The Mu2e Digitizer ReAdout Controller (DiRAC): characterization and radiation hardness

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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: $R_{\mu e} < 6 \times 10^{-17}$ **(@ 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)

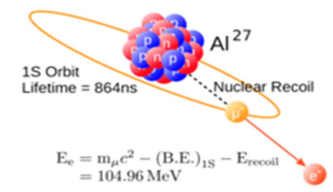
4 layers of plastic scintillator bars
Covers the entire DS and half of the TS

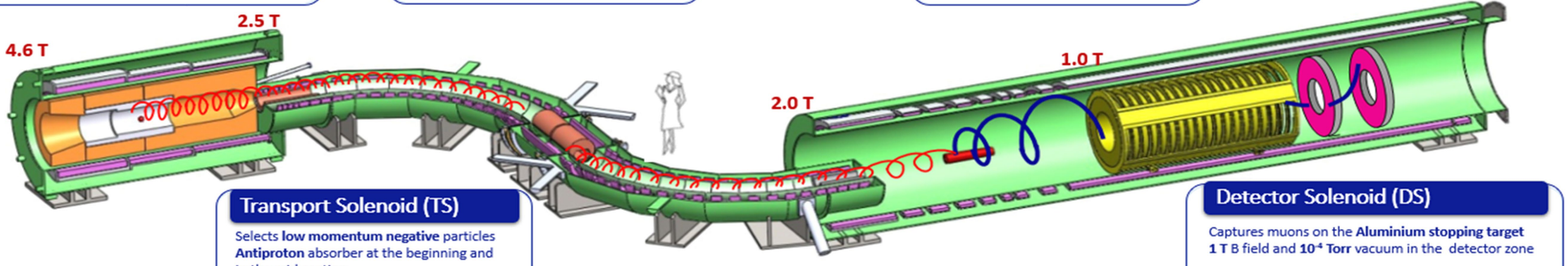
Straw Tracker (TRK)

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

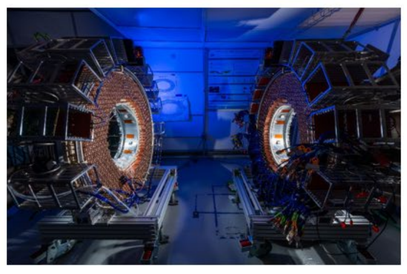
Experimental Technique

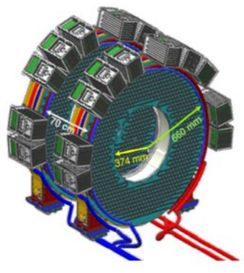
Stop muons in Aluminium target
Muons quickly get to 1S orbit
Lifetime of muonic atom is 864 ns
Look for the 105 MeV conversion electron

2. The Electromagnetic Calorimeter

The Calorimeter:

- High granularity
- 10% Energy and 500 ps Timing resolution for 100 MeV electrons
- Achieve **high levels of reliability and stability** when working in a **harsh operating environment**



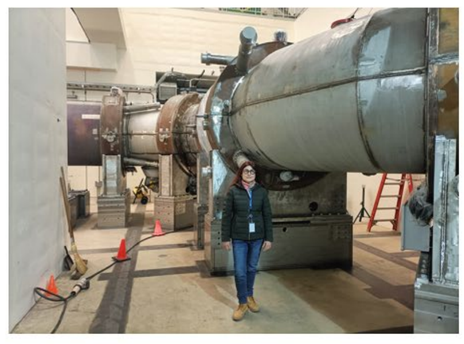


- 1348 **undoped CsI crystals** (3.4x3.4x20 cm^3)
- CsI arranged in **two disks** (inner/outer radius 37.4 cm / 66 cm, separation between disks 75 cm)
- 1 **crystal** coupled to 2 **large area UV-extended SiPM** (14x20 mm2) → **2696 electronic channels**
- **SiPM** packed in a parallel arrangement of 2 groups of 3 cells biased in series
- Each SiPM readout by preamplifiers and custom **high frequency digitizer** boards (**DiRAC**).
- DAQ crates located **inside the cryostat** → limited number of pass-through connectors and cable lenght
- 10 crates/disk with 6/8 boards / crate

3. DiRAC «environmental» specs and qualification tests

System located inside the cryostat → Harsh Environment:

- **Magnetic field** of **1 T**
- 10-4 Torr **vacuum**
- Thermal dissipation
- Total Ionizing Dose (**TID**):
  - 0.2 krad/yr (from simulation)
  - 12 Safety factor (requested from collaboration 3 MC -2 batch – 2 Fast)
  - 5 years data taking
  - Acceptance test level **12 krad**
- **Neutron flux** 2x1010 1 MeV (Si)cm2/yr (from simulation) (Displace damage)
  - Acceptance test level ? We suppose 15 (3 MC) (3x1011 cm2)
- **Hadrons flux** (E > 20 Mev) 1.8x108 cm2/year (SEU & Latch-up)
  - Acceptance test level ? We suppose 3 (3 MC) (5x108 cm2)

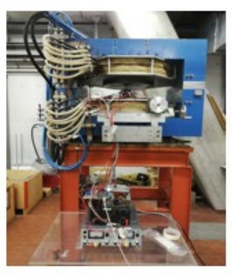


Qualification tests:

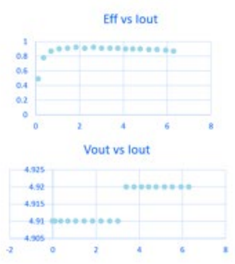
- B field
- Vacuum & Thermal
- TID & Displacement damage (neutrons)
- SEE (SEFI and SEL) (neutrons & protons)

4. B Field Test

B = 1T test@ INFN Lasa facility in Milano → Component level test (LMZM 33606)

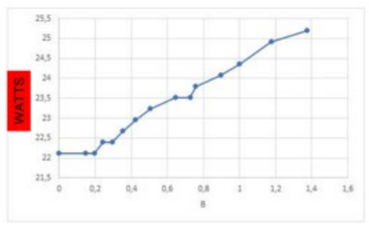


- First radiation test campaign started in 2015, the last was in Feb 2019 Texas Instruments® LMZM 33606 (3.5V÷36V Input, 1V÷20V Output, 6A)
- Test OK: no evidence of drop of performance in B=1T
- Same results for many Vout (1.8,2.5,3.3.,5) and all views (X,Y,Z)



0 <B< 1.4T @ Argonne National Lab (IL) → Full Board

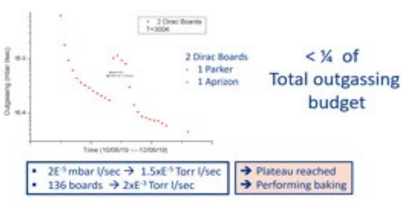
- Tested all directions
- Slight power increase at 1T ≈ 10% toward 0T in the Mu2e direction
- Previous test confirmed
- Analogical section tested in B up to 1.4T without any changes in the signal amplitude



5 . Vacuum & Thermal

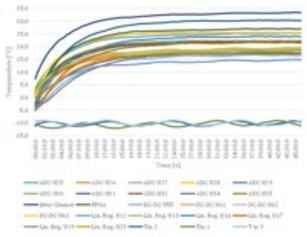
Outgassing tests crates & DiRAC:

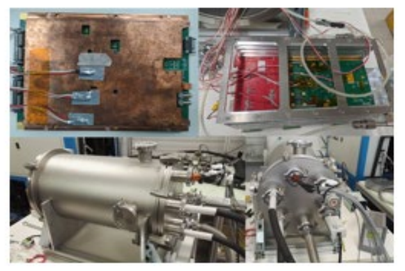
- Leak test on crates sides first: max leak detected < $1.4 \cdot 10^{-8}$atm-cc/s
- Leak test on completed crates next: no leak detected > $5 \cdot 10^{-8}$atm-cc/s
- Pressure test on crates @ 20bar: no leak created/detected



Thermal-vacuum tests:

- Experimental test of one board (Dirac + Mezzanine) in vacuum: experimental data consistent with FEM simulation
- Max temp: 33.3°C on Jitter cleaner
- Head losses measurements on crates: 1.28 bar @ -10°C, 3.85 kg/min
- To do: Perform a test with all the Mezzanine and Dirac (8+8) boards in a crate





6 . TID & Displacement

Total Ionizing Dose:
Single component test @HZDR

- γ from Bremsstrahlung (0<E<14MeV)
- Extimated dose ≈ 20 krad/h @ 600μA
- Components tested up to 20 krad

Full board@ENEA Calliope

- Gamma rays at 1.17 and 1.33 MeV from Co60.
- 3.7x10^15 Bq of activity.
- Isotropic source, flux scales with r^2
- Total dose 41krad

Displacement Damage:
Frascati Neutron Generator (FNG) is a linear electrostatic accelerator in which up to 1 mA D+ ions are accelerated onto a Tritium target

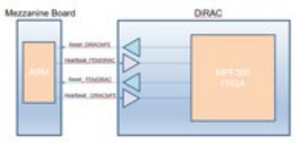
- Dirac @ 4 cm from 14 MeV neutron source for 120 minutes
- Integrated fluence of 4*10^11 MeV eq(Si) / cm^2
- No evidence of permanent damage (displacement)

7. Single Event Effects

SEU/SEE from neutrons @ FNG:

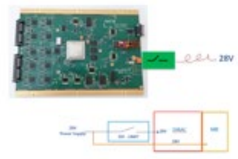
- FPGA @ 5.3 cm from 14 MeV neutron source for 2h
- Rate 2.2x108 n/ cm2/s
- 15 SEU (solved) → 14 reset + 1 power cycling
- 3 SEU/Board/Year →136 DIRAC → O(1 SEU)/Day

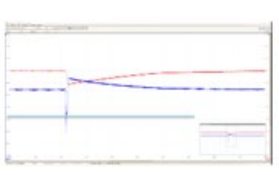
an AutoRESET was introduced in the new prototypes of MB and DiRAC (V3)



SEE with protons:

- MPC@Warrenville (IL):
  - uniform beam, Fluence 1E10p/cm2 (increasing) → 4 LU → SSF introduced
- Cyclotron@UC Davis:
  - proton beam with uniform spot ≈ 6 cm and E up to 60 MeV (very high flux)
  - Tested many components
  - Flash sensitive to Latch-Up → replaced and tested a different IC
- Synchroton@CNAO:
  - Proton beam with 60 <E< 220 MeV and a bi-gaussian profile
    - sigma depending by the energy
    - about a few 10^9 protons/s
  - Flash (new) tested with a 116 MeV p beam, arriving at 3x10^11 p/cm^2 → NO Latch-Up
  - SSF tested with 227 MeV p beam, up to 2x10^11 p/cm^2 →16 current limited events and work restarted





8. Conclusions

- The Mu2e Digitizer ReAdout Controller (DiRAC): characterization and radiation hardness was presented
- The presence of vacuum (10^{-4} Torr), high magnetic fields (1T) and radiation (Non-Ionizing Energy Loss $5x10^{11}$ n/cm^2 @ 1 MeV_{eq} (Si)/y and Total Ionizing Dose 12 Krad) makes the environment particularly harsh and the design of the board very challenging
- The DIRAC is designed to sample @200 MHz – 12 bits differential signals coming from Silicon Photo Multiplier(SIPM) and amplified by a custom Front End Electronics.
- We described the apparatus, the design specification, the characterization and radiation hardness
- The DIRAC has been qualified
- The full production is done, and the boards are going to be installed to Fermilab

16TH Pisa Meeting on advanced detectors, La Biodola, Isol d'Elba, May 26-June 1, 2024 contact email: elena.pedreschi@pi.infn.it

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