# The Waveform Digitizer System for the MU2E Experiment: conceptual design

mu2e.fnal.gov

S. Di Falco[1], S. Donati [1,2], L. Morescalchi [1,3], E. Pedreschi [1,2], G. Pezzullo [1], F. Spinella [1]

[1]INFN – Pisa, [2]University of Pisa, [3]University of Siena

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

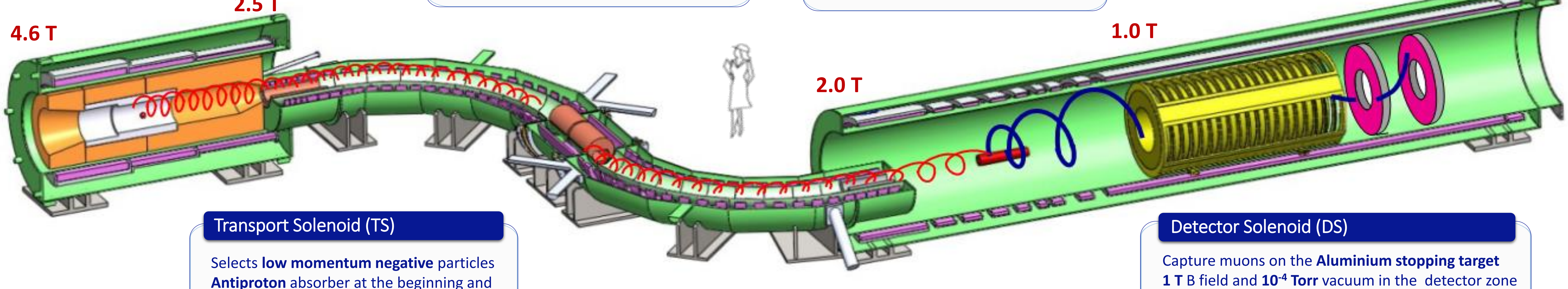
The **Mu2e Experiment** will search for coherent, neutrinoless conversion of muons into electrons in the field of a nucleus. **Such a charged lepton flavor-violating reaction allows to probe energy scales up to thousands TeV**, far above the highest energy reachable at the most powerful colliders. If 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 **180 keV/c**

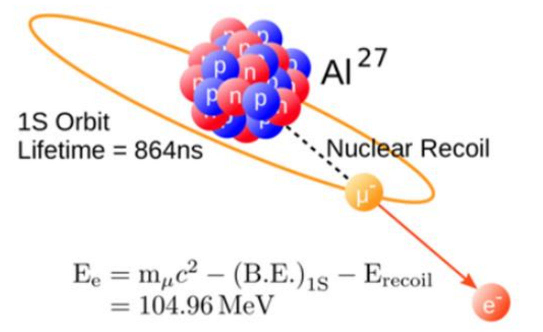
**Electromagnetic Calorimeter (ECAL)**
1348 undoped CsI crystals
Energy, Time and Position measurements




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

Schematic view of the Mu2e beamline

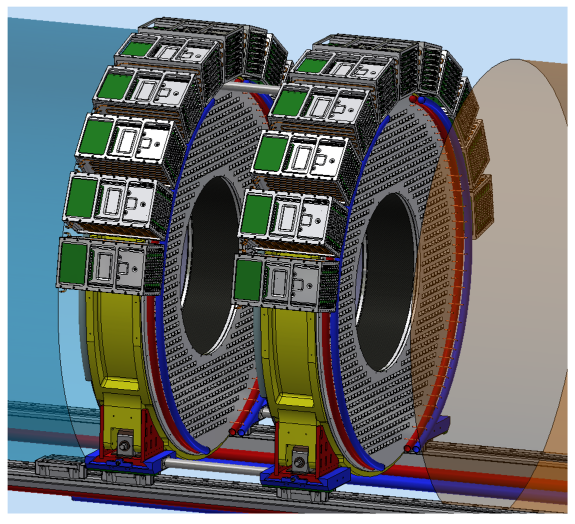
**Detector Solenoid (DS)**
Capture muons on the **Aluminium stopping target**
**1 T** B field and **$10^{-4}$ Torr** vacuum in the detector zone




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

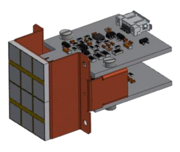
## 2. The Electromagnetic Calorimeter

The Electromagnetic Calorimeter is an high granularity crystal calorimeter consisting of about 1348 **undoped CsI crystals**, 3.4x3.4x20 cm³ 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 mm² **large area UV-extended SiPM**, for a total of **2696 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 $\mu$/e
- Seed for track pattern recognition
- Independent trigger

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

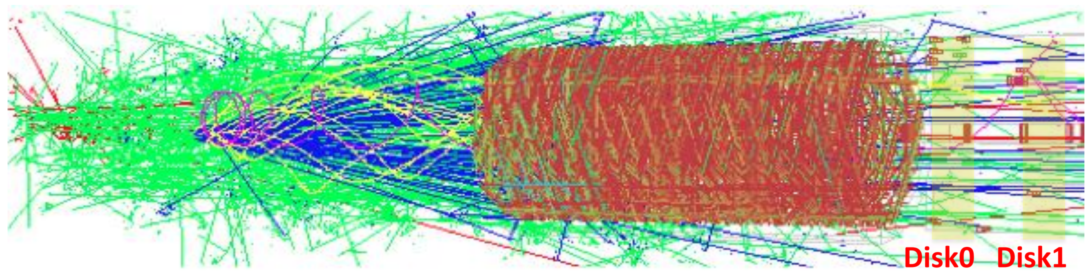
CsI crystals

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

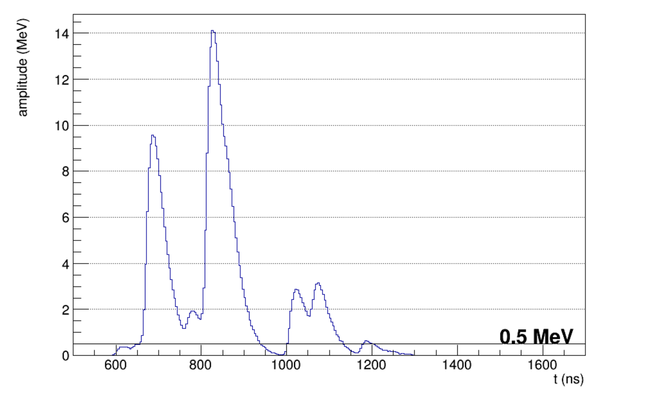
## 3. Why a digitizer ? Which are the requirements ?

**Digitizer Requirements:**

- Very intense particle flux expected in the calorimeter -> we need high sampling rate digitizers to resolve pile-up
- Sample the signal at a frequency of **200 Msamples** with **12 bits** ADC
- System located inside the cryostat -> harsh environment:
  - **high magnetic field of 1 T under a $10^{-4}$ Torr vacuum**
  - **Total Ionizing Dose (TID) of 0.5 kRad/yr**
  - **Neutron flux of 5x10$^{10}$ 1 MeV (Si)/yr**
- **Mechanical constraints:**
  - Limited space: 20 ADC channels/board
  - Limited access: high reliable design

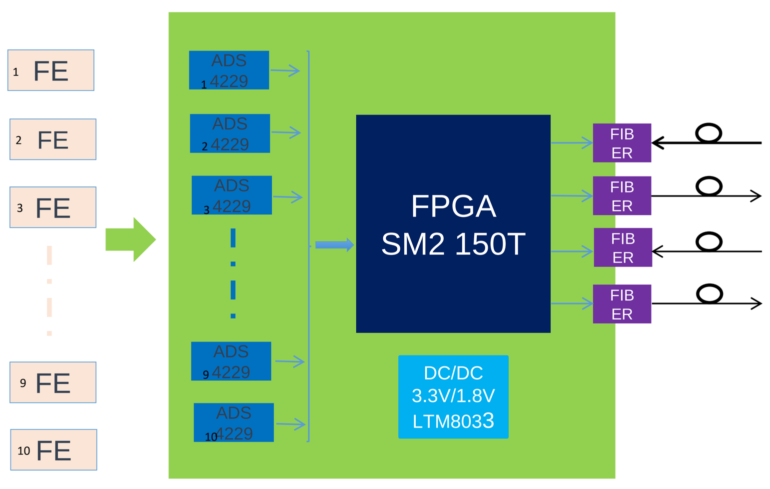



Typical 1.7 μs Mu2e event




Example of front end output

## 4. Digitizer design




Waveform digitizer block diagram

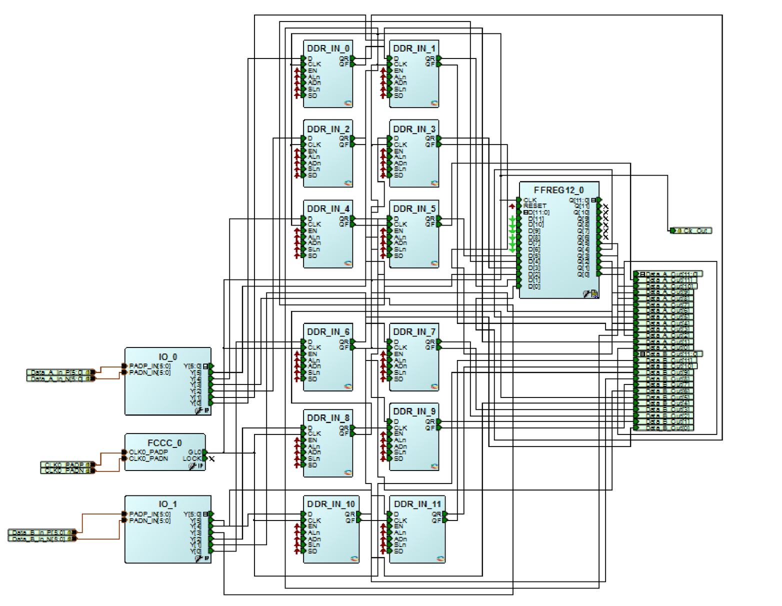
The working environment of the digitizer, together with the specified sample rate (200 Msamples) put severe limitations on the component choice. Also the cost is an important parameter just to the fact that about 3000 channels will be digitized.
After a long selection phase the main components were chosen:

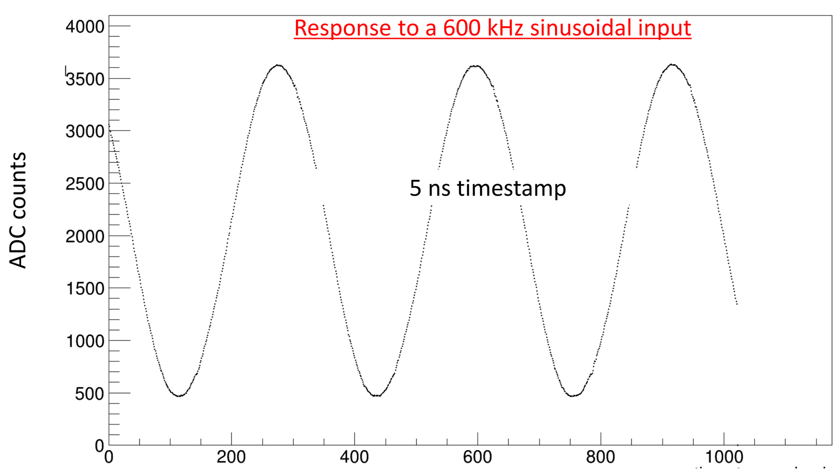
- ADC : Texas instruments ADS4229
- DCDC converter: Linear Technologies LTM8033
- FPGA (SoC): Microsemi SmartFusion 2 SM2150T
- Fiber transceiver: Cotsworks RJ-5G-SX

- All the components must be qualified for radiation tolerance and the DCDC converter must also be tested in magnetic field.
- Microsemi SmartFusion2 is 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. The compatibility between the SoC and the ADC must be tested

## 5. ADC <-> Microsemi SoC

- A preliminary firmware was designed through the Microsemi suite Libero and tested with a Smartfusion 2 demo board connected to an ADC
- The operating clock frequency was 400 MHz
- A 600 kHz sinusoidal signal was sampled at 200 Msamples, with no missing codes or bit flips

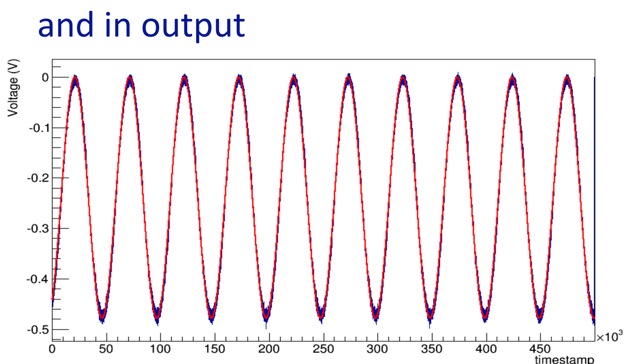





## 6. ADC & DCDC radiation tolerance test

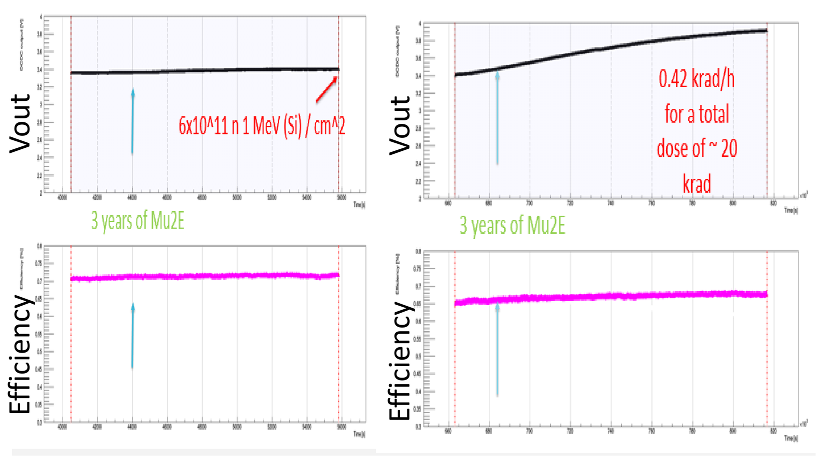
- ADC and the DCDC converter were tested both with neutrons and gamma rays for radiation tolerance.
- Neutron irradiation was performed at the ENEA Frascati Neutron Generator. The fluence was ~ 10^11 neutrons 1 MeV eq (Si)/cm^2
- Gamma irradiation was performed at the ENEA Calliope facility. We used a Co60 source. The TID was 20 Krad.

- The ADC was tested digitizing a 200 KHz sinusoidal signal and converting back to analog, testing automatically with a scope for the same signal in input and in output



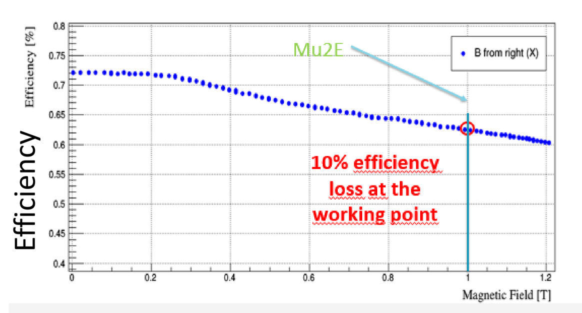

Analyzing more than 300 GB of data from both neutron and TID tests, no evidence of bit flips or waveforms shape variation emerged.

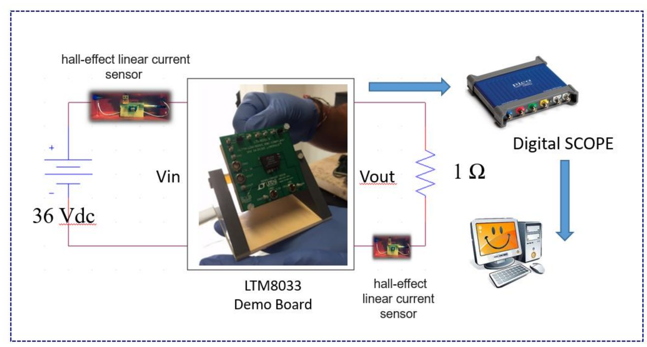
- The DCDC was tested measuring the input and output voltages and currents, monitoring conversion efficiency and output voltage




## 7. DCDC magnetic field test

- The DCDC converter was tested under a strong magnetic field at the INFN Lasa laboratory
- We used the same setup developed for radiation tests to monitor conversion efficiency and output voltage in all the 3 axes (no significative difference between axes)




## 8. Conclusions

- The Mu2e waveform digitizer has been conceptually defined
- All the relevant components have been chosen and tested individually both under radiation and magnetic field, with good results
- The compatibility between Microsemi SoC and ADC (ADS4229) has been demonstrated
- The design of the first prototype is almost completed and we will receive the prototype before the end of the year. All the tests will be repeated at the board level

*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. Fermilab is operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the US Department of Energy.*

contact email: franco.spinella@pi.infn.it