Mu2e CD3c Review
WBS 7.4 Calorimeter Photosensors

D. Hitlin, Mu2e Calorimeter Deputy, for
I. Sarra, Mu2e Calorimeter Photosensor L3 Manager

19 April 2016

Mu2e Calorimeter Organization

- 475.7 Calorimeter
  L2 - S. Miscetti (LNF)
  Deputy - D. Hitlin (Caltech)
  - 475.7.1 Project Management
    L3 – S. Miscetti – (LNF)
    CAM – D. Hitlin (Caltech)
  - 475.7.2 Crystals
    L3 – D. Hitlin (Caltech), S. Giovanella (LNF)
    CAM - D. Hitlin
  - 475.7.3 Mechanics
    L3 – F. Happacher (LNF), F. Raffaelli (Pisa)
  - 475.7.4 Photosensors
    L3 – D. Hitlin (Caltech), I. Sarra(LNF)
    CAM – D. Hitlin
  - 475.7.5 Digitizer
    L3 – F. Spinella (Pisa)
    CAM – D. Hitlin (Caltech)
  - 475.7.6 Calibration
    L3 – F. Porter (Caltech), M. Cordelli (LNF)
    CAM – D. Hitlin
  - 475.7.7 Frontend Electronics and Power
    L3 – G. Corradi (LNF)
  - 475.7.8 Assembly and Installation
    L3 – A. Saputi (LNF)
    CAM – D. Hitlin (Caltech)

Scope

WBS 475.07.04
Photosensors
David Hitlin / Caltech
Ivano Sarra / LNF

475.07.04.1 **Photosensor Design and Procurement**
This task covers the development phase, the final choice, the procurement and the testing of the pre-production and production photo-sensors for the calorimeter. It also includes the design and construction of QA test facilities to perform an acceptance test of the delivered photo-sensors.

475.07.04.2 **Photosensor Production**
This task covers all aspects of the design and assembly of the QA station to test the characteristics of the photo-sensors. The QA consists of the measurement of the photosensor gain and its dependence on wavelength, temperature and bias. Procurement of pre-production and production samples is the final implementation of this WBS. QA testing of all photosensors will then be done.

Requirements

- The calorimeter requirements are described in docdb-9864
- The 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 3×10^{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 without need for access

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

UV-extended SiPM – Hamamatsu

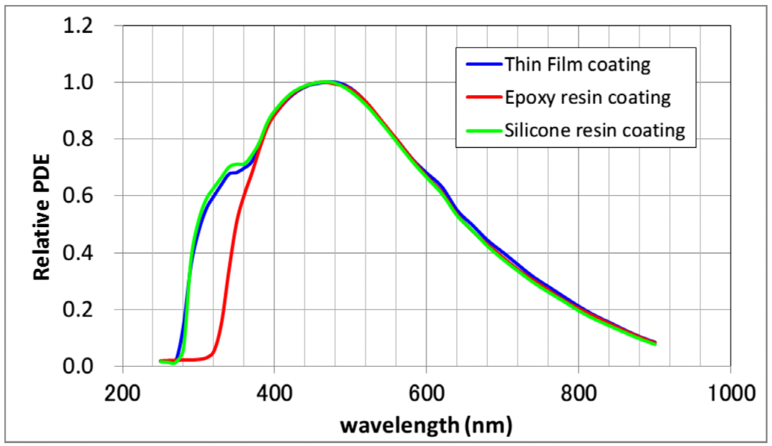
We have tested arrays of 16 3x3 mm^2 Hamamatsu TSV MPPCs (12x12 mm^2)

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

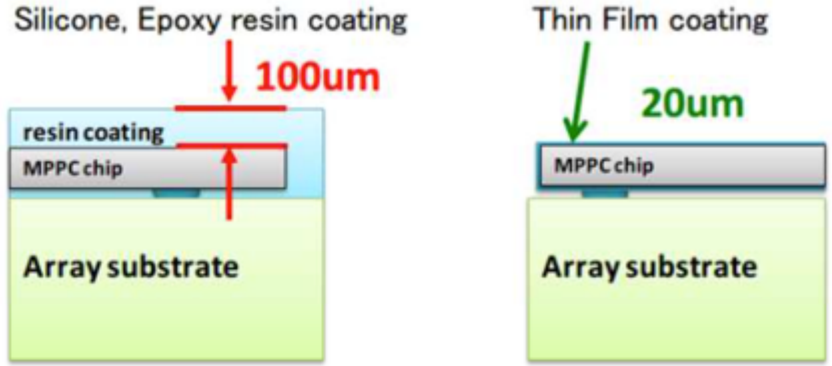
→ ~ 30 (20) p.e./MeV with (without) optical grease with Tyvek-wrapped crystals
→ Time resolution < 150 ps @ 100 MeV with 45° e^- impact angle
→ Energy resolution better than 7% at 100 MeV (leakage dominated)
→ Equivalent noise ~ 100 keV

see docDB 5701-v6, 5816

PDE comparison



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



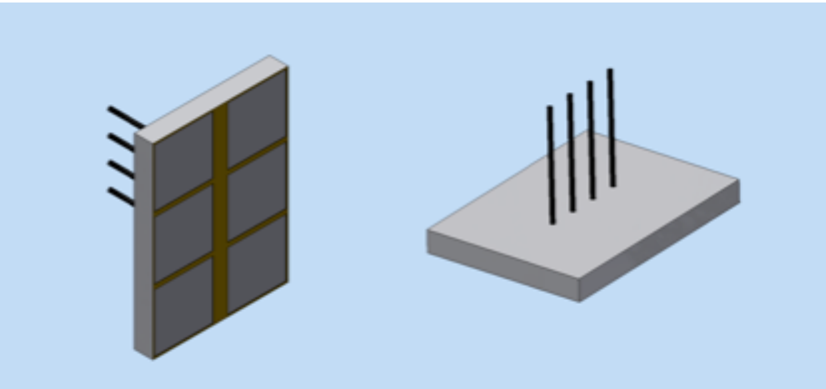
■merit
- robust to the mechanical shock
- easy handling (during assy.)
- superior transparency in UV region
  - silicone resin coating type -

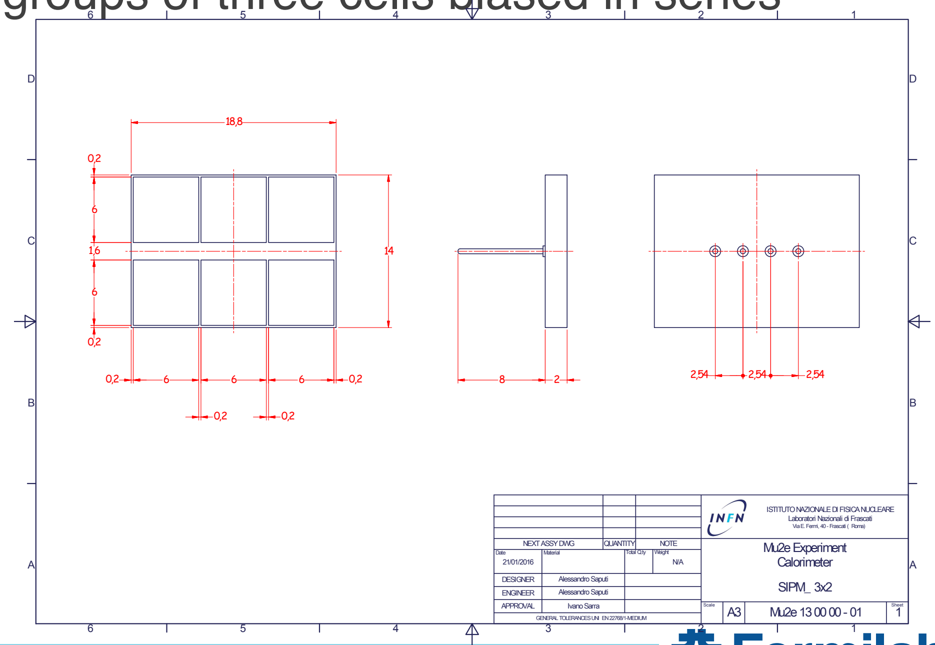
■merit
- tough coating
  (mechanical shock should be avoided)
- superior transparency in UV region
- cross-talk suppression in the coating
- super flatness (minimum bending)

Fermilab

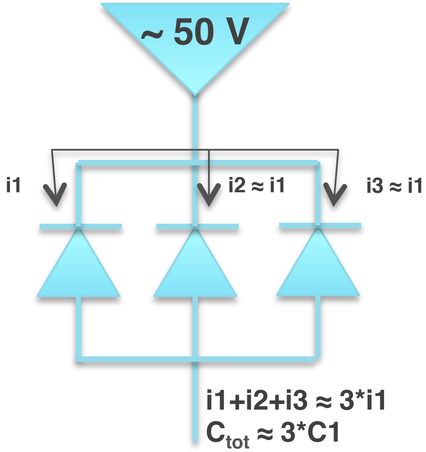
Mu2e Photosensor will be a custom SiPM

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



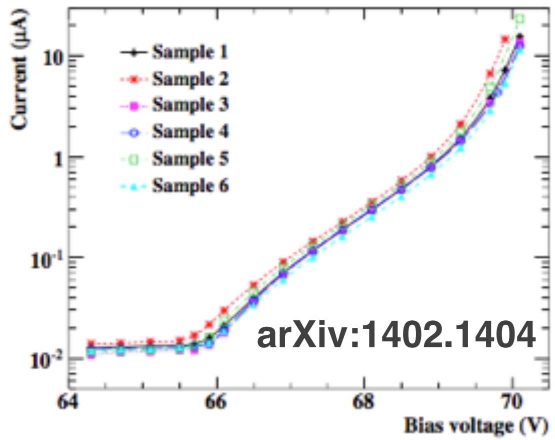


Series vs Parallel polarizations

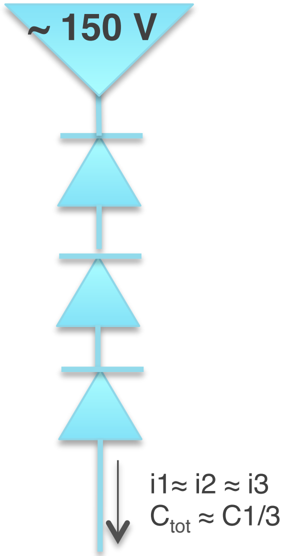


	Parallel	Series
Total Bias (Volt)		
Total Current (A)		
Power (Watt)		
Total Capacitance		
Decay Time		

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



I-V characteristics of individual SiPMs



- Decay time can be regulated at the shaping level, but a high detector capacitance increases noise (worsens the signal-to-noise ratio)
- When SiPMs are connected in series, the voltage applied to each SiPM is determined by the common leakage current. Then, the difference in breakdown voltages is absorbed, and the over-voltages are approximately aligned.

(R1, R2) → 2x3 SiPM array performance

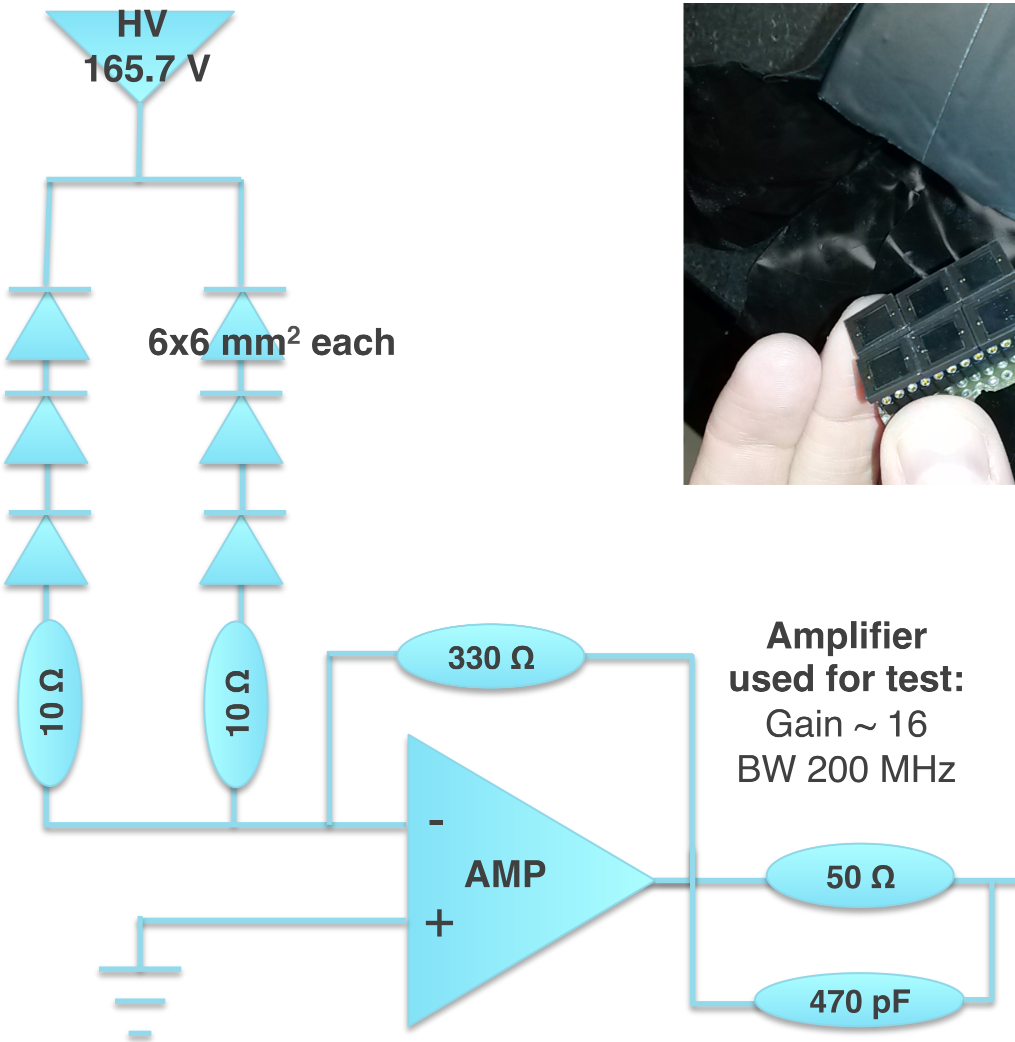
We have already received 7 monolithic MPPCs of 6x6 mm^2 dimensions
→ 6 of them have been used to build a 2x3 array with our packaging.
→ UV extended by SPL technique
→ TSV technique

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

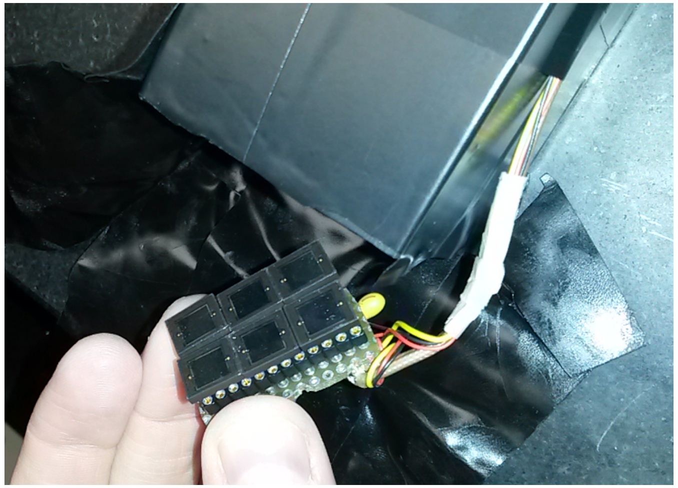
Specifications:

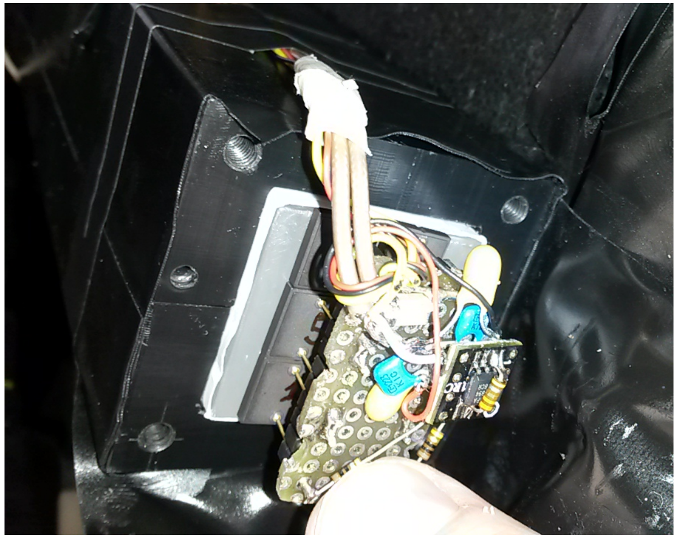
- PDE ~ 30% @ 315 nm;
- Gain > 10^6 at $V_{op} = V_{br} + 3V$
- the series connection of the three 6x6 mm^2 SiPMs should produce a signal width of about 70 ns ($\tau_r \sim 15$ ns) to minimize pileup

(R1, R2) - Polarization scheme



Amplifier used for test:
Gain ~ 16
BW 200 MHz





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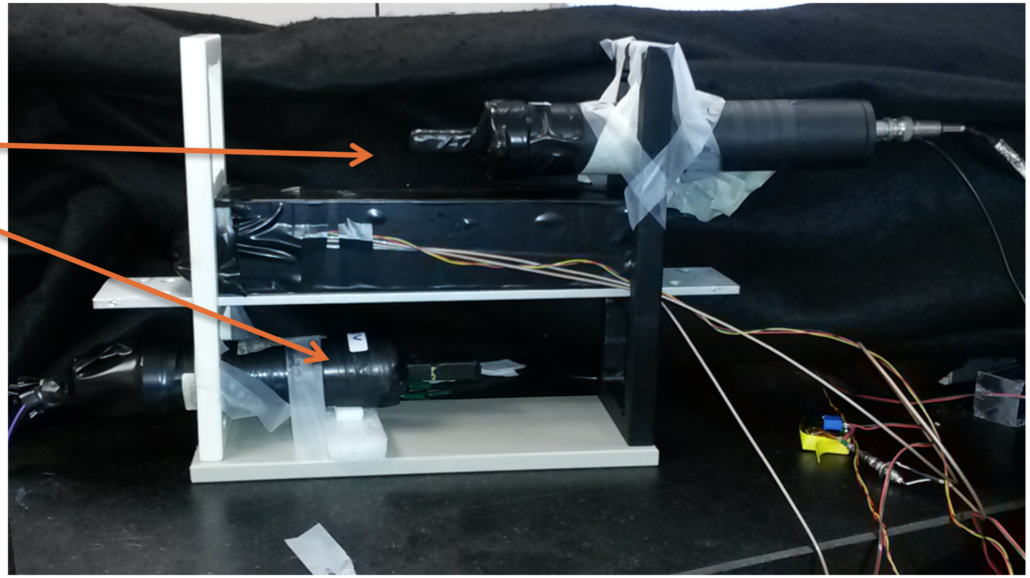
(R1, R2) - Experimental setup

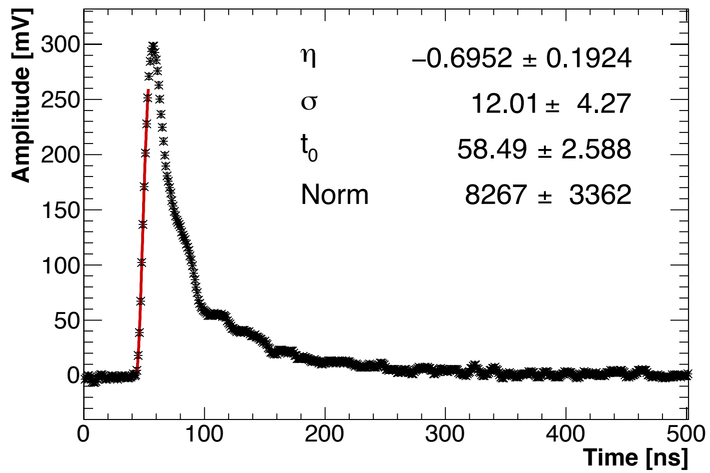
Crystal+SiPM sample between two plastic scintillation finger counters:

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



Analysis technique

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



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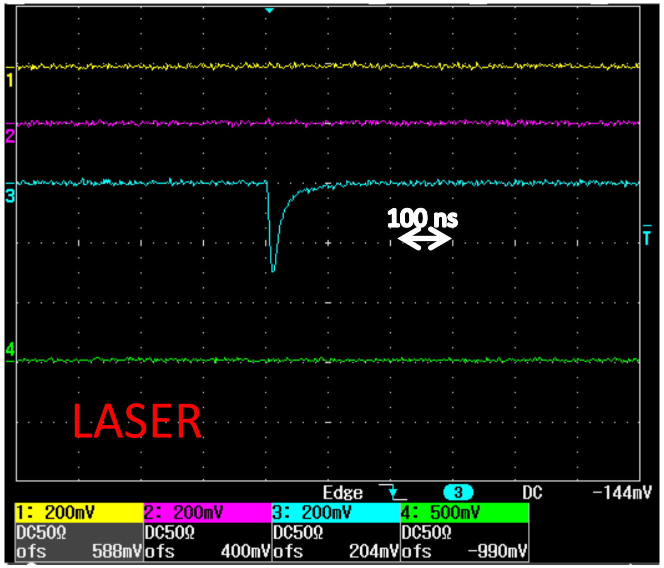
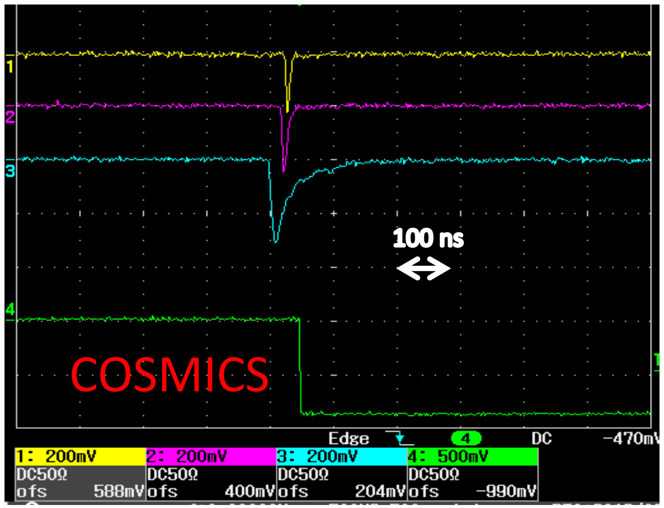
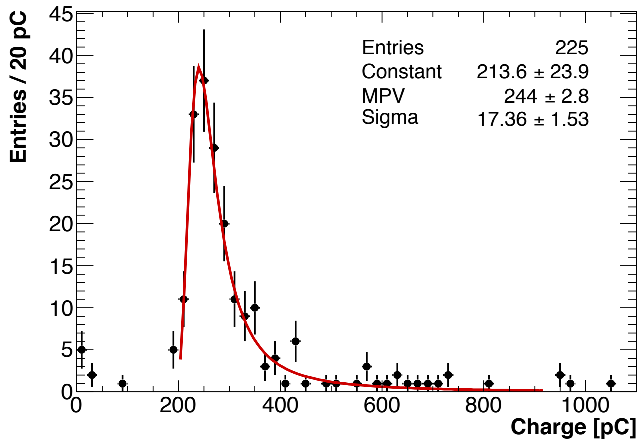
(R1, R2) – CR test of CsI+2x3 SiPM array

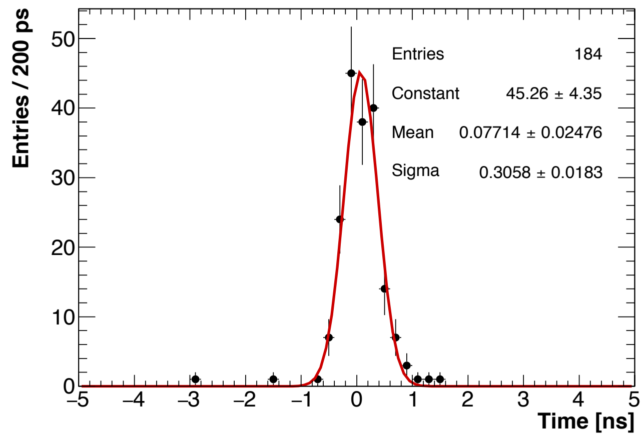






- Trigger Resolution (Δt_fingers) = 255 ps
- Final resolution for 1 MIP (~20 MeV) → ~ 170 ps

with 150 μm Tyvek wrapping and optical coupling in air



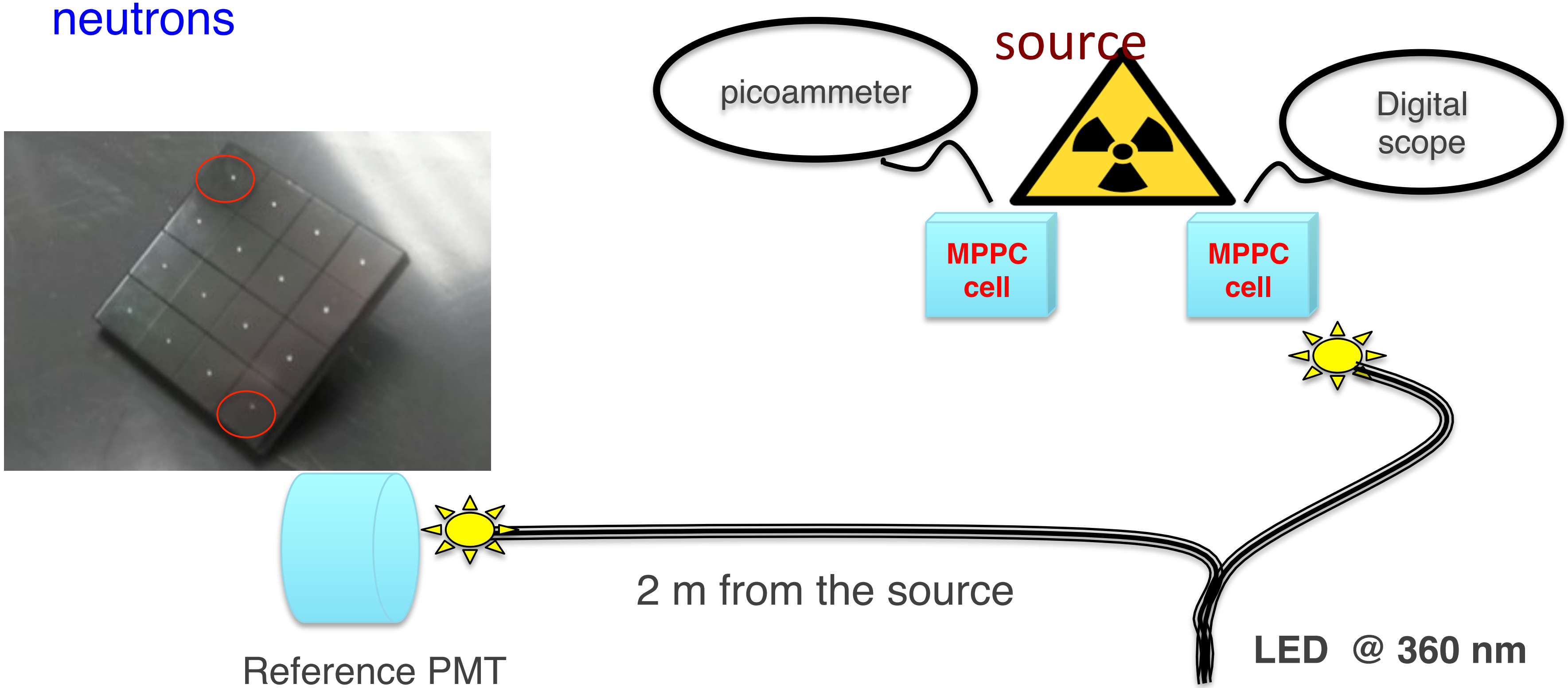
(R3) → Irradiation test of MPPC and SiPM

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

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

→ Measurement of response and leakage current

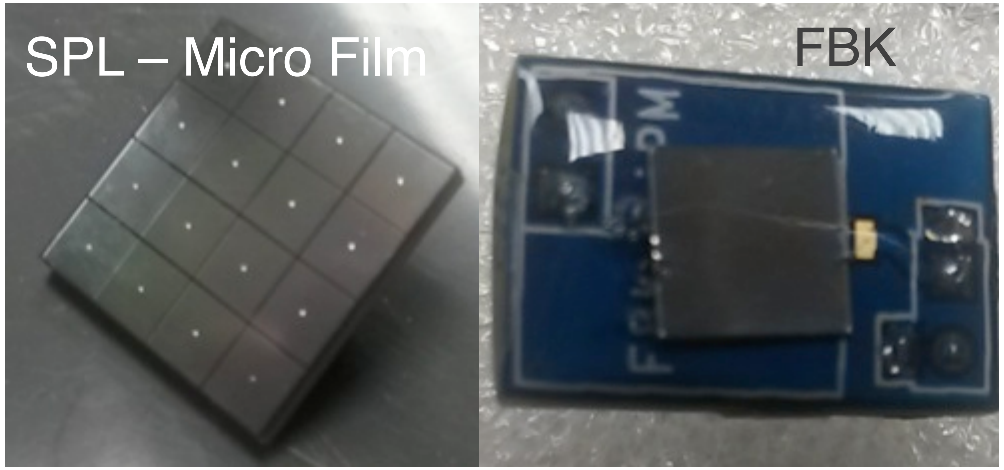
→ Also 6x6 mm^2 of UV extended SiPM from FBK have been tested with neutrons



(R3) – Irradiation with neutrons (1)

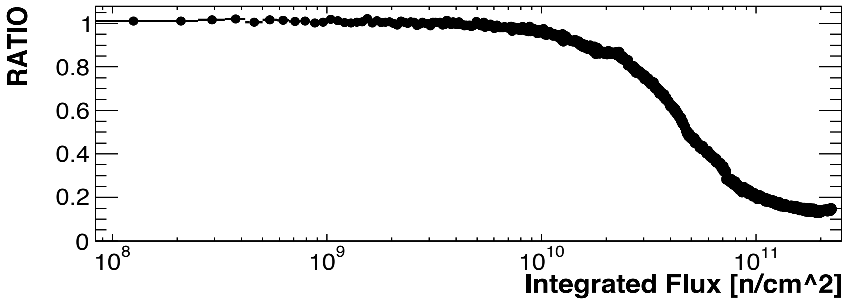
- SiPM irradiated @ FNG (Frascati) with 14 MeV neutrons in October 2015
- Total flux delivered in less than 4 hours
- Out of 16 MPPC cells:
  - ✧ 1 cell used for leakage current
  - ✧ Another cell used for response to a fixed UV LED pulse;
  - ✧ PMT used as reference for the light input.
- For the monolithic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

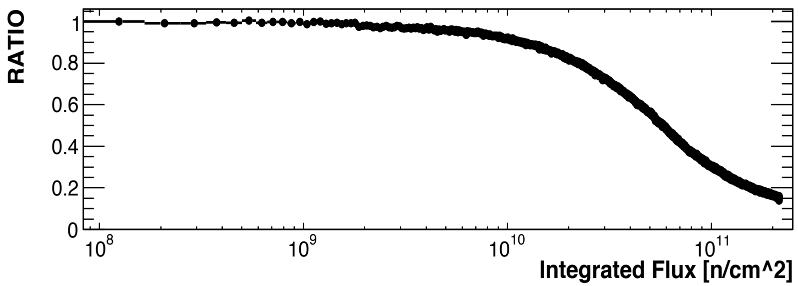
	V op (V)	Total flux (n/cm^2)	Total flux (n_1MeV/cm^2)
SPL 4 SiPM	53.9	2.2×10^{11}	4×10^{11}
Micro Film SiPM	53.95	2.2×10^{11}	4×10^{11}
FBK SiPM	32.5	2.2×10^{11}	4×10^{11}

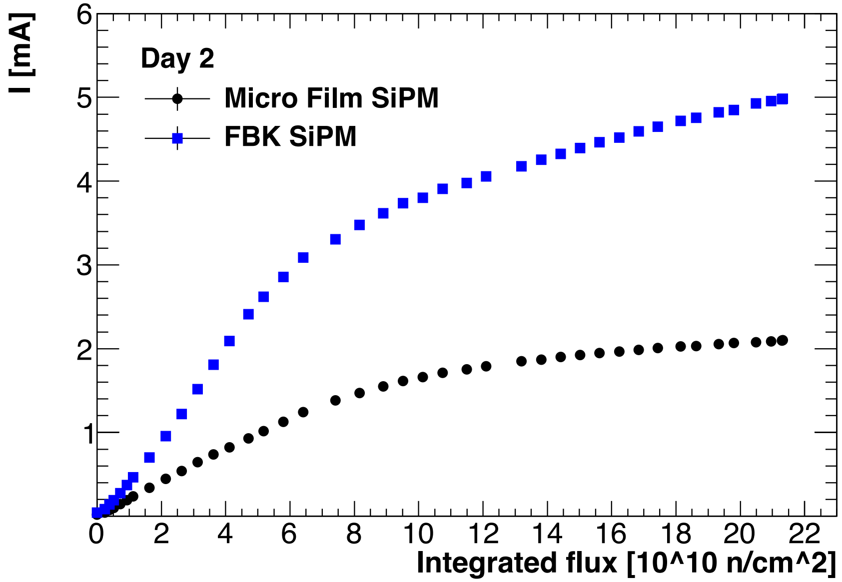


16 MPPC of 3x3 mm^2 1 SiPM of 6x6 mm^2

(R3) – Irradiation with neutrons (2)







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

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

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

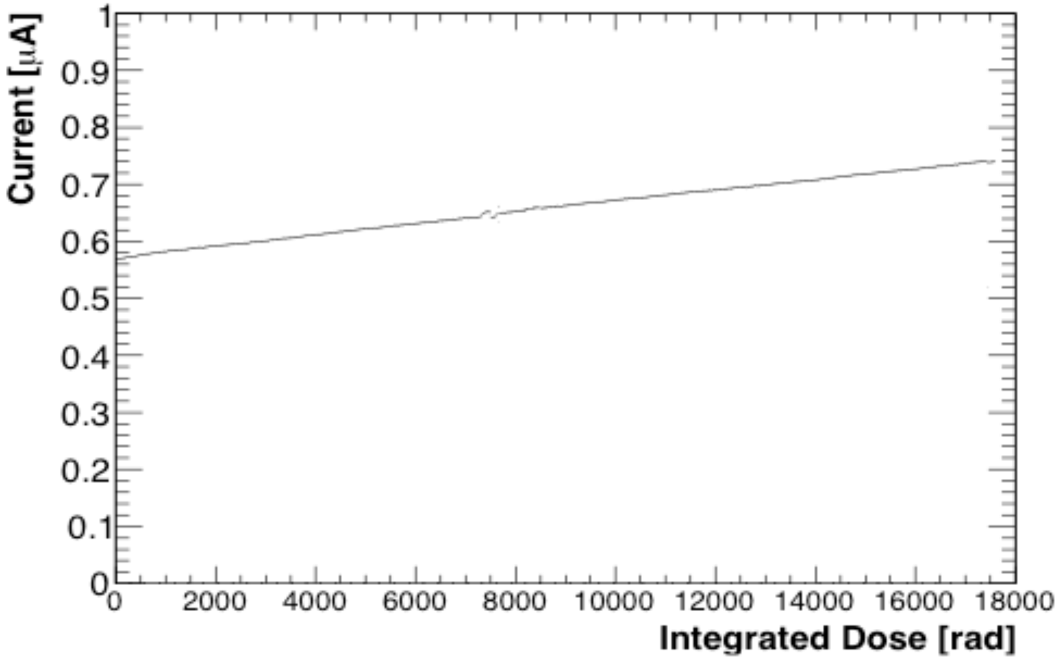
For the innermost layer a larger amplification value can be used (e.g. from 10 to 20)

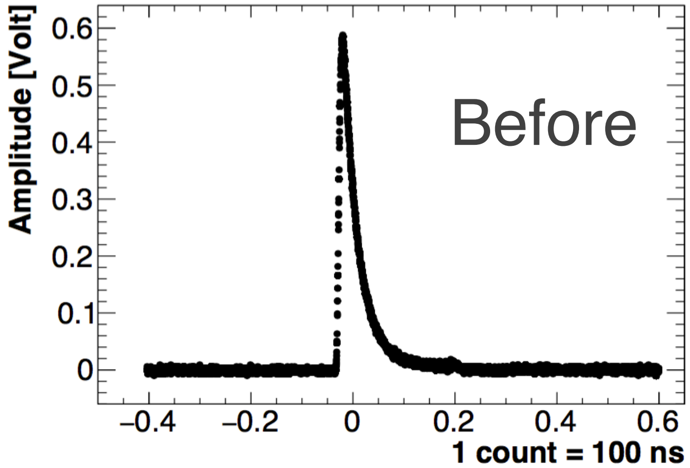
The current increased from

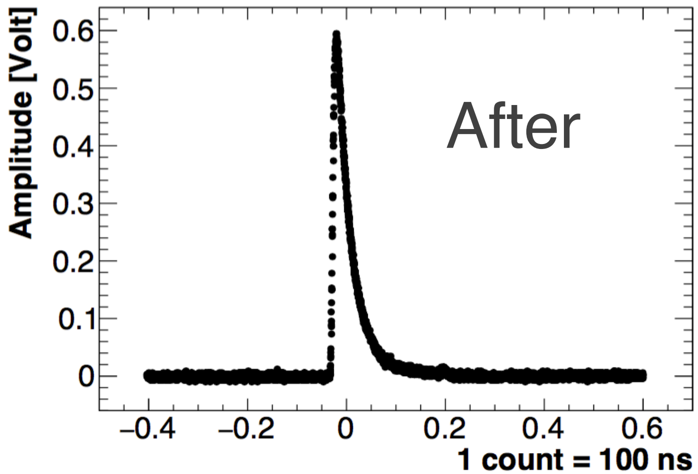
- **16 uA up to 2 mA (TF)**
- **100 uA up to 2.2 mA (SPL)**
- **86/4 uA up to 19/4 ~5 mA (FBK)**

(R3) – Irradiation with photons

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



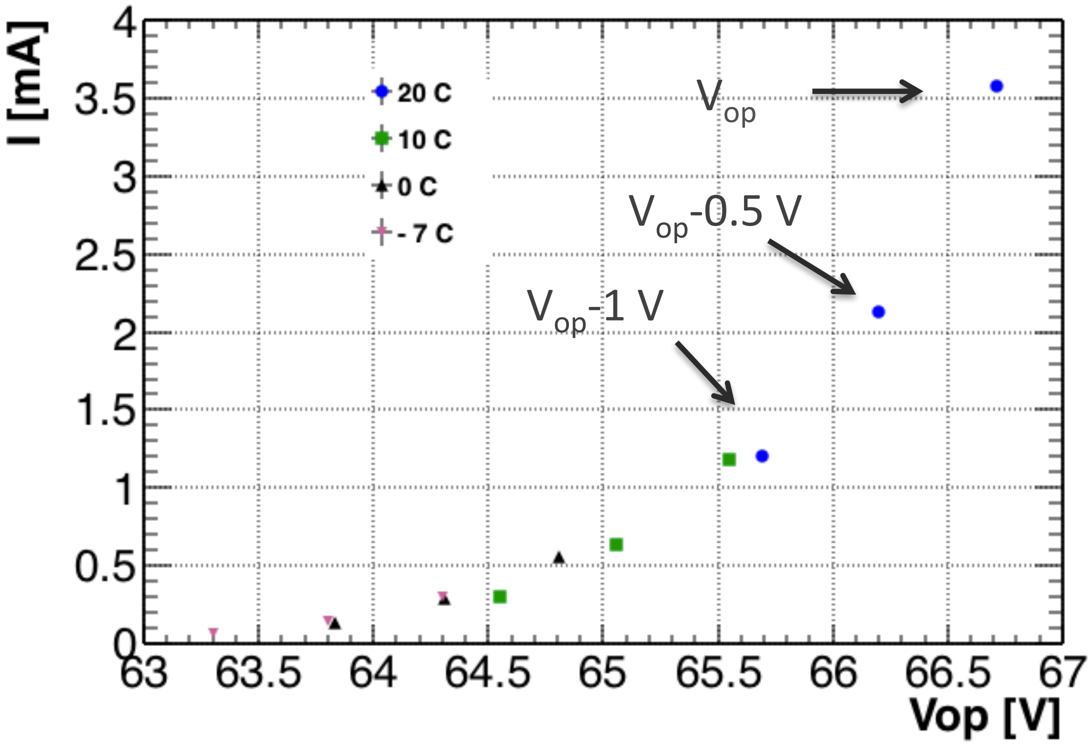




Negligible effect on the response and on the leakage current due to the dose

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

- We have measured the leakage current of the MPPCs changing the temperature and three different set of V_{bias}: V_{op}, V_{op}-0.5, V_{op}-1 Volt
- Measurement in vacuum with micro TEC Peltier and PT100 sensor.
- The data are related to a single cell (6x6 mm^2).



(R3) - Derived FEE/Cooling requirements

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

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

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

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

→ 9 mA for the parallel of two series @ 25ºC

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

→ 9/5 = 1.8 mA for the device @ 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)

→ 1.8/2 = 1 mA @ 0ºC

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

(R4) → Operation in vacuum

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

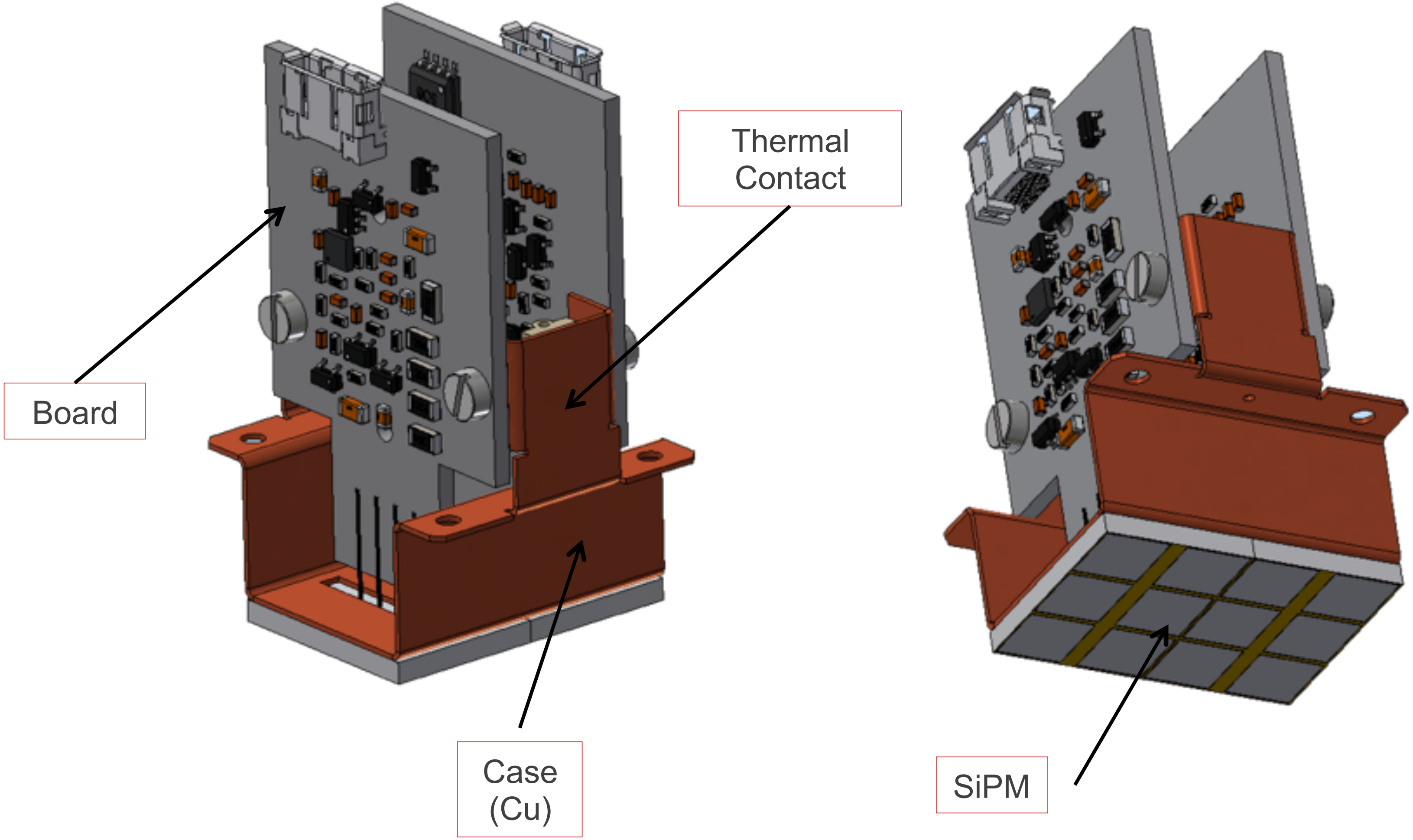
- **Outside the DS:** we will run at ~ 20ºC, $V_{bias} = V_{op}$
- **Inside the DS:** we will run at ~ 0ºC, $V_{bias} = V_{op}$ – temperature voltage coefficient

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

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

(R5) → Engineering of the final packaging

SiPM Holder



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

(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 < 2×10^6 hours

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

- Working at 0ºC, 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 is needed for the final packaging.** First test is underway: 4 $6 \times 6\ mm^2$ FBK SiPM in an oven at 50ºC After 1 month of running, all 4 SiPM are still perfectly OK.

Design Maturity

docdb 6972.

Calorimeter Subsystem	Design Completion	Remaining Work/Risks
Crystals	90%	Specification of CsI slow component - Low risk.
Photosensors	85%	SiPM packaging. Have one packaged SiPM from Hamamatsu but want to qualify other vendors - Low risk.
Mechanical Infrastructure	65%	Finalize cooling design. Optimizing tradeoffs between noise, radiation damage and operating temperature. x2 headroom - Low Risk
Front End Electronics And Digitizer (WFD)	60%	• New pre-amp design for CsI/SiPM - Low Risk. • WFD board design with 20 channels. Moderate risk that we may have to back off to 18 channel boards. Adds a small amount of complexity.
Calibration	90%	Integration of source pipes. Finalize laser optics. – Low Risk
Overall Design	**80%**	

Quality

- Photosensor plans are included in the Mu2e Quality Planning Document
  - Available on web page (docdb 7053)

Deliverable	QA or QC Step?	QA or QC Process Documentation (DocDB #)	Inspection or Acceptance Criteria/Plan	Verification
Photosensor	QA: I-V characteristic	DocDb 7053	The I-V characteristic (baseline and rise time) and the break down voltage will be measured for each of the two series connections. We will test the photosensors at three temperatures 0, 10 and 20 °C (Celsius degrees) in a temperature controlled QA station, (Photosensor Test Starion). We have two similar stations, one in Caltech and one at PISA.	The measurement will be done in a stable environment with temperature controlled. The analysis is done in an automatic manner. 25 photosensors are tested togheter. Users of the QA system will be warned if something goes wrong (low statistics, current values out of range parameters). Table of results will be atomically generated. We apply a cut for accepting the photosensors that uses the standard I-V characteristic and a breakdown voltage value in a range of ± 250 mV among the different devices in the delivered batch. The RMS provides an indication of the uniformity of the delivered batch.
Photosensor	QA: Gain	DocDb 7053	Twenty-five SiPMs will be fired at the same time with a UV led, 315 nm of wavelength (highest emission peak for un-doped CsI crystals), and with a green led, 500 nm of wavelength (corresponding to the calibration laser peak). In this way the gain curve and the uniformity of the response in the same package will be measured for each of the two series connectionss.	The measurement of the gain is made using a fix intensity of the led and changing the Vbias applyied at each SiPM. The measure of the Gain is derivated usising the formula: G(Vbias) = (I(Vbias)[led]-I(Vbais)[dark]) / (I(G=1)[led]-I(G=1)[dark])
Photosensor	QA: Relative PDE	DocDb 7053	A calibrated reference sensor will be used to obtain the relative Photon Detection Efficiency (PDE).	The PDE measurement will be relative. The current, as response to the UV led, will be used to compared the PDE with that one of the reference photosensors.
Photosensor	MTTF determination	DocDb 7053	A small number of SiPM (ten) will be randomly selected for MTTF measurement. They will be operated at Vop in a dedicated oven at high temperature, 55 °C, while illuminated with a UV LED light.	When operating the SiPM to 55 °C, the acceleration factor is 90, so that, with ten devices, we can extract the MTTF in around 3 months of burn-in. The response to the LED will be acquired with a 250 MS/s FADC using a LED driver period of 5 minutes each trigger.
Photosensor	QA: Radiation Hardness	DocDb 7053	A small number of SiPM (five), randomly selected from the batch, will be used for radiation hardness test both with gammas and neutrons.	Two of these devices will be irradiated at two different doses, 10 and 20 krad to confirm that ionization dose does not provide increase in Idark or reduction of gain. The other three devices will be instead exposed to a neutron fluency of 3x101**1 n/cm**2 (1 MeV equivalent) while kept at a thermalized temperature of 18 °C. The increase of Idark and the gain drop will be measured.

Quality Control

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

Quality Assurance - 1 -

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

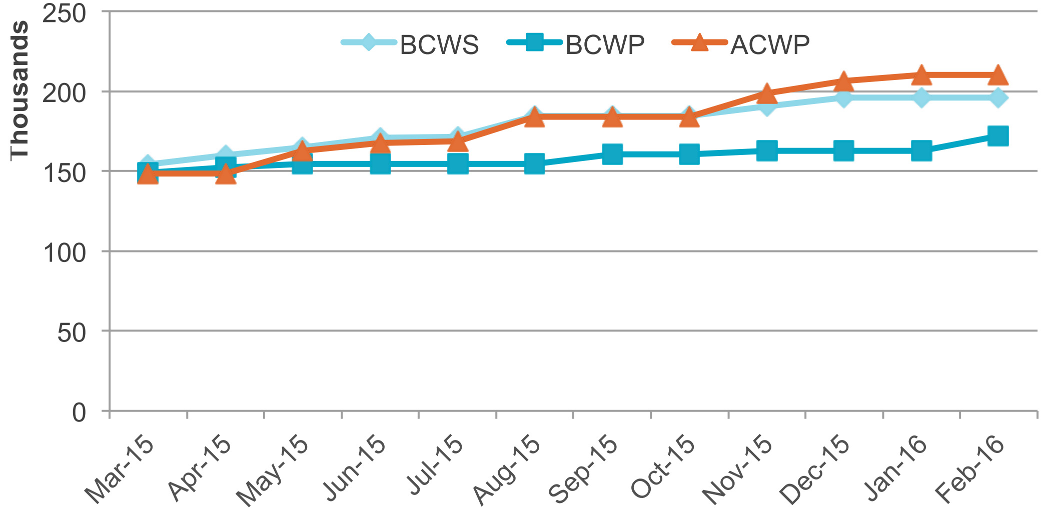
Quality Assurance - 2 -

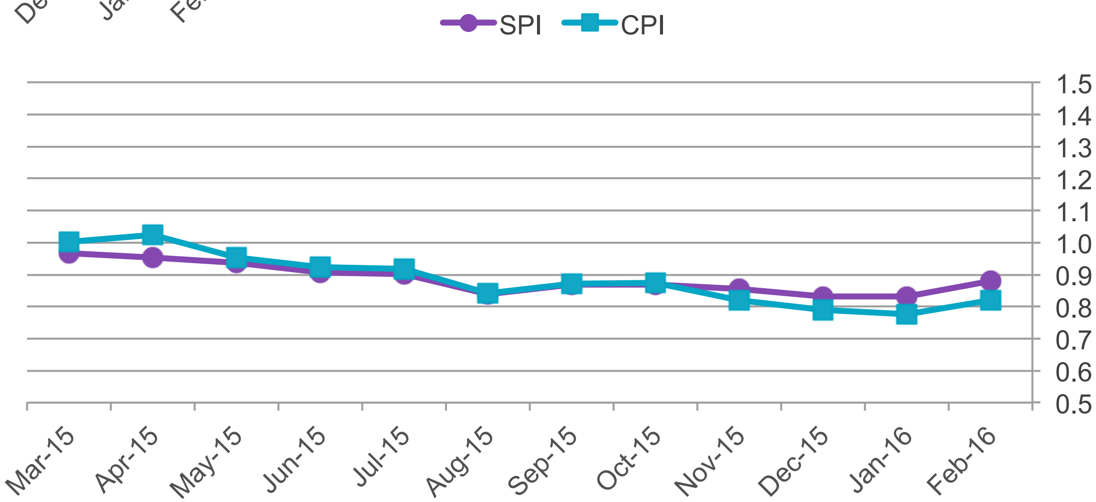
- QA: Quality Assurance Procedure – Mu2e doc-DB-7053
  - The other 185 pieces/batch will be controlled at dedicated QA photosensor stations (one in Caltech and one in Pisa). Sharing of the load for the quality control will be 50-50 between the two stations. In these stations, we will measure, for each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

Configuration Management:

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

Cost and Schedule Performance





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Performances

docdb 6774.

Report: **Mu2e_Earned Value** - Project Stoplight metrics - Control Account

Project: **Mu2e** - Mu2e Project
Status Date: 01/31/2016

Mu2e Project
January 31, 2016
Currency in: $K

	Current Period							Cumulative to Date									
Control Account, Work Package.CTC	**Budget**	**Earned**	**Actuals**	**SV ($)**	**SV (%)**	**CV ($)**	**CV (%)**	**Budget**	**Earned**	**Actuals**	**SV ($)**	**SV (%)**	**CV ($)**	**CV (%)**	**SPI**	**CPI**
475.07.04 Photodetectors	0	0	4	0	0%	-4	-	196	163	210	-33	-17%	-47	-29%	0,83	0,77
475.386 475.07.04 Photodetectors Design (PED)	0	0	1	0	0%	-1	-	26	3	26	-24	-90%	-23	-897%	0,10	0,10
475.387 475.07.04 Photodetectors (Line Item: Construction)	0	0	0	0	0%	0	0%	0	0	0	0	0%	0	0%	-	-

Mu2e Project
January 31, 2016
Currency in: $K

	At Complete				
Control Account, Work Package.CTC	**BAC**	**EAC**	**VAC**	**% Spent**	**% Complete**
475.07.04 Photodetectors	777	862	-85	24%	21%
475.386 475.07.04 Photodetectors Design (PED)	50	74	-24	35%	5%
475.387 475.07.04 Photodetectors (Line Item: Construction)	557	568	-11	0%	0%
475.691 475.07.04 Photodetectors Conceptual Design (OPC)	170	220	-50	84%	95%

Interfaces

Internal Interfaces			
Item	Interface	Descriptions	Owners
107.04.1.1	SIPM/FEE/Laser system	The disk consists of a self- standing structure built piling-up the single crystal units in a way which allows insertion and extraction of photo-sensors if repair is needed. The SIPMs are mounted in the SIPM/FEE holders attached to the rear support disk. The SIPM are closely connected to the related FEE electronics. The connectors for inserting optical fibers will be placed in the rear face in a dedicated spot in the SIPM holder. Interference between calibration services and FEE cabling have to be considered in the cabling layout at CAD level and tested in a dedicated full size mockup and in a larger size prototype (Module- 0).	475.07.04 475.07.05 475.07.06
External Interfaces			
107.04.2.1	EMC High Voltage services: supply and cable routing	The photosensors require high voltage and IFB penetrations. Interface exists with the tracker cabling for the routing. The HV power supplies reside in the electronics room in the pit.	475.07.04 475.07.07 475.03 475.05 475.06

Interfaces are understood and under control

Milestones

- **Short term:**
  → Pre-production bid in May 2016
  → QA of pre-production Sept 2016
  → Module 0 in fall 2016

- **Long Term:**

47507.4.000700	**PO issued for production photo-sensors**	**April 2017**
47507.4.000790	**QC of all photo-sensors complete**	**August 2018**

Summary

- The calorimeter photosensor design is 85% complete. The risks associated with the remaining design are understood and small. There is a clear path to the final design.
  - The performance of the photosensors satisfies the Mu2e calorimeter requirement.
  - Interfaces, risks and ES&H issues have been identified and under control
  - QA/QC plans are in place
- The current design exceeds the calorimeter detector requirements. We will use two photosensors per crystal fro redundancy, but we can still satisfy the requirements with one.
- Three different firms appear to be capable of producing our final SiPM thermal package (2x3 array of 6x6 mm^2 cells)
  - Hamamatsu, FBK and SensL
- The calorimeter photosensors are ready for CD-3c approval

SPARES

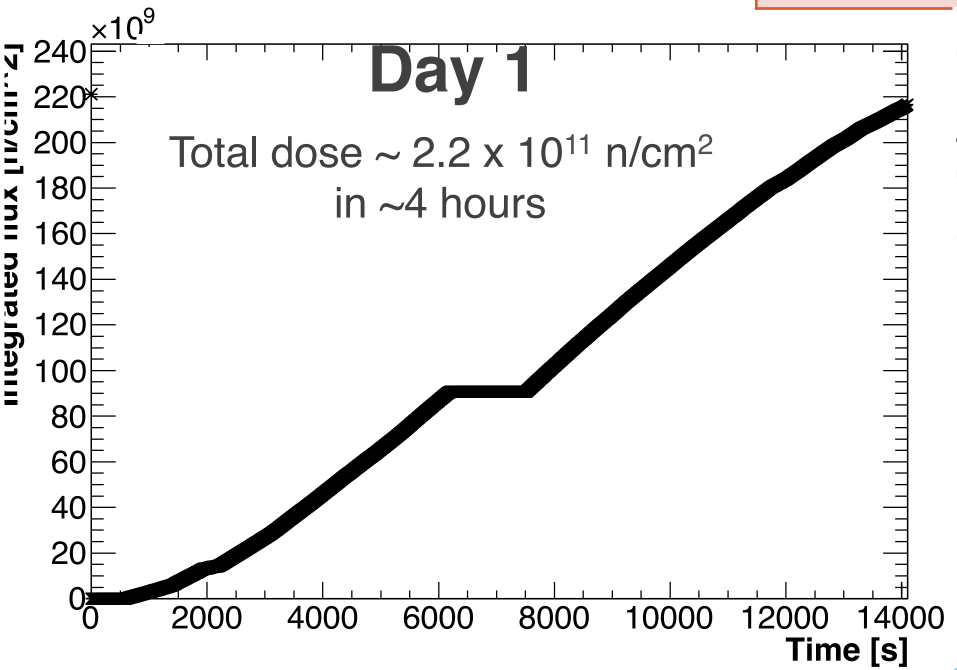
(R3) – Irradiation with neutrons

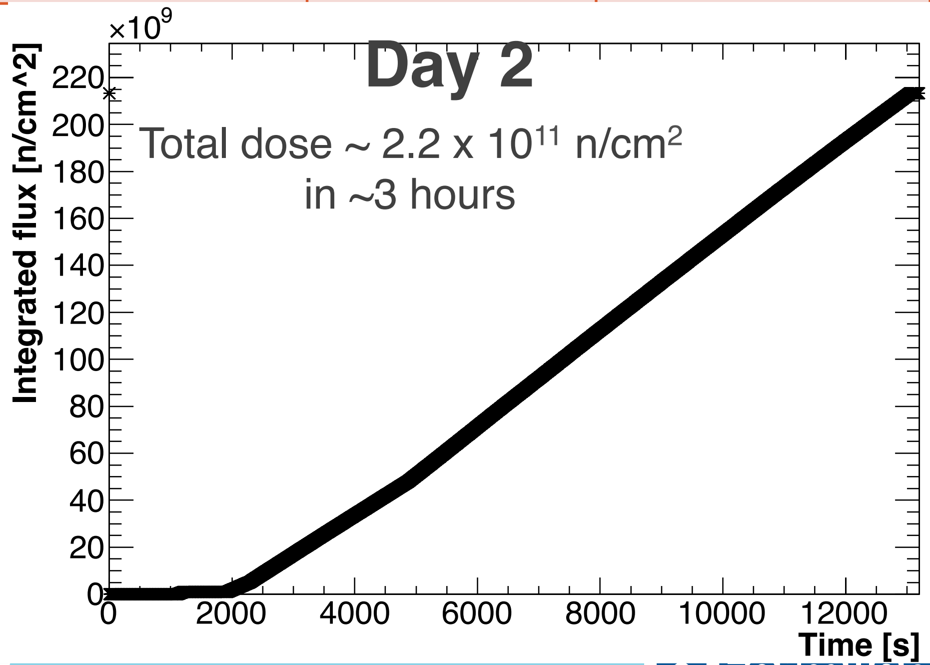
FNG provides 14 MeV neutron energy. The scaled damage is a factor of 1.8 greater than for 1 MeV neutrons:

→$2.2x10^{11} n_{14MeV}/cm^2 = 4x10^{11}\ n_{1MeV}/cm^2$

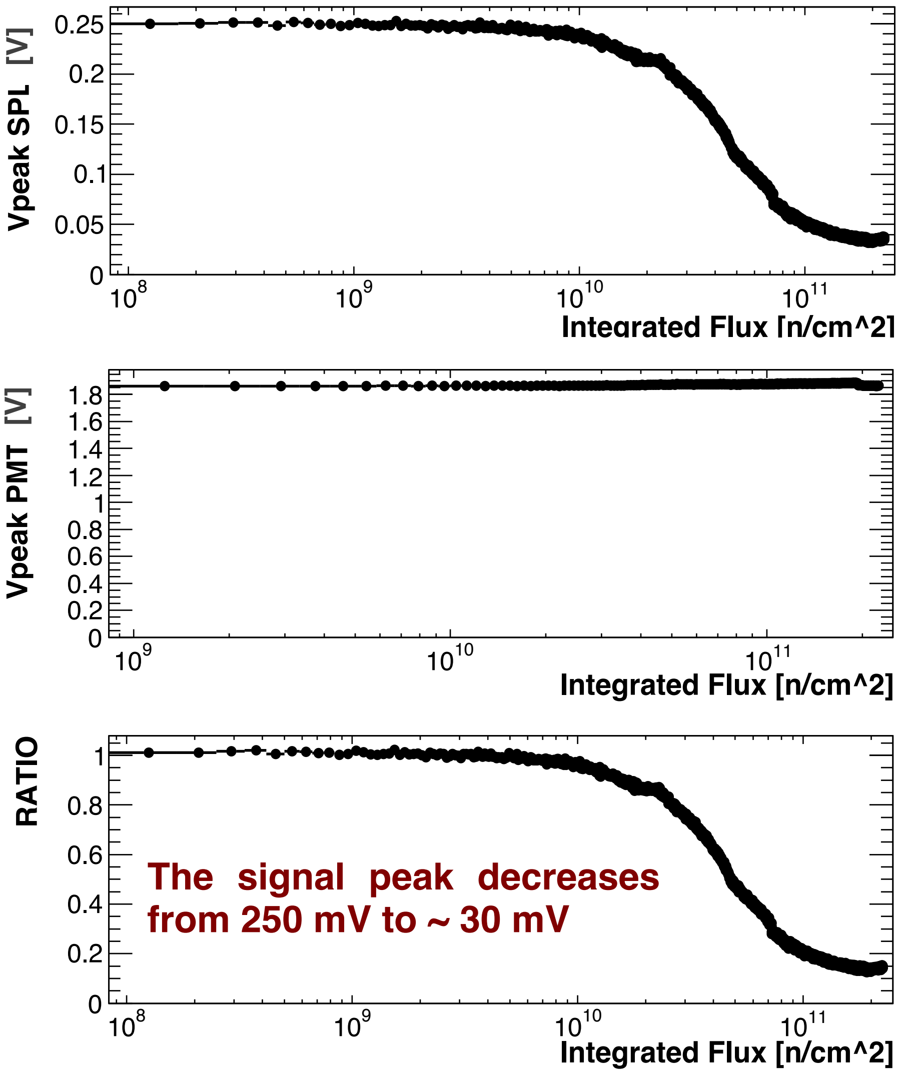
more than the required safety margin of the experiment

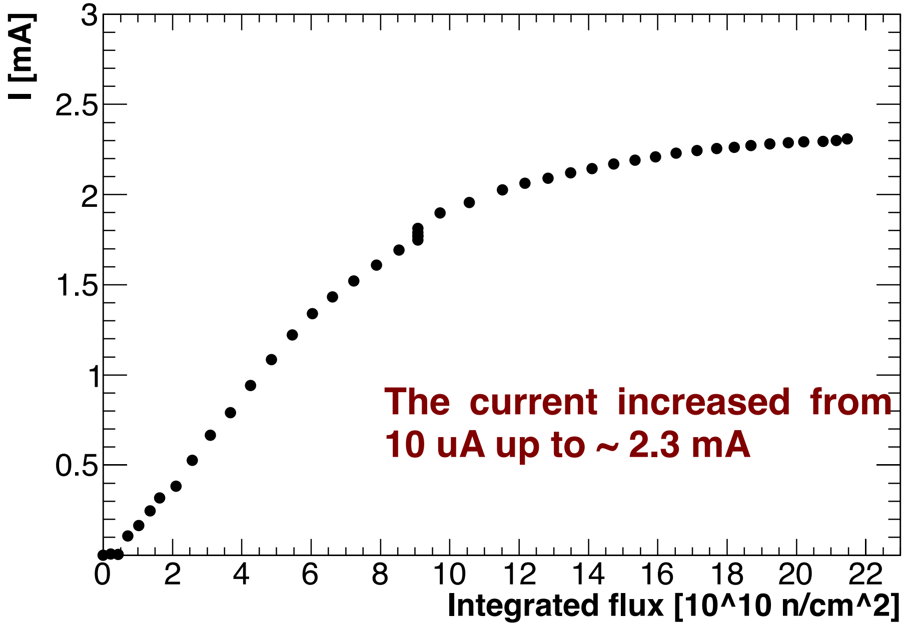
	Day 1 (SPL)	Day 2 (Thin Film)
Total neutrons from source	1.36×10^{14}	1.3×10^{14}
Average flux (n/s)	1.09×10^{10}	1.16×10^{10}
Total neutrons (14 MeV) on SIPM	2.2×10^{11} n/cm²	2.2×10^{11} n/cm²



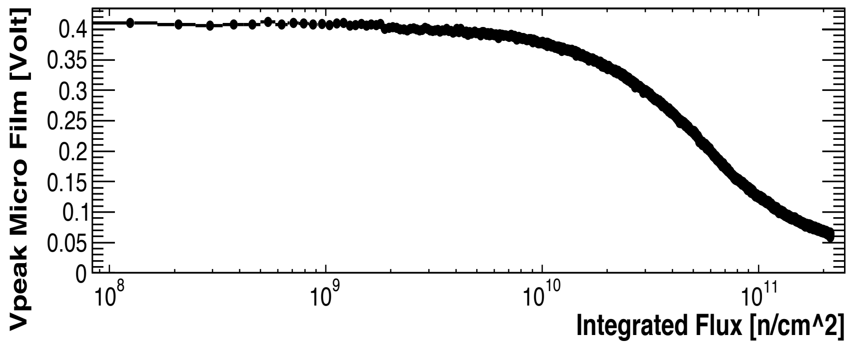


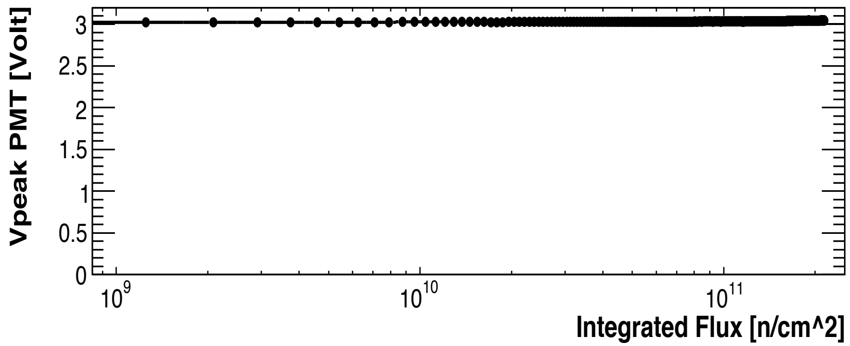
(R3) - Day 1 – SPL response

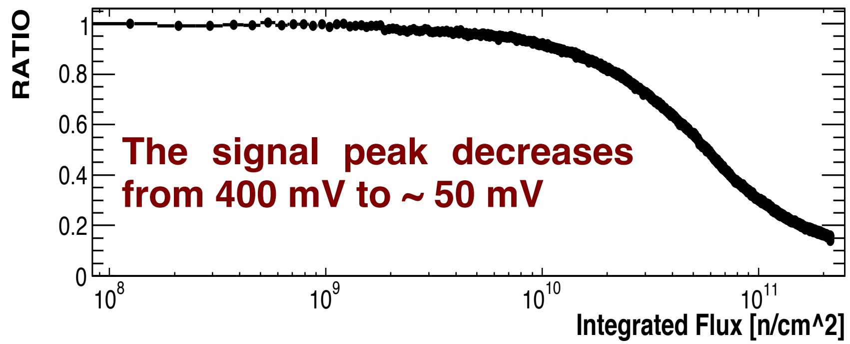




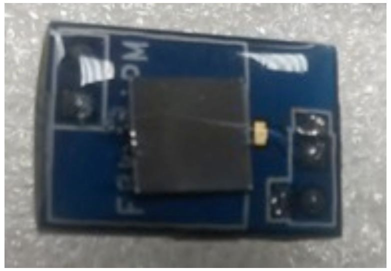
(R3) - Day 2 – Thin Film response



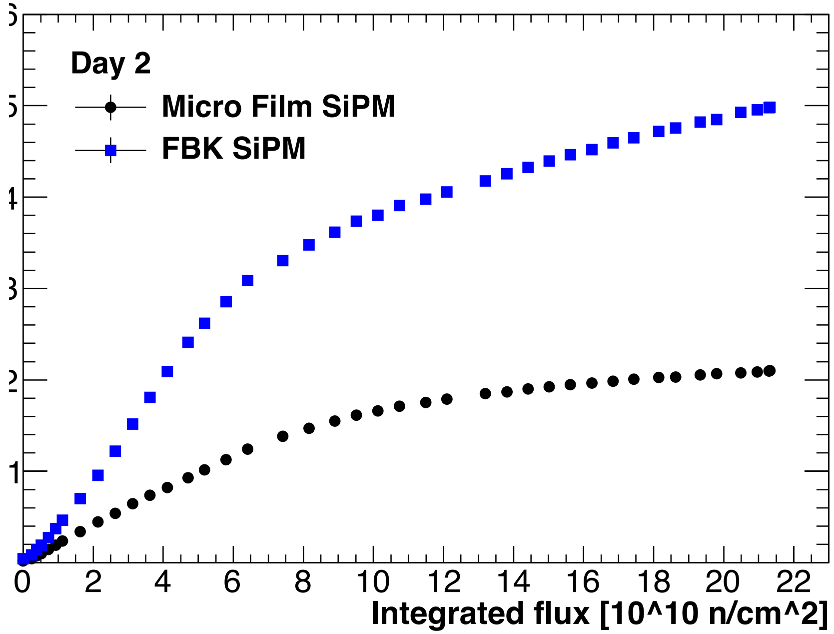




FBK: 1 SiPM of 6x6 mm²



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



The current increased from

- **16 uA up to 2.1 mA (Micro Film)**
- **86/4 uA up to 19/4 ~5 mA (FBK)**