Mu2e Photosensors

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on behalf of the calorimeter group

Pisa – MUSE General Meeting
September 28, 2016

- ***SiPM for the Mu2e calorimeter***
  - → ***Results achieved so far***
  - → ***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

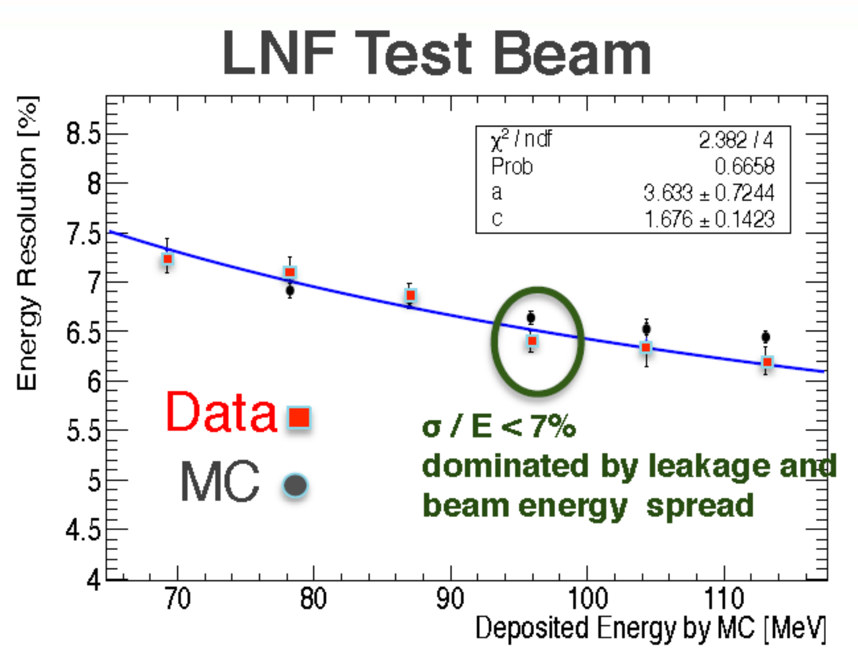
Results

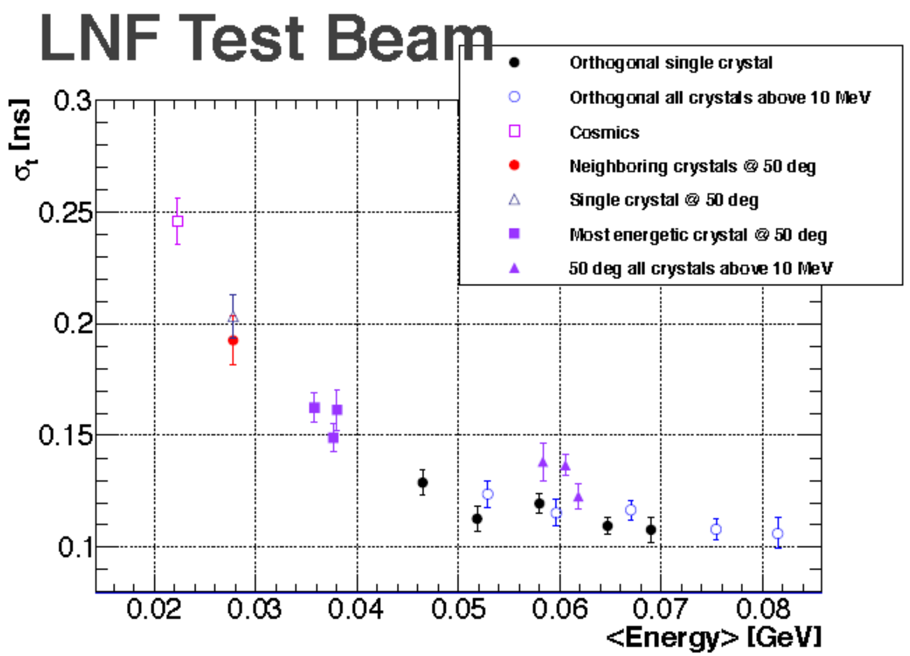
→ ~ 30 (20) p.e/MeV with (without) optical grease with Tyvek-wrapped crystals

→ Time resolution < 150 ps @ 100 MeV with 45º e^- impact angle

→ Energy resolution better than 7% at 100 MeV (leakage dominated)

→ Equivalent noise ~ 100 keV



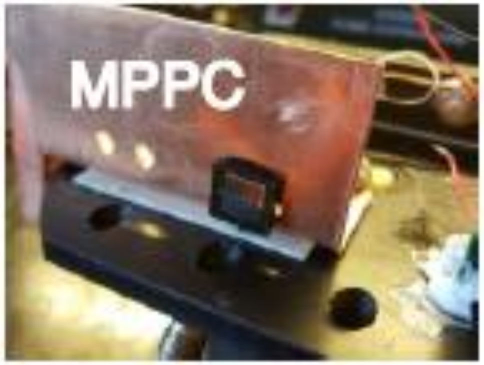


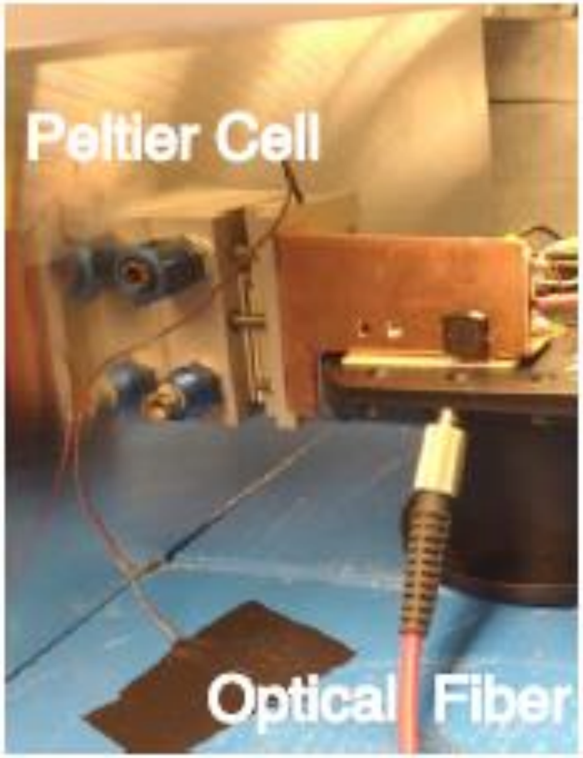
Irradiation with neutrons

- We have irradiated a monolithic MPPC of area 6x6 mm^2 SPL with ceramic package with ~ 1MeV neutrons @ HZDR of Dresden

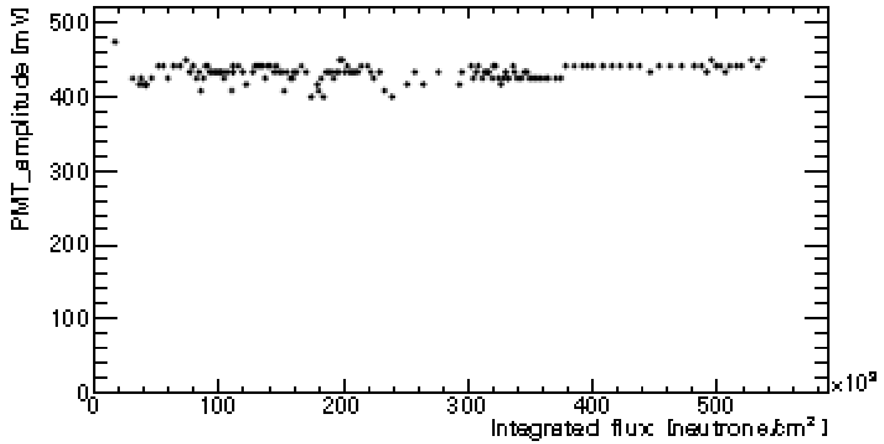
✓ We have measured the leakage current and the response to a UV led at the same time

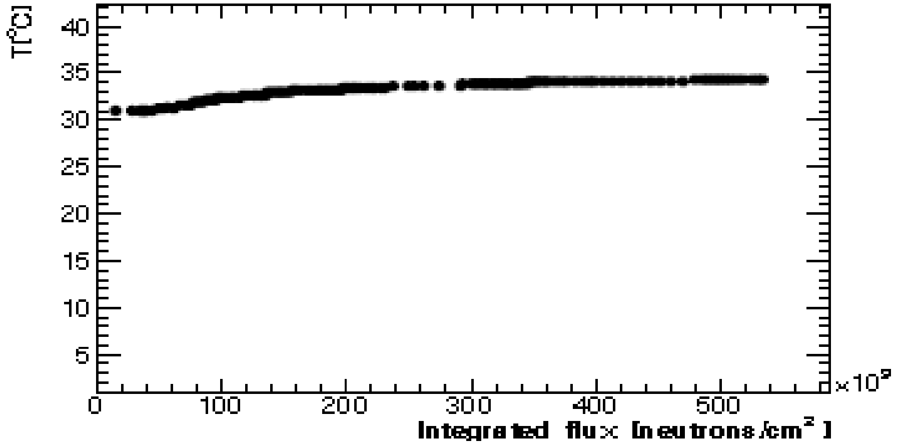
✓ Temperature kept stable using a Peltier cell and measured with a PT1000



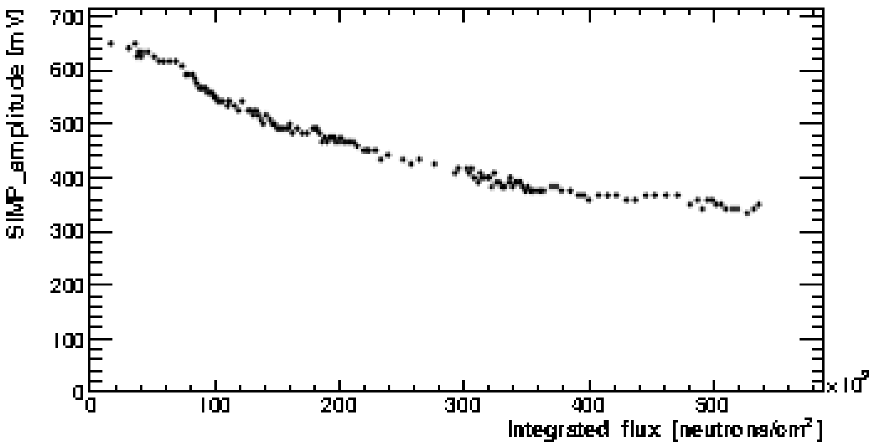


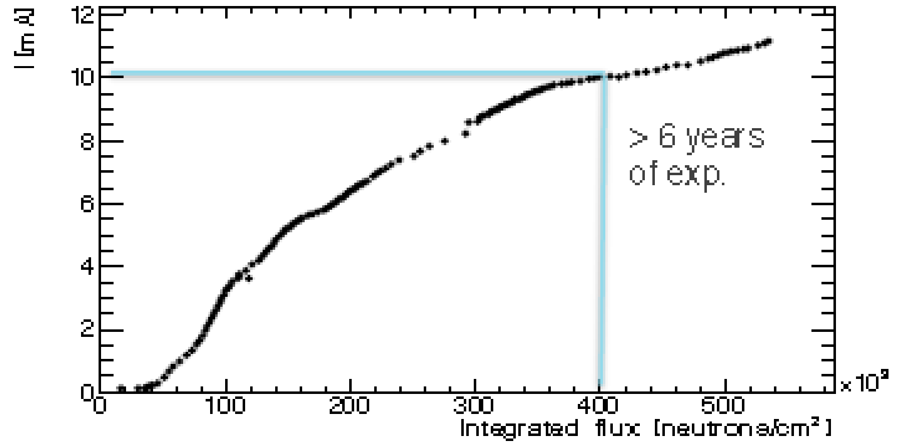
Irradiation with neutrons (2)





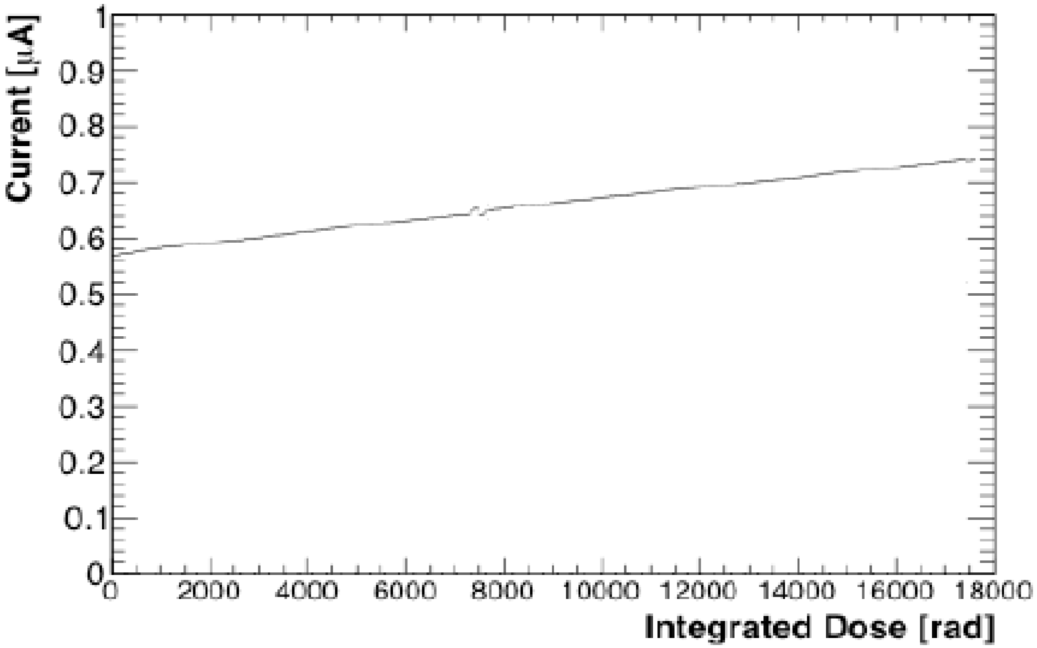
- ✓ The leakage current increases from 60 uA up to 12 mA
- ✓ The response decreases of about a factor 2

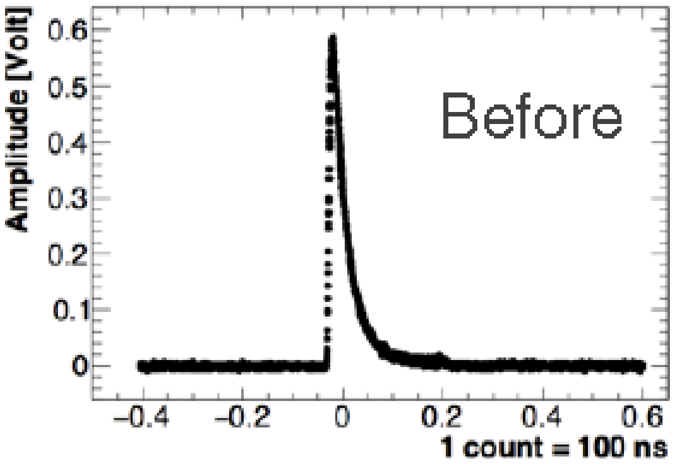


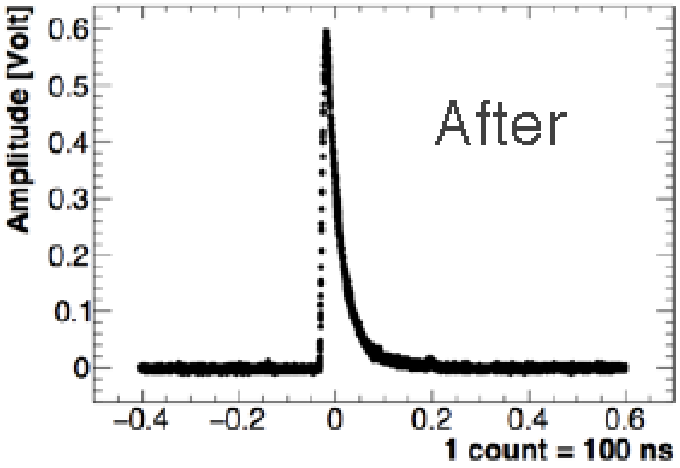


Irradiation with photons

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



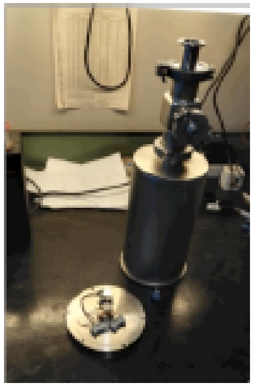


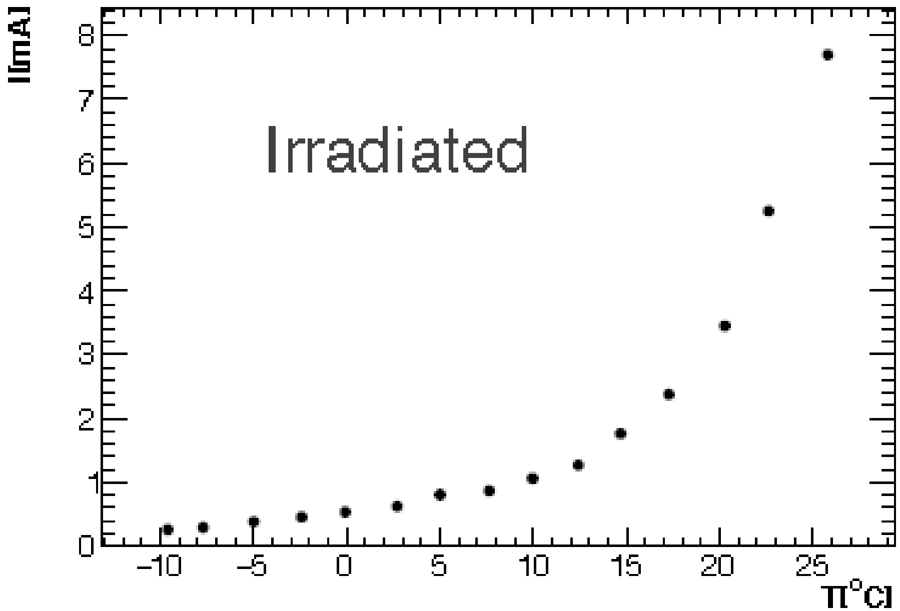


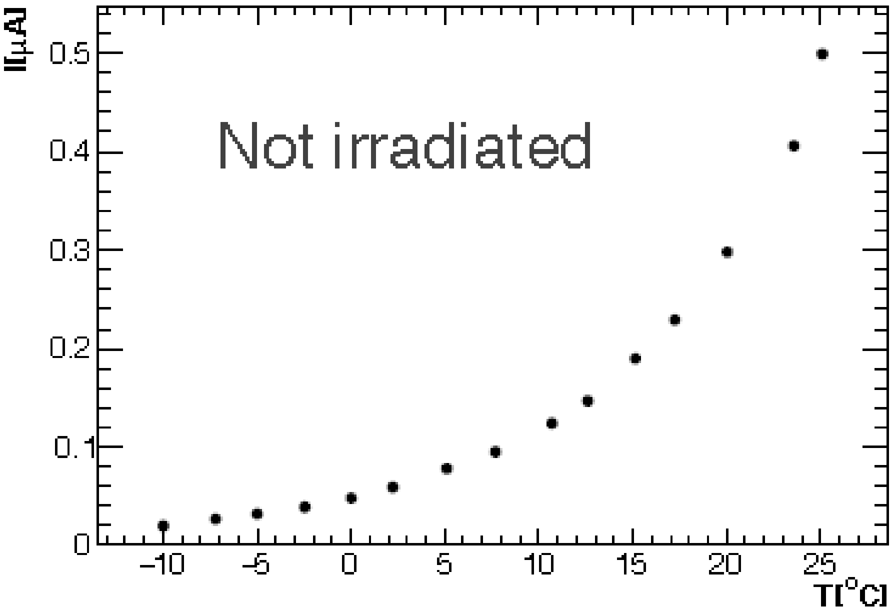
Negligible effect on the response and on the leakage current due to the dose

Leakage current vs Temperature

- We have measured the leakage current for the irradiated MPPC changing the temperature.
- The comparison with a not irradiated MPPC is also shown.
- Measurement in Vacuum with micro TEC peltier and PT100 sensor.

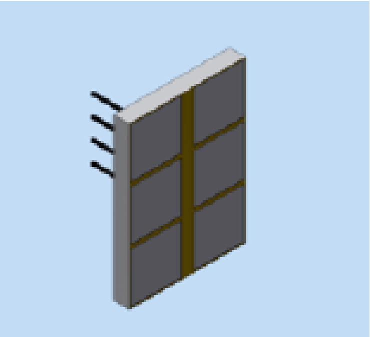




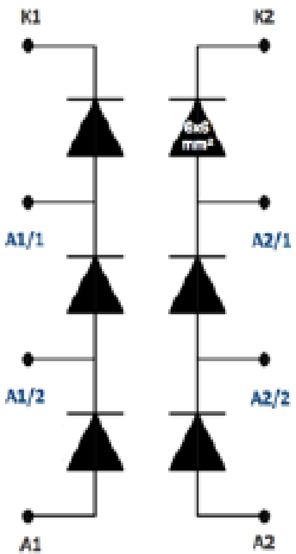


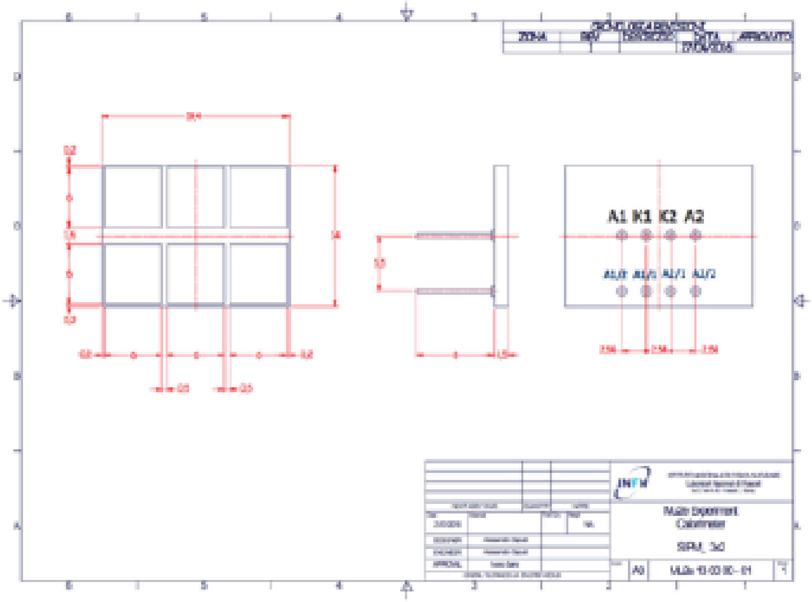
Mu2e Photosensor will be a custom SiPM

- 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, can accommodate a 2x3 array of individual 6x6 mm^2 monolithic UV extended SiPM's



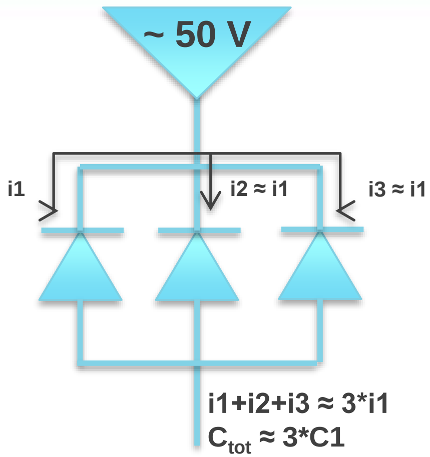
- **This layout allows us to use an air-gap while satisfying the p.e./MeV requirement with a single photosensor. Two SiPMs/crystal are used for redundancy.**





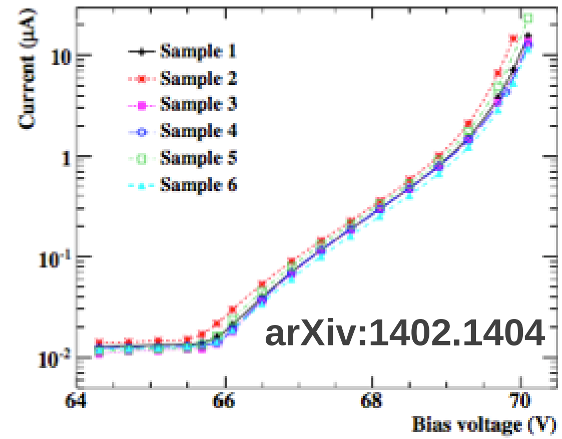
✓ We will read out the sum of the two series. Each series will be powered with an independent bias voltage (if needed).

Series vs Parallel polarizations

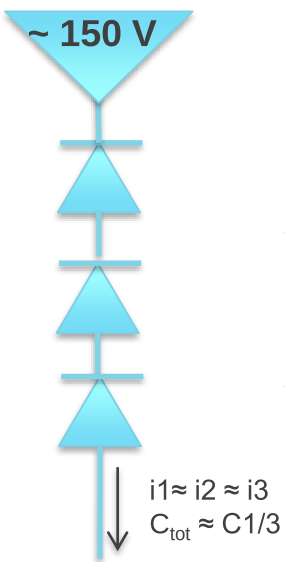


While the individual breakdown voltages differ by a few hundred millivolts, the shapes of the I-V curves are quite similar.

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



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

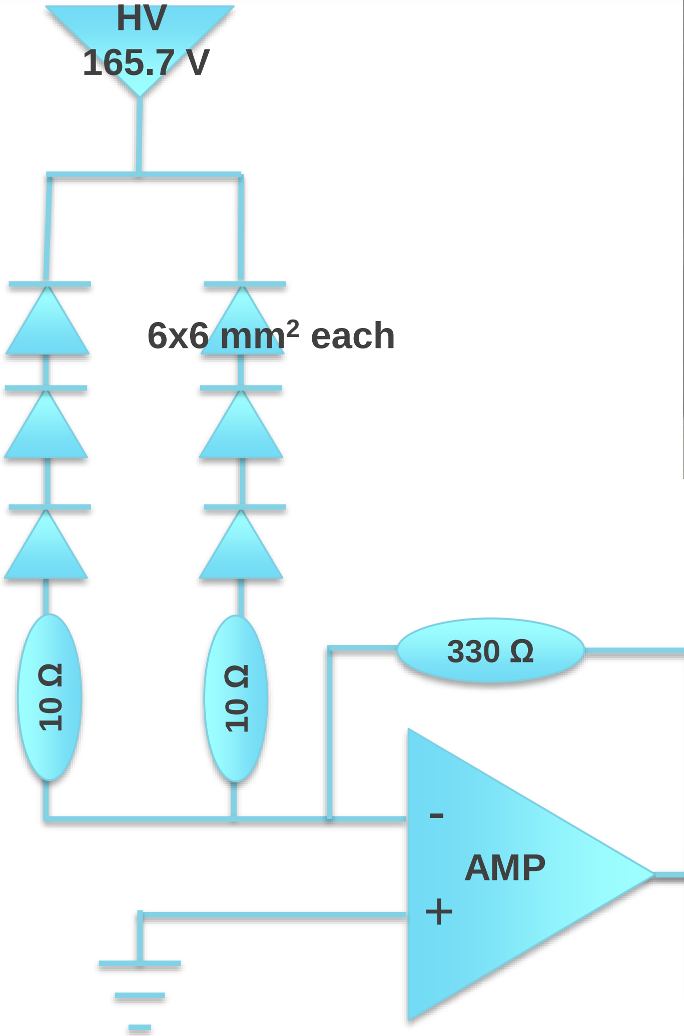
We have already received 7 monolithic SPL MPPCs of 6x6 mm^2 dimensions by Hamamatsu:

→ 1 of them has been used for the radiation hardness tests;
→ 6 of them have been used to build a 2x3 array with our packaging;
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 (τ ~ 15 ns) to minimize pileup

→ The 6 pieces have been used to measure the characteristics to design the Photosensors Test Station.

Polarization scheme

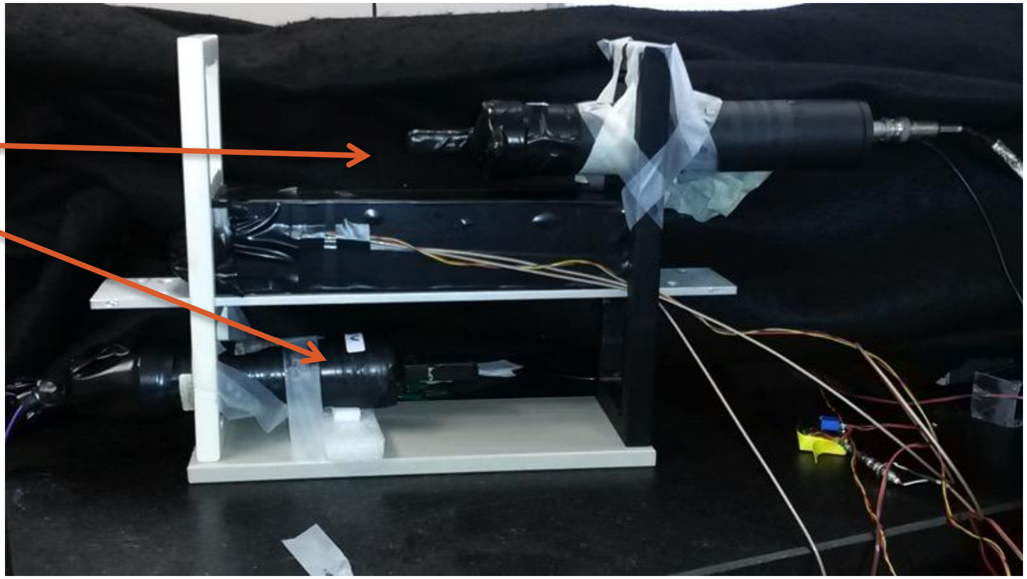


Amplifier used for test:
Gain ~ 16
BW 200 MHz

Experimental setup

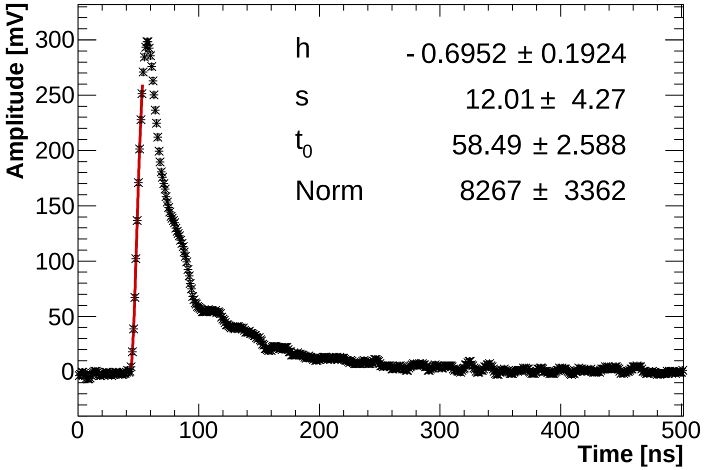
Crystal+SiPM sample between two plastic scintillation finger counters:

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

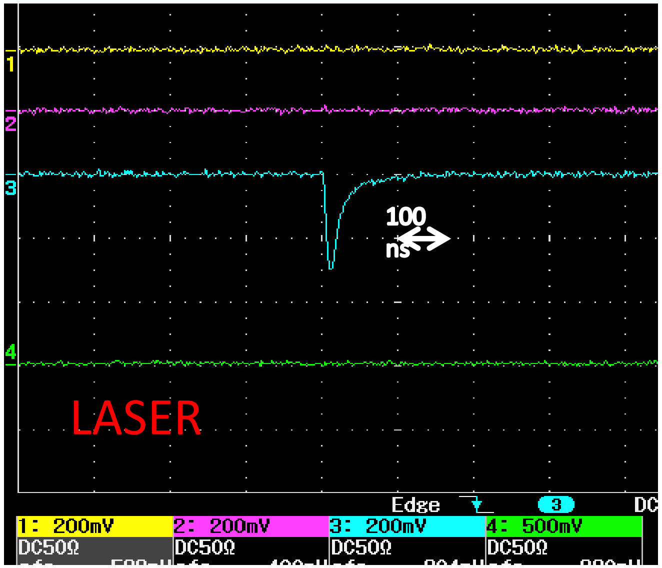


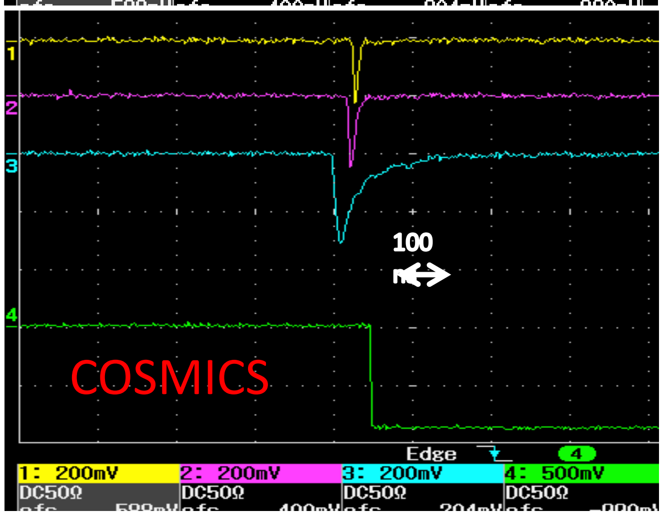
Analysis technique

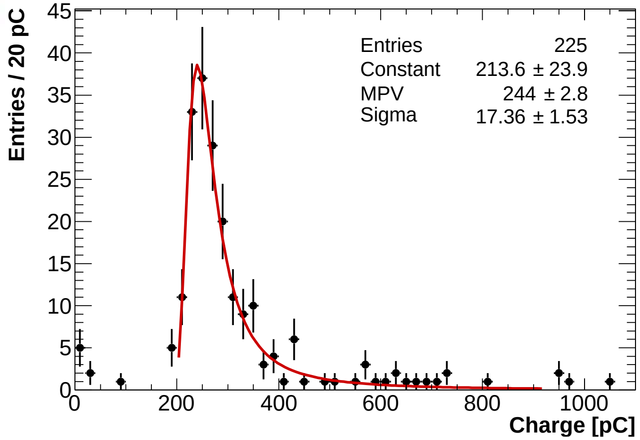
- Fit function -> **logn**
- Fit range: **(5 – 85)%** of the max amplitude (leading edge)
- Constant fraction method: best threshold 20%



CR test of CsI+2x3 SiPM array

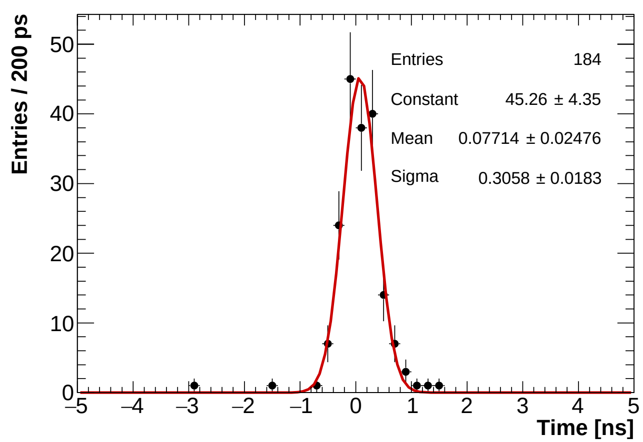






- Trigger Resolution (Δt_fingers) = 255 ps
- Final resolution for 1 MIP (~20 MeV) → ~ 170 ps

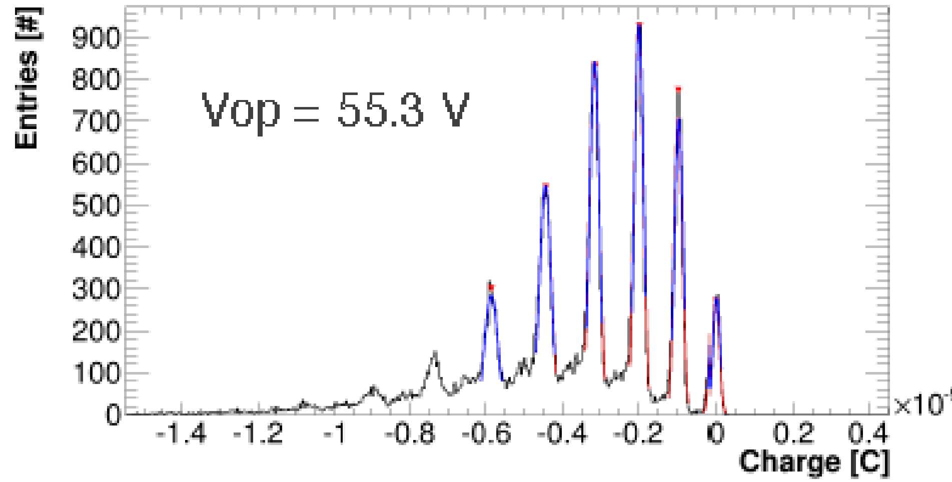
with 150 μm Tyvek wrapping and optical coupling in air

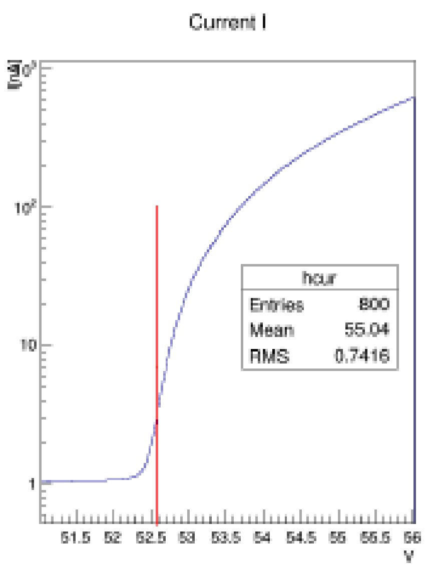


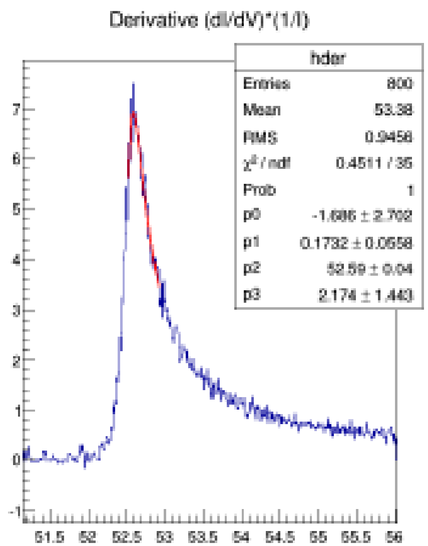
Measurements of the characteristics

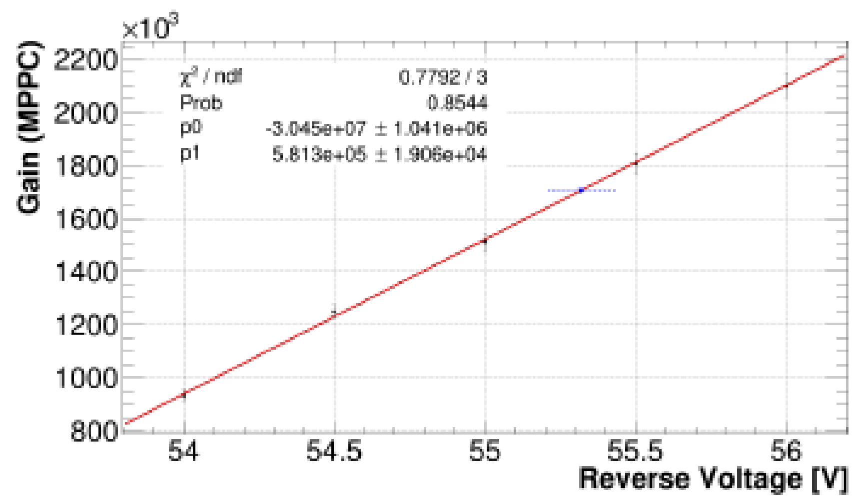
We measure the I-V characteristic, the Vbr and Gain:

- ✓ Excellent results in good agreement with the Hamamatsu specifications → i.e. Sipm n.6

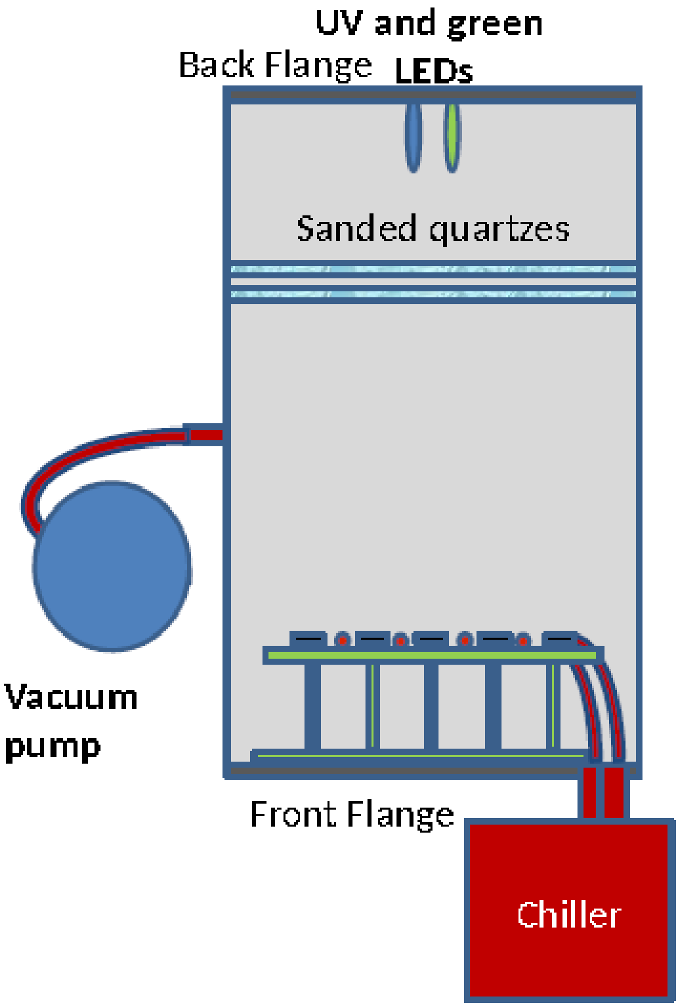








Test Station Overview



What to test:

At 0° , 10° e 20° in a mild vacuum (10^{-1} Torr):

- Dark current I(V) curve for the single sensors and for the series
  - -> $V_{breakdown}$
  - -> $V_{OP} = V_{breakdown} + 3V$
- Output current $I@V_{OP}$ a response to a calibrated light source (UV and green led)
  - -> relative Gain x PDE with respect to a calibrated SiPM

Summary

- **The current design exceeds the calorimeter detector requirements.** We will use two photosensors per crystal for redundancy, but we can still satisfy the requirements with one single sensor.

- Three different firms are capable of producing our final SiPM package (2x3 array of 6x6 mm^2 cells)

  → Hamamatsu, FBK and SensL

✓ **Delivery of the 150 prototypes expected for the October 10th.**

→ The QA station will be ready in time with the schedule

→ MTTF measurements will be shared between Frascati and Caltech

→ The new irradiation campaigns must be scheduled asap.

SPARES

Photosensors Test Station

We measure the I-V characteristic, the Vbr and Gain:

(R3) - Derived FEE/Cooling requirements

Starting point: after 6 years of Running
Simulated flux of 4×10^{11} n_1MeV/cm^2 @ 25ºC

→ This corresponds to ~10 mA for a 6x6 mm^2 MPPC @ 25ºC
1) A factor of 2 for annealing assumed.

→ 5 mA per a MPPC of 6x6 mm^2 @ 25ºC (Vop)

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

→ ~ 5 mA for each series @ 25ºC

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

→ 5/5 = 1 mA for each series @ 0ºC

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 (@ 0ºC)

→ 1/2 = 0.5 mA @ 0ºC

at the end of Mu2e life, we will get ~ 1 mA with 200 V of bias, 200 mW @ **0 ºC**
for the innermost Layer of Disk 1→ 120 crystals → 240 photosensors → 480 series

(R4) → Operation in vacuum

The calorimeter working condition will be different depending upon being 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 at the QA Photosensor Station at temperatures of 20, 10 and 0 ºC→ 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 at 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 has been calculated with a standalone simulation assuming independent behavior of 2 SiPMs/crystals.

- This estimate indicates the need of an MTTF for a 2x3 array of < 2 x 10^6 hours

- Existing measurement from literature indicates an MTTF of 4 x 10^6 hours for 3x3 mm^2 MPPCs when running @ 25 ° C **(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 the SiPM area ratio (x 4 i.e 6x6 vs 3x3) and the 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 55 ºC After 2 months of running, all 4 SiPMs are still perfectly working.

  This corresponds to a measured MTTF of < 0.5 x N_SIPM x Af x Nhours
  ➔ **2 x 88 x 1300 hours → 0.2 x 10^6 hours**

Quality Control of pre-production

- 50 devices from each firm will be delivered;
- The firm has to deliver devices already tested and characterized, while providing us with the following parameters for each SiPM 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 ± 0.5% among the different SiPMs in the device;
  - A spread on Idark of ± 15% among the different SiPMs in the device @ Vop.
  - A gain greater than 10^6 at V_{op} with a spread of ± 5% among the different SiPM in the same device;
  - A PDE in excess of 20% at 310 nm at V_{op};
  - Thermal resistance for the device below $7x10^{-4}$ m^2K/W
  - Custom package according specification drawings.

Quality Assurance of the pre-production

- 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. → ***LNF***

- ***10 SIPMs*** for each firm 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 2.5 months of burn-in. → ***LNF and Caltech***

- ***5 SIPMs*** for each firm 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. The other three devices will be instead exposed to a neutron fluency of $3x10^{11}$ 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. → ***LNF***

Quality Assurance - 2 -

- 35 SiPMs for each firm will be controlled at dedicated QA photosensor station. 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. → ***Pisa***
- **These 105 SiPMs will be used in the module 0**

<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