Modular and Custom SiPM for the Mu2e Electromagnetic Calorimeter

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Layout

Custom SiPM for the Mu2e Electromagnetic Calorimeter :

1. Mu2e Electromagnetic Calorimeter:
   A custom SiPM.

2. Pre-production and tender:
   QA, Neutron Irradiation and MTTF determination.

3. Production:
   Procurement procedure and tests @ FNAL

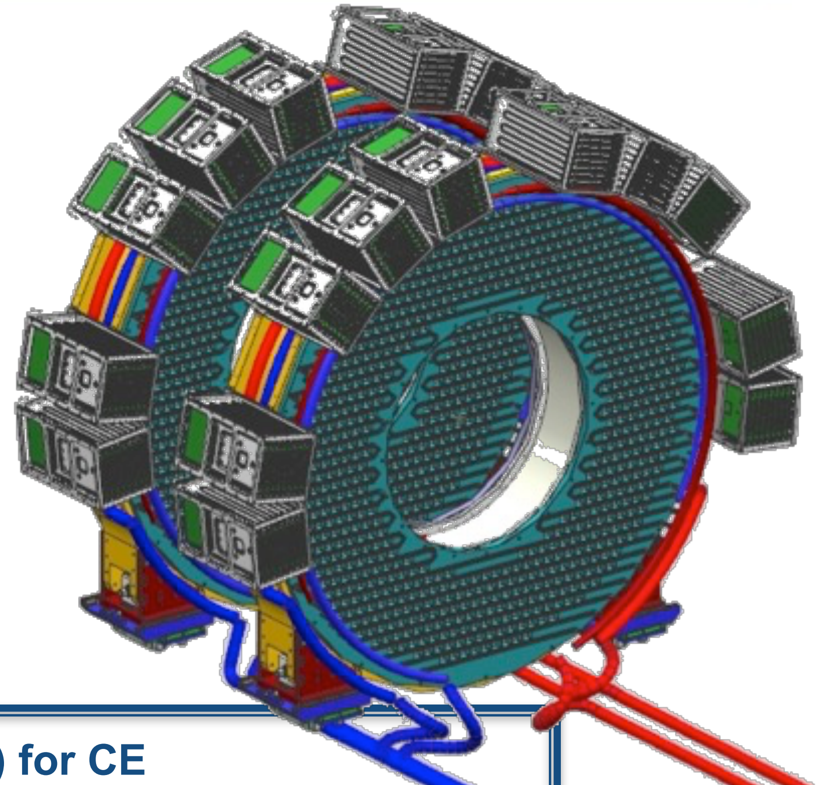
SPARES

- Series polarization

Calorimeter Summary

2 annular disks with 674 undoped CsI (34 x 34 x 200) mm^3 square crystals/each disk

- Operate in 1 T and in vacuum at 10^{-4} Torr
- R_{IN} = 374 mm, R_{OUT} = 660 mm
- Depth = 10 X_0 (200 mm), Distance 70 cm
- Redundant readout:
  2 UV-extended SiPMs/crystal
- **RA source for energy calibration**
- **Laser system for monitoring**



Requirements @ 105 MeV/c

- **$\sigma_E/E = \mathcal{O}(10\%)$ for CE**
- **σ_T < 500 ps for CE**
- **$\sigma_{X,Y} \lesssim 1$ cm**
- Fast scintillation signals (τ<40 ns)
- **Radiation hardness (with a safety factor of 3):**
  - **100 krad (45 krad) dose for crystals**
  - **$3x10^{12}$ n_{1MeV}/cm^2 for crystals**

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 **~ 1.2×10^{12}** n/cm^2 @ 1 MeV$_{eq}$ and **~ 45 krad** for photons (for 5 years of run and a factor 3 of safety);

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

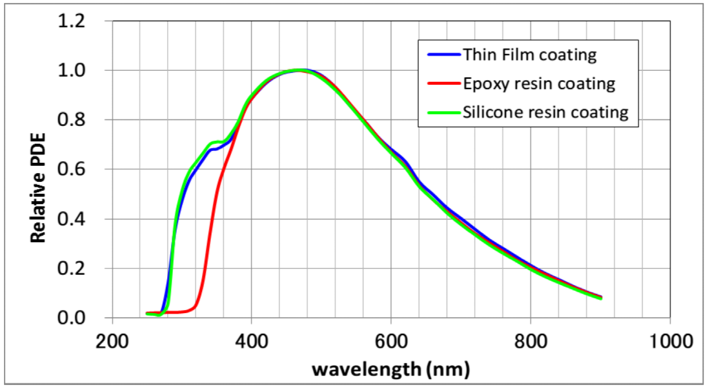
(R5) Have sufficient reliability to allow operation for 1 year w.o. interruption;

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

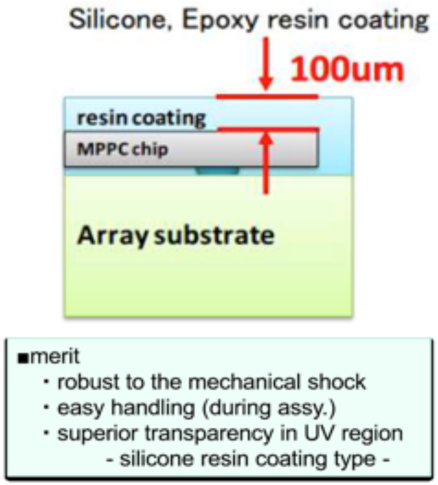
Mu2e Photosensor is a custom SiPM [1/2]

- 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)

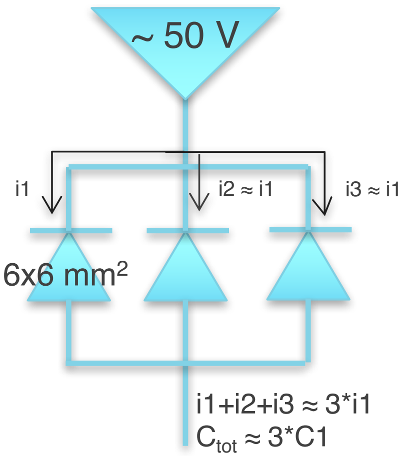


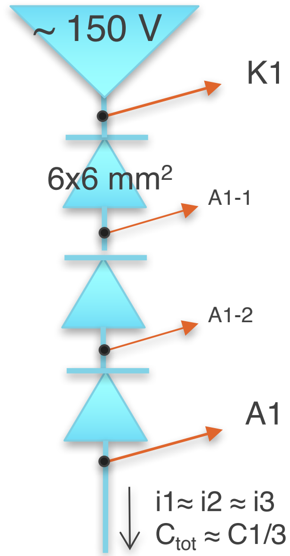
Thin Film coating and Silicon resin coating has PDE advantage in UV region.

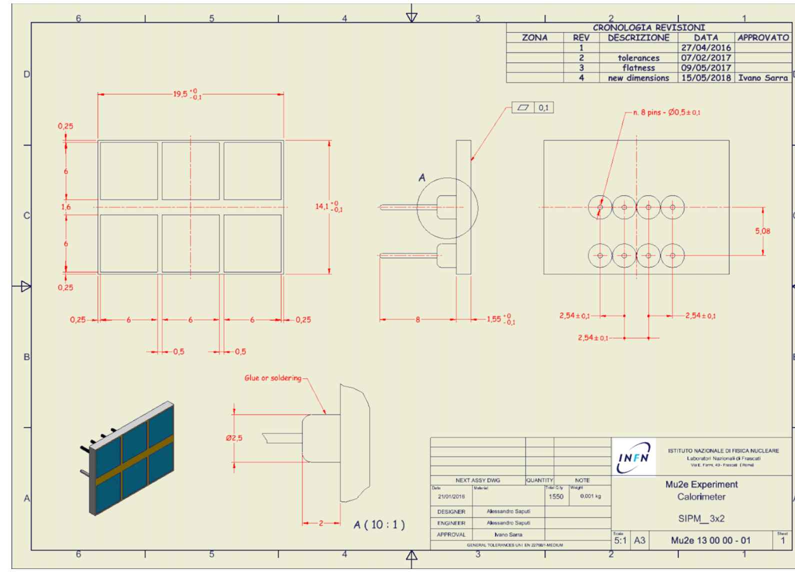


Mu2e Photosensor is a custom SiPM [2/2]

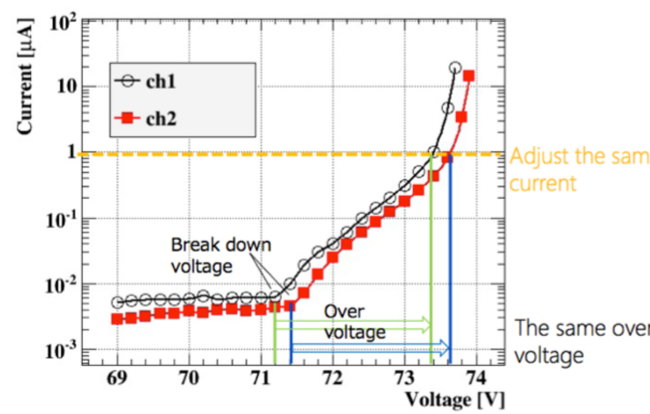
We use a parallel arrangement of two groups of three cells biased in series.





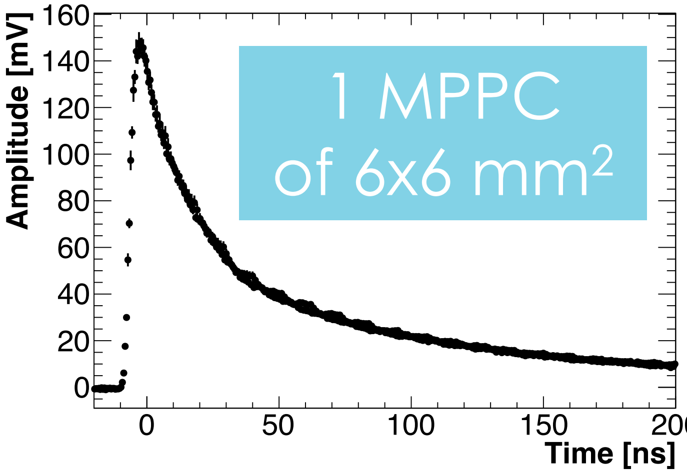


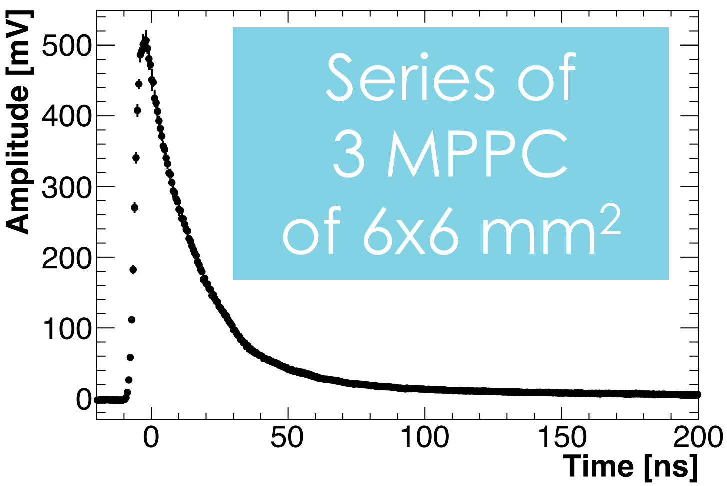
⇒ If the current is at the same level for the SiPMs in the array, their over-voltages are automatically adjusted to be the same.



Series Connection

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



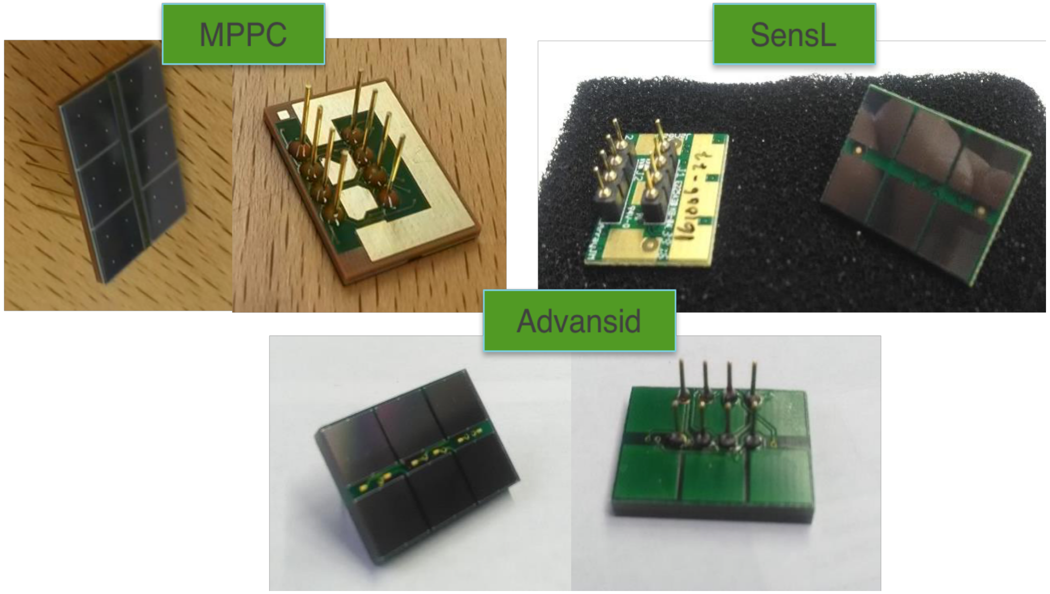


- ✓ The fast rise time is of particular importance for optimizing the time resolution
- ✓ The decay (“quenching”) time is relevant to increase pileup discrimination capability.

Tender and Pre-Production

- The procurement of 150 Mu2e pre-prod SiPMs (50 pieces for each firm, SensL, Hamamatsu, Advansid) has been completed in October 17th 2016,

- The QA tests have been started at the beginning of November.



- **Reminder: the Mu2e SiPM is a 2x3 array of 6x6 mm^2 SiPMs.**

Tender and Technical specs

For each cell (of 6x6 mm^2) of the array we require:

- relative spread in V_{op} = Vbr+3 V in the device < 0.5%;
- relative spread in I_{dark} within the device < 15%;
- Gain @V_{op} > 10^6 , for each SiPM, measured in a gate of 150 ns;
- PDE @V_{op} > 20% at 315 nm evaluated using a reference-device.

And on random sub-sample, we have also to evaluate:

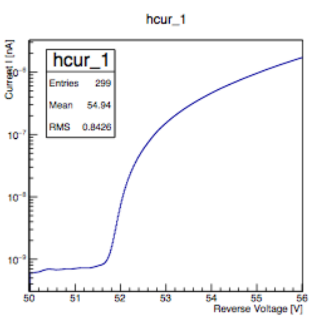
- The radiation hardness: measuring I_{dark} and response drop after an exposure to $3x10^{11}$n/cm^2 , with neutrons 1MeV-eq;
- The mean time to failure (MTTF);
- The recovery time, that has to be < 100 ns for each 6x6 mm^2 cell of the device;
- *In order to cool down the device and to improve the thermal dissipation capabilities compared to commercial designs, we required a thermal resistance of about 5×10^{-4} m^2 K/W.*

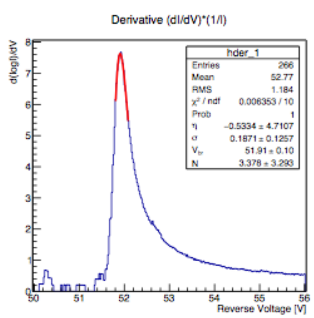
Outcome of the SiPM Tender [1/4]

➢ 150 SiPM arrays where fully characterized with a semi-automatized station:

	Hamamatsu	SensL	AdvanSid
V_{br}	(51.85 ± 0.11) V	(24.87 ± 0.06) V	(27.20 ± 0.04) V
RMS(V_{br})	$(0.070 \pm 0.005)\%$	$(0.13 \pm 0.01)\%$	$(0.11 \pm 0.01)\%$
I_{dark}	$(0.77 \pm 0.13)\ \mu$A	$(1.22 \pm 0.28)\ \mu$A	$(1.07 \pm 0.08)\ \mu$A
RMS(I_{dark})	$(6.4 \pm 0.5)\%$	$(8.1 \pm 0.8)\%$	$(4.7 \pm 0.4)\%$
Gain in 150 ns	$(2.40 \pm 0.01)\cdot 10^6$	$(1.92 \pm 0.01)\cdot 10^6$	$(1.10 \pm 0.05)\cdot 10^6$
RMS(Gain)	$(1.7 \pm 0.2)\%$	$(4.3 \pm 0.5)\%$	$(8.5 \pm 0.7)\%$
PDE @ 315 nm	$(28.0 \pm 1.2)\%$	$(32.4 \pm 1.4)\%$	$(21.3 \pm 0.9)\%$

all of them satisfied the Mu2e technical requirements.





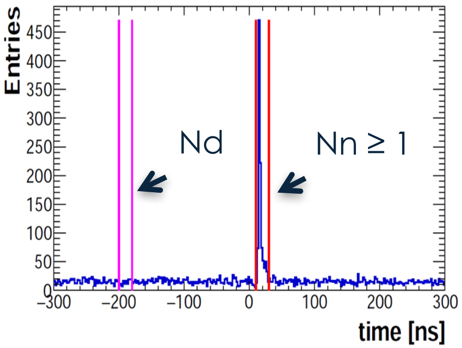
- The operating voltage Vop has been set at Vb + 3 V
- I-V scan performed in range that varies among the vendors:
  → **Hamamatsu** [50, 56] V, **SensL** [24, 30] V, **Advansid** [26, 32] V

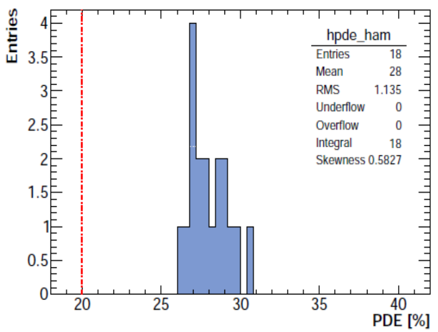
For each SiPM cell, Vbr is found as the maximum of the dlog(I)/dV

Outcome of the SiPM Tender [2/4]

To evaluate Ndark and Nn≥1, we looked 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.

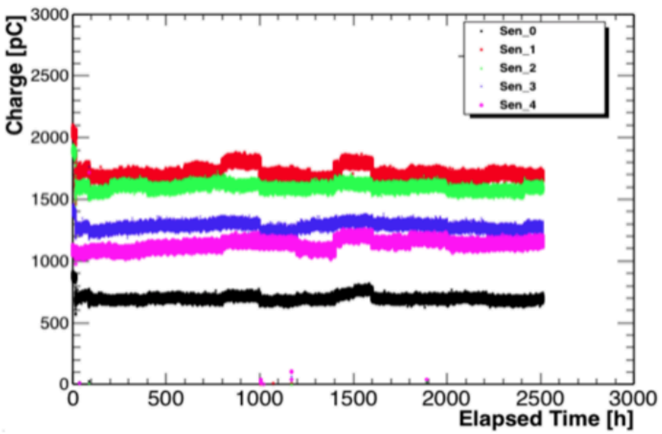
To simplify N_{gamma}, the obtained PDE has been rescaled relatively to a reference sensor of well known PDE of 22%.





- We also verified that the MTTF of these SiPM is larger than $O(10^6)$, thus satisfying the Mu2e technical requirements.

- **15 Mu2e-SiPMs** tested (5 per firm);
- Temperature @ **50 °C** using 2 Peltier cells;
- SiPM temperature monitored by a PT 1000;
- Led pulse every **2 minutes;**
- Current value measured daily
- Charge acquired continuously



Outcome of the SiPM Tender [3/4]

- ➢ The operability of the devices was also test under neutron fluence up to 10^{12} n-1MeVeq/cm^2:

- A sample of each vendor has been exposed to neutrons generated by the **Elbe Positron Source facility (Dresden);**
- The facility provides 1 MeV neutron from electron beam interacting with a tungsten target. Photons are reduced with lead shielding.
- Test results, published in **JINST 13 (2018) no.03 T03005**, show that the dark current increases almost linearly with the neutron fluence.

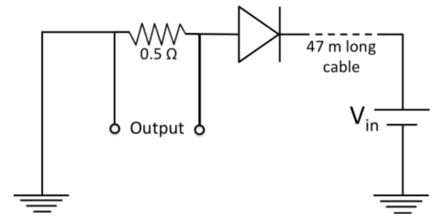
Outcome of the SIPM Tender [4/4]

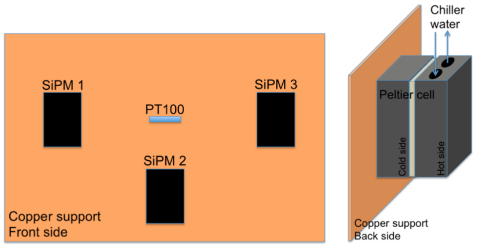
3 SiPMs were tested at the same time under bias;

Chiller+ Peltier cell to fix the temperature on the device back plate;

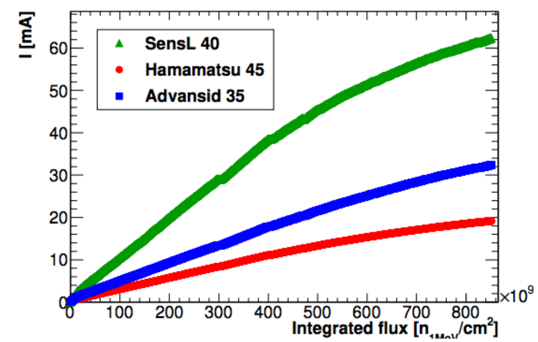
T(back plate) monitored with a PT 100;

Single cell current + temperature acquired with a Agilent 34972A Unit every 10 s.





SiPM vendor	T [°C]	V_{op} [V]	I_d [mA]	I_d (after ~ 2 months) [mA]
AdvanSiD 35	20	29.9	32.4	19.1
Hamamatsu 45	20	54.7	19.5	10.0
SenSL 40	20	27.9	62	38.8



❑ All three pre-production firms have been capable of producing our Custom SiPM array:

→ QA measurements showed good quality for the pre-production.

➢**Hamamatsu has resulted the winner for the tender:**

→ **best scores for QA and economical parts**

Production: procurement procedure

The SiPMs QA is all localized @ FNAL. Per batch:

1. Shipment at FNAL **~ 300 pieces for month** started from March 2018
2. Mechanical and dimensional inspection
3. QA test on **all** the **pieces**
4. MTTF on **15 pieces**
5. Irradiation with neutron on **5 pieces** at Dresden

After the procurament of all 4000 pieces

1. Gluing the SiPM/FEE on the mechanical holder at FNAL
2. Test of the complex SiPM-FEE unit with LED at FNAL

For each final production batch:

- QA for all pieces → Sensors not meeting specs will be rejected;
- MTTF → These sensors should all survive at least 18 days burn-in at 65 degrees;
- Radiation Hardness → If more than 3 out of 5 irradiated SiPMs fail to meet our specifications, we will reject all the received batch.

QA Laboratory Layout

1: Shipping station

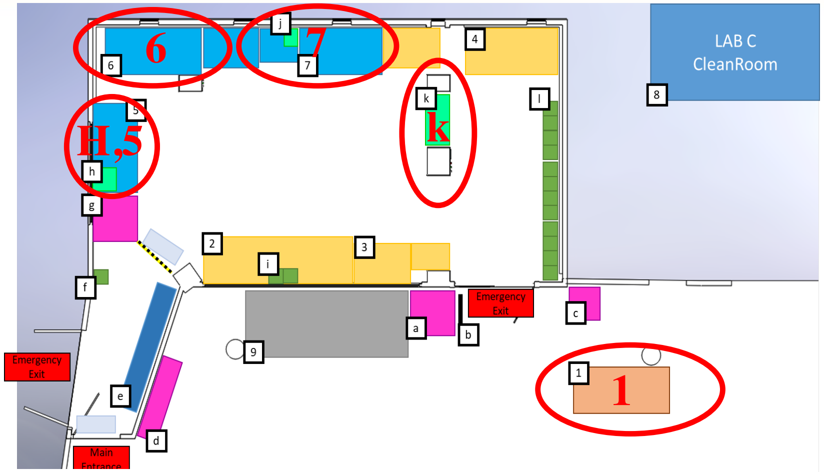
h: SiPM incoming cabinet

5: SiPM mechanic and dimensional station

6: SiPM QA station

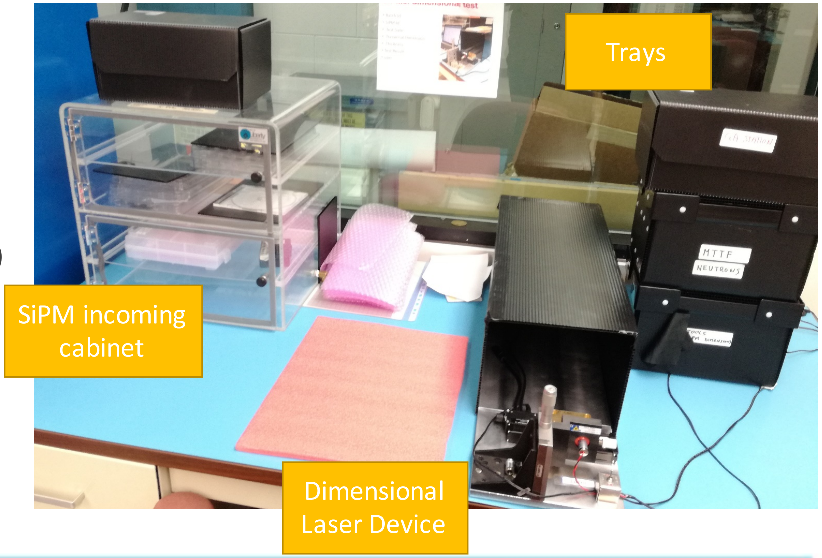
7: SiPM MTTF station

K: SiPM storage drawers



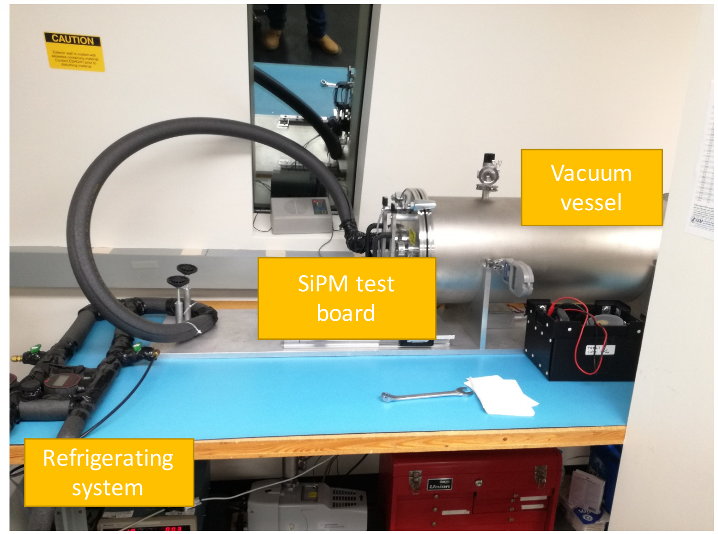
SiPM mechanical and dimensional station

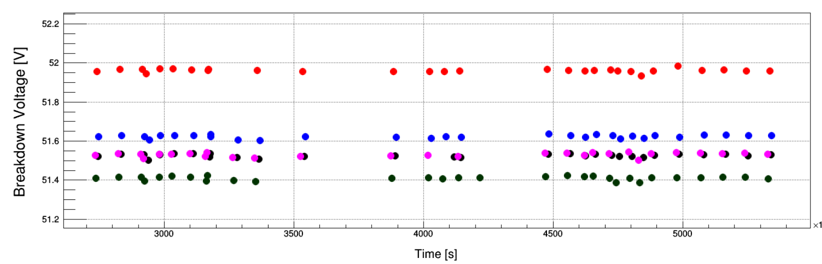
- Integrity and damages check
- Measuring of SiPM dimensions (transversal dimensions and thickness)
- Go, not-go gauge test station

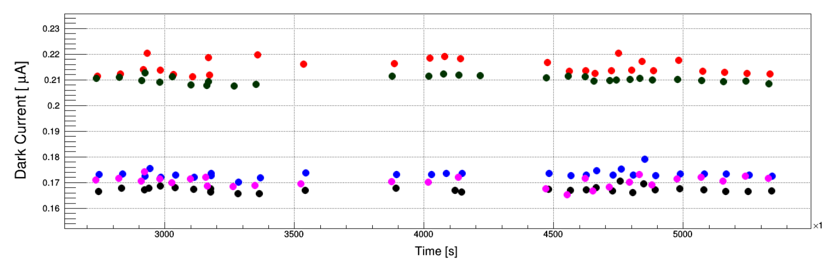


SiPM QA station

- Characterization of dark current
- Characterization of break down voltage
- Characterization of gain x PDE
- Temperatures: -10°C, 0°C, 20°C
- 20 SiPMs at time
- 15 hours per test
- 5 SiPMs as reference sensors







5 Reference SiPMs:

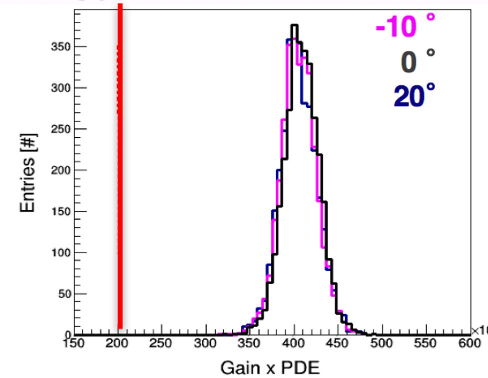
Blue → SiPM 315
Black → SiPM 489
Red → SiPM 407
Green → SiPM 259
Magenta → SiPM 485

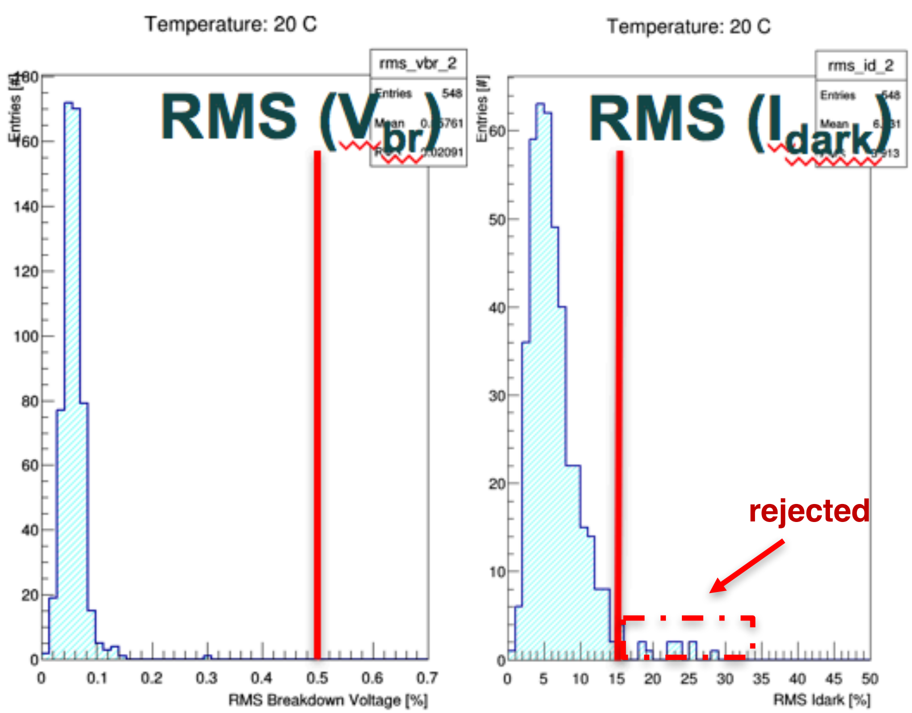
Some pictures and results

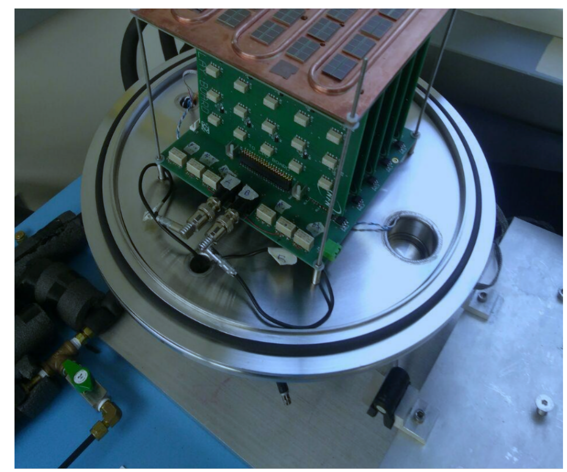
About **1100 Mu2e SiPMs already characterized**

- ~ 300 pieces/month from March 2018
- All the 6 cells tested, measuring **V_{br}, I_{dark}, Gain x PDE**
- 3 % of tested SiPMs rejected (defective or with high I_{dark} RMS)

Gain x PDE







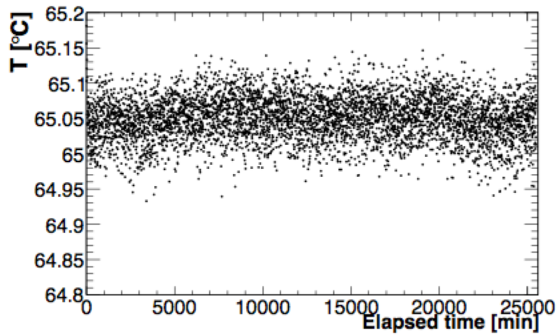
MTTF station

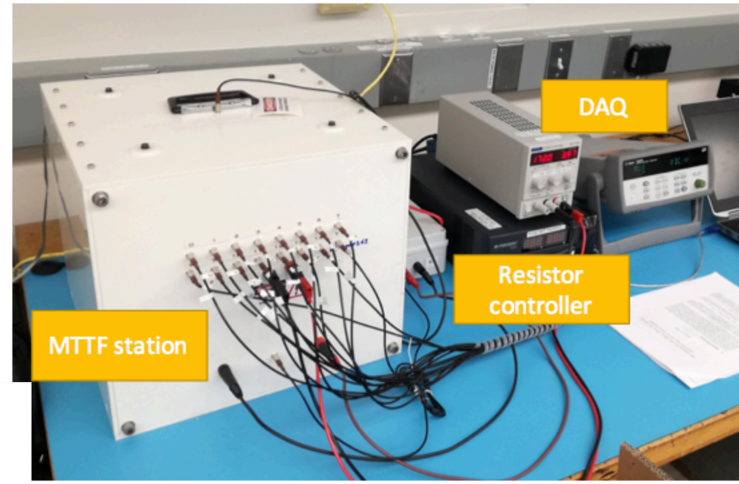
SiPM have to grant an MTTF of 1 million hours when operating at 0°C

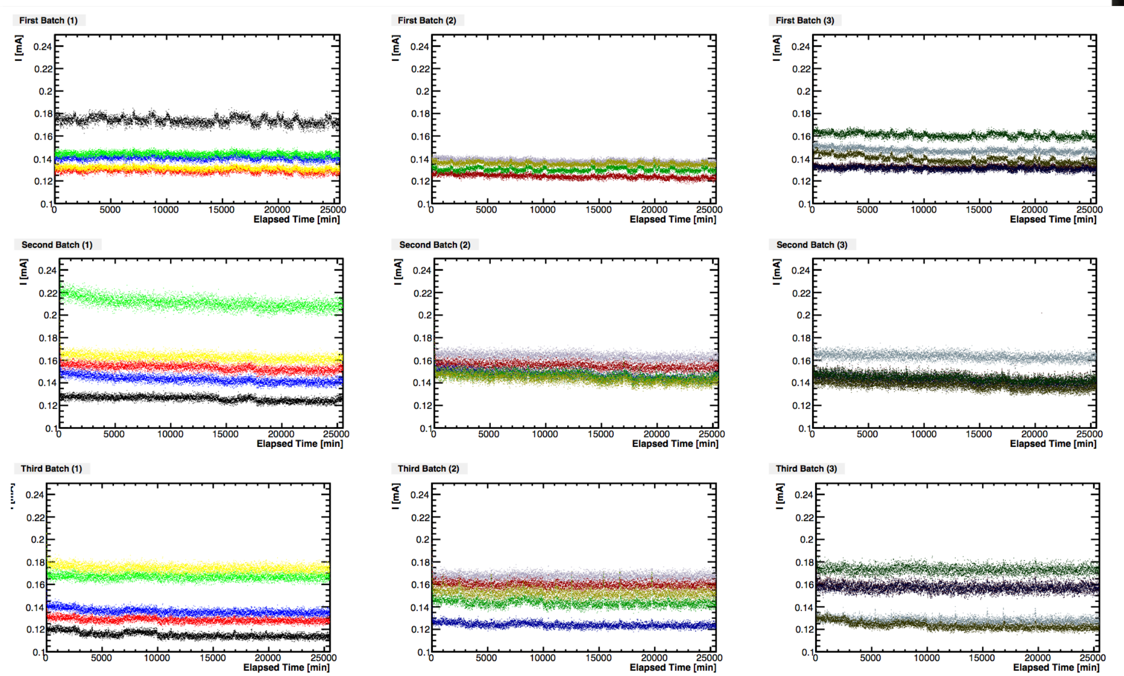
Temperature 65°C

18 days per test

15 SiPMs







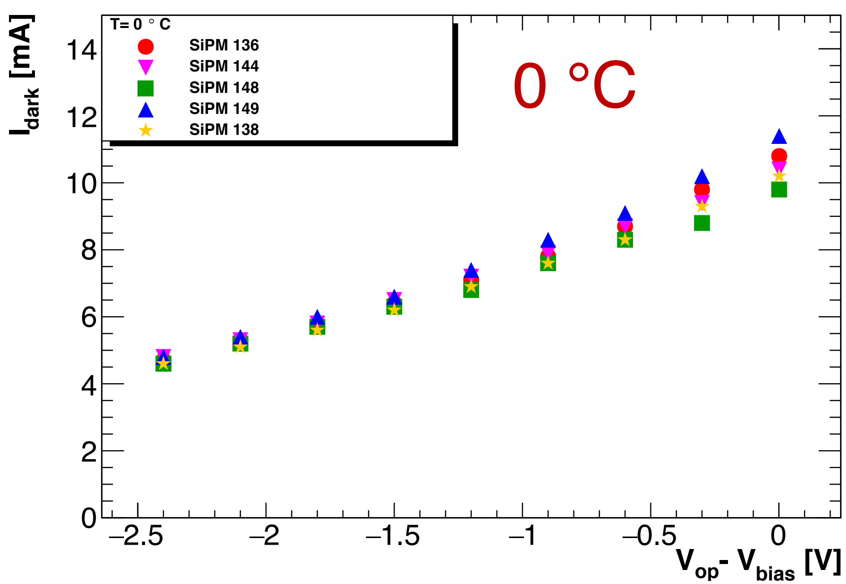
Current behaviour wrt time of the MTTF test of the first three batches

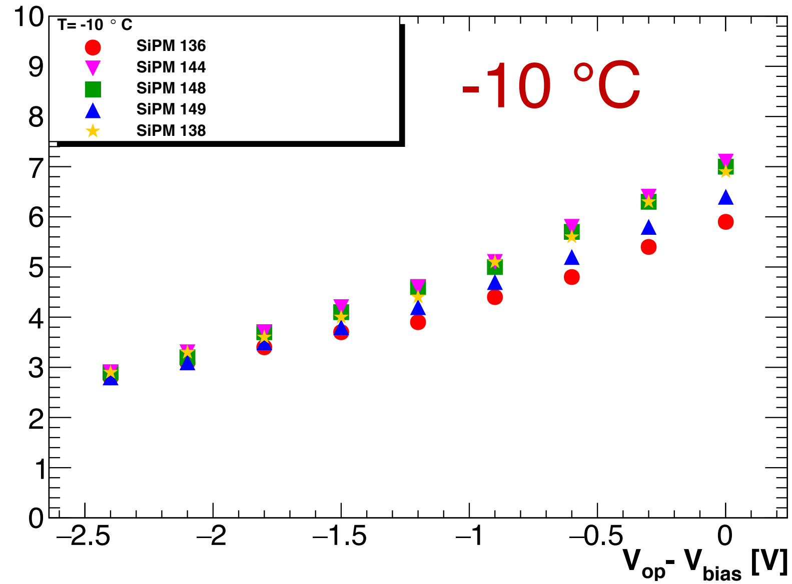
Irradiation

➢ Results for a single cell exceed the front-end electronics requirements, i.e. **I_{supply} < 2 mA/channel for the series.**

- SiPMs irradiated in the pre-production and in the production have been tested to study the current variation with respect to temperature.

❑ After completing this first study, the SiPM temperature has been fixed at 0 and -10 °C and the current has been acquired at different bias voltages.



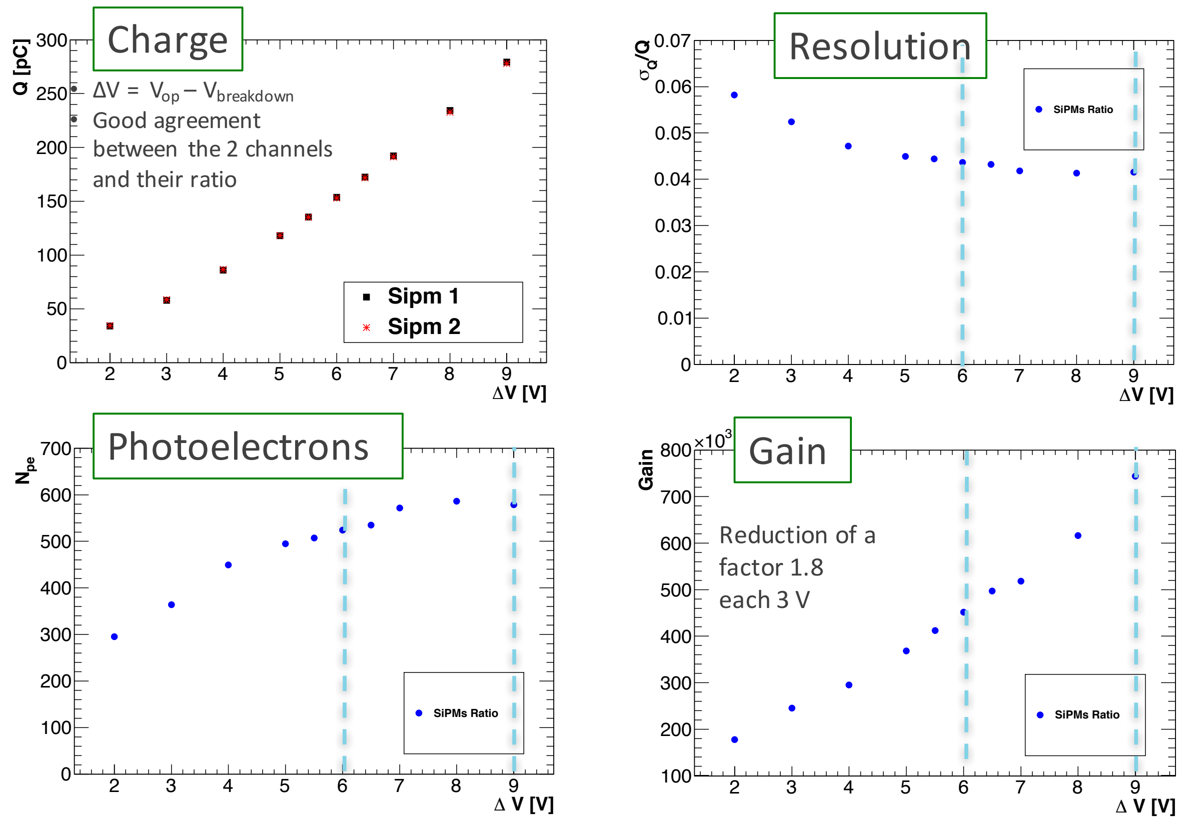


SiPM response and resolution vs V_{bias}

➢ Decreasing the SiPM temperature and/or reducing bias voltage we will keep I_{dark} below the 2 mA limit (due to power-supply).

From our measurement using an LED:

- N_{pe} reduction of 20% each 3 Volts
- Gain reduction of a factor 1.8 each 3 Volts



Conclusions

- 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

- **Large Scale Characterization shows stable results on more than 1000 Mu2e SiPMs tested.**

- SiPM temperature of 0°C is our default running condition.
  This is driven by radiation hardness considerations.

- We can operate running at -3 V, losing 20% of p.e and a factor 1.8 of gain
  → Our FEE has a switchable gain x2.

SPARES

Series polarization

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 about 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.

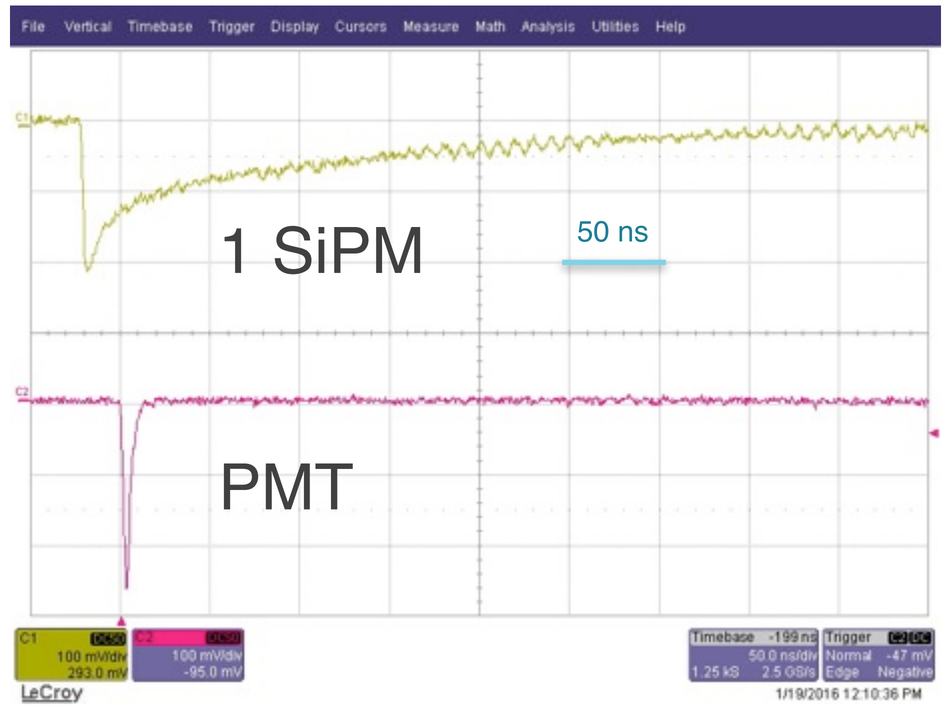
Measured performances for FBK

Voltage = Vbr + 4 V, G = 1.2×10^6 PDE = 30% @ 310 nm
We have pulsed the SiPM (6x6 mm^2) with a UV led (360 nm)

- Very long Signal due to the quenching resistors ~ 2 MΩ per pixel
- Measurement consistent with FBK values
  $\tau \sim 100$ ns
- Rules of the thumb:
  → 50 kΩ for 1 V of overvoltage. So FBK will produce for us SiPM with quenching resistors of 250/500 kΩ

We have tuned all the required parameters with Alessandro Ferri (FBK researcher) in the last days.

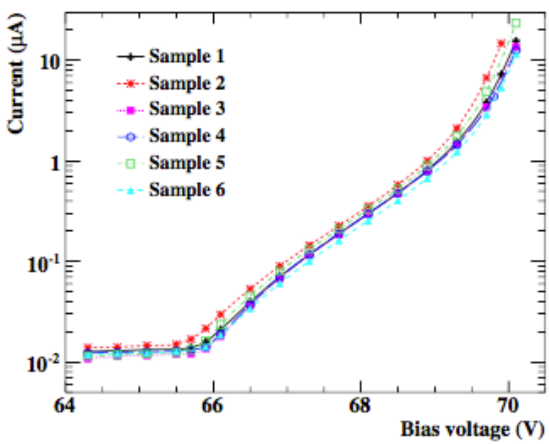
→ Cooperation with FBK is going well



Series Connection -1-

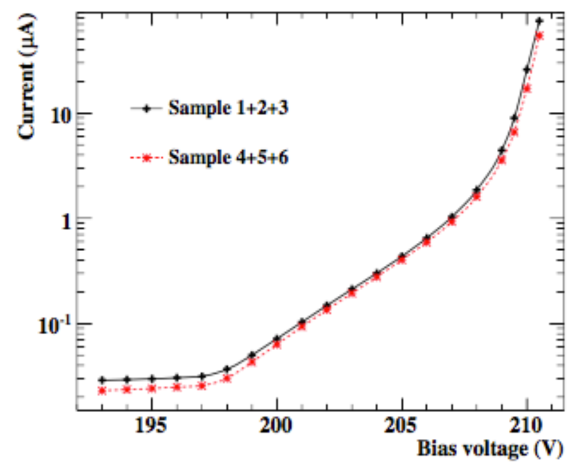
One of the advantages of the series connection compared with the more conventional parallel connection is the **automatic adjustment of over-voltage** among the three SiPMs, even if the individual breakdown voltages are different.

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

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.



I-V characteristic curves for two examples of three SiPMs operated in a series configuration

Series Connection -2-

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.

This 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.

Rules of τ

The τ of the quenching time of a SiPM depends on two factors:

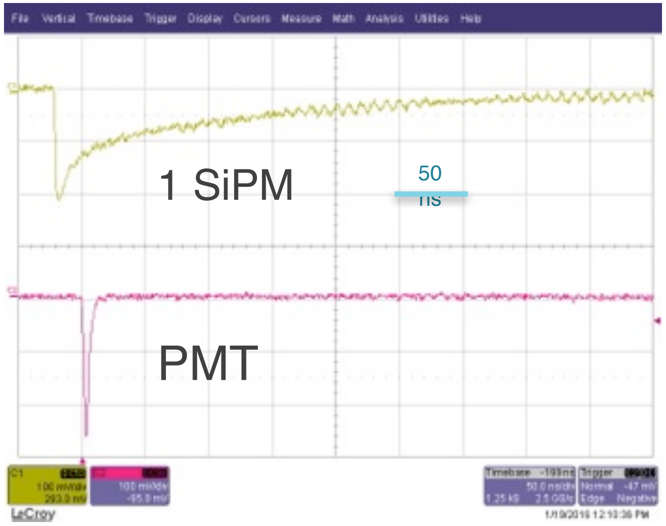
1) the single pixel contribution, given by the product of the quenching resistor and the pixel capacitance. *For FBK:*

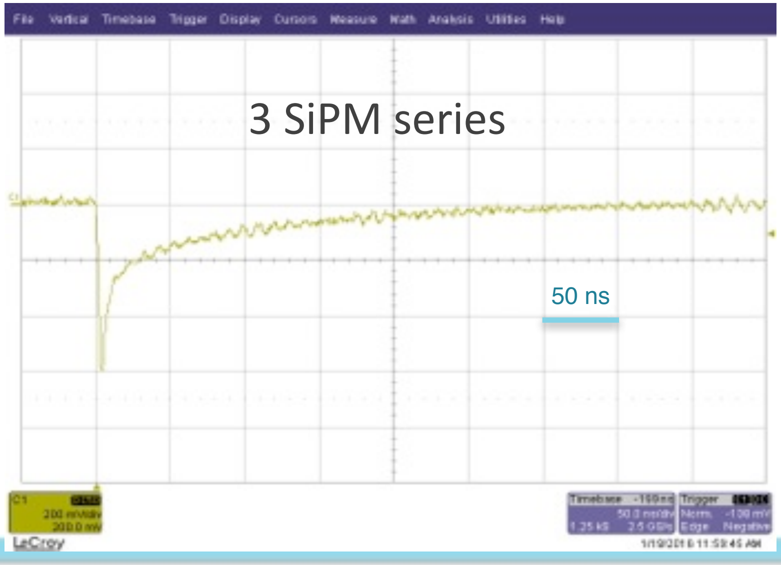
   $\tau = R_Q \times C_{pixel} \sim 2\ M\Omega \times 50\ fF = 100\ ns$

2) The overall capacitance of the device times the input resistance of the amplifier. *For the Hamamatsu/FBK 6x6 mm²:*

   $\tau = R_{amp} \times C_{MPPC} \sim 50\ \Omega \times 1.3\ nF \sim 50\ ns$

With the series connection we can reduce the second contribution, but not affect the first one





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

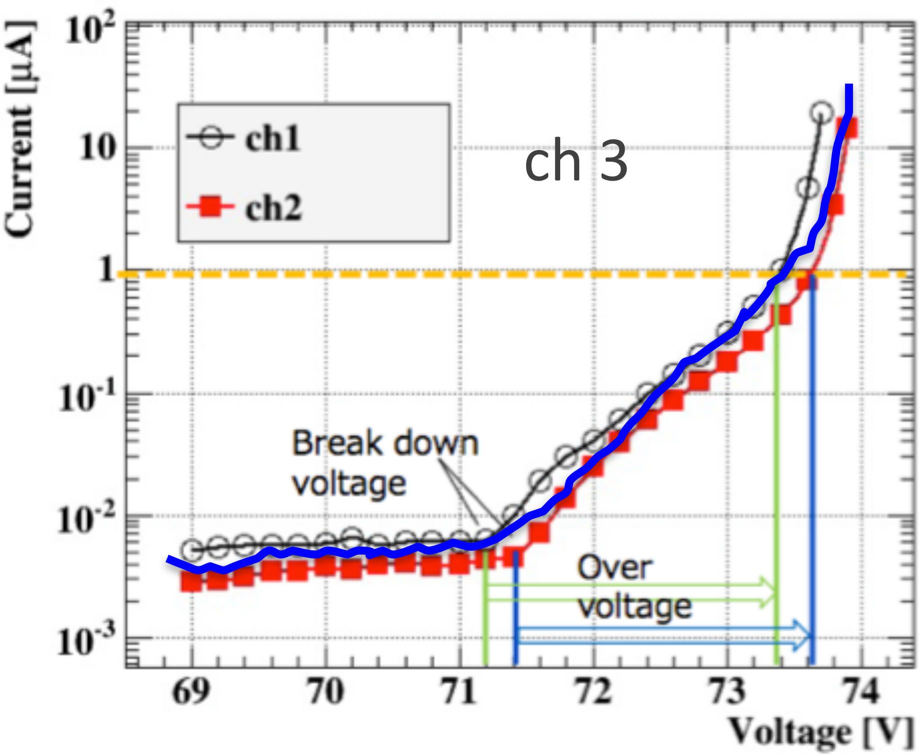
Prescription1: use at the same radius SiPMs of the same series
Prescription2: equalize always with the laser response reducing the total bias voltage applied to the series

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

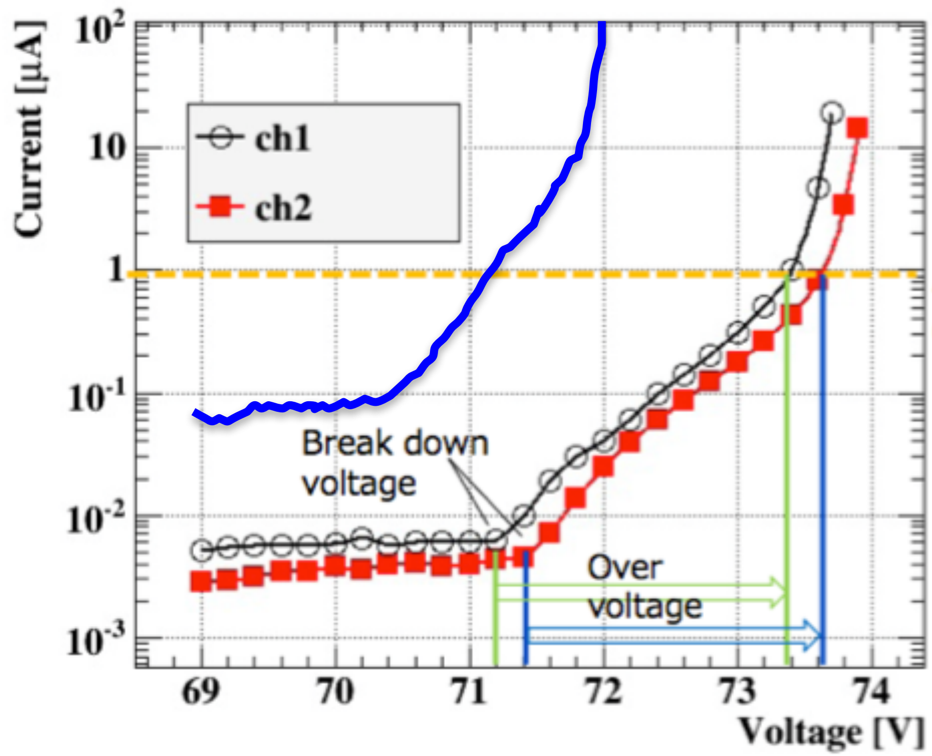
Neutron Damage Problem: IV curve example

Let me do a simple example using a blue curve

Before Irradiation

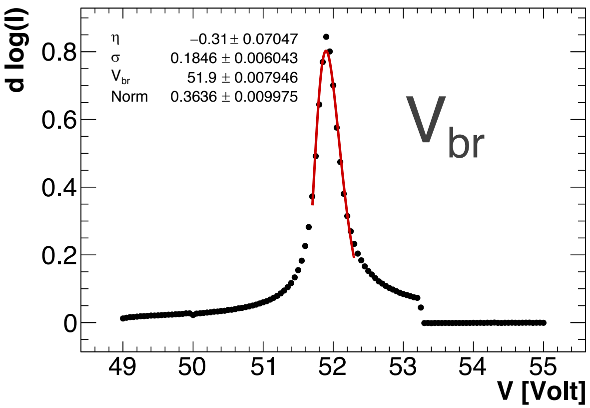


After Irradiation

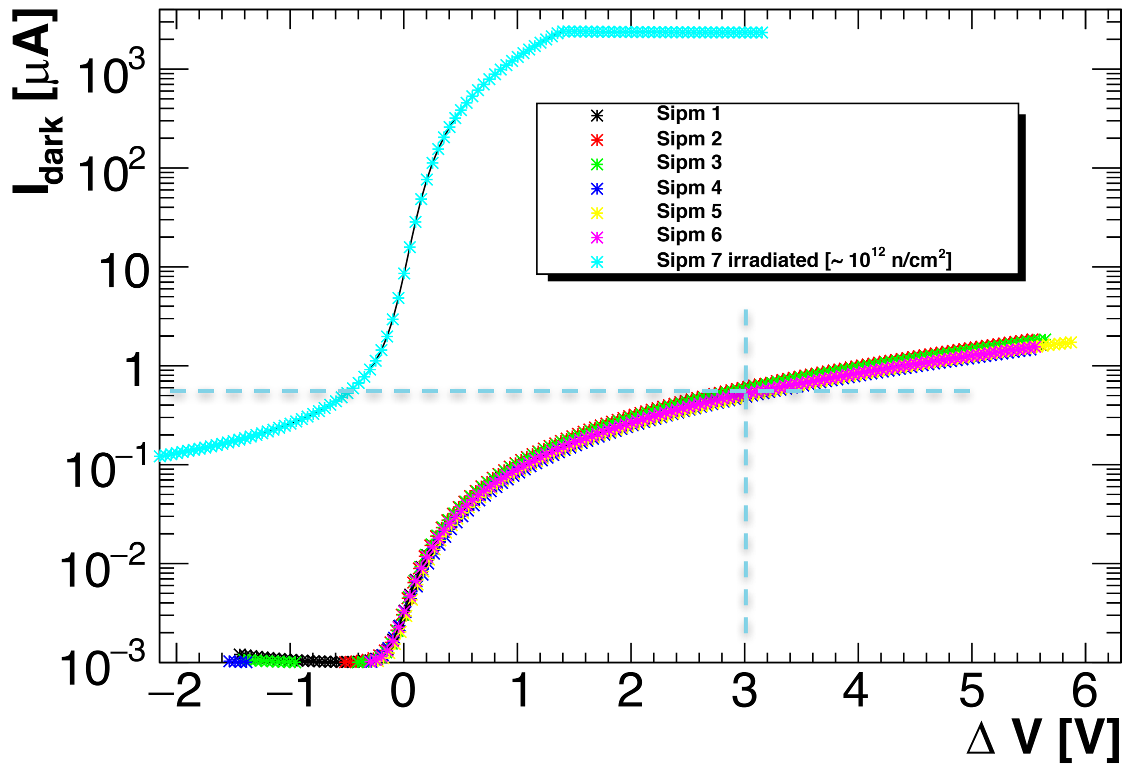


Neutron Damage Problem: IV curve REAL

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

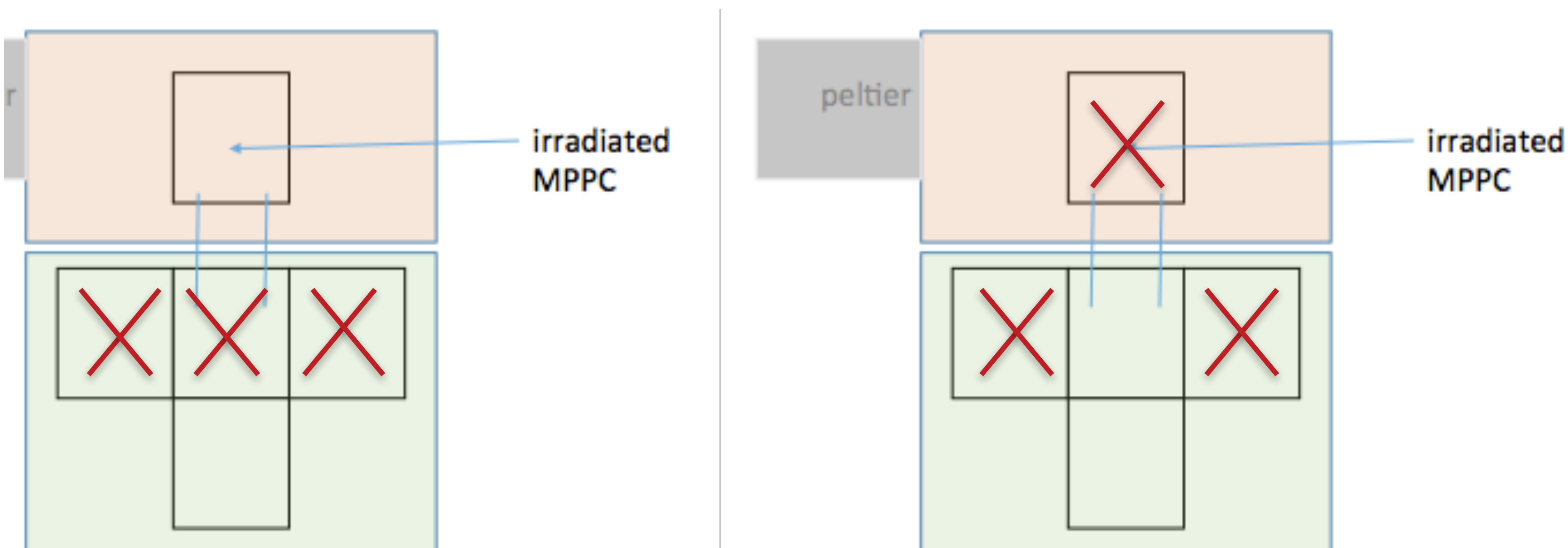


Neutron Damage Problem: Series Compared

- We have compared the response of the series connection of three MPPCs at a blue laser in the following configurations:

  - Three MPPC not irradiated

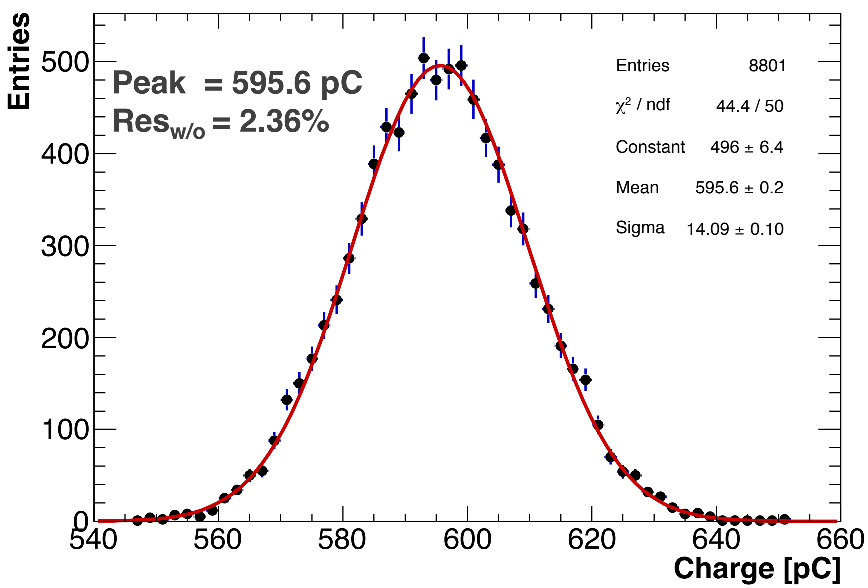
  - Two MPPC not irradiated and the one irradiated at Dresden

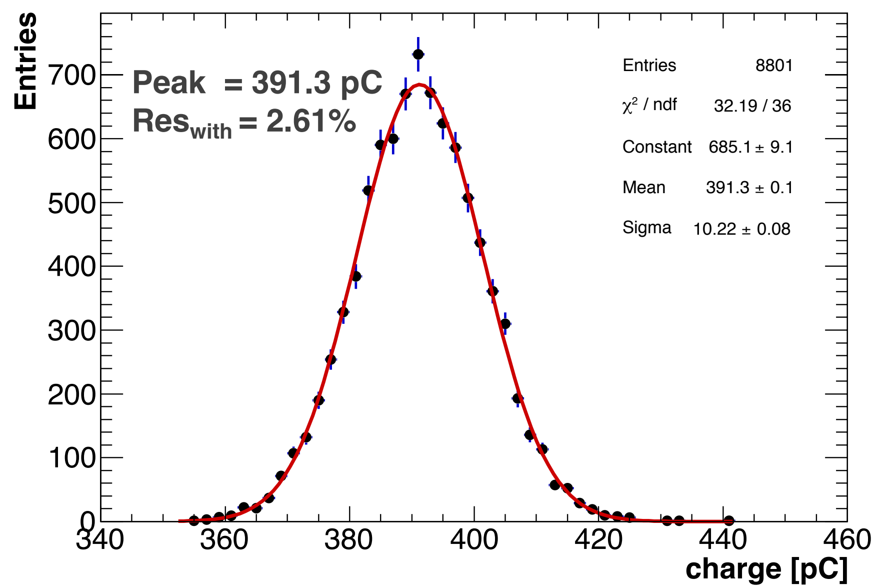


Neutron Damage Problem: Series Comparison

- 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* → $Q_{w/o\_irr} / Q_{with\_irr} = 0.66 = 2/3$

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

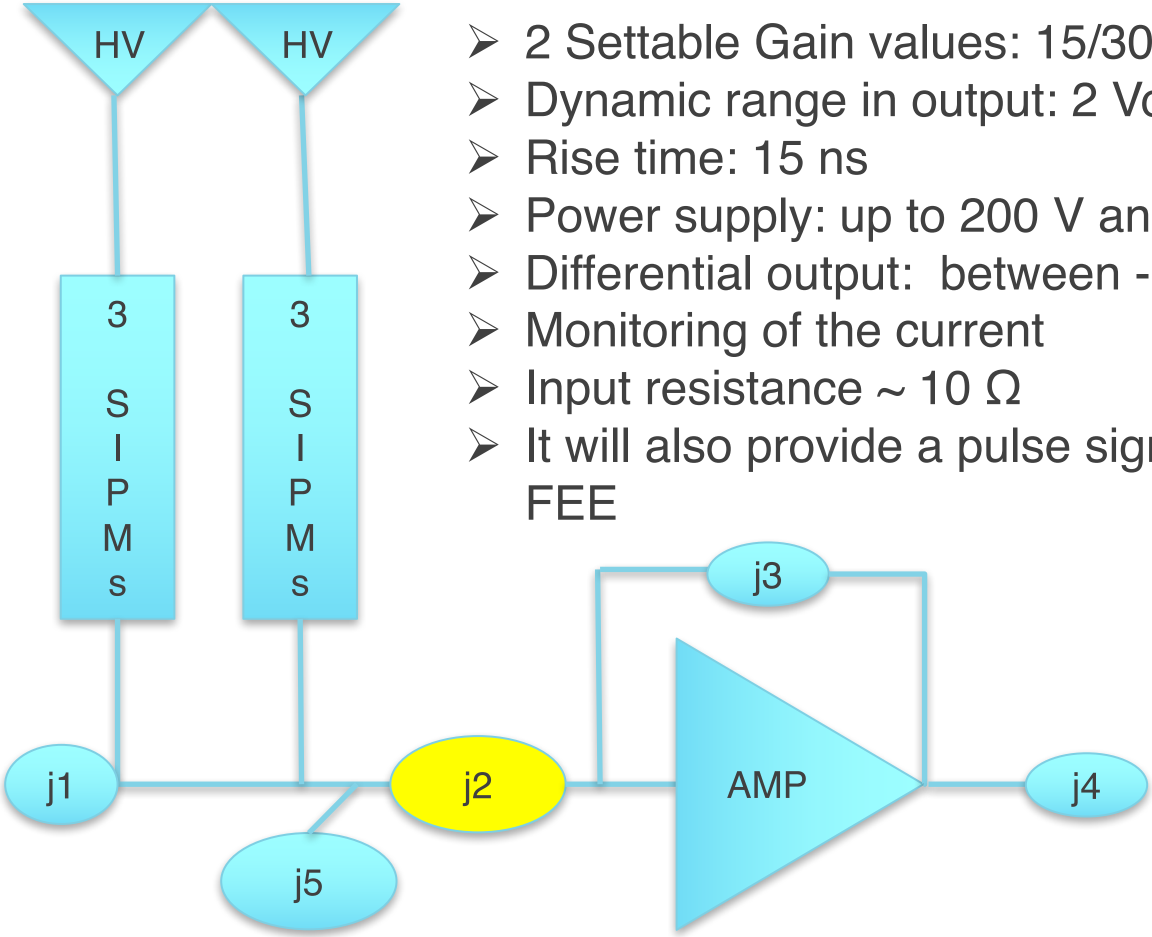
moving a and b randomly [-3,3]

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

Gain variation negligible!!

New Proposed Calorimeter FEE

- Provide both the amplification stage and a local linear regulation for the Silicon photosensor bias voltage

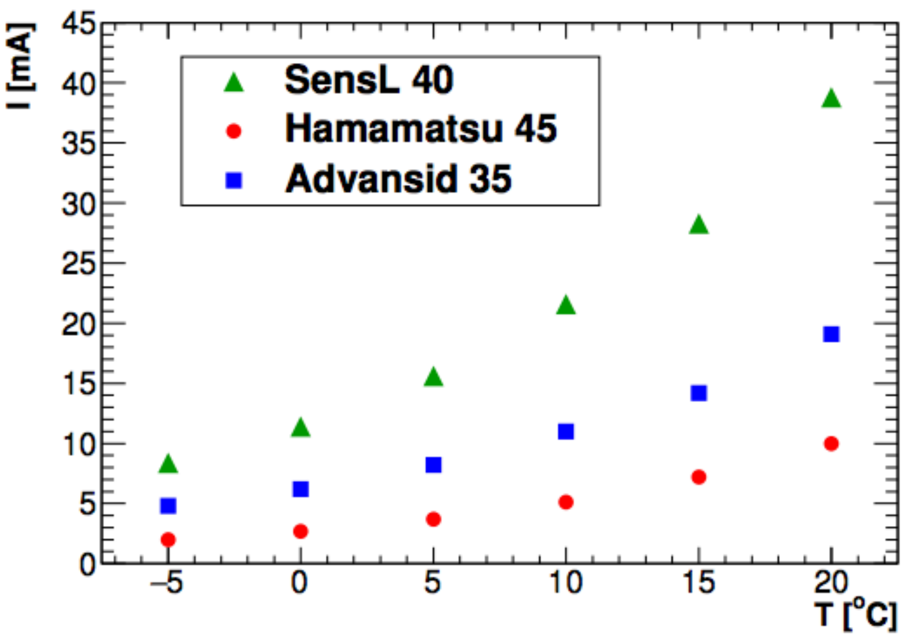


- 2 Settable Gain values: 15/30
- Dynamic range in output: 2 Volt
- Rise time: 15 ns
- Power supply: up to 200 V and 2 mA
- Differential output: between -1 and +1 Volt
- Monitoring of the current
- Input resistance ~ 10 Ω
- It will also provide a pulse signal to test the FEE

j1: Monitoring of the temperature
j2: Monitoring of the current
j3: Settable Gains
j4: Differential output
j5: Pulse Signal

Current vs Temperature

- ~1600 hours after the irradiation all irradiated SiPMs have been tested to study the current variation with the respect to temperature



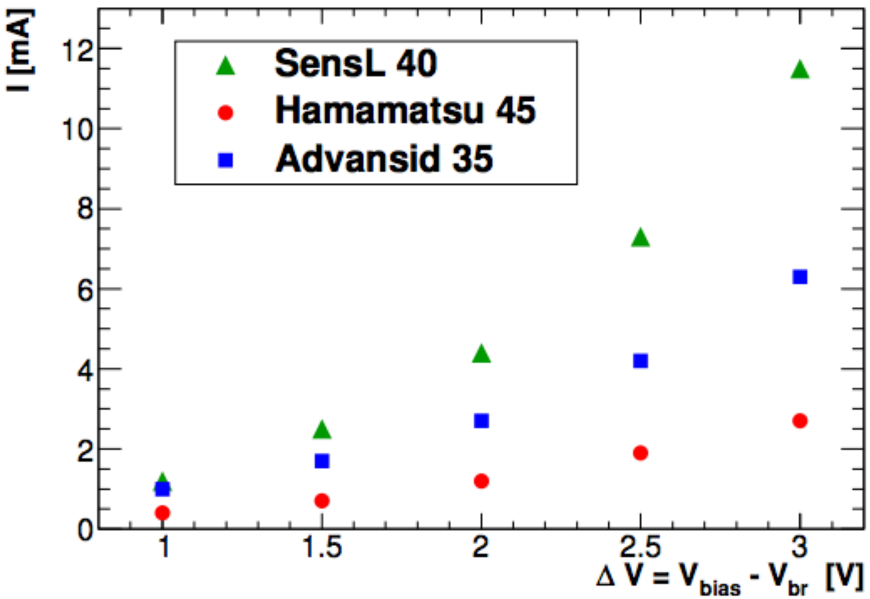
SensL: I [20˚C] = 38.8 mA, I [-5 ˚C] = 8.4 mA
Advansid: I [20˚C] = 19.1 mA, I [-5 ˚C] = 4.8 mA
Hamamatsu: I [20˚C] = 10 mA , I [-5 ˚C] = 2 mA

- After ~ 2 months of annealing the current for the three SiPMs has decreased of a factor of 2
- A decrease of 10 ˚C in the SiPMs temperature corresponds to a 50% current decrease

Results for a single cell exceed the front-end electronics requirements, i.e. **I_{supply}< 2 mA/channel for the series** **(current a factor of 2 larger than limit)**

Current vs Vbias

- After completing this first study, the SiPM temperature has been fixed at 0 °C and the current has been acquired at different bias voltages.



SensL: $I[V_{op}] = 11.5$ mA, $I[V_{op} - 2] = 1.2$ mA
Advansid: $I[V_{op}] = 6.3$ mA, $I[V_{op} - 2] = 1$ mA
Hamamatsu: $I[V_{op}] = 2.7$ mA, $I[V_{op} - 2] = 0.4$ mA

From our measurement using an LED:

- N_{pe} reduction of 20% each 1 Volts
- Gain reduction of a factor 1.5 each 1 Volts

We can operate tunning at -1 V, loosing 20% of p.e and a factor 1.5 of gain.
- Our FEE has a switchable gain x2.