Component Qualification for the Mu2e Calorimeter Waveform Digitizer

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

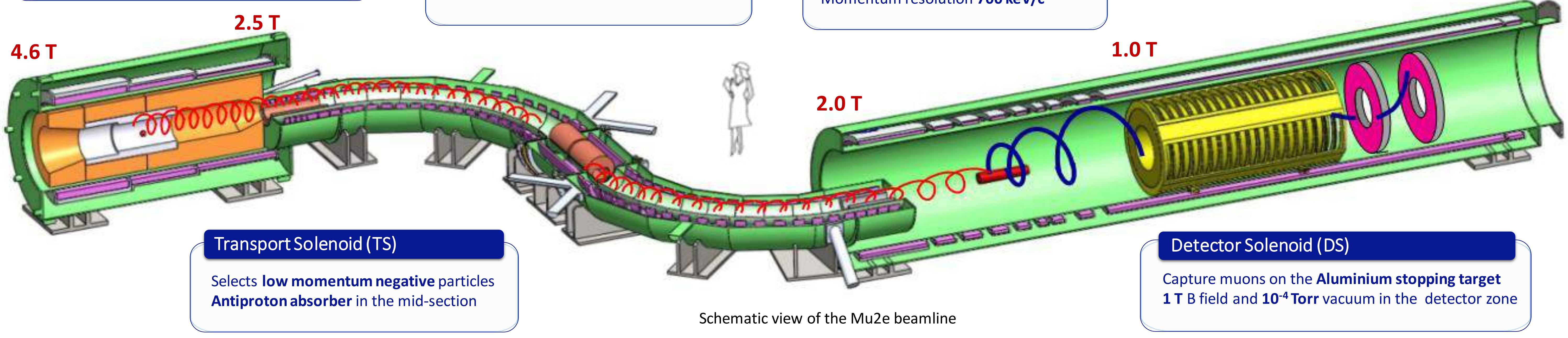
The **Mu2e Experiment** will search for coherent, neutrinoless conversion of muons into electrons in the field of a nucleus. **Such a charged lepton flavor-violating reaction allows to probe energy scales up to thousands TeV**, far above the highest energy reachable at the most powerful colliders. If no conversion events are observed in three years of running, Mu2e will set a limit on the ratio between the conversion rate and the 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)
20000 low mass straw drift tubes
Momentum resolution **700 keV/c**

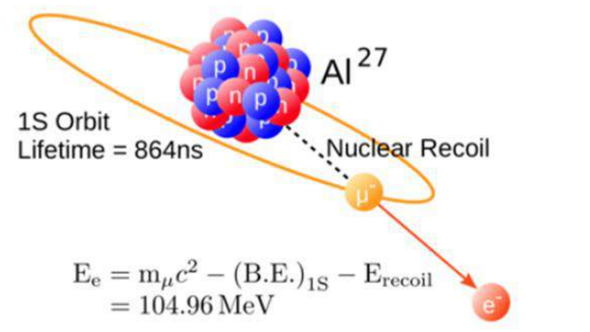
Electromagnetic Calorimeter (ECAL)
1348 undoped CsI crystals
Energy, Time and Position measurements



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

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

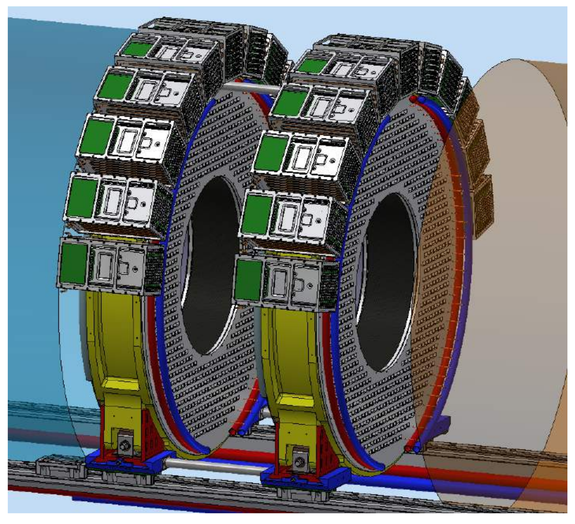
Schematic view of the Mu2e beamline



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

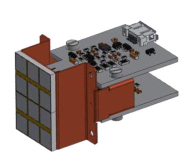
2. The Electromagnetic Calorimeter

The Electromagnetic Calorimeter is an high granularity crystal calorimeter consisting of about 1348 **undoped CsI crystals**, 3.4x3.4x20 cm^3 each. The crystals are arranged in **two disks**, separated by 75 cm, with inner and outer radii of 37.4 cm and 66 cm respectively.



Calorimeter disks

Each crystal is coupled to two 14x20 mm^2 **large area UV-extended SiPM**, for a total of **2694 electronics channels**. Photosensors are packed using a parallel arrangement of two groups of three cells biased in series.



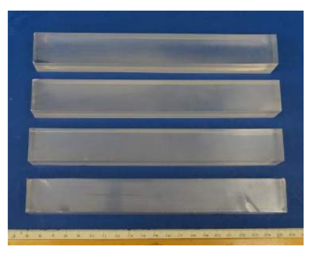
SiPM and FEE

Calorimeter Requirements:

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

⇛ **ΔE/E < 10% and Δt < 500 ps**

⇛ **Position resolution of O(1 cm)**



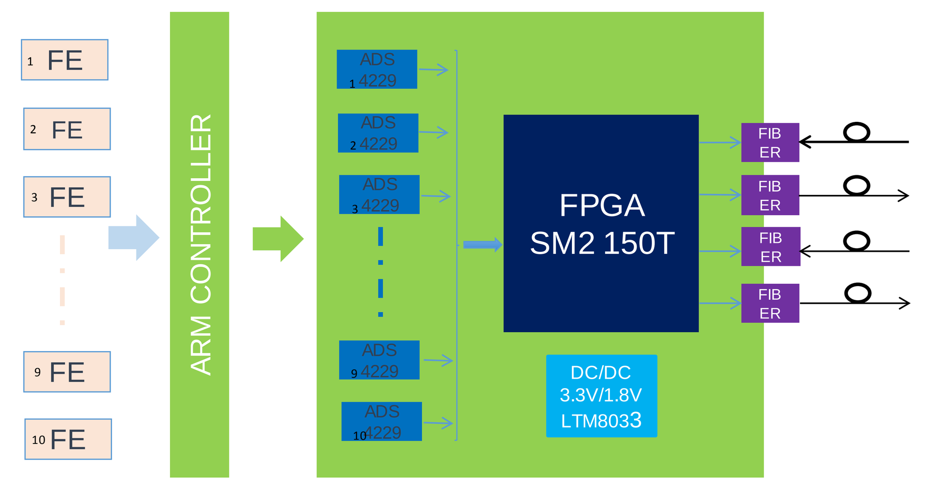
CsI crystals

Electronics crates are located **inside the cryostat** to limit the number of pass through connectors.

3. The Calorimeter Waveform Digitizer

Digitizer Requirements:

- Sample the signal at a frequency of **200 Msamples** with **12 bits** ADC
- Host 20 channels/board
- **Work in high magnetic field of 1 T under a 10^{-4} Torr vacuum**
- Have a large **reliability**
- Have an affordable **cost**



Waveform digitizer block diagram

The electronic boards, located close to the stopping target, have to stand a very heavy radiation environment:

- **Total Ionizing Dose (TID) of 0.5 kRad/yr**
- **Neutron flux of 5x10^{10} 1 MeV (Si)/yr**

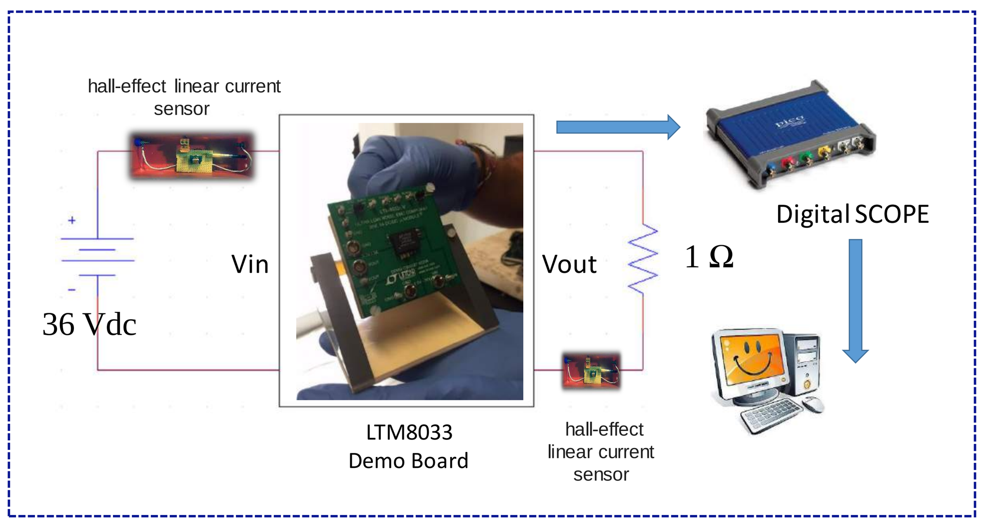
The presence of radiation, B field and vacuum place stringent limits on the choice of the components. The critical components are the **FPGA**, the **ADCs** and the **DCDC converters**. When needed, a dedicated campaign of measurements was performed to qualify them for a **radiation hardness** and **high magnetic field operation**.

4. DC/DC Converter – LTM8033

The most critical part is the DCDC converter because of the presence of a strong magnetic field. Following some studies described in literature we evaluated several products from Linear Technologies and finally **the LTM8033 survived the selection**.

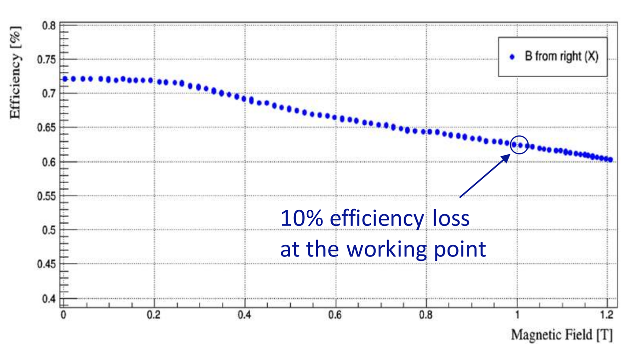
Acquisition System:

The setup was composed of an automated system capable of measuring and storing input and output voltages and currents. **One sample every 0.5 s.** The stability of the output voltage and of the conversion efficiency have been monitored during all the irradiation time and with a magnetic field up to 1.2 Tesla.



DCDC converter test setup

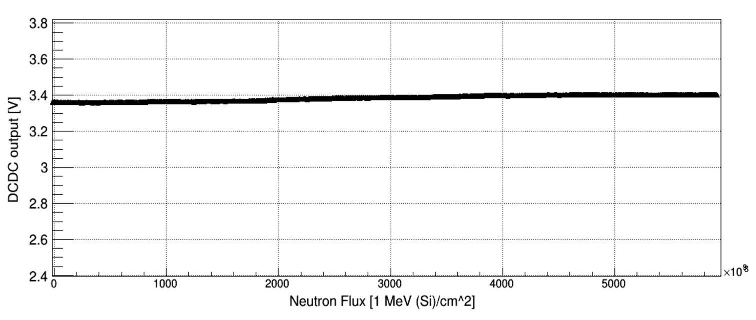
Magnetic Field Exposure Test:

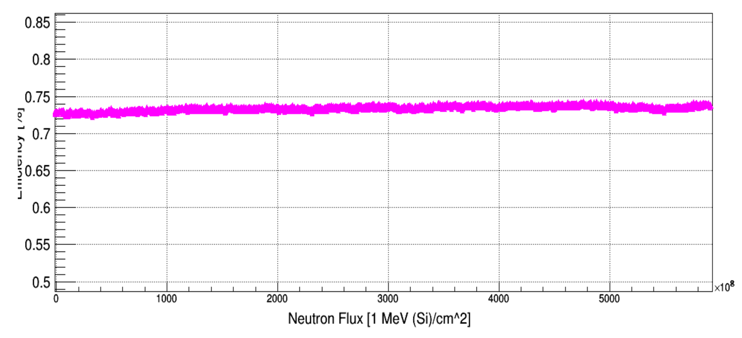


The DCDC behaviour in magnetic field was tested for different orientations at the LASA INFN laboratory of Milan Italy.

Neutron Irradiation Test:

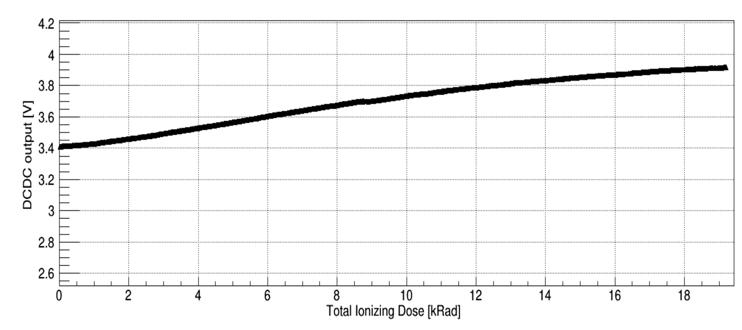
The performance when irradiated with neutrons was tested at the ENEA FNG facility in Frascati Italy.

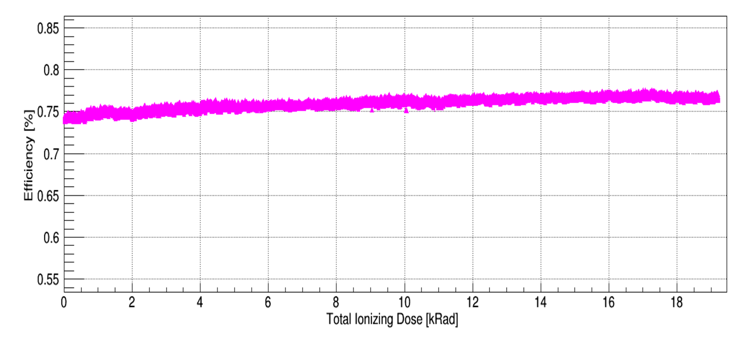




Total Ionizing Dose Test:

The test under ionizing dose was performed at the ENEA Calliope facility in Bracciano Italy.



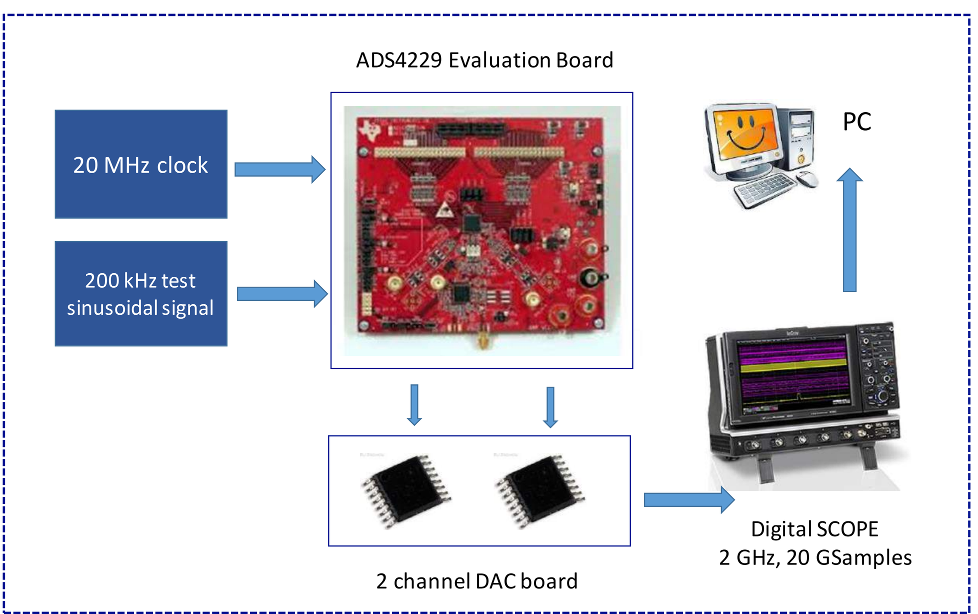


5. ADC – ADS4229

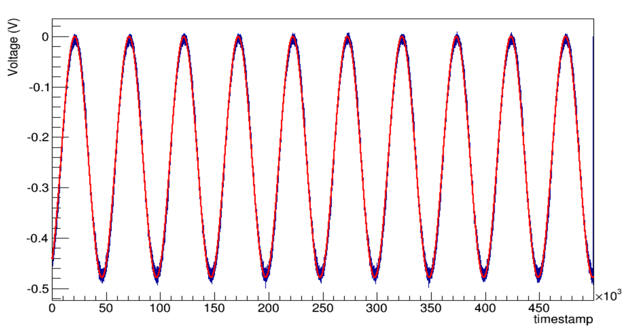
The digitizer is specified to sample at least with 200 Msamples 12 bits of resolution and, operating in vacuum, the absolute low power is a fundamental requirement. Also the cost is an important parameter just to the fact that about 3000 channels will be digitized. At the end we realized the Texas Instrument ADS4229 is the best value for money.

Also in this case a portable test setup was developed. A standard sinusoidal signal was sent in input to one ADS4229 demo board and the ADC output was first sent to a DAC custom board and after to a digital oscilloscope. We acquired at 10Hz a 50 μs sample of the DAC output waveform for both the ADC channels.

Neutron test at the Frascati Neutron Generator, ENEA



ADC portable test setup



Example of output waveform from the TID test

Analyzing more than 300 GB of data from both neutron and TID tests, no evidence of bit flips or waveforms shape variation emerged.

6. FPGA - Microsemi SmartFusion2

The selected FPGA is a Microsemi SMartFusion2, model SM2150T-FC1152. This part is already qualified by the producer so our current idea is not to qualify this part individually but only at the board prototype level.

Table 4: Configuration Single Event Upset Boundary of FIT rates

Environment	Upper Boundary of Configuration SEU FIT Rates
Ground Level (Sea Level, New York City)	Immune
Aviation (40,000 feet, New York City)	Immune
Space (Low Earth Orbit, 800 km circular, 85° inclination)	Immune

Table 5: Data SEU Summary (Single Bit Upsets)

Feature	Test Fluence (Neutrons/cm^2)	Error Rate Ground Level (Sea Level, NYC, FIT)	Error Rate Aviation (40,000', NYC, FIT)
Flip-flop	4.35 x 10^{11}	218.3 FIT / million flip-flops	1.13 x 10^5 FIT / million flip-flops
LSRAM	1.7 x 10^{11}	340.6 FIT / million bits	1.75 x 10^5 FIT / million bits
uSRAM	1.7 x 10^{11}	175.3 FIT / million bits	9.04 x 10^4 FIT / million bits

http://www.microsemi.com/document-portal/doc_view/134103-igloo2-and-smartfusion2-fpgas-interim-radiation-report

7. Conclusions

All critical components of the Mu2e calorimeter waveform digitizer board have been individually qualified:

- DCDC converter and ADC have been qualified to operate in high magnetic field and to survive to the expected ionization dose and neutron flux
- The FPGA is the same in use for all the mu2e electronics and qualified by the producer

The design of the first prototype is almost completed and we will ready to the production before the end of the year. All the qualification tests need to be repeated on the prototype before freeze the design.

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