fake events from cosmics in the signal window.

A cosmic ray muon event can mimic a conversion electron signal event. Events of this type can be vetoed using the timing information from the calorimeter.

A rejection factor of 200 can be achieved with ~95% conversion electron efficiency.
Calorimeter cluster-seeded track finding

The speed and efficiency of track reconstruction is improved by selecting tracker hits compatible with the time (|Δt| < 50 ns) and azimuthal angle of calorimeter clusters.

Calorimeter-seeded track finding improves the relative efficiency for tracks in the signal region (103.5 < p < 105 MeV/c) by ~11% and is more robust against background.
Calorimeter trigger options

Standalone trigger: 65% efficiency for background rejection of 200

Calorimeter-seeded track trigger can increase conversion electron acceptance by 10%, to 95%, for background rejection > 200
Calibration and monitoring

1) The $BABAR$ calibration source has been rebuilt to provide 6.13 MeV $\gamma$ s on demand

$$^{19}_{}F + n \rightarrow ^{16}_{}N + \alpha$$

$$^{16}_{}N \rightarrow ^{16}_{}O^* + \beta \quad t_{1/2} = 7 \text{ s}$$

$$^{16}_{}O^* \rightarrow ^{16}_{}O + \gamma(6.13 \text{ MeV})$$

2) Laser system to monitor SiPM performance

3) Cosmics + $E/p$ for DIOs at reduced $B$ field
Prototyping/testing

- Full-scale mockup
- Crate prototype
- 7x7 array
- 6 MeV source prototype
Calorimeter schedule

- CD-2 TCR FDR CD3 CRR-S CRR-All
- Pre Production Crystals
- Pre Production SiPMs
- Fabrication of all Crystals
- QC all Crystals
- Fabrication of all SiPMs
- QC all SiPMs
- Disk 1 + Disk 2 Assembly
- Critical Path

- Support DISK1
- Support DISK2
- FINAL Mechanical Drawings + Cooling Station and Mockup
- FEE DIGI final design
- FEE Pre-prod
- WFD Pre-Prod
- WFD Production
- FEE Production
- Assembly final source
- Assembly final flasher
- Calibration source final design
- Final Design LASER

- Assembly proto Source
- Installati -on
- CR Test

- FY15 FY16 FY17 FY18 FY19 FY20
Conclusions

A CsI-crystal-based calorimeter with SiPM readout meets the physics requirements for the Mu2e experiment. Its energy, time and position resolution allow the calorimeter to perform its main functions of:

- Electron identification
- $e/\mu$ separation to reject rare cosmic ray-induced background
- Cluster-seeded track finding and triggering

Full scale construction begins in 2017, commissioning begins at the end of this decade.