Design and qualification of the Mu2e electromagnetic calorimeter radiation monitor system

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on behalf of the Mu2e Calorimeter Group

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Outline

• The Mu2E experiment: goal and experiment layout
• The Electromagnetic Calorimeter
• Expected radiation on the calorimeter
• Radiation monitoring system: T-RAD
• Sensors used to measure TID and neutron fluence
• Test and calibration of the system
The Mu2e Experiment

- Mu2e searches for Charged Lepton Flavor Violation (CLFV) via the coherent conversion:

\[ \mu^- N \rightarrow e^- N \]

at Fermilab muon campus..

- Since the Standard Model prediction is \(~ (\Delta m^2 / M_w^2)^2 < 10^{-54}\), far beyond experimental reach, any observation will be clear evidence for New Physics.

- In case of no observations, Mu2e will improve by a factor \(10^4\) the current world best limit from Sindrum II experiment:

\[
R_{\mu e} = \frac{\Gamma (\mu^- + N(A,Z)) \rightarrow e^- + N(A,Z)}{\Gamma (\mu^- + N(A,Z)) \rightarrow \text{all muon captures}} \leq 8 \times 10^{-17} \text{ @ 90\% C.L.}
\]
Production Solenoid (PS)/Target

- An 8 GeV proton beam hits a tungsten target and produces mostly $\pi$.
- A graded magnetic field reflects slow forward $\mu/\pi$ and contains backward $\mu/\pi$.

Detector Solenoid (DS): stopping target and detectors

- Stops $\mu^-$ on Al foils (decay time $\sim 864$ ns).
- Events reconstructed by detectors, optimized for 105 MeV momentum.
- 1 T B field and $10^{-4}$ Torr vacuum in the detector zone.

Transport Solenoid (TS)

- $\pi$ decay to $\mu$.
- Selection and transportation of low momentum $\mu^-$. 

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Calorimeter Design

Undoped CsI + UV-extended SiPMs

- It is radiation hard
- It has a fast emission time
- Emits at 310 nm
- 30% PDE @ 310 nm
- New silicon resin window
- TSV readout, Gain = 10^6

- Two annular disks, R_{in}=374 mm, R_{out}=660 mm, 10 X_0 length, ~ 70 cm separation
- 674 + 674 square x-sec pure CsI crystals, (34×34×200) mm^3, Tyvek + Tedlar wrapping
- Each crystal is read out by two large area UV extended Mu2e SiPM’s (14×20 mm^2)

- Redundant readout: For each crystal, two custom arrays (2×3 of 6×6 mm^2) large area UV-extended SiPMs
Radiation to the calorimeter

- Calorimeter is reached by a high flux of ionizing and non-ionizing (neutrons) particles.
- Potentially very dangerous both on detector and electronics
  - Crystals: Displacement of atoms in the lattice, centre of colors, loss of transmittance
  - SiPM: increase of baseline noise, increase in dark current
  - Electronics: single event upset, latch-up, voltage variations due to the accumulated dose

Crystal Light output

<table>
<thead>
<tr>
<th>Material</th>
<th>Integrated Dose (rad)</th>
<th>Normalized LO</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaF, SIC2012, (\lambda_{em} = 220) nm</td>
<td>(10^2)</td>
<td>0.4</td>
</tr>
<tr>
<td>CsI SIC2013, 50x50x300 mm(^3)</td>
<td>(10^5)</td>
<td>0.3</td>
</tr>
<tr>
<td>LYSO CPI, 25x25x200 mm(^3)</td>
<td>(10^6)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

ADC

DCDC

*Not OK: start @ 35krad, FPGA or ADC problem?*
Radiation to the calorimeter 2

- Calorimeter is reached by a high flux of ionizing and non-ionizing (neutrons) particles.
  - Several sources:
    - BEAM-FLASH: all particles within the beam that **do not** represent a muon stopped either in the Al Stopping Target or the muon-beam dump;
    - Stopped $\mu$ out-of-target (OOT): $\mu$ stopped in the muon-beam dump;
    - $e^-$ from $\mu$ decay-in-orbit (DIO): $e^-$ from muon decay in orbit in the Al Stopping Target;
    - Processes associated with the muon-capture in the Al nuclei of the Stopping Target, followed by the nuclear disintegration of the nucleus [3]:
      - Photons;
      - Neutrons;
      - Protons;
      - Deuterons.
  - Monte Carlo simulations with Geant4 and Mars
Simulations output: Total Ionizing dose (Krad/y)

Max dose 6 Krad/y
Simulations output: Total Ionizing dose (Krad/y)

FEE front disk (4 to 0.4) Max dose 6 Krad/y

DAQ Crate (max 0.3) Max dose 0.5 Krad/y
Simulations output: Neutron flux

SiPM front disk

$\phi_n, 1\text{ MeV-eq/}[\text{#}/\text{cm}^2/\text{year}]$

- **Total**
- **FLASH**
- **DEUTERON**
- **OIT**
- **PHOTON**
- **NEUTRON**
- **PROTON**

$R [\text{mm}]$

$< 6 \cdot 10^{10} \text{n}_\text{1MeV-eq/cm}^2/\text{year}$

DAQ Crate front disk

$\phi_n, 1\text{ MeV-eq/}[\text{#}/\text{cm}^2/\text{year}]$

- **Total**
- **FLASH**
- **DEUTERON**
- **OIT**
- **PHOTON**
- **NEUTRON**
- **PROTON**

$R [\text{mm}]$

$< 2 \cdot 10^{10} \text{n}_\text{1MeV-eq/cm}^2/\text{year}$
Radiation monitoring

• Need to measure Total Ionizing Dose (TID), neutron fluence and temperature in several positions of the calorimeter.
  – About 18 “strategic” locations, but scalable
• Limits are :
  • $10^{12}$ n
  • 50 Krad of TID
  • 0 to 50 °C
• Available space limited:
  • Only few mm between calorimeter and tracker
• Limit the material in front of the calorimeter
• Data must be available to the DCS system
T-RAD system
A T-Rad System is being designed to measure dose, neutron fluence and temperature in selected positions of the Calorimeter

18 sensor mini-boards/disk (each measures TID, n, T)
T-RAD system (2)

- The T-Rad system components:
  - Sensor boards SB
  - Mezzanine MIB
  - DIRAC board: main DAQ node for Mu2e, used only as data transmission and slow control interface

2 (DIRAC + TRAD) mezzanine per disk → each card will read up to 9 sensors boards → 36 sensor boards for the full calorimeter
T-RAD system (3)
The T-Rad sensors for the T-RAD system are:

- Radfet (Varadis VT01) → Dose (rad)
- Digital Thermometer (Maxim Integrated DS18S20Z) → Temperature (T)

For neutrons we decided to use a commercial SiPM as a radiation monitor....

- SiPM (ON Semiconductor MICROFC − 60035 − SMT) → Neutron fluence (n)
T-RAD mezzanine board MB

24-28 V
Dose sensor

- Varadis VT01 it is the RADFET used as Dose Sensor
- VT01 is specified to measure up to 100 krad @ ambient temperatures
- From the Varadis datasheet the RADFET sensing circuit diagram is:
Temperature sensor

- The Temperature Sensor (DS18S20) communicates through the 1-wire bus
- DS18S20 already tested in 2018 @ Enea:
  - Dose rate 1.85 krad/h unshielded (red)
  - Dose rate 0.3 krad/h shielded (blu)

290 Krad
146 hours
Neutron sensor (1)

• The idea is to use a SiPM as a detector for neutron fluence
  ➢ $I_{dark}$ is a function of neutron fluence and temperature
• We measured the trend of $I_{dark}$ vs $n$ at $T=20^\circ$C for several SiPM

$V_{op} = V_{brk} + 3v$
Neutron sensor(2)

- We will use a SiPM similar to the tested SensL, but with lower Vbreakdown.
- ON C-Series SiPM Sensors Vbias is ~ 25V (Mu2e SiPM 170V) → use 28V from DAQ crate

tested @ ENEA-FNG in July.

ON Semiconductor MICROFC – 60035 – SMT

SENSL is now ON Semiconductor
FNG facility, ENEA Frascati lab (Rome)

Frascati Neutron Generator (FNG) is a linear electrostatic accelerator in which up to 1 mA D+ ions are accelerated onto a Tritium target

- **Up to** $10^{12}$ 14 MeV neutrons/s *in few hours*
- Almost *isotropic source*, flux scales with $r^2$
- Calibrated at 3% level using alpha particles

$$D + T \rightarrow \alpha + n$$
• 4 SiPM tested at the same time
• V-I curve varying T
• 3 Control loops:
  - T sensor + Peltier cell
  - Vacuum meter + Vacuum Pump
  - Power Supply + pico AMP
SiPM irradiation test setup (2)
test results (preliminary)

Temperature = 0°C

![Graphs showing dark current vs. neutron fluence for different SiPMs at various voltages.](image)
Conclusions

- Mu2e calorimeter is operated in a radioactive environment and needs a radiation monitor system: T-RAD
- Each T-RAD is based on a mezzanine card plus 9 sensor boards
- Neutron fluence is measured as a function of a SiPM Idark
- The idea has been successfully tested in July at the FNG neutron irradiation facility in Frascati near Rome

Thanks for the attention!

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