Use of the MPPCs for the Mu2e e.m. calorimeter

I. Sarra, **Laboratori Nazionali di Frascati**

HZDR – Helmholtz-Zentrum Dresden-Rossendorf

April 21, 2016

Talk Layout

- Silicon Photo Multiplier
  - → Introduction

- The Mu2e experiment
  - → The Mu2e e.m calorimeter

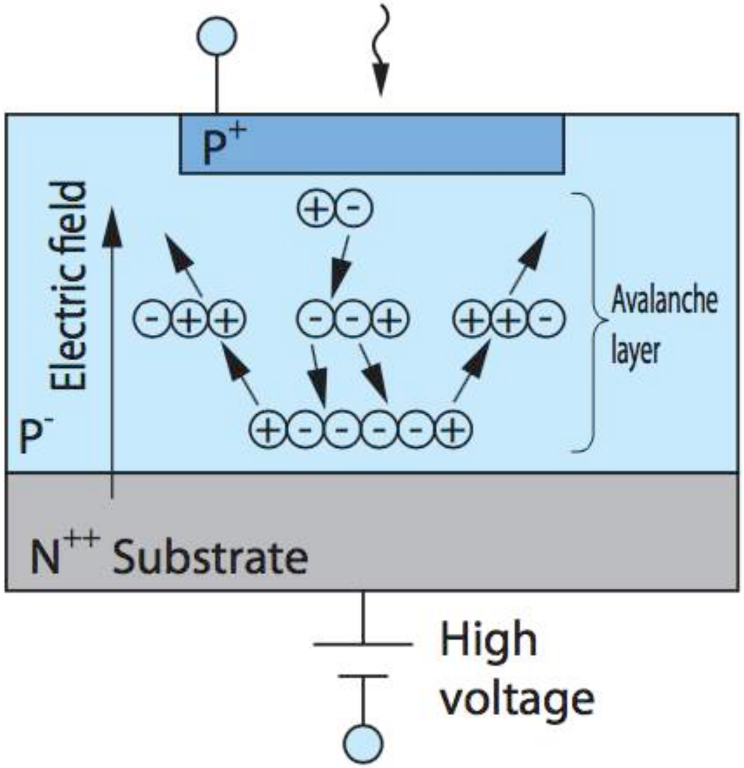
- MPPC for the Mu2e calorimeter
  - → Test Beam
  - → MPPC vs neutrons flux / photons dose
  - → Custom Device and First Tests

APD

1) A photon absorbed in the depletion region produces a new electron-hole pair;

2) The electron-hole pair is accelerated by the high electric field **generating further electron-hole pairs**;

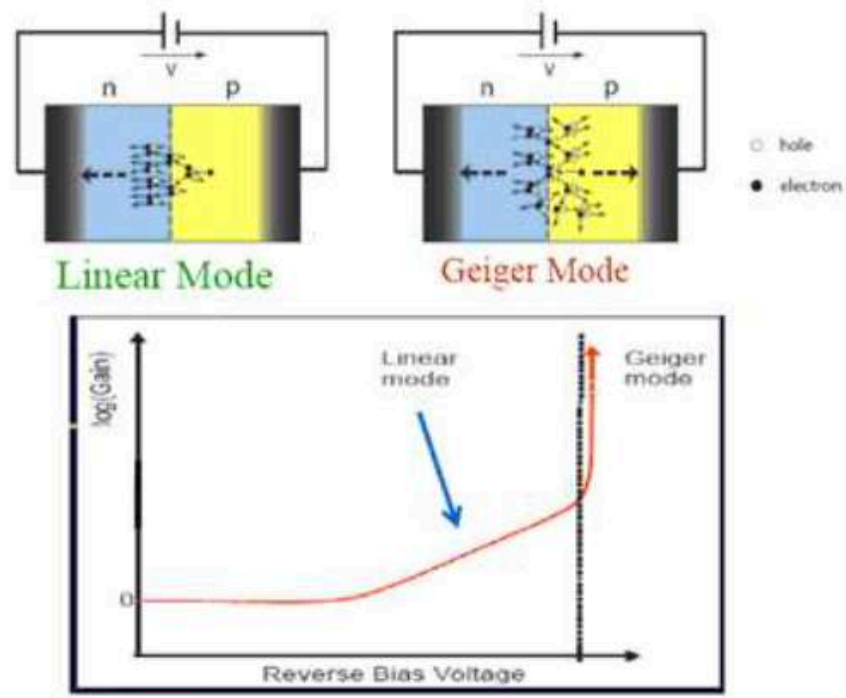
3) An Avalanche multiplication happens with a Gain proportional to the applied reverse bias voltage (G ~100-500).



I-V curve → SiPM

When the reverse voltage applied to an APD is set higher than the breakdown voltage, the electric field in the APD becomes high enough to cause a discharge (Geiger discharge) even by input of one single photon.

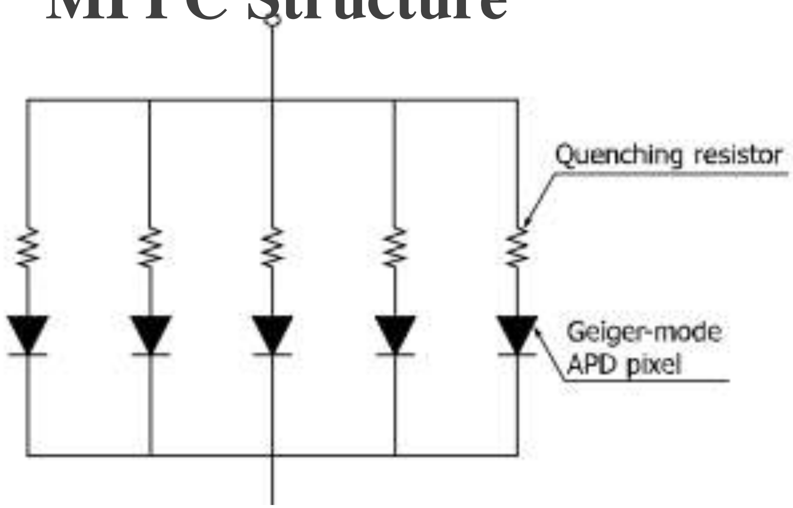
- The Geiger mode allows obtaining a large output by way of the discharge even when detecting a single photon. **Once the Geiger discharge begins, it continues as long as the electric field in the APD is maintained.**

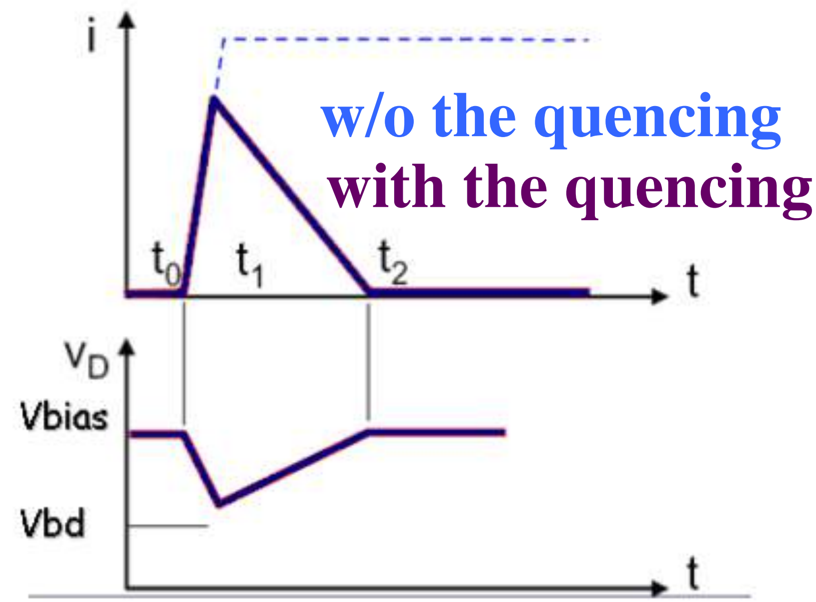


Quenching resistor

One specific example to stop the Geiger discharge is a technique using a so-called quenching resistor connected in series with the APD. This quickly stops avalanche multiplication in the APD because **a drop in the operating voltage occurs when the output current, caused by the Geiger discharge, flows.**

MPPC Structure

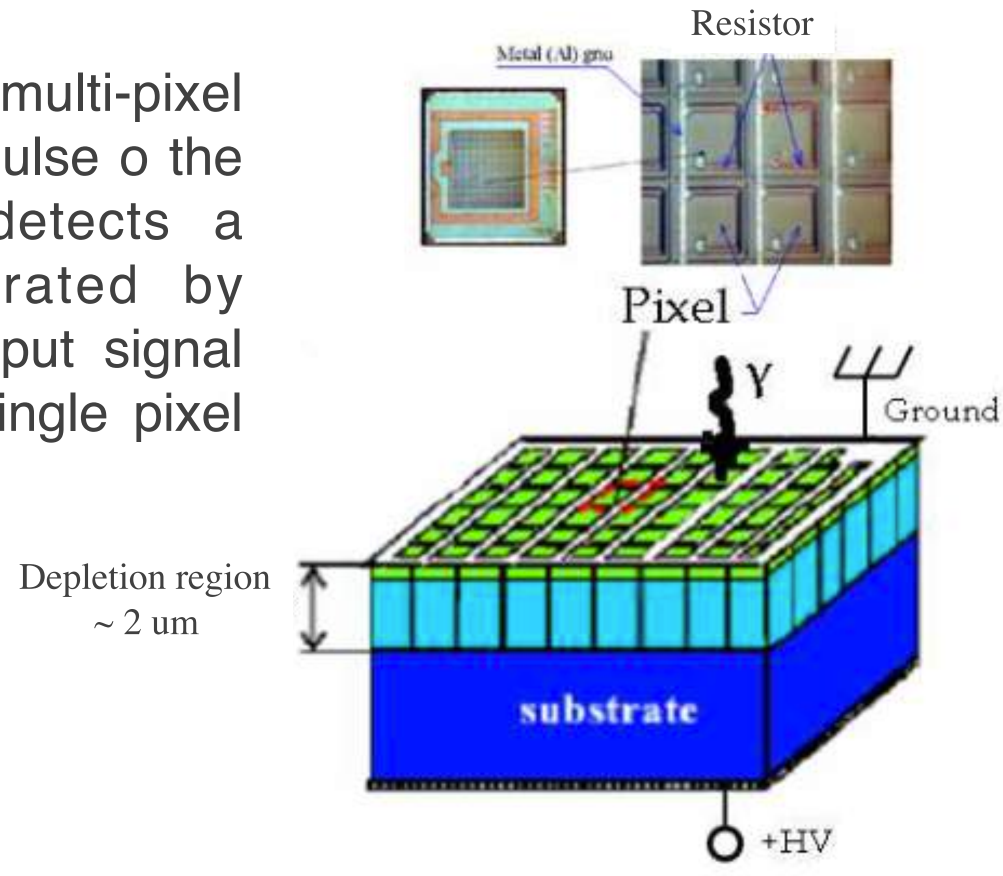




Basic operation

The basic element (pixel) of an **MPPC is a combination of the Geiger mode APD and quenching resistor**, and a large number of these pixels are electrically connected and arranged in two dimensions;

- Each pixel in the MPPC (multi-pixel photon counter) generates a pulse o the same amplitude when it detects a photon. The pulses generated by multiple pixels create the output signal as a superimposition of the single pixel pulses.



PDE

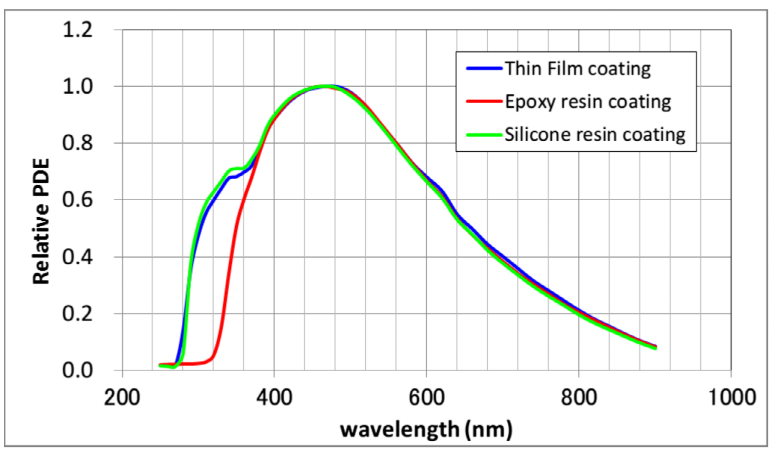
The photon detection efficiency is the product of 3 components:

1) The quantum efficiency @ the silicon surface

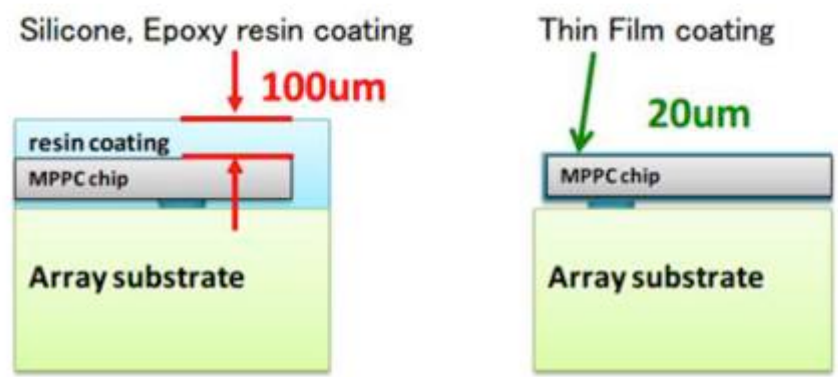
2) The “filling factor” of active area with respect to the total area of the MPPC

3) The avalanche probability (that is function of V_{bias})

PDE comparison



Thin Film coating and Silicon resin coating has PDE advantage in UV region.



■merit
- robust to the mechanical shock
- easy handling (during assy.)
- superior transparency in UV region
  - silicone resin coating type -

■merit
- tough coating
  (mechanical shock should be avoided)
- superior transparency in UV region
- cross-talk suppression in the coating
- super flatness (minimum bending)

Phototube vs SiPM

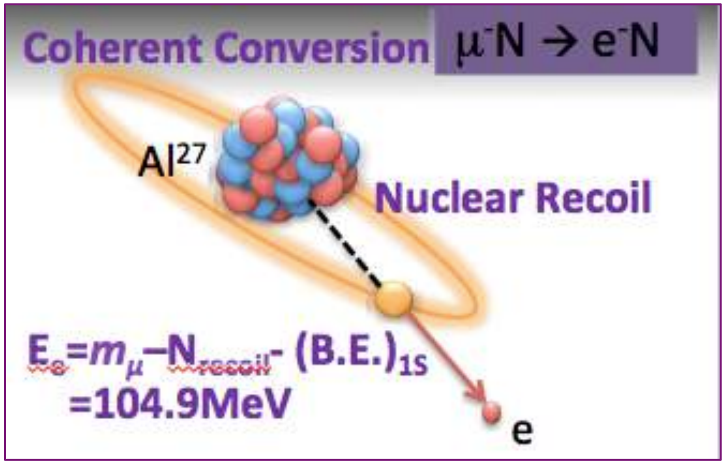
Vbias ~ kV		Vbias ~ 30-70 V	
Gain ~10^6		Gain ~10^6	
QE ~ 30%		PDE ~ 40%	
No able to work in high magnetic field		Able to work in high magnetic field	
Proportional response		Digital devices, saturation problem	

- Silicon Photo Multiplier
  - → Introduction

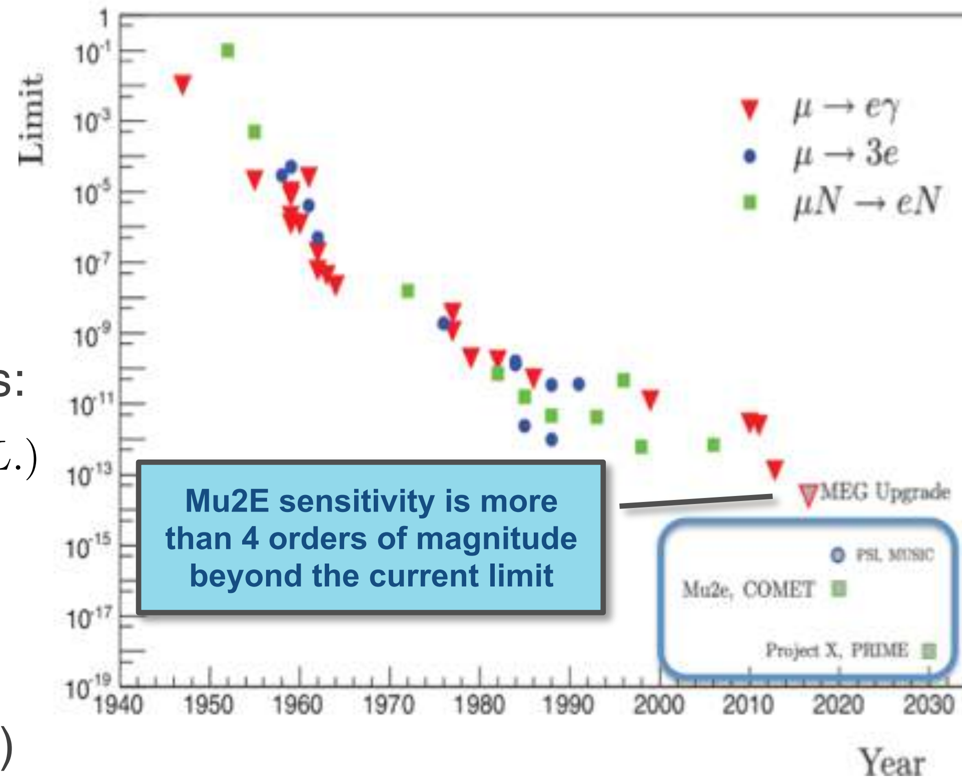
- ***The Mu2e experiment***
  - ***→ The Mu2e e.m calorimeter***

- MPPC for the Mu2e calorimeter
  - → Test Beam
  - → MPPC vs neutrons flux / photons dose
  - → Custom Device and First Tests

The Mu2e experiment



Detect the CLFV process $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$ i.e. the coherent, neutrinoless **conversion of a muon to an electron** in the field of a nucleus.



- **Goal of Mu2e:**
Measure the rate of conversion relative to ordinary muon capture on the nucleus:

$$R_{\mu e} = \frac{\mu^- Al \rightarrow e^- Al}{\mu^- Al \rightarrow capture} < 6 \times 10^{-17}\ (90\%\ C.L.)$$

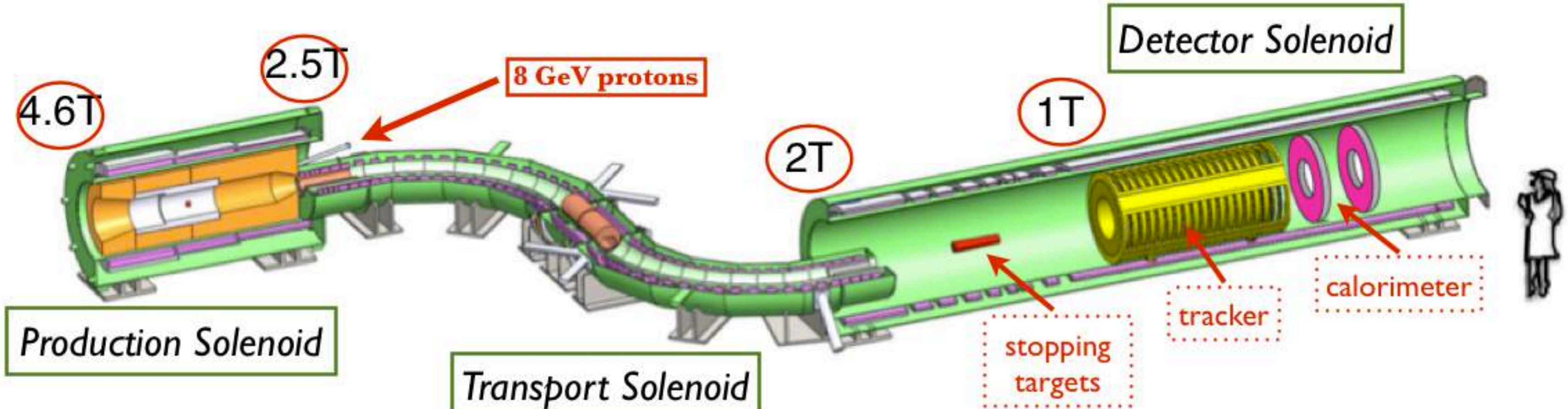
with a single event sensitivity (SES) of 2.5×10^{-17}

- **Current limits** (SINDRUM II at PSI) :
$R_{me} < 4.3\times10^{-12}$ (Ti), $R_{me} < 7\times10^{-13}$ (Au)

The Mu2e experiment layout

- *Production Solenoid:*
  - ➡ Proton beam strikes target, producing mostly pions
  - ➡ Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons

- *Detector Solenoid:*
  - ➡ Capture muons on Al target
  - ➡ Measure momentum in tracker and energy in calorimeter
  - ➡ Graded field "reflects" downstream conversion electrons emitted upstream



- *Transport Solenoid:*
  - ➡ Select low momentum, negative muons
  - ➡ Antiproton absorber in the mid-section

- *Targets:*
  - ❖ 17 Al foils; Aluminum was selected mainly for the muon lifetime in capture events (**864 ns**) that matches nicely the need of prompt separation in the Mu2e beam structure.

- *Tracker:*
  - ❖ ~25000 tubes arranged in planes on stations, the tracker has 18 stations
  - ❖ Expected momentum resolution ~ 120 keV/c

Physics and Calorimeter Requirements

The Calorimeter should:

- Provide high e^- reconstruction efficiency for μ rejection of 200
- Provide cluster-based seeding for track finding
- Provide online software trigger capability
- Survive in the radiation environment of Mu2e
- Operate for 1 year w.o. interruption in DS w/o reducing performance

In order to do so the calorimeter should have the following capability

→ Provide energy resolution σ_E/E of O(5 %) @ 100 MeV

→ Provide timing resolution σ(t) < 500 ps

→ Provide position resolution < 1 cm

→ Redundancy in FEE and photo-sensors

Solution: A crystal based disk calorimeter

Derived requirements

High granularity crystal based calorimeter with:

- ❑ 2 Disks (Anuli) geometry to optimize acceptance for spiraling electrons
- ❑ Crystals with high Light Yield for timing/energy resolution
  → **LY(photosensors) > 20 pe/MeV**
- ❑ **2 photo-sensors/preamps/crystal** for redundancy
  and reduce MTTF requirement → now set to 1 million hours/SIPM
- ❑ Fast signal for Pileup and Timing resolution **→ τ of emission < 30 ns**
- ❑ **Crystal dimension optimized** to stay inside DS envelope
  → reduce number of photo-sensor, FEE, WFD (cost and bandwidth)
  while keeping pileup under control and position resolution < 1 cm.
- ❑ Crystals and sensors should work in 1 T B-field and in vacuum of 10^{-4} Torr and:
  → **Crystals survive a dose of 100 krad and a neutron fluency of 10^{12} n/cm^2**
  → Photo-sensors survive 20 krad a neutron fluency of 3×10^{11} n_1MeV/cm^2

} Safety Factor = 3

Calorimeter Design

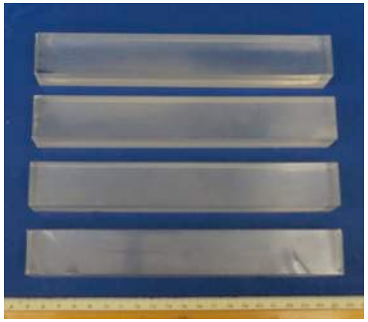
The Calorimeter consists of two disks with 674 CsI square crystals:

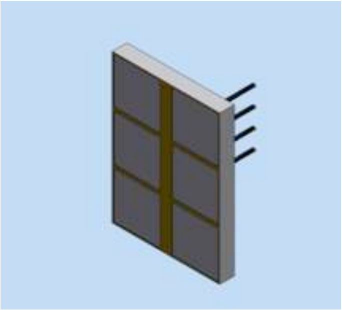
→ R_{inner} = 374 mm, R_{outer}=660 mm, depth = 10 X_0 (200 mm)

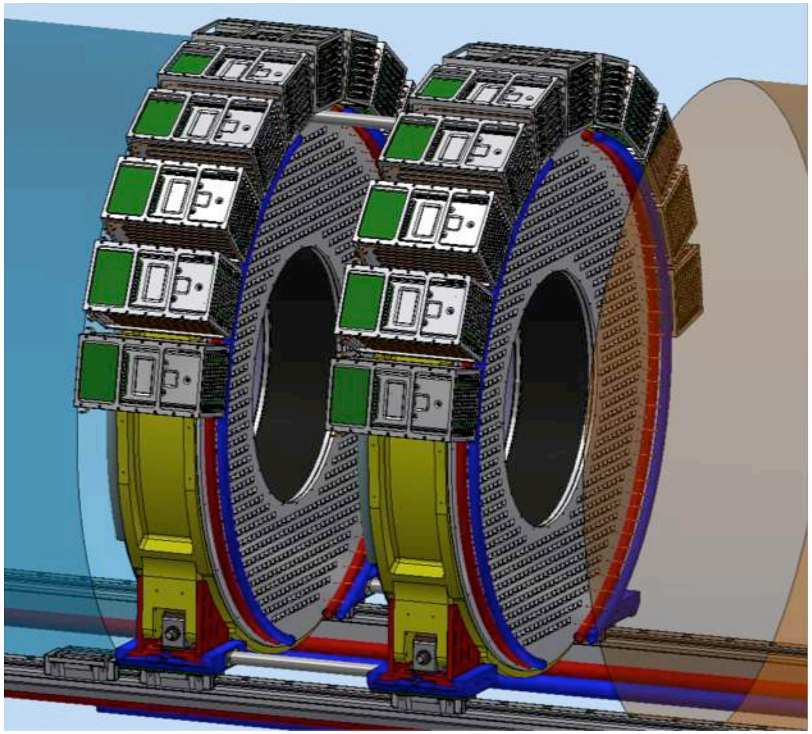
→ Each crystal is readout by two large area UV extended SIPM's (14x20 mm^2)

→ Analog FEE is on the SiPM and digital electronics located in near-by electronics crates

→ Radioactive source and laser system provide absolute calibration and monitoring capability







- Silicon Photo Multiplier
    - → Introduction
- The Mu2e experiment
    - → The Mu2e e.m calorimeter
- ***MPPC for the Mu2e calorimeter***
    - → ***Test Beam***
    - → ***MPPC vs neutrons flux / photons dose***
    - → ***Custom Device and First Tests***

Requirements

Photosensors must meet the following requirements:

(R1) Have a high quantum efficiency @ 315 nm (the emission peak for CsI) and a large active area to maximize the number of collected photoelectrons;

(R2) Have a high gain, fast signal and low noise (MeV equivalent);

(R3) withstand a radiation environment of $3x10^{11}$ n/cm^2 @ 1 MeV$_{eq}$ and 20 krad for photons;

(R4) Work in vacuum at 10^{-4} Torr;

(R5) Have sufficient reliability to allow operation for 1 year w.o. interruption;

(R6) Allow replacement of photosensors after 1 year of running if needed

UV-extended SiPM – Hamamatsu

We started testing arrays of 16 3x3 mm^2 Hamamatsu TSV MPPCs (12x12 mm^2)

- These have silicone and thin film protection layers
- SiPMs coupled to pure CsI crystals (30x30x200) mm^3

✓ A first matrix prototype has been built to test it @ the electron beam test facility (BTF) of Frascati (7-12 of April 2015).

The prototype consists of a MATRIX of 9 pure CsI crystals (30x30x200 mm^3):

- 2 CsI by Optomaterial (Sardegna, Italy)
- 7 pure CsI by ISMA (Kharkov, Ukraine)
- All crystals shown a good uniformity LRU (< 10 %) when wrapped with Tyvek and optically coupled to photosensors with Bluesil Past-7 silicon grease

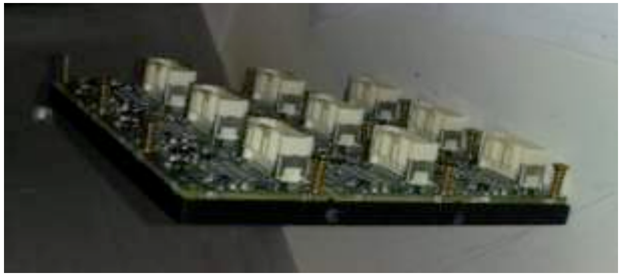
Each crystal is readout by one 12x12 mm^2 **SPL MPPCs** UV enhanced from Hamamatsu

Matrix assembly: components

100 µm Tyvek reflective wrapping

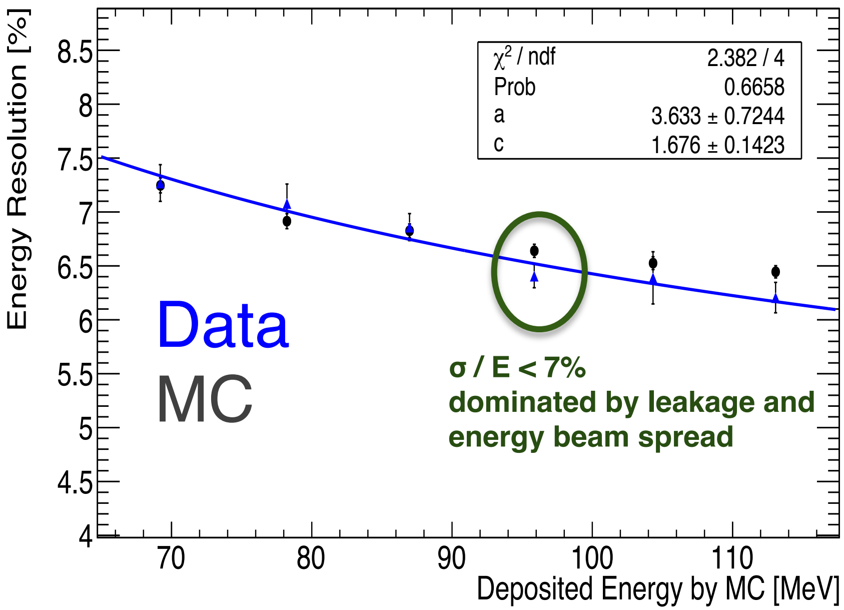
MPPC lodgments created by means of PVC 3D print

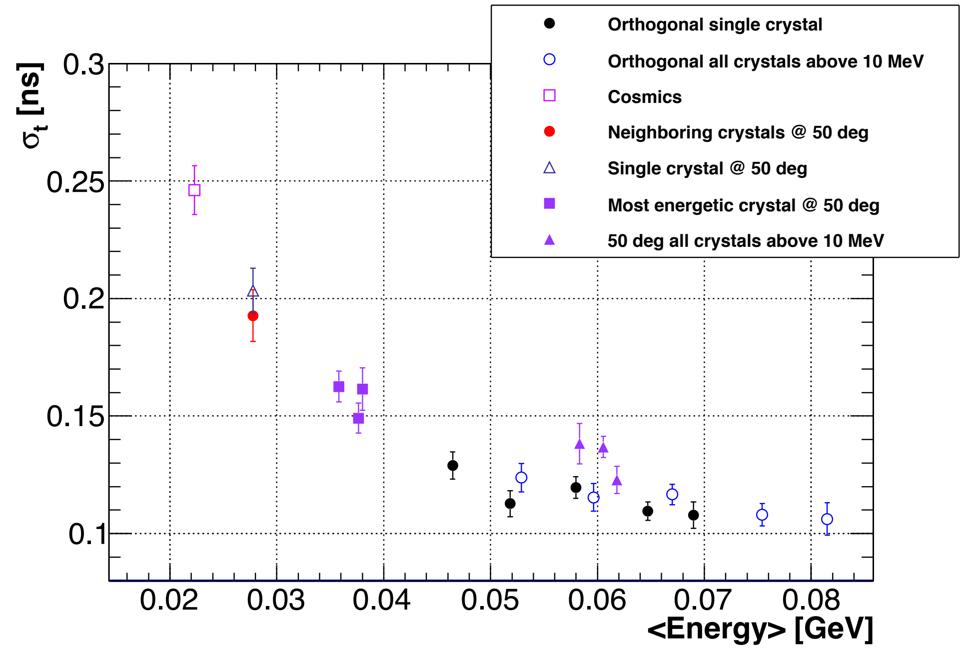
Electronics FEE: analog adder of the 16 anodes/MPPC



Results

- → ~ 30 (20) p.e/MeV with (without) optical grease with Tyvek-wrapped crystals
- → Time resolution < 150 ps @ 100 MeV with 45° e^- impact angle
- → Energy resolution better than 7% at 100 MeV (leakage dominated)
- → Equivalent noise ~ 100 keV





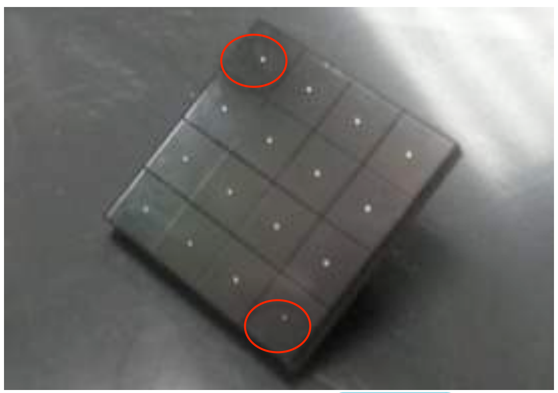
(R3) → Irradiation test of MPPC and SiPM

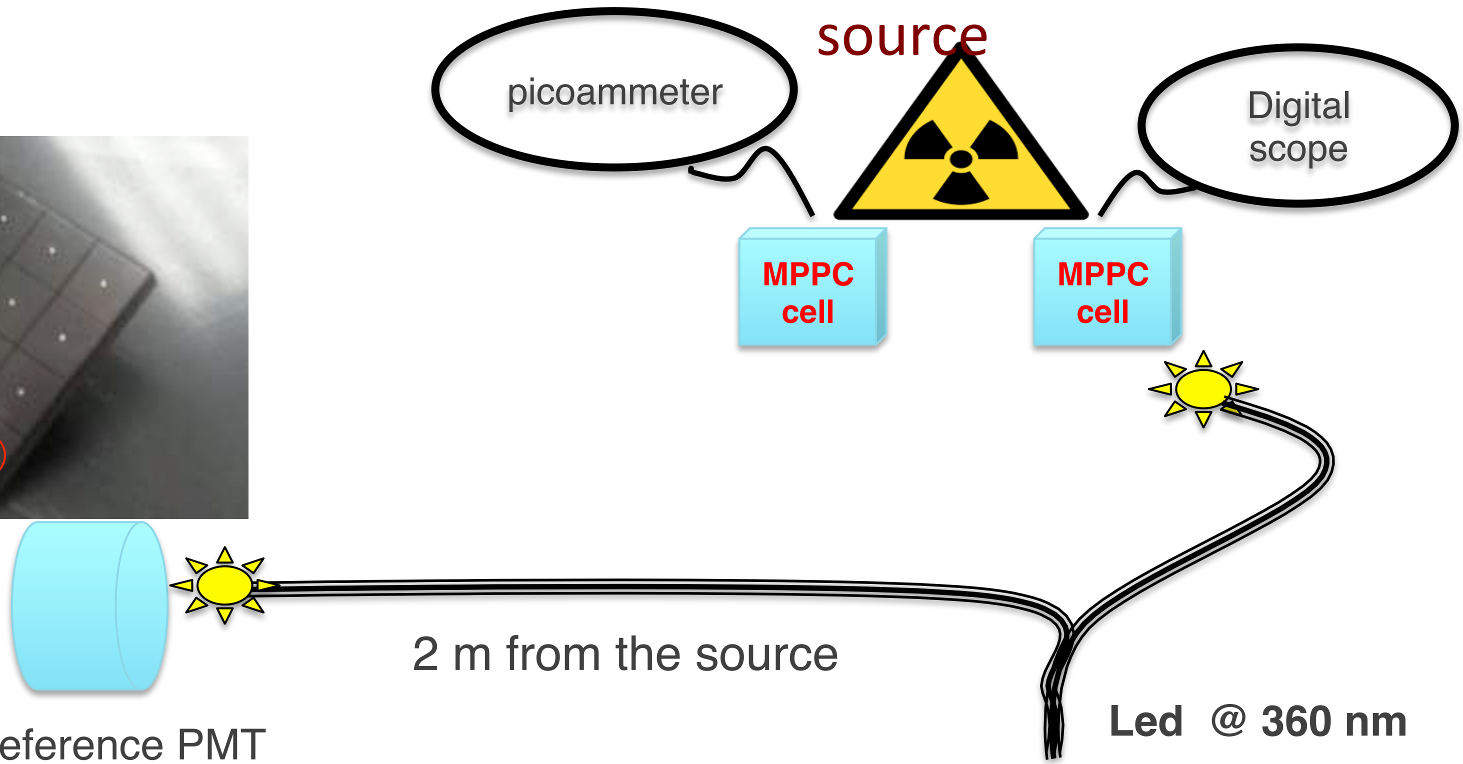
- We have tested the radiation response of the SPL and Thin Film MPPCs:

1) with neutron @ Frascati Neutron Generator (FNG)
2) with photons @ Enea Casaccia

→ *Measurement of response and leakage current*

→ *Also 6x6 mm^2 of UV extended SiPM from FBK have been tested with neutrons*

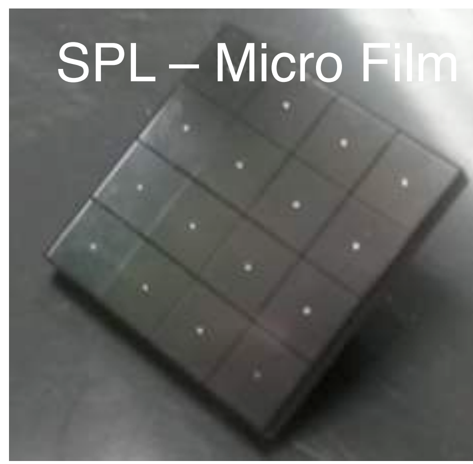




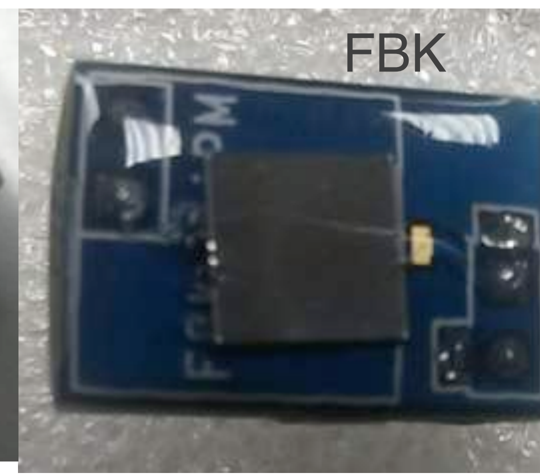
(R3) – Irradiation with neutrons (1)

- SiPM irradiated @ FNG (Frascati) with 14 MeV neutrons in October 2015.
- Total flux delivered in less than 4 hours
- Out of 16 MPPC cells:
  - --1 cell used for leakage current
  - -- Another cell used for response to a fixed UV LED pulse;
  - -- PMT used as reference for the light input.
- For the monolithic FBK we have measured only the leakage current

	V op (V)	Total flux (n/cm^2)	Total flux (n_1MeV/cm^2)
SPL 4 SiPM	53.9	2.2 x 10^{11}	4 x 10^{11}
Micro Film SiPM	53.95	2.2 x 10^{11}	4 x 10^{11}
FBK SiPM	32.5	2.2 x 10^{11}	4 x 10^{11}

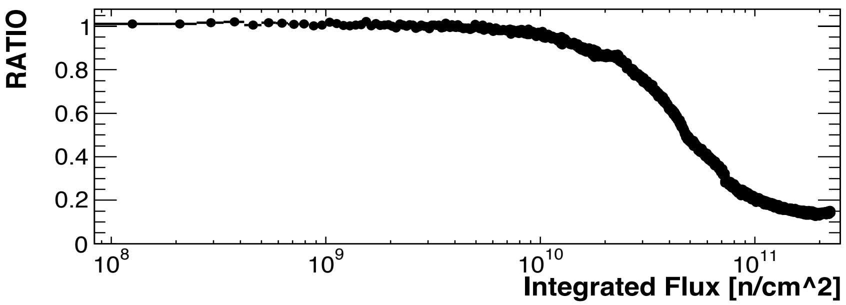


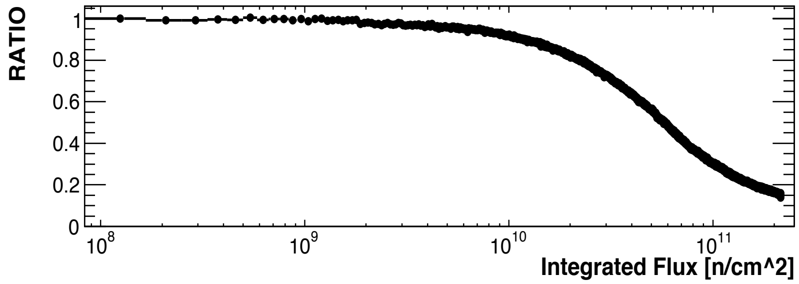
16 MPPC of 3x3 mm^2

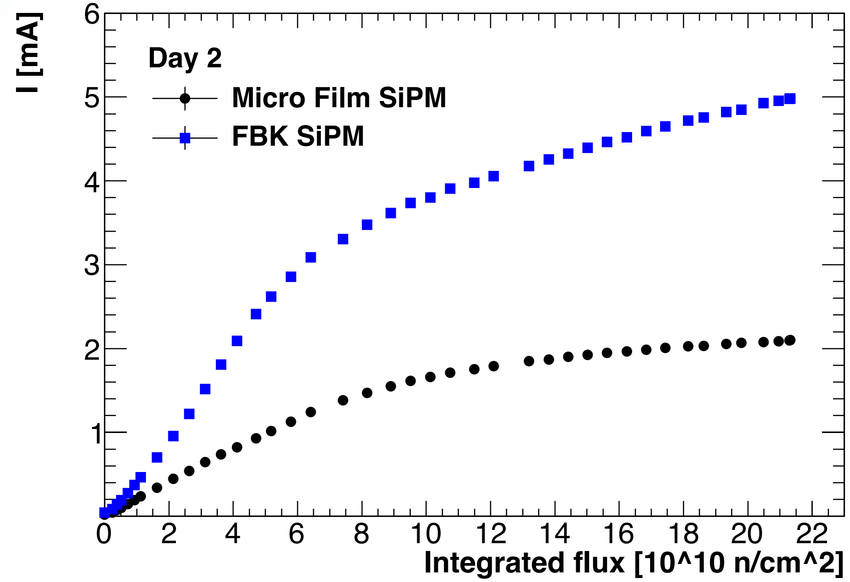


1 SiPM of 6x6 mm^2

(R3) – Irradiation with neutrons (2)







For a neutron fluence equivalent to 2.2 times the experiment lifetime, the signal peak decreases from:

- ~250 to 30 mV for SPL
- ~ 400 mV to 50 mV for TF

For the innermost layer a larger amplification value can be used (e.g. from 10 to 20)

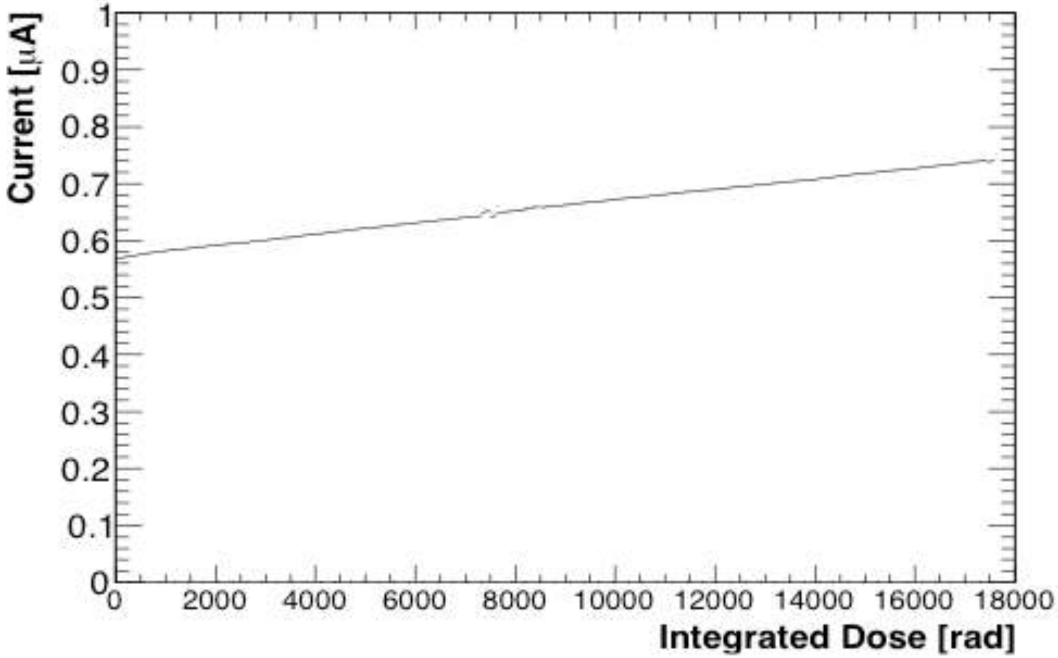
Reported current for FBK SiPM has been corrected by a factor of 4, due to the different active area.

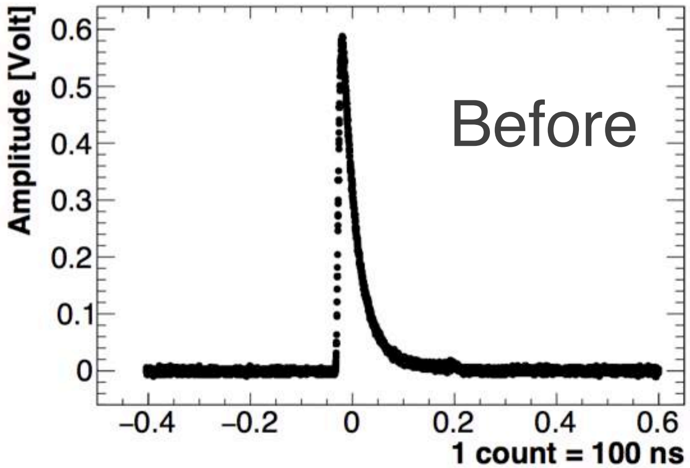
The current increased from

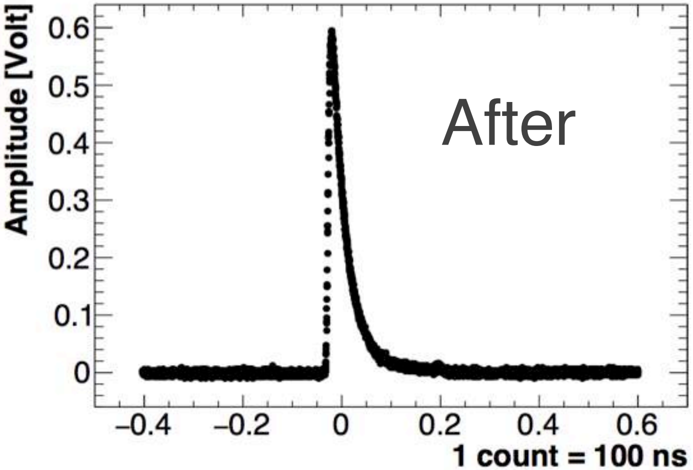
- **16 uA up to 2 mA (TF)**
- **100 uA up to 2.2 mA (SPL)**
- **86/4 uA up to 19/4 ~5 mA (FBK)**

(R3) – Irradiation with photons

We have irradiated the photosensor at ENEA Casaccia with an high intensity ^{60}Co source up to 20 krad (200 Gy)



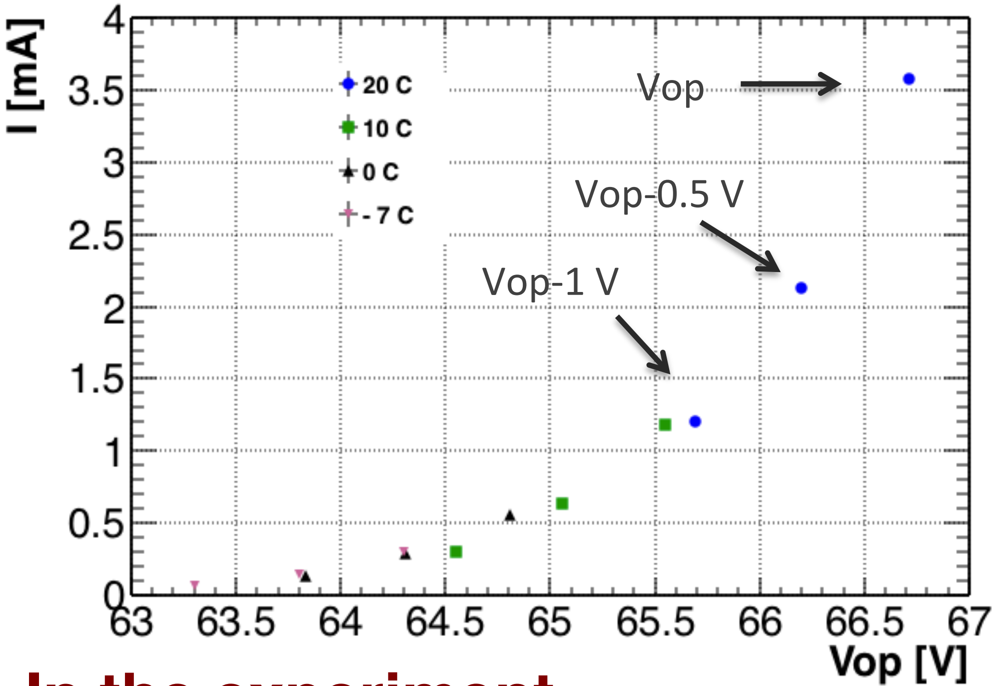




Negligible effect on the response and on the leakage current due to the dose

(R3) - Leakage Current vs Temperature and V_{bias}

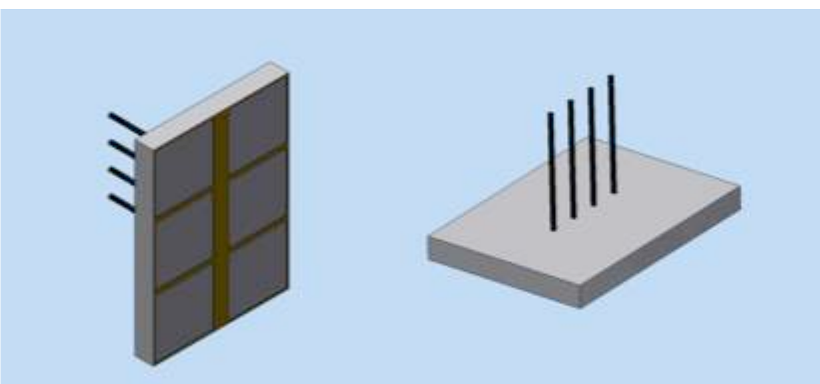
- We have measured the leakage current of the MPPCs changing the temperature and three different set of V_{bias}: Vop, Vop-0.5, Vop-1 Volt
- Measurement in Vacuum with micro TEC peltier and PT1000 sensor.
- The data are related to a single cell (6x6 mm^2).

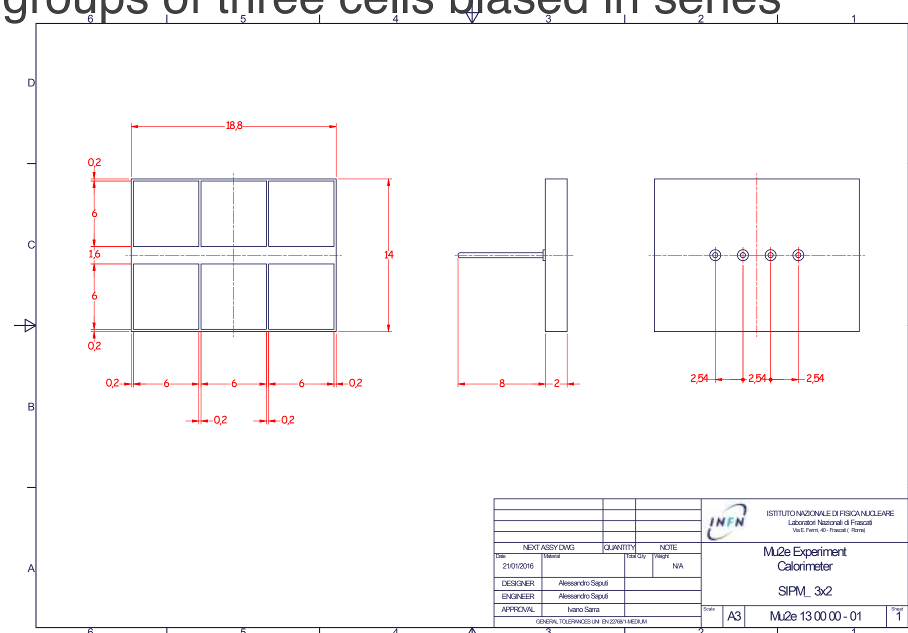


In the experiment, the Photosensors will be kept @ 0°C

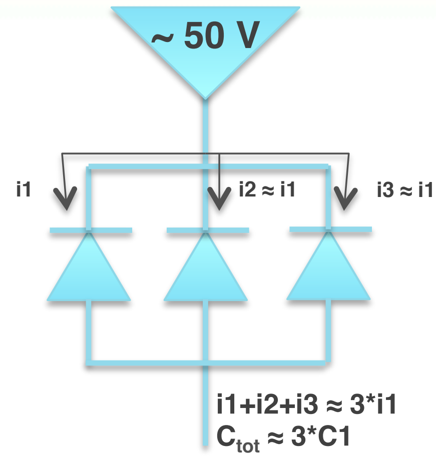
Mu2e Photosensor will be a custom SiPM

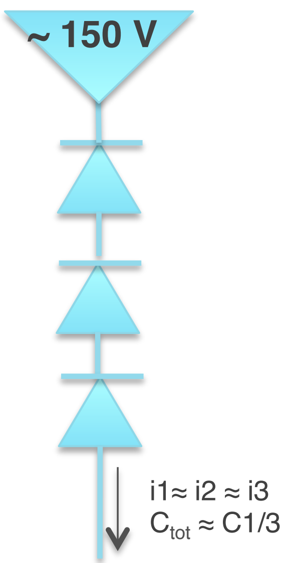
- We have chosen a modular SiPM layout that allows us to enlarge the active area, maximizing the number of collected photoelectrons.
- The crystal dimension, increased from 30x30 to 34x34 mm^2, accommodates a 2x3 array of individual 6x6 mm^2 SiPM modules
- This allows us to work use an air-gap while satisfying the p.e./MeV requirement with a single photosensor, although two are used for redundancy
- The SiPM will be made of a 2x3 matrix (6 cells) of 6x6 mm^2 UV extended SiPMs
- We use a parallel arrangement of two groups of three cells biased in series

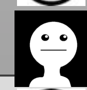




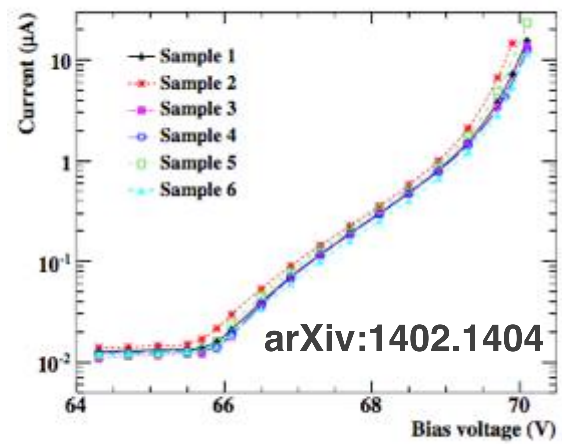
Series vs Parallel polarizations





	Parallel	Series
Total Bias (Volt)		
Total Current (A)		
Power (Watt)		
Total Capacitance		
Decay Time		

While the individual breakdown voltages differ by a few hundred millivolts, the shapes of the I-V curves are quite similar.



I-V characteristics of individual SiPMs

- Decay time can be regulated at the shaping level, but a high detector capacitance increases noise (worsens the signal-to-noise ratio)

- When SiPMs are connected in series, the voltage applied to each SiPM is determined by the common leakage current. Then, the difference in breakdown voltages is absorbed, and the over-voltages are approximately aligned.

2x3 SipM array performance

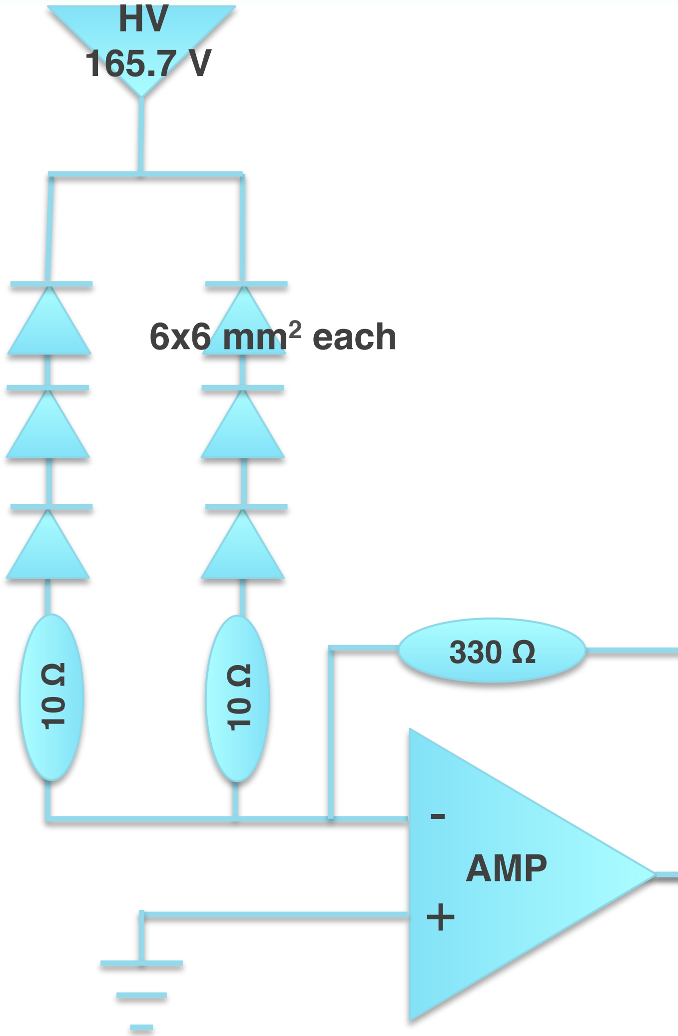
We have already received 7 monolithic MPPCs of 6x6 mm^2 dimensions
→ 6 of them have been used to build a 2x3 array with our packaging.
→ UV extended by SPL technique

Goal: Evaluate the quenching time, the equivalent capacitance, the gain and the PDE.

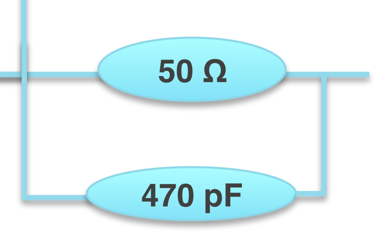
Specifications:

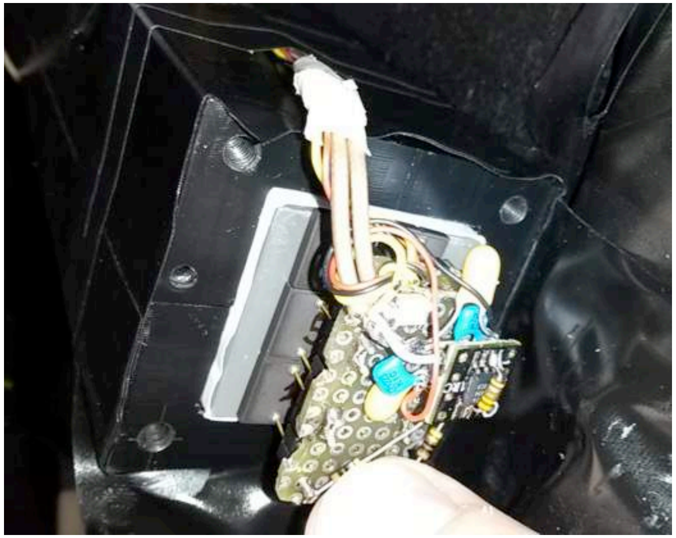
- PDE ~ 30% @ 315 nm;
- Gain > 10^6 at $V_{op} = V_{br} + 3V$
- the series connection of the three 6x6 mm^2 SiPMs should produce a signal width of about 70 ns ($\tau \sim 15$ ns) to minimize pileup

Polarization scheme



Amplifier used for test:
Gain ~ 16
BW 200 MHz

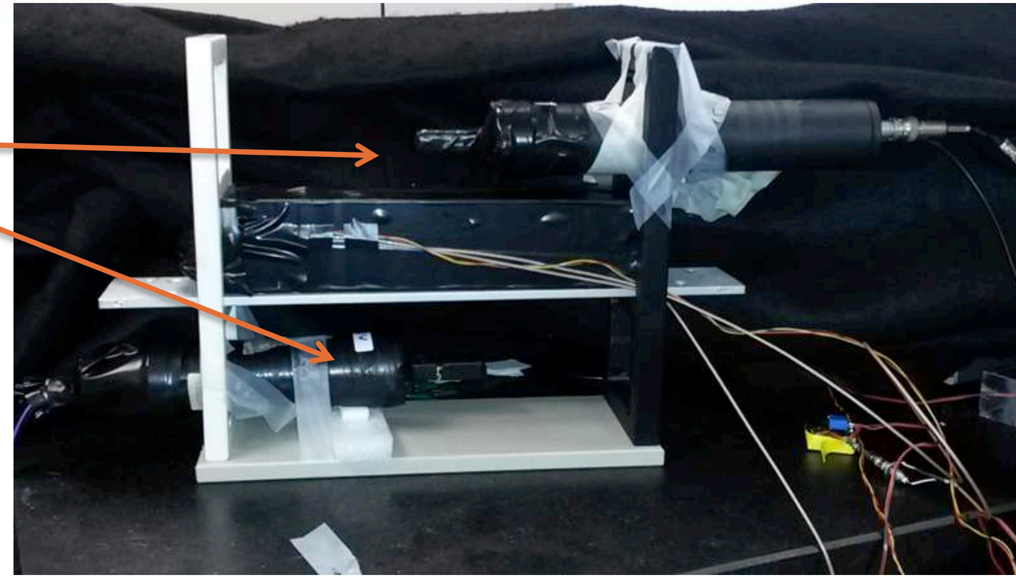




Experimental setup

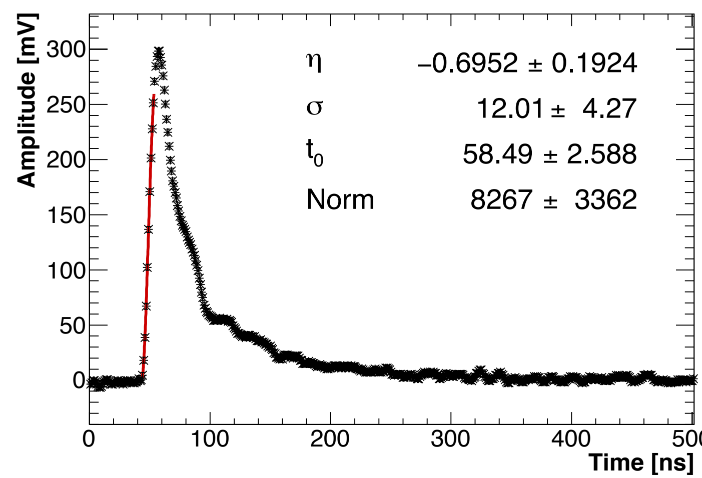
Crystal+SiPM sample between two plastic scintillation finger counters:

- TRG: counters coincidence
- Crystal wrapped with 150 μm Tyvek + coupled with air-gap to our 2x3 SiPM array

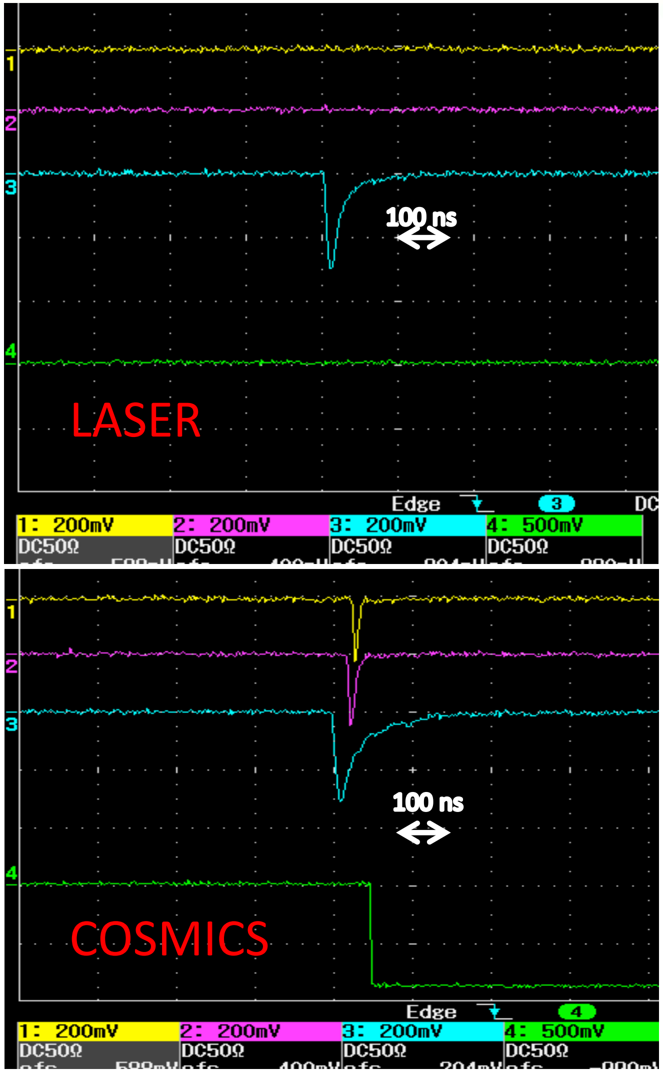


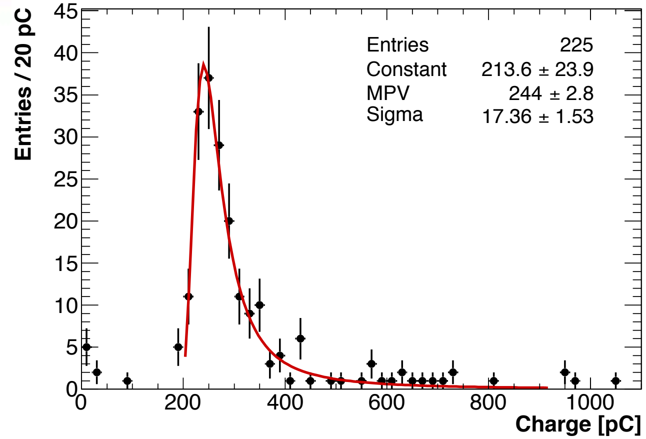
Analysis technique

- Fit function -> **logn**
- Fit range: **(5 – 85)%** of the max amplitude (leading edge)
- Constant fraction method: best threshold 20%



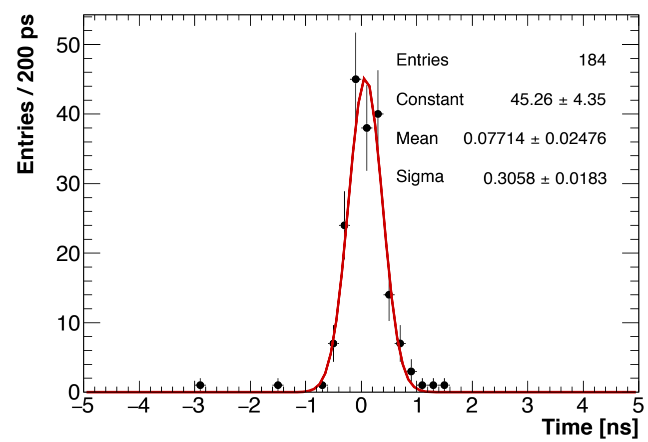
CR test of CsI+2x3 SiPM array





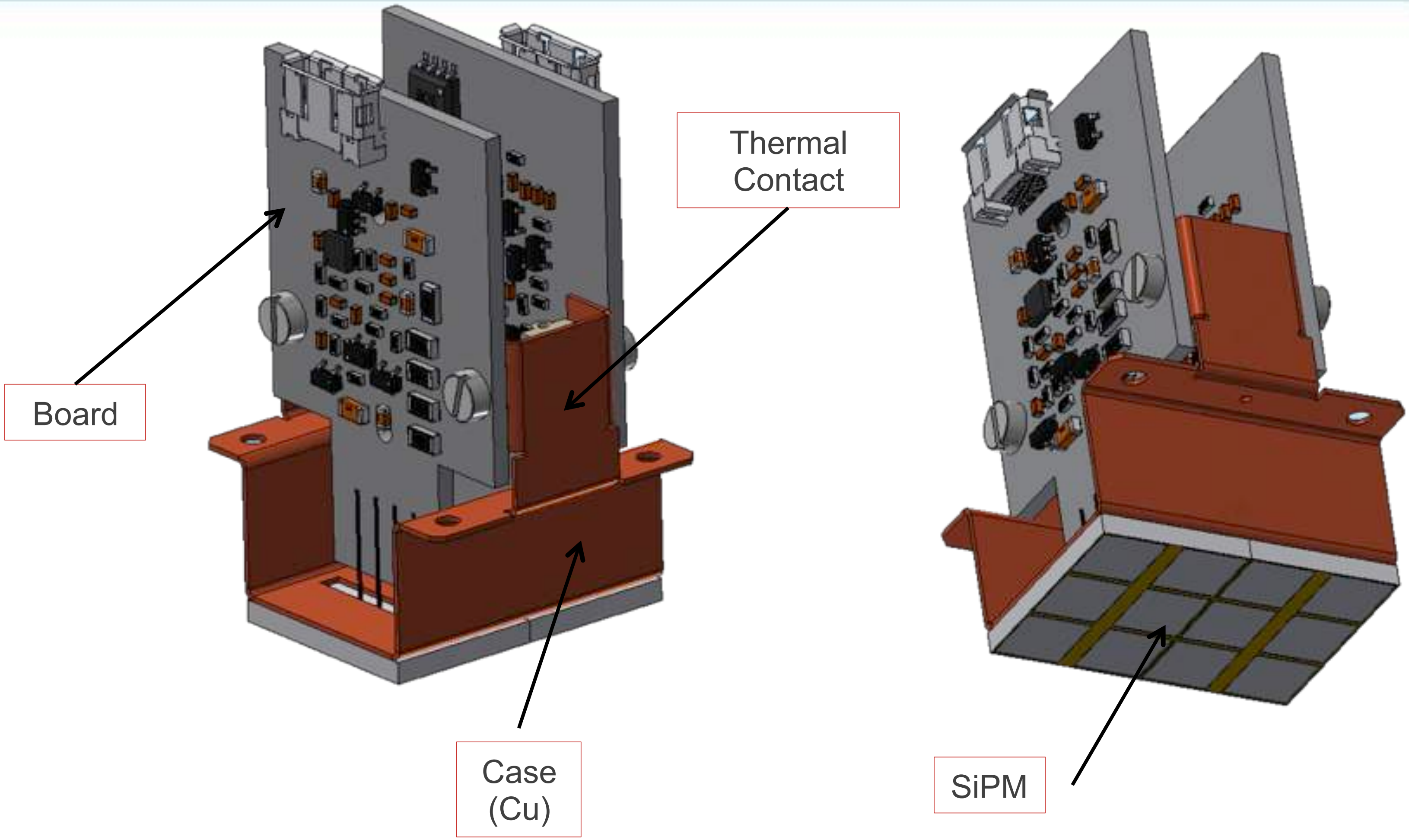
- Trigger Resolution (Δt_fingers) = 255 ps
- Final resolution for 1 MIP (~20 MeV) → ~ 170 ps

with 150 μm Tyvek wrapping and optical coupling in air



Engineering of the final packaging

SiPM Holder



Thermal conducting layer inserted in the SIPM package to cool them in vacuum (with/w.o. use of TEC Peltiers)

Summary

- The silicon photomultiplier well match the requirement as a good readout for the e.m. calorimeters
  - → caveat, keep the proportionality of the response (< 10-15% of the total pixels fired)
  - ❑ Excellent time resolution
- The MPPC radiation hardness to the neutrons flux and photons dose has been investigated
  - → keep the device at low temperature helps to mitigate the damage
- Three different firms appear to be capable of producing the Mu2e final SiPM thermal package (2x3 array of 6x6 mm^2 cells)
  - Hamamatsu, FBK and SensL

SPARES

(R3) - Derived FEE/Cooling requirements

Starting point: after 6 years of Running
We have measured, for a 3x3 mm^2 MPPC, a leakage current of 2.3 mA after a flux of 2.2×10^{11} n_14MeV/cm^2 (4×10^{11} n_1MeV/cm^2) @ 25°C

→ This corresponds to 9 mA for a 6x6 mm^2 MPPC @ 25°C
1) Assuming a factor 2 for annealing

→ 4.5 mA per a MPPC of 6x6 mm^2 @ 25°C (Vop)

for the proposed SiPM (matrix 2x3 of 6x6 mm^2) we expect:

→ 9 mA for the parallel of two series @ 25°C

2) We have measured a leakage current reduction of a factor 5 operating at 0°C

→ 9/5 = 1.8 mA for the device @ 0°C

3) we can take advantage of an additional factor of 2 if needed by lowering of 0.5 V the Vbias with respect to Vop (@ 0°C)

→ 1.8/2 = 1 mA @ 0°C

at the experiment end, we will get 1 mA with 200 V of bias, 200 mW @ 0°C , Vop-0.5 V for the innermost Layer of Disk 1→ 120 crystals → 240 photosensors

(R4) → Operation in vacuum

The working condition will be different working outside or inside the Detector Solenoid (DS):

- **Outside the DS:** we will run at ~ 20ºC, Vbias = Vop
- **Inside the DS:** we will run at ~ 0ºC, Vbias = Vop – temperature voltage coefficient

Each photosensor will be characterized with the QA Photosensor Station at 20, 10 and 0ºC→ We will know the working point for each running condition (for MPPC this corresponds to around 50 mV/ºC)

After the high radiation damage (> 2 years of run), we can still work outside the DS with an under bias setting. We will check the signal with the laser sending a x10 light output.

(R6) → Photosensor Reliability

- Determination of the MTTF requirements calculated with standalone simulation assuming independent behavior of 2 SiPMs/crystals.

- This estimate indicates the need of an MTTF of < 2 x 10^6 hours

- Existing measurement from literature indicates an MTTF for 3x3 mm^2 MPPCs of 4 x 10^6 hours when running at 25 ºC **(DOI 10.1109/NSSMIC.2013.6829584).**

- Working at 0 ºC, we gain a reliability factor of 11 so that this translates to an **MTTF of 44 x 10^6 hours**. Scaling down this result for SiPM area (x 4 i.e 6x6 vs 3x3) and number of SiPM in a Mu2e array (x 6), we have to correct by 24 → **MTTF(measured) ~ 1.8 x 10^6 hours**

- **An independent determination needed for final packaging.**
  First test underway: 4 6x6 mm^2 FBK SiPM in an oven at 50 ºC
  After 1 month of running, all 4 SiPM are still perfectly OK.

Quality Control

- QC: Silicon Photomultipliers array – Mu2e doc-DB-7053
- The firm has to deliver devices already tested and characterized, while providing us with the following parameters for each of the two series:
  - The value of the breakdown voltage, Vbr, and the corresponding operation voltage, V_{op}, that is around +3 V with respect to the breakdown voltage;
  - A spread on V_{op} of ± 250 mV among the different devices in the delivered batch;
  - A spread on V_{op} for the 2 series connection inside a device of ± 150 mV;
  - A gain greater than 10^6 at V_{op} with a spread of ± 5% among the different devices in the delivered batch;
  - A PDE in excess of 25% at 310 nm at V_{op};
  - Thermal conductivity of 20 W/(K*m);
  - Custom package according specification drawings.

Quality Assurance - 1 -

- QA: Quality Assurance Procedure – Mu2e doc-DB-7053
  - Each SiPM will be dimensionally inspected to grant that the package follows pins and planarity specifications. This will be done by inserting the SiPM in a reference holder and FEE pin socket.
  - A small number of SiPM (ten) will be randomly selected for MTTF measurement. They will be operated at V_{op} in a dedicated oven at high temperature, 55°C, while illuminated with a UV LED light. When operating the SiPM at 55°C, the acceleration factor is 90, so that, with ten devices, we can extract the MTTF in around 3 months of burn-in.
  - Another small number of SiPM (five), randomly selected from the batch, will be used for radiation hardness test both with gammas and neutrons. Two of these devices will be irradiated at two different doses, 10 and 20 krad to confirm that ionization dose does not provide increase in Idark or reduction of gain. These two devices can be still recovered as spare for the detector. The other three devices will be instead exposed to a neutron fluency of 3×10^{11} n/cm^2 (1 MeV equivalent) while kept at a thermalized temperature of 18°C. The increase of I_{dark} and the gain drop will be measured.

Quality Assurance - 2 -

- QA: Quality Assurance Procedure – Mu2e doc-DB-7053
  - The other 185 pieces/batch will be controlled at dedicated QA photosensor stations (one in Caltech and one in Pisa). Sharing of the load for the quality control will be 50-50 between the two stations. In these stations, we will measure, for each SiPM, at 0, 10 and 20°C: the I-V curve, the V_{br}, the gain and the relative PDE with respect to a calibrated photo-sensor.

<u>Configuration Management:</u>

- Use labels with barcodes for strips and test samples
- Correlate labels with QC/QA and shipping data
- Enter data into a traveler database