Mu2e calorimeter readout electronics

F. Spinella for the Mu2e Calorimeter group

INFN - Pisa

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: $R_{\mu e,}$**<6 x 10^{-17} (@ 90% C.L.).**

Production Solenoid (PS)

An **8 GeV proton beam** hits a tungsten target
A graded magnetic field reflects muons to the TS

Cosmic Ray Veto (CRV)

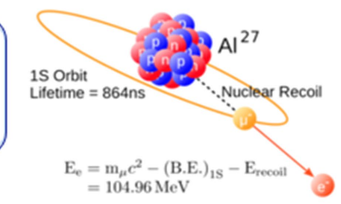
4 layers of plastic scintillator bars
Covers the entire DS and half of the TS

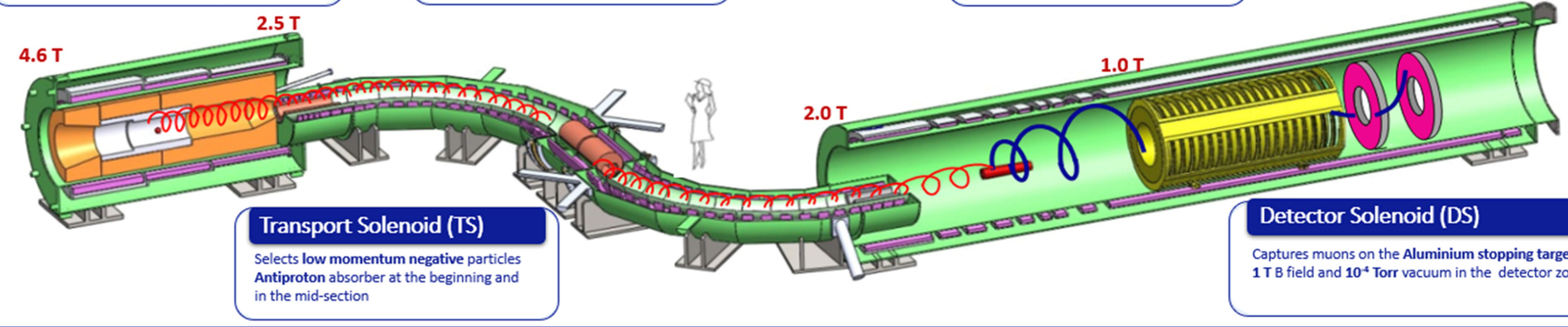
Straw Tracker (TRK)

20,000 low mass straw drift tubes
Momentum resolution **180 keV/c @100MeV/c**

Electromagnetic Calorimeter (ECAL)

1348 undoped CsI crystals
Energy, Time and Position measurements





Transport Solenoid (TS)

Selects **low momentum negative** particles
Antiproton absorber at the beginning and in the mid-section

Detector Solenoid (DS)

Captures muons on the **Aluminium stopping target**
1 T B field and **10^{-4} Torr** vacuum in the detector zone

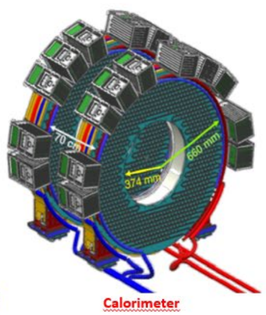
Experimental Technique

Stop muons in Aluminium target
Muons quickly get to 1S orbit
Lifetime of muonic atom is 864 ns
Look for the 105 MeV conversion electron

2. The Electromagnetic Calorimeter

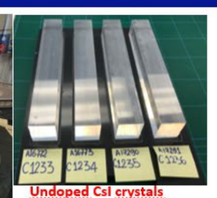
Calorimeter Provides:

- Particle identification μ/e
- Seed for track pattern recognition
- Independent trigger



Calorimeter


Calorimeter disks



Undoped CsI crystals


SiPM + Holder + FEE


Waveform Digitizer Crates

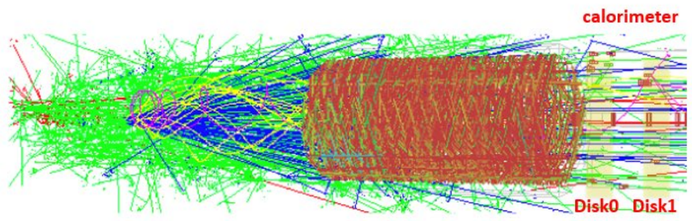
⇨ ***ΔE/E < 10% and Δt < 500 ps***
⇨ ***Position resolution of O(1 cm)***

- High granularity → made of 1348 **undoped CsI crystals** (3.4x3.4x20 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 → 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
- 10 crates/disk with 6/8 boards / crate

3. Why a digitizer ? What requirements ?

Requirements:

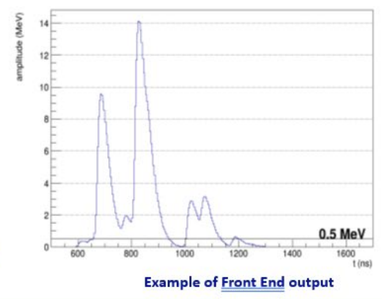
- **Very intense particle flux expected** in the calorimeter → High Sampling Rate digitizer crucial to resolve pile-up
- Sample SiPM signal at the frequency of **200 Msamples** with **12 bits** ADC



Typical 1.7 μs Mu2e event

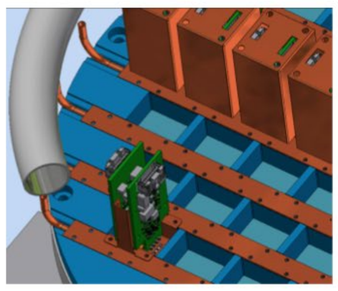
System located inside the cryostat → Harsh Environment:

- ***Magnetic field** of 1 T and 10^{-4} Torr vacuum*
- ***Total Ionizing Dose (TID):***
  - *0.5 krad/yr X 12 SF X 5 years*
  - *TID requirements of 30 krad*
- ***Neutron flux 5x10^{11}** 1 MeV (Si)/yr (from simulation)*
- **Mechanical constraints:**
  - *Limited space* → 20 ADC channels/board
  - Limited access for maintenance → *Highly Reliable Design* mandatory

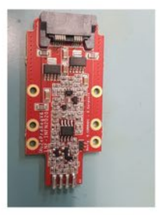


Example of Front End output

4. Front End Electronics and readout flow

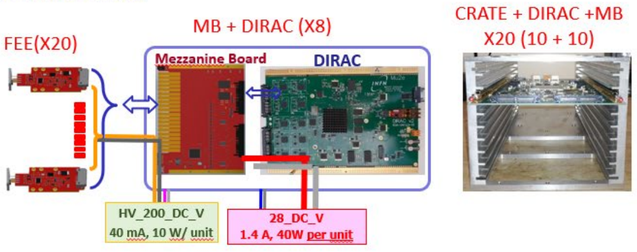


- FE Boards (FEB) connected to SiPM provide:
  - Amplification
  - Local linear regulation of the bias voltage
  - Monitoring of current and temperature
- 2696 FE boards produced + 800 spares
- 20 FEB controlled by 1 Mezzanine Board (MB)
- Differential signals from 20 FEB sent to MB and then to 1 DIRAC
- DIRAC → sampling, processing and transmission to the Mu2e DAQ



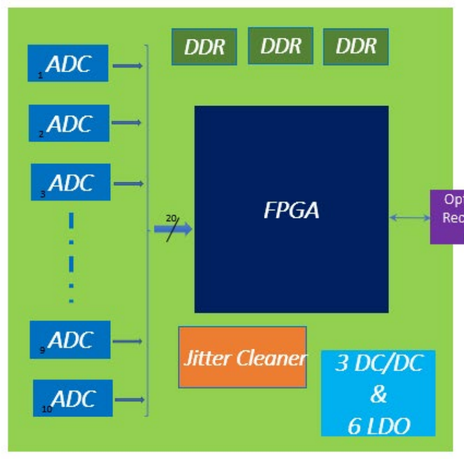
FE requirements:

- *Magnetic field of 1 T and 10^{-4} Torr vacuum*
- *Total Ionizing Dose (TID):*
  - *1,8 krad/yr x 12 SF x 5 years*
  - *TID requirement of 100 krad*
- *Neutron flux 5x10^{11} 1 MeV (Si)*



CRATE + DIRAC +MB X20 (10 + 10)

5. Digitizer architecture and design



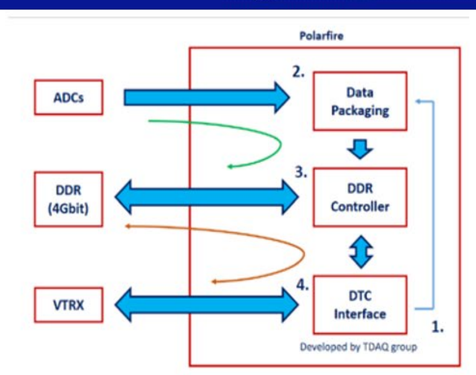
After an intense campaign of tests:

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

DIRAC PCB specs:

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

6. Digitizer architecture and design

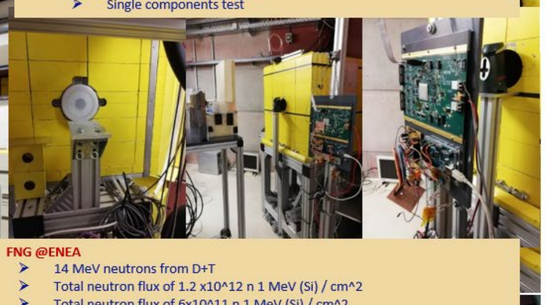


- *TDAQ sends an Heartbeat packet that contains EVENT TAG and EVENT WINDOWS*
- *DIRAC builds the calo hit applaying a zero suppression and pre-processing data*
- *Data stored in DDR*
- *Tdaq sends a specific EVENT TAG, and DIRAC retrieve requested Data Packet from DDR and sends it out to DTC*

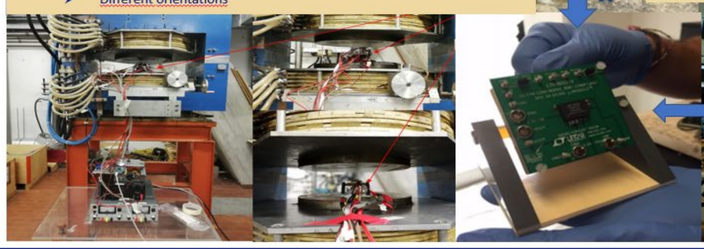
7. DIRAC Qualification Campaign

- **Calliope @ENEA**
  - Co60 source
  - Dose in function of distance: Max 2krad/h, requested 1krad/h
  - Full V1 board test

- **YELBE @HZDR**
  - γ from Bremsstrahlung (0<E<14MeV)
  - Estimated dose ≈ 20 krad/h @ 600μA
  - Single components test



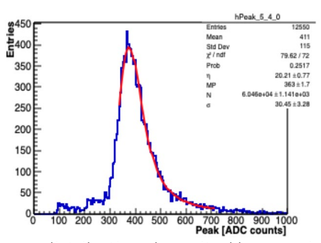
- **LASA @INFN-Milano**
  - 1 T magnetic field
  - Different orientations



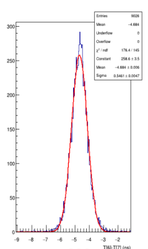
- **FNG @ENEA**
  - 14 MeV neutrons from D+T
  - Total neutron flux of 1.2 x10^12 n 1 MeV (Si) / cm^2
  - Total neutron flux of 6x10^11 n 1 MeV (Si) / cm^2

8. Vertical Slice test

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



Energy distribution deposited by cosmic rays


$\sigma_T \sim 390$ ps

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

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