Characterization of crystal and SiPM of the Mu2e electromagnetic calorimeter

102° Congresso SIF

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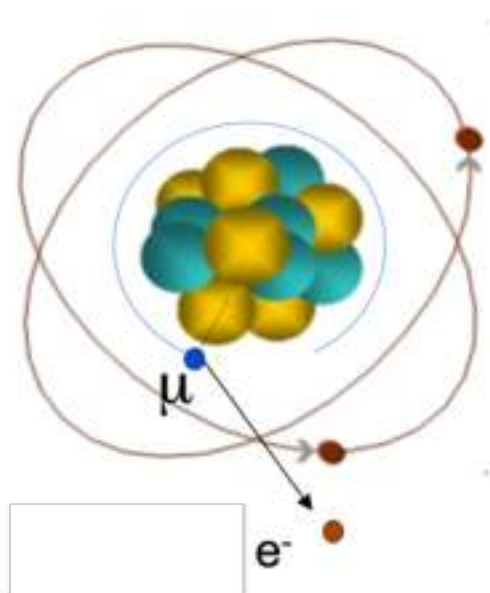
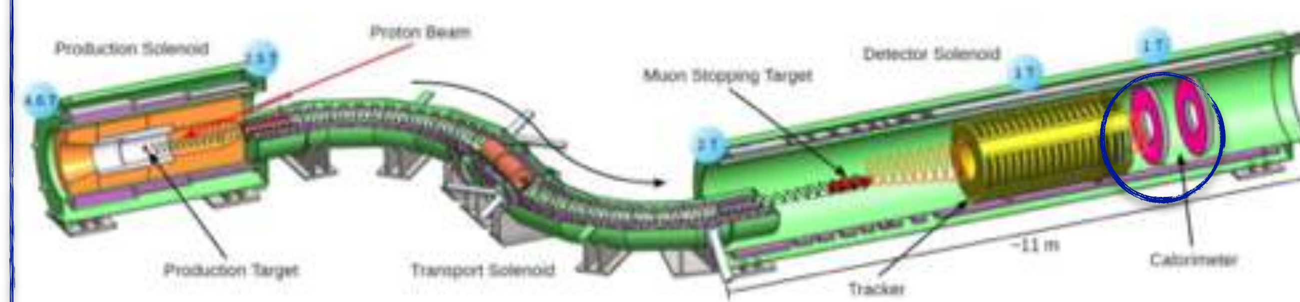
Roma Tre & LNF

Outline

Charged Lepton Flavor Violation

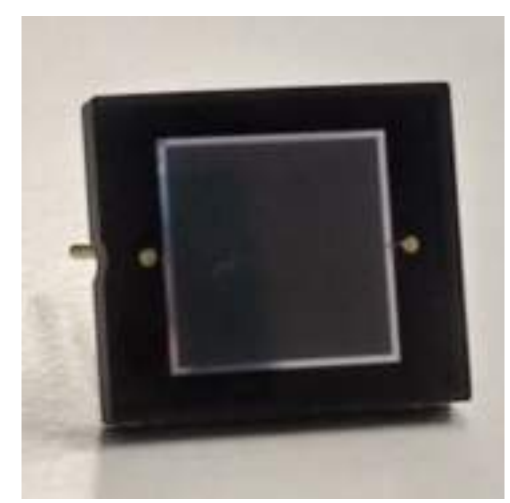


Mu2e experiment



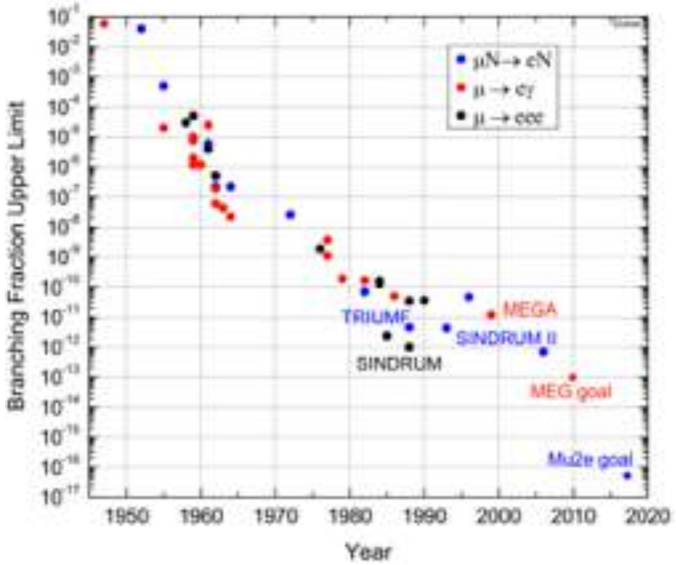
Crystal test

SiPM test



The Mu2e experiment: the goal

- Detect the CLFV conversion process $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$ in the field of a nucleus
- Negligible in the SM ($BR=10^{-52}$ assuming neutrino oscillations)
- Observation of CLFV single is a clear evidence of New Physics

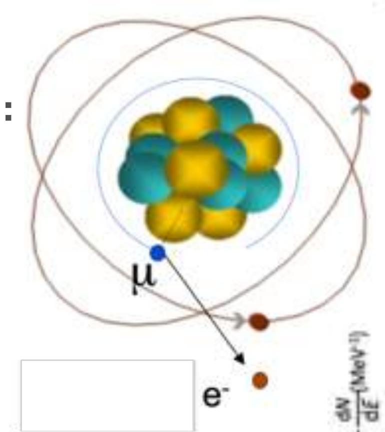


Design sensitivity for a 3 years run:
- 2.5×10^{-17} Single Event Sensitivity
- $<6 \times 10^{-17}$ BR limit at 90% CL

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \rightarrow e^- + N(A,Z)}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{ all muon capture})} \leq 6 \times 10^{-17} \text{ (@90\%CL)}$$

Muons are captured in a Al stopping target and fall to a 1S ground state:

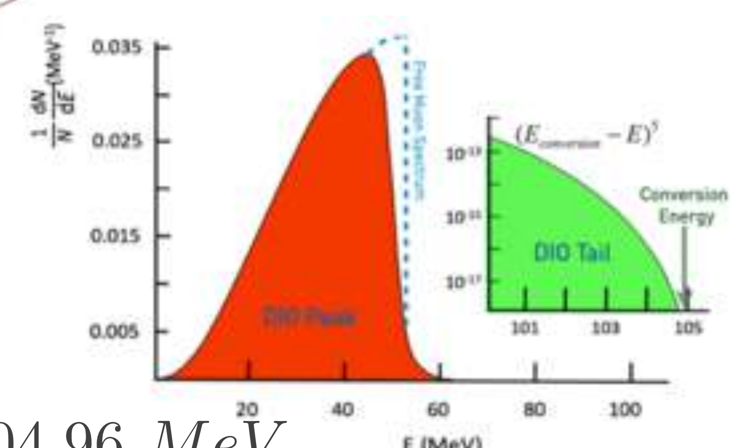
- Muon decay in orbit (DIO) $\mu^- + Al \rightarrow e^- \overline{\nu}_e \nu_\mu + Al$ (40%)
- Muon capture $\mu^- + Al \rightarrow \nu_\mu + Mg$ (60%)
- <u>Neutrinoless muon to electron conversion</u> $\mu^- + Al \rightarrow e^- + Al$



Initial state: muonic atom

Final state:

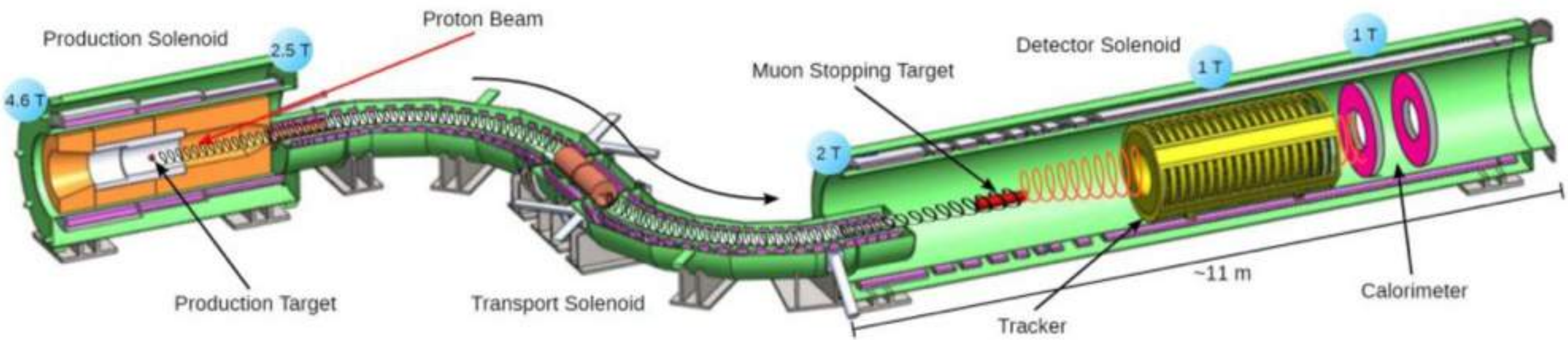
- Single mono-energetic electron
- Recoiling intact nucleus



$$E_e = m_\mu c^2 - B_\mu(Z) - C(A) \approx 104.96\ MeV$$

Experimental set up

Production Solenoid (PS):
- 8 GeV proton beam strikes target, producing almost pions.
- Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons

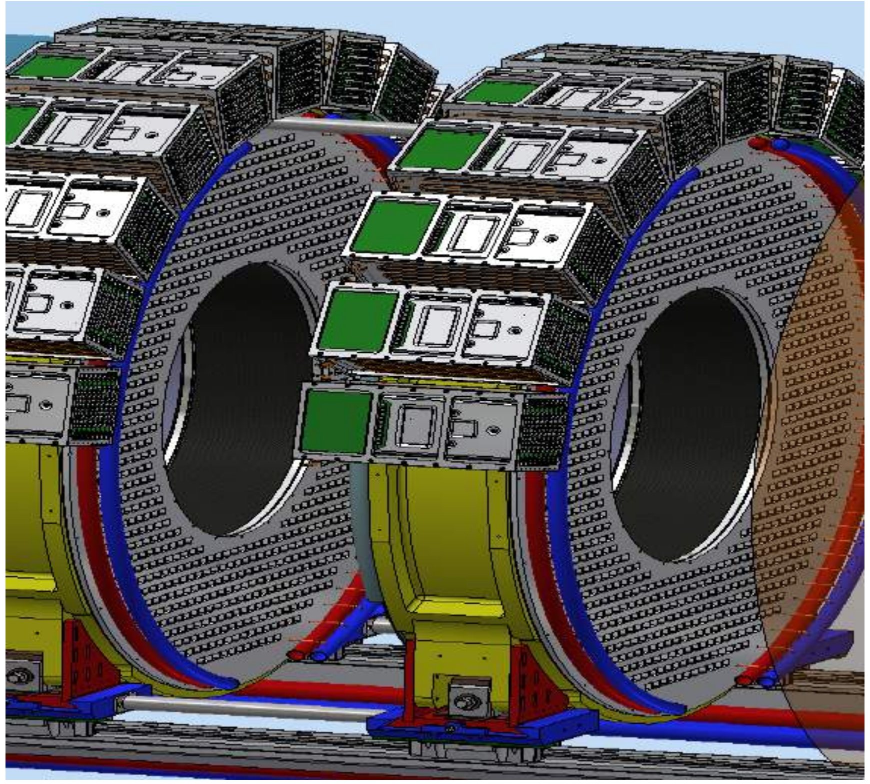


Transport Solenoid (TS):
- S-shaped
- Selects low momentum, negative muons
- Antiproton absorber in the mid-section

Detector Solenoid (DS):
- Capture muons on Al target,
- Measure momentum in tracker and energy/time in calorimeter
- Cosmic Ray Veto detector surrounds the solenoid to make CR contribution negligible

EM Calorimeter Design

- Energy resolution ~ 5% (5 MeV at 100 MeV)
- Time resolution better than ~0.5 ns
- Position resolution $\sigma_{r,z}$ ~1 cm
- Provide PID information to be combined with other from tracker in order to distinguish electrons from muons
- Provide a trigger to identify events with significant energy deposit
- Operate in a high-rate environment, with radiation exposure up to ~15 Krad/year and in a neutron flux equivalent to 10^{11}MeV/cm^2
- Temperature and gain stability
- Operate in 1T magnetic field



Each calorimeter disk consists of 674 CsI 34x34x200 mm^3 crystals

CsI Crystal	
Radiation length X_0 [cm]	1.86
Light Yield [% NaI(Tl)]	3.6
Decay Time[ns]	30
Wavelength [nm]	315

- Adequate radiation hardness
- Slightly hygroscopic
- 30 ns emission time, small slow component
- Emit at 315 nm

Each crystal read out by a 2x3 array of individual 6x6 mm^2 SiPM

Specification from Hamamatsu Mppc	
Pixel pitch [μm]	50
Effective photosensitive area [mm]	6.0x6.0
number of pixels	14400
Window material	Silicon resin
Gain (at 25)	1.7 x 10^6

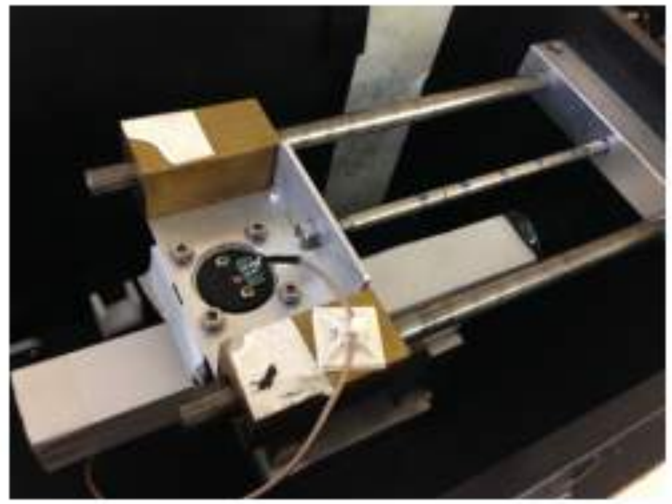
- High quantum efficiency at 315 nm(~25%)
- Large active area to maximise the number of collected photoelectrons
- High gain, fast signal and low noise
- Work in vacuum at 10^{-4} Torr

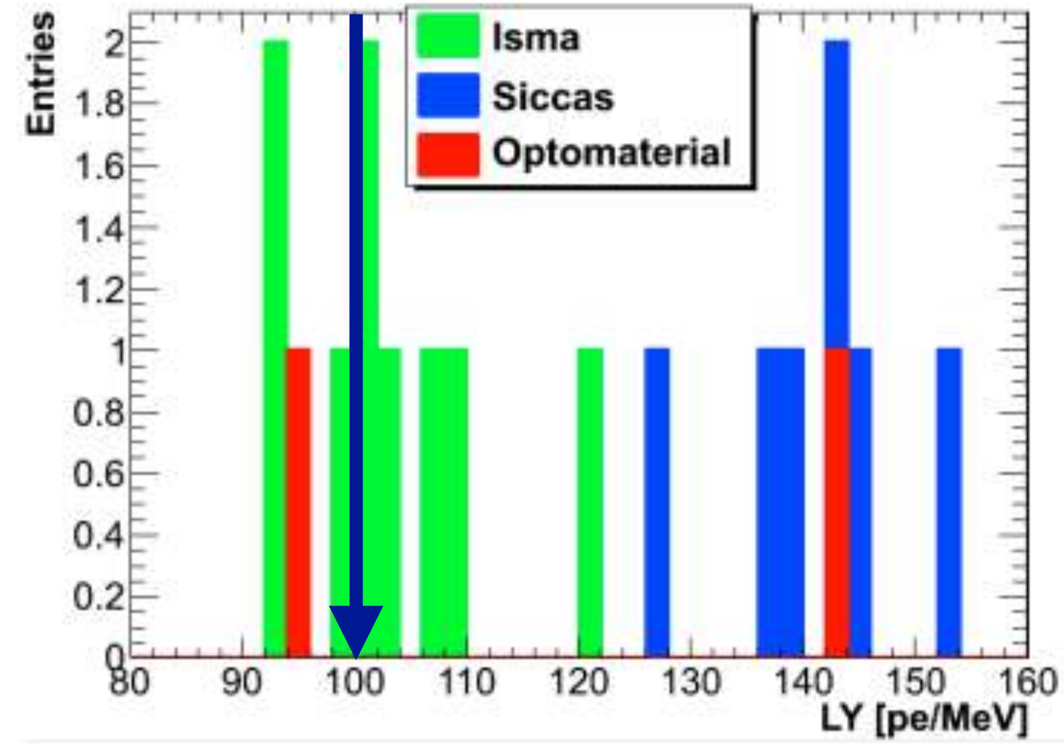
Crystal characterization:light output

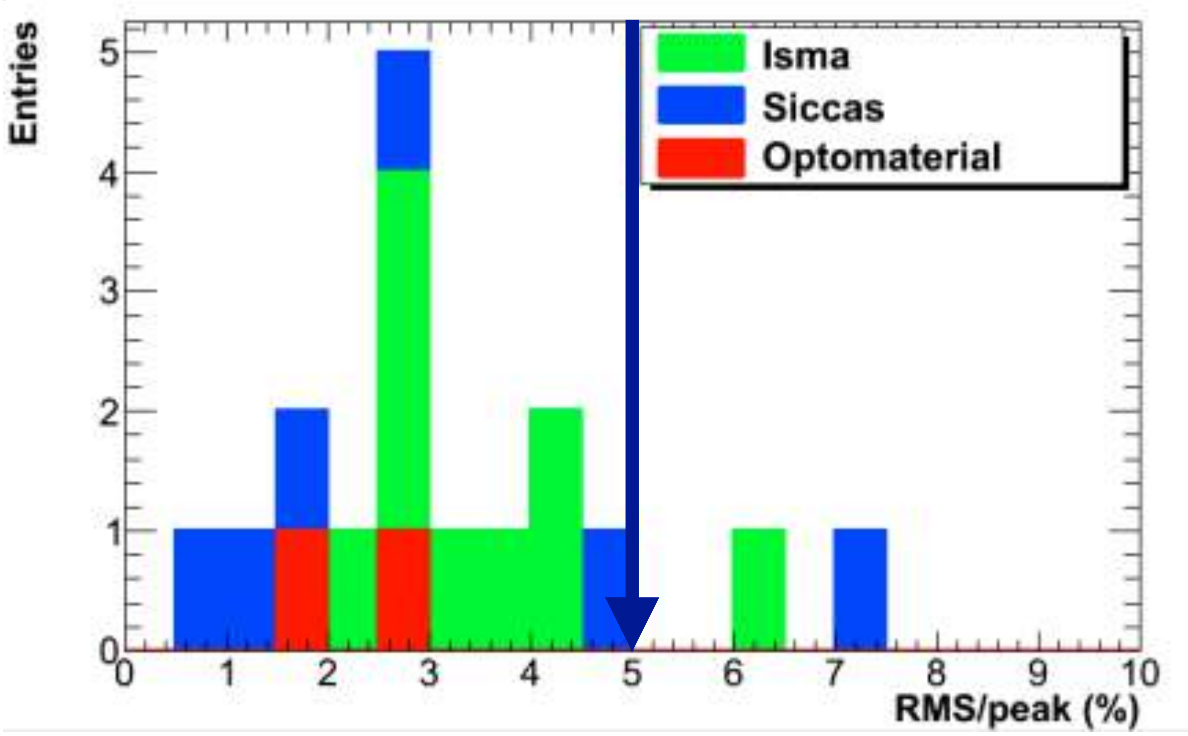
New measurements of light emission of CsI have been performed in order to verify that crystals from different vendors could meet the Mu2e requirements:

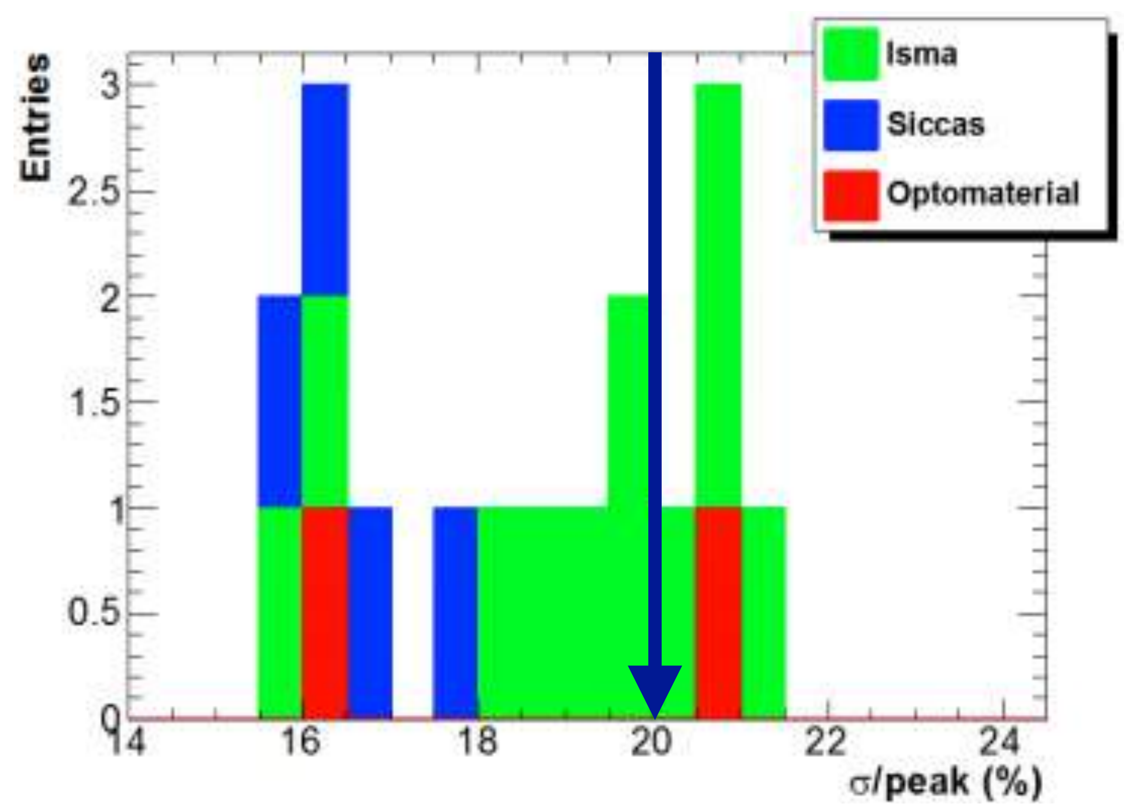
- LY>100 p.e./MeV
- LRU<5%
- Energy resolution< 20%

Setup:
- ^{22}Na source
- crystal wrapped with 150 μm thick Tyvek
- 2”UV-extended PMT
- Measurement repeated at 8 points along the crystal









Radiation induced noise

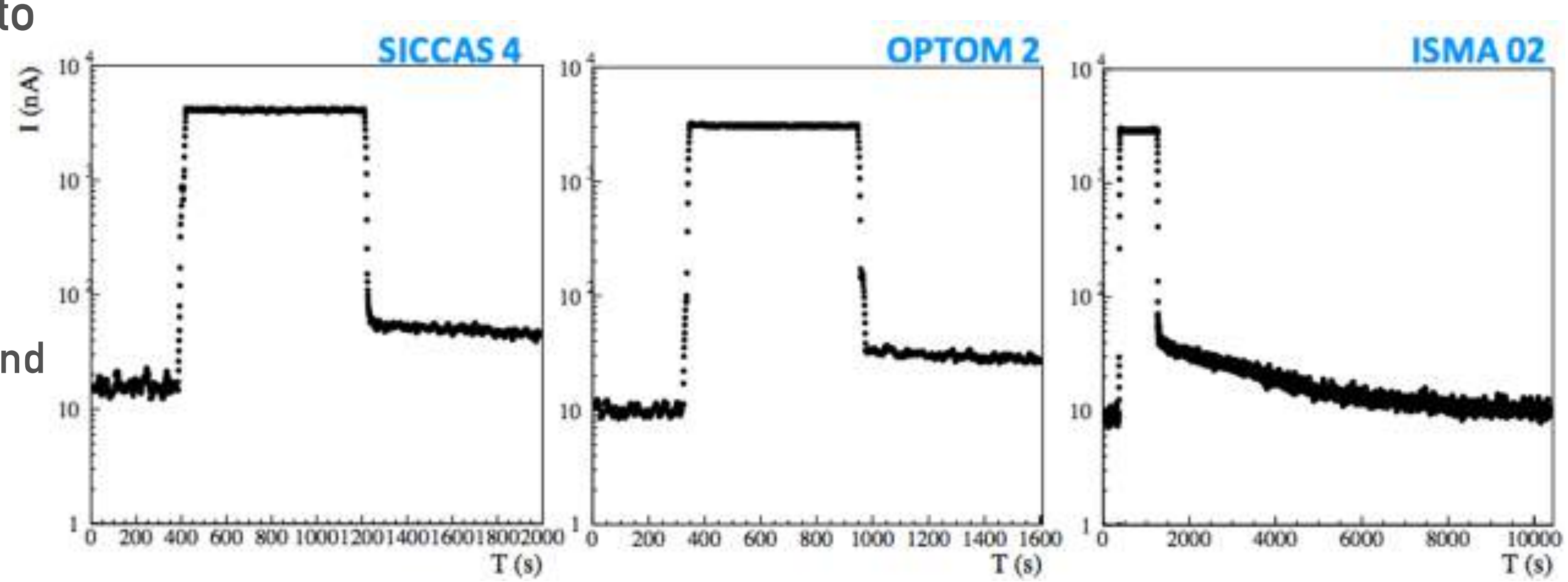
- Thermal neutrons from HOTNES facility (ENEA Frascati) with an Am B source(flux 700 n cm^{-2} s^{-1}) with polyethylene moderator
- PMT Gain(@ 1400 V)$2.1x10^6$
- Crystal from ISMA, SICCAS and OPTOMATERIALS tested

Measurement strategy: 5' for Idark+ 15' irradiation +15' after extraction

- Few measurements lasting ~ 3 hours to check the decay time
- I_{dark}~ 10 nA
- $I_{Neutrons}$ ~5-10 μA

$$F = \frac{\frac{I}{e \times G_{PMT}}}{\phi_n}$$ Radiation induced p.e. per second

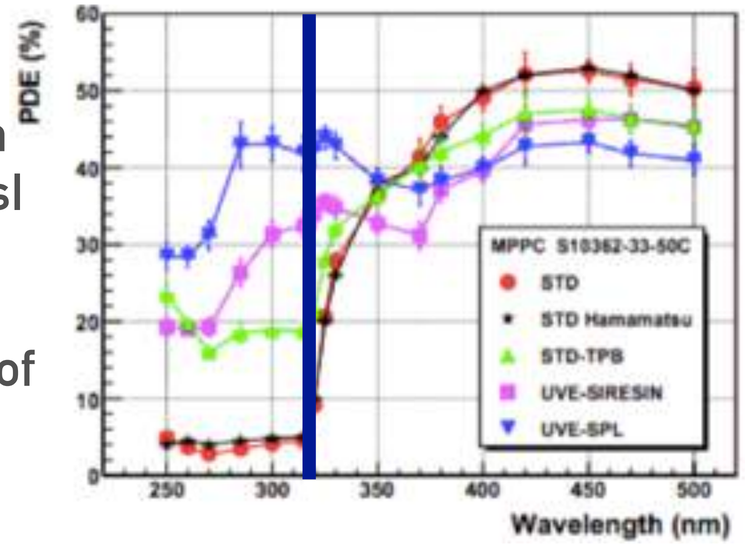
$$RIN = \frac{\sqrt{N_{pe}}}{LY}$$ Radiation Induced Noise



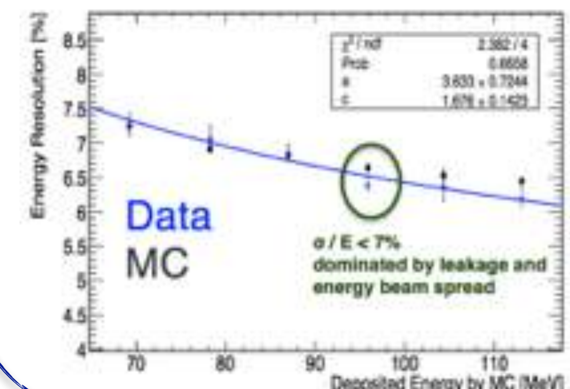
RIN from thermal neutrons in the hottest region: 60-85 keV. Well inside the Mu2e requirements (RIN< 0.6 MeV)

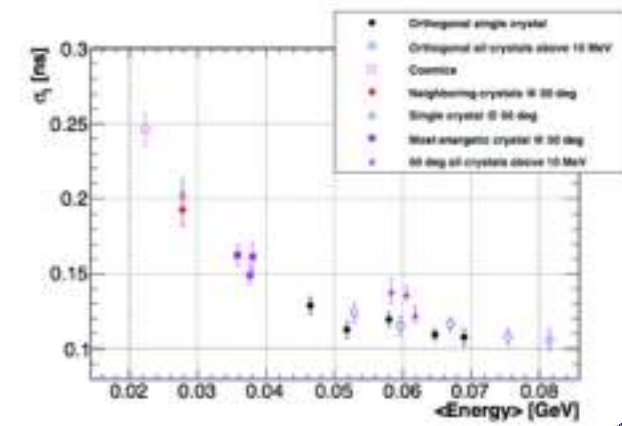
Mu2e custom SiPMs

UV extended SiPMs ensure a high quantum efficiency @ 315 nm (CsI emission peak) and a large active area to maximize the number of collected p.e.

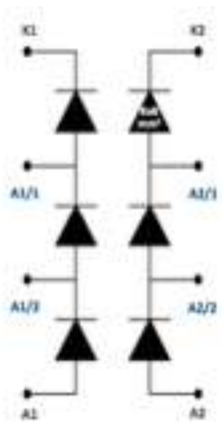


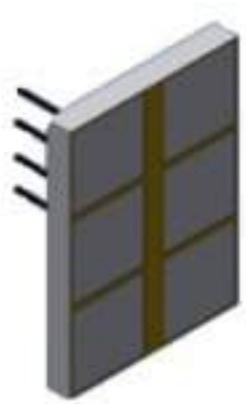
- ~20 p.e./MeV with Tyvek-wrapped crystals
- Time resolution < 150ps @ 100MeV with 45º e^- impact angle
- Energy resolution better than 7% @100 MeV





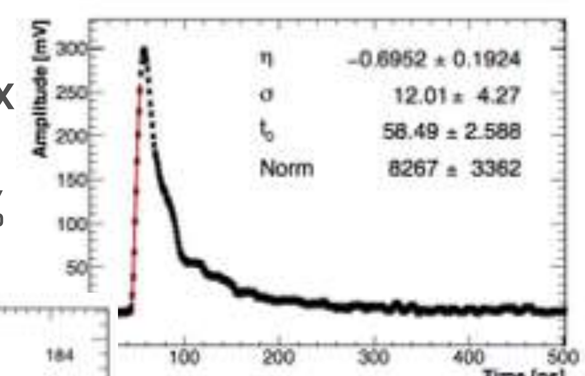
- The Mu2e SiPM will be made of a 2x3 matrix (6 cells) of 6x6 mm^2 UV extended SiPMs

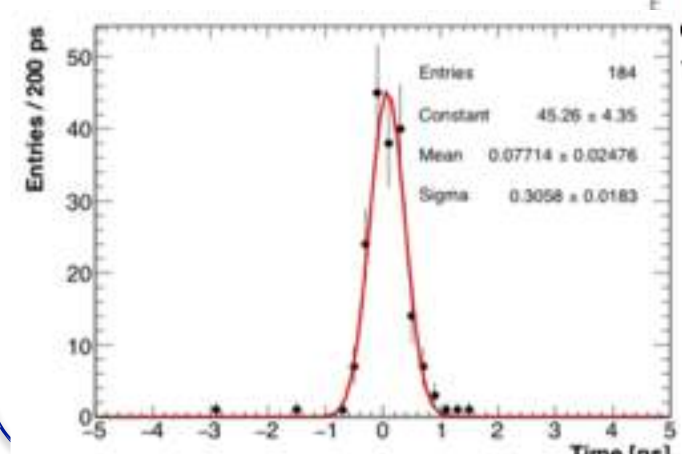




- A parallel arrangement of two groups of three cells biased in series
- 2 SiPMs per crystal → ensure redundancy
- Fast signal for pileup and timing resolution

- Fit function: Logn
- Fit range (5-85)% of max amplitude
- Constant fraction at 20%



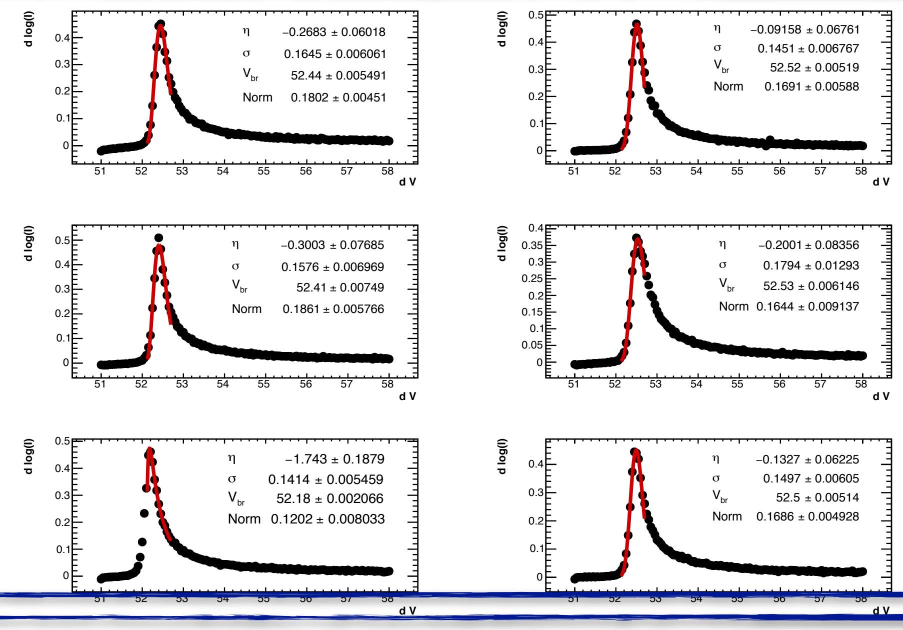


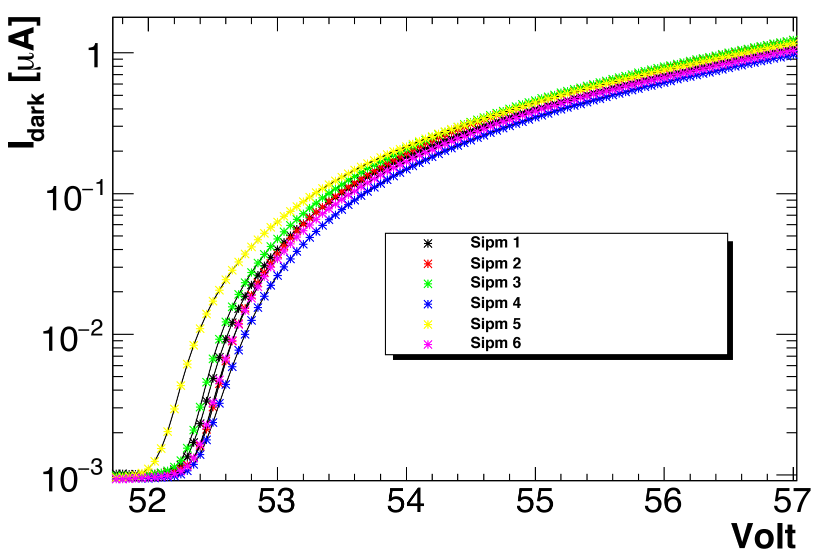
Time resolution ~ 170 ps

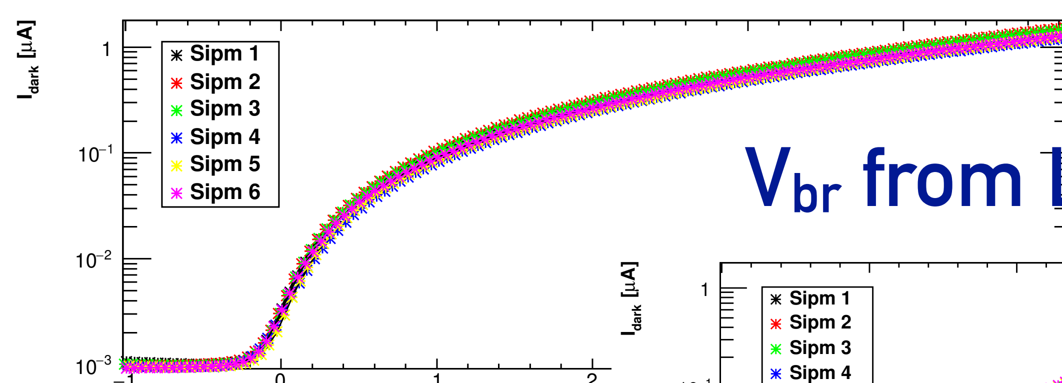
I_{dark}-V curves& V_{br} measurement

- 6x6 mm² SiPM from Hamamatsu(13360-6050CS) have been tested in order to:
  - compare V_{br} from data sheet with experimental one
  - measure fluctuation at same overvoltage

- If $V>V_{br}$ I increases faster the linear.Total increase rate of I is between V^n and e^V
- Calculate derivative of I curve in log scale. Local maximum value is V_{br}

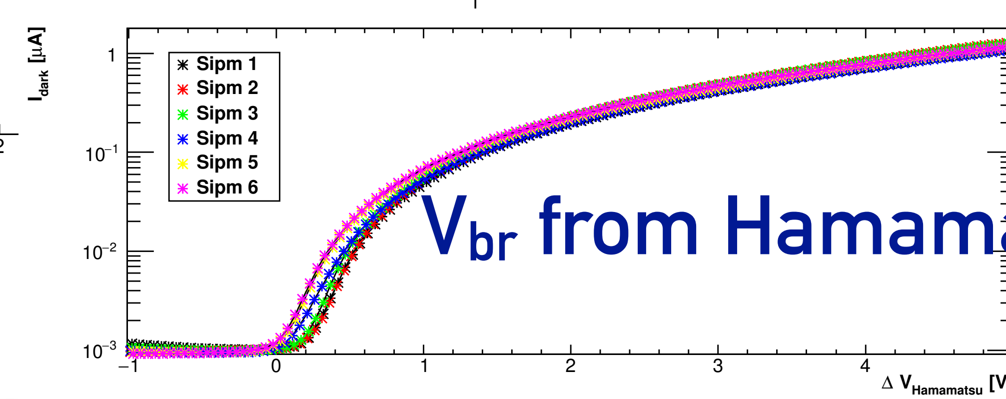






V_{br} from LNF fit

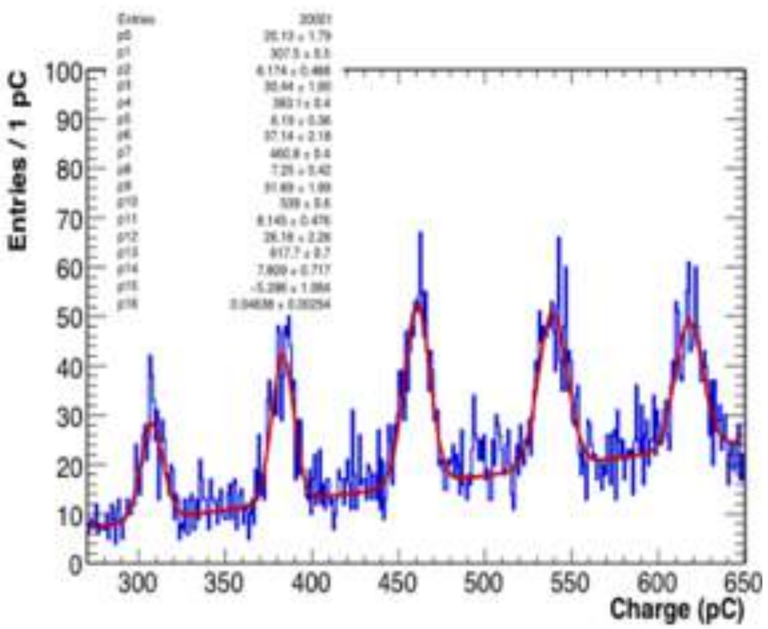
$\Delta V_i = V_{bias} - V_{br}$

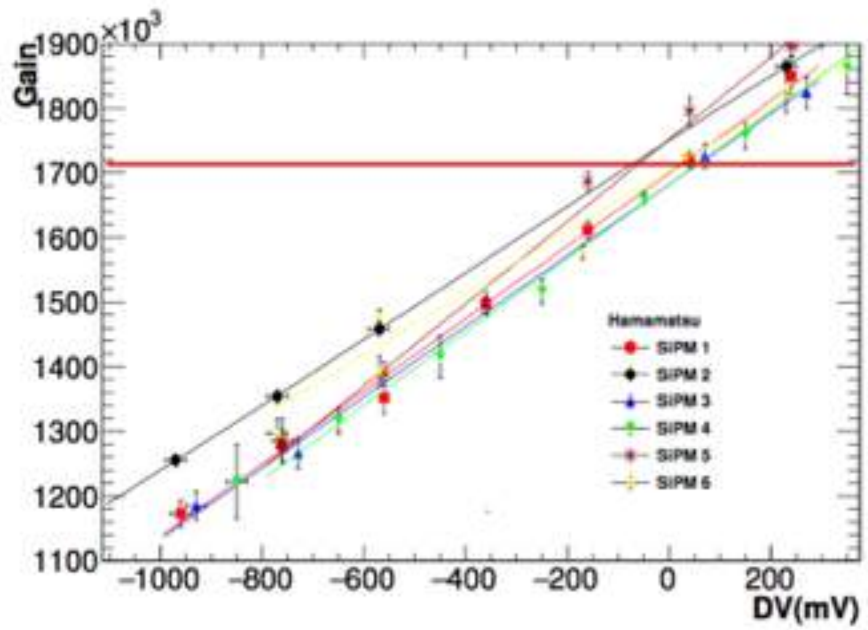


V_{br} from Hamamatsu

Gain

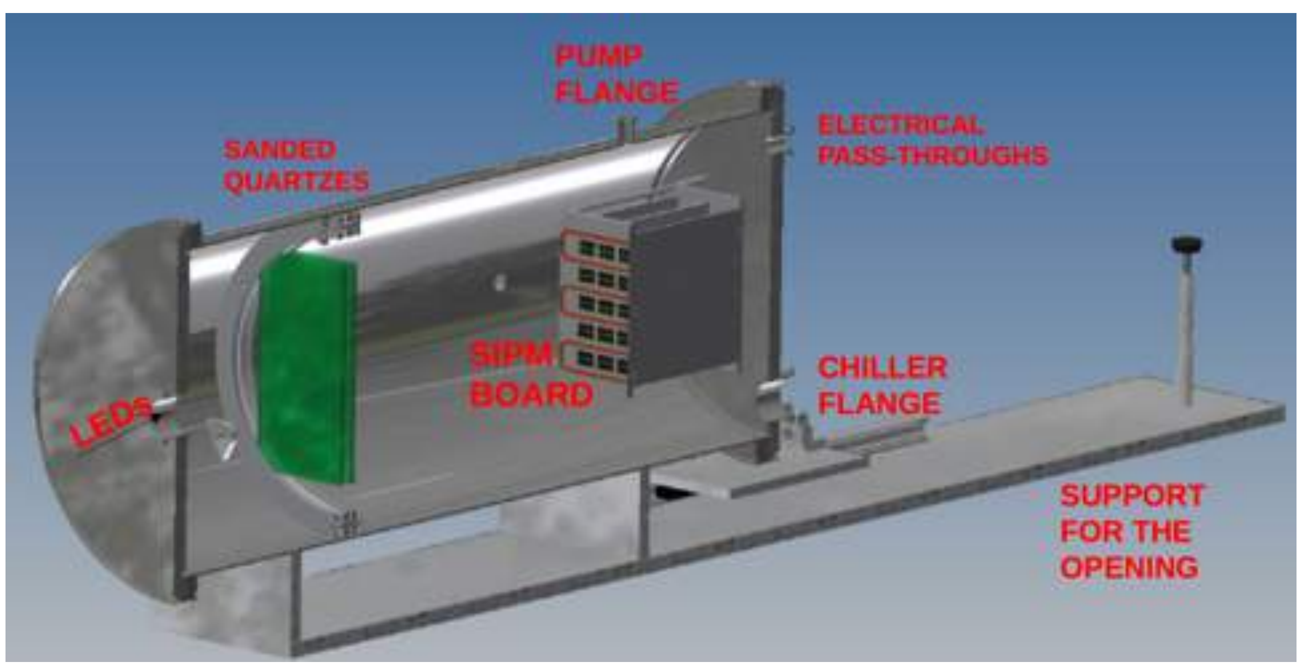
- Gain SiPM measuring difference between 2 adjacent peaks at different $\Delta V = \pm$ 200/400/600 mV





$$Q_n = G_{amp} \times G_{SiPM} \times N_{pe} \times e \Rightarrow G_{SiPM} = \frac{\Delta Q}{G_{amp} \times e}$$

- Evaluate max gain variation at V_{op}: ~8% → results consistent with the requirements ✔✔
- Evaluate V_{op} spread at same gain: ΔV_{op}~120 mV. Given V_{op}~55V δV_{op}=2.3‰ compatible with the requirements ✔✔

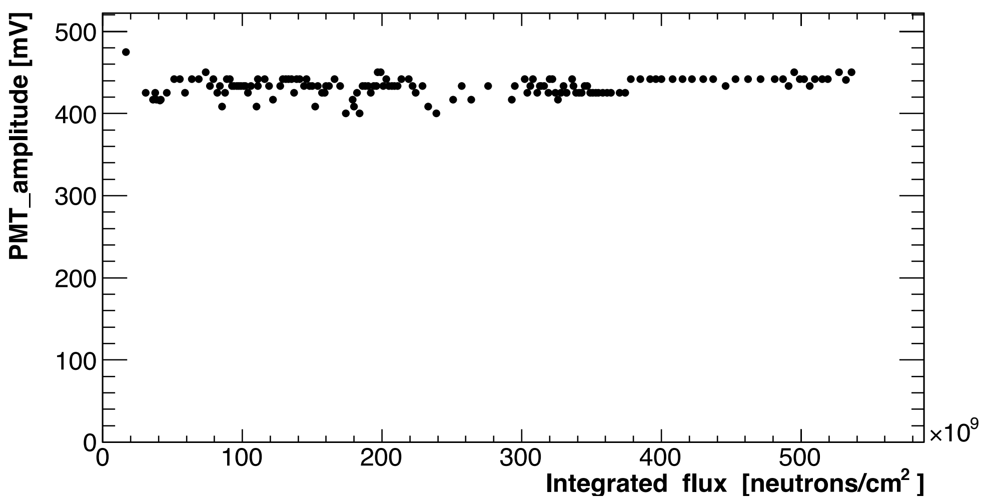


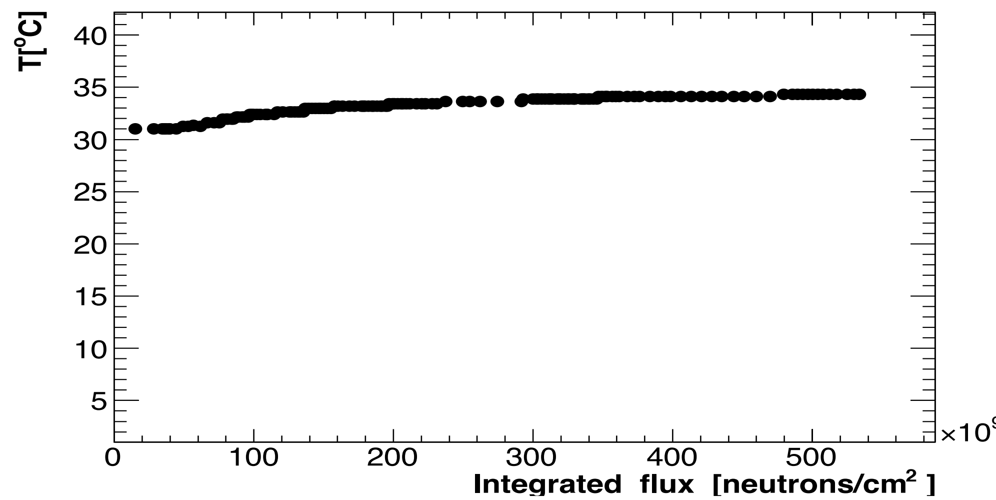
- Automatic test station under construction @ INFN Pisa:
  - 20 SiPMs tested + 5 for reference
  - uniform illumination
  - Temperature monitoring
  - Vacuum 10^{-1} Torr

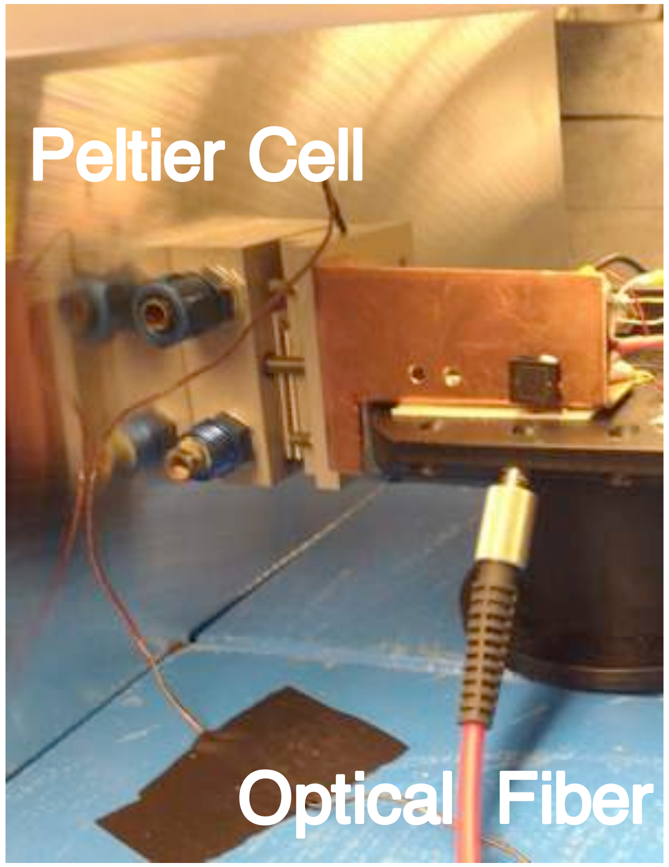
Irradiation with neutrons

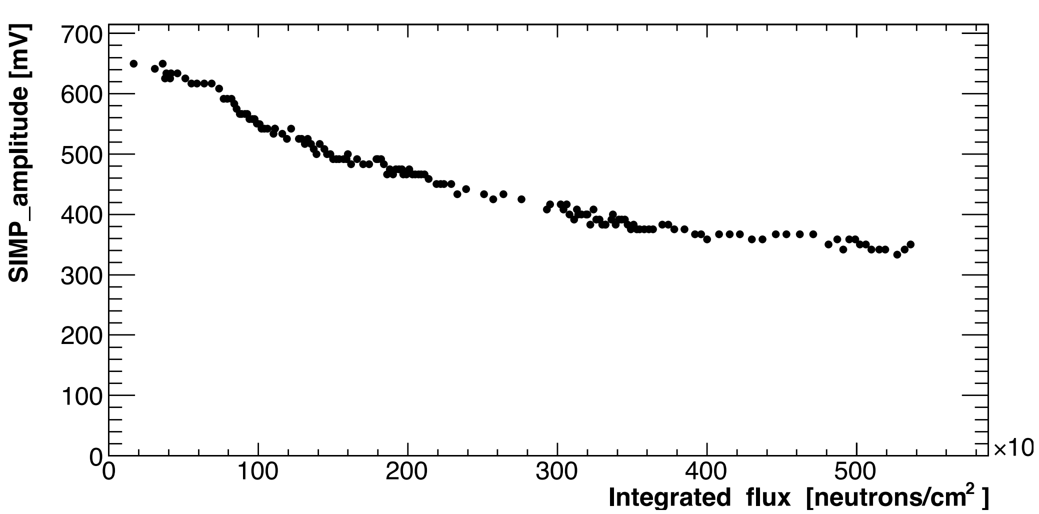
6x6 mm^2 SiPM with ceramic package irradiated with ~ 1MeV neutron at HZDR Dresden.

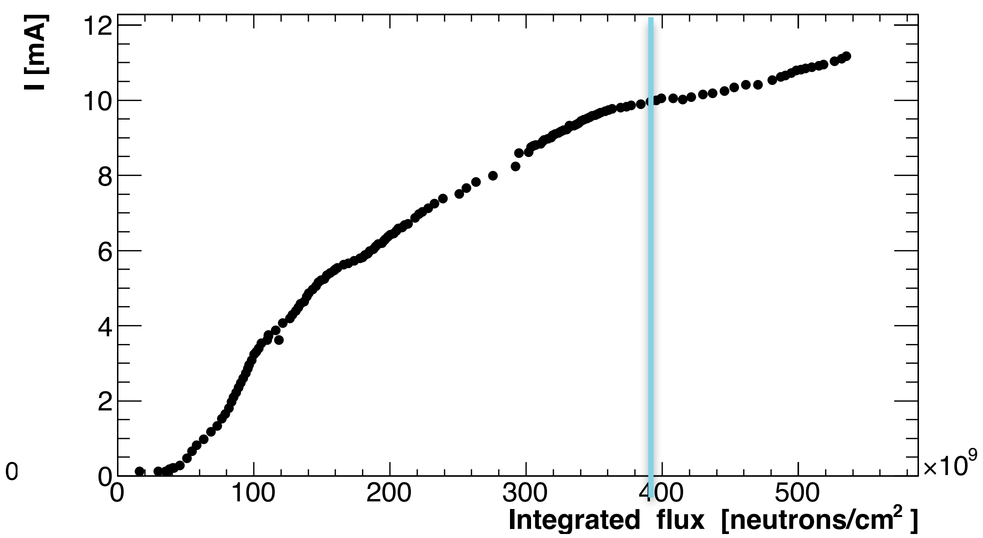
- Measure the SiPM response to UV led
- Measure leakage current







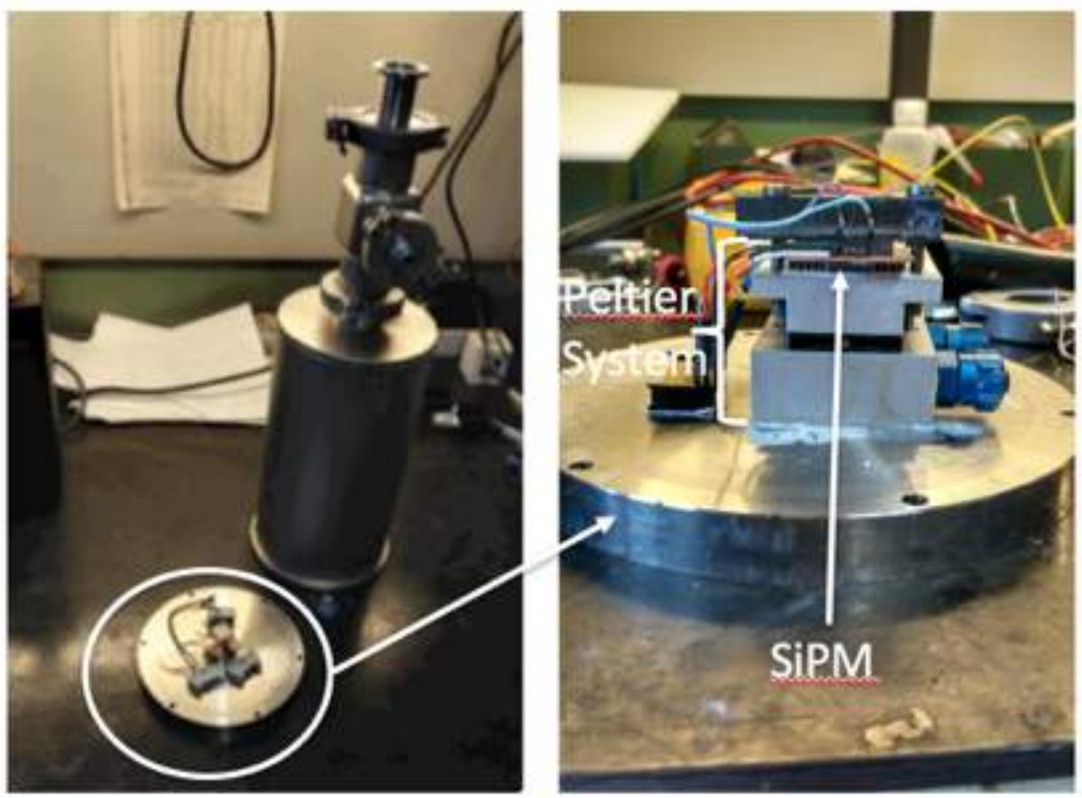


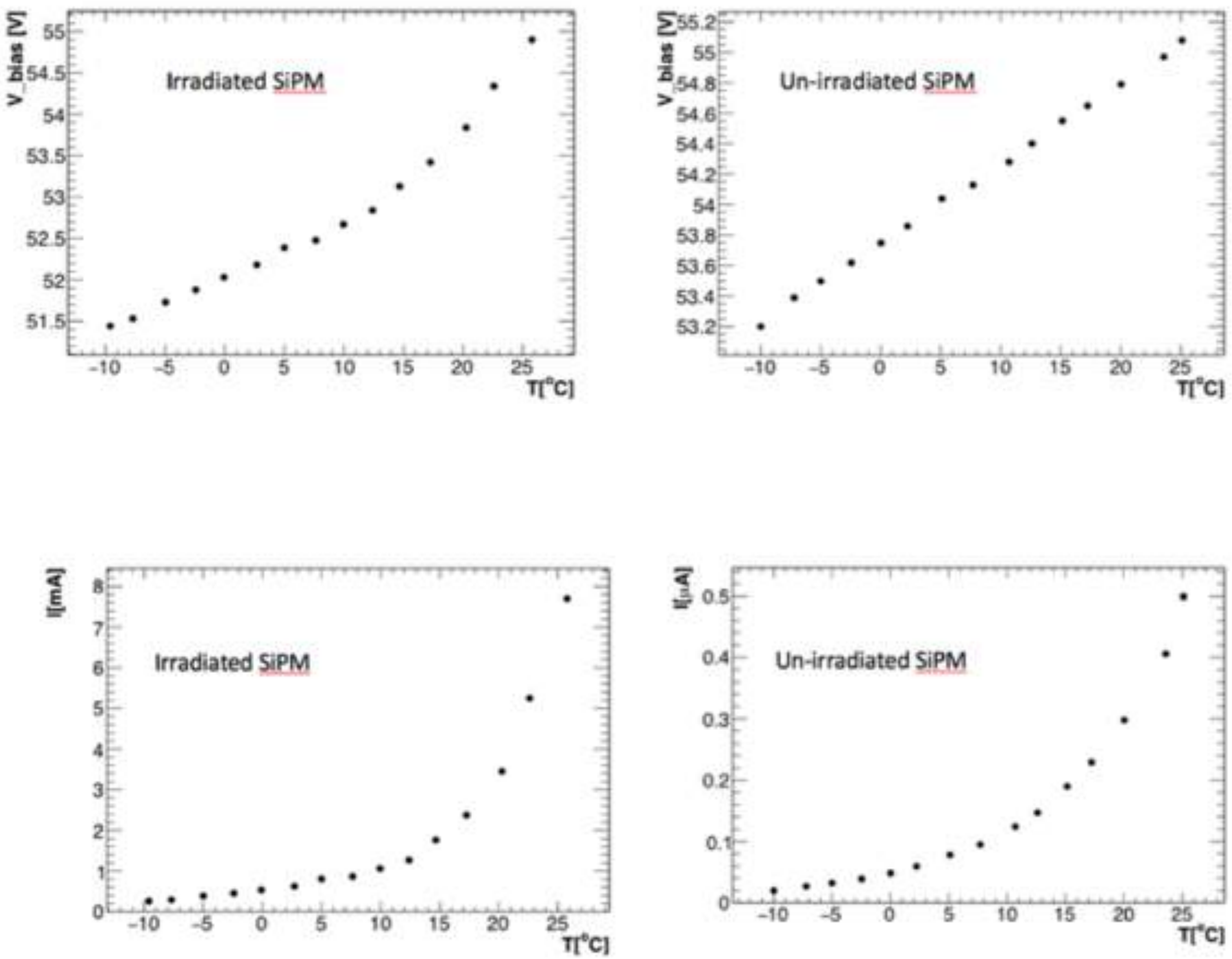


- SiPM temperature kept ~stable using a Peltier cell and monitored with a PT1000
- I from 60 µA up to 12 mA
- The response decreases of

Temperature dependency

- Leakage current and operation voltage measurements performed maintaining a fixed gain
- Measurements in vacuum (@10-4 mbar) with a system of two Peltier cells and a PT1000
- SiPM illuminated with UV led





It is necessary to cool down the SiPM system at 0°C

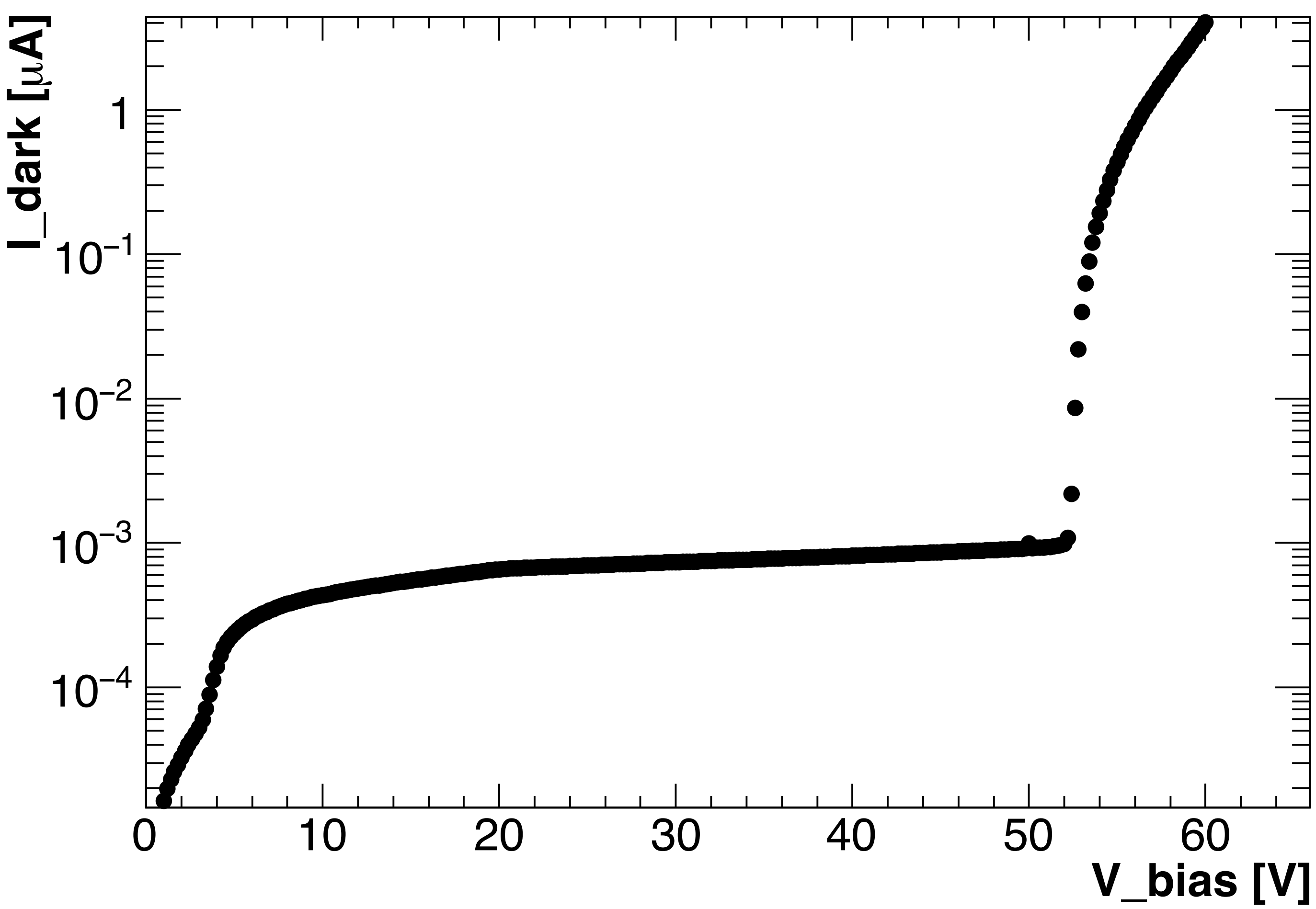
Conclusions

- Results from crystal test.
  Most of the crystals tested meet the Mu2e requirements
  - ✓ LY>100 pe/MeV
  - ✓ LRU<5%
  - ✓ Energy resolution (σ/peak) <20%
  - ✓ RIN<0.6 MeV

- Results from SiPM test:
  - ✓ Good agreement between V_{br} measured and the data sheet
  - ✓ Gain and gain spread meet compatible with the requirements
  - ✓ Gain changes due to irradiation are still acceptable for the running experiment. Leakage current too high → cool down the SiPM
  - ✓ Need to cool down the system at 0°C

BACKUP SLIDES

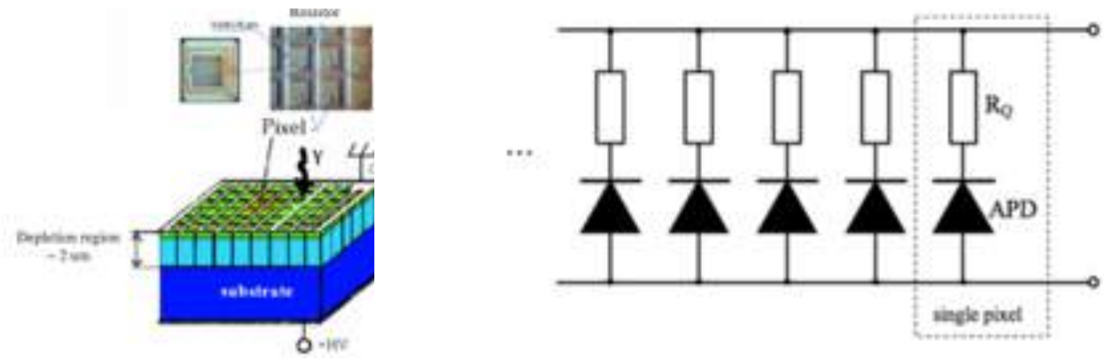
I_{dark}-V curves



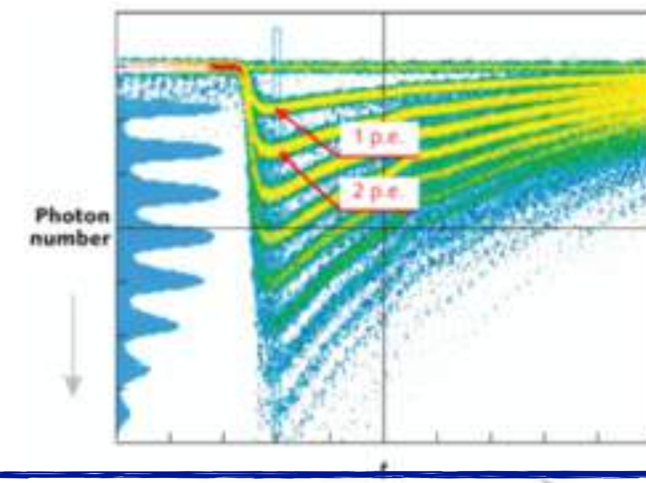
- $V \ll V_{br}$: I monotonically increase with V
- $V \sim V_{br}$: I increases more rapidly with each voltage step, reaching the highest rate of increase when $V = V_{br}$
- $V > V_{br}$: Geiger mode, gain is linearly proportional to ΔV

Silicon Photomultipliers (SiPM)

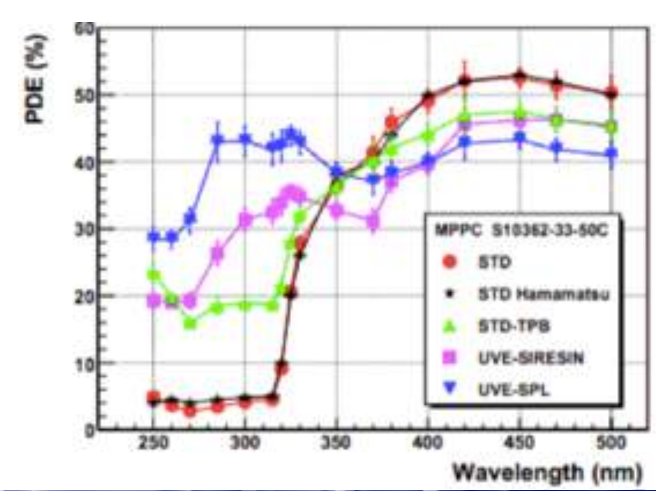
- Photodetector consisting of pixels connected in parallel. One pixel is a series combination of an Avalanche PhotoDiode (APD) and a quenching resistor



- Each pixel in the SiPM generates a pulse at the same amplitude when it detects a photon. Pulses generated by multiple pixels create the output signal as a superimposition of the single pixel pulses

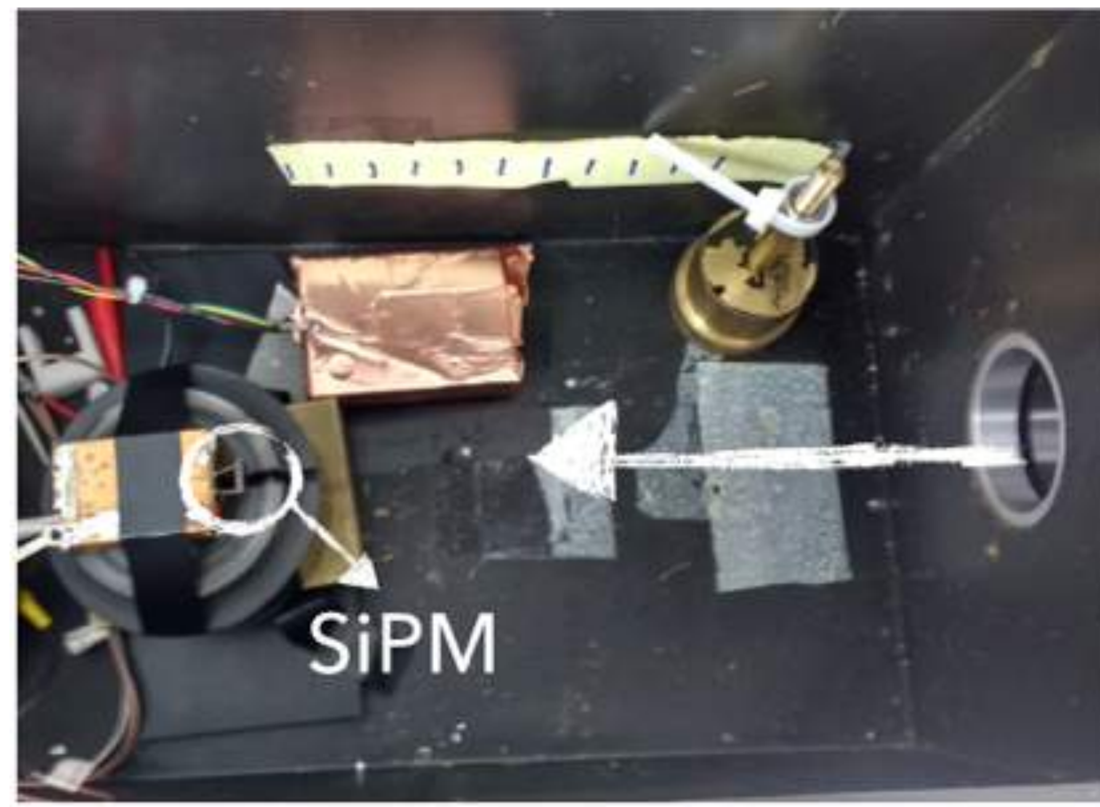


- Photon detection efficiency is the product of 3 components:
  - Quantum efficiency: ratio of the number of carriers collected to the number of photons of a given energy incident on the device
  - Avalanche probability: probability that an incident photon starts an avalanche
  - “Filling Factor”: ratio between pixel dimension and the total SiPM dimension

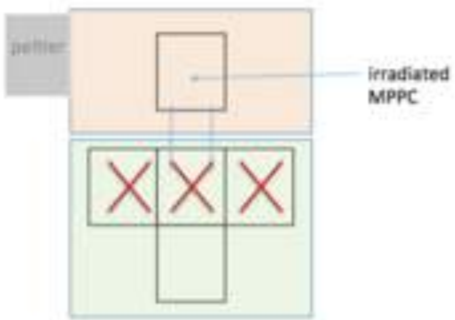


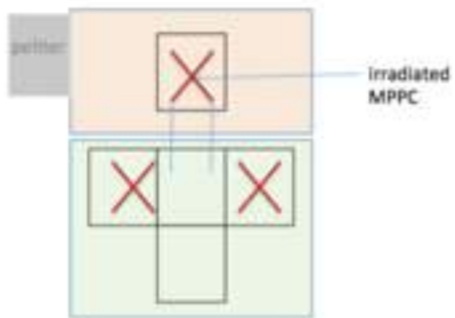
Gain: experimental setup

- Black box containing experimental set up
- Blue led (λ=425 nm) driven by a fast pulser
- Polaroid filter
- Custom amplifier x300
- CAEN DT5751



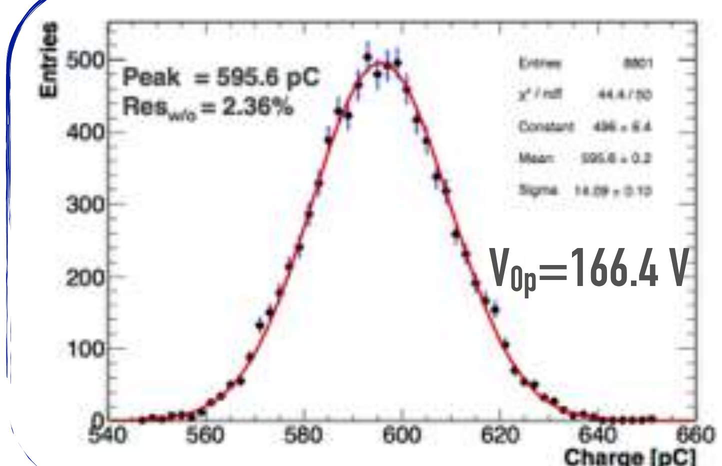
Series comparison

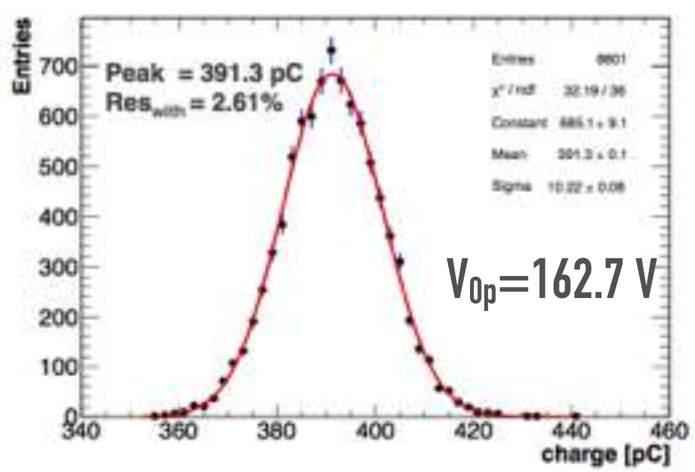




Compare the response of the series of three MPPCs at a blue laser in the following configurations:

- Three SiPM not irradiated
- Two SiPM not irradiated and the one irradiated @ HZDR

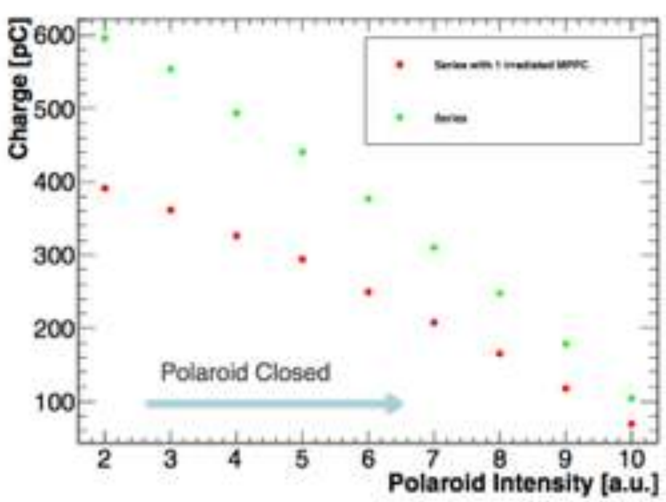


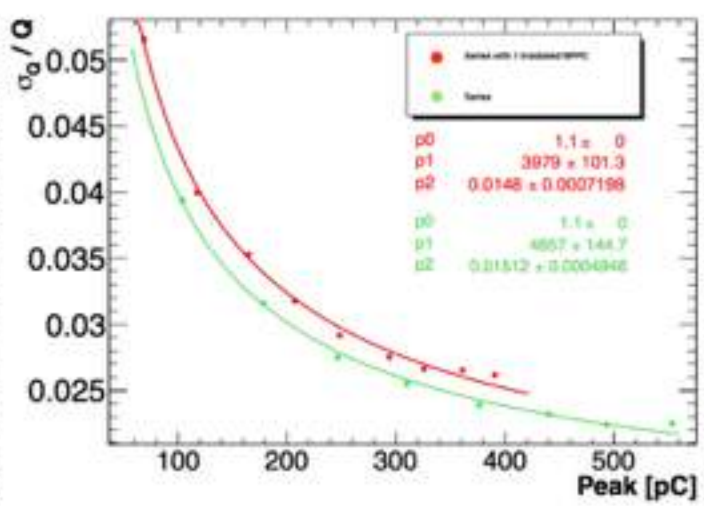


Operational point at 0.54 μA:

- 166.4 V for the series w/o the irradiate SiPM
- 162.7 V for the series with the irradiated SiPM

The different of the mean charge is compatible with the hypothesis ΔV ~ 0 V for the irradiated SiPM



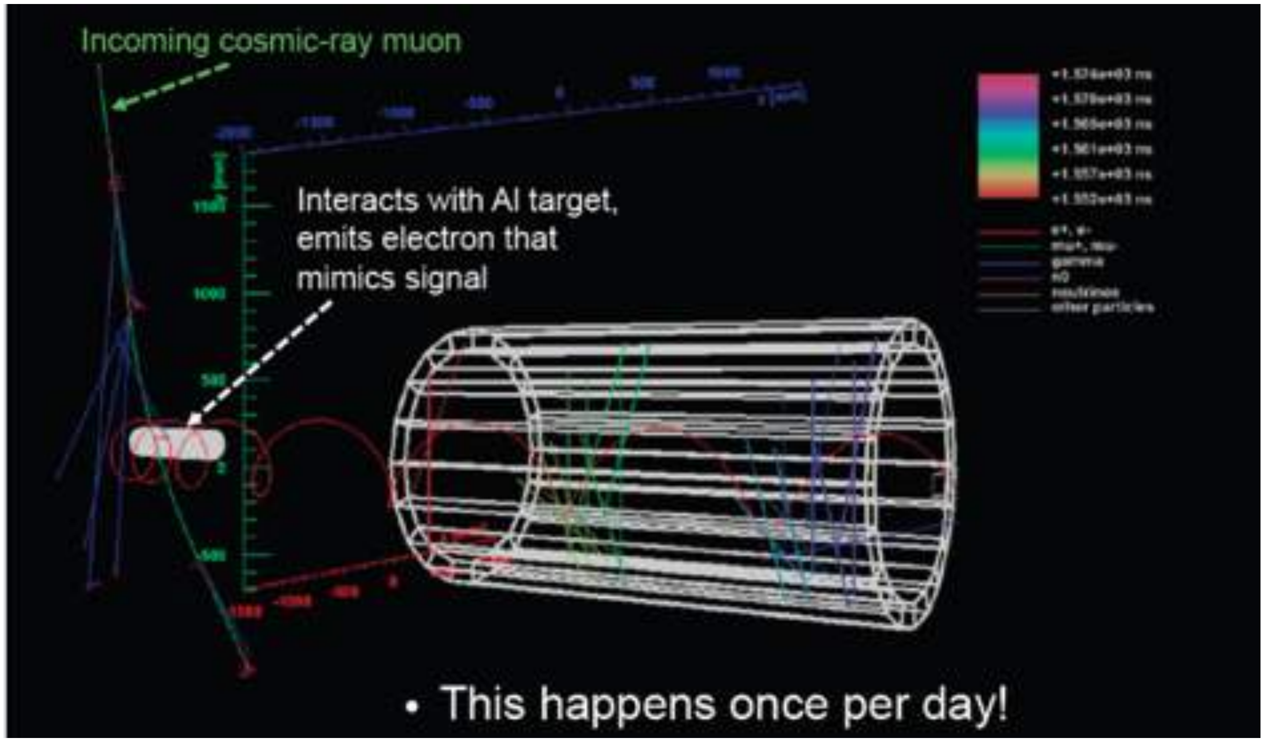


Resolution vs peak fitted with: $\sqrt{F/(Q/A)}$

F=1.1 (excess noise), Npe=Q/A (A= pC/pe)

Series with the irradiated and w/o the irradiated SiPM in good agreement

Particle Identification & muon rejection



2.2 events with cosmic muons with 103.5 < P < 105 MeV/c enter the detector bypassing the CRV counters and surviving all analysis cuts.

muon rejection of 200:

combination of tracker and calorimeter informations