Design and status of the Mu2e crystal calorimeter

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On behalf of the Mu2e calorimeter group

Meeting of the American Physical Society Division of Particles and Fields
Fermilab, July 31 – August 4, 2017
• Charged Lepton Flavor Violation (CLFV)
  o Introduction to Mu2e
  o Mu2e Detector

• **Electromagnetic calorimeter**
  o Requirements
  o Components
  o Single Channel Tests
  o “Module-0” performance
• CLFV strongly suppressed in SM: Branching Ratio $\leq 10^{-54}$
  $\Rightarrow$ Observation would indicate New Physics

• CLFV@Mu2e: $\mu$ - $e$ conversion in a nucleus field
  $\Rightarrow$ discovery sensitivity to many NP models

• Goal:
  $10^4$ improvement w.r.t. current limit (SINDRUM II)

  $\mu$-$e$ conversion in the presence of a nucleus

  $$ R_{\mu e} = \frac{\mu^- + N(A, Z) \rightarrow e^- + N(A, Z)}{\mu^- + N(A, Z) \rightarrow \nu_{\mu} + N(A, Z - 1)} \leq 8.4 \times 10^{-17} $$

  Nuclear captures of muonic Al atoms

  (@ 90% CL, with ~ $10^{18}$ stopped muons in 3 years of running)
Mu2e experiment design

1. Generate low momentum $\mu^-$ beam
2. Stop the muons in an Al target $\rightarrow$ trapped in orbit around the nucleus
3. Look for an excess around 105 MeV/c in the electron spectrum

**Production Solenoid / Target**
- Protons hitting target and producing mostly $\pi$

**Transport Solenoid**
- Selects and transports low momentum $\mu^-$

**Detector Solenoid: stopping target and detectors**
- Stops $\mu^-$ on Al foils
- Events reconstructed by detectors optimized for 105 MeV/c momentum

More information in Y.Oksuzian talk and A.Lucà poster

The Mu2e Calorimeter, R.Donghia
The electromagnetic calorimeter (EMC) should provide high acceptance for reconstructing energy, time and position of CEs for:

1) **PID**: $e/\mu$ separation
2) EMC seeded track finder
3) Standalone trigger

**Requirements @ 105 MeV/c**

- $\sigma_E/E = \varnothing(5\%)$ for CE
- $\sigma_T < 500$ ps for CE
- $\sigma_{X,Y} \leq 1$ cm
- Fast scintillation signals ($\tau < 40$ ns)
- Operate in 1 T and in vacuum at $10^{-4}$ Torr
- Redundancy in readout (2 sensors+FEE/crystal)
- **Radiation hardness (with a safety factor of 3):**
  - 100 krad (45 krad) dose for crystals (sensors)
  - $3 \times 10^{12} n_{1\text{MeV/cm}^2}$ ($1.2 \times 10^{12} n_{1\text{MeV/cm}^2}$) for crystals (sensors)
- Low radiation induced readout noise < 0.6 MeV
The Mu2e Calorimeter, R. Donghia

2 annular disks with 674 undoped CsI (34 x 34 x 200) mm³ square crystals/each disk

- $R_{IN} = 374$ mm, $R_{OUT} = 660$ mm
- Depth = 10 $X_0$ (200 mm), Distance 70 cm
- Readout: 2 UV-extended SiPMs/crystal
- FEE on the SiPMs, Digital readout on crates
- RA source for energy calibration
- Laser system for monitoring
Simulation includes full background and digitization and cluster-finding, with split-off and pileup recovery.

Simulation of CsI+SiPM performance

Simulation includes full background and digitization and cluster-finding, with split-off and pileup recovery.

Energy resolution

Dependence on LRU and photostatistics

Specification is LRU < 5%

Nominal photoelectron yield is 30 pe/MeV, dropping to 20 pe/MeV after irradiation.

LRU: RMS/MEAN of Light Output values along axis
Small prototype: Test Beam

- Small prototype tested @ BTF (Frascati) in April 2015, 80-120 MeV $e^-$
- 3×3 array of 30×30×200 mm$^3$ undoped CsI crystals coupled to one Hamamatsu SiPM array (12×12) mm$^2$ with Silicon optical grease
- DAQ readout: 250 Msps CAEN V1720 WF Digitizer

Good agreement between the DATA and MC

Log-normal fit
Time and Energy resolution

Significant leakage contribution due to block dimensions w.r.t. the shower.

\[ \sigma_E \approx 6.5\% \text{ at } 100 \text{ MeV} \]

\[ \sigma_T \approx 110 \text{ ps at } 100 \text{ MeV} \]

1 year long R&D phase for the final test of the option CsI + UV extended SiPM.

72 crystals + 150 SiPM + 150 FEE chips completed in 2016.
Pre-production Crystals

- 24 crystals from three different vendors: **SICCAS, Amcrys, Saint Gobain**
- Optical properties tested with 511 keV γ's along the crystal axis
- Crystals wrapped with 150 µm of Tyvek and coupled to an UV-extended PMT

**Un-doped CsI crystals perform well**

- **Excellent LRU and LY:**
  - 100 pe/MeV with PMT readout
  - LRU < 5%

- τ of 30 ns with small slow component

- **Radiation hardness OK**
  Smaller than 40% LY loss
  @ 100 krad

More information in B.Echenard talk

• The Mu2e Calorimeter, R.Donghia

August 2, 2017 10
Pre-production test: SiPMs (1)

Mu2e custom silicon photosensors:

$\rightarrow$ 2 arrays of $3 \times 6 \times 6 \text{ mm}^2$ UV-extended SiPMs: total area $(12 \times 18) \text{ mm}^2$

The readout series configuration reduces the overall capacitance and allows us to generate faster signals.

150 sensors: $3 \times 50$ Mu2e pre-production SiPMs from Hamamatsu, SenSi and AdvanSiD

- $3 \times 35$ were fully characterized for all six cells in the array.

Gain

Operating Voltage

$\sim 150 \text{ V}$

More information in poster session
Large EMC prototype: **51 crystals, 102 SiPMs, 102 FEE boards**

**Mechanics and cooling system similar to the final ones!**

**Goals:**
- Integration and assembly procedures
- Test beam May 2017, 60-120 MeV $e^-$
  Analysis in progress
- Next: work under vacuum, low temperature, irradiation test
- Log-normal fit on leading edge
- Constant Fraction method used $\rightarrow$ CF = 5%
- Selection on single particle

**Fit Example**

**Central crystal time distribution**

$$ (T_{SiPM_1} - T_{SiPM_2}) $$

$\sigma (T1+T2)/2 \sim 94$ ps

$@ E_{beam} = 100$ MeV
- Calibration completed for first ring around central crystal
- Noise observed in test beam too high to extend calorimeter clustering after first ring
- Data quality still good to extract preliminary resolution in agreement with 3x3 prototype

\[ \sigma_E \sim 7.3\% \text{ within } 1^\circ \text{ ring} \]

@ \[ E_{\text{beam}} = 100 \text{ MeV} \]
The Mu2e calorimeter has concluded its prototyping phase satisfying the Mu2e requirements:

- **Un-doped CsI crystals perform well**
  - Excellent LRU and LY 100 pe/MeV (PMT+Tyvek wrapping)
  - $\tau$ of 30 ns with negligible slow component
  - Radiation hardness OK for our purposes: 40% LY loss at 100 krad

- **Mu2e SiPMs quality OK**, high gain, high PDE, small $I_{\text{dark}}$, small spread inside array
  - SiPM performance after irradiation OK
  - SiPM MTTF > 0.6 million hours

- **Single calorimeter channel**: timing resolution of 215 ps /MIP

- **Small prototype** tested with e⁻ beam
  - Good time and energy resolution achieved @ 100 MeV

- **Module 0 built and first tests done**. Data analysis is still ongoing
  - Preliminary results satisfies the requirements

- Calorimeter production phase will start by the end of 2017
- Detector installation expected for beginning of 2020
Spares

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  \( \mu - e \) conversion in the presence of a nucleus

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

Nuclear captures of muonic Al atoms

(@ 90% CL, with ~ 10^{18} stopped muons in 3 years of running)

- The Mu2e Calorimeter, R.Donghia

More information in Y.Oksuzian talk
• 1 sample per vendor has been exposed to neutron flux up to $8.5 \times 10^{11} \text{n}_{1\text{MeVeq}}/\text{cm}^2$ (@ 20 °C)

• 5 samples per vendor have been used to estimate the mean time to failure value

Requirement: obtain an MTTF of 1 million hours when operating at 0 °C

SiPMs will operate @ 0 °C: a decrease of 10 °C in SiPMs temperature corresponds to a $I_d$ decrease of 50%

Lower $V_{op}$ also helps to decrease the $I_d$

MTTF evaluated operating SiPMs @ 50 °C for 3.5 months

No dead channels observed

MTTF ≥ $6 \times 10^5$ hours
SG crystal + Hamamatsu SiPM + FEE
Optical coupling in air.

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

- \textbf{Cosmic ray test} \rightarrow 2 SiPMs readout
  - TRG: crystal between 2 small scintillators

\begin{itemize}
  \item \textbf{Cosmic ray test} \rightarrow 2 SiPMs readout
    - TRG: crystal between 2 small scintillators
\end{itemize}
• TRG time resolution ~ 170 ps
• Constant fraction method used
• Pulse height correction applied (slewing)

After jitter subtraction:

SiPM 1 – \( \sigma_T \) ~ 330 ps
SiPM 2 – \( \sigma_T \) ~ 340 ps

\[ T(\text{SiPM}1 - \text{SiPM}2)/2 \rightarrow \sim 215 \text{ ps} \]

@ ~ 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 \( \rightarrow \) 215 ps (now) vs 250 ps (old).
Few samples per vendor have been exposed both to \textit{ionizing dose} and \textit{neutrons}.

- Irradiation test up to 100 krad.
- Requirement: normalized LY \textit{after 10/100 krad} > 85/60%.

**Most crystals have LY larger than 100 p.e./MeV after 100 krad (40% max. loss), promising a robust CsI calorimeter.**

- \textbf{Radiation Induced Noise (RIN)} \textit{@} 1.8 rad/h required is < 0.6 MeV
  - All 72 samples tested. All OK apart some Amcrys crystals that do not satisfy the required limit.
  - Negligible LY and LRU variation after $1.6 \times 10^{12} \text{n}_{\text{MeV/cm}^2}$ \textit{integrated flux}.
  - Neutron RIN is also smaller than the one from dose.
With a CRV inefficiency of $10^{-4}$ an additional rejection factor of ~ 200 is needed to have < 0.1 fake events from cosmics 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 ~ 40 MeV.
- Likelihood rejection combines
  $$\Delta t = t_{\text{track}} - t_{\text{cluster}} \text{ and } E/p:$$
  $$\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta t) + \ln P_{e,\mu}(E/p)$$

**$\mu$ mimicking the CE**

A rejection factor of 200 can be achieved with ~ 95% efficiency for CE.

- The Mu2e Calorimeter, R. Donghia
Calibration source and laser

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

The Mu2e Calorimeter, R. Donghia

10k entries/crystal/min

Liquid source prototype

Laser system - test station
• 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
    • \( \varepsilon \approx 95\% \) for background rejection of 200
  • Standalone calorimeter trigger that uses only calo info
    • \( E \approx 65\% \) 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](image1)
  ![Calorimeter selection](image2)

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

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The Mu2e Calorimeter, R.Donghia

August 2, 2017
Calorimeter radiation damage

- Calorimeter radiation dose driven by beam flash (interaction of proton beam on target)
- Dose from muon capture is x10 smaller
- Dose is mainly in the inner radius
- Highest dose ~10 krad/year
- Highest n flux on crystals ~ $2 \times 10^{11}$ n/cm$^2$/year
- Highest n flux on SiPM ~ $10^{11}$ n$_{1\text{MeVeq}}$/cm$^2$/year

- Qualify crystals up to ~ 100 krad, $10^{12}$ n/cm$^2$
- Qualify SiPM up to ~ $10^{12}$ n$_{1\text{MeVeq}}$/cm$^2$

This includes a safety factor of 3 for a 3 year run.
Calorimeter radiation damage

- Offline simulation including background hits
- Experimental effects included: longitudinal response uniformity (LRU), electronic noise, digitization, etc
- Waveform-based analysis to improve pileup separation

pile-up separation

CE + background
Three years run
Expectation by full Simulation

\[
\begin{align*}
\text{stat. errors only} \\
N_{\text{POT}} &= 3.6 \times 10^{20} \\
R_{\mu-e} &= 10^{-16} \\
N_{\text{CE}} &= 3.72 \pm 0.01 \\
N_{\text{DIO}} &= 0.20 \pm 0.02 \\
\end{align*}
\]

No PID selection applied

Signal Window
\[103.85 < p < 105.10 \text{ MeV/c}\]
The Mu2e Calorimeter, R. Donghia

\[ L_{CLFV} = \frac{m_\mu}{(\kappa + 1)} \Lambda^2 \bar{\mu} R \sigma_{\mu \nu} e_L F^{\mu \nu} + \frac{\kappa}{(1 + \kappa)} \Lambda^2 \bar{\mu} L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L) \]

Loops dominate for \( \kappa \ll 1 \)

\[ \mu \rightarrow e \gamma \]

\[ \mu N \rightarrow eN \]

\[ \mu \rightarrow eee \]

Contact terms dominate for \( \kappa \gg 1 \)

\[ \mu \rightarrow e \gamma \]

\[ \mu N \rightarrow eN \]

\[ \mu \rightarrow eee \]