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

More info in G. Pezzullo talk

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

$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} = 104.96 MeV$$

μ-e conversion in the field of a nucleus

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

Nuclear capture of muonic Al atom

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

The Mu2e experiment

PRODUCTION SOLENOID

- Protons hitting the target and producing mostly π
- Graded magnetic field reflects slow forward π

TRANSPORT SOLENOID

- π decay to μ
- Selection and transportation of low momentum μ^-

DETECTOR SOLENOID

- Capture μ on the Al target
- Momentum measurement in the tracker and energy reconstruction with calorimeter
- CRV to veto cosmic ray events

Calorimeter requirements

High acceptance for reconstructing energy, time and position of signals for:

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

@ 105 MeV

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
 - 3×10^{12} n/cm² for crystal
 - 1.2×10^{12} n/cm² for sensor

Calorimeter Design

2 disks each with 674 undoped (34x34x200)mm³ 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

Mu2e EMC: MC performance

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**, **Amcrys**, **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 mm² SiPMs
 - total active area of (12x18) mm²
 - 50 μ m pitch
- Photon Detection Efficiency (@ 315 nm) > 20%
- The series configuration $\rightarrow$ narrower signals
- **150 Pre-production SiPMs** (3x50 Mu2e SiPMs from **Hamamatsu**, **SensL** and **AdvanSiD**):
 - 3x35x6 cells fully characterized (**V_{op}**, **G**, **I_{dark}**, **PDE**)
 - 1 sample/vendor exposed up to a fluence of 8.5×10^{11} n_{1MeVeq}/cm² (@ 20 °C)
 - Mean Time To Failure estimated by operating 15 SiPM at 50 °C for 3.5 months $\rightarrow$ MTTF > 0.6×10^6 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 :
 $\sigma_E \sim 7.5\%$
 @ $E_{\text{beam}} = 100 \text{ MeV}$

Module-0: Single Sensor Time resolution

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

$$\sigma (T1+T2)/\sqrt{2} \sim 132 \text{ ps}$$

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

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

CsI RIN

SiPM dimensional test

SiPM QA

SiPM MTF

First QA results - Crystal

Dimensional test

Optical test

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

RIN test

First QA results -SiPMs

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

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($\sim 8\%$) achieved @ 100 MeV
- Calorimeter production **phase started in March 2018**
- Detector installation expected to begin in 2020

spares

Vendor Comparison -time

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

Energy fluctuation

CF discriminator

Small prototype TB

JINST 12 (2017) P05007

- Small prototype tested @ BTF (Frascati) in April 2015, 80-120 MeV e^-
- 3×3 array of $30 \times 30 \times 200$ mm³ undoped CsI crystals coupled to one Hamamatsu SiPM array (12x12) mm² with Silicon optical grease
- DAQ readout: 250 Msps CAEN V1720 WF Digitizer

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 → 2 SiPMs readout
 - TRG: crystal between 2 small scintillators

Single channel – CR test

- TRG time resolution ~ 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

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

@ ~ 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 → 215 ps (now) vs 250 ps (old).

Particle Identification

With a CRV inefficiency of 10^{-4} an additional rejection factor of ~ 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 μ have $\beta \sim 0.7$ and a kinetic energy of ~ 40 MeV

- Likelihood rejection combines

$$\Delta t = t_{\text{track}} - t_{\text{cluster}}$$

$$\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta t) + \ln P_{e,\mu}(E/p)$$

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

Liquid source prototype

Laser system - test station

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) $\rightarrow$ end point @ signal energy
 - Radiative Muon Capture $\rightarrow \pi N \rightarrow \gamma N'$; $\gamma \rightarrow e^+e^-$
 - 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:
 - 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 ($\tau_{\pi}^{\text{Al}} = 26 \text{ ns}$) $\pi^{-} N \rightarrow \gamma N^{*} \rightarrow e^{+} e^{-} N^{*}$
 - π/μ decay in flight
- **Muonic atomic life $\gg$ prompt background**
- Narrow pulsed proton beam
- Delayed signal window starting 700 ns after the initial proton pulse
- Out-of-time proton suppressed by $O(10^{10})$