A DIgitizer ReAdout Controller (DIRAC) board for the Mu2e CsI electromagnetic calorimeter data acquisition system

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Poster Number
N-07-101

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

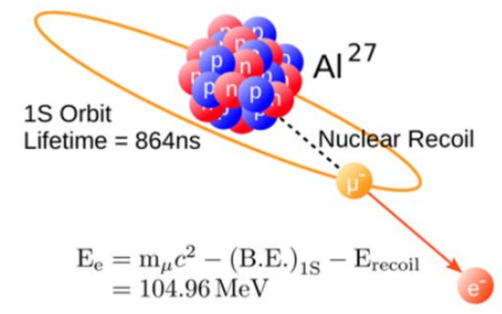
Mu2e will search for the coherent, neutrinoless muon-to-electron conversion in the field of a nucleus**. This charged lepton flavor-violating process allows to probe energy scales up to thousands TeV**, far above the existing colliders. If no conversion events are observed in 3 years of running, Mu2e 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

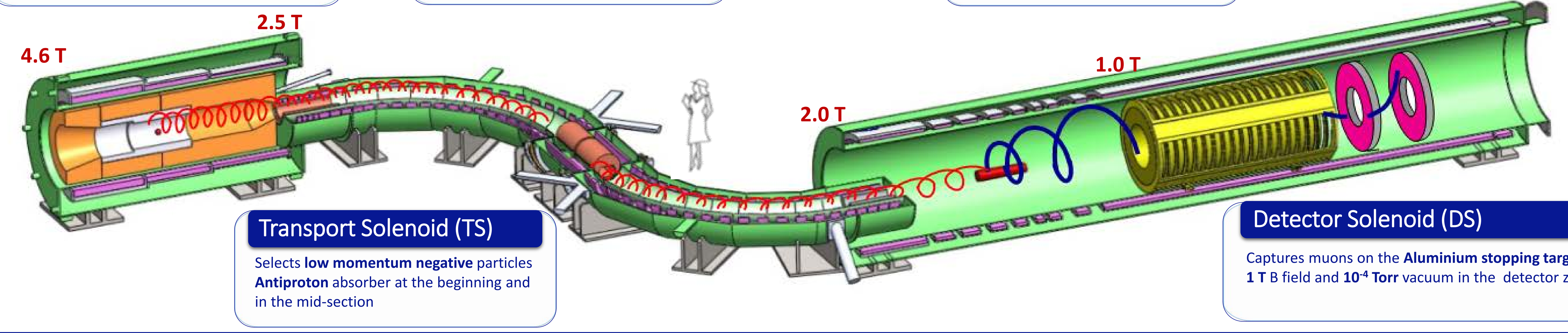
Cosmic Ray Veto (CRV)
4 layers of plastic scintillator bars
Covers the entire DS and half of the TS

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



$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} = 104.96\,MeV$$



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

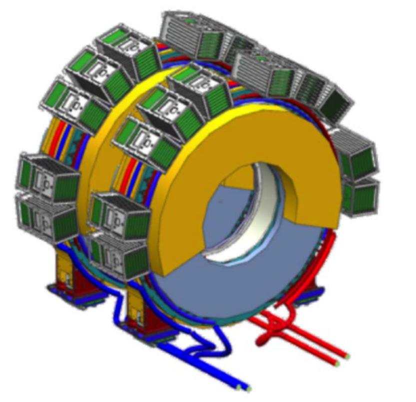
Transport Solenoid (TS)
Selects **low momentum negative** particles
Antiproton absorber at the beginning and in the mid-section

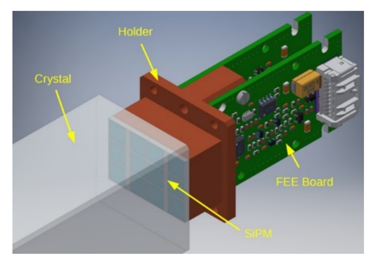
Detector Solenoid (DS)
Captures muons on the **Aluminium stopping target**
1 T B field and **10^{-4} Torr** vacuum in the detector zone

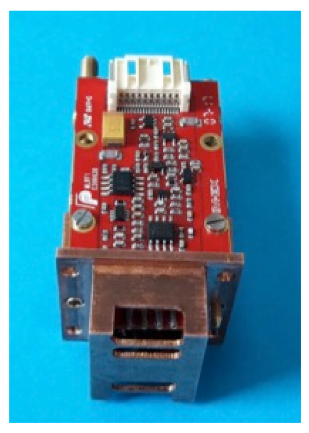
2. The Electromagnetic Calorimeter

Calorimeter Provides:

- Particle identification μ/e
- Seed for track pattern recognition
- Independent trigger
  - ***ΔE/E < 10% and Δt < 500 ps***
  - ***Position resolution of O(1 cm)***


Calorimeter disks


CsI + SiPM + Holder + FEE


SiPM + Holder + FEE

- 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

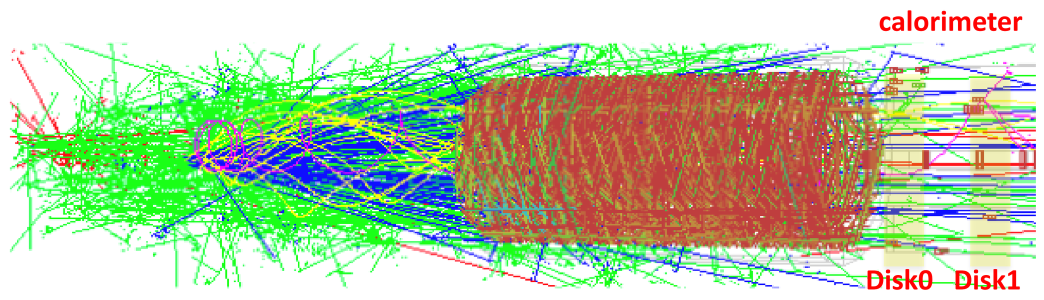

CsI crystals

DAQ crates located **inside the cryostat** to limit the number of pass-through connectors.

3. Why a digitizer ? What requirements ?

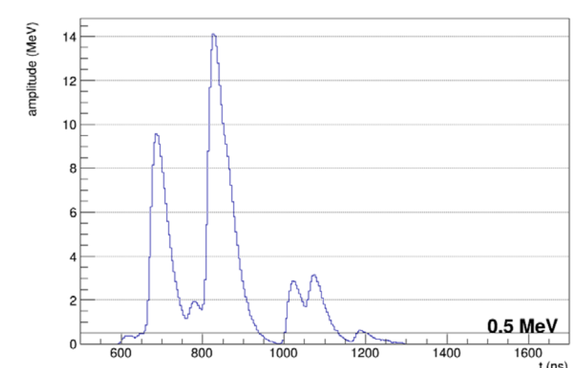
Requirements:

- 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



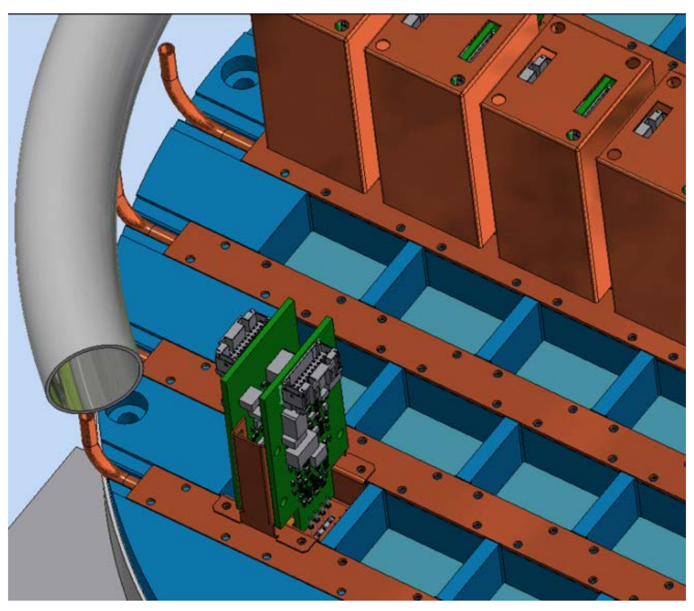
Typical 1.7 µs Mu2e event

- **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 (from simulation)*
  - *Neutron flux 5x10^{10} 1 MeV (Si)/yr (from simulation)*
- **Mechanical constraints:**
  - *Limited space* → 20 ADC channels/board
  - Limited access for maintenance → *Highly Reliable Design* mandatory

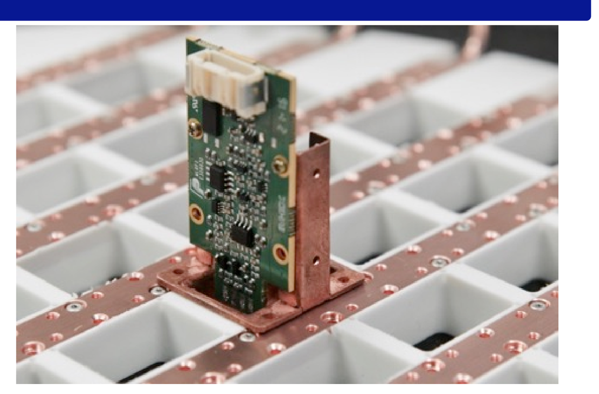


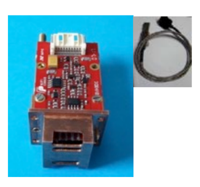
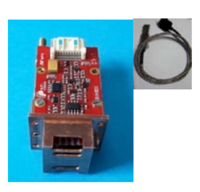
Example of front end output

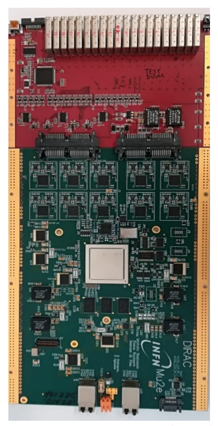
4. Front End Electronics

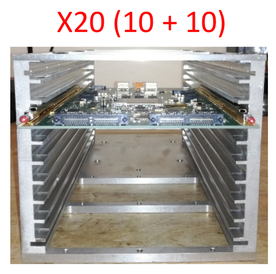


- FE boards connected to SiPM to provide:
  - Amplification
  - Local linear regulation of the bias voltage
  - Monitoring of current and temperature
  - Test pulse



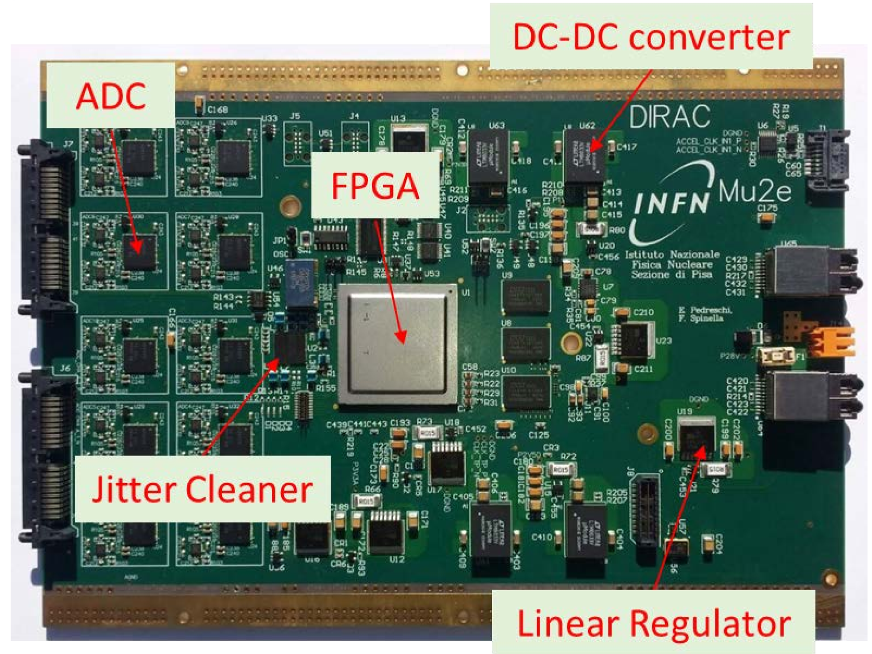

FEE (X20)



MB + DIRAC (X8)

CRATE + DIRAC +MB X20 (10 + 10)


- 20 FE boards controlled by 1 Mezzanine Board (MB) → SiPM LV and HV distributed by an ARM controller
- Differential signals from 20 FE boards sent to MB and then to 1 DIRAC
- DIRAC → sampling, processing and transmission to the Mu2e DAQ

5. Digitizer design



- The Harsh Environment and the sampling rate (200 Msamples) → severe limitations on the components choice
- ≈ 3,000 digitized channels → the cost is an important parameter

After an intense campaign of tests, our choice:

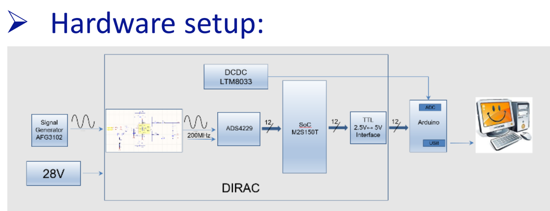
- ADC → Texas instruments ADS4229
- DCDC converter → Linear Technologies LTM8033
- FPGA (SoC) → Microsemi SmartFusion 2 SM2150T
- Fiber transceiver → Cotsworks RJ-5G-SX

- All components must be qualified for *Radiation Tolerance*
- The DCDC converter must also be tested for operation in 1 T magnetic field
- Microsemi SmartFusion2 already qualified for radiation by the producer, but the ADC is read out through a DDR bus, so it must be operated at 400 MHz, which is near the maximum allowed for the device. Compatibility between the SoC and the ADC must be tested.

6. DIRAC radiation test and magnetic field compatibility

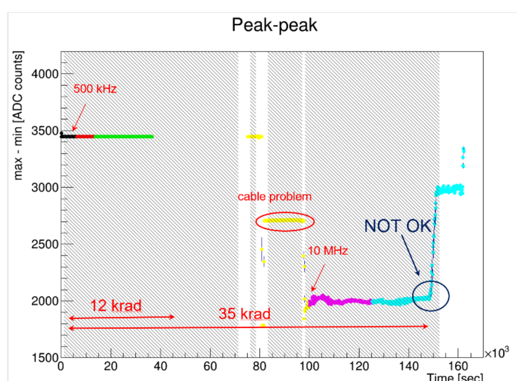
DIRAC test @ ENEA Casaccia Research Center

- Hardware setup:



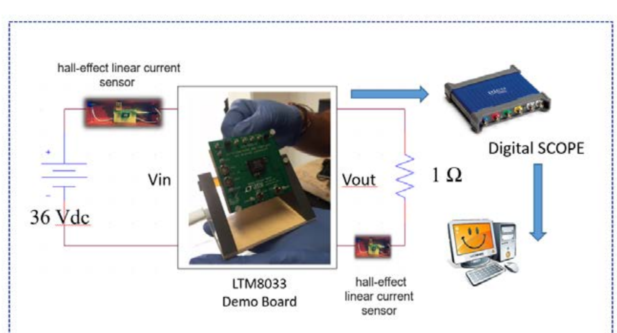
- ϒ irradiation (Co^{60})
- Test Start → June 13 @ 1.30 PM
- Test Stop → June 15 @ 9.20 AM
- Dose requested → 1Krad/ h → TID ≈ 41 krad

- Up to *35 Krad* the *DIRAC works fine*

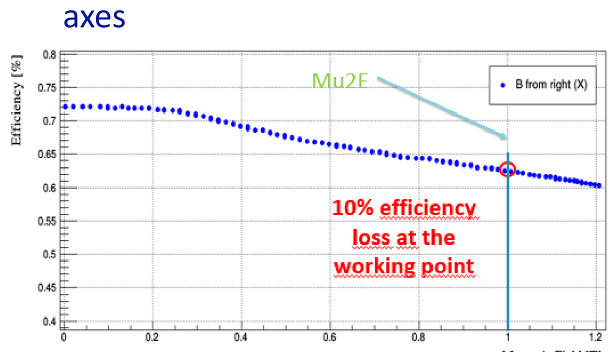


DC-DC Converter Test @ INFN Lasa Laboratory

- Magnetic Field Compatibility → LTM8033 tested in a strong Magnetic field
- The hardware setup was the same used for radiations tests to monitor convertion efficiency



- DCDC test: measure input/output voltages to monitor conversion efficiency and output voltage in all the 3 axes

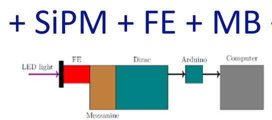


No significant difference between axes

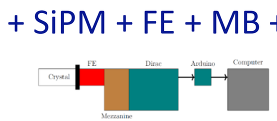
7. Slice test → full chain 1 channel

- The test was performed in two different configurations:

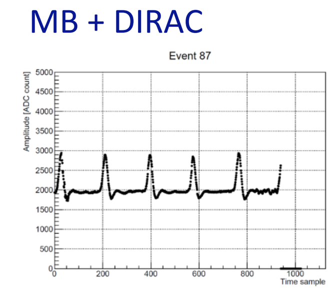
1. LED + SiPM + FE + MB + DIRAC



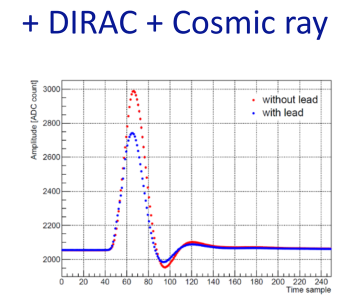
2. CsI + SiPM + FE + MB + DIRAC + Cosmic ray



LED + SiPM + FE + MB + DIRAC


Readout signal 200 MHz 12 bit

CsI + SiPM + FE + MB + DIRAC + Cosmic ray


Readout signal 200 MHz 12 bit

The input signal, in both cases, is correctly reconstructed at the output

8. Conclusions

- Mu2e DIRAC board conceptually defined and designed
- All relevant components chosen and tested both under radiation and magnetic field, with good results
- Compatibility between Microsemi SoC and ADC (ADS4229) demonstrated
- First digitizer prototype constructed, tested for radiation and one channel full chain successfully tested
- New prototype radiation tolerance tests planned at Helmholtz Zentrum Dresden Rossendorf in 2019, stay tuned.

This work was supported by the US Department of Energy; the Italian Istituto Nazionale di Fisica Nucleare; the US National Science Foundation; the Ministry of Education and Science of the Russian Federation; the Thousand Talents Plan of China; the Helmholtz Association of Germany; and the EU Horizon 2020 Research and Innovation Program under the Marie Sklodowska-Curie Grant Agreement No.690385 and 734303. Fermilab is operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the US Department of Energy.