Development of the Mu2E electromagnetic calorimeter front-end and readout electronics

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Outline

• The Mu2E experiment: goal and experiment layout
• The Electromagnetic Calorimeter
• Calorimeter electronics scheme
• Front End electronics
• Why a digitizer?
• Which requirements?
• Digitizer spec, architecture and design
• Qualification tests
• Conclusions
Mu2e goal

- 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

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

Nuclear captures of muonic Al atoms

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

More information at mu2e.fnal.gov
Mu2e experiment layout

Production Solenoid (PS)/Target
- An 8 GeV proton beam hits a tungsten target and *produces* mostly π
- A *graded magnetic* field reflects slow forward μ/π and contains backward μ/π

Transport Solenoid (TS)
- π decay to μ
- *Selection and transportation* of low momentum μ

Detector Solenoid (DS): stopping target and detectors
- Stops μ⁻ on Al foils (decay time ~ 864 ns)
- *Events reconstructed by detectors, optimized for 105 MeV momentum*
- 1 T B field and 10⁻⁴ Torr vacuum in the detector zone
The Electromagnetic Calorimeter

Calorimeter provides:
• **Particle Identification**: e/μ separation → reject μ background
• Improve the track pattern recognition
• Standalone trigger

**Calorimeter requirements**
• energy resolution \( \sigma_{E/E} < 10\% \)
• timing resolution \( \sigma(t) < 200 \text{ ps} \)
• position resolution < 1 cm
• Work in vacuum @ 10\(^{-4}\) Torr
• 1 T Magnetic Field

1. **CsI Crystals coupled with Silicon PhotoMultipliers(SiPM)**
   • Light Yield(photosensor)>20 pe/MeV
   • Fast signal for pileup and timing

2. **Detector must Survive high radiation environment**
   • TID of 90 krad/5 year for crystal
   • TID of 75 krad/5 year for sensor
   • 3x10\(^{12}\) n/cm\(^2\) for crystal
   • 1.2x10\(^{12}\) n/cm\(^2\) for sensor
Calorimeter design

- **High granularity** → 1348 undoped CsI crystals (3.4x3.4x20 cm³)
- **Crystals arranged in 2 disks** (inner/outer radius 37.4 cm / 66 cm, separation between disks 75 cm)
- **1 crystal coupled to 2 UV-extended SiPMs** (14x20 mm² area) → 2696 electronic channels
- SiPM packed in a parallel arrangement of 2 groups of 3 cells biased in series
- DAQ **crates located inside the cryostat** to limit the number of pass-through connectors
Front End Electronics

- FE boards connected to SiPMs to provide:
  - Amplification & shaping
  - Local linear regulation of the bias voltage
  - Monitoring of current and temperature
  - Test pulse
Why a digitizer?

Very intense particle flux expected in the calorimeter

We need high-sampling rate digitizers to resolve pile-up
«Physics» requirements:

- Digitization requirements = function (calorimeter requirements)
- \textit{Particle-id}:
  - $\sigma_t < 200 \text{ ps} @ 100 \text{ MeV}$
  - $\sigma_{E/E} < 10\% @ 100 \text{ MeV}$
- We need to define:
  - \textit{Sampling frequency} and number of \textit{ADC readout bits} (impact time and energy resolution)
  - \textit{Thresholds} (impact the total data throughput and Energy resolution)
  - \textit{Zero suppression algorithm} (big amount of data)
ADC requirements

• Simulation results show that a digitizer with:
  o Sampling frequency of **200 MHz**
  o ADC with **12 bits resolution**

*Matches the calorimeter requirements* on time and energy resolution

<table>
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<th>150 MHz</th>
<th>200 MHz</th>
<th>250 MHz</th>
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<td>470 ps</td>
<td>440 ps</td>
<td>440 ps</td>
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<td>370 ps</td>
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<td><strong>12 bits</strong></td>
<td>300 ps</td>
<td><strong>170 ps</strong></td>
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Time resolution versus sampling frequency and ADC-bits

• **Time** is reconstructed by fitting the leading edge
• Time resolution for Conversion Electrons (~105 MeV)

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<thead>
<tr>
<th></th>
<th>150 MHz</th>
<th>200 MHz</th>
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<tbody>
<tr>
<td><strong>8 bits</strong></td>
<td>9.8 MeV</td>
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<td><strong>10 bits</strong></td>
<td>6.5 MeV</td>
<td>5.5 MeV</td>
<td>5.5 MeV</td>
</tr>
<tr>
<td><strong>12 bits</strong></td>
<td>6.2 MeV</td>
<td><strong>5.5 MeV</strong></td>
<td>5.5 MeV</td>
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</table>

Energy resolution versus sampling frequency and ADC-bits

• **Energy** is reconstructed from the total number of ADC counts
• Energy resolution (FWHM/2.35) for Conversion Electrons (~105 MeV)
Environmental requirements?

• **System located inside the cryostat → Harsh Environment:**
  - **Magnetic field of 1 T and 10^{-4} Torr vacuum**
  - **Total Ionizing Dose (TID):**
    - 0.2 krad/yr (from simulation)
    - 12 Safety factor (requested from collaboration)
    - 5 years data tacking
    - TID 12 krad
  - **Neutron flux 5×10^{10} 1 MeV (Si)/yr (from simulation)**

• **Mechanical constraints → DAQ crates located inside the cryostat:**
  - **Limited space →** 20 ADC channels/board
  - Limited access for maintenance → **Highly Reliable Design** mandatory
DIRAC architecture

Mezzanine Board

ADC

ADC

ADC

ADC

ADC

ADC

ADC

ADC

ADC

ADC

ADC

Jitter Cleaner

DC/DC & LDO

Optical Receiver

Optical Receiver
DIRAC design

After an intense campaign of tests:

- **ADC**: ADS4229 (Texas Instruments®)
- **FPGA**: Polarfire MPF300 (Microsemi®)
- **DC-DC**: LMZM33606
- **LDO**: MIC69502 (Micrel®)
- **Jitter Cleaner**: LMK04828 (Texas Instruments®)
- **Optical Transceiver**: CERN VTRX

PCB specs:

- **Material**: FR408-HR
- **Layers**: 16
- **Dimensions**: 233x165 mm
- **Thickness**: 2.127 mm
- **Differential lines**: 100 Ω
- **Single ended lines**: 50 Ω
DIRAC qualification tests

Several test campaigns were performed:

• **Total Ionizing Dose (TID)** → requested 12 krad:
  - YELBE @HZDR
    - γ from Bremsstrahlung (0<E<14MeV)
    - Estimated dose ≈ 20 krad/h @ 600µA
    - Single components test
  - Calliope @ENEA
    - Co60 source
    - Dose in function of distance: Max 2krad/h, requested 1krad/h
    - Full board test

• **Magnetic Field (B):**
  - LASA @INFN Milano (1T)

• **Neutron irradiation test**
  - FNG @ENEA
    - Total neutron flux of $1.2 \times 10^{12}$ n 1 MeV (Si) / cm$^2$
    - Total neutron flux of $6 \times 10^{11}$ n 1 MeV (Si) / cm$^2$
    - LMZM33606 test
Photons is produced per Bremsstrahlung by the electron beam hitting a niobium foil in the accelerator hall.

Nominal beam conditions: 17 MeV electrons, 600μA, 12.4 um niobium radiator foil.

Simulated *dose rate* $\approx 18.6$ krad/h

Active dosimetry used to confirm simulated dose rate.
Calliope facility, ENEA Lab (Bracciano-Rome)

- Gamma rays at 1.17 and 1.33 MeV from $^{60}\text{Co}$.
- $3.7 \times 10^{15}$ Bq of activity.
- *Isotropic source*, flux scales with $r^2$.
- Uniform magnetic field up to 1.2 T
- We tested different orientations of the DCDC with respect to the magnetic field
- Same setup of the radiation tests
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* $10^{11}$ 14 MeV neutrons/s
- almost *isotropic source*, flux scales with $r^2$
- calibrated at 3% level using alpha particles

\[ D + T \rightarrow ^\alpha + n \]
DIRAC: TID test results

- Input waveform → 4.5@10MHz, readout waveform:
  - LMZM33606 and MIC69502 Vout(rad;t)

**Conclusions:**
- 41 h beam time
- Nominal Dose Rate ≈ 1krad/h
- TID ≈ 41krad
- No evidence of broken components up to 35 krad
- LDO small increase, fast recover if no beam
Tests in magnetic field results

**Test conditions:**
- View X (parallel to B)
- Vin 28V, Vout 2.5V
- Variable load
- Switching frequency

**Efficiency quite low (still acceptable), higher if Vin lower**

**Test conditions:**
- View X (parallel to B)
- Vin 28V, Vout 3.3V
- Variable load
- Constant frequency

**Vout constant**
Main firmware flow ... 6 Gbyte/sec ...

1. TDAQ sends Heartbeat packet that contains EVENT TAG and EVENT WINDOWS

2. DiRAC builds the calo hit applying a zero suppression and pre-processing data

3. Data are stored in the DDR

4. TDAQ sends Data Request for a specific EVENT TAG, and DiRAC retrieve requested Data Packet from DDR and sends it out to DTC
Slice test results

An example of the resulting waveform (Fig.A) and the distribution of the peak amplitude versus the integrated charge (Fig.B) is shown.

Fig.A: Resulting waveform

Fig.B: Energy distribution deposited by cosmic rays (ADC counts)
Conclusions

- A waveform digitizer designed to operate in Mu2e hostile environment has been presented. Named DIRAC.
- The DIRAC is designed to sample @200 MHz differential signals coming from SiPM and amplified by a custom FEE.
- The presence of vacuum ($10^{-4}$ Torr), high magnetic fields (1T) and radiation (Non-Ionizing Energy Loss $5 \times 10^{10}$ n/cm$^2$ @ 1 MeV$_{eq}$ (Si)/y and Total Ionizing Dose 12 Krad) makes the environment particularly harsh and the design of the board very challenging
- We described the apparatus, the design specification, the architecture and all the technical choice
- The system has been qualified

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Thank you!

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