Pre-production and quality assurance of the Mu2e Silicon Photomultipliers

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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 process 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)

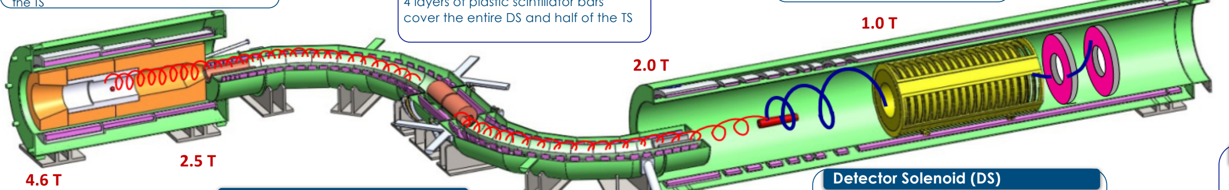
4 layers of plastic scintillator bars cover the entire DS and half of the TS

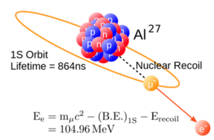
Straw Tracker

20000 low mass straw drift tubes
Momentum resolution **160 keV/c**

Electromagnetic Calorimeter

1348 undoped CsI crystals
Energy, Time and Position measurements





Experimental Technique

Stop muons in Aluminium target
Muons quickly get to 1S orbit
Lifetime of muonic atom is 864 ns
Signature: a mono-energetic 105 MeV conversion electron

Transport Solenoid (TS)

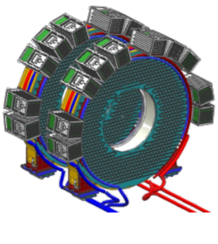
Selects **low momentum negative** particles
Antiproton absorber in the mid-section

Detector Solenoid (DS)

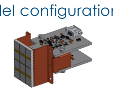
Capture muons on the **Aluminium stopping target**
1 T B field and **10^{-4} Torr** vacuum in the detector zone

The Electromagnetic Calorimeter

The Electromagnetic Calorimeter is a high granularity crystal calorimeter made of 1348 **undoped CsI crystals** of parallelepiped shape (3.4x3.4x20 cm³). Crystals are arranged in **two disks**, separated by 75 cm, with inner and outer radii of 37.4 cm and 66 cm respectively.



Each crystal is coupled in air to two 14x20 mm² **large area UV-extended SiPM**, for a total of **2694 electronics channels**. SiPMs are packaged in a parallel configuration of two groups of three cells biased in series.

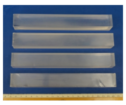


SiPM and FEE

Calorimeter Requirements:

- Particle identification: μ/e rejection of 200
- Seed for track pattern recognition
- Tracking independent trigger

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



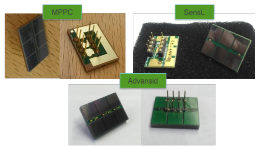
CsI crystals

Electronics crates are located **inside the cryostat** to limit the number of feed-throughs

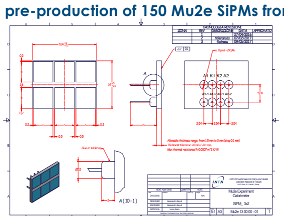
The Mu2e Custom SiPMs

The Mu2e SiPM is made by a 2x3 array (6 cells) of 6x6 mm² UV extended SiPMs

- Ensure a high quantum efficiency @ 315 nm (CsI emission peak)
- A parallel arrangement of two groups of three cells biased in series
- 2 SiPMs per crystal to ensure redundancy
- Fast signal for pileup and timing resolution



A pre-production of 150 Mu2e SiPMs from 3 firms (Hamamatsu, Sensl and Advansid) completed.



SiPM Requirements:

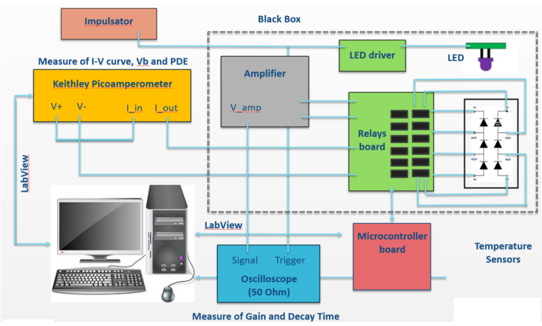
- A Gain greater than 10^6
- A PDE above 20% at 310 nm
- A fast rise and recovery time
- A large reliability
- Able to survive in a heavy radiation environment:
  - **Total Ionizing Dose (TID) of 7 kRad/yr**
  - **Neutron flux of 1x10¹¹ 1 MeV (Si)/yr**

Quality Assurance Process

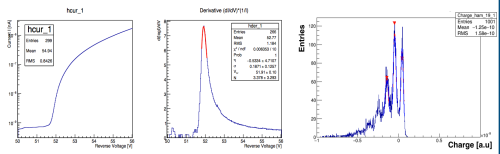
QA Test Station:

Each 6x6 mm² SiPM cell has been tested using a semi-automatized station controlled by Labview.

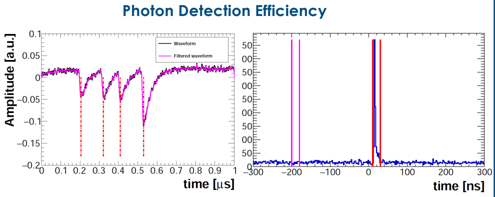
- **Light tight box** to **prevent external light** on the Sensor Under Test (SUT) that is encapsulated in a copper box → provide a **thermal coupling** between the package and the copper.
- Copper support refrigerated by a chiller to keep the SiPM at a **stable temperature of 20°C.**
- Custom relay board to select the cell biased by a KEITHLEY 6487 to perform: **I-V curve** and **Breakdown Voltage** measurements
- SiPM cells illuminated with a 315 nm LED light
- Cascade of Mar-8 ampliers, with a total gain of G_{amp} = 250,→**Gain and PDE** measurements



I-V Dark Curve and Breakdown Voltage **Gain**

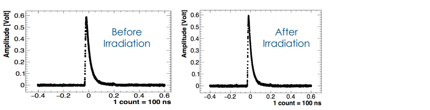


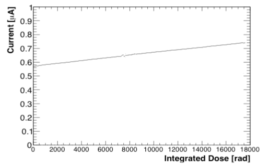
Photon Detection Efficiency



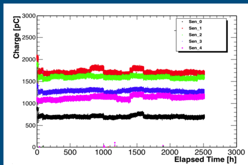
Radiation Hardnes - Dose

Photosensor irradiated with an high intensity ⁶⁰Co source up to 20 krad (200 Gy) @ CALLIOPE - Gamma Irradiation Facility (Casaccia, ENEA)
➢ **Negligible effect on the response and on the leakage current due to the dose**





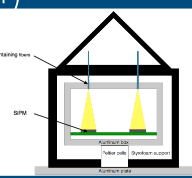
Mean Time To Failure (MTTF)



MTTF >0.5 x N_{hours} x AF x N_{SiPM}

2556 100.1 5 per vendor

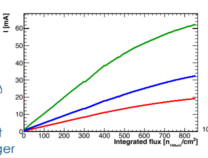
- Stress temperature 50 °C for 3.5 months
- Charge response to a LED light acquired every 2 minutes
- No "deads" →MTTF> **0.6 x 10⁶ hours**



Radiation Hardness – Neutron flux

3 SiPMs irradiated @ EPOS (HZDR, Dresden)

- Integrated flux 8.5 x 10¹¹ n_{1MeV}/cm²
- Cooling system: chiller + Peltier cell
- Temperature stabilized at 20 °C and monitored by a PT100
- Single cell current and temperature acquired with a Agilent 34972A LXI Data Acquisition / Data Logger Switch Unit every 10 s



I_{dark} @ start and end of the irradiation:

Hamamatsu: 3 μA -19.5 mA
AdvansiD: 22 μA – 32.4 mA
SensL: 29 μA – 62 mA

Conclusions

A pre-production of **150 Mu2e SiPMs** from 3 firms (Hamamatsu, Sensl and Advansid) completed in feb-2017. Dedicated quality assurance, QA, has been carried out on each SiPM for the **determination of its own operating voltage, gain, quenching time, dark current and PDE.** The MTTF measurement, on a small random pre-production sample, has been also completed as well as the determination of the **dark current increase as a function of the neutron**

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