The Mu2e undoped CsI crystal Calorimeter

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on behalf of the Mu2e Calorimeter Group

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The Mu2e experiment

A search for Charged Lepton Flavor Violation (CLFV)

via the coherent conversion:

\[ \mu^- + \text{Al} \rightarrow e^- + \text{Al} \]

At Fermilab Muon Campus

Will improve by a factor \(10^4\) the world best sensitivity (SINDRUM II*) on:

\[
R_{\mu e} = \frac{\Gamma (\mu^- + N \rightarrow e^- + N)}{\Gamma (\mu^- + N \rightarrow \text{all captures})}
\]

down to \(3 \cdot 10^{-17}\)

SM prediction is \(O(10^{-54})\): any observation will be clear evidence for New Physics

The Mu2e Experiment at Fermilab: the muon beam

Production Solenoid: $p$ on tungsten, graded field sweeps low momentum particles downstream

Transport Solenoid: transmit negative particles with the right momentum, antiproton absorber

Detector Solenoid: Al stopping target, proton absorber, graded field to direct to detectors
The Mu2e Experiment at Fermilab: tracker

Tracker: >20k straw tubes each read by 2 ADCs and 2 TDCs

\[ \sigma_p \sim 180\text{keV/c} \]
\[ \sigma_t \sim 1\text{ ns} \]
Suppress background due to standard decays

Momentum resolution

Core sigma:
\[ 180\text{ keV/c} \]
High-side tail
\[ <1\% \]

Graded fields:
suppress background, increase sensitivity to muon conversion improving geometrical acceptance

Calorimeter
The Mu2e Experiment at Fermilab: cosmic veto

Cosmic ray induced events: 1 per day can mimic a 105 MeV/c conversion electron (CE)

Cosmic ray veto system surrounding Detector Solenoid and part of the Transport Solenoid

4 staggered layers of scintillator bars: inefficiency < $10^{-4}$
Requirements for Mu2e calorimeter

The Mu2e electromagnetic calorimeter (ECAL) is needed to:

- identify conversion electrons
- suppress cosmic muons by an additional factor ~200
- provide a tracking independent trigger to measure tracker trigger and track reconstruction efficiency
- (optional) seed the tracker pattern recognition to reduce hit combinations

ECAL must operate in an harsh experimental environment:

- magnetic field: 1 T
- vacuum: $10^{-4}$ Torr
- max ionizing dose: up to 90 krad (in 5 years including a 3 safety factor)
- max neutron fluence: $3 \times 10^{12} \text{n}_{(1\text{MeV})}/\text{cm}^2$ (in 5 years including a 3 safety factor)
- high particle rate also in selection window $\rightarrow$ granularity in time and space
The Mu2e calorimeter

**Geometry (acceptance optimized)**
2 disks spaced by 70 cm
inner radius: 37.4 cm
outer radius: 66 cm

**Active material:**
pure CsI crystals
674 crystals/disk
3.4x3.4x20 cm³

**Sensors:**
Arrays of 6 UV-extended of SiPMs
2 arrays/crystal of 14x20 mm² each

**Readout electronics:**
Preamplifiers on sensors back
Voltage control and Waveform Digitizers in crates around disks

**Calibration/monitoring system:**
Fluorinert liquid in front of each disk
Laser and electronic pulses
Calorimeter mechanics

- Source_Plate
- 10 Readout electronics crates
- Crystals
- SiPM+FEE support and cooling Plate
- Inner ring
- Outer ring
- Foot
- Zoom of SiPM/FEE disk and holders

- Manifolds
- Hydraulic connections
- Inner steps
- Outer steps
- Alignment targets
- SiPM running temperature at 0 °C, Coolant at -10 °C

SiPM = Silicon PhotoMultiplier
FEE = Front End Electronics
ECAL CsI crystals

Wrapping: 150 μm Tyvek foil

Quality tests in Caltech and Frascati (LNF):
- light yield, transmittance and response uniformity
- time response (slow component)
- ionizing and neutron rad hardness, induced emission

<table>
<thead>
<tr>
<th>Property</th>
<th>CsI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>4.51</td>
</tr>
<tr>
<td>Radiation length (cm)</td>
<td>1.86</td>
</tr>
<tr>
<td>Moliere Radius (cm)</td>
<td>3.57</td>
</tr>
<tr>
<td>Interaction length (cm)</td>
<td>39.3</td>
</tr>
<tr>
<td>dE/dX (MeV/cm)</td>
<td>5.56</td>
</tr>
<tr>
<td>Refractive index</td>
<td>1.95</td>
</tr>
<tr>
<td>Peak luminescence (nm)</td>
<td>310</td>
</tr>
<tr>
<td>Decay time (ns)</td>
<td>26</td>
</tr>
<tr>
<td>Light yield (rel. to NaI)</td>
<td>3.6%</td>
</tr>
<tr>
<td>Variation with temperature</td>
<td>-1.4% / deg-C</td>
</tr>
</tbody>
</table>

Intensity (arb. units) vs Wavelength (nm)
QA Tests on CsI crystals

- 3 Vendors tested: SICCAS, Saint Gobain, Amcryx
- First 2 selected because of lower slow component
- Measurement of optical properties (511 keV $\gamma$ along crystal axis):
  - Light Yield (LY) > 100 p.e/MeV (with PMT readout)
  - Longitudinal Response Uniformity (LRU) < 5%
  - Fast component to Total Ratio (F/T) > 75%

- Measurements of radiation hardness:
  - Radiation Induced Noise @1.8 rad/h < 0.6 MeV (phosphorescence)
  - LY Degradation < 40% after 100 krad (check 2 crystals/batch)
**UV extended SiPMs**

Each crystal is coupled with 2 arrays
Each array is the parallel of 2 series of 3 6x6 mm$^2$ SiPMs each:
- signal decay time $\sim$100 ns,
- redundancy x2

<table>
<thead>
<tr>
<th>Pixel pitch [µm]</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective photosensitive area [mm]</td>
<td>6.0 x 6.0</td>
</tr>
<tr>
<td>Number of pixel</td>
<td>14400</td>
</tr>
<tr>
<td>Window material</td>
<td>Silicon resin</td>
</tr>
<tr>
<td>Gain (at 25°C)</td>
<td>$2.4 \times 10^6$</td>
</tr>
<tr>
<td>PDE @ 310 nm</td>
<td>28%</td>
</tr>
</tbody>
</table>

Monolithic UV extended SiPM Particle Detection Efficiency (PDE):
$\sim$30% @ CsI emission peak

Gain at $V_{OP} = V_{BR} + 3V > 10^6$

Quality tests in LNF, Pisa and Caltech:
- dark current, breakdown voltage, PDE and gain vs Temperature
- time response
- hardness to ionizing and neutron radiation, mean time to failure (MTTF)
QA Tests on SiPMs: gain and uniformity

- 3 Vendors tested: Hamamatsu, Advansid, Sensl
- First selected because of better time response
- Selection criteria ensures sensor uniformity and photoelectrons yield
- Automatized station to test sensors at single cell level:
  - Breakdown voltage (Vbr) spread in sensor < 0.5%
  - Dark current spread in sensor < 15%
  - Gain > $10^6$ for each cell (on a 150 ns gate)
  - PDE > 20% for each cell
QA Tests on SiPMs: radiation hardness

- 2 samples/batch will be exposed to neutron flux up to $3 \times 10^{11} \text{n}_{1\text{MeVeq}}/\text{cm}^2$
- Requirement after irradiation: $I_d < 10 \text{ mA}$
- In Mu2e SiPMs will operate @ 0 °C to keep the dark current below 2 mA

- 15 samples/batch will be used to estimate the mean time to failure (MTTF)
- MTTF will be evaluated operating SiPMs @ 50 °C for 30 days
- No dead channels observed
  -> MTTF $\geq 6 \times 10^5 \text{ hours}$
Readout electronics

2 SiPM arrays/crystal
1 FEE board/array

FEE board:
amplification, shaping
and voltage regulation

Waveform Digitizer:
Reads 20 channels
at 200 Mhz
(1 sample each 5 ns)
“Module 0” prototype

• Large size prototype in April 2017:
  -> 51 crystals, 102 sensors
  -> 102 FEE prototype chips
  -> 5 MB boards prototype

• Assembled with crystals and SiPMs that passed the selection tests

• WD board prototypes under construction
“Module 0” test beam

- Module Zero tested in May 2017 at the BTF Facility (LNF) with a 100 MeV electrons beam
- 1 GHz CAEN high-speed digitizers (DRS4 chip) used as redout (2 boards x 32 channels)
- Waveforms re-sampled at 200 MHz with software algorithm

- Run Configuration:
  - Beam orthogonal @ 0 deg, fired on the center of each crystal to equalize channels
  - Beam @ 50 deg, the most probable incidence angle for Conversion Electrons, to evaluate performances

- Charge and time reconstruction:
  - **Charge**: Numerical integration of digitized samples in a 400 ns gate after pedestal subtraction
  - **Time**: Log-normal fit on leading edge, optimized constant fraction method used
“Module 0” performances for 100 MeV e\(^-\) at 50°

- Energy reconstructed by equalizing and summing first ring of crystals + 3 closer in beam direction
- Time resolution evaluated by the time difference of 2 sensors reading the most energetic crystal

\[ \sigma(\Delta t) = 358 \text{ ps} \]
\[ \sigma_1 = \frac{\sigma(\Delta t)}{\sqrt{2}} \sim 250 \text{ ps} \]

2 sens./crystal: \( \sigma_1 = \frac{\sigma(\Delta t)}{2} \sim 180 \text{ ps} \)

\[ \sigma(\Delta t) = 466 \text{ ps} \]
\[ \sigma_1 = \frac{\sigma(\Delta t)}{\sqrt{2}} \sim 330 \text{ ps} \]

2 sens./crystal: \( \sigma_1 = \frac{\sigma(\Delta t)}{2} \sim 230 \text{ ps} \)

Noise in test beam didn't allow to further extend clustering. Better results expected with final electronics. Nonetheless already with these results

Calorimeter time and energy resolutions satisfy the requirements
Mu2e Calorimeter tasks

☑ Provide energy resolution $\sigma_E/E$ of $<10\%$
☑ Provide timing resolution $\sigma(t) < 500~\text{ps}$

☑ Particle Identification capabilities with mu/e rejection of 200
☑ A trigger independent on tracker
☑ “Seeds” to improve track finding
Mu2e particle identification

Tracker track – calorimeter cluster association + likelihood using:
- time matching
- Energy/momentum ratio

- Conversion Electrons
- 105 MeV/c muons

Electron efficiency = 92.5%

Rejection factor 200 makes cosmic muon background negligible wrt cosmic induced electron background
Mu2e trigger and DAQ

Acquire:
- events (1.7 μs microbunch) with an high momentum electron within tracker acceptance within 500-1700 ns from proton pulse
- calibration events

Bandwidth from average event size: ~31GB/s
Storage limit: 7 PB/y ~ 0.7 GB/s

Trigger requirements:
Event rate suppression: ~100
Event processing time: < 3.6 ms

Trigger Example
Calorimeter trigger using shower peak amplitude, time and position and highest energy deposits in neighbour crystals:
Efficiency on physics dataset: 85-90%
Rejection factor: 100
Processing time: 1 ms
Calorimeter seeded pattern recognition

1.7 μs event (no hit selection)

Select tracker hits matching time and position of ECAL cluster

1.7 μs event (hit selection)

Track reconstruction efficiency improves and is more stable against background level
Summary and Outlook

- Mu2e calorimeter is a key component of the Mu2e experiment that will improve by a factor $10^4$ the existing limit on charged lepton flavor violating conversion of muons to electrons in the atomic field.

- Simulation supported by quality tests and test beam results confirms that the proposed ECAL design is able to operate in the Mu2e harsh environment performing muon identification, track seeding and trigger at the desired level.

- Preproduction crystals and photosensors have been fully characterized and QA and QC procedures have been set.

- Crystals and photosensors will start to be produced at the end of 2017 and will undergo massive QA tests in 2018.

- Module 0 prototype has been tested. A full scale mockup is underway.

- Calorimeter assembly will start at the end of 2018 and will be completed at beginning of 2020 in time for the Mu2e commissioning.
Backup
Mu2e schedule
## Mu2e background after 3 years (3.6x10^{20} POT)

<table>
<thead>
<tr>
<th>Process</th>
<th>Event Yield</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIO</td>
<td>0.14±0.11</td>
<td></td>
</tr>
<tr>
<td>RMC</td>
<td>&lt;0.004</td>
<td>Kinematically suppressed</td>
</tr>
<tr>
<td>Pion capture</td>
<td>0.025±0.003</td>
<td>Cross section can be measured</td>
</tr>
<tr>
<td>Muon DIF</td>
<td>&lt;0.003</td>
<td></td>
</tr>
<tr>
<td>Pion DIF</td>
<td>0.001± 0.001</td>
<td></td>
</tr>
<tr>
<td>Beam electrons</td>
<td>(2.5±1.2)x10^{-4}</td>
<td>Assumes 10^{-10} extinction factor</td>
</tr>
<tr>
<td>Antiprotons</td>
<td>0.05±0.02</td>
<td></td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>0.25±0.07</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>0.5±0.1</td>
<td></td>
</tr>
</tbody>
</table>

Single Event Sensitivity = [3.01±0.03(stat)±0.41(syst)]x10^{-17}
“Modulo 0” performances for 100 MeV e− at 0°

- Energy reconstructed by equalizing and summing first ring of crystals + 3 closer in beam direction
- Time resolution evaluated by the time difference of 2 sensors reading the most energetic crystal

\[ \sigma_t = \frac{\sigma(\Delta t)}{\sqrt{2}} \]

\[ \sigma_t = \frac{\Delta t}{2} \approx 140 \text{ ps} \]

\[ \sigma_t = \frac{\Delta t}{2} \approx 210 \text{ ps} \]

Noise in test beam didn’t allow to further extend clustering.
Better results expected with final electronics.
2015 Test beam results

80->120 MeV electron beam at
Beam Test Facility (BTF) in Frascati

σ_t <150 ps for 100 MeV e^-

σ/E~7% for 100 MeV e^- at 50° (LEAKAGE dominated)
Calorimeter calibration

← 6 MeV liquid source in front of crystals (energy calibration)

Laser pulses (energy and time Calibration)
FEE pulses

→

← Cosmic muons (energy and time calibration)
E/\rho \text{ and } \Delta t \text{ from muon decays in orbit (DIO) and } \pi \rightarrow e\nu \text{ decays at reduced B field (energy and Tracker-ecal time)}

→

DIO spectrum
Calorimeter cooling
Qualification of electronic components

- FPGA
  - SEL free
  - SEU free

→

DCDC converter in magnetic field

DCDC converter n irradiation
(1.5x10^{11} n/cm^2 @ 1 MeV_{eq} = 3 years)

ADC after 20 krad
(1.5 krad = 3 years)
Expected performances from simulation: x, y, E, t

- $\sigma_x \sim 16\,\text{mm}$
- $\sigma_y \sim 16\,\text{mm}$
- $\sigma_E/E \sim 4\%$
- $\sigma_t \sim 110\,\text{ps}$

CE + background

CE only
Mu2e track reconstruction

A typical Mu2e tracker event integrated over 500-1695 ns window

Hits filtered according to their time, energy and position
Low momentum electrons hits rejected by dedicated algorithm
Candidate tracks searched by grouping hits in 50 ns time windows
Mu2e track reconstruction

1.7 μs event (no hit selection)

Select tracker hits matching time and position of ECAL cluster

1.7 μs event (ECAL hit selection)

Calorimeter information helps track reconstruction and makes it more stable against background level