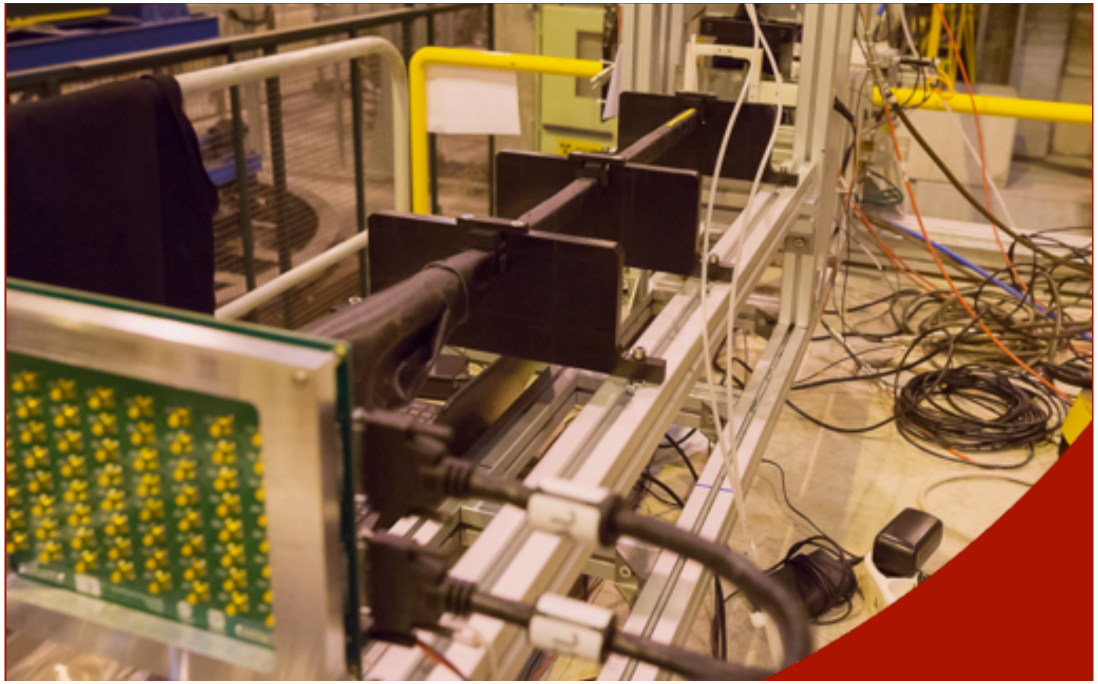


A small dual readout calorimetric module readout by SiPM:

Lab activity in preparation for the 2017 beam test

R. Santoro, M. Caccia, M. Antonello (Insubria University – COMO)

On behalf of the RD52 2016 test beam team:
R. Wigmans, J. Hauptman, S. Lee, M. Cascella, S. Franchino, R. Ferrari, F. Scuri

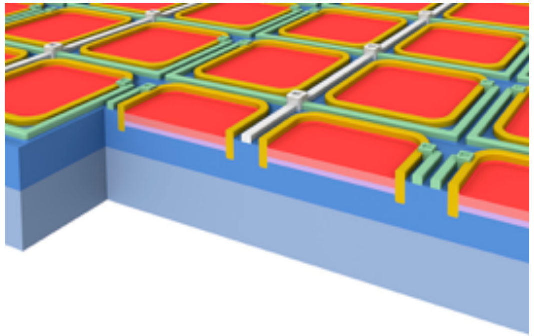
Outlook

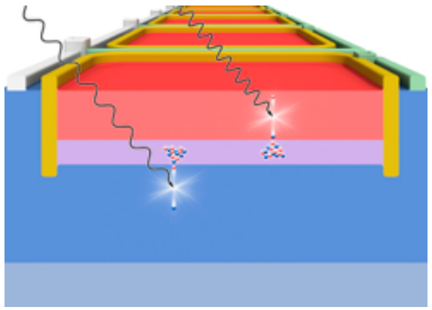
- First SiPM based dual readout calorimetric module tested on beam in 2016
- Lab activities for the 2017 beam test

SiPM: short introduction

I Principles

SiPM = High density (~10^4/mm^2) matrix of diodes with a common output, reverse biased, working in Geiger-Müller regime

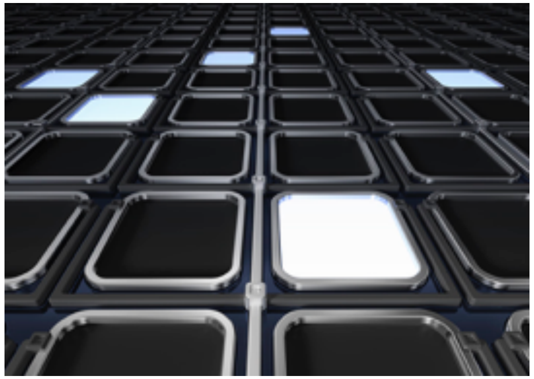




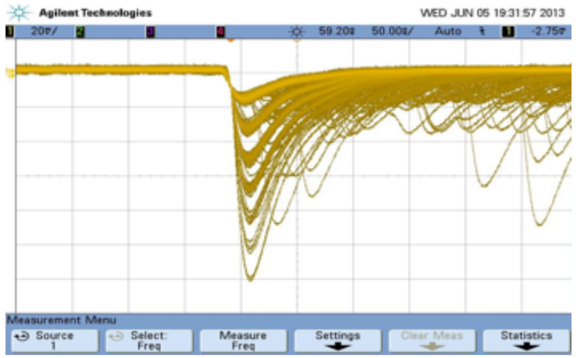
When a photon hits a cell, the generated charge carrier triggers an avalanche multiplication in the junction by impact ionization, with gain at the 10^6 level

Courtesy http://www.vk.rim.or.jp/~reyhori/pages/galacc2_e.html

II Operation



SiPM may be seen as a collection of binary cells, fired when a photon is absorbed



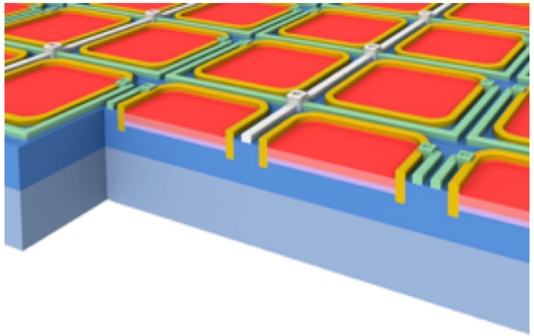
Bu the output signal is proportional to the number of fired cells providing an information about the intensity of the incoming light

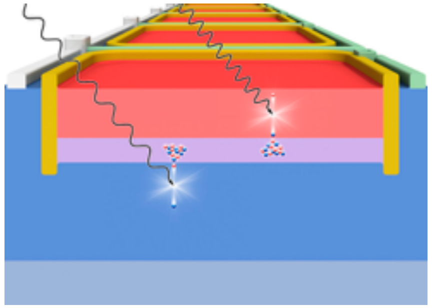
SiPM: short introduction

I Principles

SiPM = High density (~10^4/mm^2) matrix of diodes with a common output, reverse biased, working in Geiger-Müller regime

Courtesy http://www.vk.rim.or.jp/~reyhori/pages/galacc2_e.html





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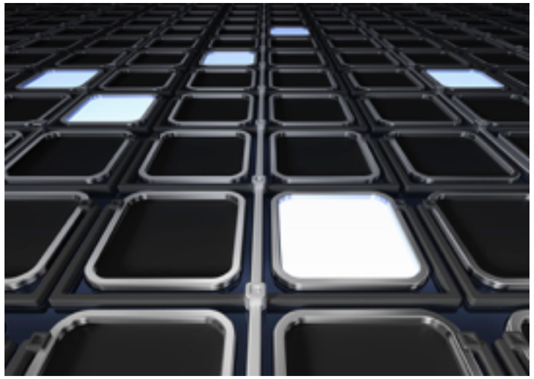
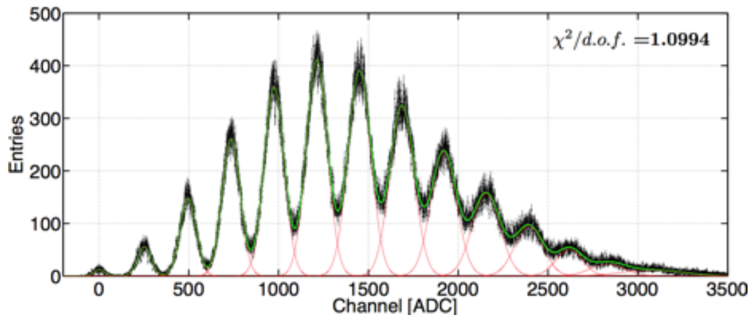
II Operation



SiPM may be seen as a collection of binary cells, fired when a photon is absorbed



This is what you get integrating the SiPM output signal. Each peak correspond to a specific number of cells fired.

A typical characterization protocol

- ***I-V measurements*** (leakage current, quenching resistor, breakdown voltage)
- ***Noise measurements*** (vs over voltage and vs temperature):
  - Dark counting rate (DCR)
  - Optical cross-talk
  - Afterpulse

Important points for calorimetry

- ***Spectrum Analysis*** (vs temperature)
  - Resolution power (how many photons can I distinguish?) & gain
  - Working point optimization (at low and large flux)
  - System noise and cell-to-cell gain variations
- ***Linearity*** & ***dynamic range***

Important points for calorimetry

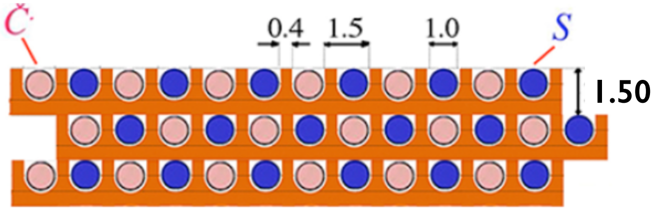
- ***Spectral response*** (PDE vs λ, PDE vs temperature)
- **Timing properties** and time resolution (currently O(100ps))

Outlook

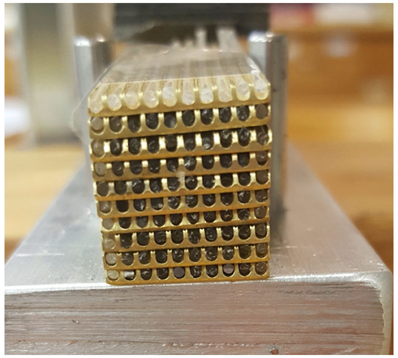
- First SiPM based dual readout calorimetric module tested on beam in 2016

- Lab activities for the 2017 beam test

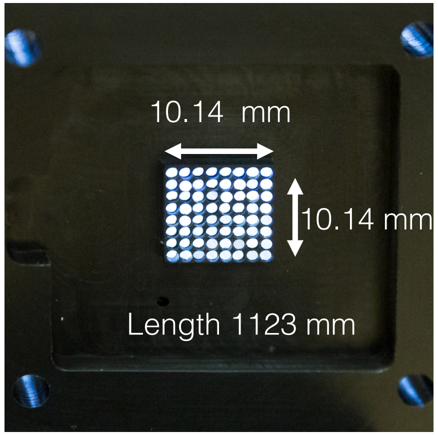
Calorimetric Module

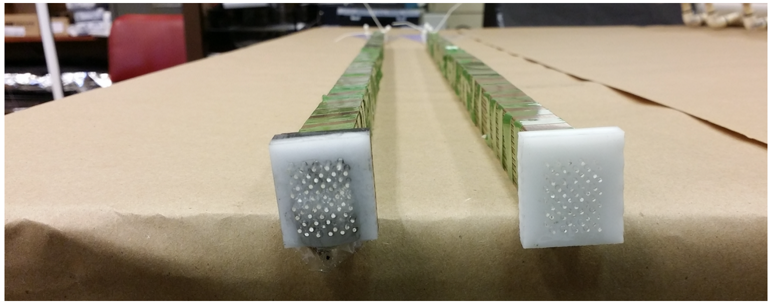


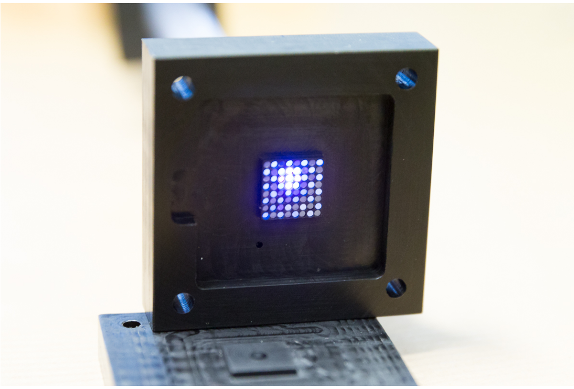
The module is built from stacked copper layers, housing 1mm diameter clear & scintillating fibres with a pitch of 1.5 mm



10x10 fibers

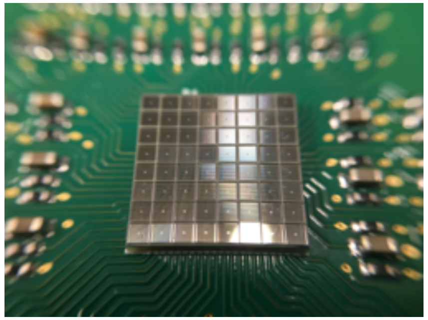


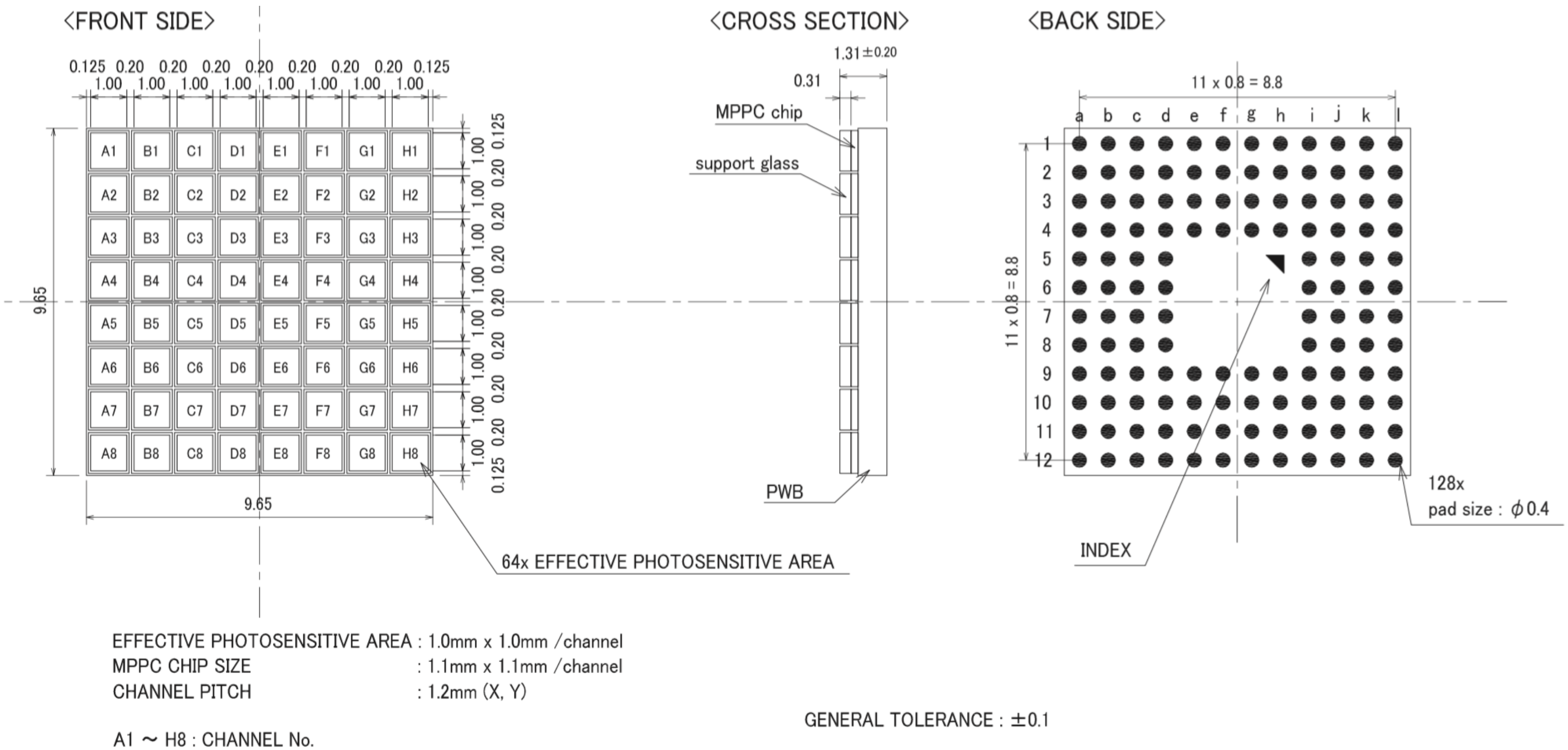




The Sensor

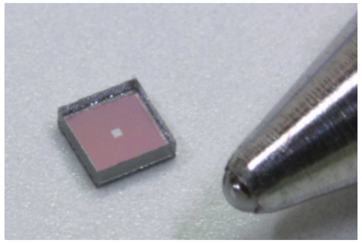
The sensor is an array 8x8 of SiPMs (Hamamatsu series 13615) mounted on the same substrate with the Through Silicon Via (TSV) technology. Each SiPM is 1x1 mm^2



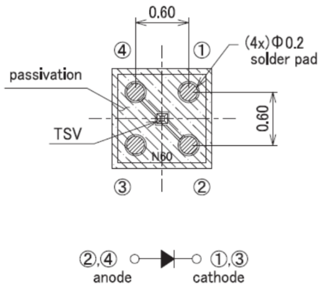


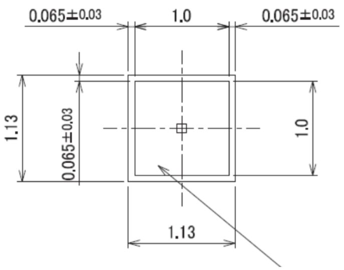
The SiPM

The sensor used has 50 μm cell pitch (S13615-1050)



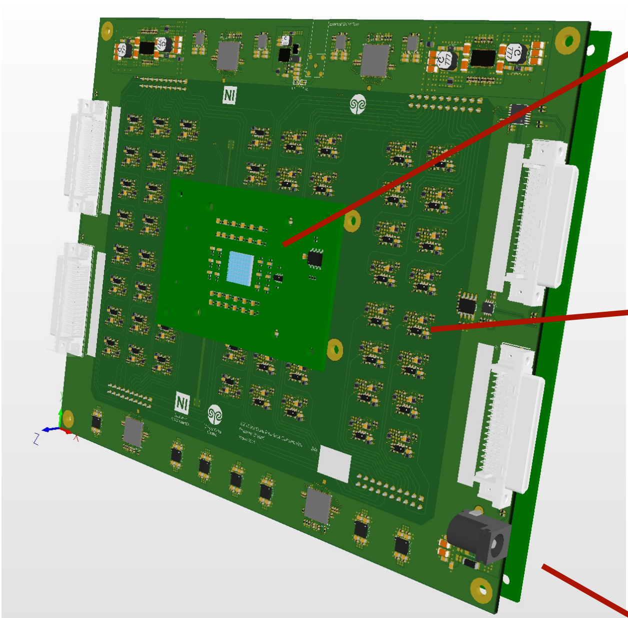
Parameters	S13615 -1025	S13615 -1050	Unit
Effective photosensitive area	1.0x1.0		mm^2
Pixel pitch	25	50	μm
Number of pixels / channel	1584	396	-
Geometrical fill factor	47	74	%

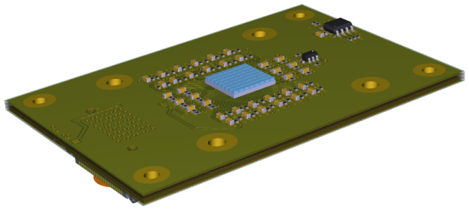




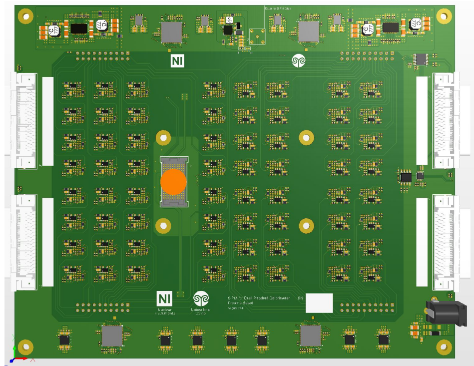
Parameters		Symbol	S13615 -1025	S13615 -1050	Unit
Spectral response range		λ	320 to 900		nm
Peak sensitivity wavelength		λp	450		nm
Photon detection efficiency at λp*3		PDE	25	40	%
Breakdown voltage		V_{BR}	53 ±5		V
Recommended operating voltage*4		V_{op}	V_{BR} + 5	V_{BR} + 3	V
Dark Count	Typ.	-	50		kcps
	Max.		150		
Crosstalk probability	Typ.	-	1	3	%
Terminal capacitance		Ct	40		pF
Gain*5		M	7.0×10^5	1.7×10^6	-

Sensor Board

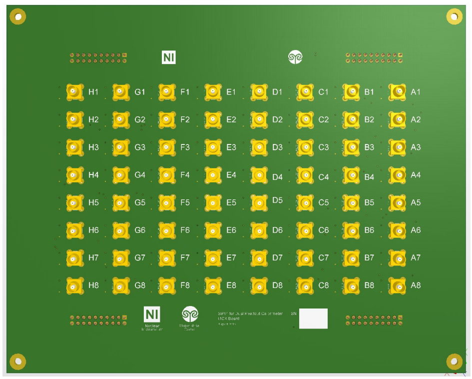




1. The daughter board, providing an independent bias to the 64 SiPMs and integrating temperature measurement for gain compensation



2. The mother board
- Amplifying & shaping the output of each sensor
- Routing the signals to the digitisation system



3. The backplane board allowing to probe via mcx connectors each channel

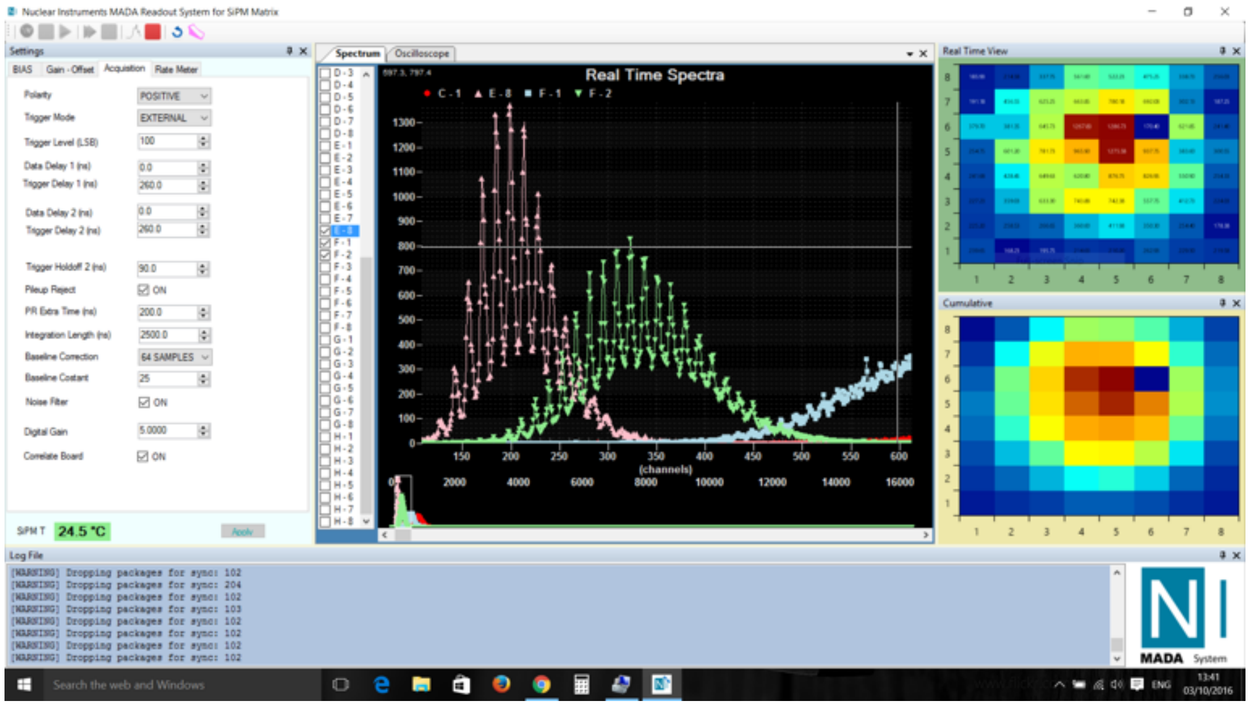
Nuclear Instruments

The DAQ System

Nuclear Instruments

- Two MADA boards (32 channel digitizer each)
- Sampling rate 80MSpS/14-bit ADC
- FPGA based charge integration algorithm
- FEE designed to stretch the signal over ≈ 1 μs (1 ph-e)

On Line Display

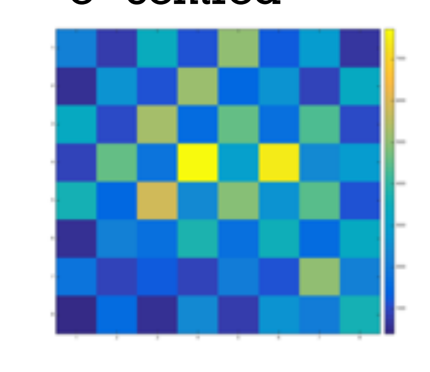


Data Taking condition

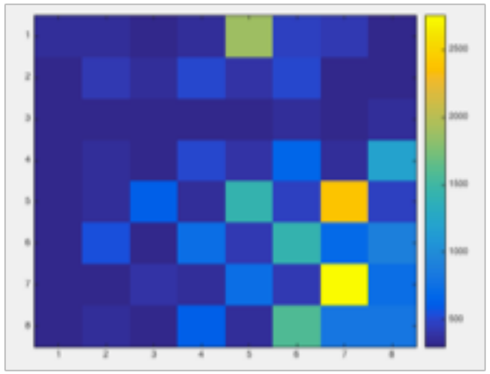
- Two modules used: both based on the array with 50 μm pitch cells:
  - Module 1: both scintillating and Cherenkov fibres connected to the SiPM array
  - Module 2: only Cherenkov fibers connected (strategy used to study the light cross talk among fibres)

Module 1: Event display

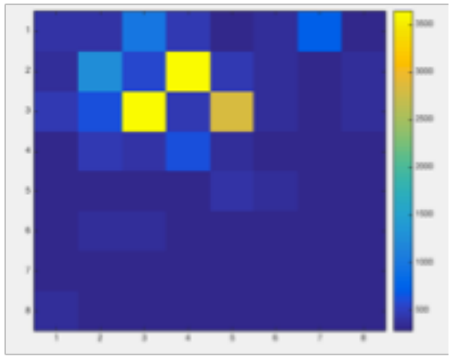
e^+ centred



e^+ off centred



Muon

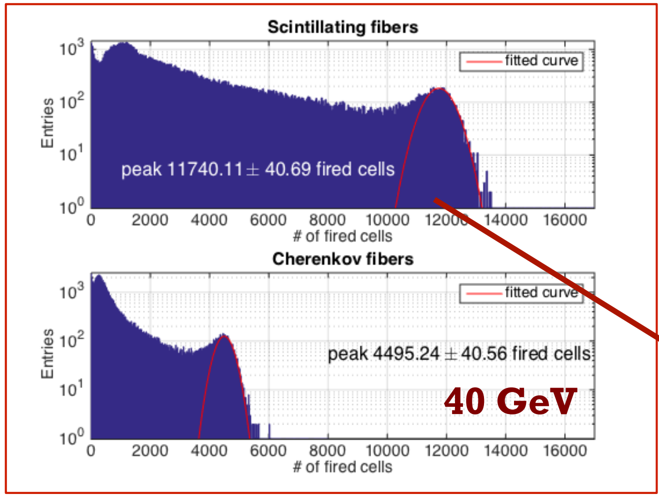


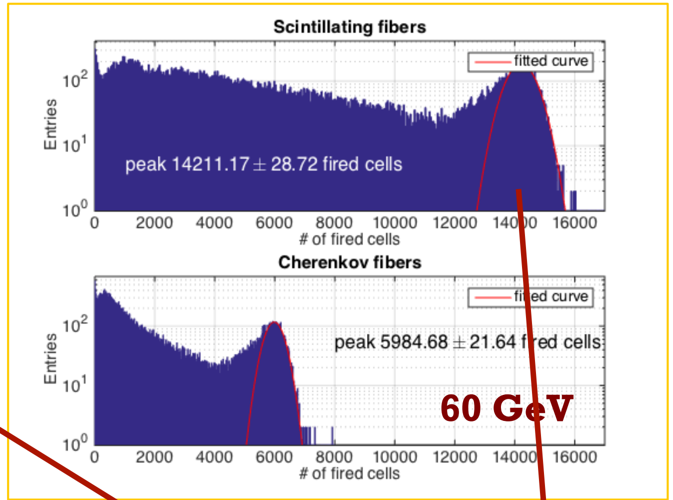
40 GeV Beam

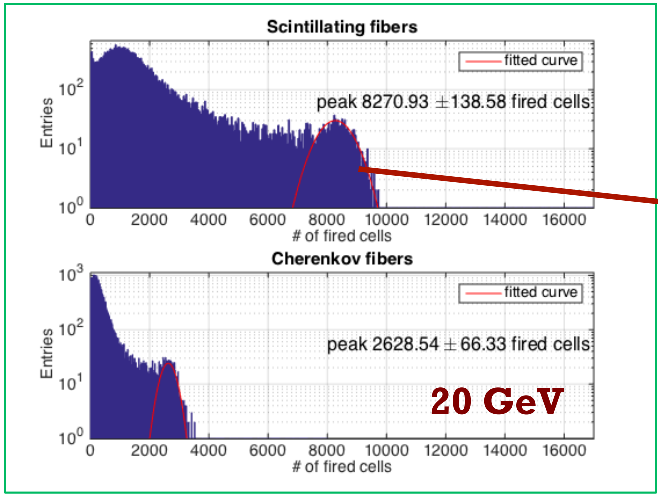
Module 1: Results

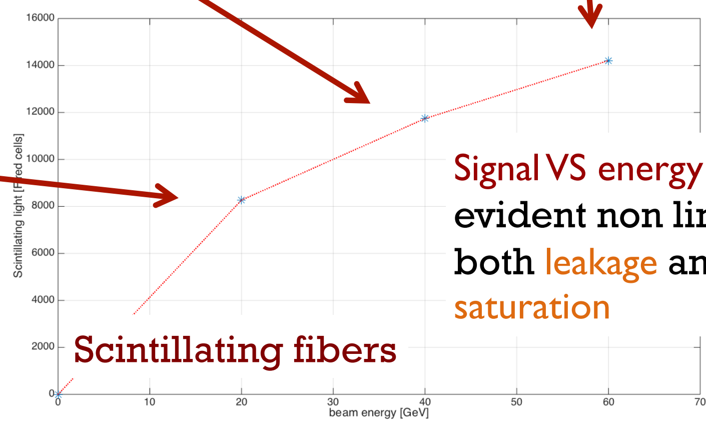
Test-Beam 2016

Spectra of the Total Signal Amplitude integrated over the full signal development: 32 channels used for the scintillating spectra and 32 channels for the Cherenkov spectra









Signal VS energy
evident non linearity due to both leakage and SiPM response saturation

Module 1: Results

Test-Beam 2016

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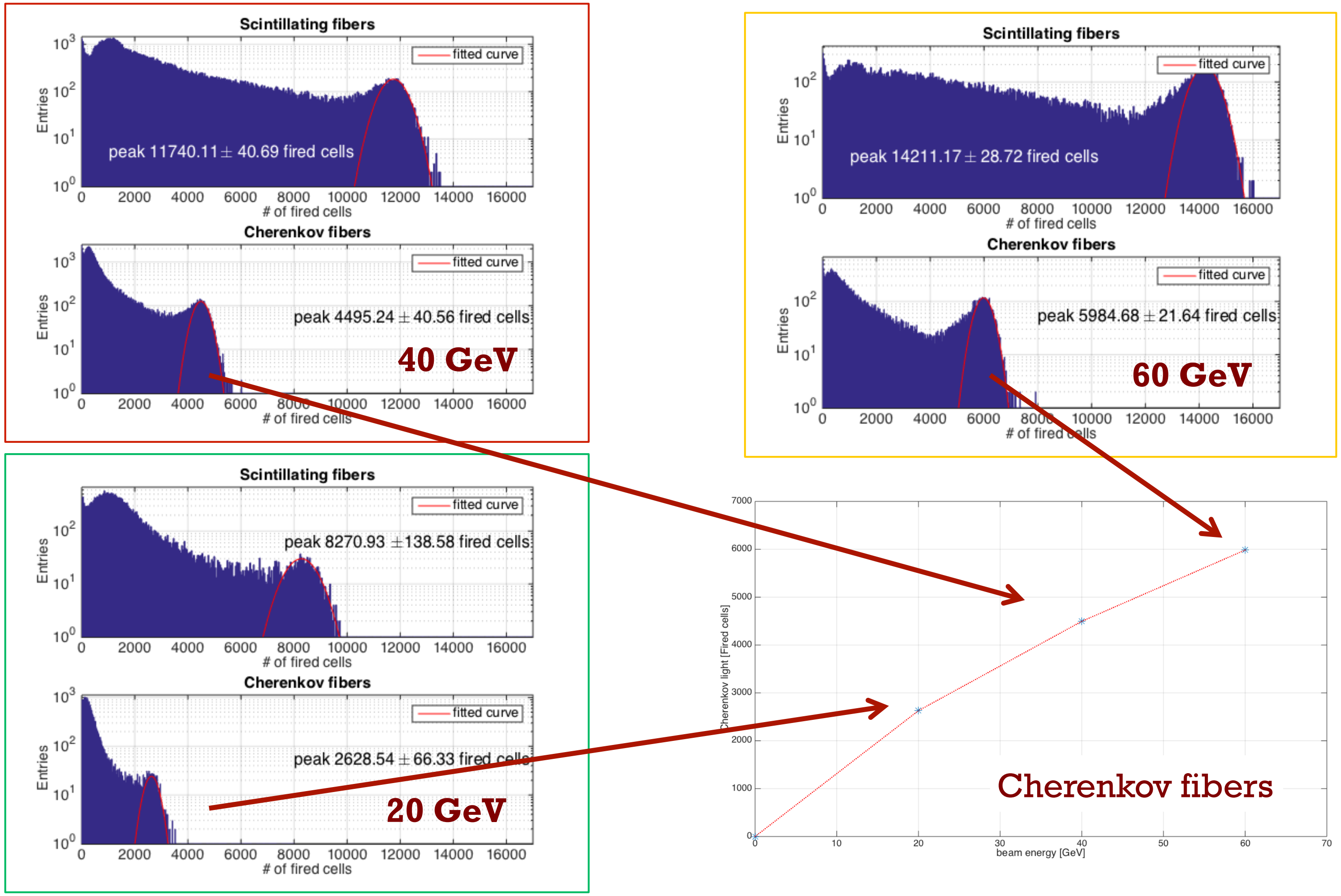
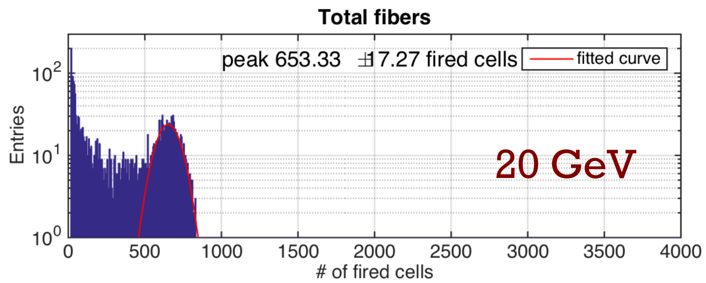
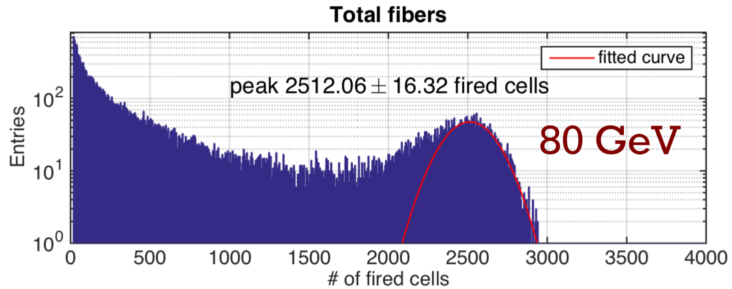
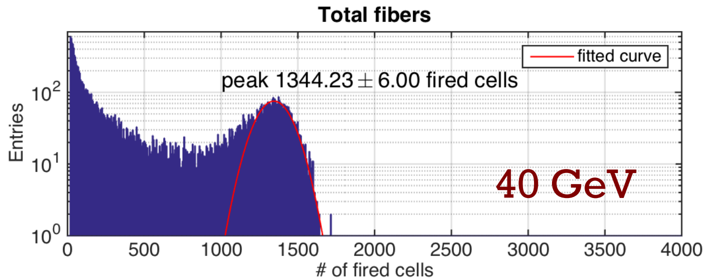


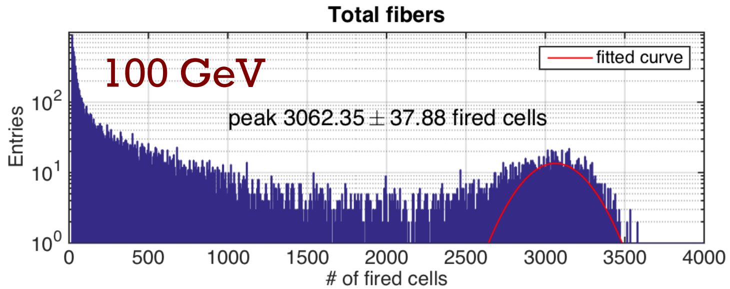
Module 2: Results (only Cherenkov fibers connected)

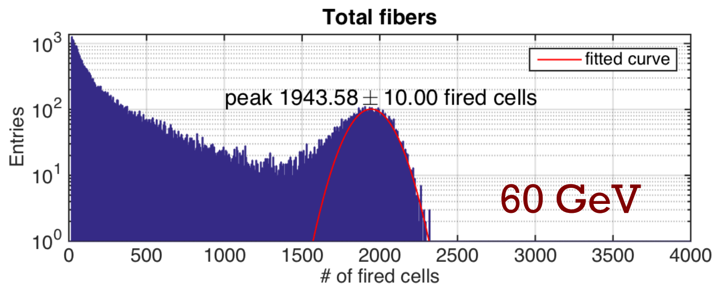
For these distributions was considered all the light from the 64SiPMs because it belongs to the connected Cherenkov plus the light cross talk

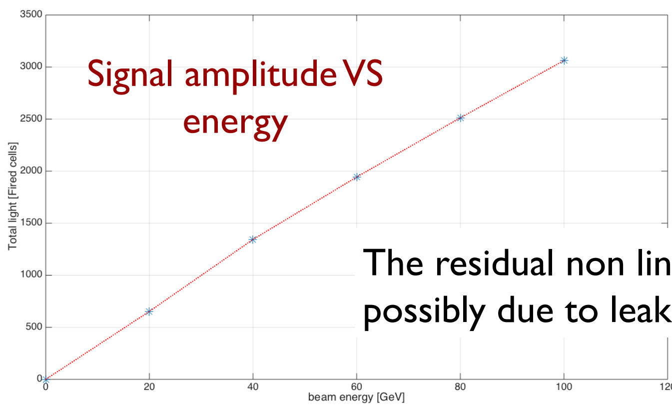








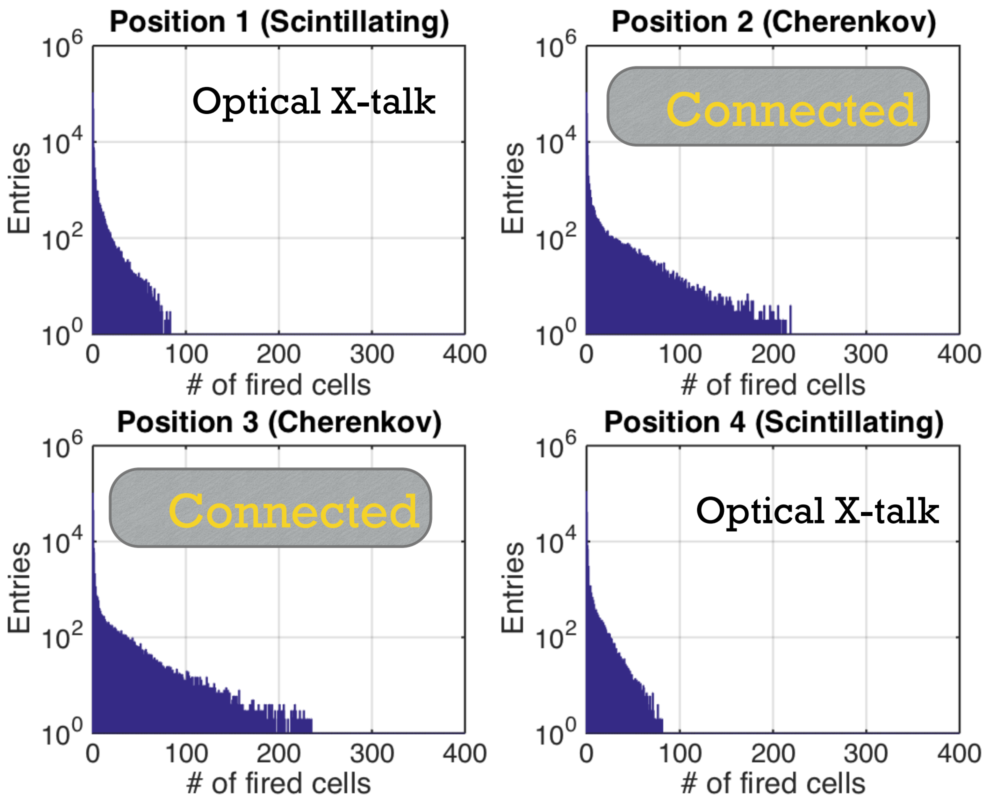


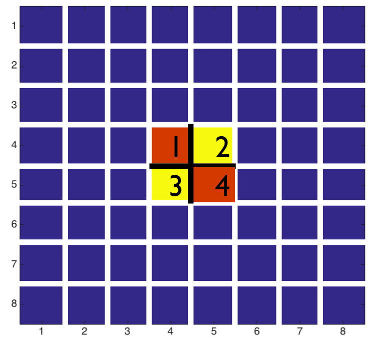


The residual non linearity is possibly due to leakage

Module 2: Results (only Cherenkov fibers connected)

Centred Fibers light distribution (100 GeV beam)





Measured Light Cross-talk among fibres

Energy (GeV)	20	40	60	80	100
X-Talk (%)	25.1	25.4	25.9	26.4	26.8

Outlook

- First SiPM based dual readout calorimetric module tested on beam in 2016

- Lab activities for the 2017 beam test

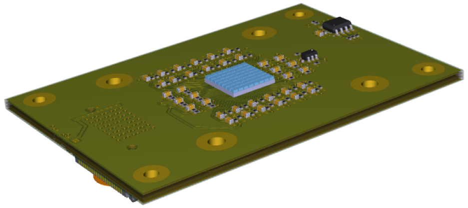
Calorimetric Module for the 2017 Test Beam

- SiPMs SMD mounted on two separate boards to avoid the optical cross-talk among fibres as much as possible

- Basic module assembled starting connecting the fibres to the sensor to improve the SiPM VS fibres alignment

- SiPM with 25 μm cell to increase the SiPM dynamic range
  - The number of cells goes from 396 to 1584
  - The PDE goes from 40% to 25% (from data-sheet) mainly due to different fill factor

Sensor Board (2017)



The daughter board (2016), providing an independent bias to the 64 SiPMs and integrating temperature measurement for gain compensation

Replaced by

Two layer daughter board + Extender cable (2017)

1st Layer: 32 SiPMs to be connected to clear fibres + 32 holes to allow the scintillating fibres to intercept the 2nd layer

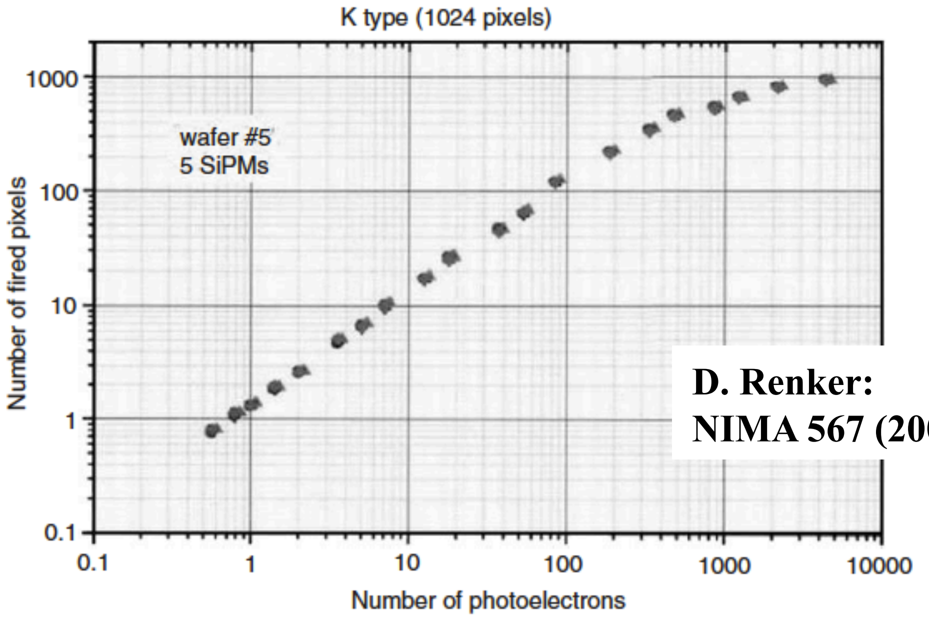
2nd Layer: 32 SiPMs to be connected to scintillating fibres

Extender Cable: to plug the daughter board to the mother board

Considerations on high flux of light (I)

- When the SiPM is operated at high flux of light the occupancy (Number of photons / Number of cells available) has to be accounted for to recover the linear response

$$N_{fired} = N_{total} \times \left[1 - e^{-\frac{N_{photons} \times PDE}{N_{total}}}\right]$$



D. Renker:
NIMA 567 (2006) 48–56

Considerations on high flux of light (II)

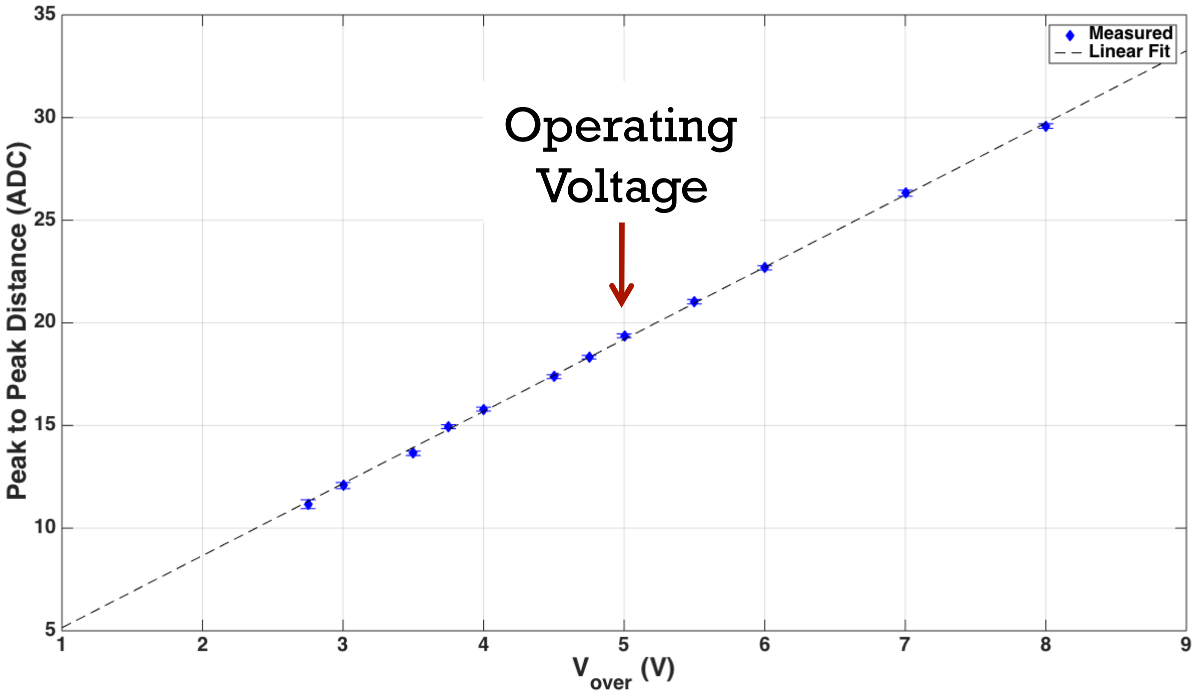
- The typical way to reduce the non linearity is to increase the number of cells / mm^2 in the SiPM. Even if it would bring to a reduced efficiency

cell size (μm)	number of cells / mm^2	typical PDE (%)	series
50	396	40	S13615-1050
25	1584	25	S13615-1025
15	4489	25	S12571-010C
10	10000	10	S12571-015C

- For the 2017 test beam we run SiPMs with 25 μm pitch
- We are also investigating the possibility to run the sensor at reduced over-voltage to gain even more dynamic range

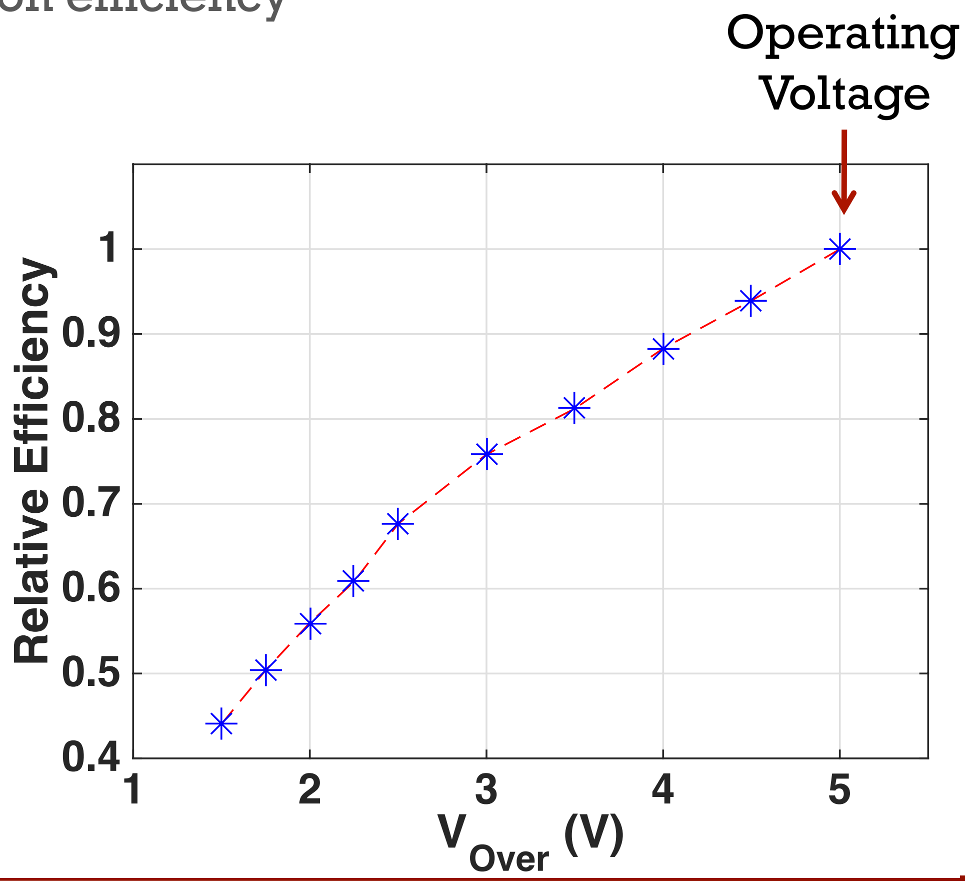
Peak to Peak distance VS V_{Bias}

- At lower overvoltage, the Peak to Peak decreases linearly
- The distance is visible up to 3V below the operation voltage, and it can be extrapolated for lower voltages



Relative Efficiency VS V_{Bias}

- Lower Overvoltage effects the PDE as well
  - Light chosen to be away from saturation: 21% occupancy
  - The overvoltage scan at fixed amount of light allows to measure the relative detection efficiency



Some speculation …

- … in numbers:

Beam Energy (GeV)	Expected photons*	pitch (μm)	V_bias	PDE (%)	Number of fired cells**	Occupancy (%)
100	7000	25	nominal	25	1059	67
100	7000	25	nominal – 3V	14	730	46

Options which will be investigated in the 2017 test beam

*Number from Richard: expected photons in a single scintillating fiber
** Number corrected for the occupancy and the SiPM PDE

Some speculation …

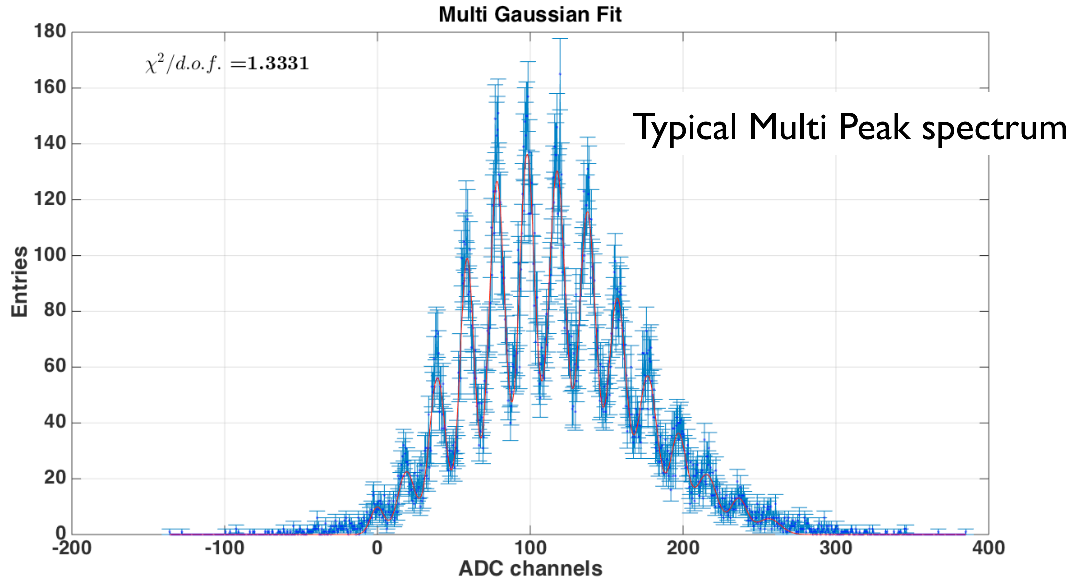
- … in numbers:

Beam Energy (GeV)	Expected photons*	pitch (μm)	V_bias	PDE (%)	Number of fired cells**	Occupancy (%)
100	7000	25	nominal	25	1059	67
100	7000	25	nominal – 3V	14	730	46
100	7000	15	nominal	25	1450	32
100	7000	10	nominal	10	675	6.8

*Number from Richard: expected photons in a single scintillating fiber
** Number corrected for the occupancy and the SiPM PDE

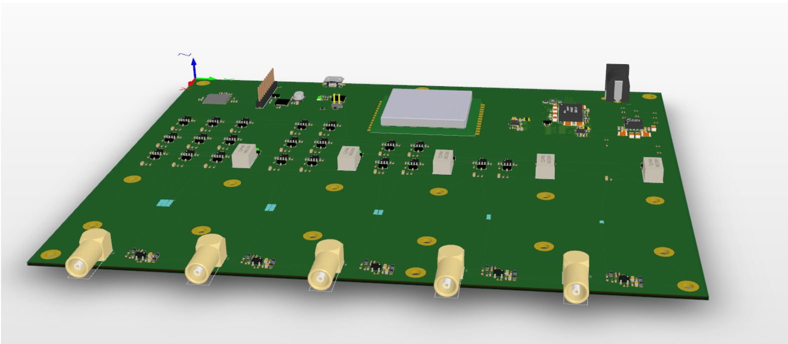
Sensors Qualification

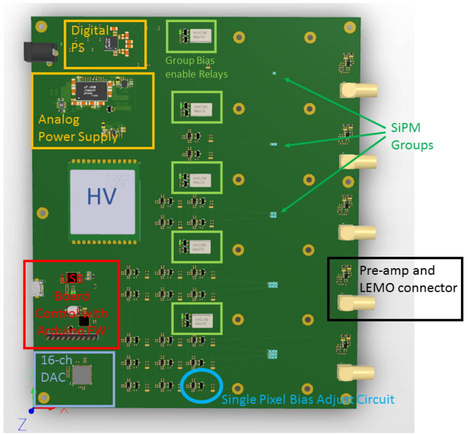
- Bias adjusted to have the same Peak To Peak distance in all SiPMs
  - Maximum difference in bias is 300 mV
- Peak To Peak distance obtained:
  - mean value = 19.3 ADC
  - STD = 0.3 ADC



Outlook

- If in the future we decide not to readout SiPMs individually, we could consider to group the analogue output signals. In this case, The main question to be addressed is:
  - How many SiPMs can be grouped maintaining the Multi-Photon spectrum?
  - This requirement would allow to monitor the gain variation VS temperature and to access the gage from ADC to number of fired cells





Electronics to study the grouping will be delivered by the end of next week

- The FEE used for the test beam is only used in the proof of concept. The next step will be the ASIC design to allow a system which could be scalable

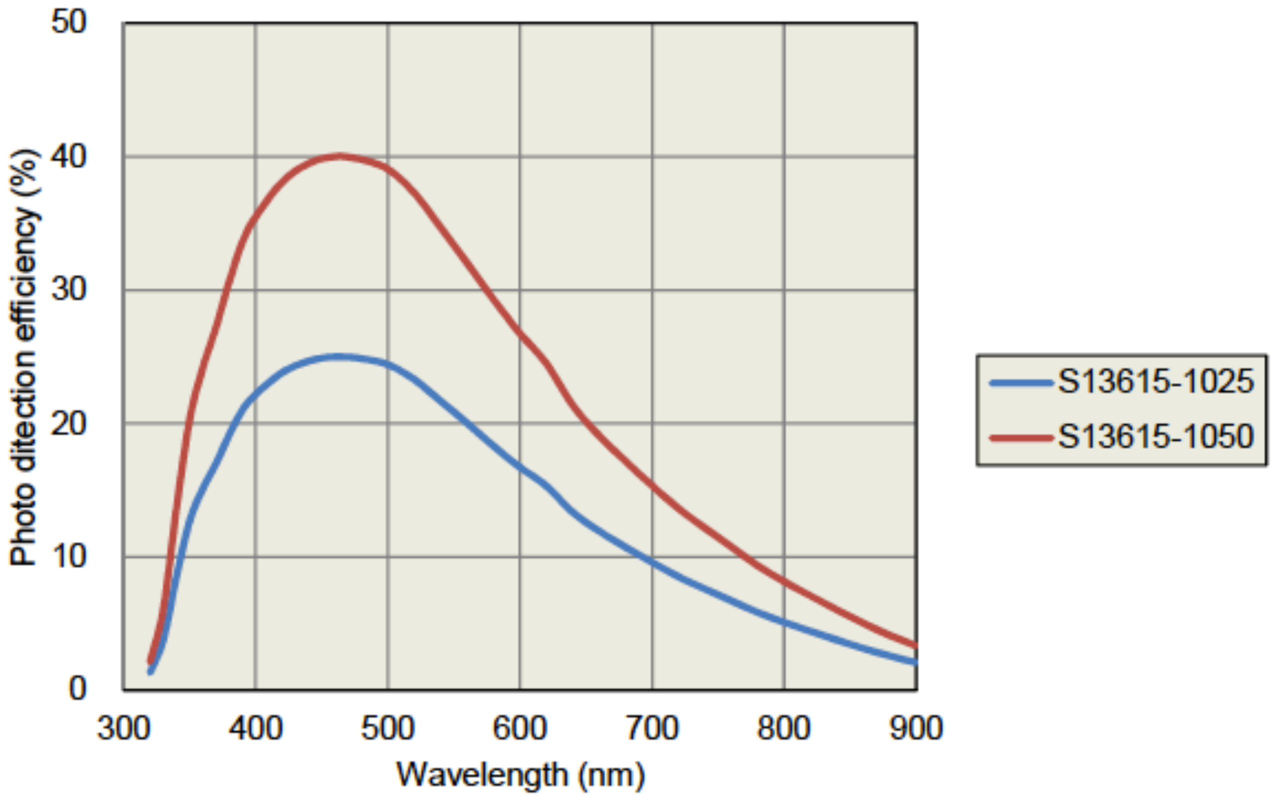
Conclusion

- A dual read-out module was interfaced to a SiPM array. It was qualified and commissioned on beam for the first time in 2016
- As a proof-of-concept, it was a success and it allowed to identify some issues which will be addressed in the 2017 test beam
  - Light cross talk among fibers when connected to the SiPM
  - SiPM saturation
- For the next step we should really consider to instrument a larger module

Backup slides

Photon detection efficiency vs. wavelength

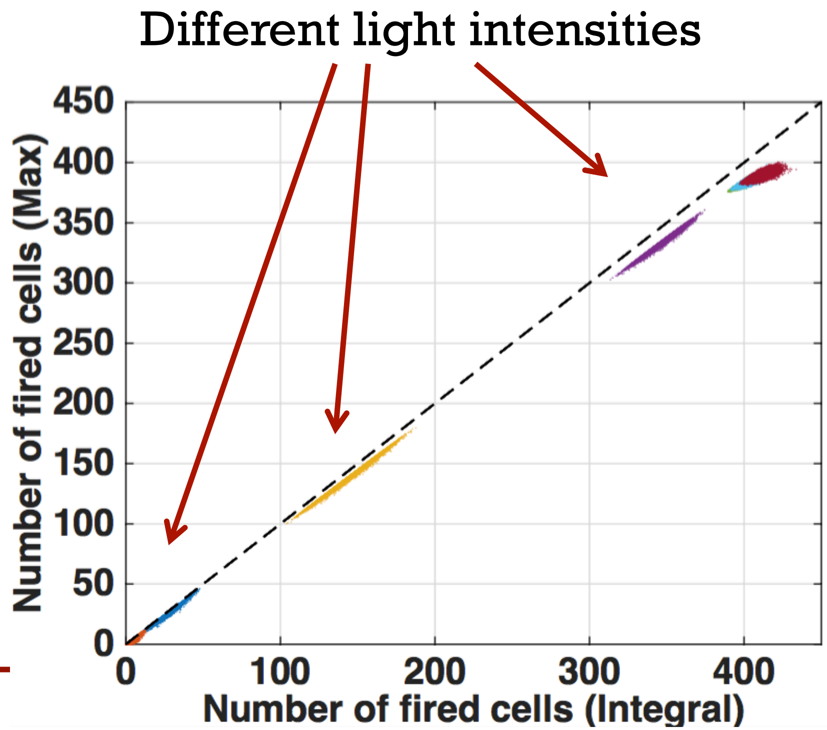
Hamamatsu data-sheet



Considerations on high flux of light (II)

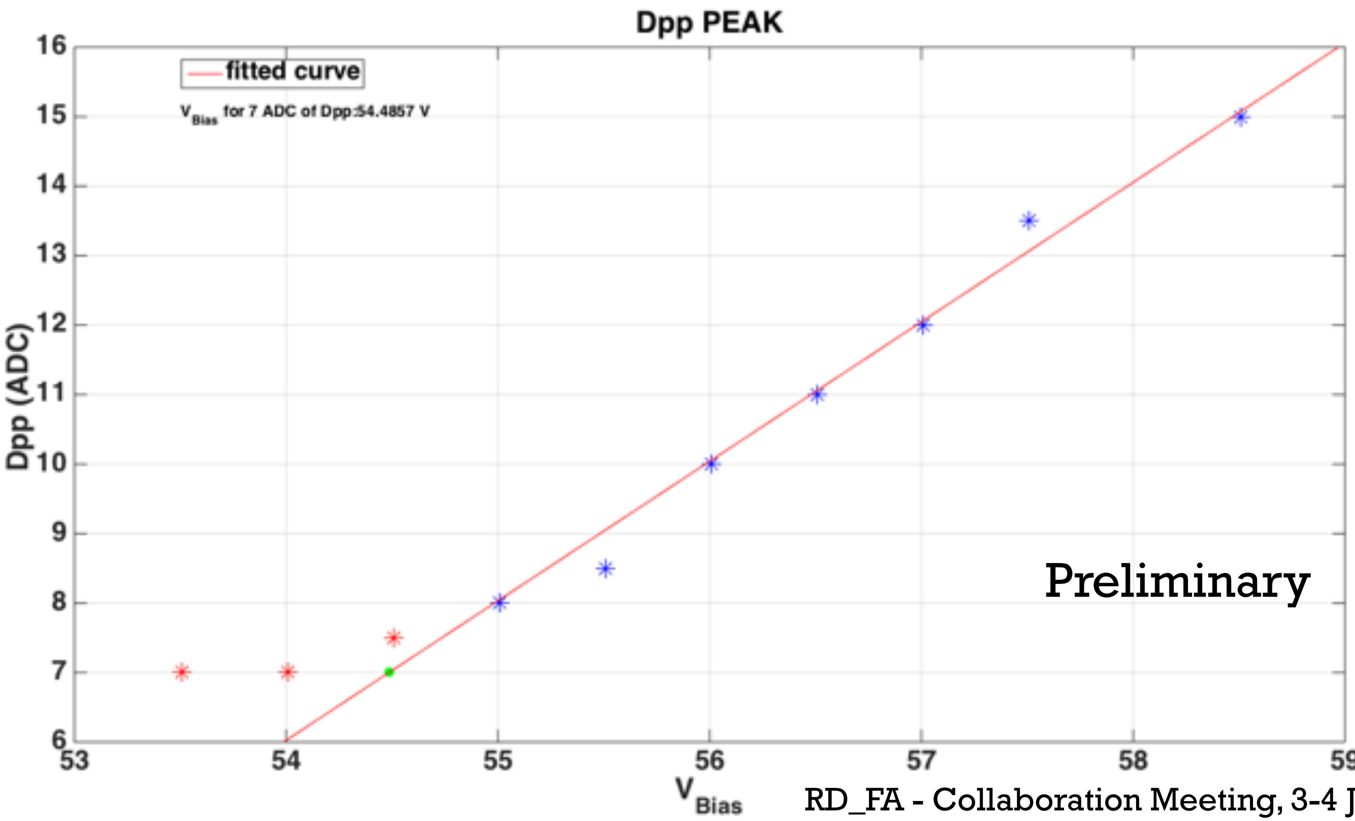
Test performed close to the saturation:

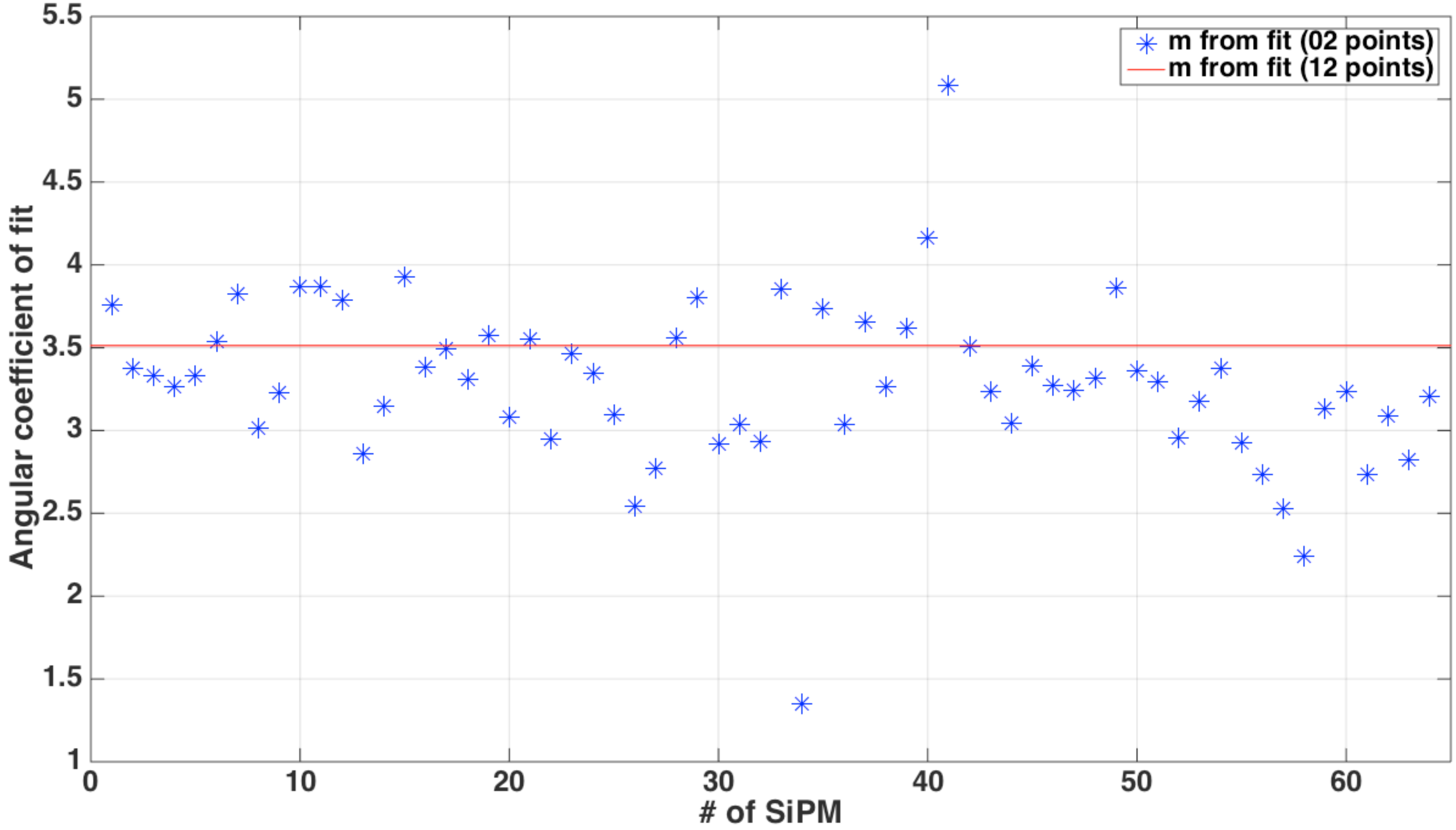
- Sensor under test S13615-1050: 400 cells, 50 μ m pitch
- we verified the behaviour up to the saturation looking at the signal integral VS the signal peak
- The small excess in the integral is mainly due to After Pulse (< 3%)



Dynamic range

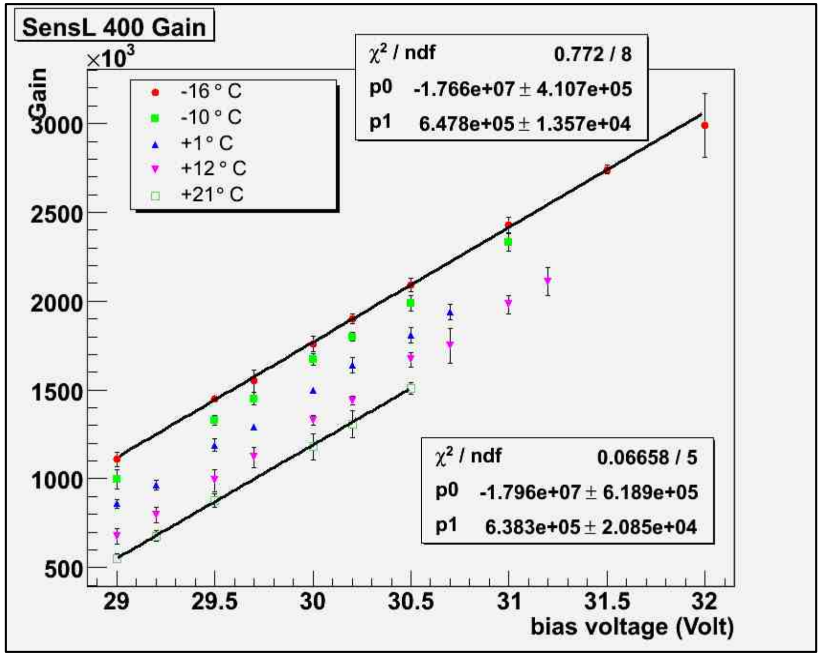
- 1584 cells for each SiPM (25 um pitch) 16 384 ADC available channels (14 bit)
- Baseline of 5000 ADC —> 11 384 ADC channels
- Number of possible fired cells: ~ 875 for VBias = 57.51 V (13 ADC of Dpp)
- No saturation —> ~ 1626 for VBias = 54.51 V (7 ADC of Dpp)

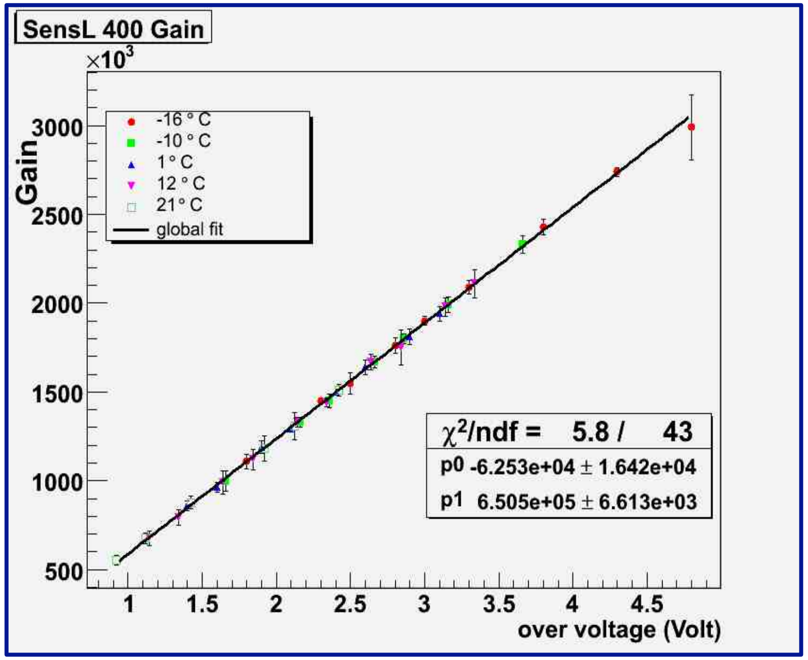




m from fit (02 points)
m from fit (12 points)
Angular coefficient of fit
# of SiPM
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0
10
20
30
40
50
60

Gain temperature variations





$$\frac{dV}{dT} = -\frac{dG}{dT}\frac{1}{\frac{dG}{dV}}$$

$$V_{BD} = \frac{dV}{dT}(T - T_{RT}) + V_{RT}$$

Breakdown Voltage rescaled accounting for temperature variation

M. Ramilli: IEEE NSS Conf. (2008), pp. 2467