Design and qualification of the Mu2e electromagnetic calorimeter radiation monitor system

Franco Spinella

on behalf of the Mu2e Calorimeter Group

INFN – Sezione di Pisa

TWEPP-21

Topical Workshop on Electronics for Particle Physics

Outline

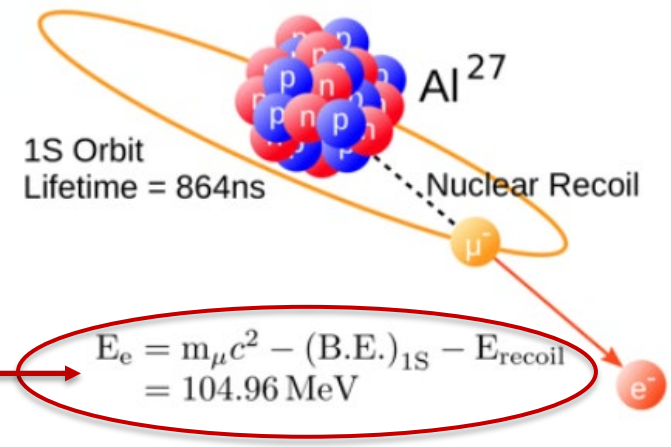
- The Mu2E experiment: goal and experiment layout
- The Electromagnetic Calorimeter
- Expected radiation on the calorimeter
- Radiation monitoring system: T-RAD
- Sensors used to measure TID and neutron fluence
- Test and calibration of the system

The Mu2e Experiment

- Mu2e searches for Charged Lepton Flavor Violation (CLFV) via the coherent conversion:

$$\mu^- \mathbf{N} \rightarrow e^- \mathbf{N}$$

at Fermilab muon campus..



Clear experimental signature!

$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil} = 104.96\,\text{MeV}$$

- Since the Standard Model prediction is ~ $(\Delta m_\nu^2 / M_w^2)^2 < 10^{-54}$, far beyond experimental reach, any observation will be clear evidence for New Physics.

- In case of no observations, Mu2e will improve by a factor 10^4 the current world best limit from Sindrum II experiment:

$$R_{\mu e} = \frac{\Gamma\left(\mu^- + \mathrm{N(A,Z)}\right) \rightarrow e^- + \mathrm{N(A,Z)}}{\Gamma\left(\mu^- + \mathrm{N(A,Z)}\right) \rightarrow \text{all muon captures})} \leq 8 \times 10^{-17} \text{ @ } 90\% \text{ C.L.}$$

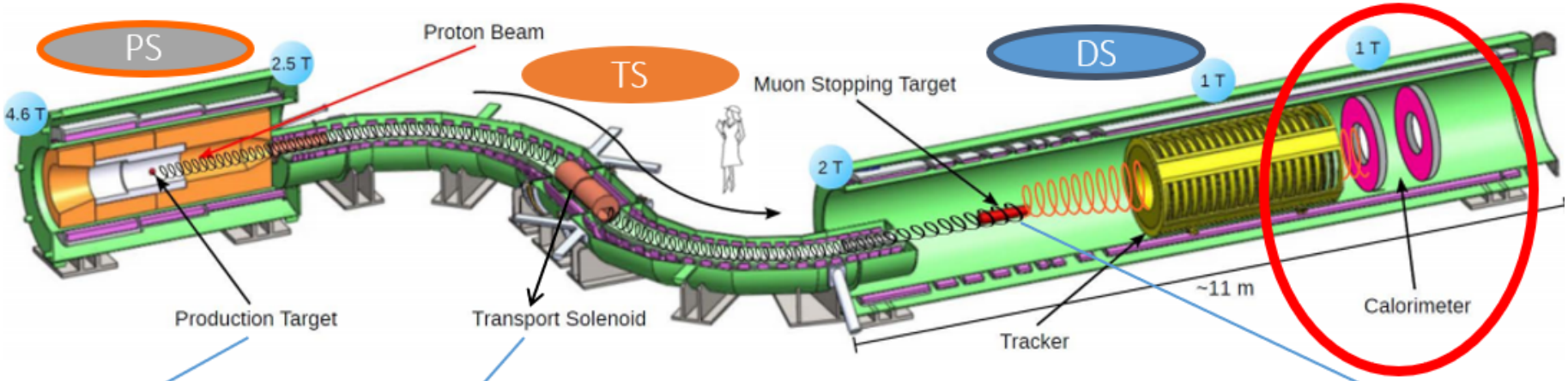
Mu2e

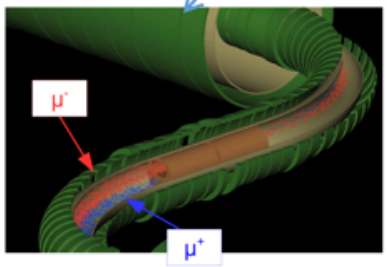
Production Solenoid (PS)/Target

- An 8 GeV proton beam hits a tungsten target and ***produces*** mostly π
- A ***graded magnetic*** field reflects slow forward μ/π and contains backward μ/π

Detector Solenoid (DS): stopping target and detectors

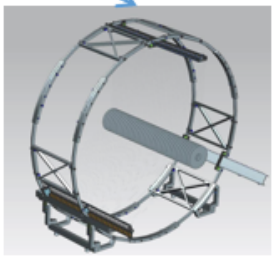
- Stops μ^- on Al foils (decay time ~ 864 ns)
- ***Events reconstructed by detectors, optimized for 105 MeV momentum***
- 1 T B field and 10^{-4} Torr vacuum in the detector zone



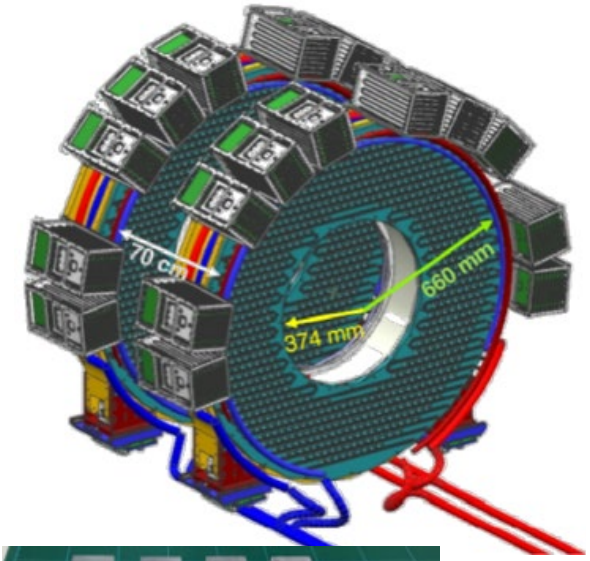


Transport Solenoid (TS)

- π decay to μ
- ***Selection and transportation*** of low momentum μ^-



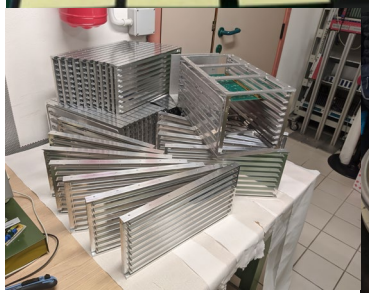
Calorimeter Design

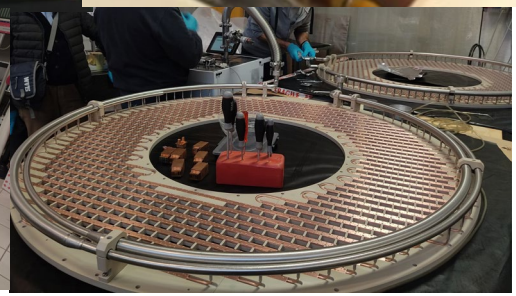


Undoped CsI + UV-extended SiPMs

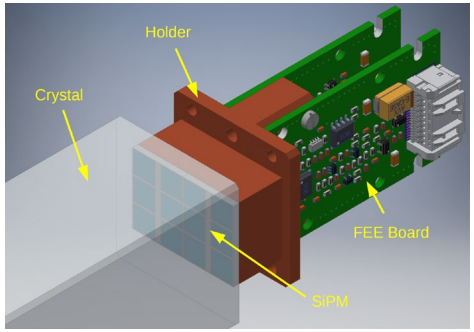
- → It is radiation hard
- → It has a fast emission time
- → Emits at 310 nm

- → 30 % PDE @ 310 nm
- → New silicon resin window
- → TSV readout, Gain = 10^6





- ❑ Two annular disks, R_{in}=374 mm, R_{out}=660 mm, 10 X_0 length, ~ 70 cm separation
- ❑ 674 + 674 square x-sec pure CsI crystals, (34×34×200) mm^3, Tyvek + Tedlar wrapping
- ❑ Each crystal is read out by two large area UV extended Mu2e SiPM's (14x20 mm^2)

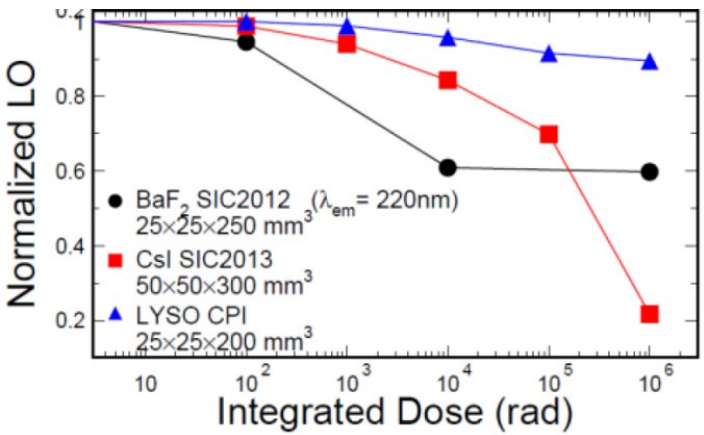


- ❑ Redundant readout: For each crystal, two custom arrays (2×3 of 6×6 mm2) large area UV-extended SiPMs

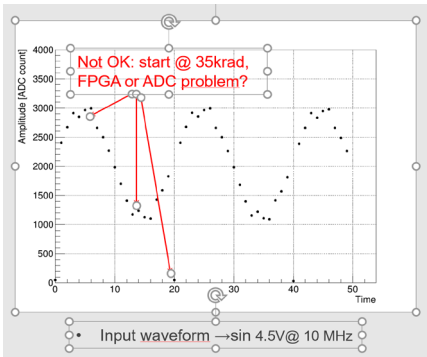
Radiation to the calorimeter

- Calorimeter is reached by a high flux of ionizing and non-ionizing (neutrons) particles.
- Potentially very dangerous both on detector and electronics
  - Crystals: Displacement of atoms in the lattice, centre of colors, loss of transmittance
  - SiPM: increase of baseline noise, increase in dark current
  - Electronics: single event upset, latch-up, voltage variations due to the accumulated dose

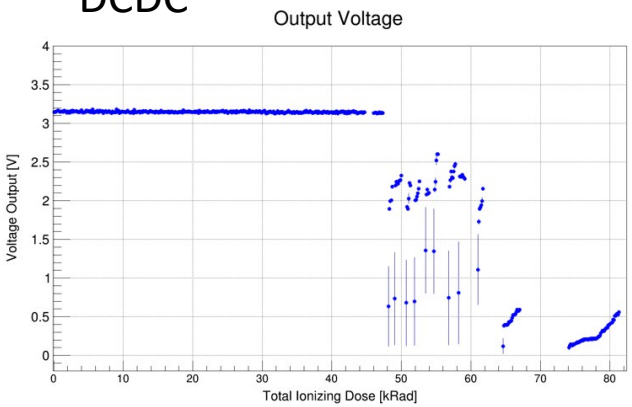
Crystal Light output



ADC



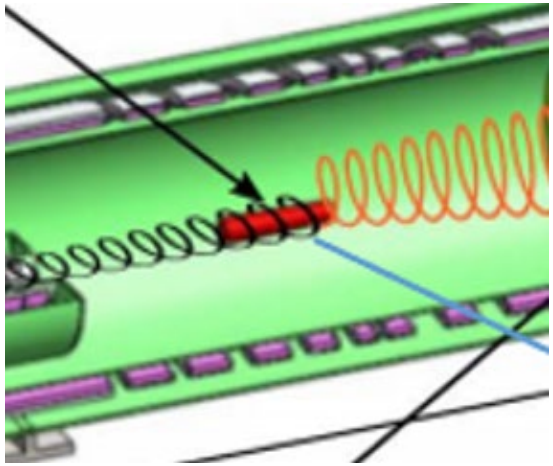
DCDC



Radiation to the calorimeter 2

- Calorimeter is reached by a high flux of ionizing and non-ionizing (neutrons) particles.
- Several sources:

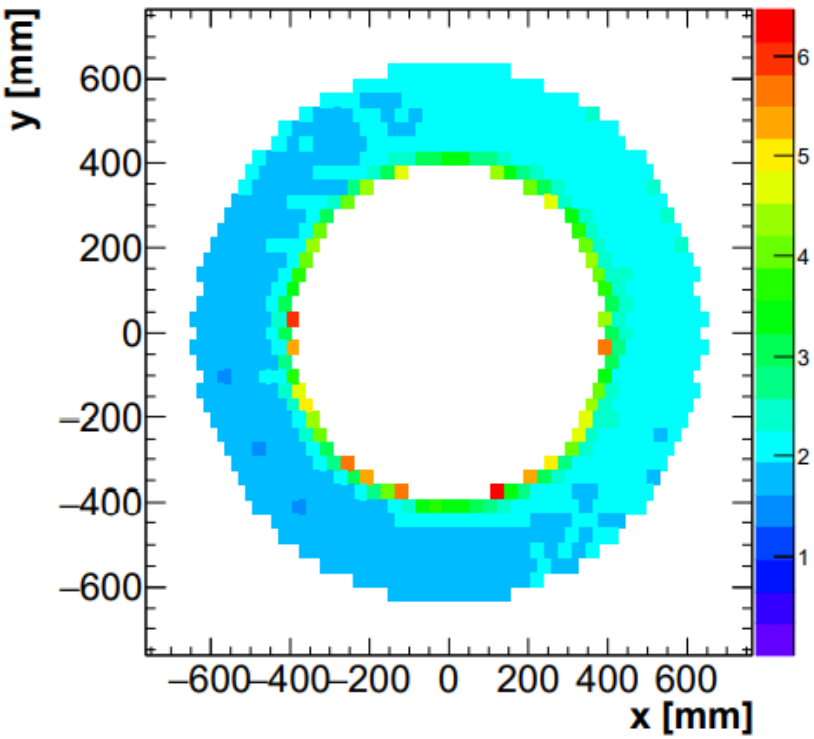
- **BEAM-FLASH**: all particles within the beam that **do not** represent a muon stopped either in the Al Stopping Target or the muon-beam dump;
- **Stopped μ out-of-target (OOT)**: μ stopped in the muon-beam dump;
- e^- **from μ decay-in-orbit (DIO)**: e^- from muon decay in orbit in the Al Stopping Target;
- Processes associated with the muon-capture in the Al nuclei of the Stopping Target, followed by the nuclear disintegration of the nucleus [3]:
  - **Photons**;
  - **Neutrons**;
  - **Protons**;
  - **Deuterons**.



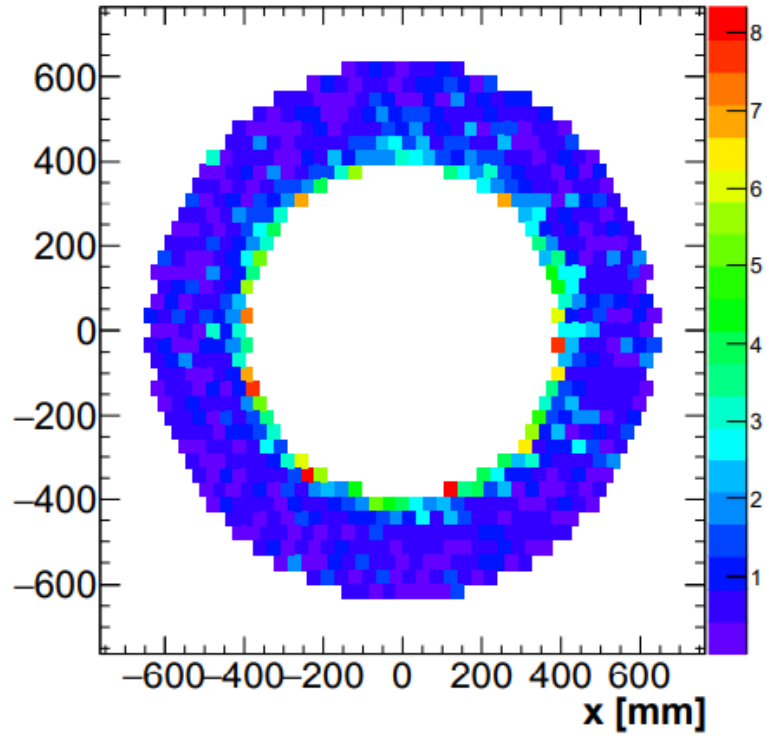
- Monte Carlo simulations with Geant4 and Mars

Simulations output: Total Ionizing dose (Krad/y)

Crystals front disk



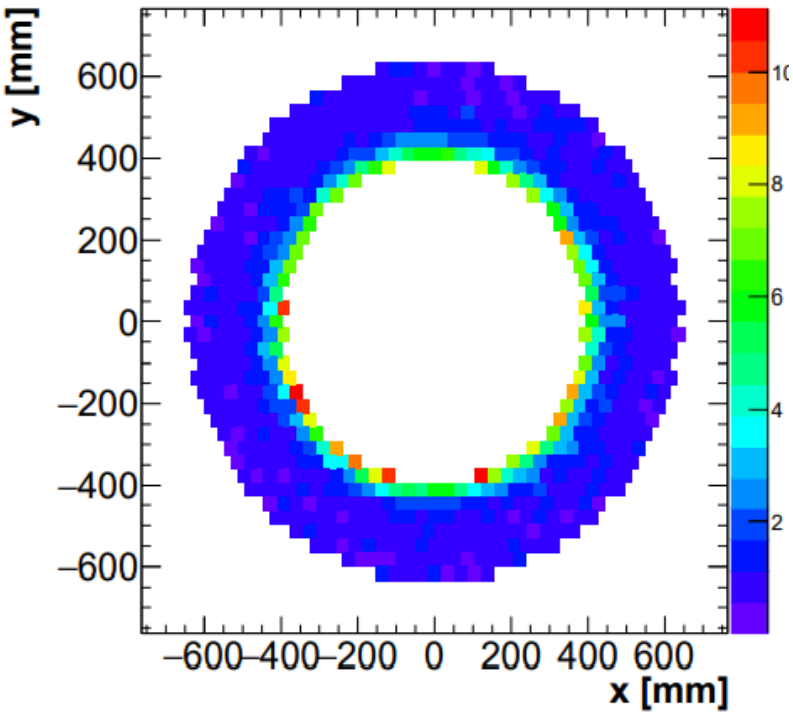
SiPM front disk (divide /2)



Max dose 6 Krad/y

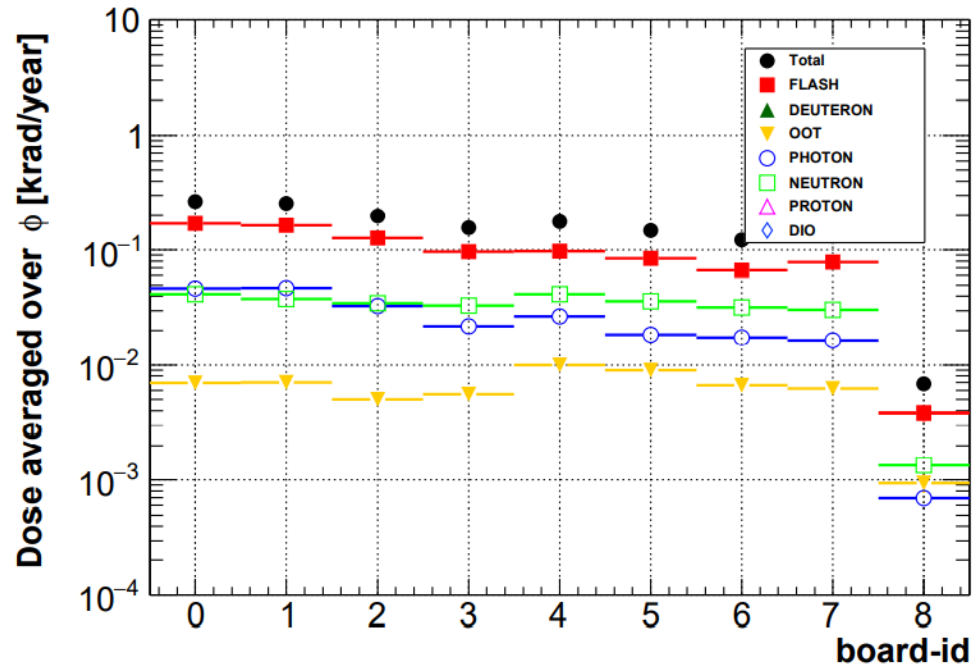
Simulations output: Total Ionizing dose (Krad/y)

FEE front disk (4 to 0.4)



Max dose 6 Krad/y

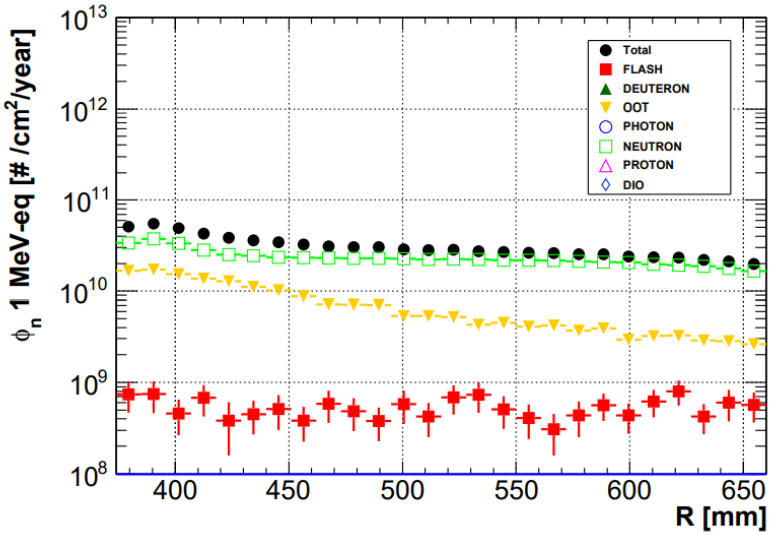
DAQ Crate (max 0.3)



Max dose 0.5 Krad/y

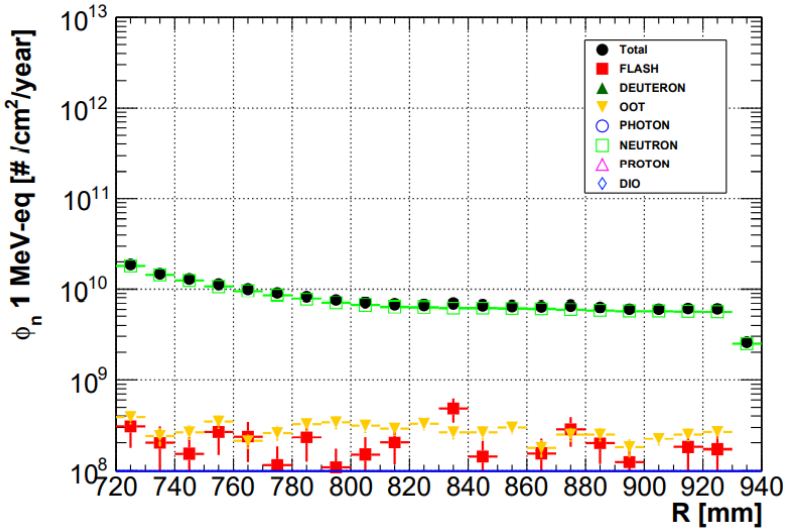
Simulations output: Neutron flux

SiPM front disk



$< 6 \cdot 10^{10}\ n_{1MeV-eq}/cm^2/year$

DAQ Crate front disk



$< 2 \cdot 10^{10}\ n_{1MeV-eq}/cm^2/year$

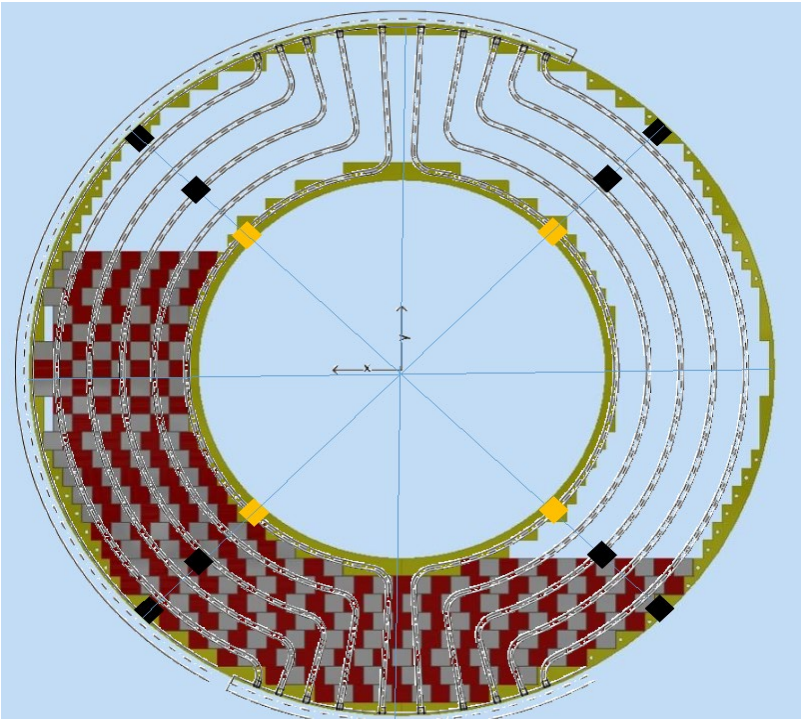
Radiation monitoring

- Need to measure Total Ionizing Dose (TID), neutron fluence and temperature in several positions of the calorimeter.
  - About 18 “strategic” locations, but scalable
- Limits are :
  - 10^12 n
  - 50 Krad of TID
  - 0 to 50 C
- Available space limited:
  - Only few mm between calorimeter and tracker
- Limit the material in front of the calorimeter
- Data must be available to the DCS system

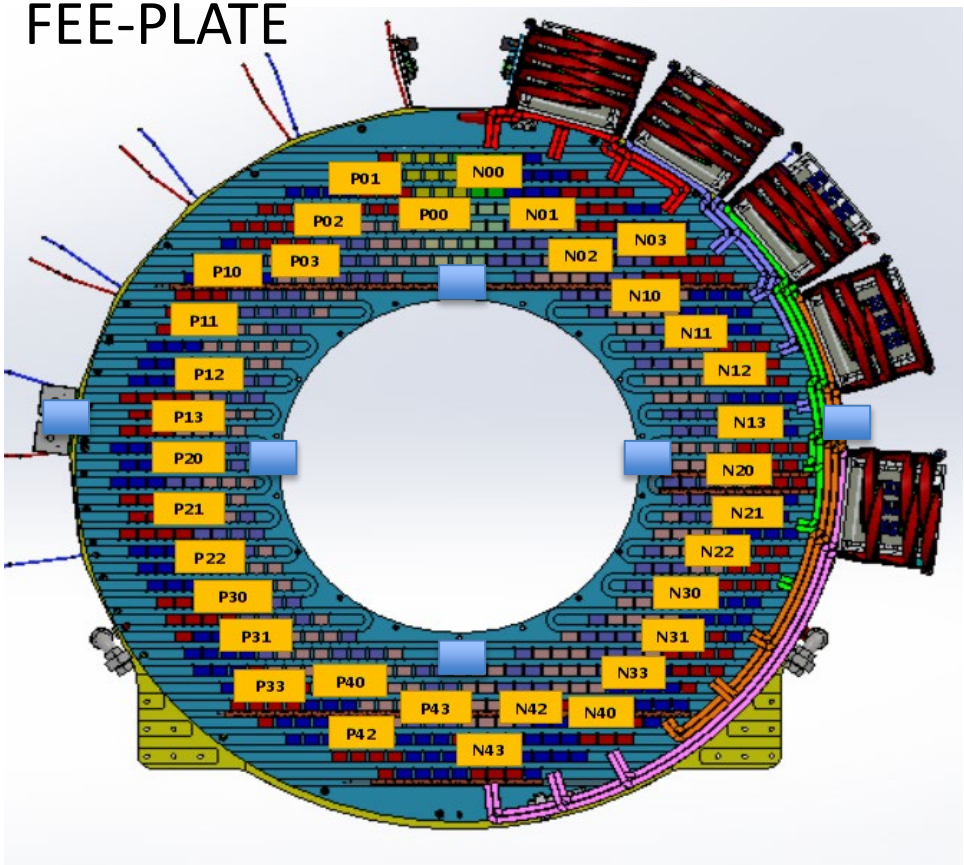
T-RAD system

A T-Rad System is being designed to measure dose, neutron fluence and temperature in selected positions of the Calorimeter

FRONT-FACE



FEE-PLATE

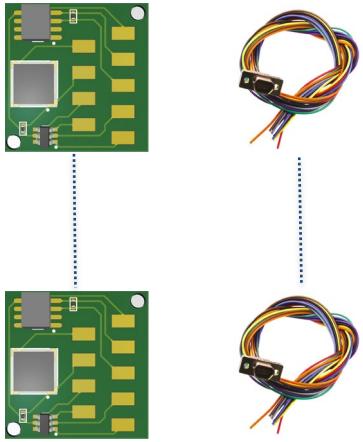


18 sensor mini-boards/disk (each measures TID,n,T)

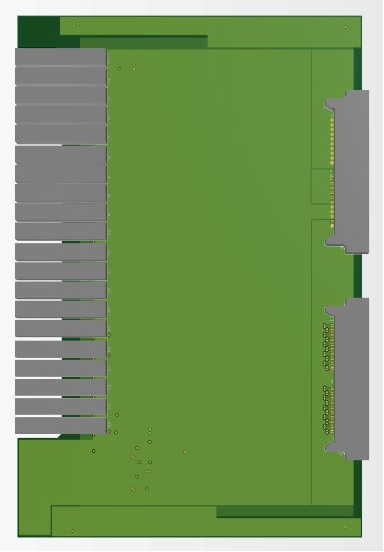
T-RAD system (2)

- The T-Rad system components:
  - Sensor boards SB
  - Mezzanine MIB
  - DIRAC board: main DAQ node for Mu2e, used only as data transmission and slow control interface

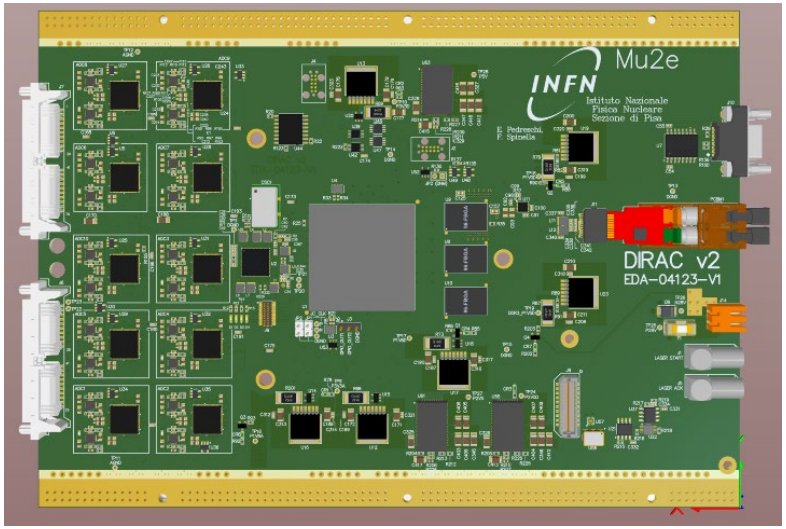
SBs



MIB

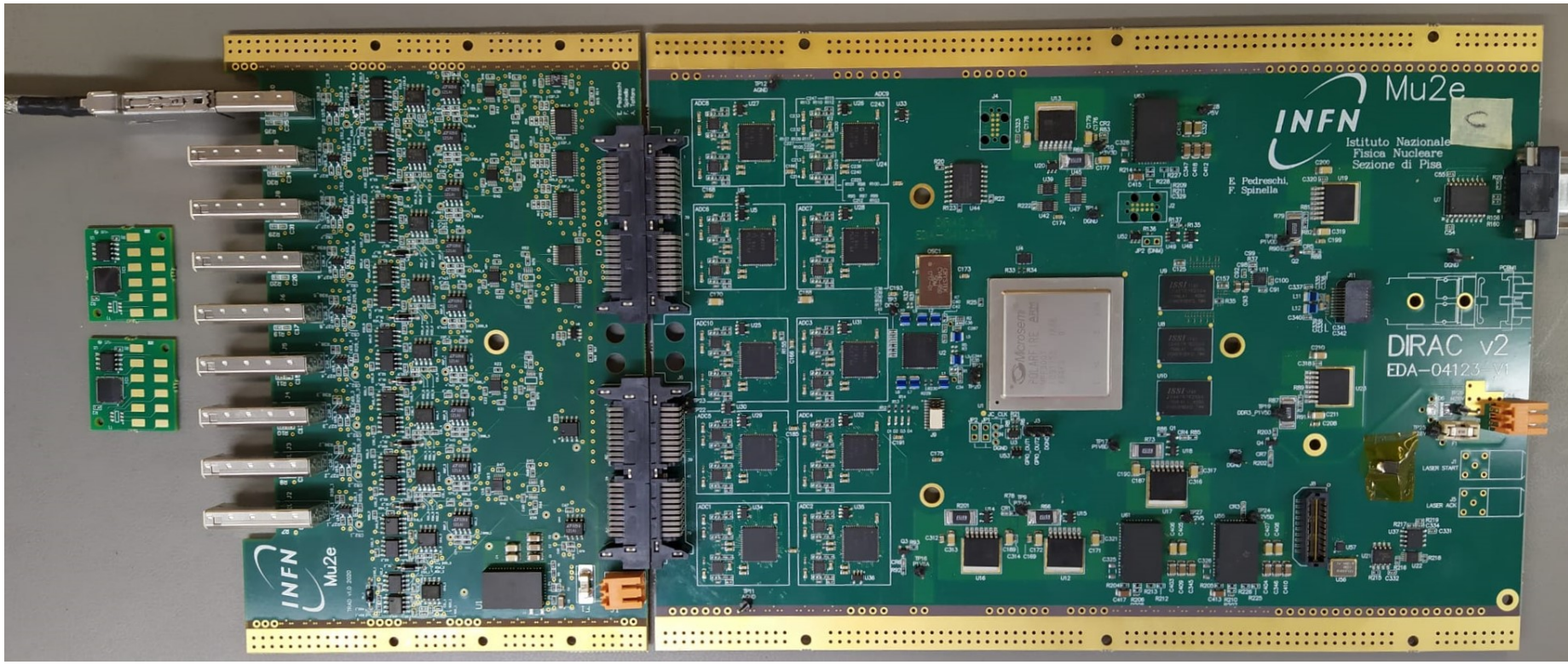


DIRAC



2 (DIRAC + TRAD) mezzanine per disk → each card will read up to 9 sensors boards → 36 sensor boards for the full calorimeter

T-RAD system (3)

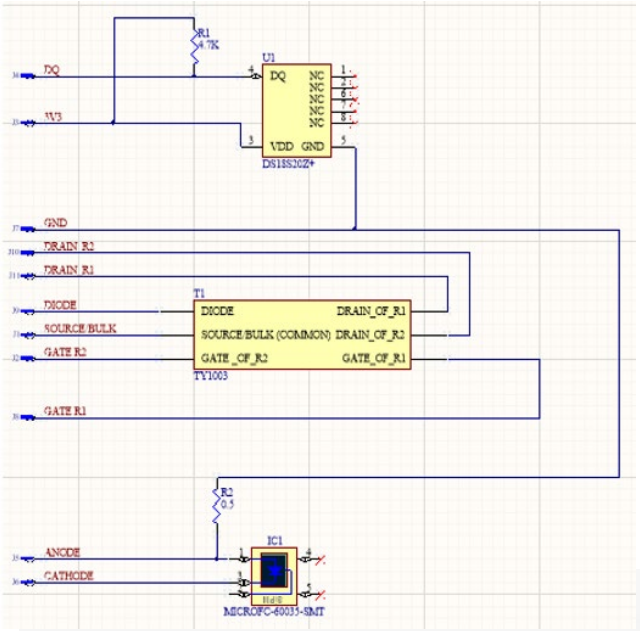


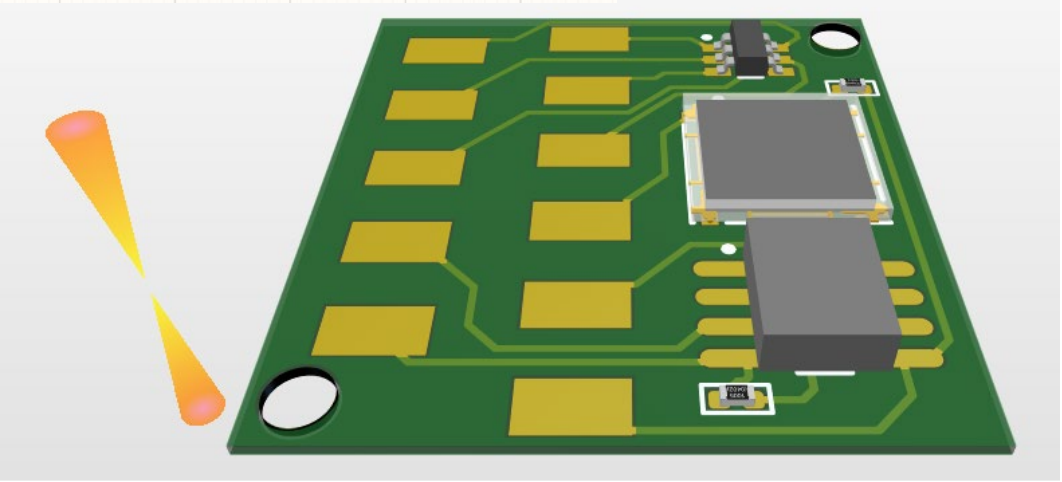
T-RAD sensor board SB

- Radfet (Varadis VT01) → Dose (rad)
- Digital Thermometer (Maxim Integrated DS18S20Z) →Temperature (T)

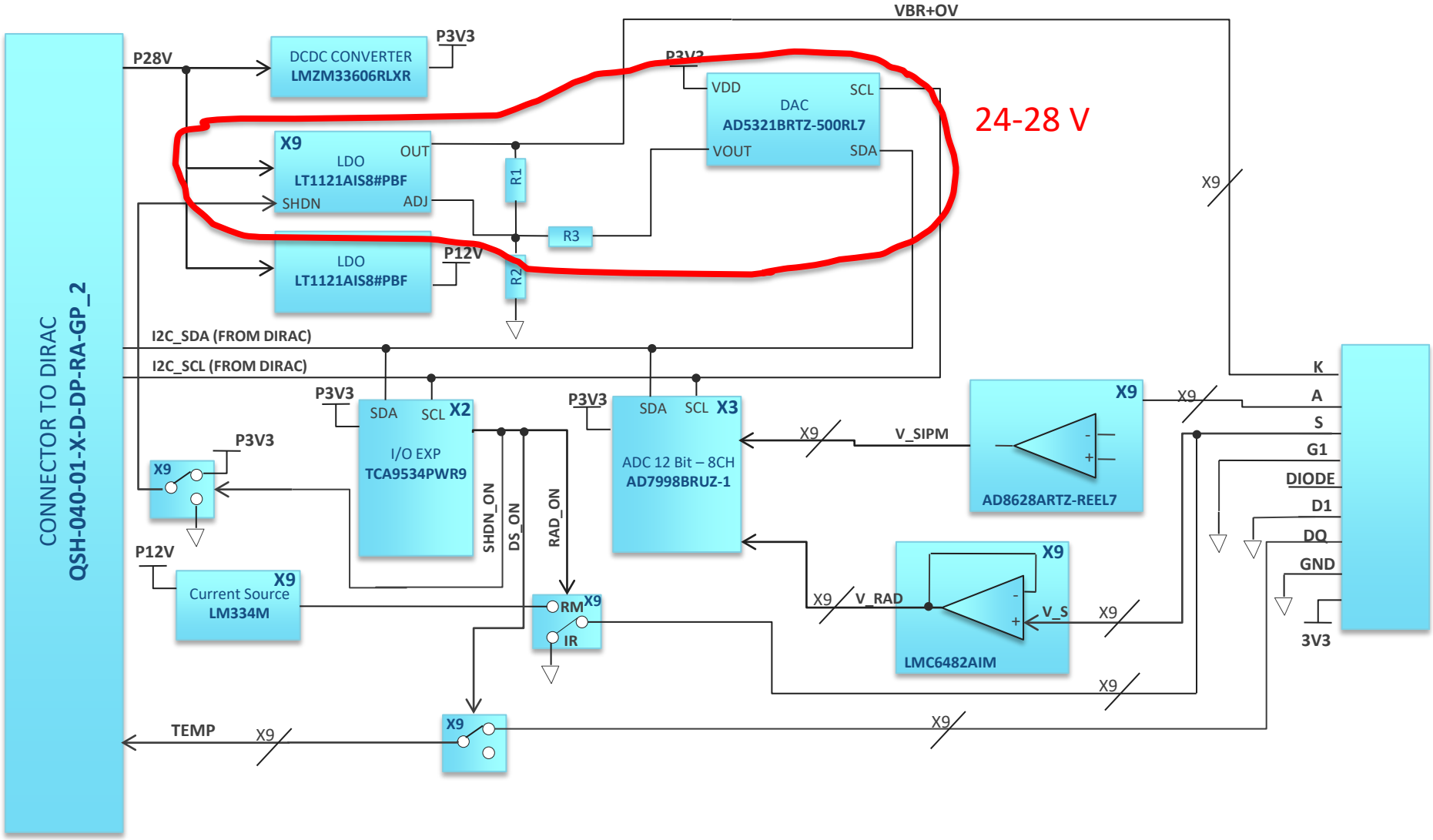
For neutrons we decided to use a commercial SiPM as a radiation monitor ....

- SiPM (ON Semiconductor MICROFC − 60035 − SMT) → Neutron fluence (n)





T-RAD mezzanine board MB



Dose sensor

Varadis

DATASHEET: VT01

TECHNICAL DATA
VT01
400nm RADFET
in 6L SOT-23 Plastic package

VT01 Description and Pin-Out

The VT01 is Varadis 400nm RADFET chip packaged in a plastic SOT-23 six lead package.

The part consists of two identical RADFETs, R1 and R2, and a diode (see Figure 1 and Table 1). The RADFETs' gate oxide thickness is 400nm and W/L is 300µm/50µm. The RADFETs have individual gate and drain terminals, while the source and bulk are common and connected together; this is also the diode bulk contact.

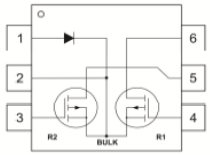


Figure 1: VT01 pin-out drawing.

Table 1: VT01 pin-out description.

Pin Number	Description
1	Diode anode
2	Source/bulk (common)
3	Gate of R2
4	Gate of R1
5	Drain of R2
6	Drain of R1

Calibration Data

The calibration curve for the RADFET shows evolution of ΔV (the change in RC threshold voltage with reference to its pre-irradiation value) with dose. Note that a specific calibration curve, obtained using the Co-60 source, is associated with each RADFET production batch. The calibration curve, together with analytical equation and fitting coefficients, will be provided with the supplied parts. For illustration, typical calibration curve is shown in Figure 4.

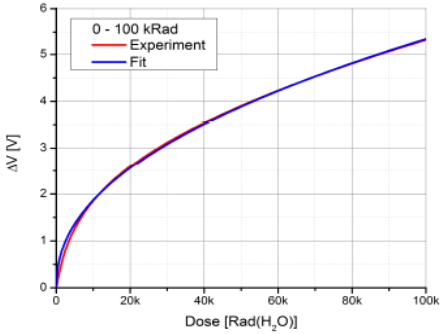
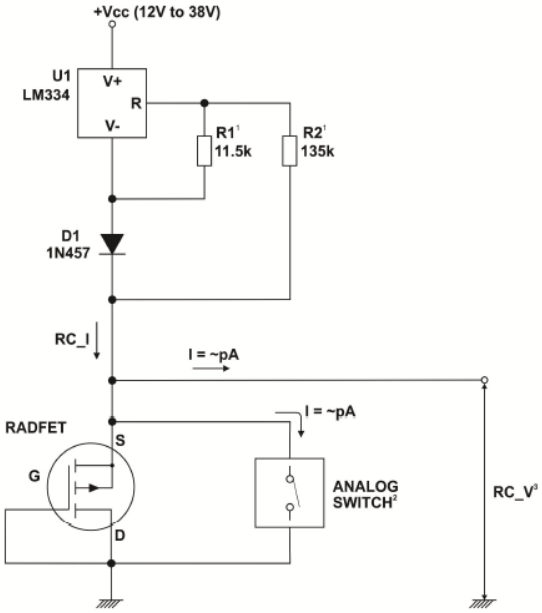


Figure 4: Typical calibration curve indicating change in RC_V during irradiation. Irradiation at room temperature with Co-60 gamma source, dose rate ~50 Gy/h (5 krad/h).. Voltage measurements performed at room temperature using 0.2% duty cycle with all terminals grounded between measurements

3 rev 1.4 (June 2020)

- Varadis VT01 it is the RADFET used as Dose Sensor
- VT01 is specified to measure up to 100krad @ ambient temperatures
- From the Varadis datasheet the RADFET sensing circuit diagram is:



Temperature sensor

DS18S20 **High-Precision 1-Wire Digital Thermometer**

General Description

The DS18S20 digital thermometer provides 9-bit Celsius temperature measurements and has an alarm function with nonvolatile user-programmable upper and lower trigger points. The DS18S20 communicates over a 1-Wire bus that by definition requires only one data line (and ground) for communication with a central microprocessor. In addition, the DS18S20 can derive power directly from the data line ("parasite power"), eliminating the need for an external power supply.

Each DS18S20 has a unique 64-bit serial code, which allows multiple DS18S20s to function on the same 1-Wire bus. Thus, it is simple to use one microprocessor to control many DS18S20s distributed over a large area. Applications that can benefit from this feature include HVAC environmental controls, temperature monitoring systems inside buildings, equipment, or machinery, and process monitoring and control systems.

Applications

- Thermostatic Controls
- Industrial Systems
- Consumer Products
- Thermometers
- Thermally Sensitive Systems

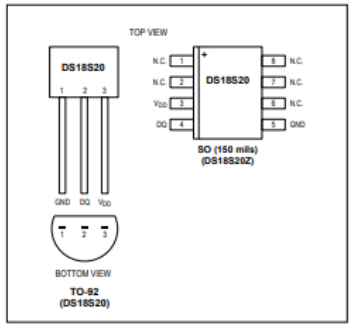
Ordering Information ***appears at end of data sheet.***

1-Wire is a registered trademark of Maxim Integrated Products, Inc.

Benefits and Features

- Unique 1-Wire® Interface Requires Only One Port Pin for Communication
- Maximize System Accuracy in Broad Range of Thermal Management Applications
  - Measures Temperatures from -55°C to +125°C (-67°F to +257°F)
  - ±0.5°C Accuracy from -10°C to +85°C
  - 9-Bit Resolution
  - No External Components Required
- Parasite Power Mode Requires Only 2 Pins for Operation (DQ and GND)
- Simplifies Distributed Temperature-Sensing Applications with Multidrop Capability
  - Each Device Has a Unique 64-Bit Serial Code Stored in On-Board ROM
- Flexible User-Definable Nonvolatile (NV) Alarm Settings with Alarm Search Command Identifies Devices with Temperatures Outside Programmed Limits
- Available in 8-Pin SO (150 mils) and 3-Pin TO-92 Packages

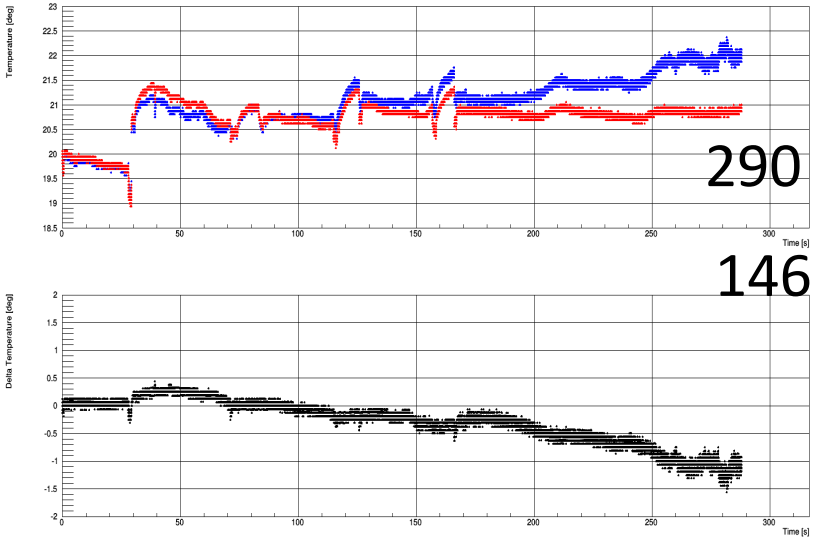
Pin Configurations



maxim integrated.

19-5474; Rev 3; 4/15

- The Temperature Sensor (DS18S20) comunicates through the 1-wire bus
- DS18S20 already tested in 2018 @ Enea:
  - Dose rate 1.85 krad/h unshielded (red)
  - Dose rate 0.3 krad/h shielded (blu)

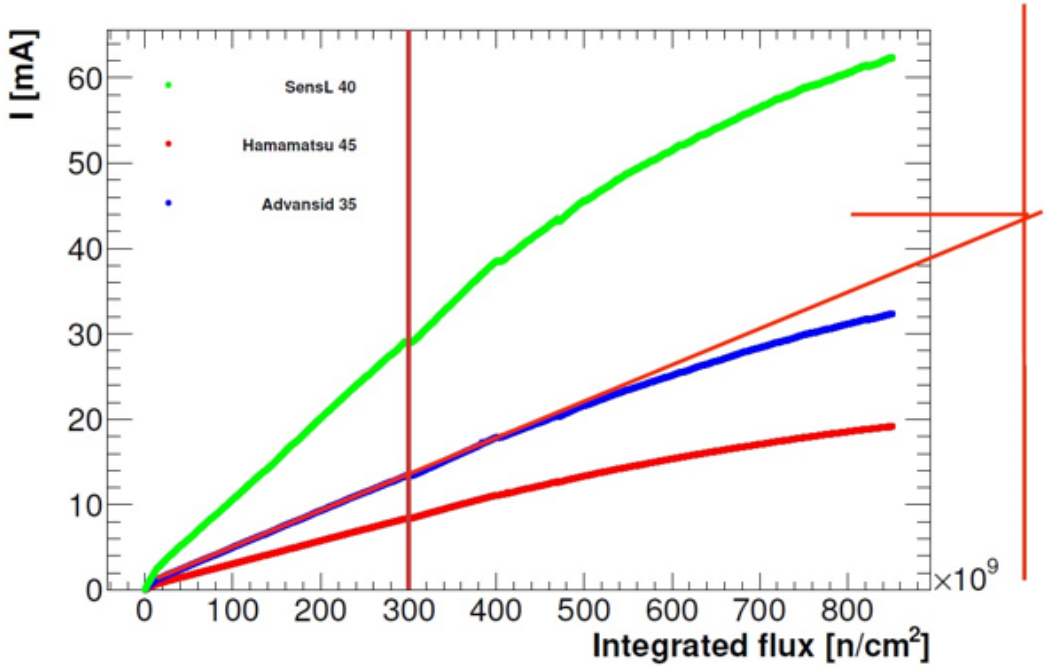


290 Krad

146 hours

Neutron sensor(1)

- The idea is to use a SiPM as a detector for neutron fluence
  - Idark is a function of neutron fluence and temperature
- We measured the trend of Idark vs n at T= 20ºC for several SiPM



Vop = Vbrk + 3v

Neutron sensor(2)

C-Series SiPM Sensors

Silicon Photomultipliers (SiPM), Low-Noise, Blue-Sensitive

The C−Series low-light sensors from ON Semiconductor feature an industry-leading low dark-count rate combined with a high PDE. For ultrafast timing applications, C-Series sensors have a fast output that can have a rise time of 300 ps and a pulse width of 600 ps. The C−Series is available in different sensor sizes (1 mm, 3 mm and 6 mm) and packaged in a 4-side tileable surface mount (SMT) package that is compatible with industry standard, lead-free, reflow soldering processes.

The C−Series Silicon Photomultipliers (SiPM) form a range of high gain, single-photon sensitive, UV-to-visible light sensors. They have performance characteristics similar to a conventional PMT, while benefiting from the practical advantages of solid-state technology: low operating voltage, excellent temperature stability, robustness, compactness, output uniformity, and low cost. For advice on the usage of these sensors please refer to the Biasing and Readout Application Note.

ON Semiconductor®

www.onsemi.com

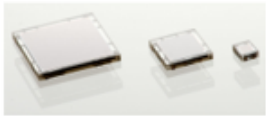


Figure 1. C−Series Sensors

ORDERING INFORMATION

See detailed ordering and shipping information on page 15 of this data sheet.

Table 1. PERFORMANCE PARAMETERS

Sensor Size	Microcell Size	Parameter (Note 1)	Overvoltage	Min.	Typ.	Max.	Units
1 mm	10μ, 20μ, 35μ	Breakdown Voltage (Vbr) (Note 3)		24.2		24.7	V
3 mm	20μ, 35μ, 50μ						
6 mm	35μ						
1 mm	10μ, 20μ, 35μ	Recommended overvoltage Range (Voltage above Vbr) (Note 2)		1.0		5.0	V
3 mm	20μ, 35μ, 50μ						
6 mm	35μ						
1 mm	10μ, 20μ, 35μ	Spectral Range (Note 4)		300		950	nm
3 mm	20μ, 35μ, 50μ						
6 mm	35μ						
1 mm	10μ, 20μ, 35μ	Peak Wavelength (λp)			420		nm
3 mm	20μ, 35μ, 50μ						
6 mm	35μ						

SENSL is now ON Semiconductor

November, 2018 − Rev. 6

Publication Order Number:
MICROC−SERIES/D

- We will use a SiPM similar to the tested SensL, but with lower Vbreakdown
- ON C-Series SiPM Sensors Vbias is ~ 25V (Mu2e SiPM 170V) → use 28V from DAQ crate

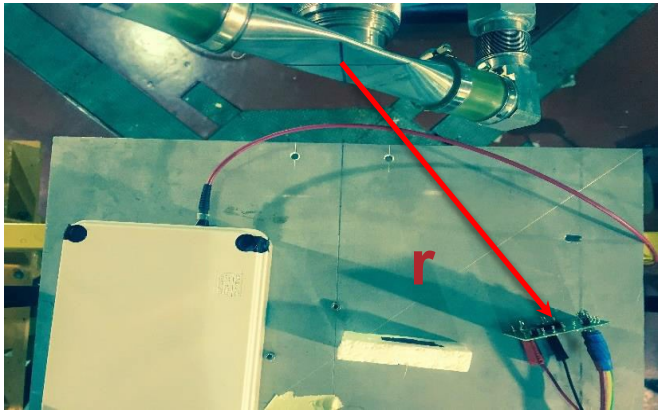
tested @ ENEA-FNG in July.

ON Semiconductor MICROFC − 60035 − SMT

FNG facility, ENEA Frascati lab (Rome)

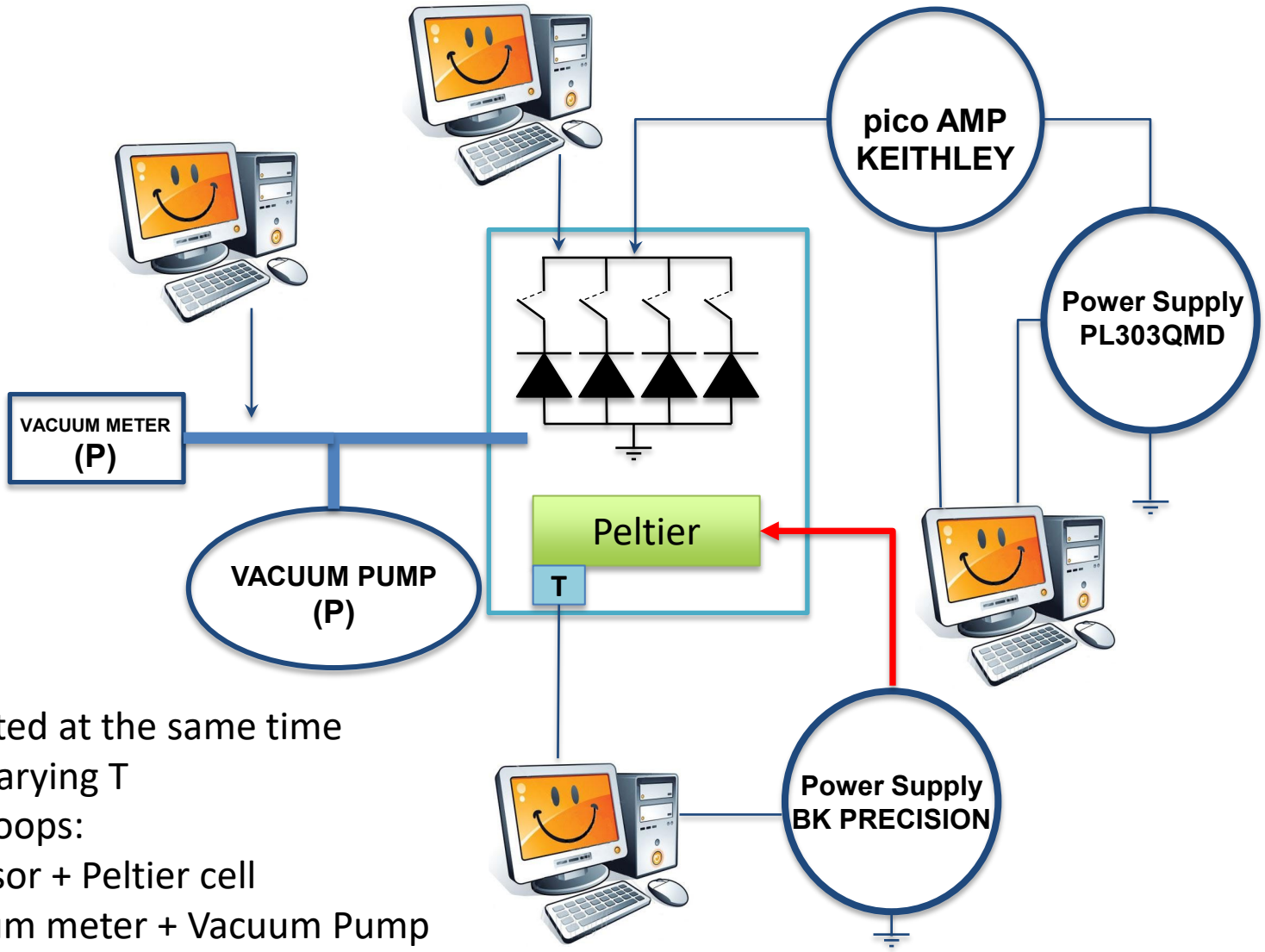
Frascati Neutron Generator (FNG) is a linear electrostatic accelerator in which up to 1 mA D+ ions are accelerated onto a Tritium target

- *Up to 10^12 14 MeV neutrons/s in few hours*
- Almost *isotropic source*, flux scales with r^2
- Calibrated at 3% level using alpha particles



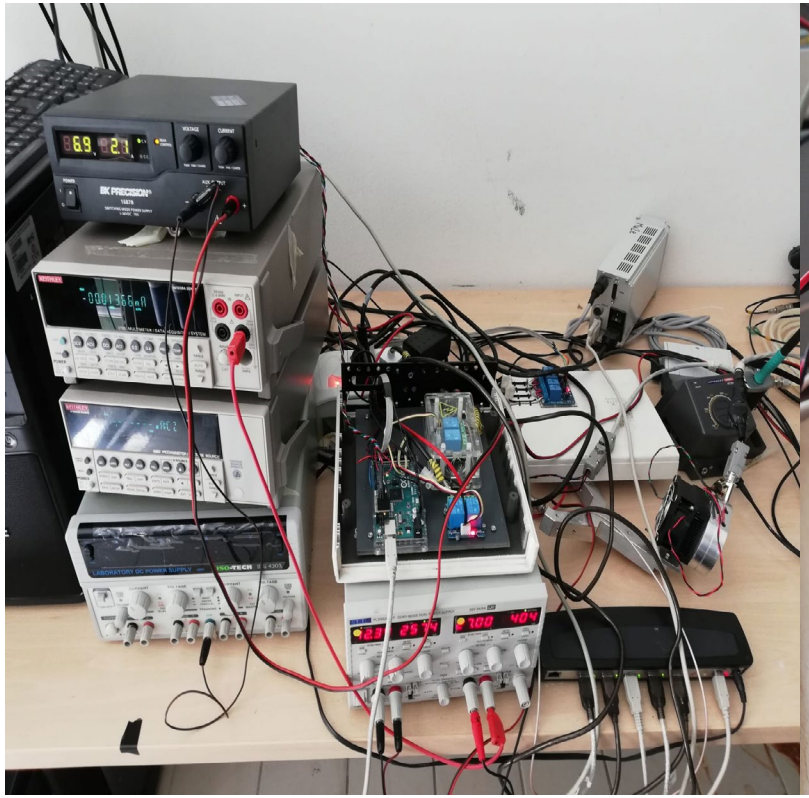
$$D + T \rightarrow \alpha + n$$

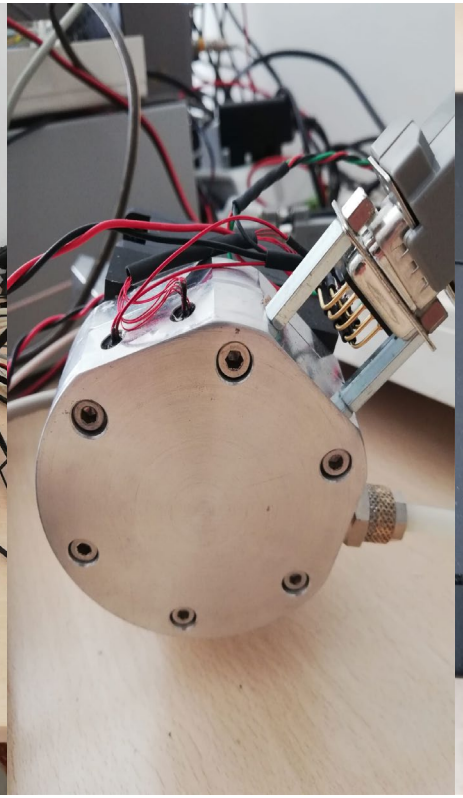
SiPM irradiation test setup

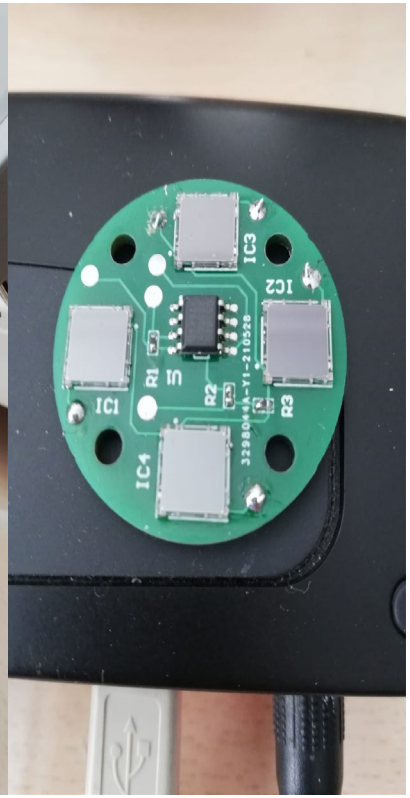


- 4 SiPM tested at the same time
- V-I curve varying T
- 3 Control loops:
  - T sensor + Peltier cell
  - Vacuum meter + Vacuum Pump
  - Power Supply + pico AMP

SiPM irradiation test setup (2)

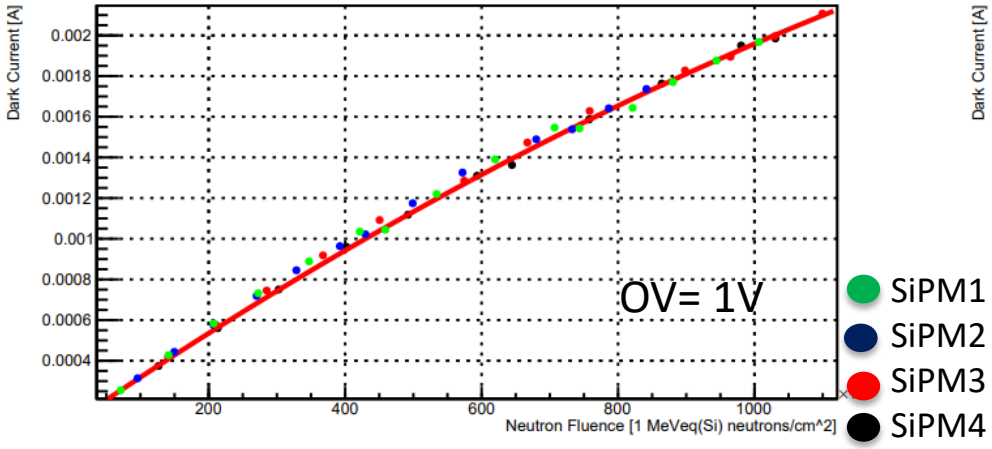


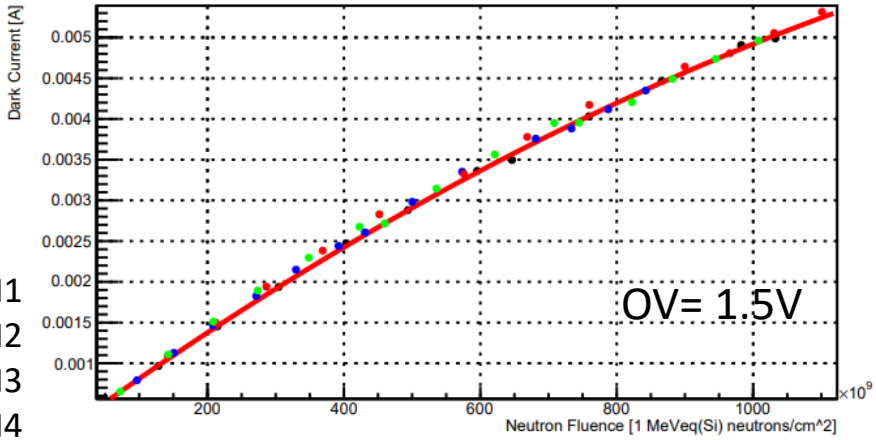


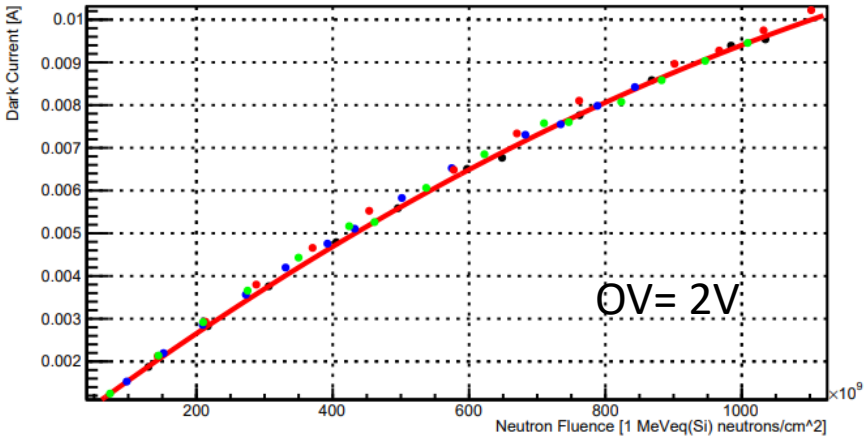


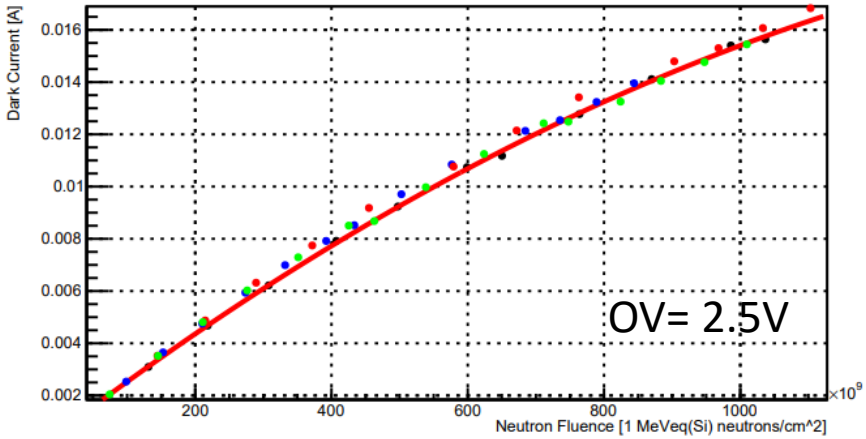
test results (preliminary)

Temperature= 0 C









Conclusions

- Mu2e calorimeter is operated in a radioactive environment and needs a radiation monitor system: T-RAD
- Each T-RAD is based on a mezzanine card plus 9 sensor boards
- Neutron fluence is measured as a function of a SiPM Idark
- The idea has been successfully tested in July at the FNG neutron irradiation facility in Frascati near Rome

Thanks for the attention!

This work was supported by the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Grant Agreement no 734303, 822185, 858199, 101003460