The Mu2e crystal calorimeter

Eleonora Diociaiuti
LNF-INFN and Tor Vergata University
on behalf of the Mu2e calorimeter group

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Talk overview

• The Mu2e experiment
  - CLFV introduction
  - Experiment layout

• Mu2e Electromagnetic Calorimeter
  - Components
  - Performance
  - Production status
Charged Lepton Flavor Violation

- **CLFV processes are forbidden in SM**
  - Even allowing neutrino oscillation BR ~ $10^{-54}$

- **Observation of a CLFV process: clear evidence of New Physics**

- **Mu2e**: Coherent muon conversion in the electric field of a nucleus
  - Broad sensitivity across different models
  - Very clear signature: **monoenergetic electron**

  \[
  R_{\mu e} = \frac{\mu^- + N(A, Z) \rightarrow e^- + N(A, Z)}{\mu^- + N(A, Z) \rightarrow \nu_\mu + N(A, Z - 1)} < 8 \times 10^{-17}
  \]

- **Improve of 4 orders of magnitude** the previous limit set by the SINDRUM II experiment ($6.1 \times 10^{-13}$)

More info in G. Pezzullo talk
**The Mu2e experiment**

**PRODUCTION SOLENOID**
- Protons hitting the target and producing mostly $\pi$
- Graded magnetic field reflects slow forward $\pi$

**TRANSPORT SOLENOID**
- $\pi$ decay to $\mu$
- Selection and transportation of low momentum $\mu^-$

**DETECTOR SOLENOID**
- Capture $\mu$ on the Al target
- Momentum measurement in the tracker and energy reconstruction with calorimeter
- CRV to veto cosmic ray events
High acceptance for reconstructing energy, time and position of signals for:

- **Particle Identification:** $e/\mu$ separation $\rightarrow$ reject $\mu$ background
- Improve the track pattern recognition
- Standalone trigger

### Calorimeter requirements

- Energy resolution $\sigma_E/E < 10\%$
- Timing resolution $\sigma(t) < 500$ ps
- Position resolution $< 1$ cm
- Work in vacuum @ $10^{-4}$ Torr
- 1 T Magnetic Field

### Crystals coupled with Silicon PhotoMultipliers (SiPM)

- Light Yield (photosensor) $> 20$ pe/MeV
- Fast signal for pileup and timing
- **Survive an high radiation environment**
  - Total Ionizing Dose (TID) of 90 krad/5 year for crystal
  - TID of 75 krad/5 year for sensor
  - $3 \times 10^{12}$ n/cm$^2$ for crystal
  - $1.2 \times 10^{12}$ n/cm$^2$ for sensor

@ 105 MeV
Calorimeter Design

2 disks each with 674 undoped (34x34x200)mm$^3$ square pure CsI crystals

- Readout: 2 UV-extended SiPMs/crystal
- Analog FEE and digital electronics located in near-by electronics crates
- Source for energy calibration
- Laser system for monitoring gain stability
The calorimeter energy resolution is estimated taking into account signal and predominant background, as the difference of the conversion electron energy and the cluster energy.

\[ \text{FWHM/2,35} = 3.8 \pm 0.1 \text{ MeV} \]

The overall resolution depends on the crystal features.
Crystal preproduction

- 24 crystals from three different vendors: **SICCAS**, **Amcryys**, **Saint Gobain**
- $^{22}$Na source to test crystal properties along the crystal axis
- Crystals coupled in air to an UV-extended PMT

**Optical properties:**
- 100 pe/MeV with PMT readout
- LRU < 5%
- Fast/Total > 75%

**Radiation hardness**
- Smaller than 40% LY loss @ 100 krad
- Radiation Induced Noise <0.6 MeV

Selected vendors: **SICCAS** and **Saint Gobain**
SiPM preproduction

- 2 arrays of three 6x6 mm$^2$ SiPMs
  - total active area of (12x18) mm$^2$
  - 50 µm pitch
- Photon Detection Efficiency (@ 315 nm) > 20%
- The series configuration implies narrower signals
- **150 Pre-production SiPMs** (3×50 Mu2e SiPMs from Hamamatsu, SensL and AdvanSiD):
  - 3×35x6 cells fully characterized ($V_{op}$, $G$, $I_{dark}$, $PDE$)
  - 1 sample/vendor exposed up to a fluence of $8.5 \times 10^{11}$ n$_{1MeVeq}$/cm$^2$ (@ 20 °C)
  - Mean Time To Failure estimated by operating 15 SiPM at 50 °C for 3.5 months → MTTF > 0.6x10$^6$ h

Selected vendor: Hamamatsu
Module-0

Large size prototype: 51 crystals coupled to 102 sensors

- Goals:
  - Test the performances
  - Test integration and assembly procedures
  - e⁻ beam (60-120 MeV), May 2017
    - Orthogonal and 50° incidence (CE)
  - Operate under vacuum, low temperature and irradiation tests
- Readout: 1 GHz CAEN digitizers (DRS4 chip), 2 boards x 32 channels
Module-0: Energy resolution

- Single particle selection
- Calibration:
  - Cosmic
  - Beam

Orthogonal Run: 
$\sigma_E \sim 5\%$

Tilted Run: 
$\sigma_E \sim 7.5\%$

@ $E_{\text{beam}} = 100$ MeV

Orthogonal incidence

50° incidence
Module-0: Single Sensor Time resolution

- Log Normal fit on leading edge
- Constant Fraction method used CF = 5%
- Comparison between 1GHz (TB sampling) and 200 MHz (Mu2e sampling) shows no deterioration in the resolution

σ (T1+T2)/√2 ~ 132 ps
@ E_{beam} = 100 MeV

Central Crystal

Entries / (0.0075 ns)

- Constant: 240.9 ± 7.6
- Mean: 0.1664 ± 0.0049
- Sigma: 0.1874 ± 0.0035

Perpendicular beam
- 1 GHz sampling rate
- 200 MHz sampling rate

σ_t = \frac{a}{E} \oplus b
QA room @ FNAL for production

- QA tests started on March 2018
  - ~1000 SiPMs tested (25% of the total number)
  - ~300 crystals (23% of the total number)

### CsI dimensional test

![CsI QA diagram]

- Motor on the back moves source + tagger
- Rotating motor (to test a and b sides)
- Translation motor (CsI & sphere)

### CsI RIN

- 2 SiPMs per crystal
- 2 crystals tested at the same time

### SIPM dimensional test

![SIPM QA diagram]

- LED driver
- SiPM Power
- UV PMT
- Diffusing sphere (Gain measurement)

### SiPM QA

- S.Giovannella – Status of QA–CsI – 1 March 2018

### Automation for crystal station completed. Four motors to test both a and b sides

- CsI RIN
- CsI QA
- CsI dimensional test
- SiPM dimensional test
- SiPM QA
- SiPM MTTF

07/07/2018

E. Diociaiuti | LNF-INFN
First QA results - Crystal

- 99% of crystals satisfy the specifications concerning optical properties
- Some problems to satisfy the mechanical specs

07/07/2018
First QA results - SiPMs

- 96% of SiPMs satisfy the Mu2e requirements
- Performances after the irradiation OK

- MTTF > 4x10^6 hours

- 38 rejected SiPMs (3.4%)
Summary

• **Mu2e calorimeter** is a state of the art Crystal Calorimeter with energy (<10 %) and timing (< 500 ps) resolution @ 100 MeV.

• Preproduction of crystals and SiPMs completed
  - Un-doped CsI crystals perform well
  - Mu2e SiPMs performances in agreement with requirements

• Large size prototype tested with e⁻ beam in May 2017
  - Good time (~100 ps) and energy resolution (~8%) achieved @ 100 MeV

• Calorimeter production **phase started in March 2018**

• Detector installation expected to begin in 2020
spares
Vendor Comparison - time

\[ E_{\text{beam}} = 100 \text{ MeV} \]

\[ T_{\text{rise}} = T_{90\% \text{ max}} - T_{10\% \text{ max}} \]

- Hamamatsu - \( T_{\text{rise}} = 29 \text{ ns} \)
- SensL - \( T_{\text{rise}} = 38 \text{ ns} \)
- AdvanSiD - \( T_{\text{rise}} = 37 \text{ ns} \)

\[ \sigma^2_{\text{tot}} = \sigma^2_{\text{Landau}} + \left( \frac{t_{\text{rise}}}{S/N} \right)^2 + \left( \frac{V_{\text{thr}}}{S/t_{\text{rise}}} \right)^2 \]

- Hamamatsu
  - \( \sigma_T \sim 93.5 \pm 2 \text{ ps} \)
  - Entries: 1531
  - \( \chi^2 \text{/ ndf}: 19.56 / 15 \)
  - Constant: 240.9 \pm 7.6
  - Mean: 0.1664 \pm 0.0049
  - Sigma: 0.1874 \pm 0.0035

- SensL
  - \( \sigma_T \sim 115 \pm 2 \text{ ps} \)
  - Entries: 1657
  - \( \chi^2 \text{/ ndf}: 18.68 / 23 \)
  - Constant: 237.8 \pm 7.0
  - Mean: 0.1584 \pm 0.0054
  - Sigma: 0.2313 \pm 0.0042

- AdvanSiD
  - \( \sigma_T \sim 106.5 \pm 2.1 \text{ ps} \)
  - Entries: 1633
  - \( \chi^2 \text{/ ndf}: 29.69 / 21 \)
  - Constant: 225.1 \pm 7.2
  - Mean: 0.1647 \pm 0.0054
  - Sigma: 0.2131 \pm 0.0043
Small prototype TB

- Small prototype tested @ BTF (Frascati) in April 2015, 80-120 MeV e⁻
- 3×3 array of 30×30×200 mm² undoped CsI crystals coupled to one Hamamatsu SiPM array (12x12) mm² with Silicon optical grease
- DAQ readout: 250 Msps CAEN V1720 WF Digitizer

Good agreement between the DATA and MC

Log-normal fit

\[ \chi^2/\text{ndf} = 101.6/66 \]

\[ \eta = 0.3457 \pm 0.0204 \]

\[ \sigma = 6.106 \pm 0.092 \]

\[ E_{\text{peak}} = 85.47 \pm 0.17 \]

\[ N = 3999 \pm 66.7 \]
Single channel slice test

SG crystal + Hamamatsu SiPM + FEE
Optical coupling in air.

- $^{22}$Na source
  - TRG: small scintillator readout by a PMT
  - Study distance effect for air-coupling

- Cosmic ray test $\rightarrow$ 2 SiPMs readout
  - TRG: crystal between 2 small scintillators

~ 10% loss
Single channel – CR test

- TRG time resolution \( \sim 170 \) ps
- Constant fraction method used
- Pulse height correction applied (slewing)

After jitter subtraction:
- SiPM 1 – \( \sigma_T \sim 330 \) ps
- SiPM 2 – \( \sigma_T \sim 340 \) ps

\[ T(\text{SiPM1 - SiPM2})/2 \rightarrow \sim 215 \text{ ps} \]

@ \( \sim 23 \) MeV energy deposition
(MIP energy scale from Na\(^{22}\) source peak)

Timing result well compares with old tests:
- Reduced light output/SiPM
  (22 vs 30 pe/MeV)
- 2 SiPMs/crystal
- LY of 44 vs 30 \( \rightarrow \) 215 ps (now) vs 250 ps (old).
With a CRV inefficiency of $10^{-4}$ an additional rejection factor of $\sim 200$ is needed to have $< 0.1$ fake events from cosmic in the signal window.

- 105 MeV/c $e^-$ are ultra-relativistic, while 105 MeV/c $\mu$ have $\beta \sim 0.7$ and a kinetic energy of $\sim 40$ MeV
- Likelihood rejection combines

$$\Delta t = t_{\text{track}} - t_{\text{cluster}} \text{ and } E/p:\n\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta t) + \ln P_{e,\mu}(E/p)$$

$\mu$ mimicking the CE

A rejection factor of 200 can be achieved with $\sim 95\%$ efficiency for CE
Calorimeter Calibration

- Liquid source FC 770 + DT generator: 6 MeV + 2 escape peaks
- Laser system to monitor SiPM performance
Calorimeter trigger

- Calo info can provide additional trigger capabilities in Mu2e:
  - Calorimeter seeded track finder
    - Factorized into 3 steps: hit pre-selection, helix search and track fit
    - $\epsilon \sim 95\%$ for background rejection of 200
  - Standalone calorimeter trigger that uses only calo info
    - $E \sim 65\%$ for background rejection 200
Calorimeter seeded track finder

- Cluster time and position are used for filtering the straw hits:
  - time window of ~ 80 ns
  - spatial correlation

  **no selection**

  **calorimeter selection**

- **black crosses** = straw hits, **red circle** = calorimeter cluster, **green line** = CE track
Calorimeter Mechanics

SiPM = Silicon PhotoMultiplier
FEE = Front End Electronics
Background for Mu2e

• Intrinsic physics background:
  - Muon Decay in Orbit (DIO) → end point @ signal energy
  - Radiative Muon Capture → πN → γN'; γ → e⁺e⁻
  - Neutron from muon nuclear capture
  - Proton from muon nuclear capture

• Beam related backgrounds:
  - Radiative Pion Capture (RPC)
  - Beam electron
  - Muon decay in flight
  - Neutron
  - Antiprotons producing pions when annihilating in the target

• Cosmic rays
DIO background

• Electron energy distribution from the decay of bound muons follows a modified-Michel spectrum:

  o The Michel spectrum is distorted by the presence of the nucleus and the electron can have an energy similar to the one of CE if neutrino are almost at rest

→ To separate DIO endpoint from CE line Mu2e needs an high Resolution Spectrometer
Minimizing prompt background

- Prompt backgrounds arise from the interaction occurring at the stopping target
  - Radiative Pion Capture \( (\tau_{\pi}^{\text{Al}} = 26 \text{ ns}) \): \( \pi^- N \rightarrow \gamma N^* \rightarrow e^+ e^- N^* \)
  - \( \pi/\mu \) decay in flight
- **Muonic atomic life >> prompt background**
- Narrow pulsed proton beam
- Delayed signal window starting 700 ns after the initial proton pulse
- Out-of-time proton suppressed by \( O(10^{10}) \)

![Graph showing POT pulse and arrival/capture times](image)