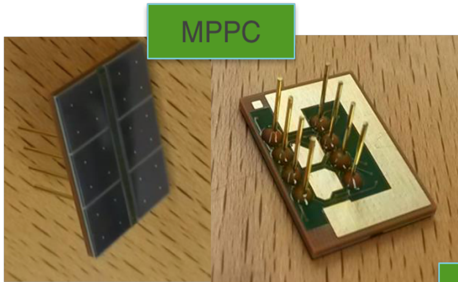

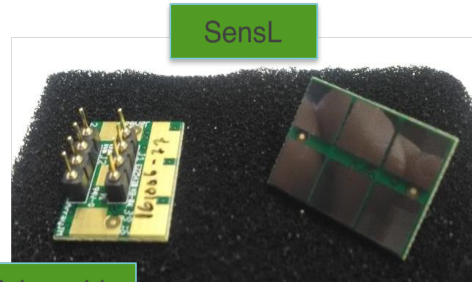

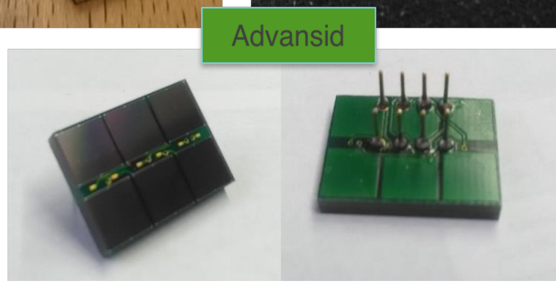

The Mu2e calorimeter SiPMs

Ivano Sarra,
Universita' degli Studi Guglielmo Marconi
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On behalf of the Mu2e calorimeter group

TECHNOLOGY AND INSTRUMENTATION IN PARTICLE PHYSICS'17

BEIJING - 25 May 2017

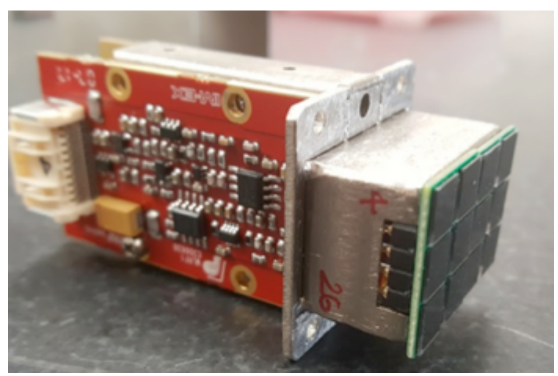
Mu2e Calorimeter

- ✓ **Calorimeter with O(5%) energy resolution, < 500 ps timing resolution**
  Technical choice: A crystal calorimeter organized in 2 disks:
- ✓ Each disk contains 678 undoped CsI crystals 3.4 x 3.4 x 20 cm^3 with each crystal readout by 2 independent SiPMs
- ✓ undoped CsI provides:
  → light yield > 100 pe/MeV with PMT readout
  → longitudinal response uniformity < 10%,
  → emission decay time τ ~ 16 ns @ 310 nm
- ✓ **Photosensor choice: custom array 2x3 of 6x6 mm^2 UV-extended SiPM**

undoped CsI

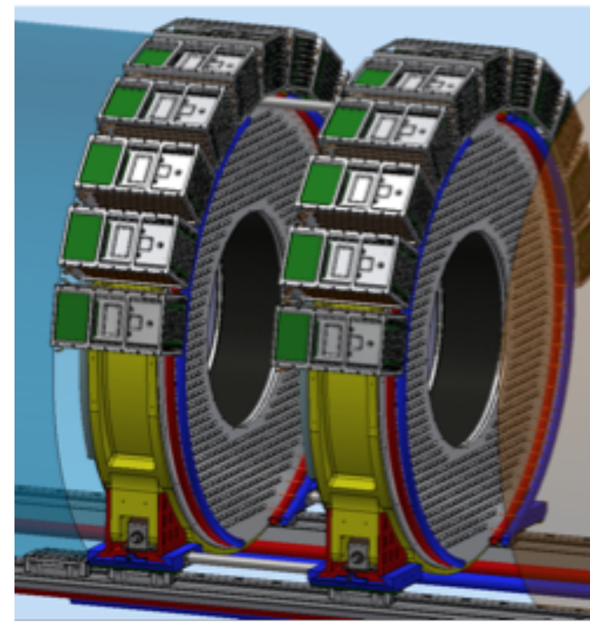
(R. Y. Zhu talk)

SiPM array + FEE



Subject of this talk

Calorimeter



(G. Pezzullo talk)

Mu2e Photosensors Requirements

Photosensors must meet the following requirements:

(R0) Work in B-field of 1 Tesla → **Silicon photomultiplier**

(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 → **20-30 pe/MeV with SiPM readout**

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

(R3) Withstand a radiation environment of **~10^{12}** n/cm^2 @ 1 MeV$_{eq}$ and **~50 krad** for photons;

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

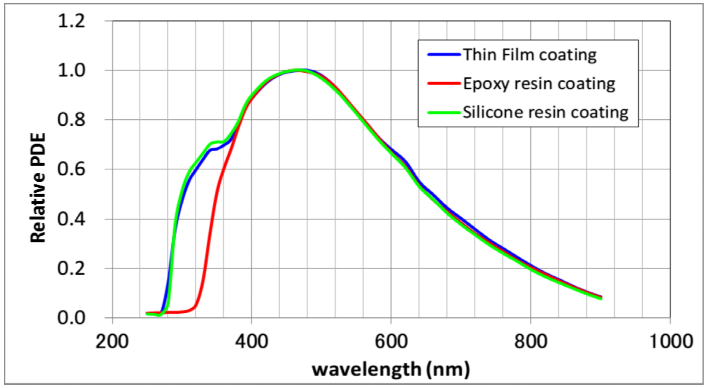
(R5) Have sufficient reliability to allow operation for 1 year w.o. interruption;

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

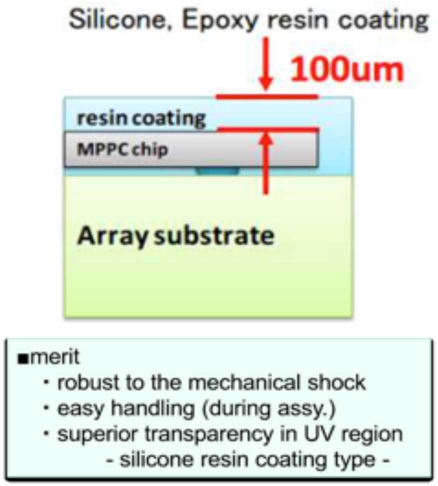
Mu2e Photosensor will be a custom SiPM [1/2]

- We have chosen a modular SiPM layout to enlarge the active area and maximize the number of collected photoelectrons.
- To replace sensors and reduce outgassing we coupled the sensors to the crystal with an air-gap **while satisfying the p.e./MeV requirement with a single photosensor**. Two SiPMs/crystal are used for redundancy;
- **The SiPM will be made of a 2x3 matrix (6 cells) of 6x6 mm^2 UV extended SiPMs (cells in the following).**

  → ~ 30 (20) p.e/MeV with (without) optical grease with Tyvek-wrapped crystals (34 x 34 x 200 mm^3)

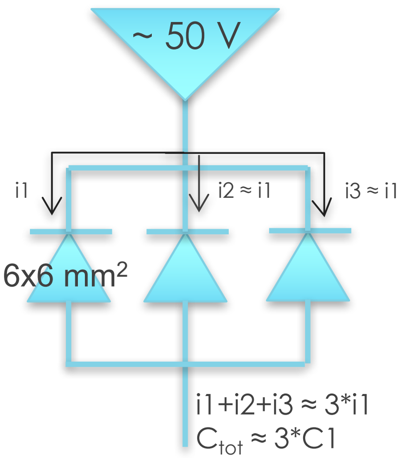


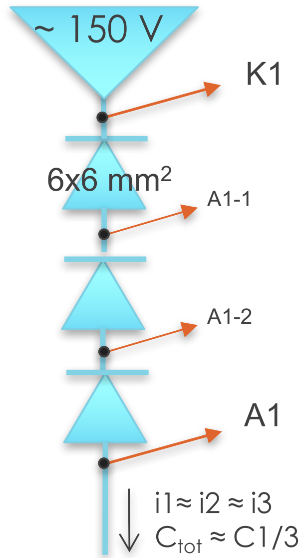
Thin Film coating and Silicon resin coating has PDE advantage in UV region.

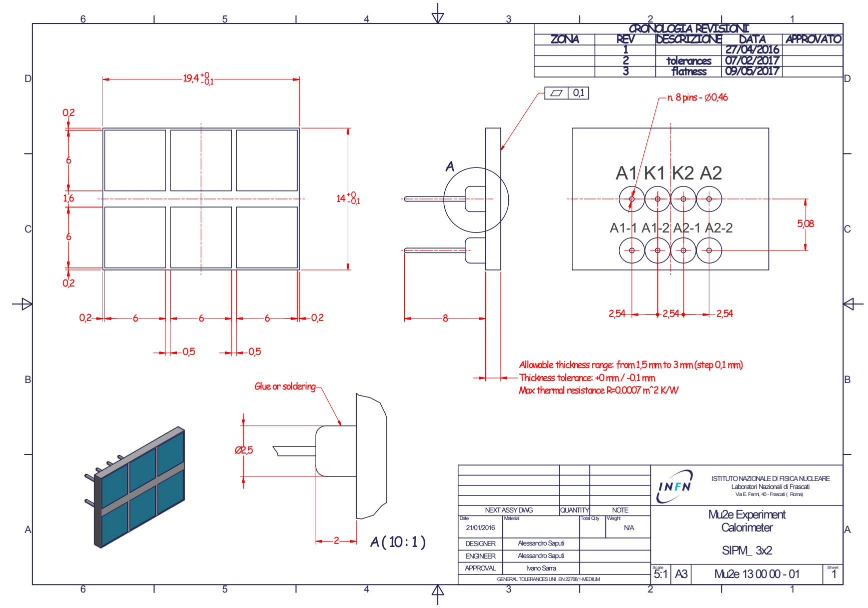


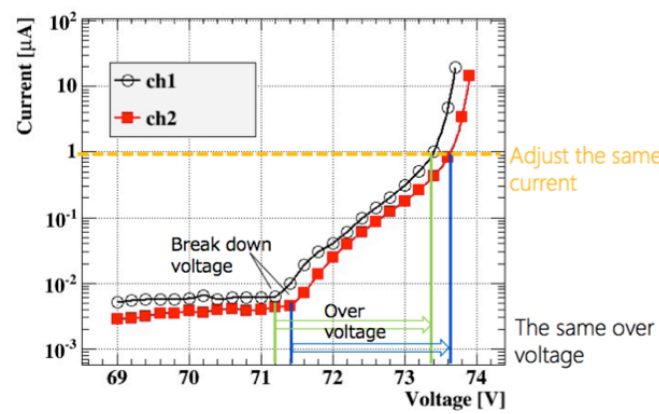
Mu2e Photosensor will be a custom SiPM [2/2]

- We use a parallel arrangement of two groups of three cells biased in series;





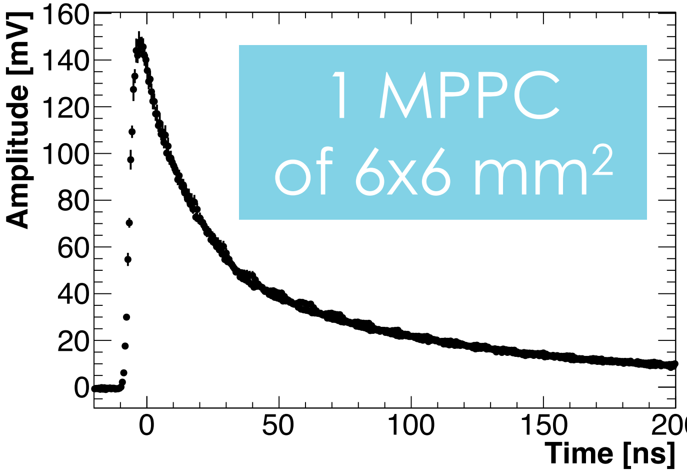


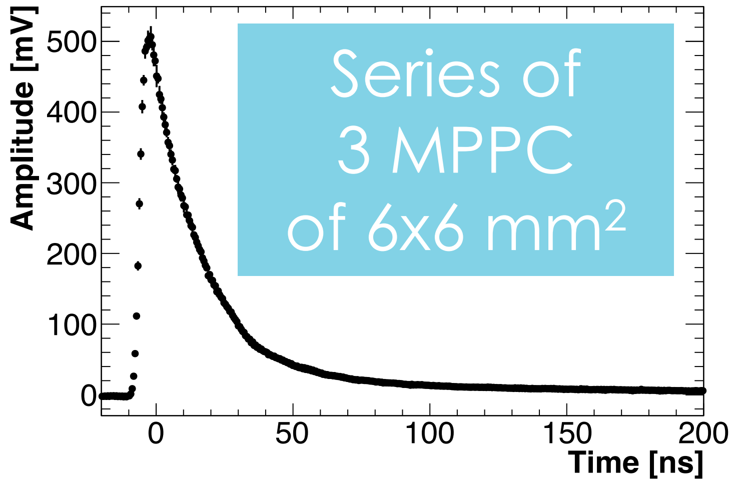


⇒ If the current is at the same level for the SiPMs in the array, their over-voltages are automatically adjusted to be the same.

Series Connection

Advantage: the resultant pulse shape becomes narrower, while in a parallel connection the signal becomes wider and pulse shaping is required.





- ✓ 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.

Procurement Plans and pre-production

An international tender is in progress for the procurement:

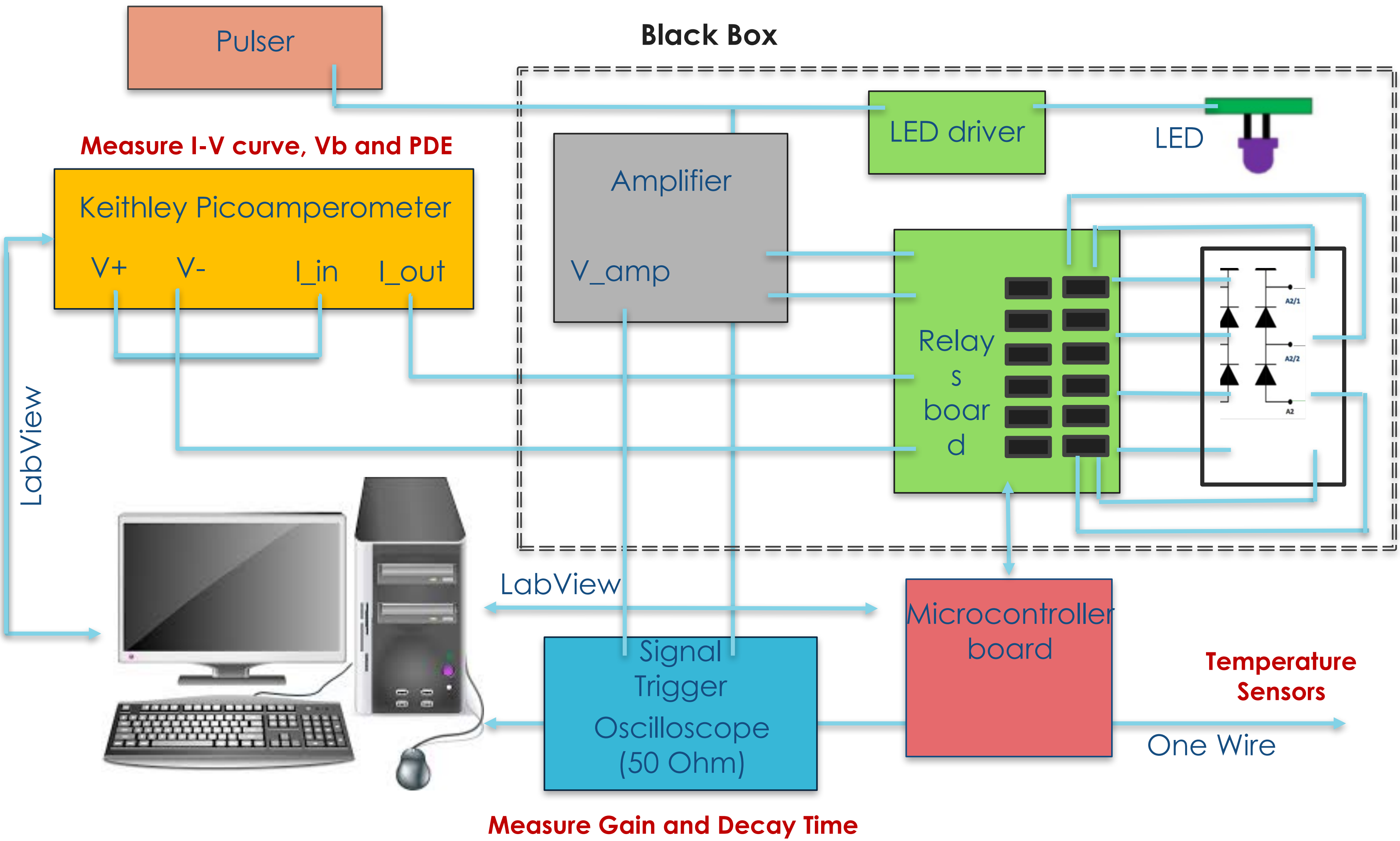
- 3 firms selected to provide pre-production SiPMs for technical evaluation
- Pre-production of 50 pieces/firm with final packaging received in Oct 2016

October 2016 – May 2017 → **Quality Test of SiPMs:**

- Size/Packaging
- Gain / PDE / Shape specifications
- Radiation hardness: Irradiation campaigns
- MTTF measurement

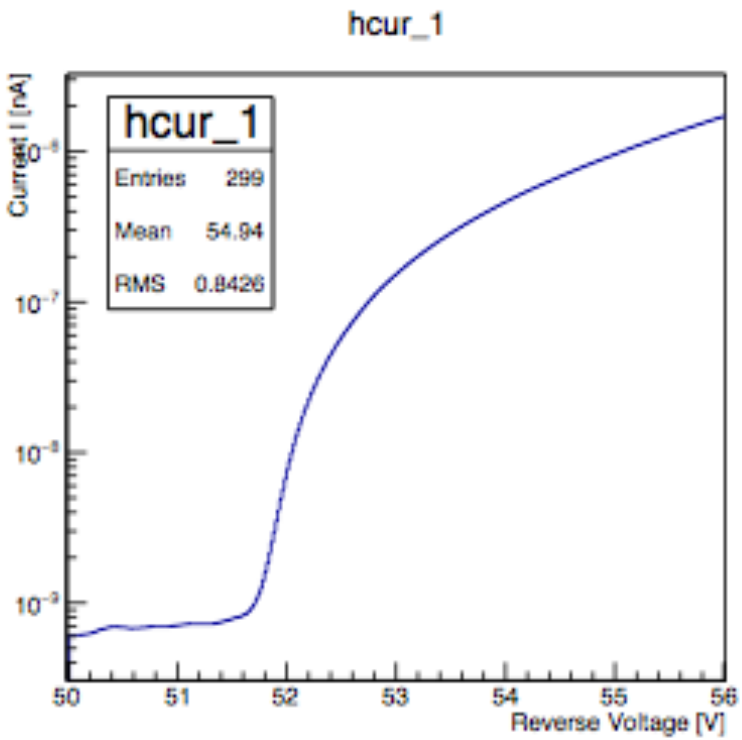
In final production → sensors do not meeting specs will be rejected

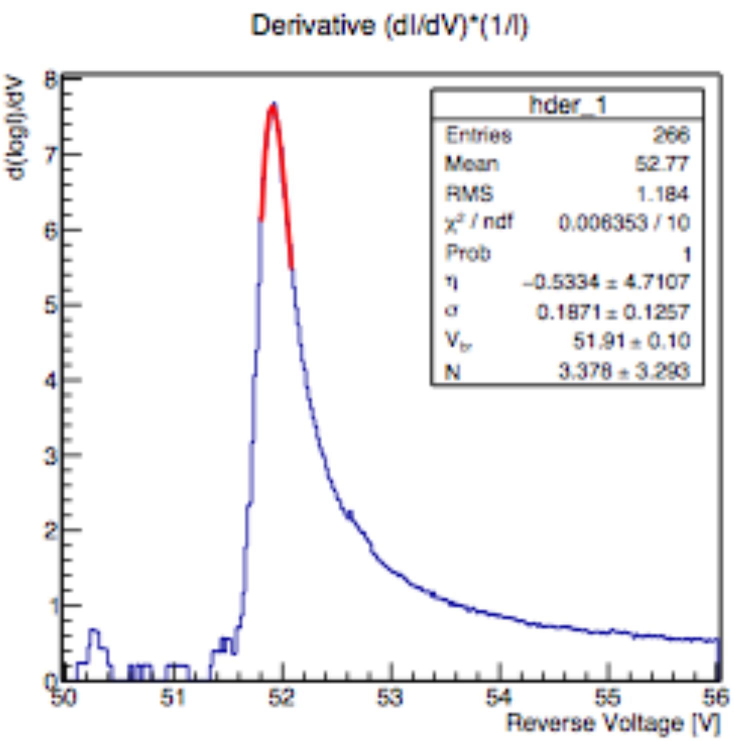
Experimental setup for pre-production QA



Determination of Operating Voltages

- The operating voltage Vop has been set at Vb + 3 V
- I-V scan performed in range that varies among the vendors:
  → **Hamamatsu** [50, 56] V, **SensL** [24, 30] V, **Advansid** [26, 32] V
- For each SiPM cell, Vbr is found as the maximum of the dlog(I)/dV

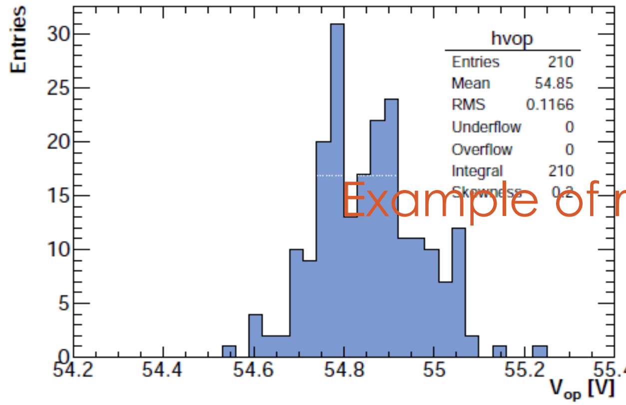




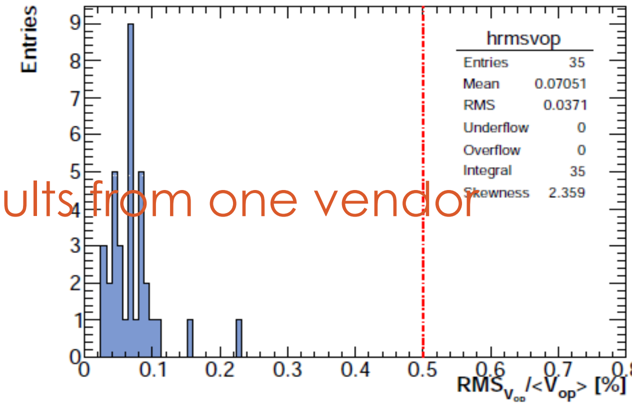
Operating Voltage - Results

Required:
a relative spread in Vop between the sensor cells < 0.5%.

Measured Vop



RMS Vop

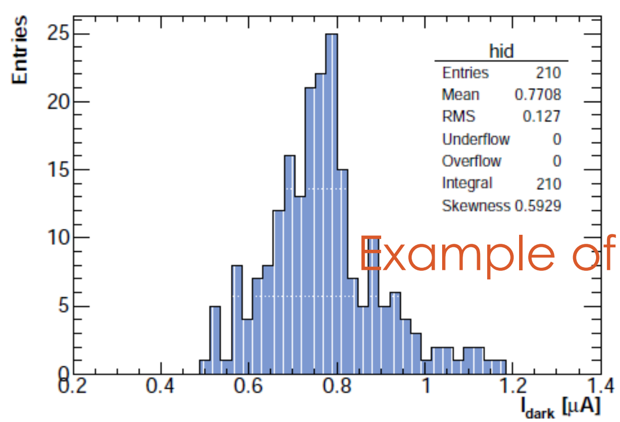


Example of results from one vendor

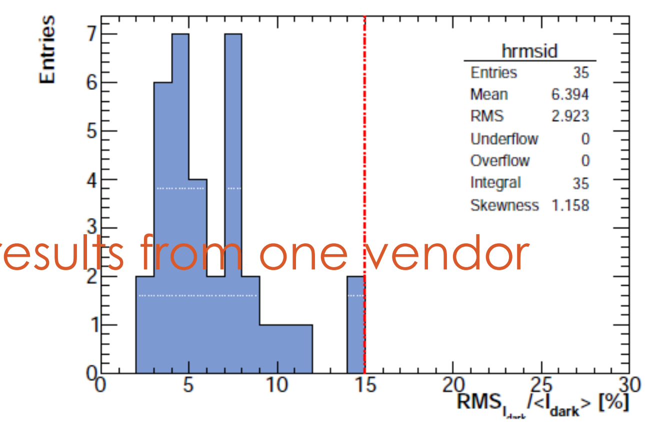
Dark Current at Vop - Results

Required:
a relative spread in the dark current at V_{op} between the sensor cells < 15%.

Measured Id



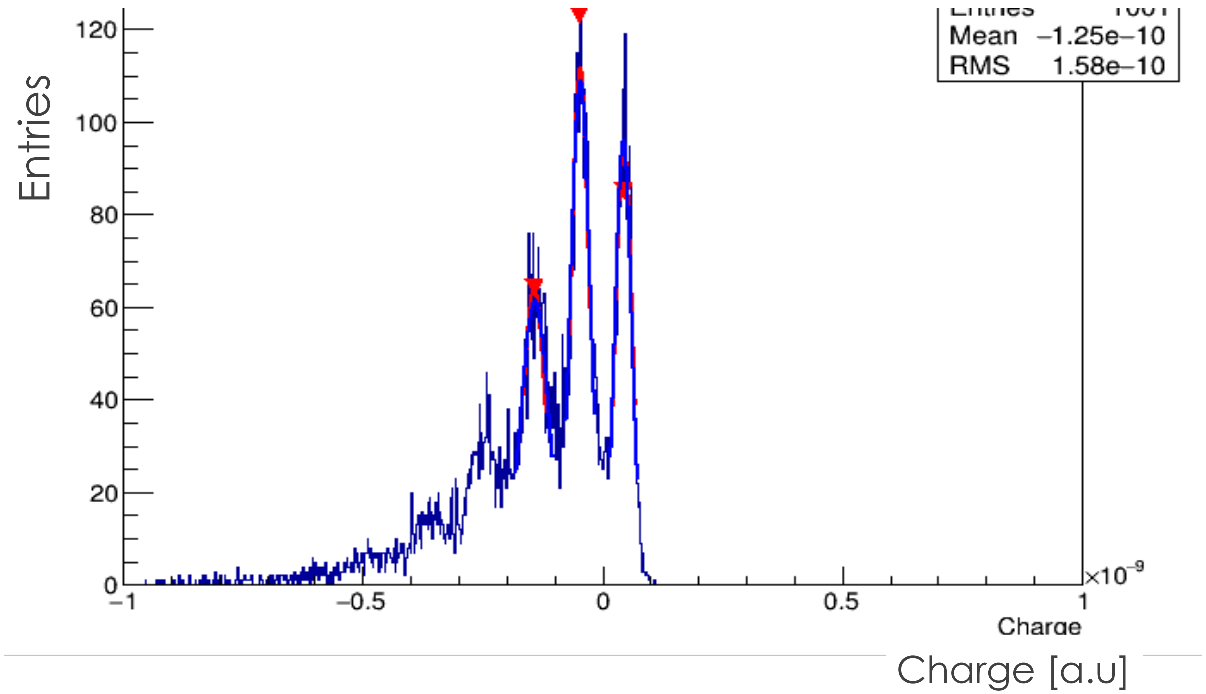
RMS Id



Example of results from one vendor

Gain at V_{op}

- 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
- Each charge peak corresponds to 0, 1, 2 .. n photons hitting the sensor.
- The gain is then obtained by the relation $G = \Delta Q_{peak} / (e^{-} * G_{amp.})$.



Gain at V_{op} - Results

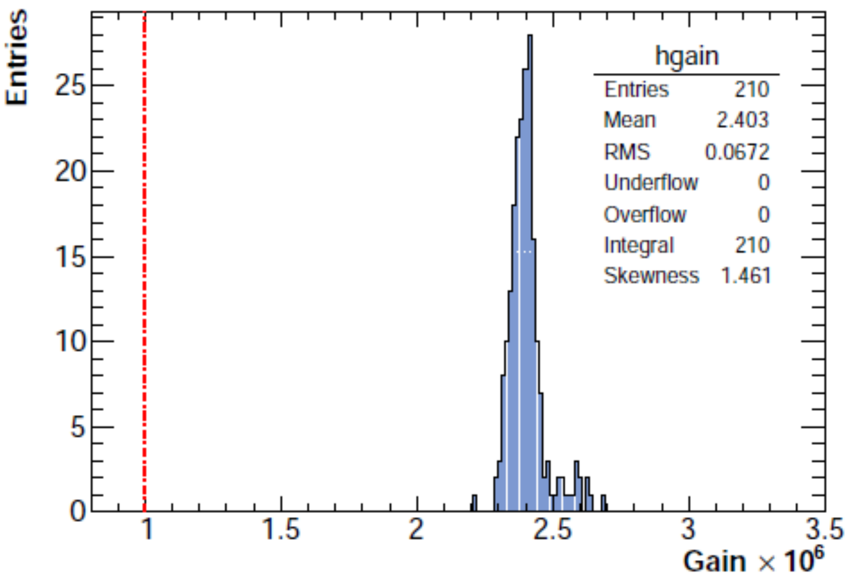
Required:

a gain at Vop > 10^6 for each cell.

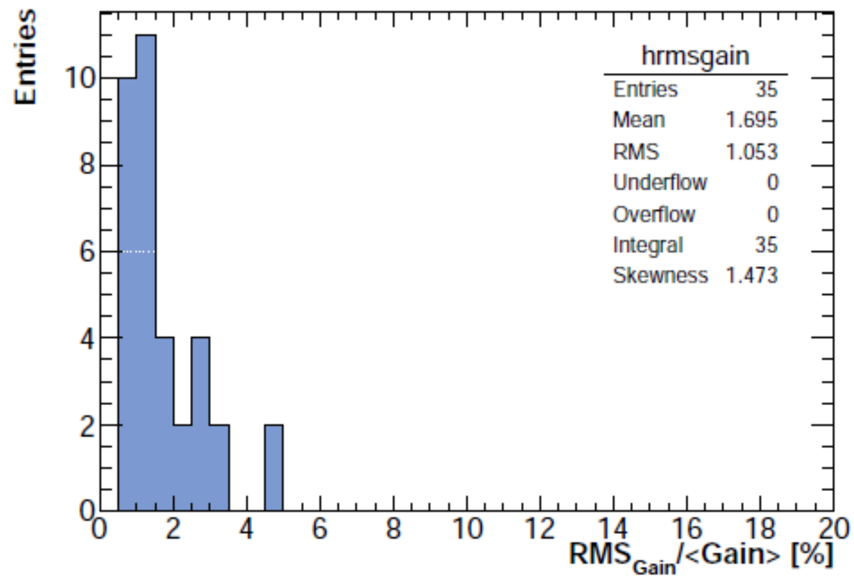
Inside each array, the gain uniformity (RMS/mean) will be evaluated.

The uniformity has to be < 10%

Measured Gain



RMS Gain



Example of results from one vendor

Relative PDE at V_{op} [1/2]

Required: PDE @ V_{op} > 20% at 315 nm, evaluated with a reference device.

- 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}:

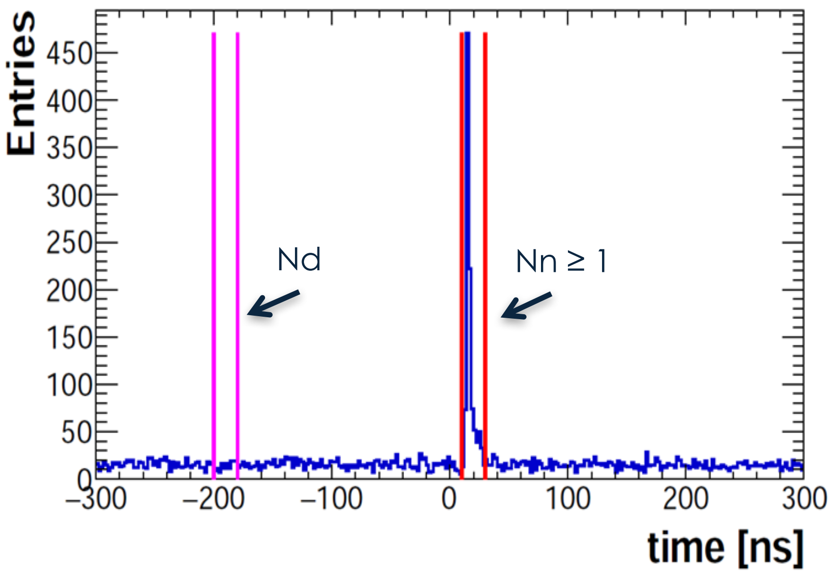
$$n_{pe} = -ln(P(0, n_{pe}, n_{dark})) + ln(P(0, n_{dark}))$$

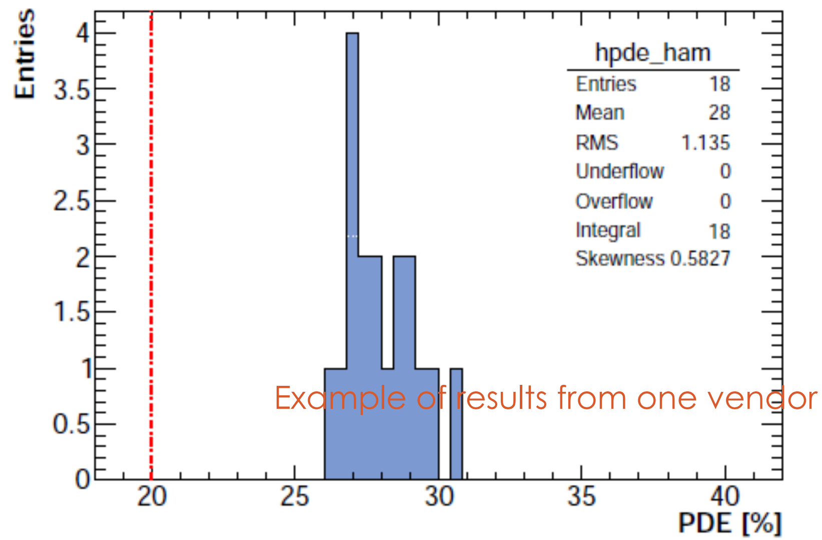
- Finally, expressing the two probabilities in quantities measurable by analyzing the signal waveforms, Nn>1 and Ndark:

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

Relative PDE at Vop [2/2]

- To evaluate Ndark and Nn≥1, we look at the distribution of the peak times, in two fixed time gates of 20 ns each. One in the signal region and one in the "Dark" region. The signal region is in time with the external LED pulser used.





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

MTTF: What we measured

Required: 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**

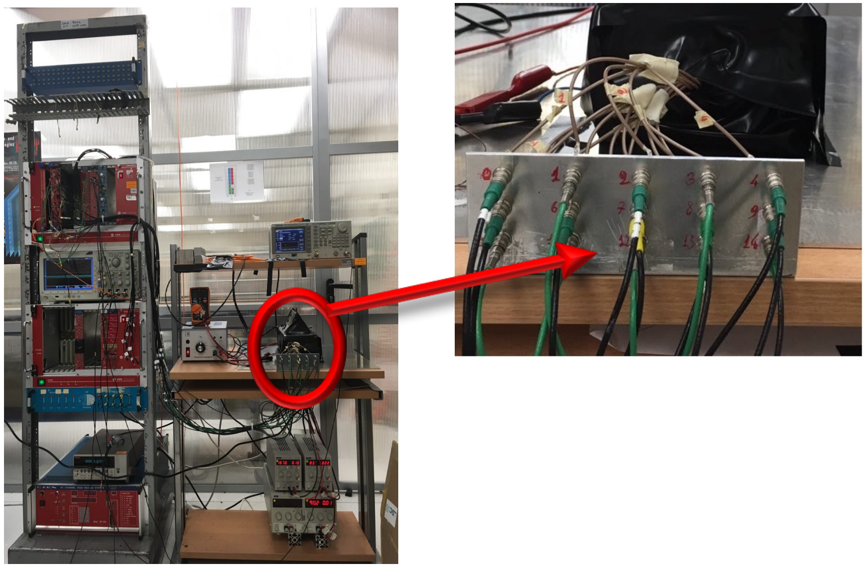
- The Acceleration Factor is extracted from the Arrhenius equation:

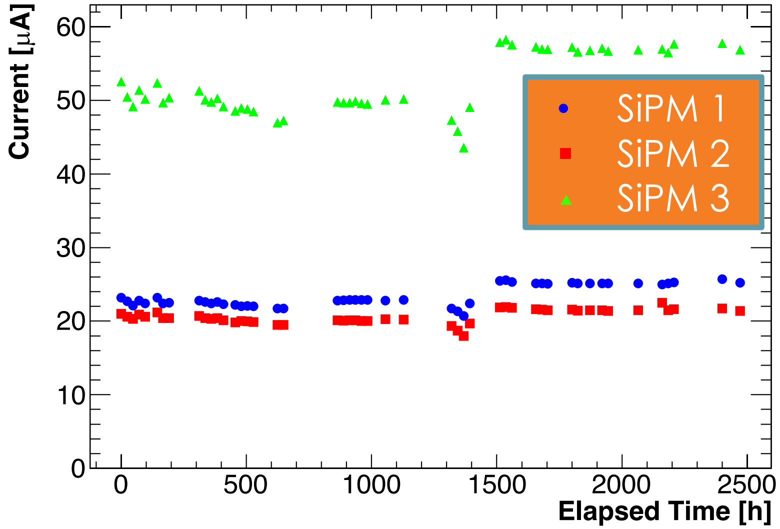
$$AF = exp\left[\frac{E_a}{k}\left(\frac{1}{T_{use}} - \frac{1}{T_{stress}}\right)\right]$$

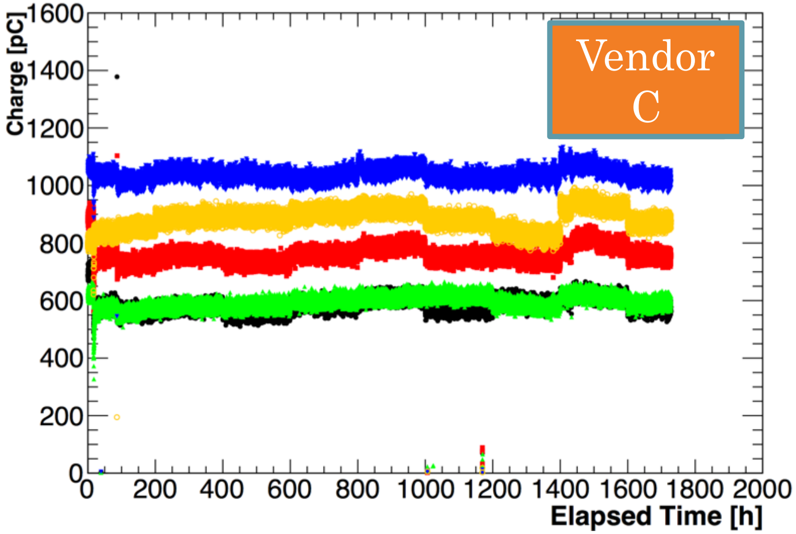
where E_a = 0.6 eV for Silicon, T_{use}= 273 °K and T_{stress}= 323 °K

MTTF - experimental setup & results

- **15 Mu2e-SiPMs** tested;
- Temperature **@ 50 °C** using 2 Peltier cells;
- SiPM temperature monitored by a PT 1000;
- Led pulse every **2 minutes;**
- Current value measured daily





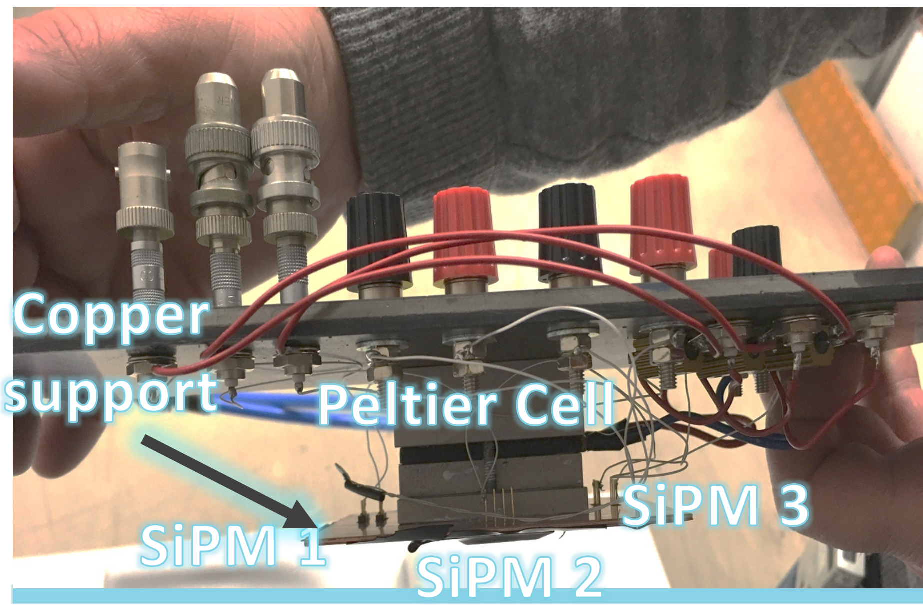


Radiation Hardness: what we have measured

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:

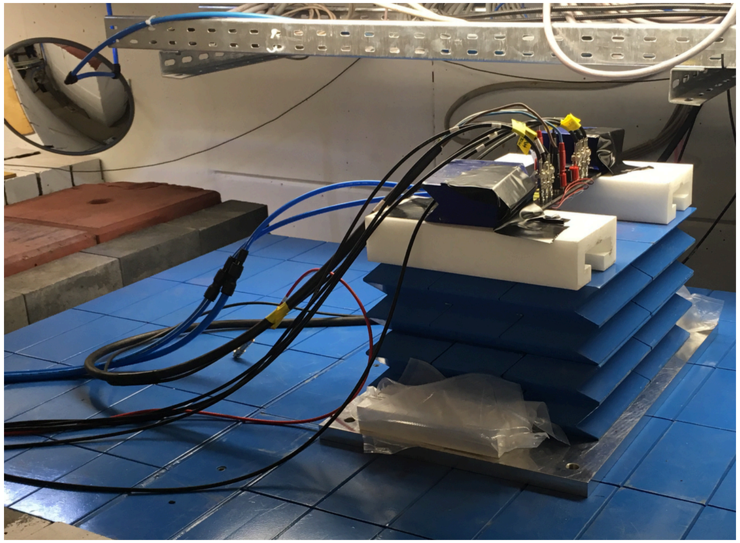
When exposing the SiPM to a neutron fluence of $3x10^{11} n_{1MeVeq}/cm^2$, the acceptable levels of deterioration (for each cell in the array) are:

- A dark current smaller than 10 mA
- A gain reduction of up to a factor of 4

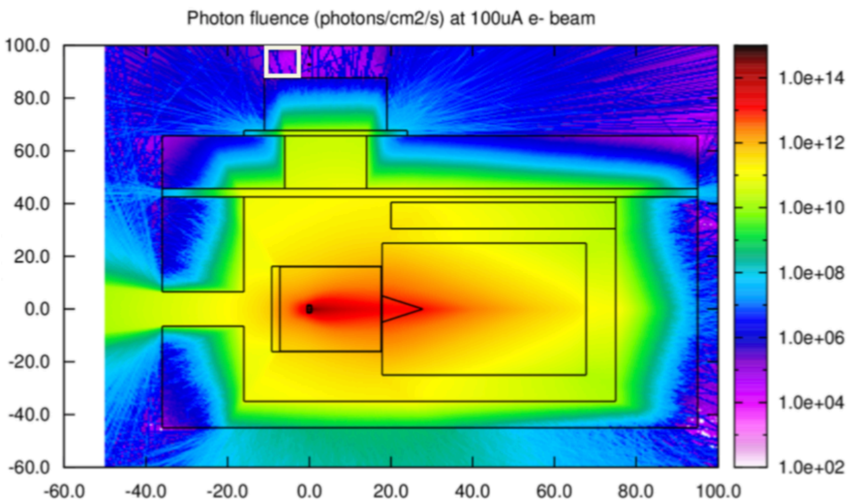


- The test is done reading the dark current with a picoammeter while keeping the array at 20 °C.

Radiation Hardness: Neutron test @ HZDR



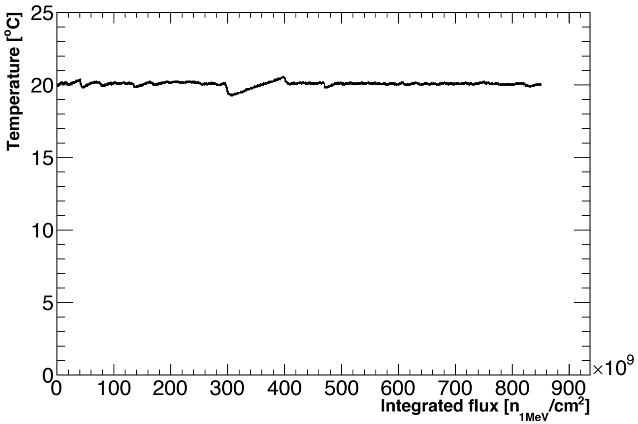
- Test in March at Helmholtz-Zentruf Dresden Rossendord (HZDR, Dresden , Germany).
- It provides **neutrons peaked at 1 MeV**
- Integrated neutron flux reached
  $8 \times 10^{11}\ n_{1\ MeV}/cm^2$



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

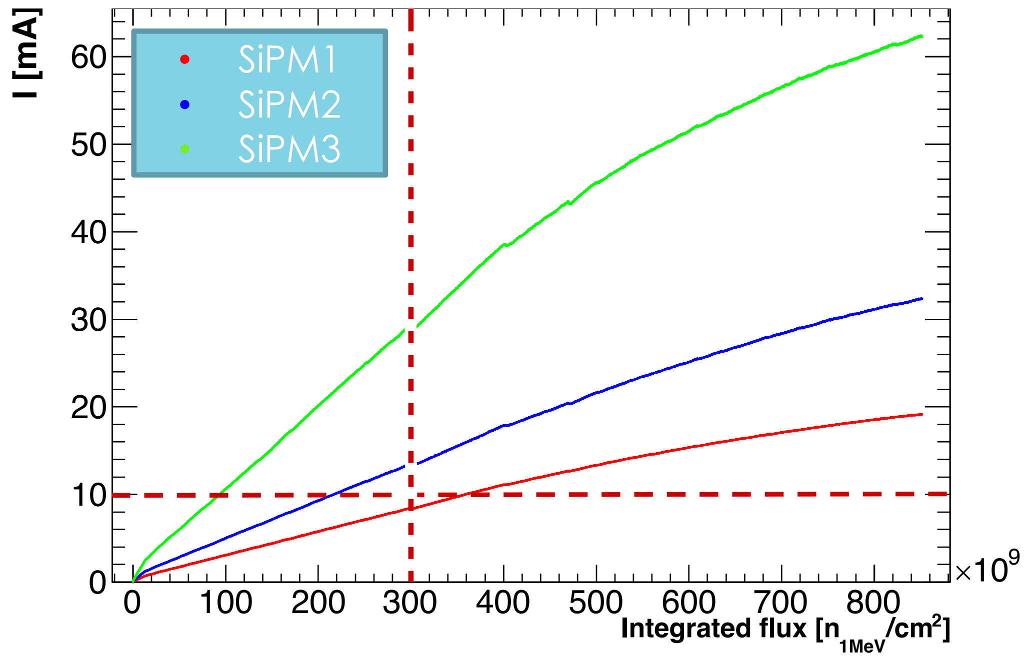
Radiation Hardness - Results

Temperature kept practically stable during all irradiation period (1.5 days of data taking)



To compare with the flux limit imposed in the bid we evaluated the currents at a fluence of @ $3x10^{11}$ n/cm^2 obtaining:

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



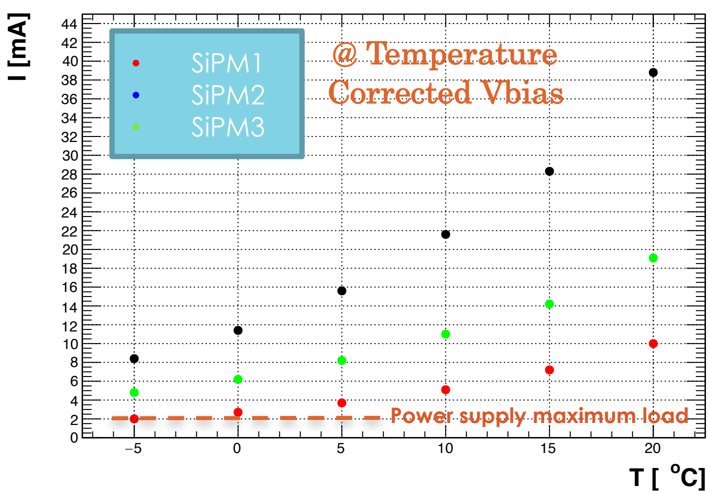
Operation in vacuum

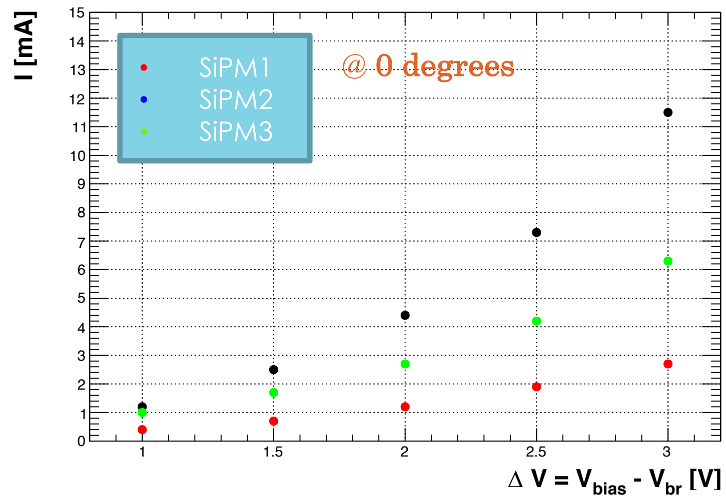
➢ **Inside the DS:**

we will run at ~ 0°C, Vbias = Vop – temperature voltage coefficient

Each photosensor will be characterized in the QA Photosensor Station at **20 and 0°C** → to determine the working point for each running condition (for MPPC this corresponds to around 50 mV/°C).

- Leakage current vs Temperature and vs Vbias for the irradiated SiPM after 1.5 months of annealing at room temperature.





Summary

- The Mu2e SiPMs well match the requirements as photo-sensor for the Mu2e calorimeter
  → They keep the proportionality of the response since at 100 MeV less than 10-15% of the total pixels will be fired
  → Provide an excellent time resolution

- The SiPM radiation hardness to neutrons and ionization dose has been investigated
  → keeping the device at low temperature helps to mitigate the damage

- Three different firms have delivered pre-production SiPM arrays conforming with the Mu2e final SiPM thermal package
  (2x3 array of 6x6 mm^2 cells)
  - ❑ Hamamatsu, FBK and SensL

  → **Measurements showed good quality for the pre-production.**
  → **The international tender will be completed in the next months.**

SPARES

Series polarization -2-

From the maximum acceptable variation in the gain spread (σ_G/G of 3% i.e. small compared to a 5% total resolution) we can derive the maximum acceptable dark current (Idark) variation in one series.

- ❑ The gain dependence on Voltage is linear.
  Typical gain variation is +30%/V → +3% in 100 mV

- ❑ The Idark variation on Voltage is abaut quadratic.
  Typical Idark variation is +100%/V → +10% in 100 mV

We can accept a gain variation in sigma of 3%, this, for a uniform distribution, corresponds to a maximum variation of

100 mV *sqrt(12) → 340 mV → 34% on Idark.

Neutron Damage Problem

How to care catastrophic effect of the leakage current can increment due to the neutron damage?

- ❑ Solution: If only in one (let me say “unlikely to happen”) of the three diodes starts to flow a factor 2000 more of the leakage current, therefore (Vop – Vbr) of this diode will be also reduced

Prescription1: use at the same radius SiPMs of the same series
Prescription2: equalize always with the laser response reducing the total bias voltage applied to the series

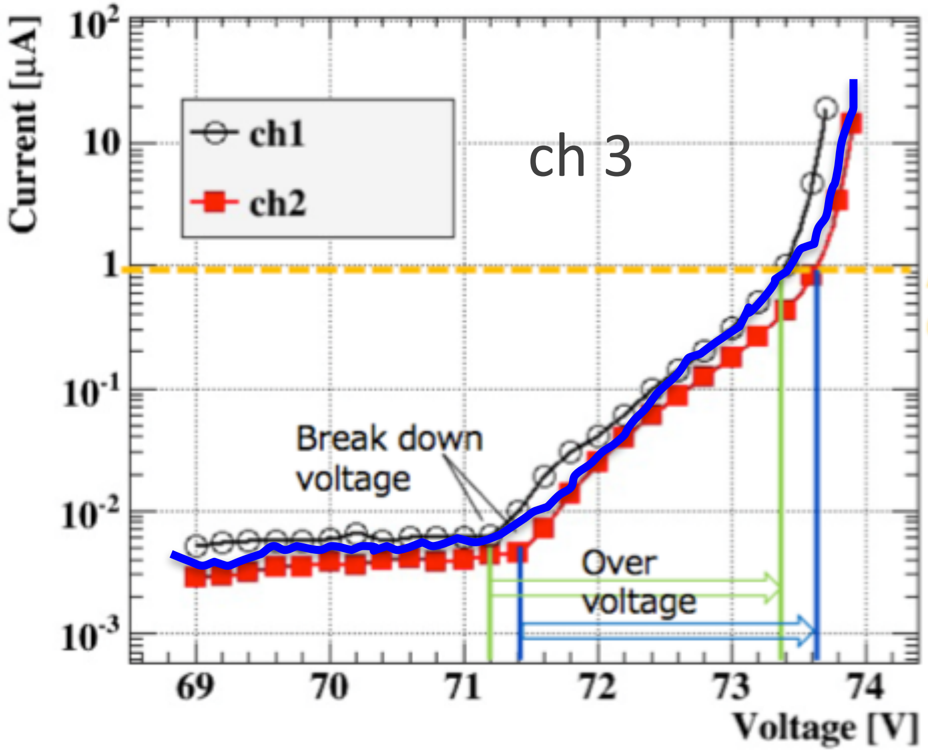
→ **No effect on the other two SiPMs**
→ **We are organizing to measure this effect asap**

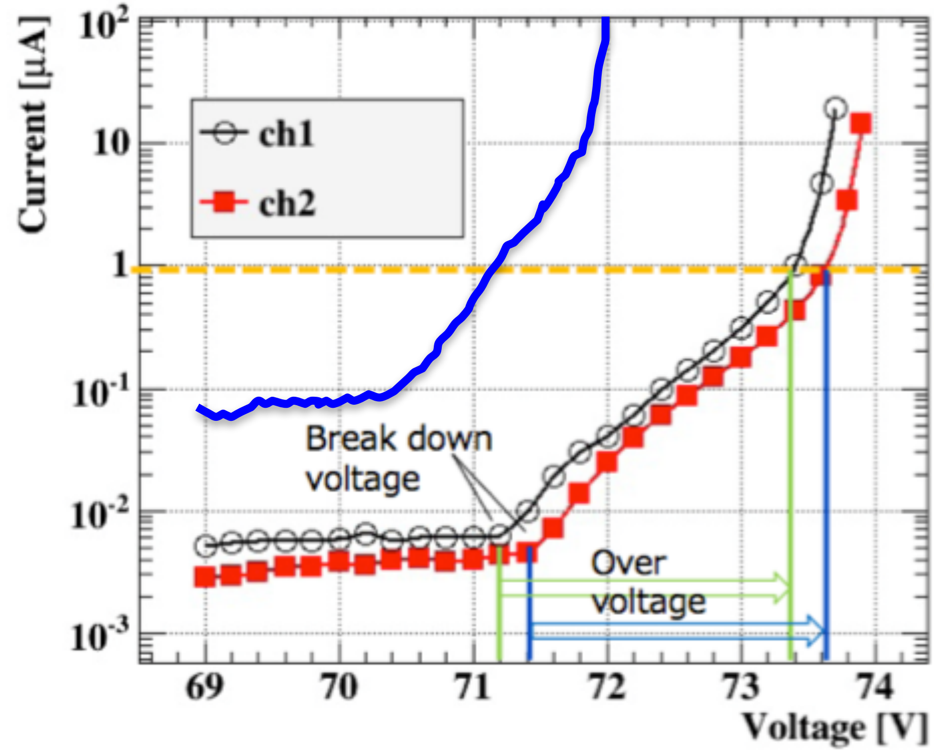
Neutron Damage Problem: IV curve example

Let me do a simple example using a blue curve

Before Irradiation

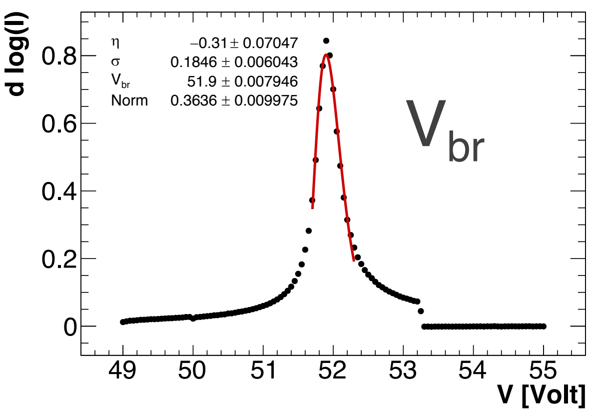
After Irradiation

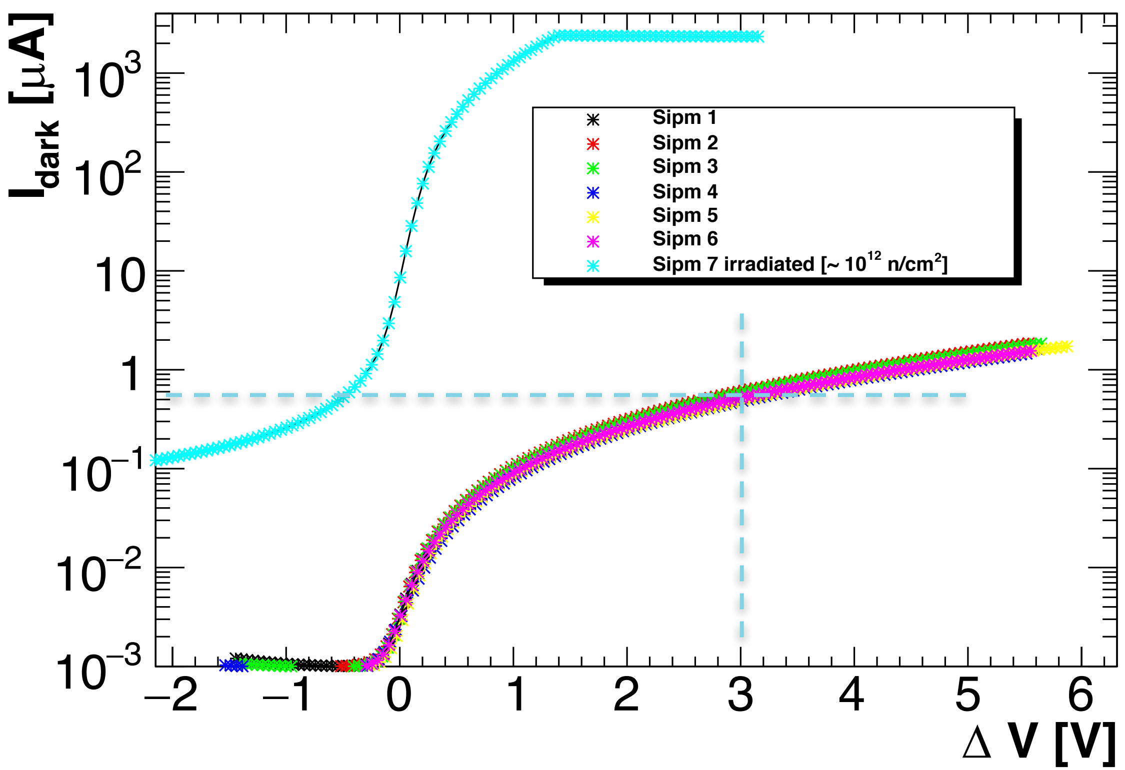




Neutron Damage Problem: IV curve REAL

We have measured I_{dark} vs $V_{op} - V_{br}$ for the 6x6 mm^2 MPPC irradiated at Dresden with ~ 10^{12} n/cm^2 after 1 month (natural annealing occurred);

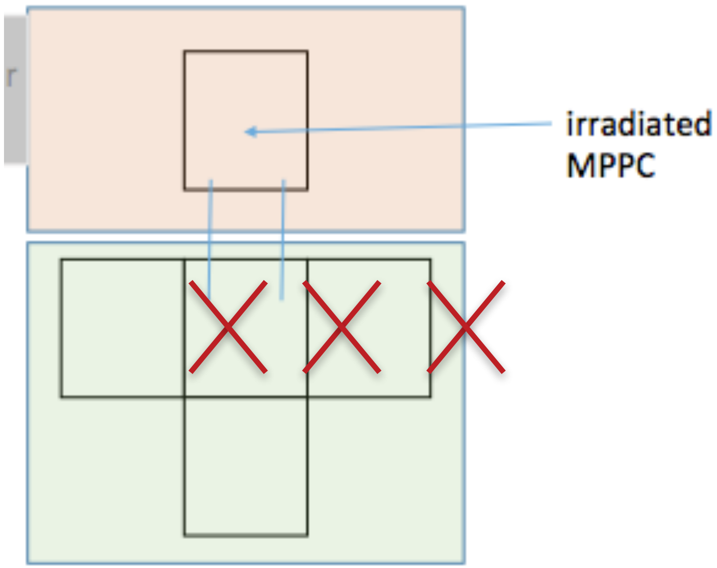


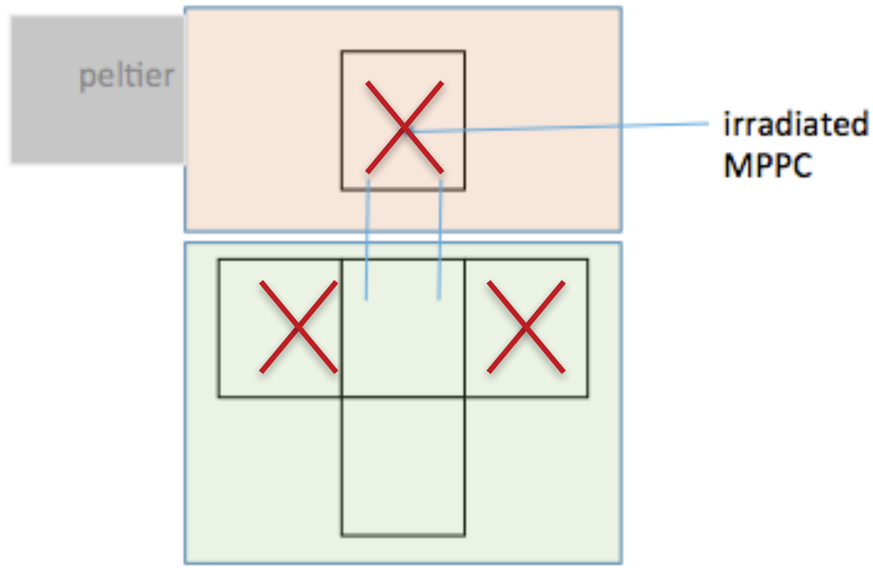


Fixing the operational point at 0.54 uA → ΔV ~0 V for the irradiated MPPC

Neutron Damage Problem: Series Compared

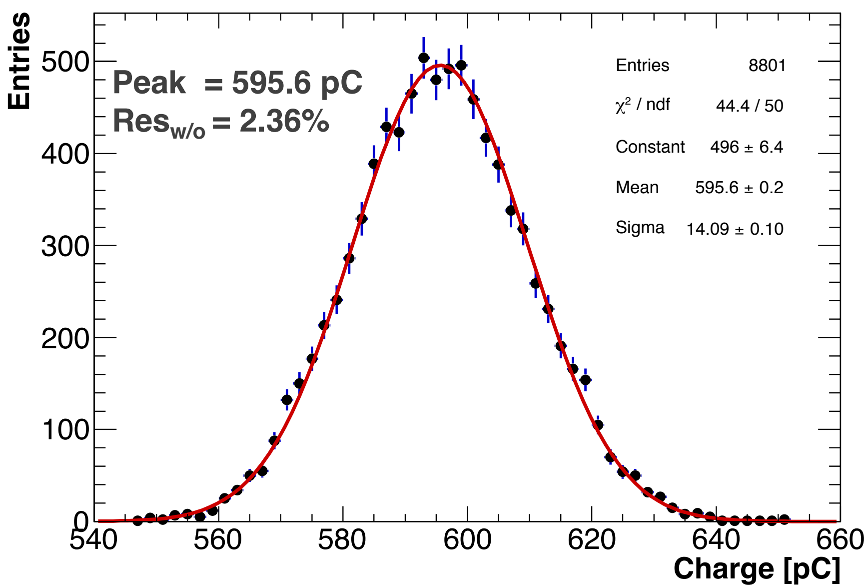
- We have compared the response of the series connection of three MPPCs at a blue laser in the following configurations:
  - Three MPPC not irradiated
  - Two MPPC not irradiated and the one irradiated at Dresden

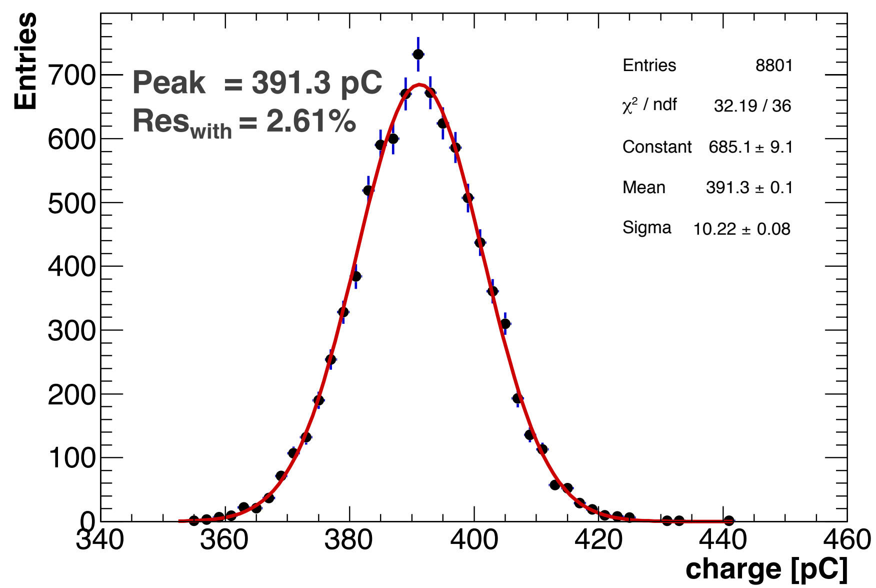




Neutron Damage Problem: Series Comparison

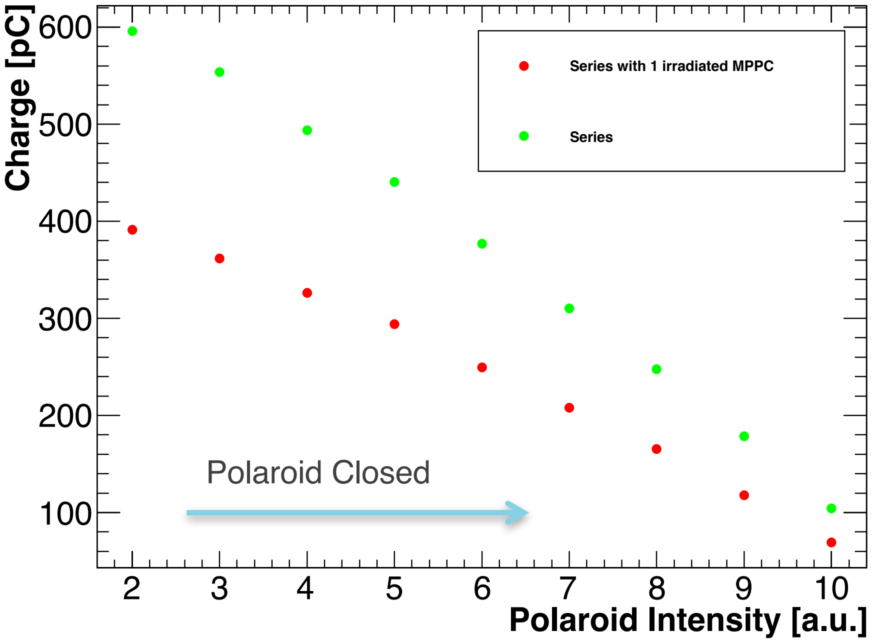
- We have set the operational point at 0.54 uA
  → 166.4 V for the series w/o the irradiated MPPC
  → 162.7 V for the series with the irradiated MPPC
- The light of the laser hits about uniformly the surface of the 3 MPPCs

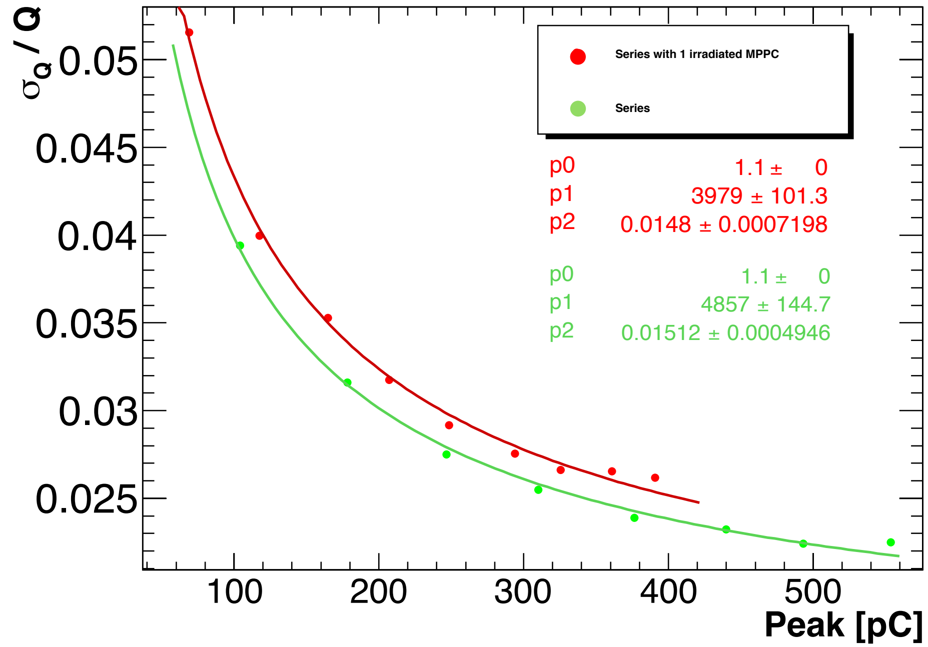




The different of the mean charge is compatible with the hypothesis *ΔV ~ 0 V for the irradiated MPPC* → $Q_{w/o\_irr} / Q_{with\_irr} = 0.66 = 2/3$

Neutron Damage Problem: Series Comparison





The ratio between the series and the series with the irradiated MPPC is: 3979/4857 = 0.82 ± 0.05 even better than expected

✓ Closing the polaroid we lose the uniformity of the light on the three MPPCs

Contribution to the resolution

The contribution of the series polarization to the total charge and thus to the energy resolution could be describes as follow:

$$Q/e = N1G1 + N2G2 + N3G3 =$$
$$(N0 \pm \sqrt{N}1)(G + \Delta G1) + (N0 \pm \sqrt{N}2)(G + \Delta G2) + (N0 \pm \sqrt{N}3)(G + \Delta G3) =$$
$$3N0[G + \frac{1}{3}(\Delta G1 + \Delta G2 + \Delta G2)] + G(\pm\sqrt{N}1 \pm \sqrt{N}2 \pm \sqrt{N}3) + \epsilon =$$
$$3N0G' + \Delta Q_{standard} + \epsilon$$

$$\epsilon = \pm\sqrt{N}1\Delta G1 + \pm\sqrt{N}2\Delta G2 \pm \sqrt{N}3\Delta G3$$

We can measured the contribution with a simple MC

500 pe/SIPM, 3 SIPMs , sigma/Q = 2,5%

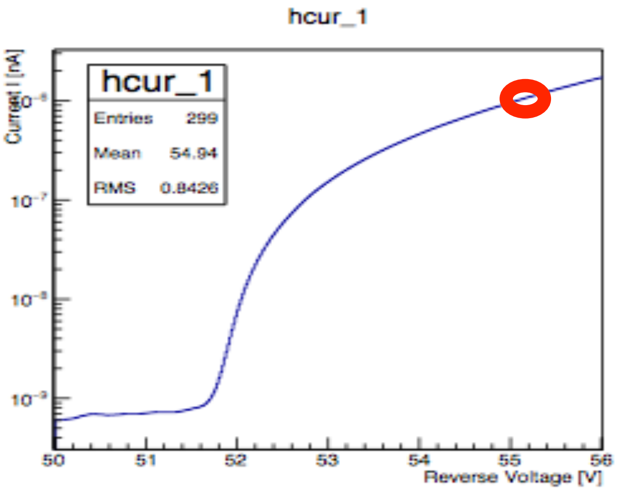
Qtot = G1*N0 + G2*N0+G3*N0
G1 = G0, G2=G0+10%*a, G3=G0+10*b

moving a and b randomly [-3,3]

-60%,-60% → Resol = 2,85%
+40%,+40%→ Resol = 2,6%
-60%,+60% → Resol = 2.8%

Gain variation negligible!!

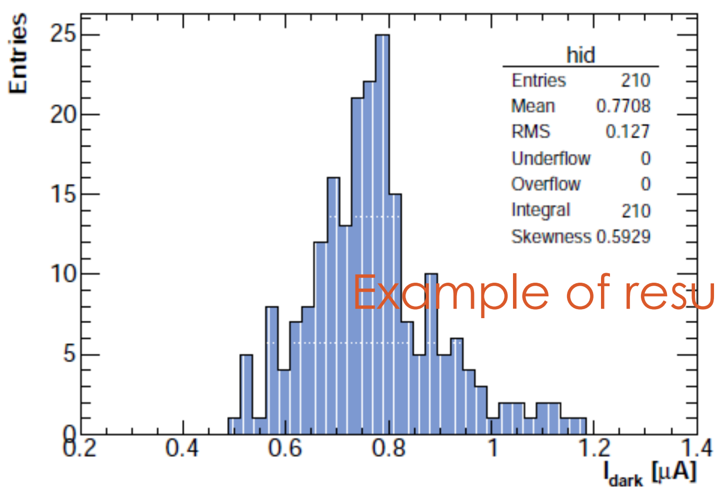
Dark Current at Vop - Results



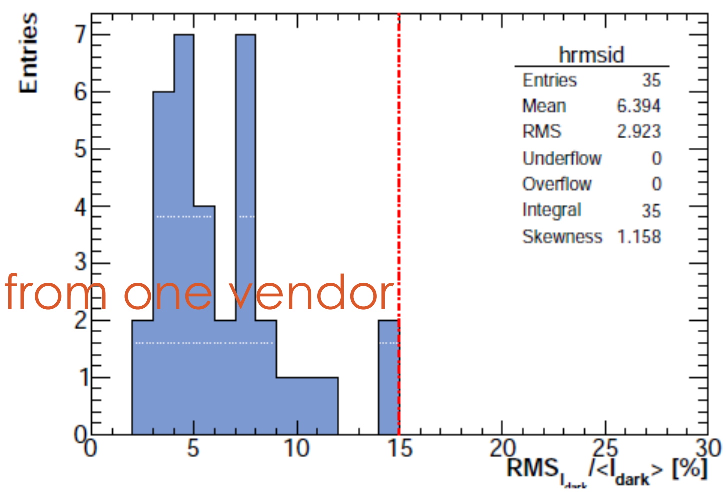
From the same I-V scan we obtained also the I_{dark} value at V_{op}

R2) a relative spread in the dark current at V_{op} between the sensor cells < 15%.

Measured Id



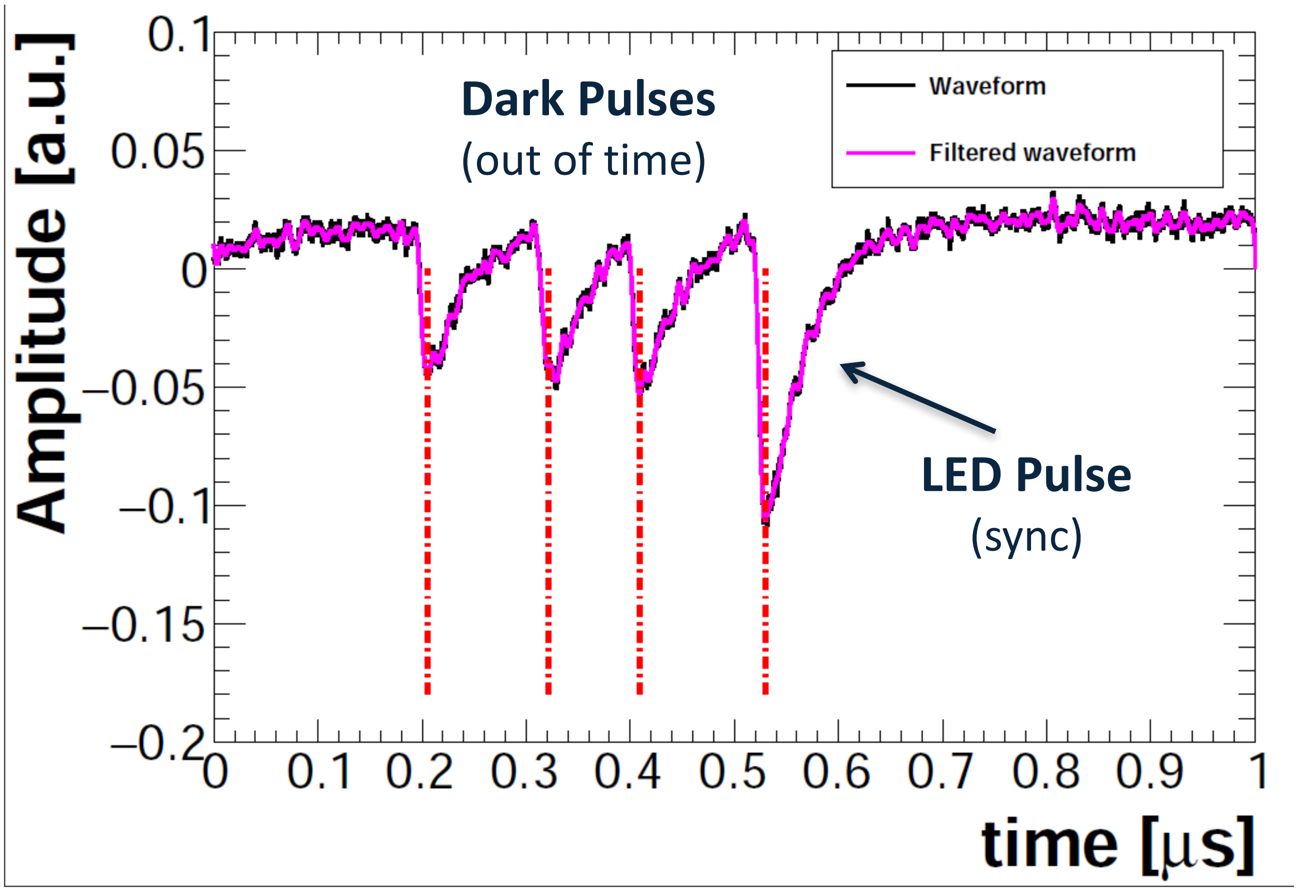
RMS Id



Example of results from one vendor

R4 - Relative PDE at Vop [2/3]

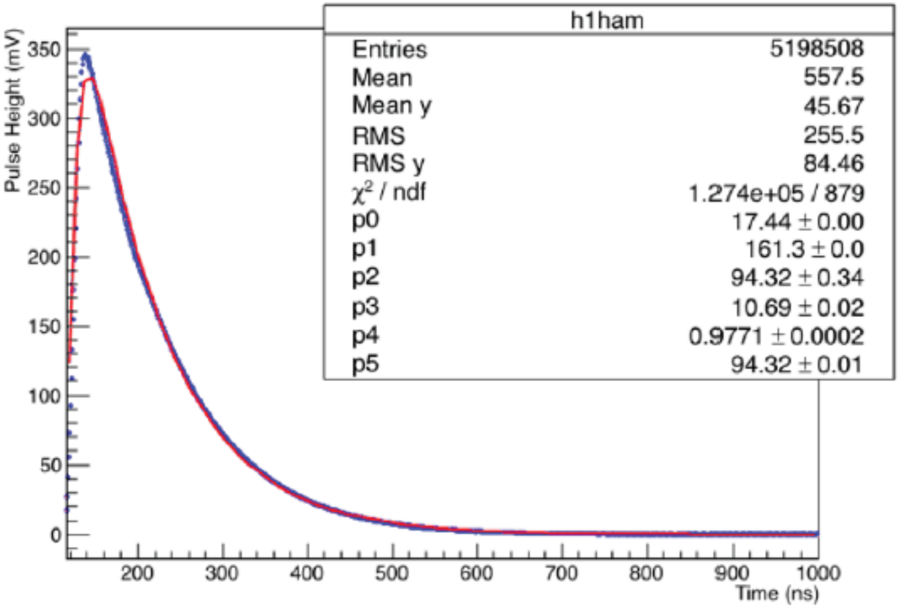
- The LED is powered by 20 ns wide pulses at a frequency of 100 kHz.
- Triggering on the light pulse, a waveform of 1 s is acquired.
- The peak time of each pulse is stored.



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.



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

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)

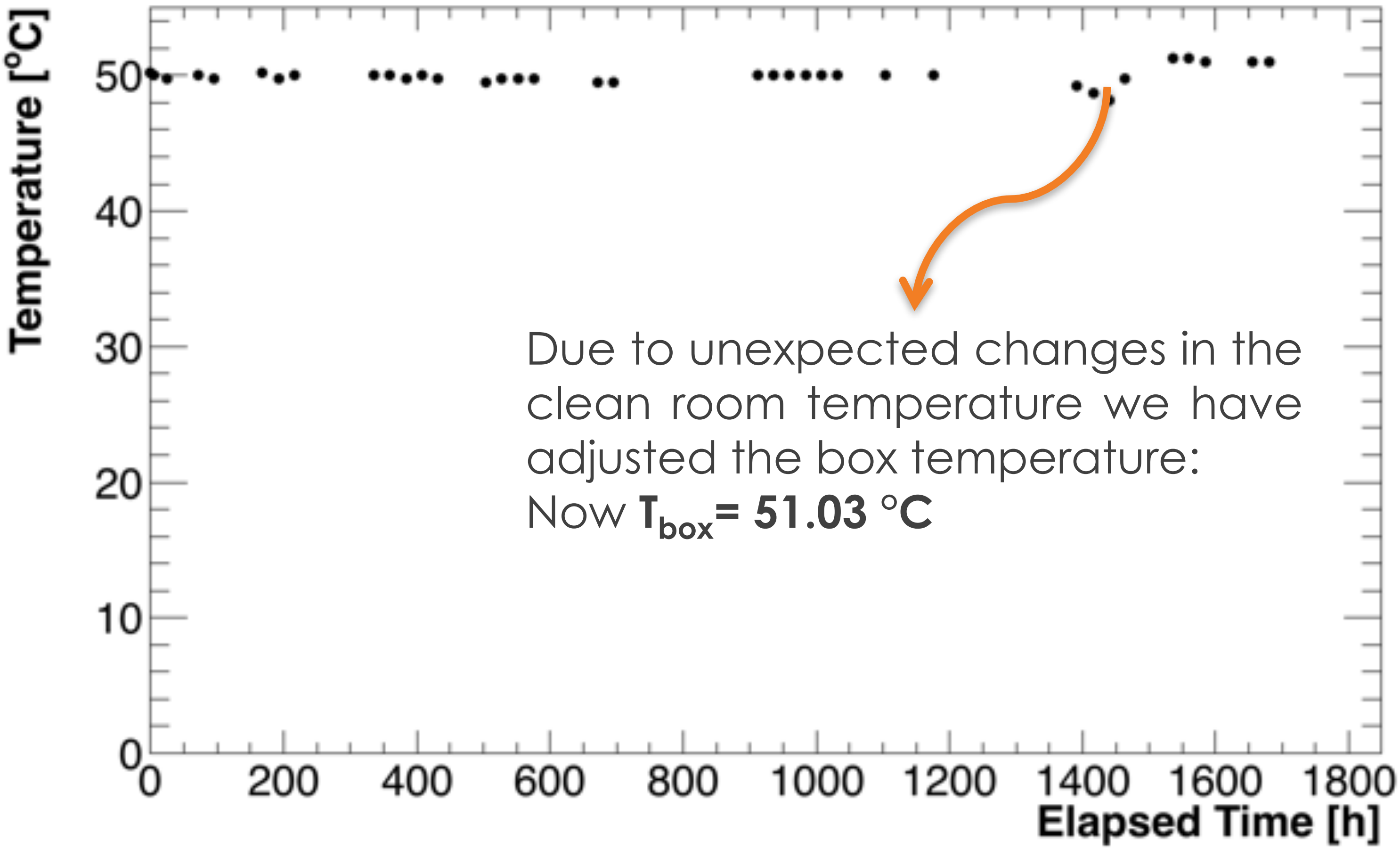
After the high radiation damage (> 2 years of run), we can still work outside the DS with an under bias setting. We will check the signal with the laser

sending a x10 light output.

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.

MTTF – Temperature monitoring



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