# The Mu2e calorimeter: QA of production crystals and SiPMs and results from Module-0 beam test


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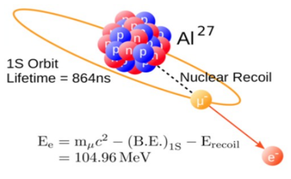
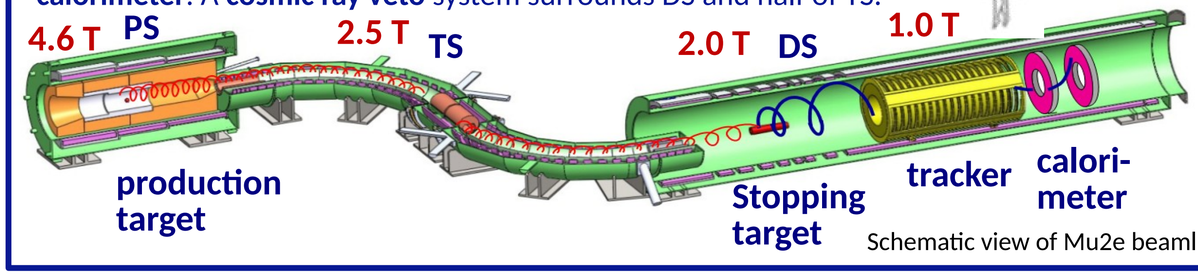
## 1. The Mu2e Experiment: a Search for $\mu + N \rightarrow e + N$

The **Mu2e Experiment at Fermilab** will search for **charged lepton flavor violation** looking for a coherent, neutrinoless conversion of muons into electrons in the field of an Al nucleus.

Mu2e aims to **improve by a factor $10^4$** the current best world sensitivity.

8 GeV protons entering from right in the production solenoid (PS) interact with a tungsten target producing pions and kaons. M**uons** produced in their decays are guided by a magnetic field gradient to the transport solenoid (TS) where they are selected in momentum and charge. Muons arriving in the detector solenoid (DS) are stopped in an **Al target** and the eventual **monochromatic electrons** produced in the muon conversions are identified by **tracker** and **calorimeter**. A **cosmic ray veto** system surrounds DS and half of TS.



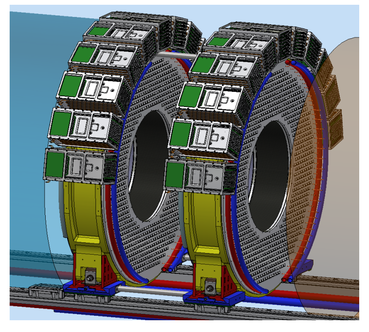




Schematic view of Mu2e beamline

## 2. The Electromagnetic Calorimeter

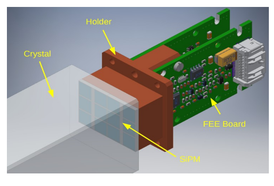
**Calorimeter tasks:**
- Particle identification $\mu$/e
- Seed for track pattern recognition
- Tracking independent trigger

⇨ **Calorimeter requirements:**
**ΔE/E < 10%**
**Δt < 500 ps**
**Δx,Δy ~ 1 cm**



Each disk contains 674 **undoped CsI crystals**, 3.4x3.4x20 $cm^3$ each.
Each crystal is coupled to two 14x20 $mm^2$ **large area UV-extended SiPM arrays**, Each array consists of a parallel arrangement of two groups of three cells biased in series.

SiPM array




CsI crystal + 2 SiPM arrays + FEE

Front end electronics (FEE) is located just on the back of SiPMs.
20 digital and control electronics crates servicing a total of **2694 channels** are located around the disks.
Everything is inside the DS cryostat in a $10^{-4}$ Torr vacuum and a 1 T magnetic field.

Electronics crate with 3 (out of 9) digitizer boards

## 3. CsI crystals characterization

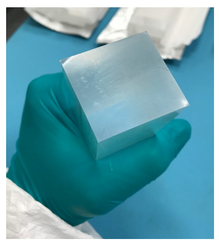
**Crystal quality controls:**
- Mechanical parameters
- Light Yield>100 p.e/MeV (with reference PMT))
- Longitudinal Response Uniformity (LRU) < 5%
- Fast emission to Total Ratio > 75%
- Average Radiation induced noise (RIN): < 0.6 MeV @1.8rad/h
- Radiation Hardness: normalized light output after 10 (100) krad > 85 (60)%

**SICCAS**

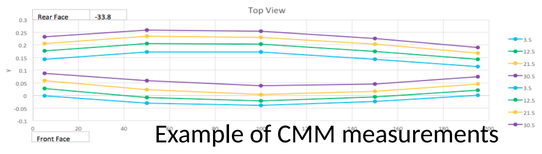

**SAINT GOBAIN**

Two vendors have been selected after an international bid. Production is ongoing: 52 (SIC) and 100 (SG) delivered as of May 2018

### OPTICAL INSPECTION AND DIMENSIONS



Reject crystals with dents, scratches or notches. Dimensional tolerance: ±100 μm Coordinate measuring machine (CMM) checks: transversal thickness, longitudinal length, face parallelism and perpendicularity



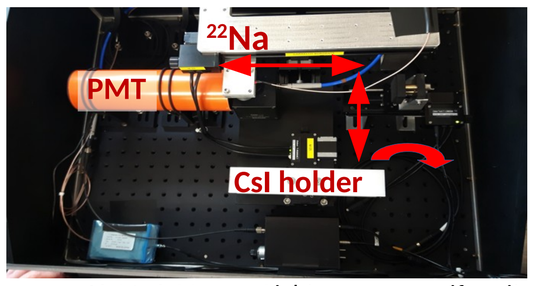

Example of CMM measurements

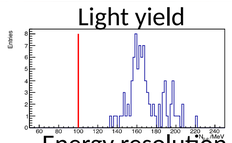
### WRAPPING

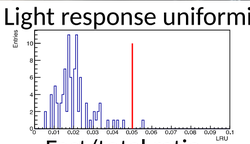
Crystals are wrapped with 150 μm of diffusive Tyvek

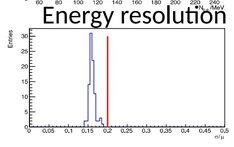
### LIGHT YIELD AND LRU TEST STATION

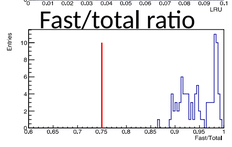
An automated station allows to measure light response to a $^{22}Na$ source in different positions



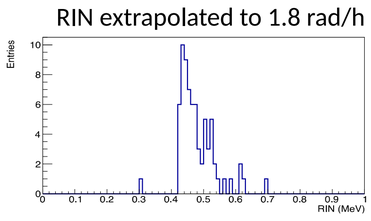




### RIN TEST STATION

A $^{137}Cs$ radiates 6 crystals with a dose of 0.042 rad/h


RIN extrapolated to 1.8 rad/h




### RADIATION HARDNESS

A $^{137}Cs$ source is used in Caltech to irradiate crystals with a dose of 10 and 110 rad

| Crystal ID | Dose (krad) | Normalized light output |
|---|---|---|
| SIC-C0002 | 10 | 82% |
| | 110 | 70% |
| SIC-C0012 | 10 | 79% |
| | 110 | 61% |
| SG-6827 | 10 | 80% |
| | 110 | 67% |
| SG-6828 | 10 | 86% |
| | 110 | 78% |
| SG-634 | 10 | 84% |
| | 110 | 76% |
| SG-6835 | 10 | 72% |
| | 110 | 64% |
| SG-6838 | 10 | 82% |
| | 110 | 75% |
| SG-6840 | 10 | 83% |
| | 110 | 72% |

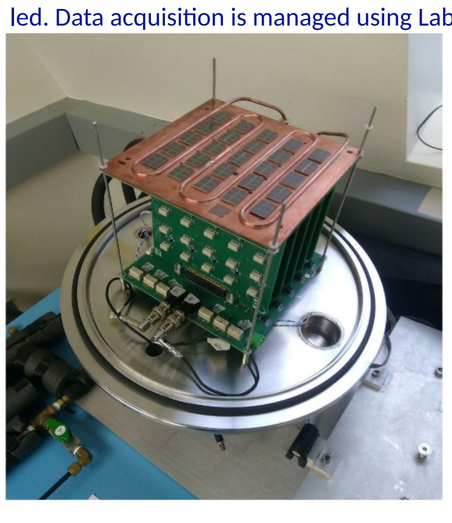
## 4. SiPMs Characterization

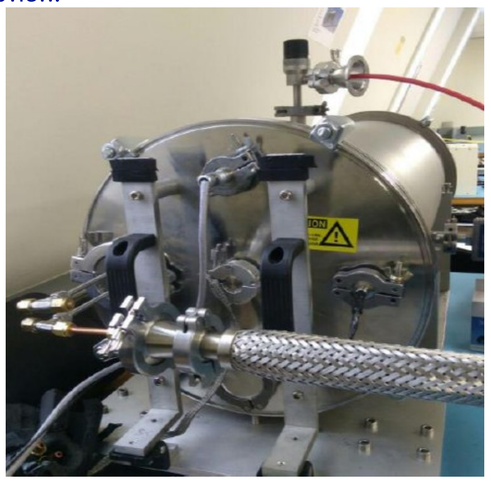
**SiPM array quality controls:**
- 6 cells homogeneity
- gain greater than $10^6$
- PDE above 20% at 310 nm
- fast rise and recovery time
- Mean time to failure > $10^6$ hours
- Radiation hardness up to 7 kRad/yr and $1x10^{11}$ 1 MeV (Si) neutron/yr

Hamamatsu devices have been selected after and international bid.
Production is ongoing: 1 batch of 300 SiPM arrays/month
Each of the 6 cells in the SiPM array is tested individually
QA process will involve 24k cell characterizations!
(1k performed as of May 2018).

### SIPM QUALITY ASSURANCE TEST STATION

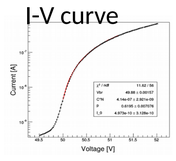
An automatized Test Station is used to measure break down voltage, dark current and PDExGain at 3 different temperatures (20°, 0°, -10° C) in a $10^{-1}$ Torr vacuum for the 6 cells of each SiPM array. Custom electronics is used to control a set of relays to power and readout each single cell (via a Keithley multimeter) and to switch on and off a UV led. Data acquisition is managed using Labview.

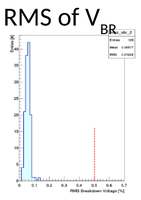




25 sensors/time (20 tested + 5 as reference)
One cell characterization/1.2 min!

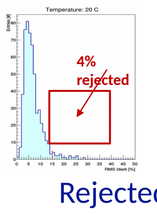
The break-down voltage ($V_{BR}$) is obtained from the measured I-V curve



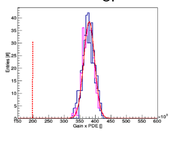




The gain x PDE and the homogeinity of response of the 6 cells are measured at the operating voltage:
$V_{OP}=V_{BR}+3$ V

RMS of Dark Current @$V_{OP}$



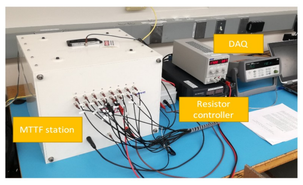

Gain x PDE @$V_{OP}$



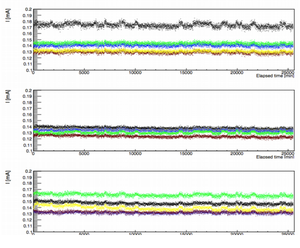
Rejected 4%

### MEAN TIME TO FAILURE

Accelerated aging test @65° C for 18 days with 15 SiPM arrays per batch



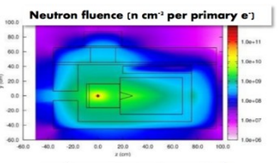

Test ensures MTTF>$10^6$ hours for each batch.

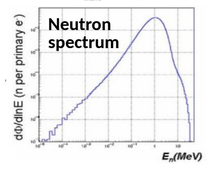


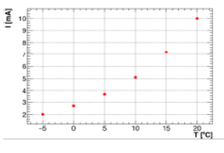
No failures observed

### RADIATION HARDNESS

For each batch, 5 SiPMs are irradiated @ EPOS (HZDR, Dresden) with a neutron Integrated flux of $1.7 \times 10^{12}$ $n_{1MeV}$ (Si) / $cm^2$



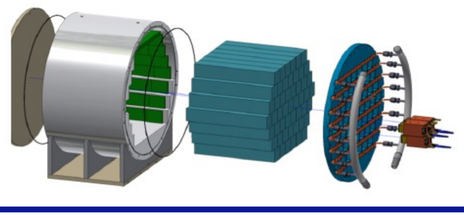




Dark current @ 20° C after irradiation must be < 10 mA to ensure a current ~2 mA in the experiment

## 5.The Module-0 prototype

A calorimeter prototype (Module-0) has been built to validate the design. The module used crystal and SiPM preproduction samples tested for the international bid.



51 CsI crystals (AMCRYS, SAINT GOBAIN, SICCAS)
102 SiPM arrays (ADVANSID, HAMAMATSU, SENSL)
Cooling system and FEE close to the final one.
CAEN Digitizer.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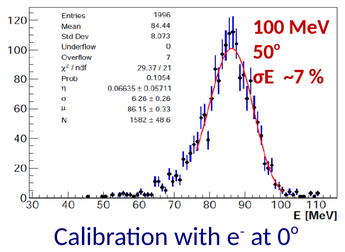
## 6. Beam Test results

Module-0 with preliminary electronics has been tested in May 2017 at INFN Beam Test Facility (BTF) in Frascati. Electrons produced by muon conversions in Mu2e will reach the calorimeter with an energy of ~100 MeV and an average impact angle of ~50° .

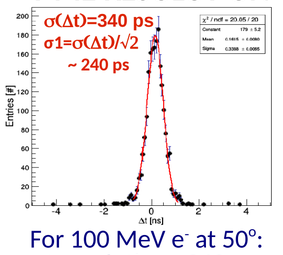
e⁻ beam energy:
70,80,90,100,110,120 MeV
Horizontal impact angle: 0°, 50°

### ENERGY RESOLUTION




Calibration with e⁻ at 0°
For 100 MeV e⁻ at 50°:
Energy resolution ~7%

### TIME RESOLUTION




Δt: Time difference between two sensors reading the same crystal.
Beam impact on crystal center

For 100 MeV e⁻ at 50°:
Δt resolution ~340 ps
Single sensor resolution ~240 ps

**Calorimeter time and energy resolutions well satisfy the requirements**