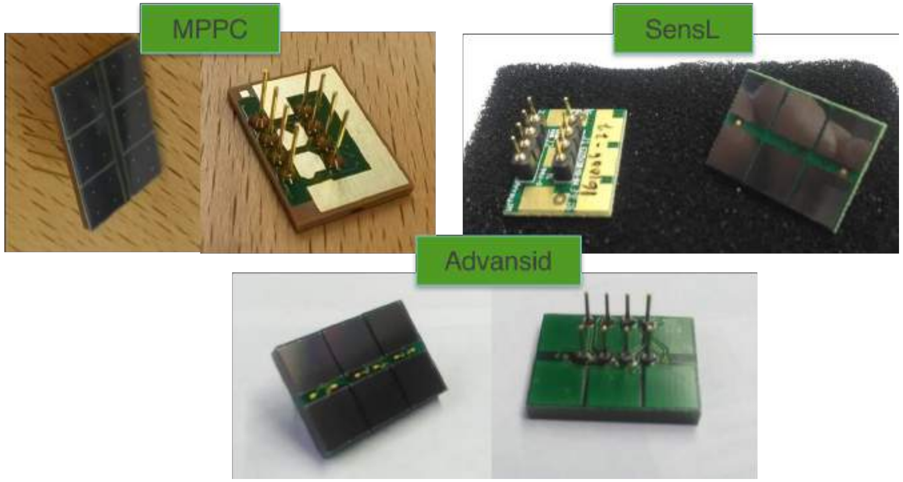

Use of the SiPMs for the Mu2e e.m. calorimeter

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Universita' degli Studi Guglielmo Marconi
Laboratori Nazionali di Frascati

MUSE outreach program for University students
University of Rome "Tor Vergata", 15 May 2017

Talk Layout

- ***Silicon Photo Multiplier***
  - ***→ Introduction***

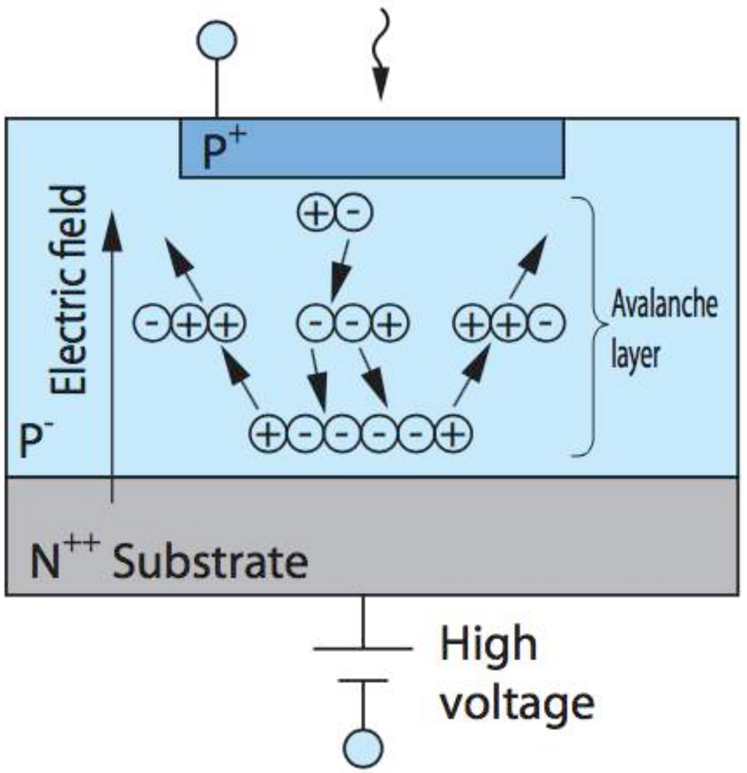
- SiPMs for the Mu2e calorimeter
  - → A Custom Layout

- An international Bid
  - → Measurements performed

A step back: APD

In the beginning there was the APD:
A photodiode with a high depleted region:

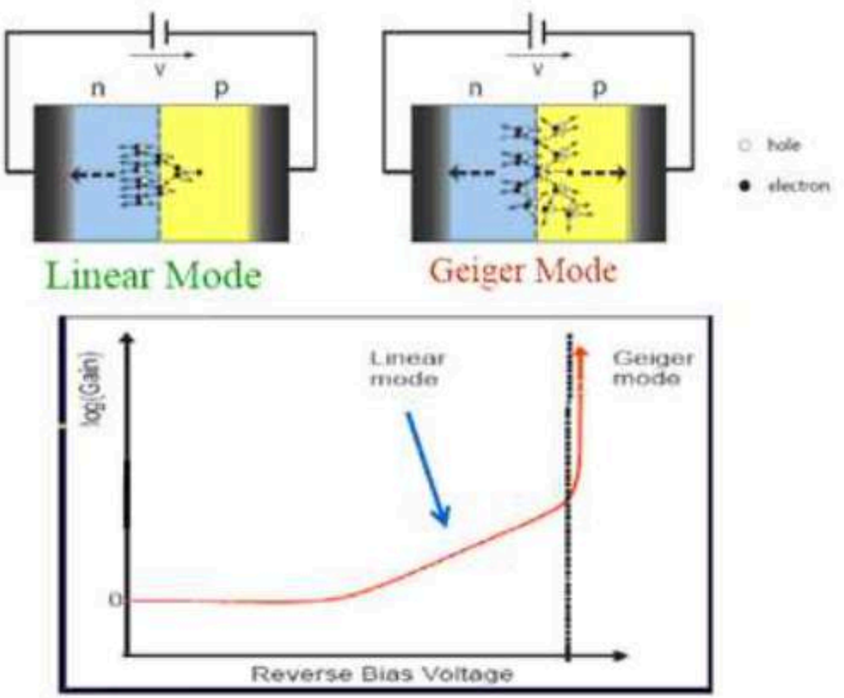
1. A photon absorbed in the depletion region produces a new electron-hole pair;
2. The electron-hole pair is accelerated by the high electric field generating further electron-hole pairs;
3. An Avalanche multiplication happens with a Gain proportional to the applied reverse bias voltage
(Gain ~100-500).



Then: the SiPM

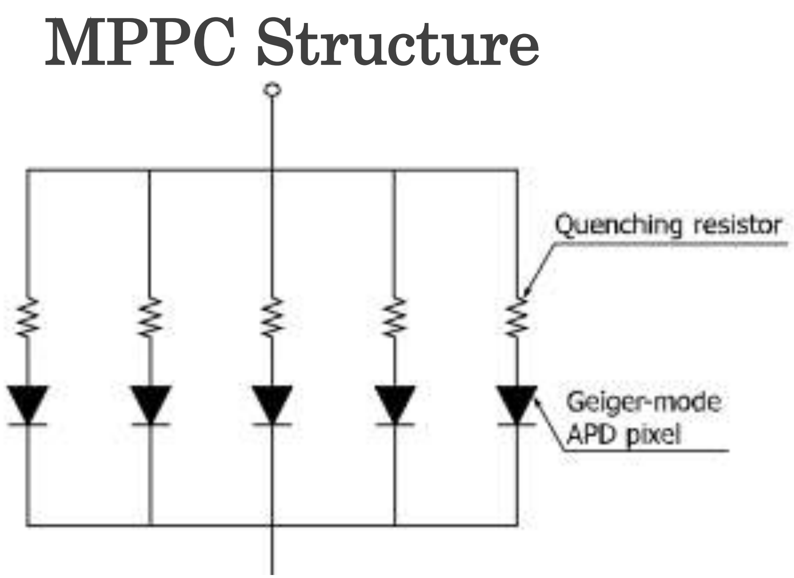
When the reverse voltage applied to an APD is **set higher than the breakdown voltage**, the electric field in the APD becomes high enough to cause a discharge (Geiger discharge) even by input of one single photon.

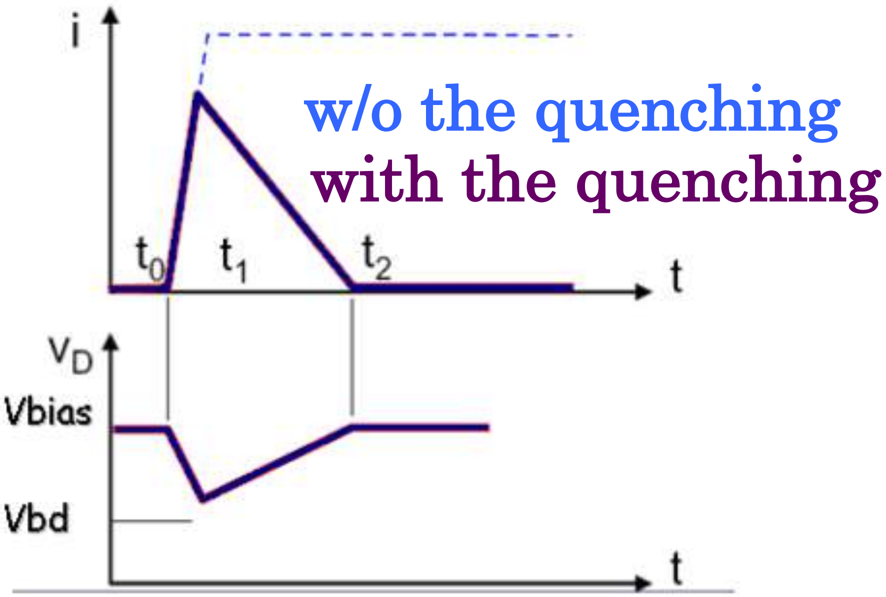
- The Geiger mode allows obtaining a large output by way of the discharge even when detecting a single photon. Once the Geiger discharge begins, it continues as long as the electric field in the APD is maintained.



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.**

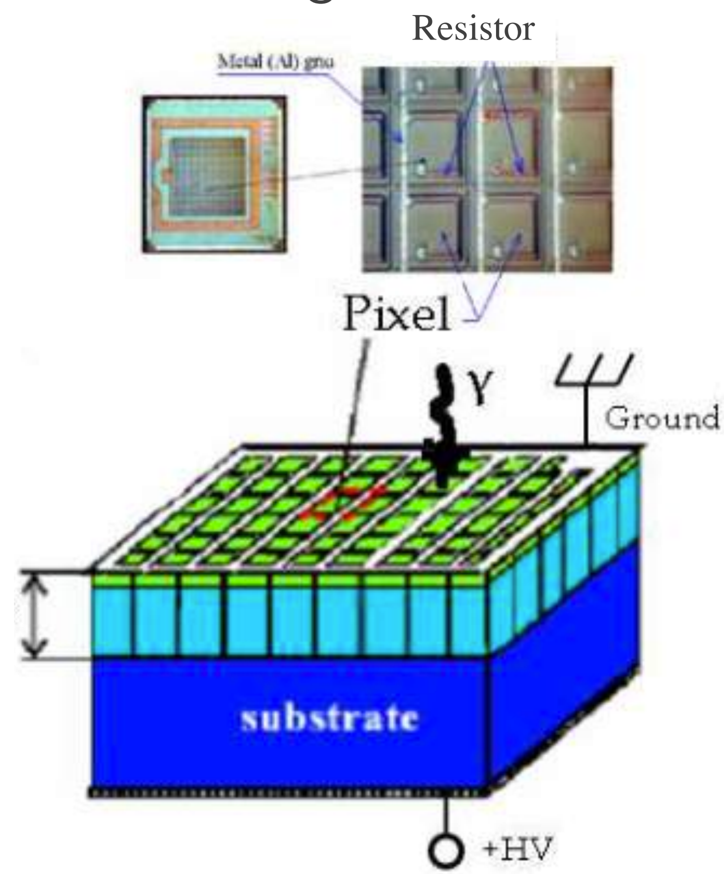




A parallel combination of many pixels

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 array;

- Each pixel in the MPPC (multi-pixel photon counter) generates a pulse of 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.



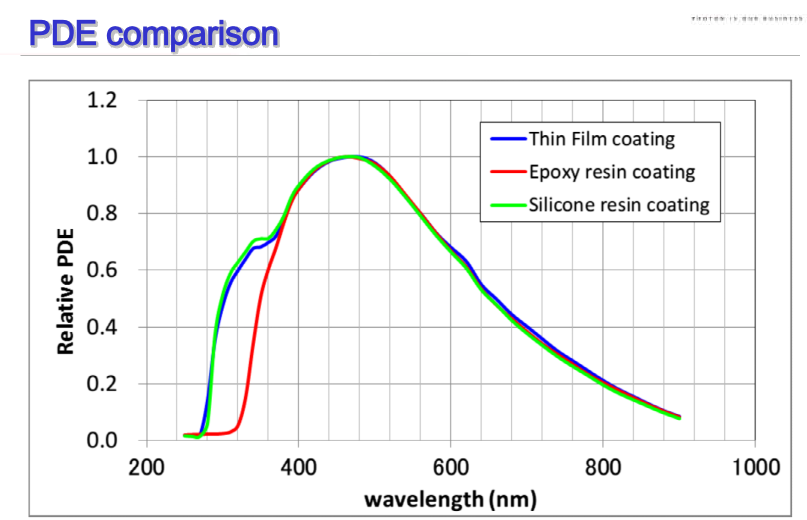
PDE

The photon detection efficiency is the product of 3 components:

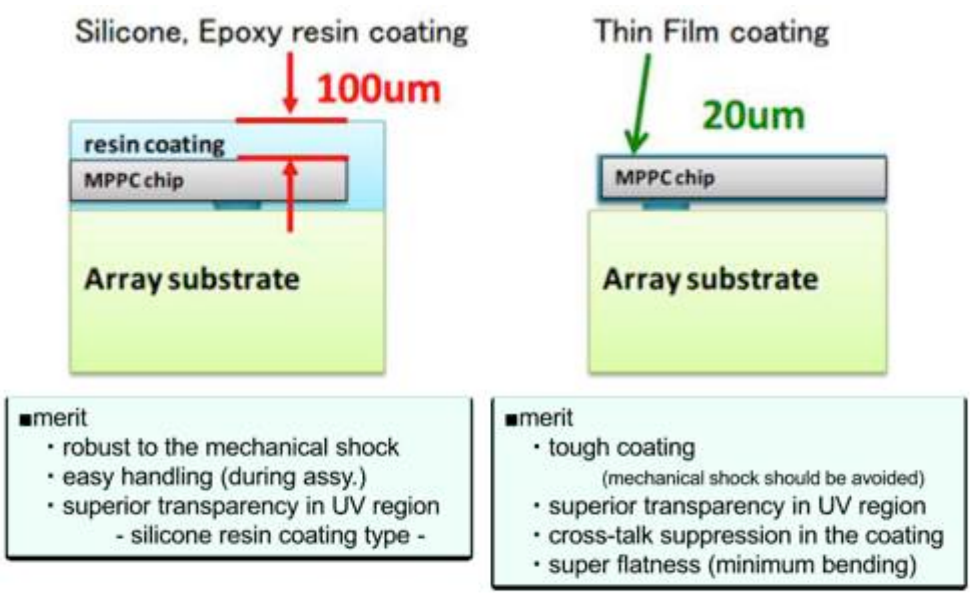
1) The quantum efficiency @ the silicon surface

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})



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



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
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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;

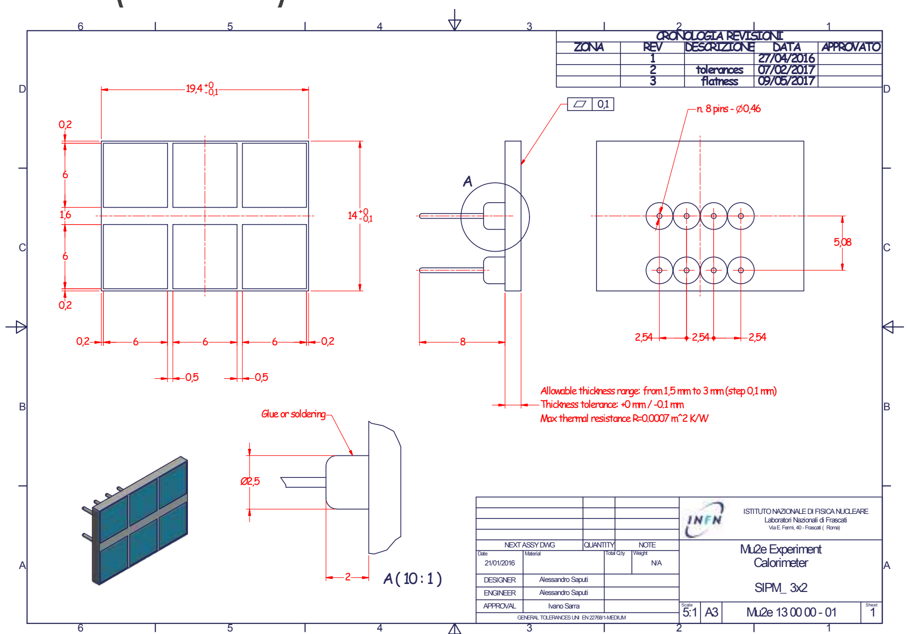
(R5) Have sufficient reliability to allow operation for 1 year w.o. interruption;

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

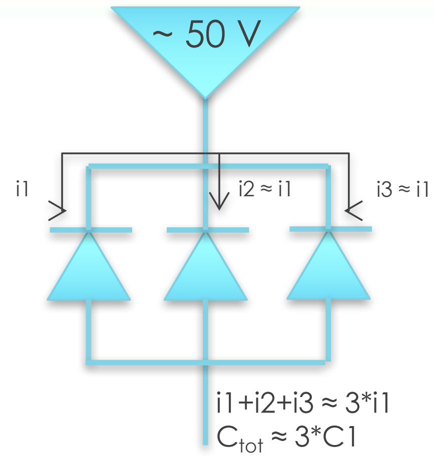
Mu2e Photosensor will be a custom SiPM

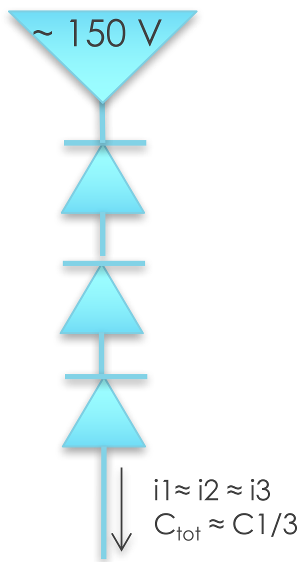
- We have chosen a modular SiPM layout that allows us to enlarge the active area, maximizing the number of collected photoelectrons.
- The crystal dimension, increased from 30x30 to 34x34 mm^2, accommodates a 2x3 array of individual 6x6 mm^2 SiPM modules
- This allows us to work use an air-gap while 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

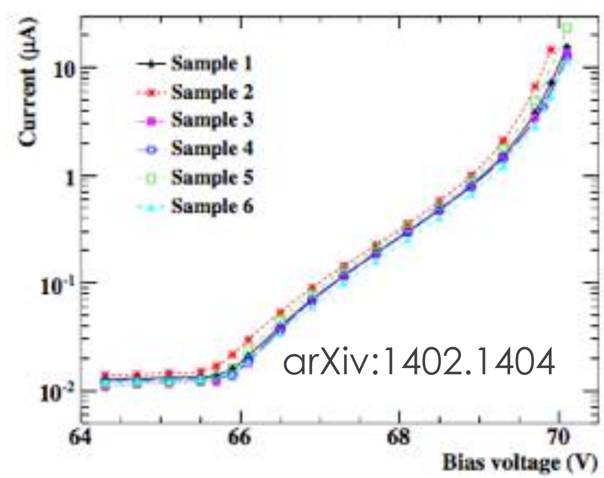




- When SiPMs are connected in series, the voltage applied to each SiPM is determined by the common leakage current. Then, the difference in breakdown voltages is absorbed, and the over-voltages are approximately aligned.

- 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

Series Connection

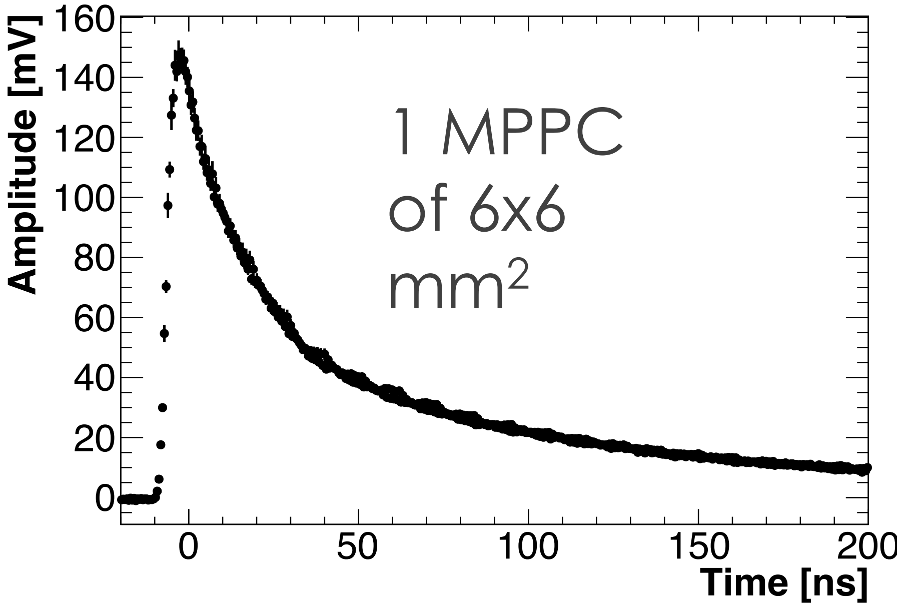
The advantage of series connection is that the resultant pulse shape becomes narrower than that from a single SiPM. This is in contrast to the case of parallel connection, where the signal becomes wider and pulse shaping is required.

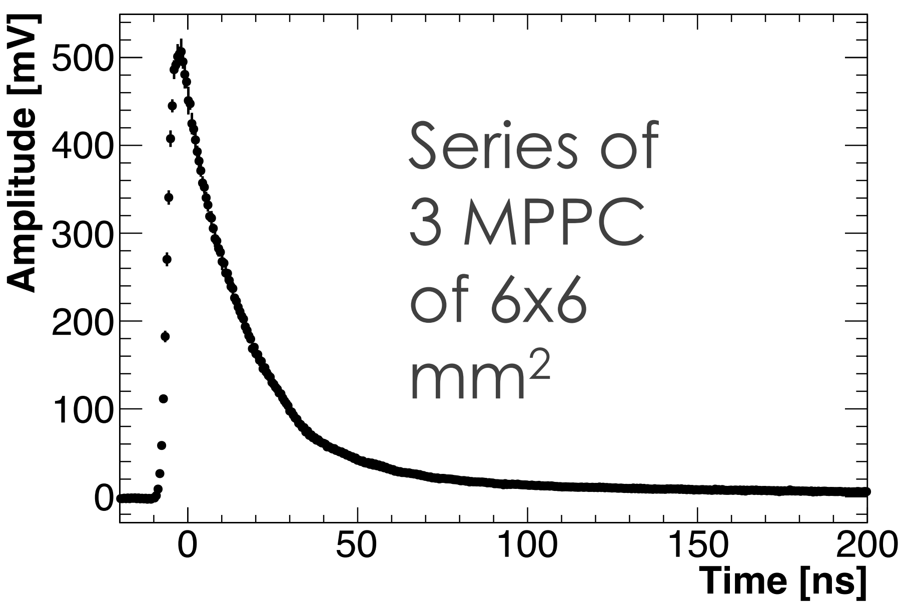
This effect is due to the reduction of the total capacitance of the series circuit consisting of the junction capacitances of the reverse-biased diodes and the associated stray capacitances.

- ✓ The fast rise time is of particular importance for optimizing the time resolution.
- ✓ The decay (“quenching”) time is relevant to reduce the overall slow component of the Crystal+SIPM response and increase pileup discrimination capability.

Shape

- Example: Hamamatsu MPPC series connection shows a good signal shape (when coupled to a 50 Ω voltage amplifier) when fired with a ps blue laser





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- ***An international Tender***
  - ***→ Measurements performed***

Procurement Plans

An international tender has been open for the procurement of the our custom SiPMs:

- 3 factories have been selected to provide SiPMs for evaluation
- 50 pieces each with the final packaging

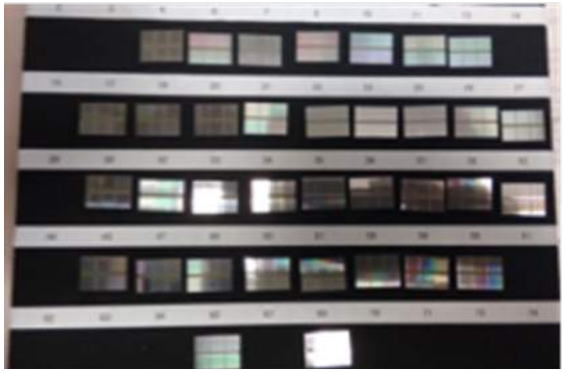
October 2016 – May 2017 → test of the SiPMs:

- Size/Packaging
- Gain / PDE / Shape specifications
- Radiation hardness: Irradiation campaigns
- MTTF measurement
- Sensors that don't meet the requirements are rejected.

- The ones those meet the requirements have been mounted in the Module-0 and used for the test beam.

What we measured (1)

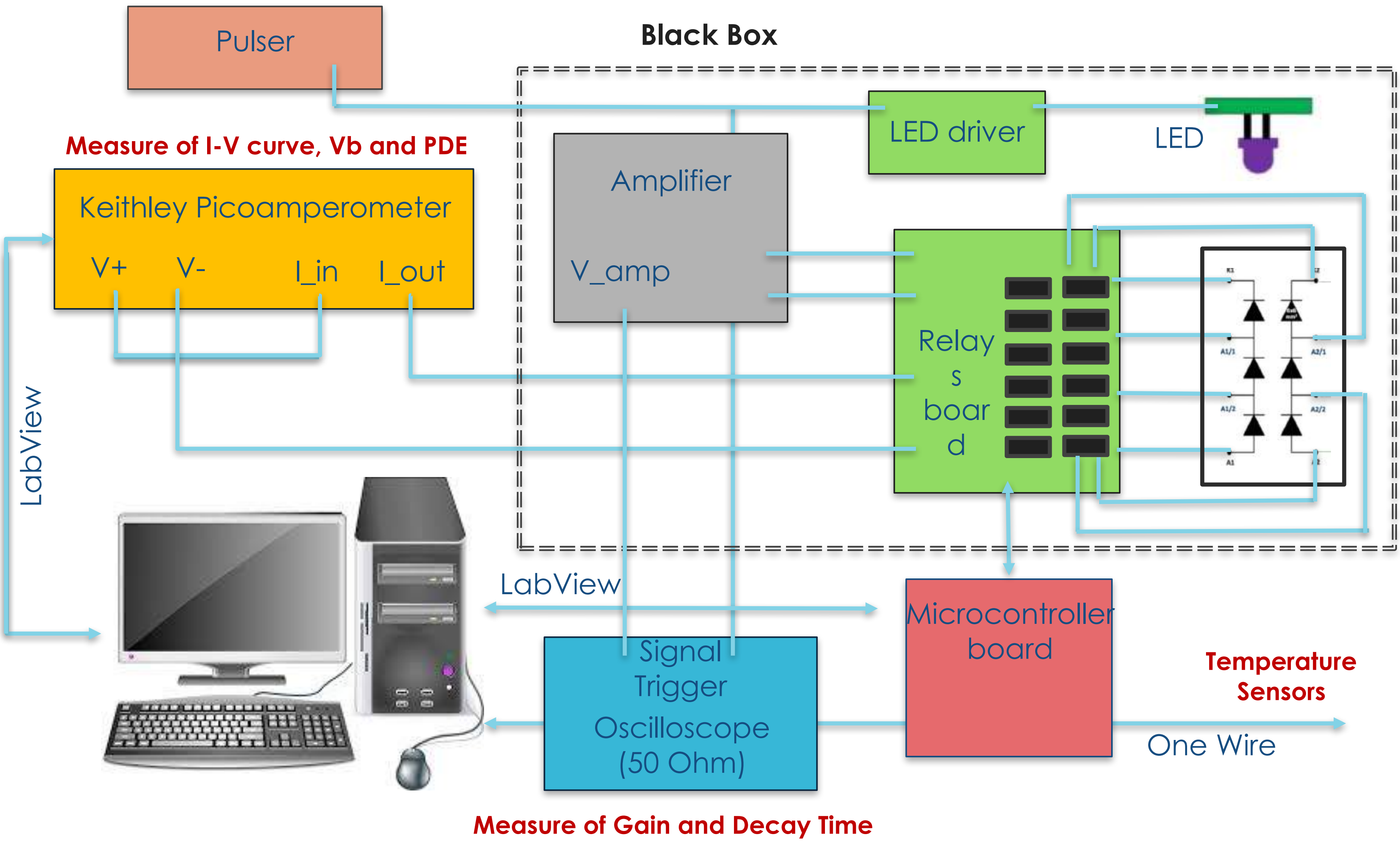
- The test involved 105 photosensors from the pre-production, 35 from each of the three vendors: Hamamatsu, SensL and Advansid-FBK.
- These SiPMs will be assembled in the Modulo-0.



The QA procedure has been performed in a temperature controlled station at 20 that provides for each cell:

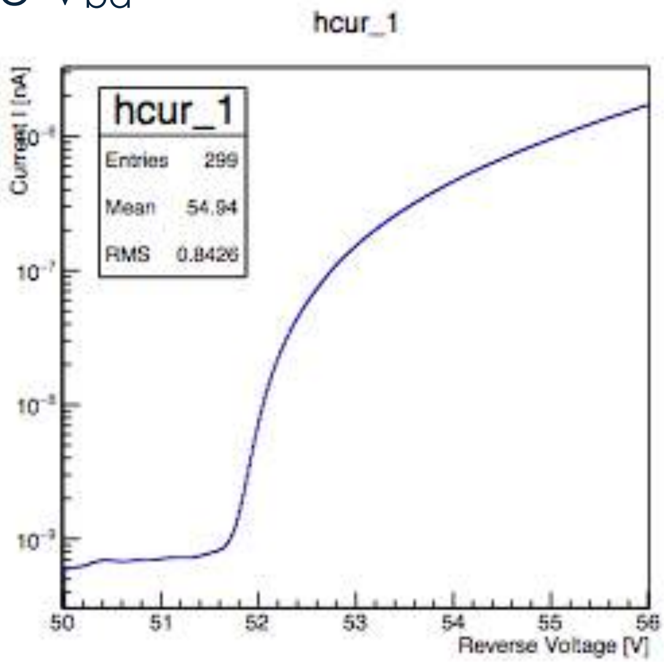
(i) the I-V dark curve from which the breakdown voltage is extracted
(ii) the Gain at Vop using the photo peaks method
(iii) the PDE by uniformly flashing the cell with 315 nm few-photons light pulses.

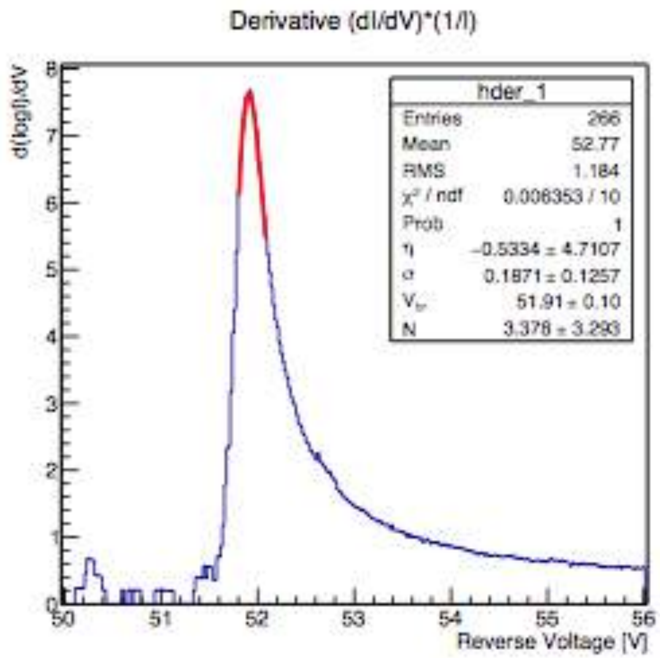
Experimental setup for pre-production QA



R1: Operative Voltage

- The operative voltage has been defined as Vop = Vb + 3 V.
- We acquired the I-V dark curve in a range that varies among the vendors:
  → Hamamatsu [50, 56] V, SensL [24, 30] V, Advansid [26, 32] V
- For each cell we find the peak of dlog(I)/dV curve to determine the V_{bd}

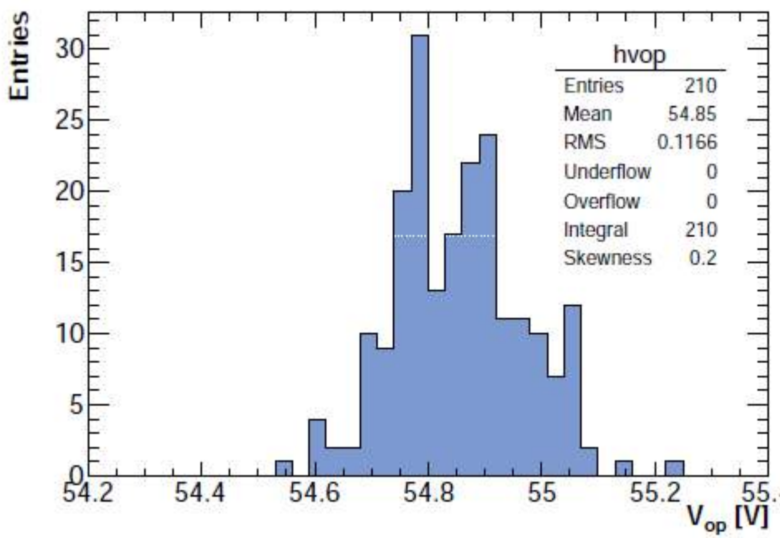




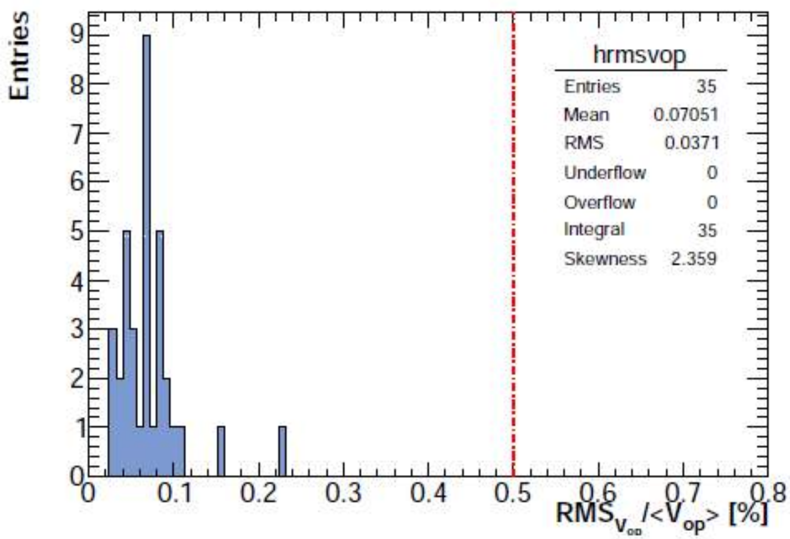
R1: Operative Voltage - Results

R1) a relative spread in Vop (operational voltage) between the sensor cells < 0.5%.

Measured Vop



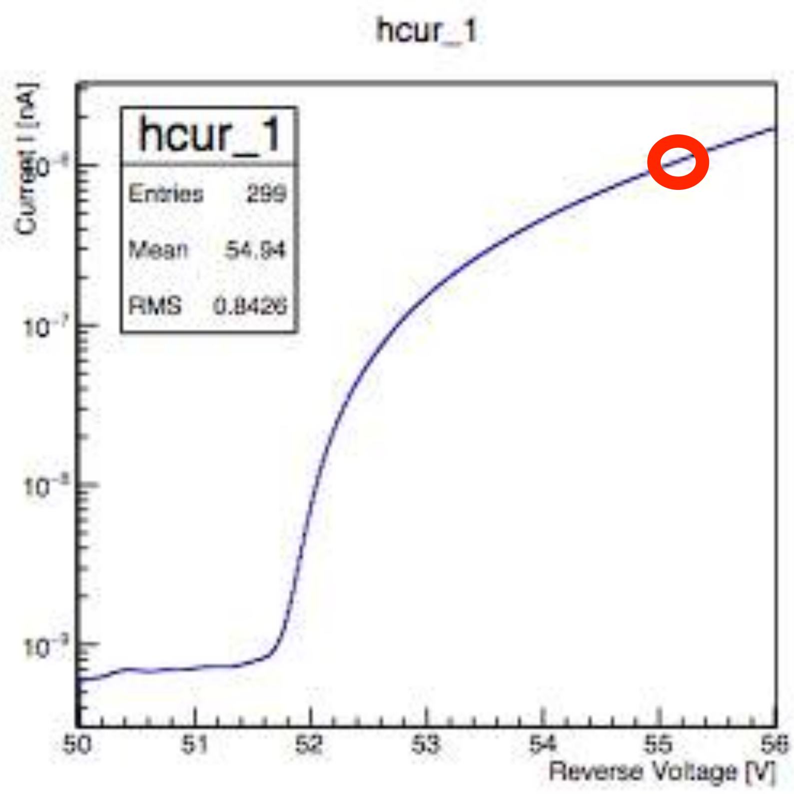
RMS Vo p



Example of results from one vendor

R2: Dark Current at Vop

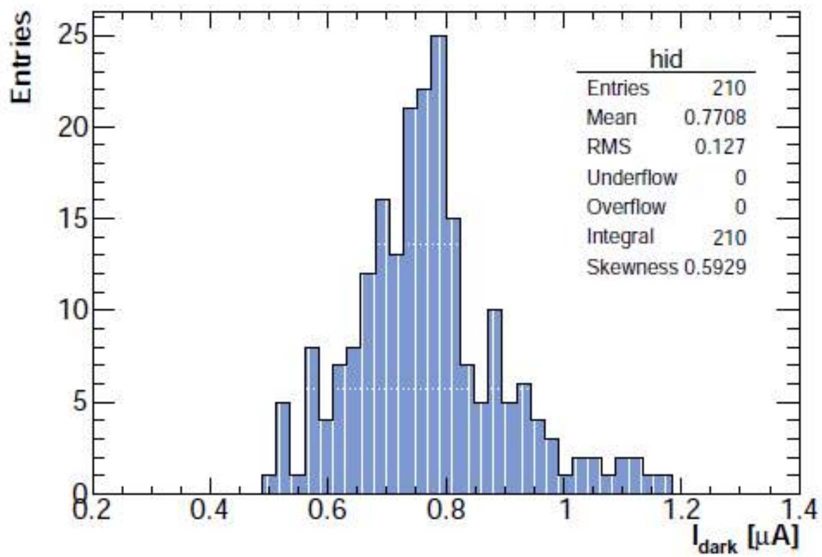
- From the same I-V scan we obtain also the Idark value at Vop for each cell.



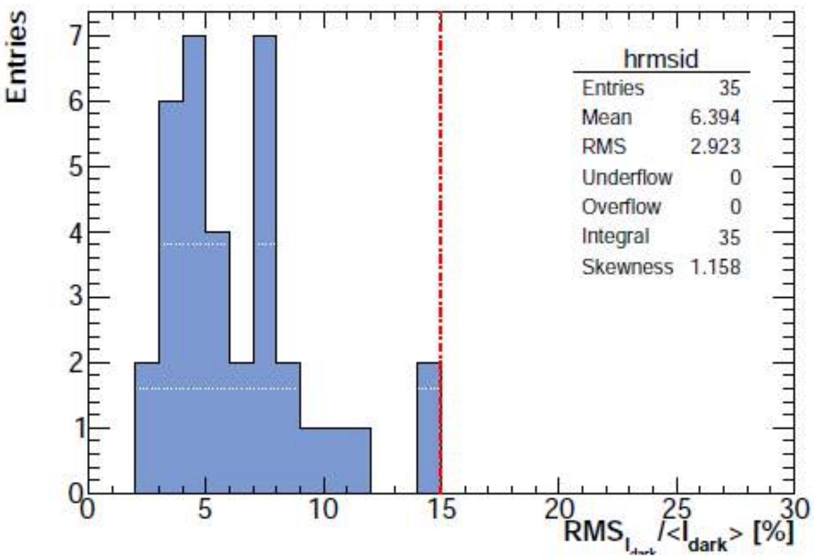
R2: Dark Current at Vop - Results

R2) a relative spread in the dark current at Vop between the sensor cells < 15%.

Measured Id



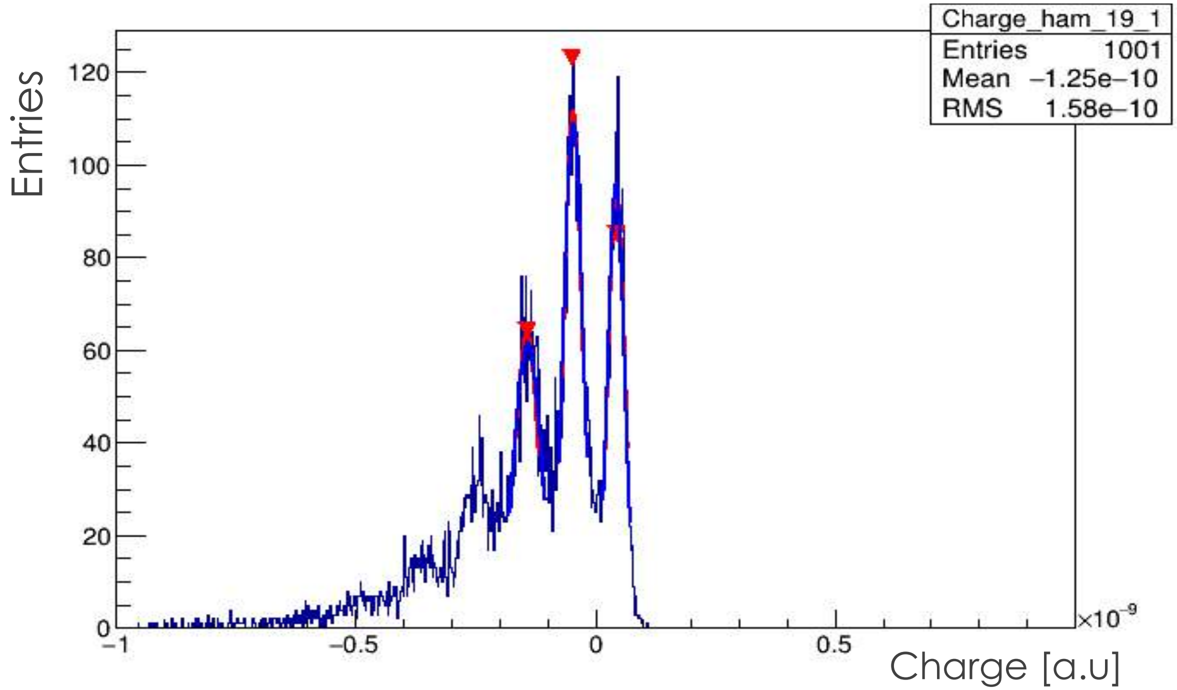
RMS Id



Example of results from one vendor

R3: Gain at Vop

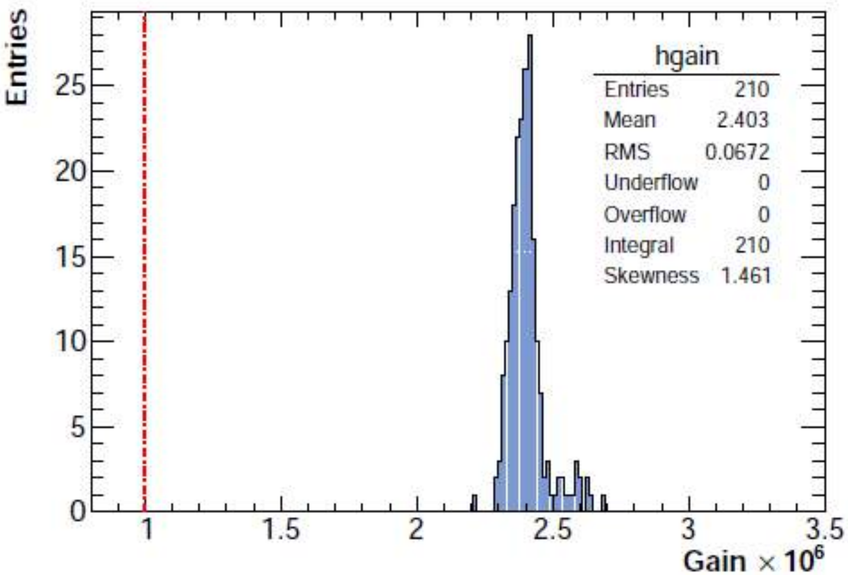
- The LED is powered by 20 ns wide pulses at a frequency of 100 kHz.
- The amplified pulses is integrated in a gate of 150 ns (tender requirement).
- Each charge peak corresponds to 0, 1, 2 .. n photons hitting the sensor.
- The gain is therefore obtained from $G = \Delta Q_{peak} / (e^{-} * G_{amp.})$.



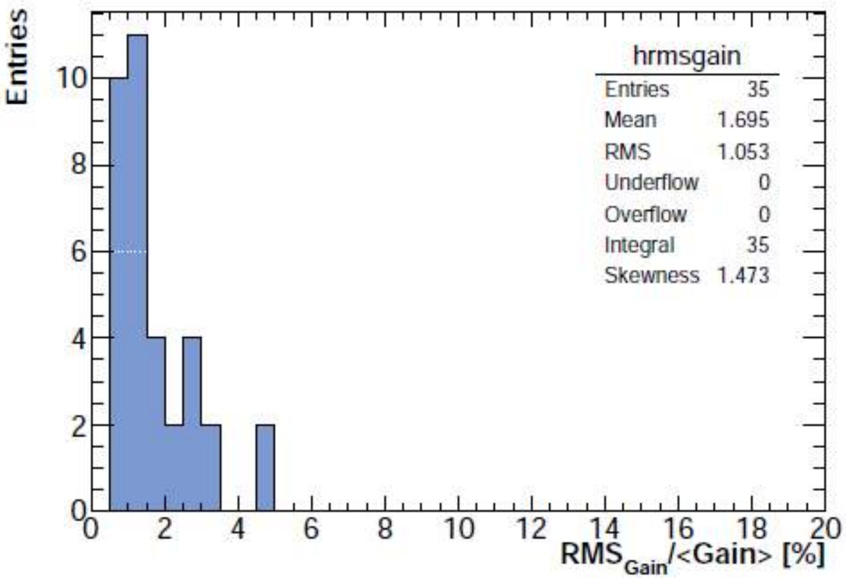
R3: Gain at Vop - Results

R3) a gain (measured in a gate of 150 ns) at Vop > 10^6 for each cell. Will be evaluated the uniformity (relative RMS) inside each array.

Measured Gain



RMS Gain



Example of results from one vendor

R4 - Relative PDE at Vop [1/3]

- The PDE is defined as the ratio between N_{pe}, the average number of detected photoelectrons, and N_{gamma}, the average number of incident photons on the sensor.
- The probability P(n) of detecting n photons by the sensor is given by the Poisson distribution:

$$P(n, n_{pe}, n_{dark}) = \frac{(n_{pe} + n_{dark})^n \cdot e^{-(n_{pe}+n_{dark})}}{n!}$$

- Inverting the Poisson equation, it is possible to obtain N_{pe}:

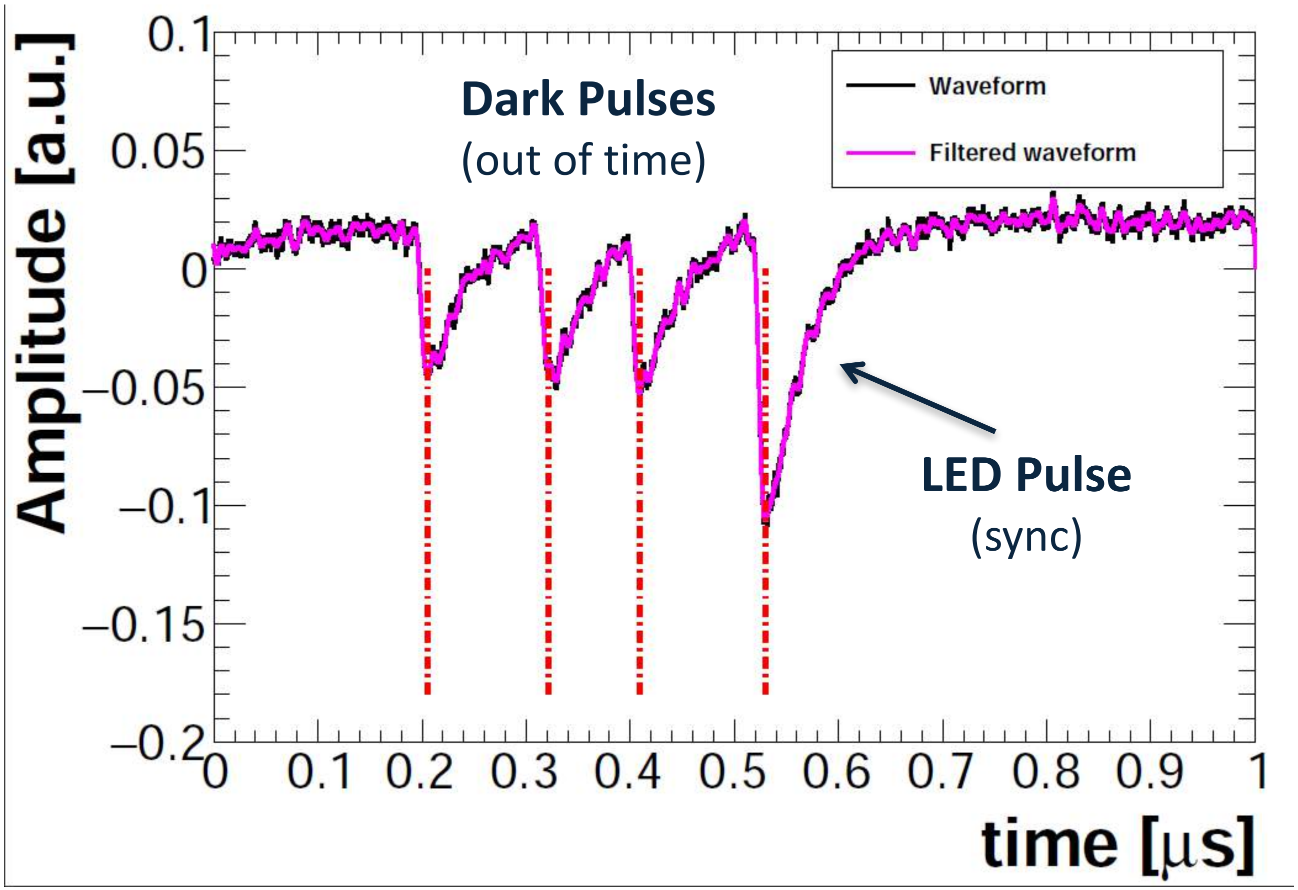
$$n_{pe} = -ln(P(0, n_{pe}, n_{dark})) + ln(P(0, n_{dark}))$$

- And express the two probability in quantities measurable by analyzing the signal waveforms, Nn>1 and Nd:

$$n_{pe} = -ln(1 - \frac{N_{n\geq 1}}{N_T}) + ln(1 - \frac{N_D}{N_T})$$

R4 - Relative PDE at Vop [2/3]

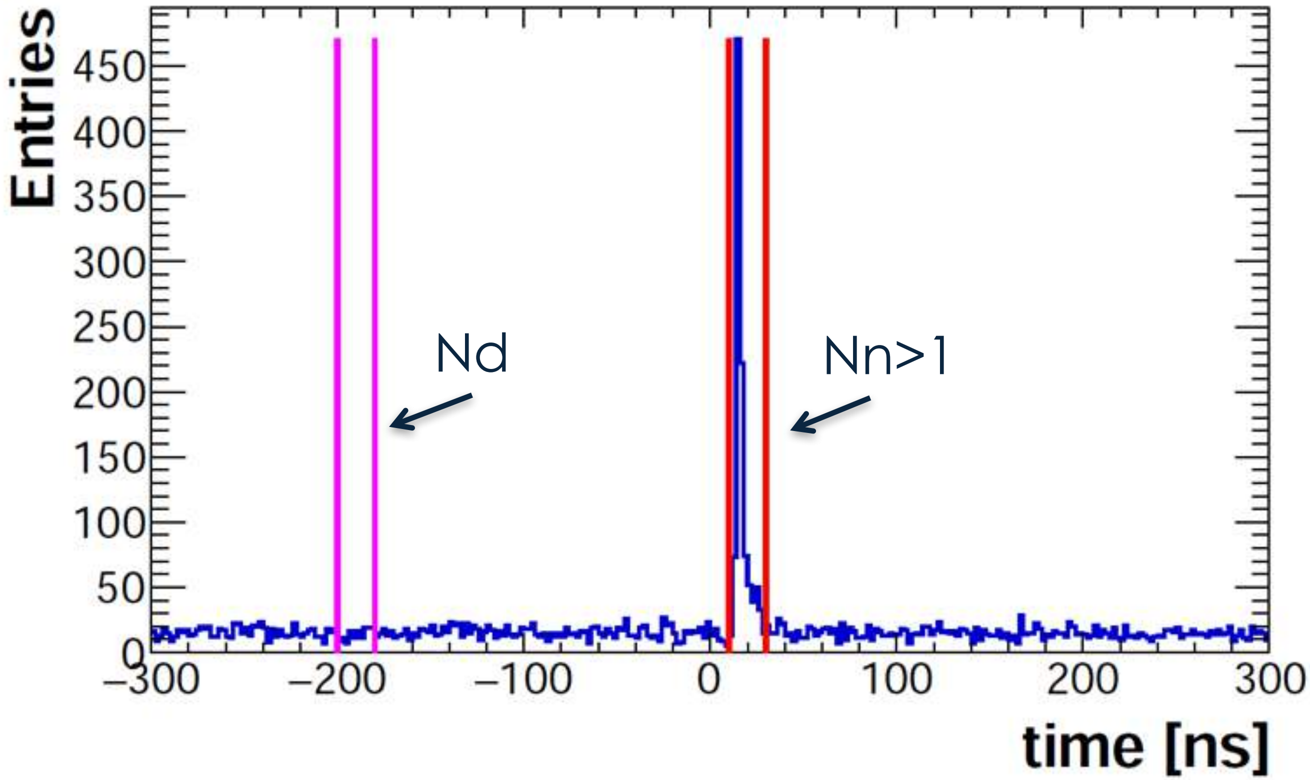
- The LED is powered by 20 ns wide pulses at a frequency of 100 kHz.
- Triggering on the light pulse, a waveform of 1 s is acquired.
- The peak time of each pulse is stored.



Fermilab

R4 - Relative PDE at Vop [3/3]

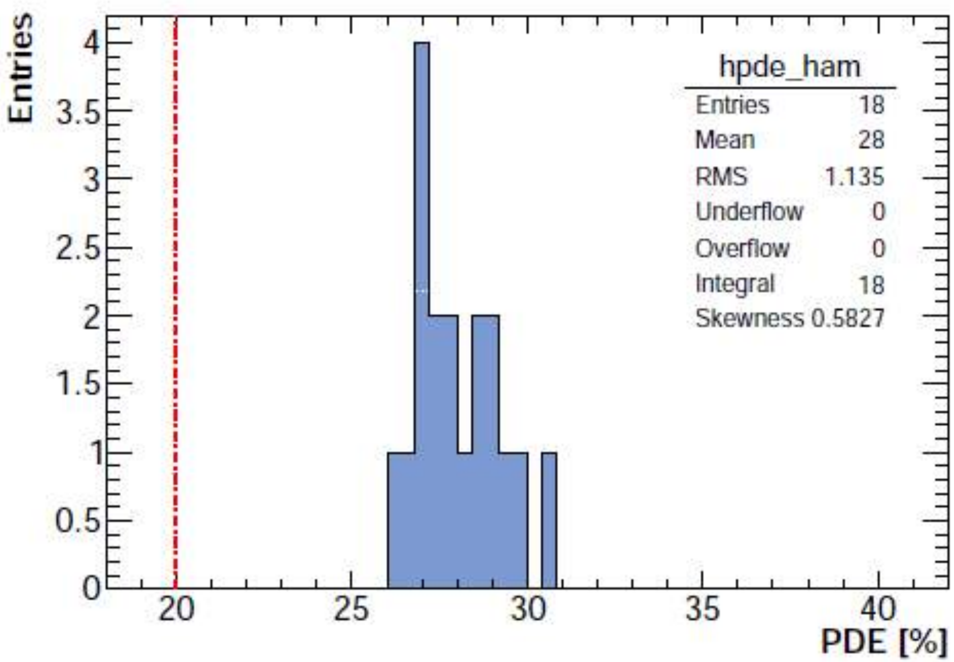
- To evaluate Ndark and Nn>1, we look at the distribution of the peak times, fixing two time gates of 20 ns each.



- To simplify N_{gamma}, the obtained PDE has been rescaled relatively to a reference sensor of well known PDE of 22%.

R4 - Relative PDE at Vop - Results

R4) a PDE at Vop > 20% for 315 nm, evaluated using a reference-device.



Example of results from one vendor

What we measured (2)

The SiPMs have to grant an MTTF of 1 million hours when operating at 0 °C.

- For the MTTF evaluation the following equation is used:

$$\mathbf{0.5 \times N_{hours} \times AF \times N_{SiPM} \sim 0.6 \times 10^6\ hours}$$

- Where $\mathbf{N_{hours}}$ **= 2 556** (start: 25 November 2016, end: 12 March 2017), $\mathbf{N_{SiPM}}$ **= 5** (per each vendors), **AF =100**

- The Acceleration Factor is extracted from the Arrhenius equation:

$$AF = exp\left[\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{stress}}\right)\right]$$

where E_a = 0.6 eV for Silicon, T_{use}= 273 °K and T_{stress}= 323 °K

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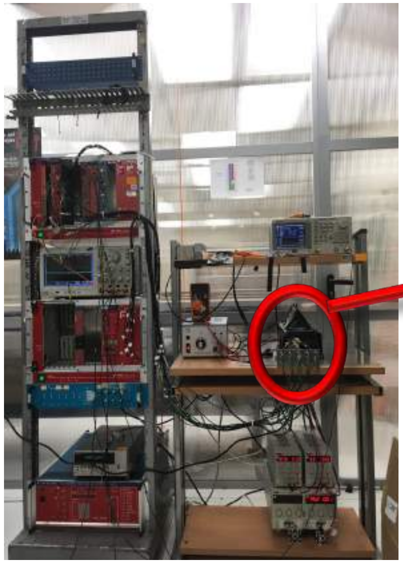
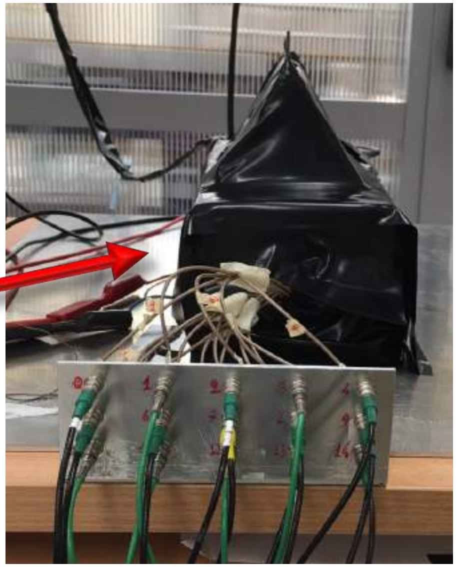
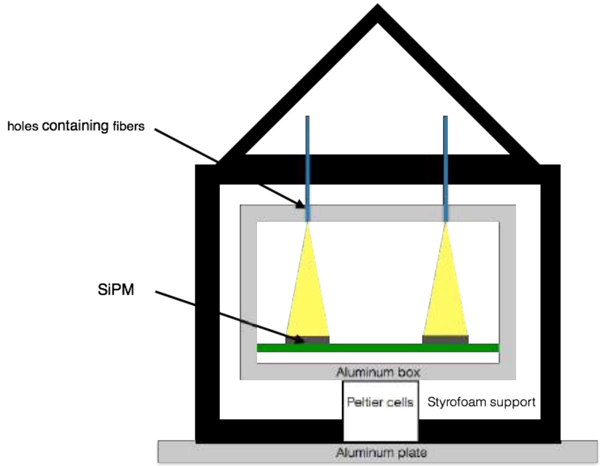
MTTF - experimental setup

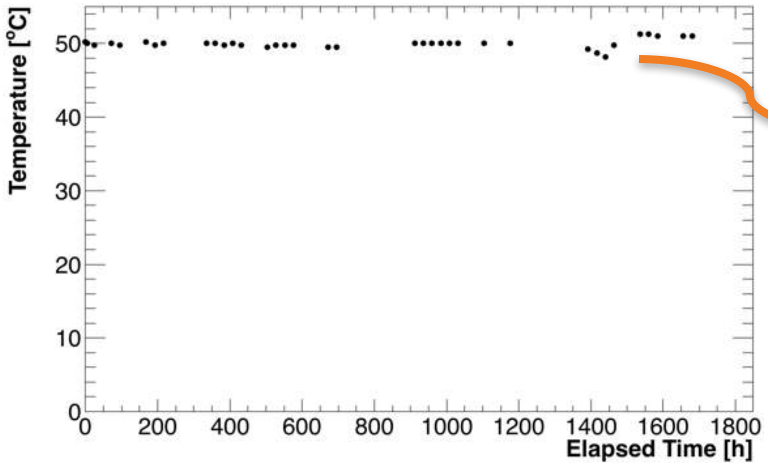
- **15 SiPMs** (parallel of 2 series made of 3 6x6 mm^2 SiPMs) from different vendors tested;
- Temperature **@ 50 °C** using 2 Peltier cells;
- SiPM temperature monitored by a PT 1000;
- Led pulse every **2 minutes;**
- Current value acquired once a day if possible.



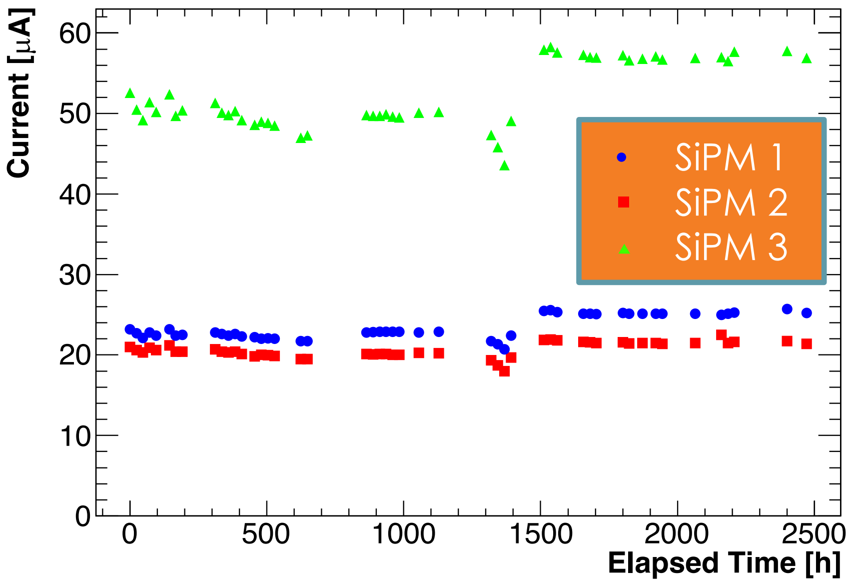


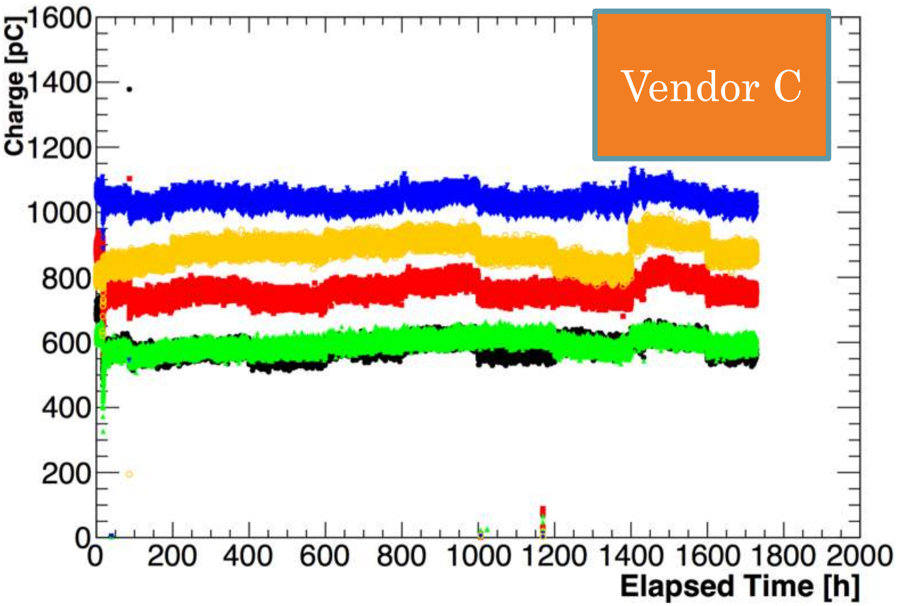


MTTF - Results



Due to unexpected changes in the clean room temperature we have adjusted the box temperature:
Now $\mathbf{T_{box} = 51.03\ °C}$





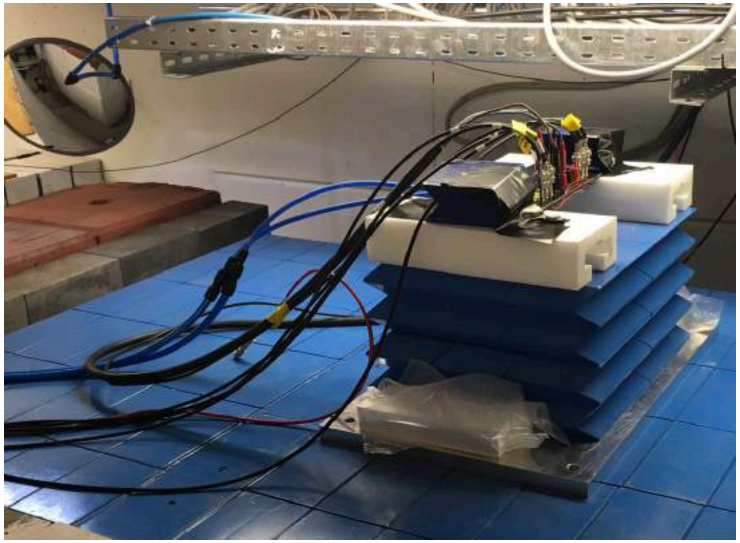
What we measured (3)

Irradiation with both **neutrons** and ionization dose (for a randomly selected sub-sample) is one of the evaluation criteria for the qualification of the pre-production SiPMs.
It is required that:

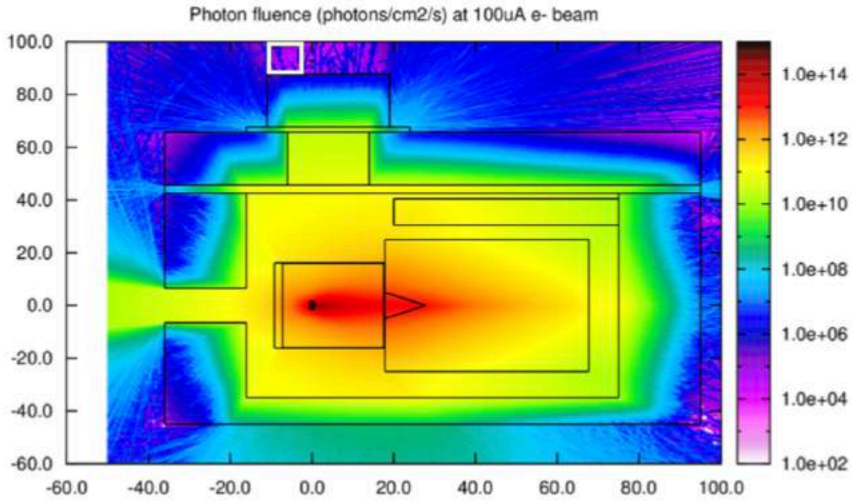
- When the SiPM is exposed to a **neutron fluency of $3x10^{11}$ n_{1MeVeq}/cm^2**, the acceptable levels of deterioration (for each 6x6 mm^2 SiPM cell in the array) are:
  - a dark current smaller than 10 mA
  - a gain reduction of up to a factor of 4

- The test will be done reading the dark current with a picoammeter and measuring the response to a UV led during the irradiation while keeping the array at 25 °C

Radiation Hardness: Neutron test @ HZDR

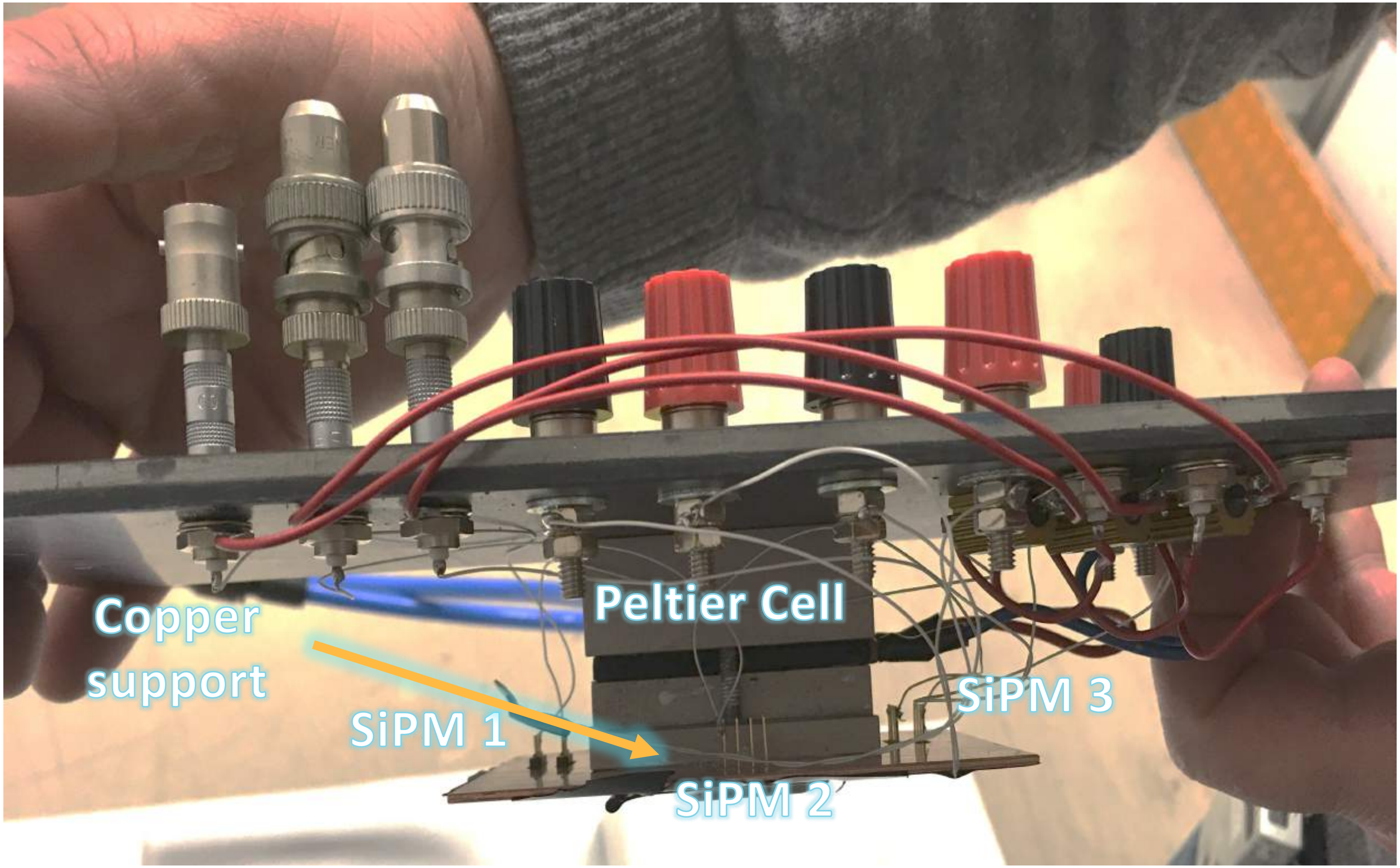


- Helmholtz-Zentruf Dresden Rossendord (HZDR, Dresden , German) test in March.
- It provides **neutrons of 1 MeV**
- Max Integrated flux: **$8x\ 10^{11}\ n_{1\ MeV}/cm^2$**



- **3 Sipm tested at the same time**
- Single cell current acquired with a Keythley
- Chiller+ Peltier cell
- T_{back} monitored with a PT 100

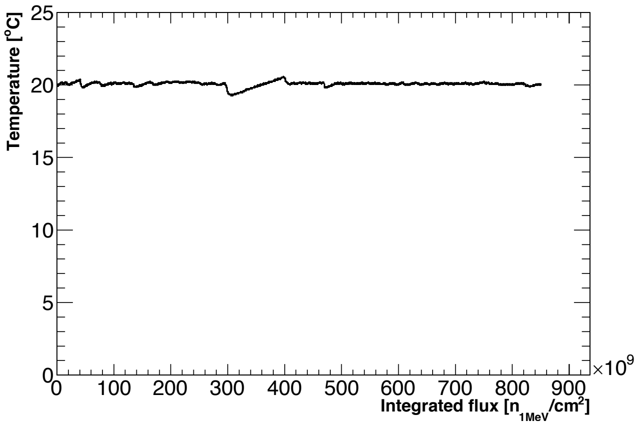
Radiation Hardness: Setup [1/2]



Radiation Hardness: Setup [2/2]

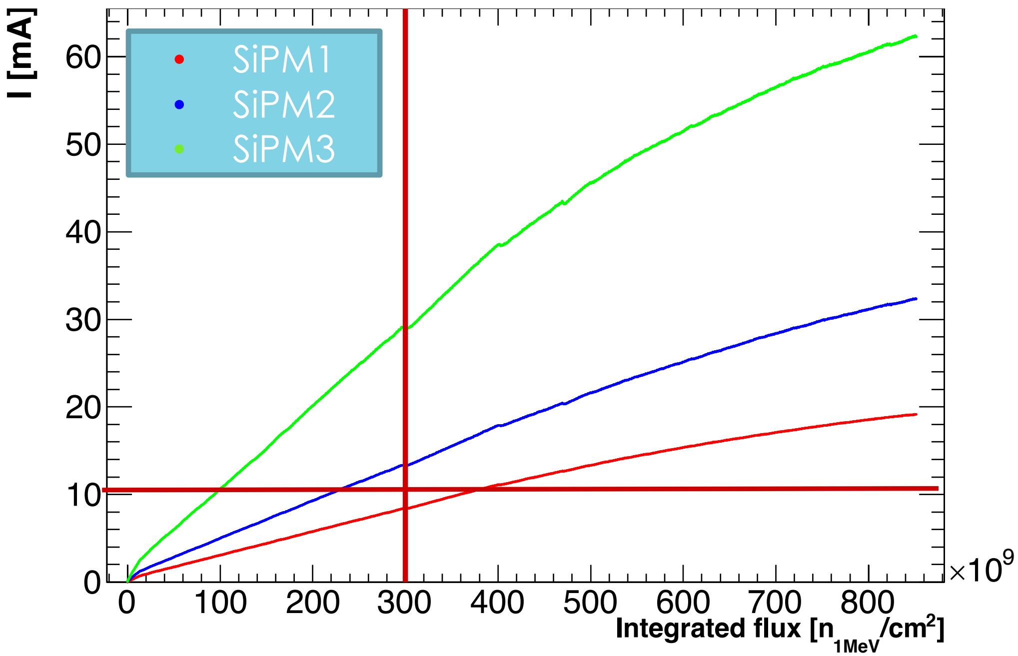
Radiation Hardness - Results

Temperature kept almost stable during all the irradiation test



Considering the flux limit imposed in the bid we obtained that:

- **I_SiPM1 = 8.39 mA**
- I_SiPM2 = 13.33 mA
- I_SiPM 3 = 28.98 mA



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

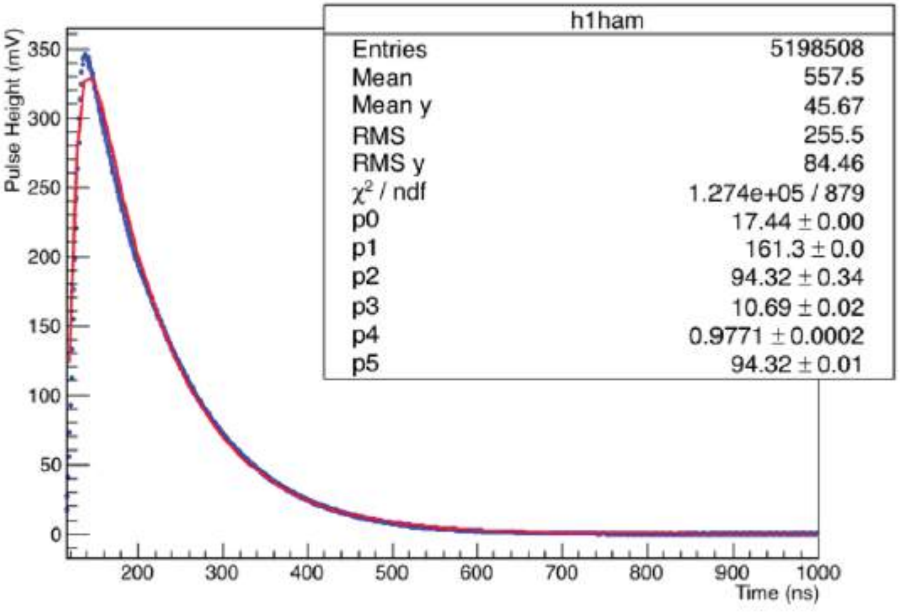
- Three different firms appear to be capable of producing the Mu2e final SiPM thermal package (2x3 array of 6x6 mm^2 cells)
  - Hamamatsu, FBK and SensL
  → The international tender will conclude at the end of June

SPARES

R5 – Recovery Time

R5) a recovery time τ < 100 ns on a load greater than 15 Ω

- The measurements have been performed using a load of 50 Ohm and after rescaling the time to a 50 Ohm load.



Fermilab

(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 $2.2x10^{11}$ n_14MeV/cm^2 ($4x10^{11}$ 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 ~ 20°C, Vbias = Vop
- **Inside the DS:** we will run at ~ 0°C, Vbias = Vop – temperature voltage coefficient

Each photosensor will be characterized with the QA Photosensor Station

at 20, 10 and 0°C→ We will know the working point for each running condition (for MPPC this corresponds to around 50 mV/°C)

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 °C (DOI 10.1109/NSSMIC.2013.6829584).

- Working at 0 °C, 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 °C
  After 1 month of running, all 4 SiPM are still perfectly OK.