Design and test of the Mu2e undoped CsI + SiPM crystal calorimeter

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On behalf of the Mu2e calorimeter group

May 29, 2018
Frontier Detectors for Frontier Physics
14th Pisa Meeting on Advanced Detectors
• Mu2e
  o CLFV Introduction
  o Experiment layout and detectors

• Calorimeter requirements
  o Components
  o Single Channel Tests
  o Prototypes’ performance
  o Production phase
Charged Lepton FlavorViolation

• CLFV strongly suppressed in SM: Branching Ratio $\leq 10^{-54}$
  → Observation would indicate New Physics

• CLFV@Mu2e: $\mu$ - e conversion in a nucleus field
  → 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

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

Nuclear captures of muonic Al atoms

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

Mu2e Calorimeter, R.Donghia

$E_{CE} = m_\mu c^2 - E_b - E_{recoil} = 104.97$ MeV

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

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

**Requirements @ 105 MeV/c**

- $\sigma_E/E = 0(10\%)$ 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
- **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
- Simulation includes full background and digitization and cluster-finding, with split-off and pileup recovery
  - The overall resolution depends on crystals features
  - Several crystals considered

<table>
<thead>
<tr>
<th></th>
<th>LYSO</th>
<th>BaF$_2$</th>
<th>CsI</th>
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<tbody>
<tr>
<td>Radiation Length $X_0$ [cm]</td>
<td>1.14</td>
<td>2.03</td>
<td>1.86</td>
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<td>Light Yield [% NaI(Tl)]</td>
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<td>4/36</td>
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<td>Decay Time [ns]</td>
<td>40</td>
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<td>20</td>
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<td>Photosensor</td>
<td>APD</td>
<td>RMD APD</td>
<td>SiPM</td>
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<tr>
<td>Wavelength [nm]</td>
<td>402</td>
<td>220/300</td>
<td>310</td>
</tr>
</tbody>
</table>
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
- Redundant readout: 2 UV-extended SiPMs/crystal
- 1 FEE / SiPM, Digital readout on crates
- RA source for energy calibration
- Laser system for monitoring
Small prototype: Time and Energy resolution

Small prototype 3x3 tested @ BTF (LNF) in 2015, 80-120 MeV e⁻

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

σₚₑ / E = \frac{a}{E [GeV]} \oplus b

\begin{align*}
\sigma_E \sim 7 \% \text{ at 100 MeV} \\
\sigma_T \sim 110 \text{ ps at 100 MeV}
\end{align*}

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

\begin{align*}
\chi^2 / \text{ndf} = 2.866 / 3 \\
a = 1.38 \pm 0.3253 \\
b = 4.911 \pm 1.092
\end{align*}

\begin{align*}
\sigma_T = a/E + b
\end{align*}

\begin{align*}
\chi^2 / \text{ndf} = 38 / 17 \\
a = 0.0049 \pm 0.00015 \\
b = 0.087 \pm 0.0033
\end{align*}

Mu2e Calorimeter, R.Donghia

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• 24 crystals from SICCAS, Amcrys, Saint Gobain
• Optical properties tested with $511$ keV $\gamma$'s along the crystal axis
• 150 $\mu$m Tyvek wrapping and UV-extended PMT readout

Un-doped CsI crystals perform well:

• Excellent LRU and LY:
  -100 pe/MeV
  -LRU < 5%

  $\tau$ of 30 ns (small slow component)

• Radiation hardness OK
  LY loss < 40% (@ 100 krad)
Mu2e custom silicon photosensors:
→ 2 arrays of 3×6×6 mm²
UV-extended SiPMs: total area (12×18) mm²
The readout series configuration reduces the overall capacitance → faster signals

150 sensors: 3×50 Mu2e pre-production SiPMs from Hamamatsu, SenSi and AdvanSiD
• 3×35 were fully characterized for all six cells in the array

Gain

- Mu2e Calorimeter, R. Donghia

Neutron test

- Hamamatsu
- SenSi
- AdvanSiD

We need to cool down SiPMs at 0 °
Module 0

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⁻**
  (beam @ 0° and @ 50°)
- Work under vacuum, low temperature, irradiation test

Readout: 1 GHz CAEN digitizers (DRS4 chip), 2 boards x 32 channels

- Mu2e Calorimeter, R.Donghia

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**Final readout details in Caiulo’s poster**
Module 0
Energy resolution

- Single particle selection
- Calibration
  - MIPs
  - 100 MeV $e^-$ beam, up to ring $2$
- Threshold applied after noise run @ 3 $\sigma$

$E_{\text{beam}} = 100$ MeV
$\sigma_E \sim 5.4\%$

Good agreement Data - MC

$\text{Mean} = 88.19$
$\text{Std Dev} = 7.885$
$\chi^2 / \text{ndf} = 12.36 / 12$
$\eta = 0.2267 \pm 0.0859$
$\sigma = 4.816 \pm 0.206$
$\mu = 89.89 \pm 0.30$
$N = 1578 \pm 48.4$

$E_{\text{beam}} = 100$ MeV
$\sigma_E \sim 7.3\%$

$\sigma_E = \frac{a}{\sqrt{E}} + \frac{b}{E} + c$

$\chi^2 / \text{ndf} = 1.132 / 1$
$a = 0.200 \pm 0.092$
$b = 0.329 \pm 0.021$
$c = 3.807 \pm 0.323$

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• Selection on single particle
• Log-normal fit on leading edge
• Constant Fraction method used → CF = 5%

\[ \sigma (T1+T2)/2 \approx 94 \text{ ps} \]

@ \( E_{\text{beam}} = 100 \text{ MeV} \)

\[ \chi^2 / \text{ndf} = 106.6 / 20 \]
\[ \eta = 0.6526 \, 0.0444 \]
\[ \sigma = 17.12 \, 1.21 \]
\[ \mu = 216.6 \, 0.7 \]
\[ N = 8782 \, 640.2 \]

Mu2e Calorimeter, R.Donghia
QA status of basic components

New laboratory built at FNAL. QA tests of all components started on March 2018.

More information in Di Falco’s poster.
Crystals QA status

More than 100 crystals already tested
- SICCAS rate: 60 crystals / month
- SG almost same rate, mechanical problem not fixed yet

- Mu2e Calorimeter, R. Donghia
About 550 Mu2e SiPMs already characterized
- 300 pieces/month from March 2018
- All the 6 cells tested, measuring $V_{\text{br}}$, $I_{\text{dark}}$, Gain x PDE
- 4% of tested SiPMs rejected (defective or with high $I_{\text{dark}}$ RMS)
- **Irradiation with $\sim1\times10^{12}$ neutrons/cm$^2$ (MTTF)** test on 5 (15) SiPMs/batch

**Mu2e Calorimeter, R.Donhia**

**SiPMs QA status**

**RMS ($V_{\text{br}}$)**

**RMS ($I_{\text{dark}}$)**

**MTTF**
- Requirement: grant an MTTF of 1 million hours at 0°
- Sensors tested 18 days burn-in at 65°
- SiPM $\text{MTTF} > 3$ million hours

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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 $I_{dark}$, small spread inside array
- SiPM performance after irradiation OK
- SiPM MTTF > 3 million hours
- **Calorimeter prototypes** tested with $e^-$ beam
  - Good time and energy resolution achieved @ 100 MeV

Calorimeter production phase started

In 2020 installation of the calorimeter in the Mu2e experimental all begins!
Spares

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Module 0
SiPM-vendors comparison

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

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\( E_{\text{beam}} = 100 \text{ MeV} \)

\( \tau_{\text{rise}} = T_{90\% \text{max}} - T_{10\% \text{max}} \)

- Hamamatsu - \( \tau_{\text{rise}} = 29 \text{ ns} \)
- SensL - \( \tau_{\text{rise}} = 38 \text{ ns} \)
- AdvanSiD - \( \tau_{\text{rise}} = 37 \text{ ns} \)
• CLFV strongly suppressed in SM: \( BR \leq 10^{-54} \)  
   Observation indicates New Physics

• CLFV@Mu2e: \( \mu \rightarrow e \) conversion in a nucleus field  
   \( \rightarrow \) discovery sensitivity on many NP models

• **Goal:**  
  \( 10^4 \) **improvement w.r.t. current limit** (SINDRUM II)  
  \( \mu \rightarrow e \) conversion in the presence of a nucleus

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

Nuclear captures of muonic Al atoms

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

- Mu2e Calorimeter, R. Donghia
Small prototype: Test Beam

- Small prototype tested @ BTF (Frascati) in April 2015, 80-120 MeV $e^-$
- $3\times3$ array of $30\times30\times200$ mm$^2$ undoped CsI crystals coupled to one Hamamatsu SiPM array ($12\times12$) mm$^2$ with Silicon optical grease
- DAQ readout: 250 Msps CAEN V1720 WF Digitizer

Log-normal fit

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Pre-production test: SiPMs (2)

- 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 $V_{\text{op}}$ also helps to decrease the $I_d$

- MTTF evaluated operating SiPMs @ 50 °C for 3.5 months
- No dead channels observed

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

- **22Na 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

• Cosmic ray test → 2 SiPMs readout
  - TRG: crystal between 2 small scintillators
Single channel Cosmic Rays Test

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

After jitter subtraction:
\[ \text{SiPM 1} - \sigma_t \sim 330 \text{ ps} \]
\[ \text{SiPM 2} - \sigma_t \sim 340 \text{ ps} \]

\[ T(SiPM1 - SiPM2)/2 \rightarrow 215 \text{ ps} \]
@ ~ 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 → 215 ps (now) vs 250 ps (old).

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Pre-production test: Crystals (2)

Few samples per vendor have been exposed both to ionizing dose and neutrons.

- Irradiation test up to 100 krad
- Requirement: normalized LY 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.

- Radiation Induced Noise (RIN) @ 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 $1.6 \times 10^{12} n_{1\text{MeV}/cm^2}$ integrated flux
- Neutron RIN is also smaller than the one from dose

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Pedestal correction: Results

- The integration range reduced to (150,400) ns
- Pedestal distribution reduction better than a factor 2

Example of pedestal correction

![Graph showing Pedestal energy vs Crystal number](image)

- FWHM/2.355 = 0.870 MeV
- FWHM/2.355 = 0.148 MeV
- FWHM/2.355 = 0.424 MeV

Noise width in the new charge increase linearly with the number of crystals added
Module 0
Event selection

1) We reject events with laser trigger

2) We reject events with cosmic trigger

3) We ask for a single particle in the beam counters

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Module 0
Event selection

Cosmic trigger used to provide the equalization of all channels

Scale Factor [cosmic]

cosmic_beam
Entries: 25
Mean: 0.9865
Std Dev: 0.03967

Scale Factor [beam]

cosmic_beam
Entries: 25
Mean: 0.9348
Std Dev: 0.02165

Dedicated runs with beam centered on each crystal of the inner part of the matrix (up to second ring included)

In all the analysis cosmic equalization is used
$\chi^2 / \text{ndf} = 89.91 / 4$
$p = 12.47 \pm 0.02236$

$pC$ to MeV = $1 / p = 0.0802$
With a CRV inefficiency of $10^{-4}$ an additional rejection factor of $\sim 200$ 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 $\sim 40$ MeV.
- Likelihood rejection combines $\Delta t = t_{\text{track}} - t_{\text{cluster}}$ and $E/p$:
  \[ \ln L_{e,\mu} = \ln P_{e,\mu}(\Delta t) + \ln P_{e,\mu}(E/p) \]

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

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Calibration source and laser

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

10k entries/crystal/min

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• 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
    • $\varepsilon \sim 95\%$ for background rejection of 200
  • Standalone calorimeter trigger that uses only calo info
    • $\varepsilon \sim 65\%$ for background rejection 200
• Cluster time and position are used for filtering the straw hits:
  ✓ time window of ~ 80 ns
  ✓ spatial correlation

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

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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 ~ $2 \times 10^{11} \text{n/cm}^2/\text{year}$
- Highest n flux on SiPM ~ $10^{11} \text{n}_{1\text{MeVeq}}/\text{cm}^2/\text{year}$

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

This includes a safety factor of 3 for a 3 year run.

Mu2e Calorimeter, R. Donghia

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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

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CE + background
Calorimeter mechanics

- Source Plate
- 10 Readout electronics crates
- Crystals
- Inner ring
- Outer ring
- Foot
- SiPM+FEE support and cooling Plate
- Manifolds
- Hydraulic connections
- Inner steps
- Outer steps
- Alignment targets
- SiPM running temperature at 0 °C, Coolant at -10 °C
- SiPM holder

SiPM = Silicon PhotoMultiplier
FEE = Front End Electronics
Calorimeter 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)
Three years run
Expectation by full Simulation

- \( N_{\text{POT}} = 3.6 \times 10^{20} \)
- \( R_{\mu-e} = 10^{-16} \)
- \( N_{\text{CE}} = 3.72 \pm 0.01 \)
- \( N_{\text{DIO}} = 0.20 \pm 0.02 \)

No PID selection applied

Signal Window
103.85 < \( p \) < 105.10 MeV/c

DIO
CE

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The Lagrangian for CLFV is given by:

\[ \mathcal{L}_{\text{CLFV}} = \frac{m_{\mu}}{(\kappa + 1)} \frac{\Lambda^2}{\kappa} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)} \frac{\Lambda^2}{\kappa} \bar{\mu}_L \gamma_5 \gamma^\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L) \]

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

\[ \mu \rightarrow e \gamma \]

\[ \mu N \rightarrow eN \]

\[ \mu \rightarrow e e e \]

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

\[ \mu \rightarrow e \gamma \]

\[ \mu N \rightarrow eN \]

\[ \mu \rightarrow e e e \]