Mu2e calorimeter readout electronics
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1. Mu2e: Search for $\mu + N \rightarrow e + N$

Mu2e will search for the coherent, neutrinoless muon-to-electron conversion in the field of a nucleus. This charged lepton flavor violating process allows to probe energy scales up to thousands TeV, far above the existing colliders. If no conversion events are observed in 3 years of running, Mu2e will set a limit on the ratio between the muon conversion and the muon capture rate, $R_{\mu e} < 10^{-14}$ ($\mu$ 90% C.L.).

- Production Scolenoid (PS)
  - A time projection chamber of tangential layout
  - A graded magnetic field reflects muons to the TS
  - 4.7 T

- Cosmic Ray veto (CRV)
  - Veto of large cosmic ray flux
  - Covers the entire Mu2e and half of the TS
  - 2.5 T

- Straw Tracker (TRK)
  - 20000 straw tubes for WP and Mu2e
  - Momentum resolution 500 MeV/Br (16% RMS)
  - 2.0 T

- Electromagnetic Calorimeter (ECAL)
  - 2MM undoped CsI crystals
  - Energy, Time and Position measurements
  - 1.0 T

- Detector Scolenoid (DS)
  - Captures muons on the Aluminum chopping target
  - 1 T field and 35% bar vacuum in the detector bore
  - 0.5 T

2. The Electromagnetic Calorimeter

- Calorimeter Provides:
  - Particle identification $\pi/E$
  - Seed for track pattern recognition
  - Independent trigger

- $E_p/E_\gamma < 10%$ and $\Delta E < 500$ ps
- Position resolution of $0.1$ cm

- High granularity made of 3448 undoped CsI crystals ($3.43 \times 20 \times 20$ cm$^3$)
- Crystals arranged in two disks (inner/outer radius: 37.4 cm/66 cm, separation between disks 75 cm)
- 1 crystal coupled to 2 large (14x20 mm$^2$) area UV-extended SiPM $> 2686$ electronic channels
- SiPM packed in a parallel arrangement of 2 groups of 3 cells biased in series
- DAQ crate located inside the cryostat to limit the number of pass-through connections
- 10 crates/disk with 6/8 boards/crate

3. Why a digitizer? What requirements?

- Requirements:
  - Very intense particle flux expected in the calorimeter $\rightarrow$ High Sampling Rate digitizer
  - Crucial to resolve pile-up
  - Sample SiPM signal at the frequency of 200 Msamples with 12 bits ADC

- System located inside the cryostat $\rightarrow$ Harsh Environment:
  - Magnetic field of 1 T and 3.0 T torr vacuum
  - Total ionizing Dose (TID):
    - 0.5 krad$/yr$ for 12 $\pm$ 5 years
    - TID requirements of 80 krad
  - Neutron flux $5 \times 10^{13}$/1 MeV (Si)/cm$^2$/s (from simulation)
  - Mechanical constraints:
    - Limited space $\rightarrow$ 20 ADC channels/boards
    - Limited access for maintenance $\rightarrow$ Highly Reliable Design mandatory

4. Front End Electronics and readout flow

- FE Boards (FEB) connected to SiPM provide:
  - Amplification
  - Local linear regulation of the bias voltage
  - Monitoring of current and temperature
  - 2969 FEB boards produced $\rightarrow$ 900 years
  - 20 FEB controlled by 1 Mezzanine Board (MB)
  - Differential signals from 20 FEB sent to MB and then to 1 DRAC
  - DRAC $\rightarrow$ sampling, processing and transmission to the Mu2e DAQ

- FE requirements:
  - Magnetic field of 1 T and 10$^3$ Torr vacuum
  - Total ionizing Dose (TID):
    - 1.8 krad$/yr$ x 12 SFR$\pm$5 years
    - TID requirement of 100 krad
  - Neutron flux $5 \times 10^{13}$/1 MeV (Si)

5. Digitizer architecture and design

- After an intense campaign of tests:
  - ADQ: ADS4229 (Texas Instruments$^*$)
  - FPGA: Xilinx Virtex 300 (Micron$^*$)
  - DC-DC: LIN15000G
  - LOO: MC35052 (Texas Instruments$^*$)
  - Optical Transceiver: CERN VITRIX

- DIRAC PCB specs:
  - Material: FR4@0.8
  - Layers: 32
  - Dimensions: 233x205 mm
  - Thickness: 2.127 mm
  - Differential lines: 500 $\Omega$
  - Signal ended lines: 50 $\Omega$

6. Digitizer architecture and design

- TDAQ sends an heartbeat packet that contains EVENT TAG and EVENT WINDOWS
- DRAC builds the calo hit applying a zero suppression and pre-processing data
- Data stored in DEB
  - Tag sends a specific EVENT TAG, and DRAC retrieve requested Data Packet from DQR and sends it out to DTC

7. DIRAC Qualification Campaign

- 1. Comparison with commercial digitizer showed no differences in performances
- 2. Obtained time resolution in accordance with expectations
- 3. Noise level and dynamic scale as expected

8. Vertical slice test

- Large scale EMC prototype:
  - 51 CsI crystals
  - 102 Mu2e SiPMs
  - 102 FEE boards
  - 1 DRAC board handles 20 channels
  - Mechanics and cooling system are similar to the final ones

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