A SILICON PHOTOMULTIPLIER BASED DUAL READ-OUT CALORIMETER MODULE

- 2016 module & main beam test results
- 2017 update & main results
- Next Steps

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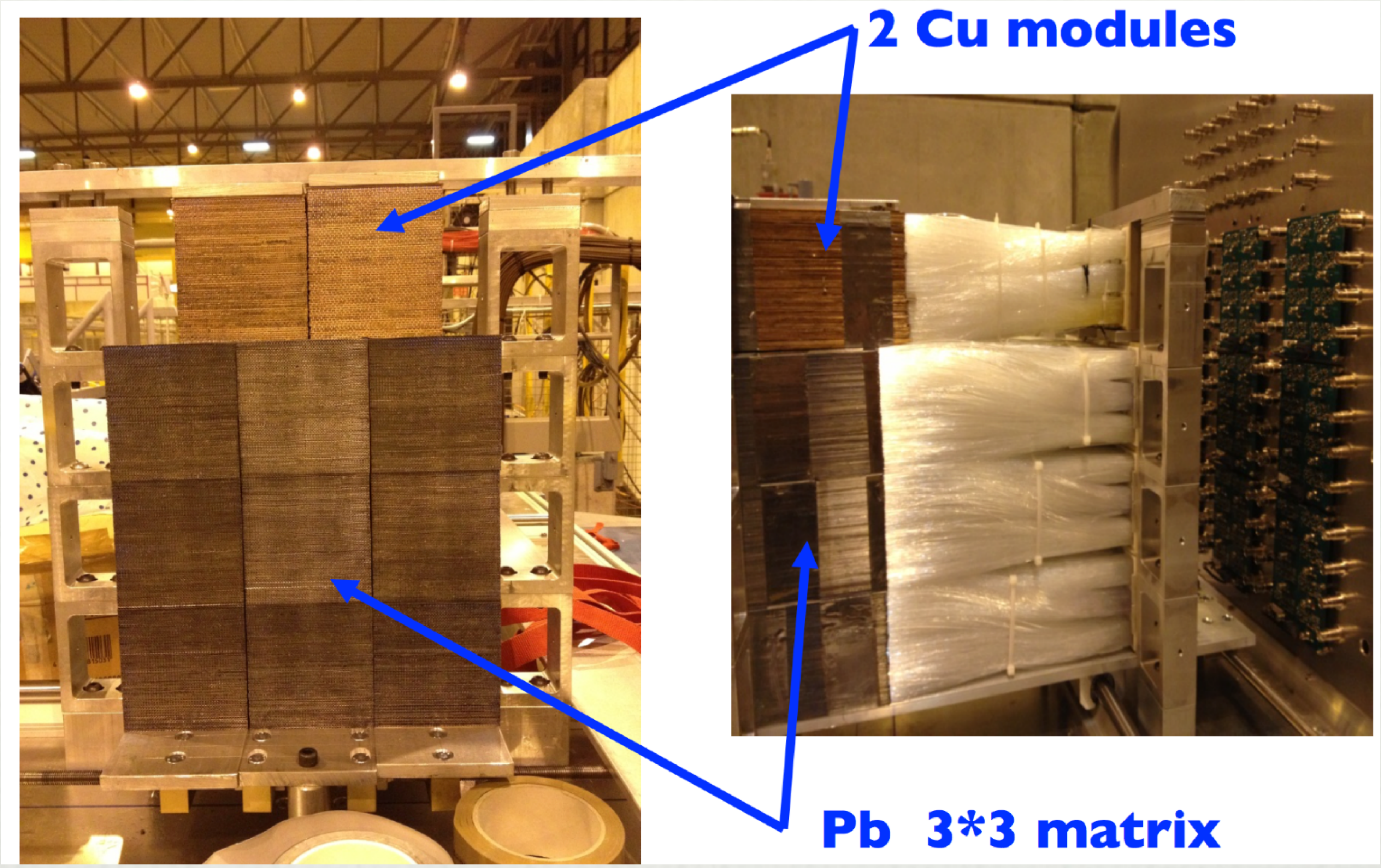
INFN Referee Report 20171205

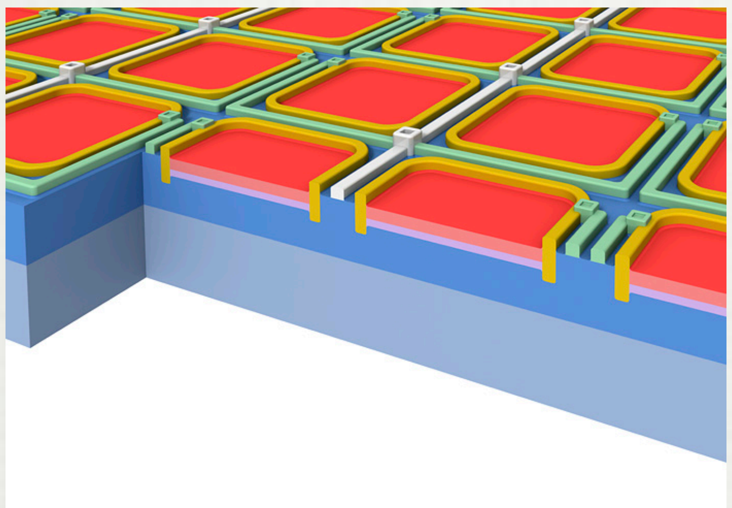
So far, so good.

BUT (there is always a BUT in life)

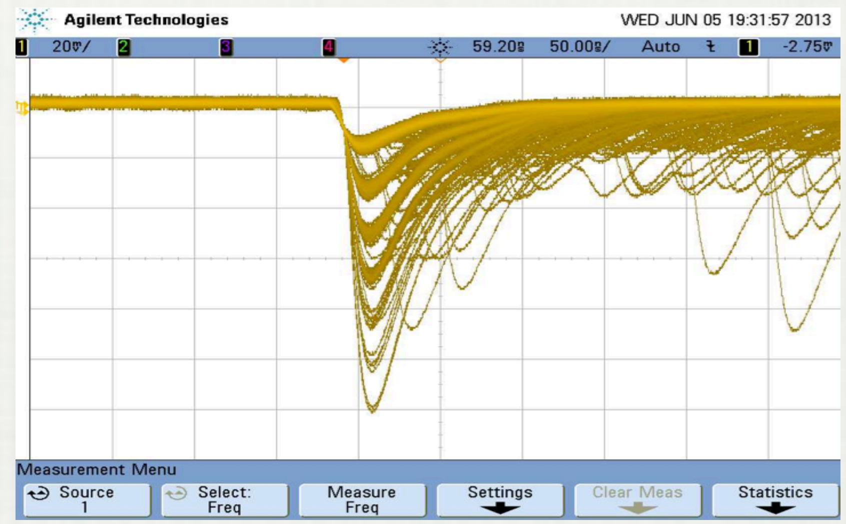


How to fit such a geometry in a collider experiment?

1. In order to get rid of the forest of fibres and try to make the design compliant with the integration in a real experiment, move away from the good old PMT's and step into the digital age, using Silicon Photomultipliers

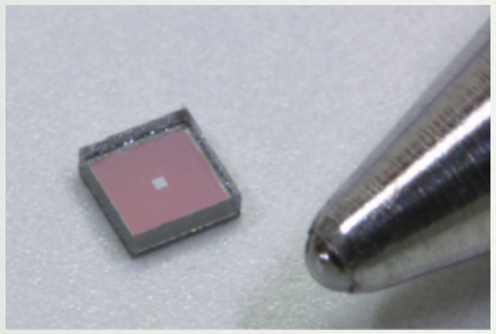


A pictorial view of a SiPM

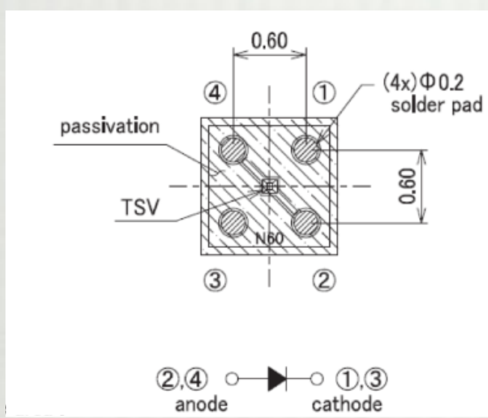


The sensor response to a pulse of light

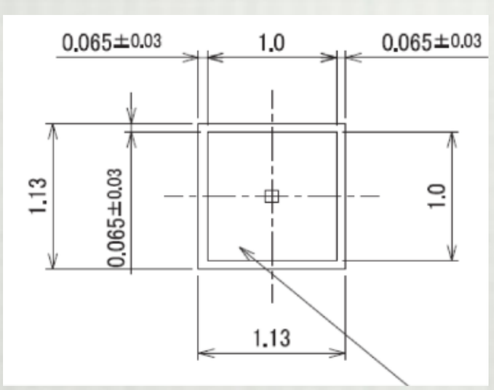
Recently, thanks to the Through Silicon Via (TSV) technology, HAMAMATSU offered arrays built up on a mosaic of 1x1mm² sensors, quite appealing for the envisaged application:



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	%

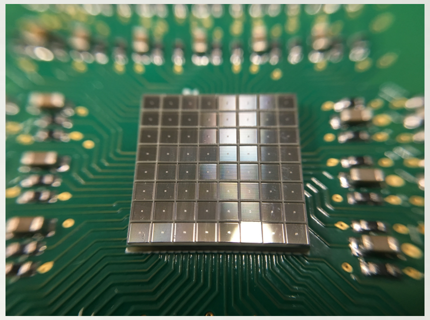


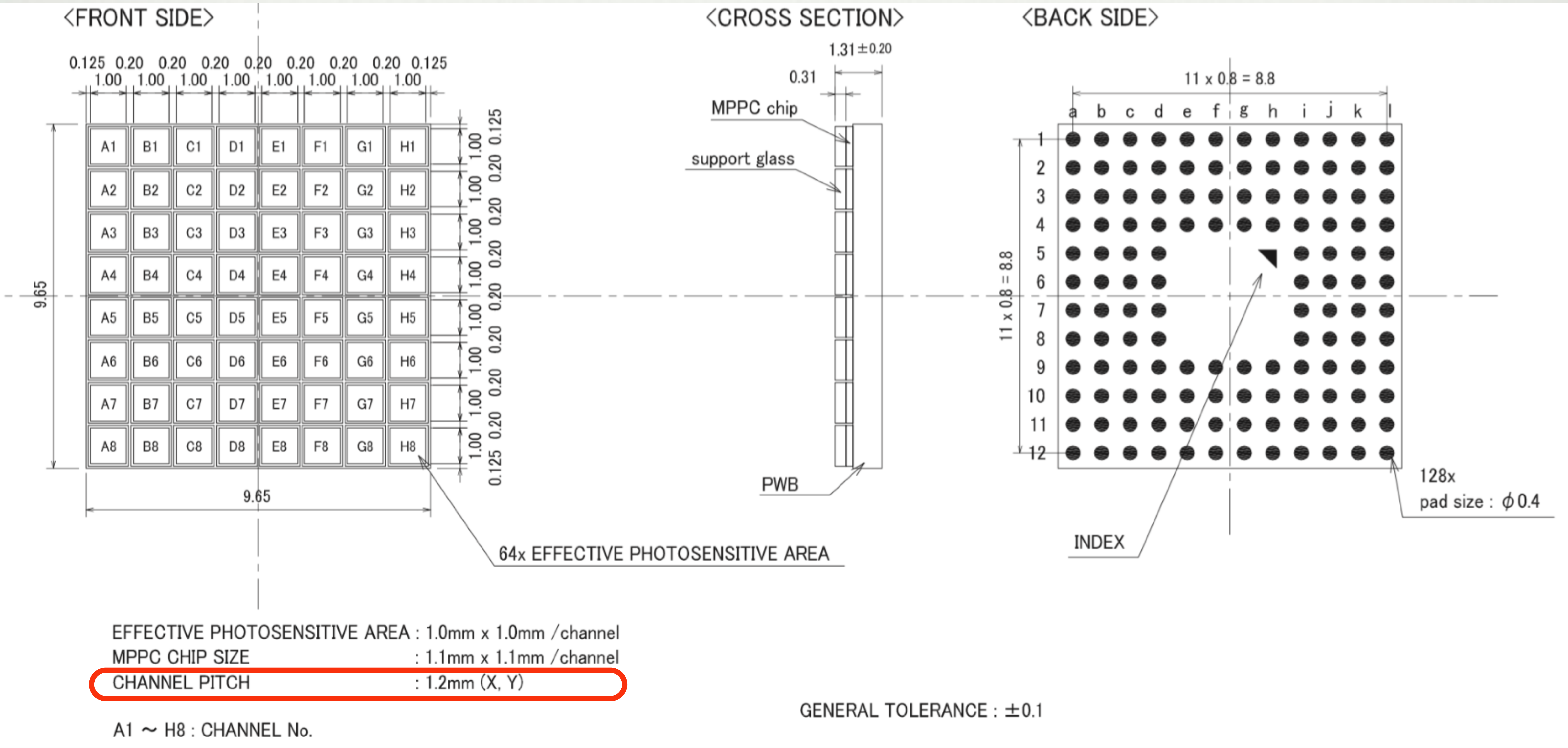
Parameters		Symbol	S13615 -1025	S13615 -1050	Unit
Spectral response range		λ	320 to 900		nm
Peak sensitivity wavelength		λp	450		nm
Photon detection efficiency at λp[*3]		PDE	25	40	%
Breakdown voltage		V_{BR}	53 ±5		V
Recommended operating voltage[*4]		V_{op}	V_{BR} + 5	V_{BR} + 3	V
Dark Count	Typ.	-	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	-



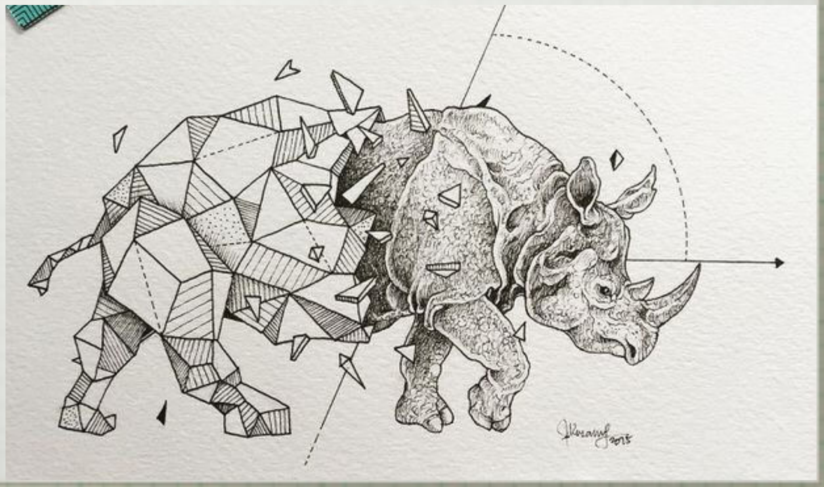
Main characteristics of the "building block"

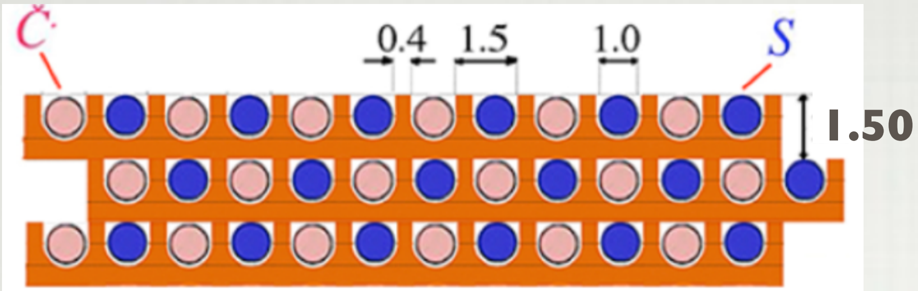
The 2016 development was based on 8x8 channel arrays and we have got in September 2016 the first samples ever produced (serial no. 1 & 2) with both 25 µm and 50 µm pitch [the latter only was used in the test beam]





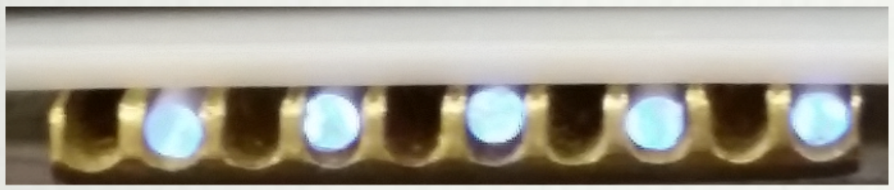
2. Design, machine and produce a module pairing with the sensor array [Iowa state] (equally valid for the 2016 & 2017 module)



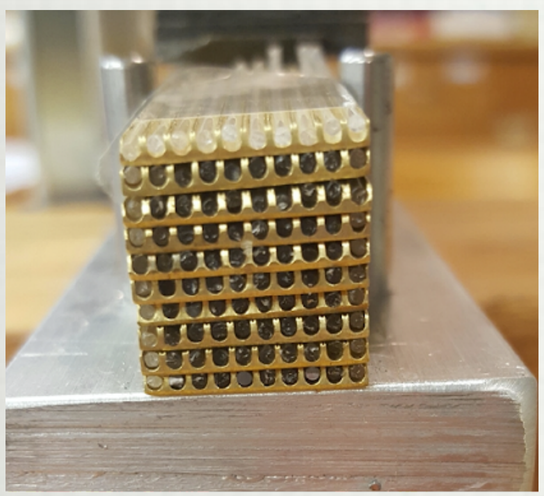


The module(s) are built from stacked copper layers, housing 1mm diameter clear & scintillating fibers* with a pitch of 1.5 mm [sampling fraction 4.5%]

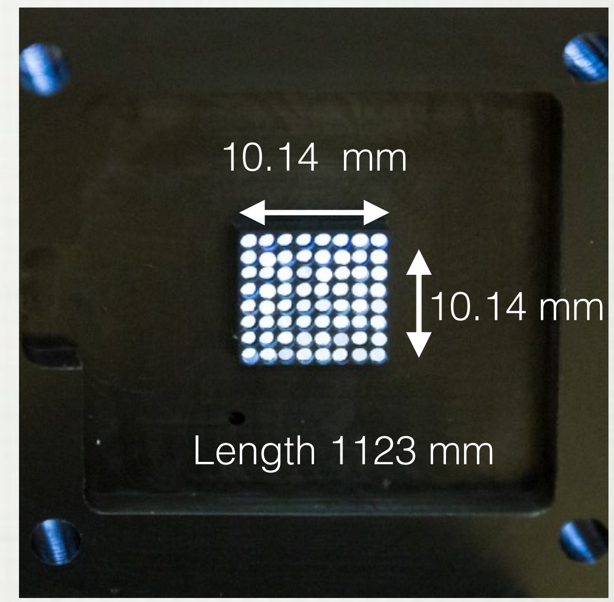
dimensions in mm (spacing in the actual module was 1.65 mm due to imperfections in the skiving procedure)



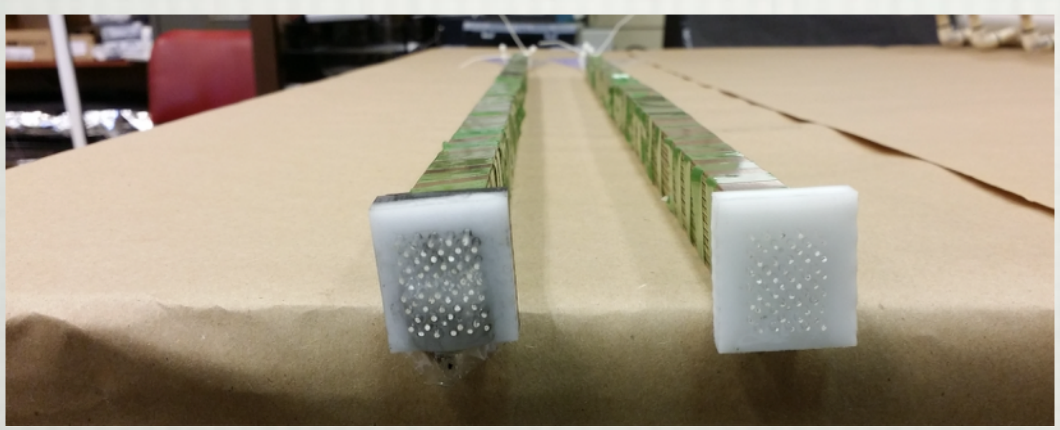
1D



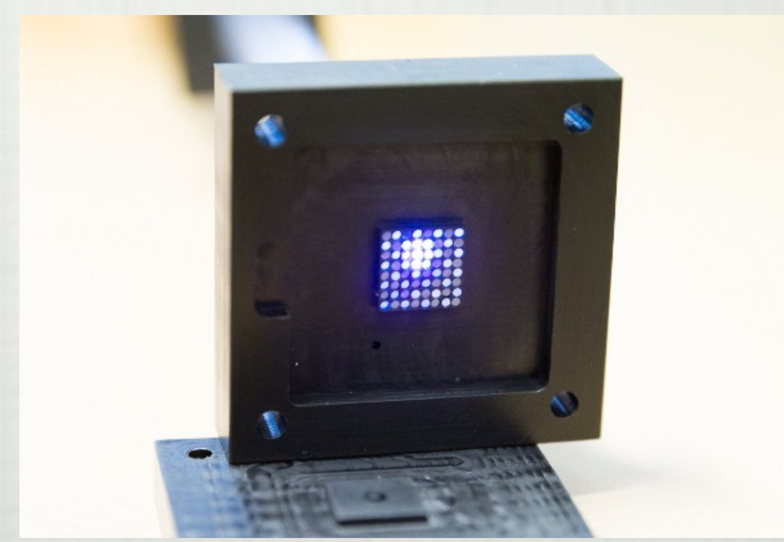
10x10 fibers



2D



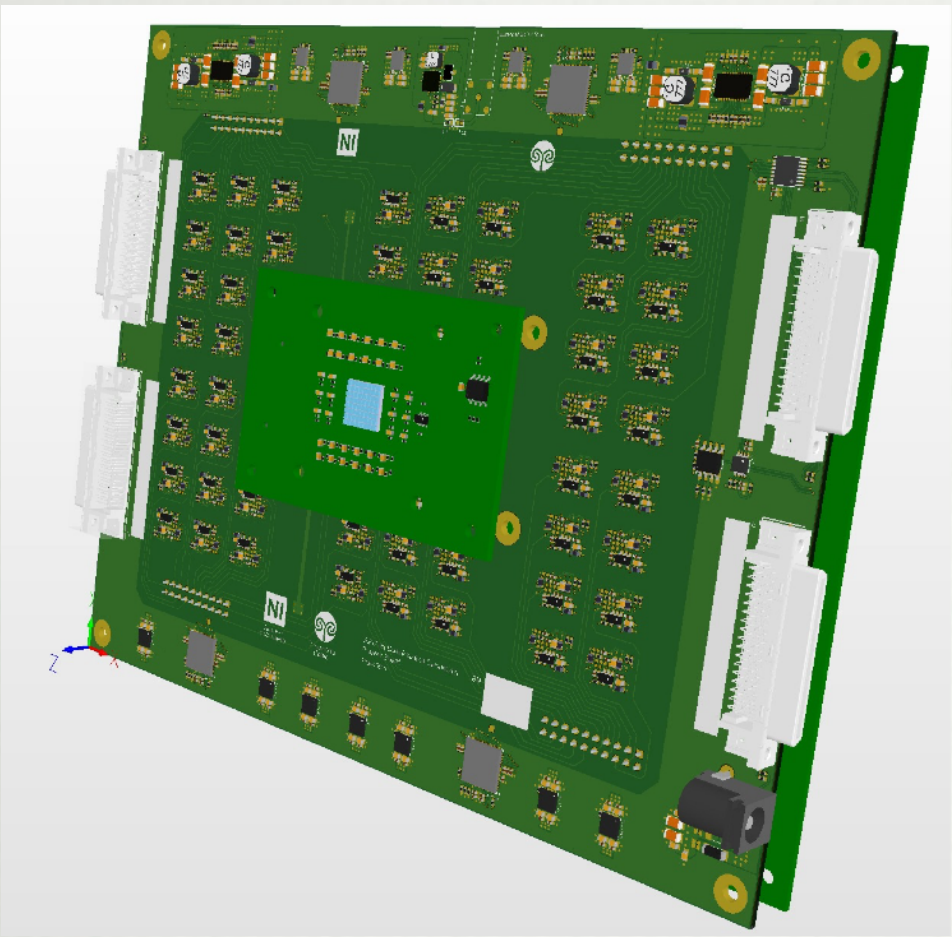
3D

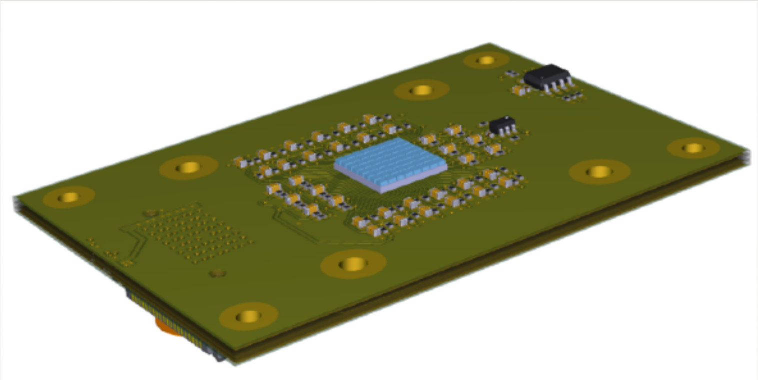


* [KURARAY SCSF-78, with 2.8 ns scintillation light decay time]

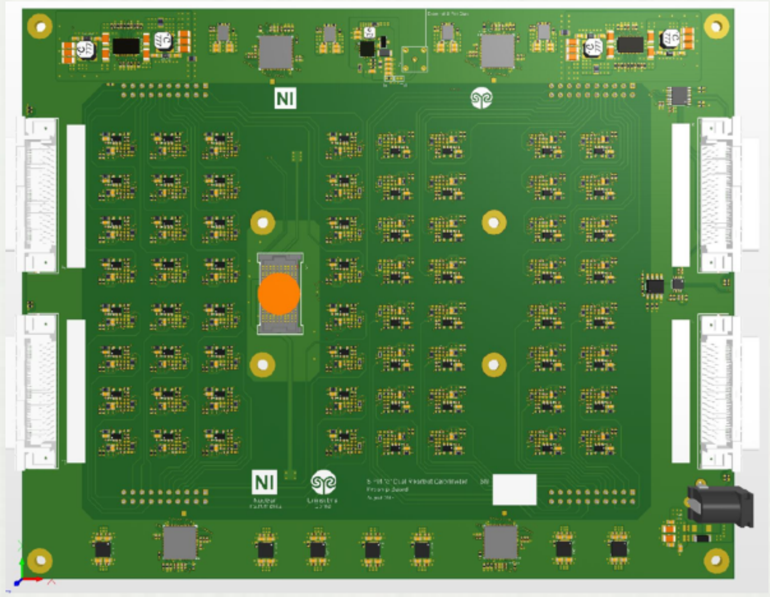
3. Design, produce, commission and qualify the boards hosting the sensor and the DAQ [Nuclear Instruments and Uni. Insubria]

The sensor system

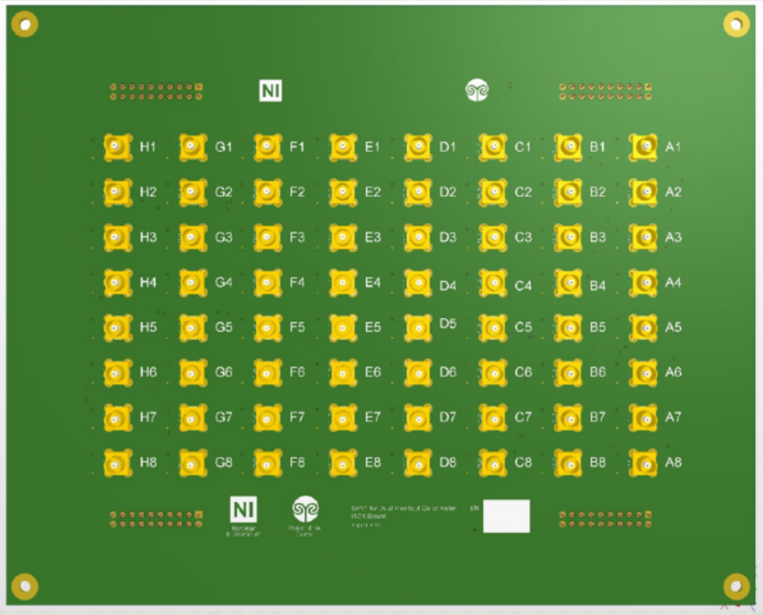




1. the daughter board,
providing an independent bias to the 64 sensors and integrating T measurement for gain compensation



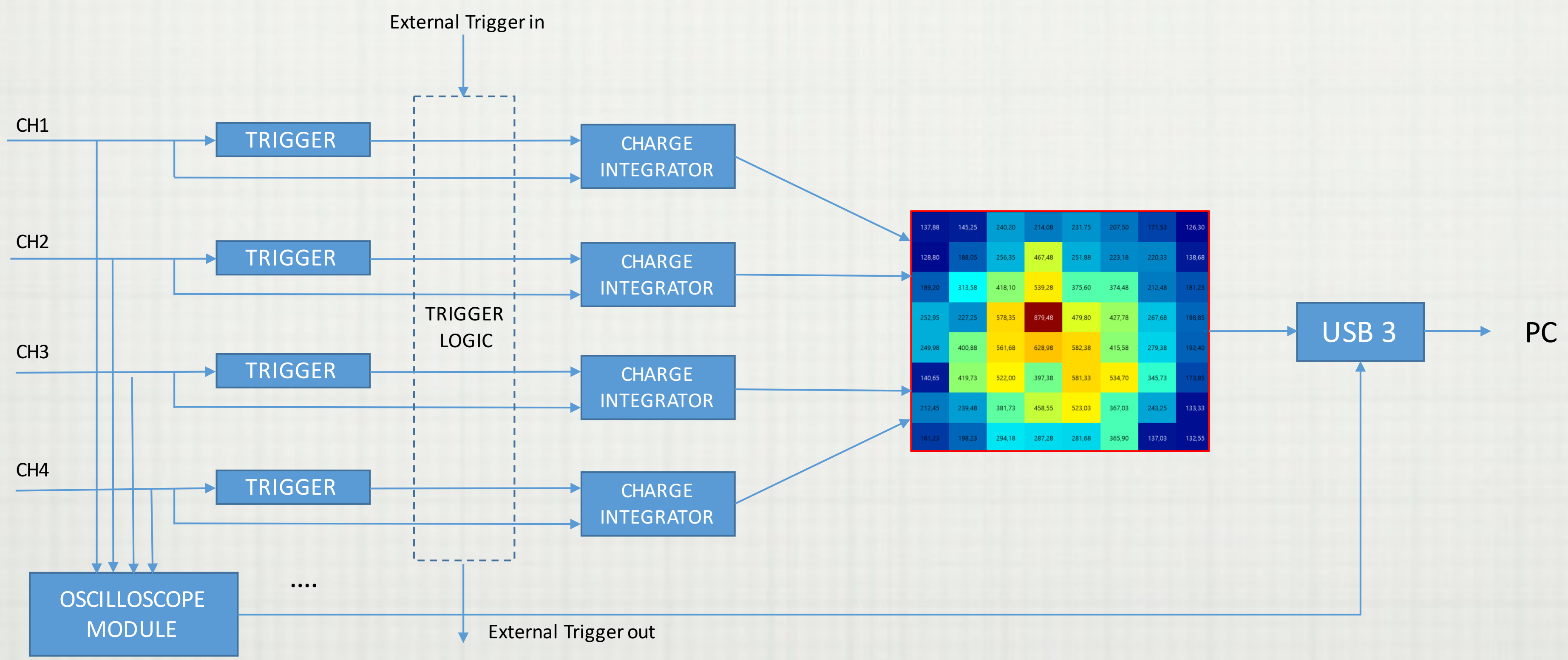
2. the mother board
   - amplifying & shaping the output of each sensor
   - routing the signals to the digitisation system



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

The DAQ system

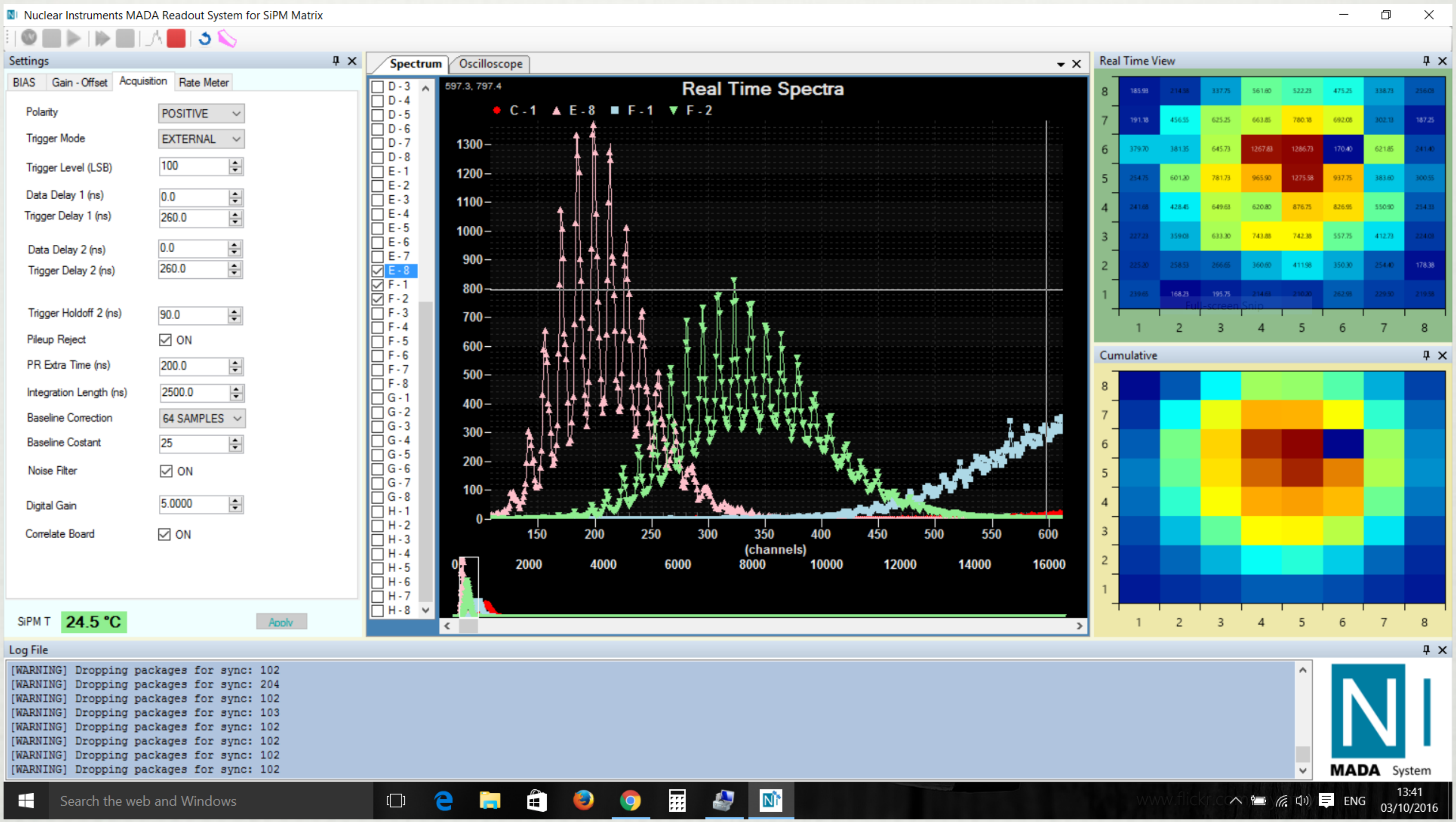
- the MADA is a 32 channel digitiser with on-bord intelligence
- sampling rate 80MSpS/14-bit ADC
- FPGA based charge integration algorithm.
- the output of the board is a list of timecode events providing the integrated signal in every sensor



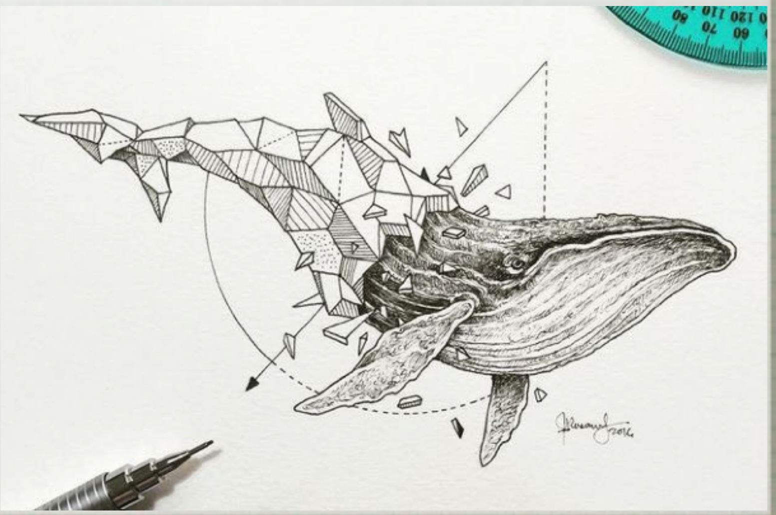
TRIGGER LOGIC:

- Pixel mode: each pixel is indipendet and fire a data transfer on a singe channel
- Frame mode: if a pixel fire a trigger, a charge integration process is performed on all channels and a whole frame is transfered to the PC

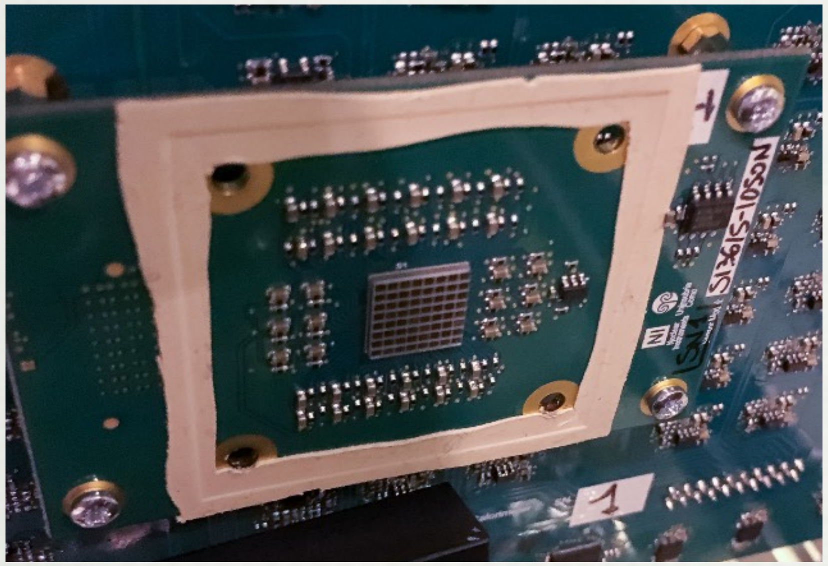
A nice example of the response of the system to a light pulse, during the qualification phase

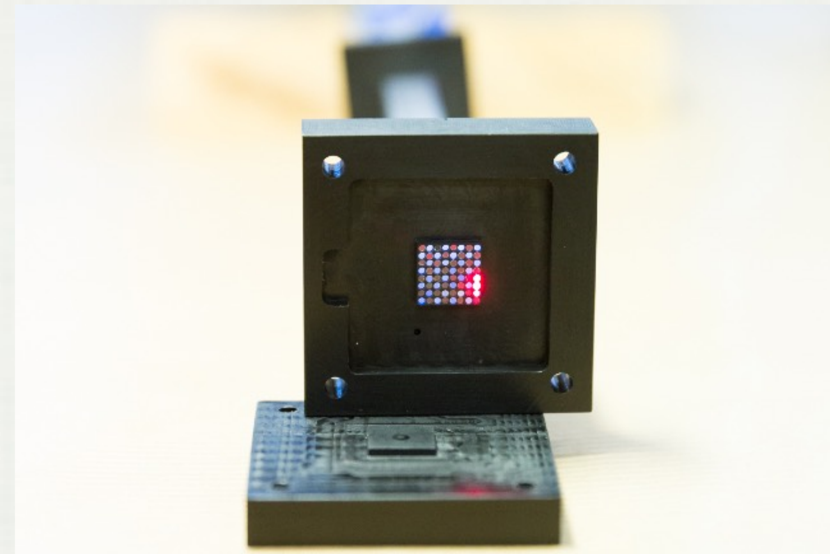


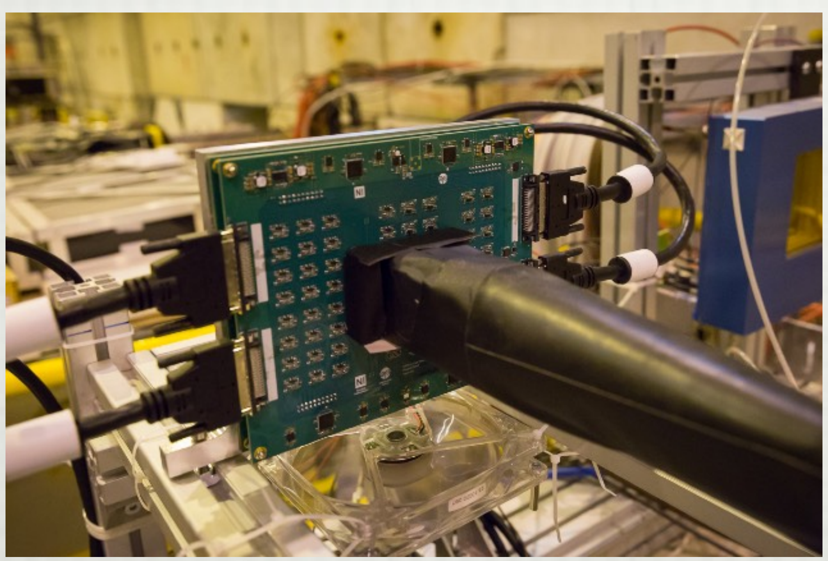
4. Integrate the module to the sensor and qualify it

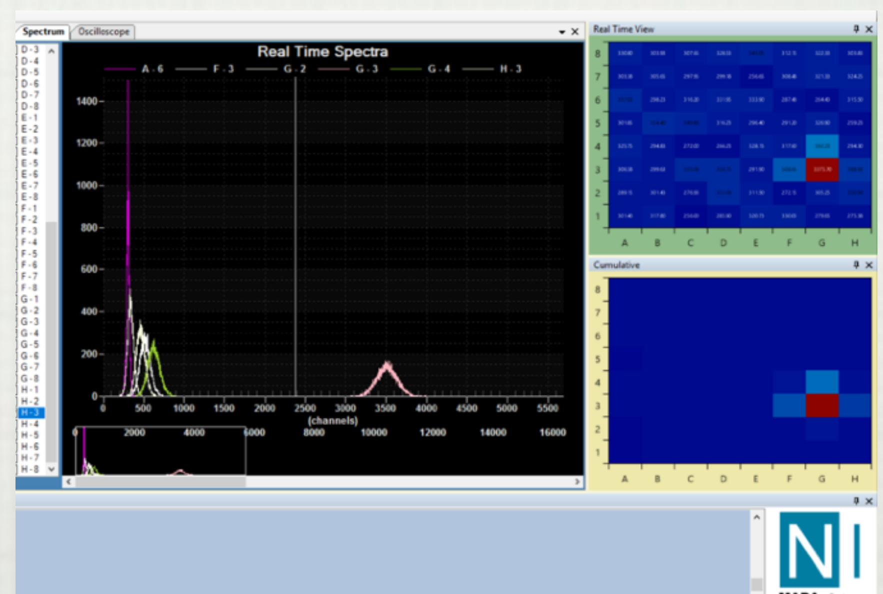


4 pictures to summarise 1 week of work (and stress)





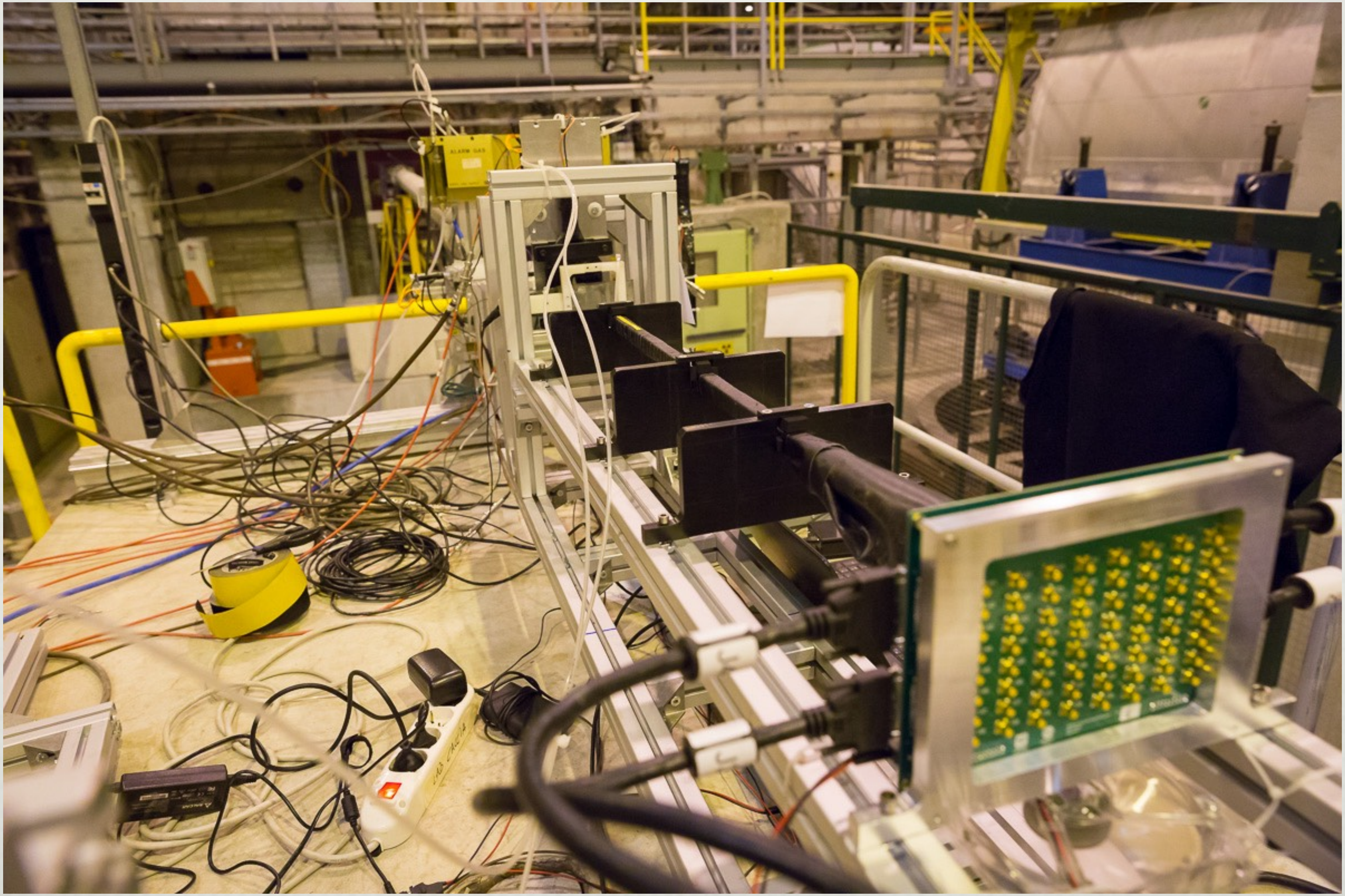




optical cross-talk between the fibers: possibly the most critical issue

5. ON BEAM, at last [mid October 2016, @CERN]!

The module on the CERN North Area beam line



A short summary of the data taking conditions:

- two modules, both based on the array with 50 μm pitch cells:
  - module 1: both scintillating and Cherenkov fibres connected to the pixels of the array
  - module 2: Cherenkov fibers only were connected

driven by two main reasons:

- the saturation of the sensors connected to the scintillating fibres
- the study of the optical cross talk

- recorded data:

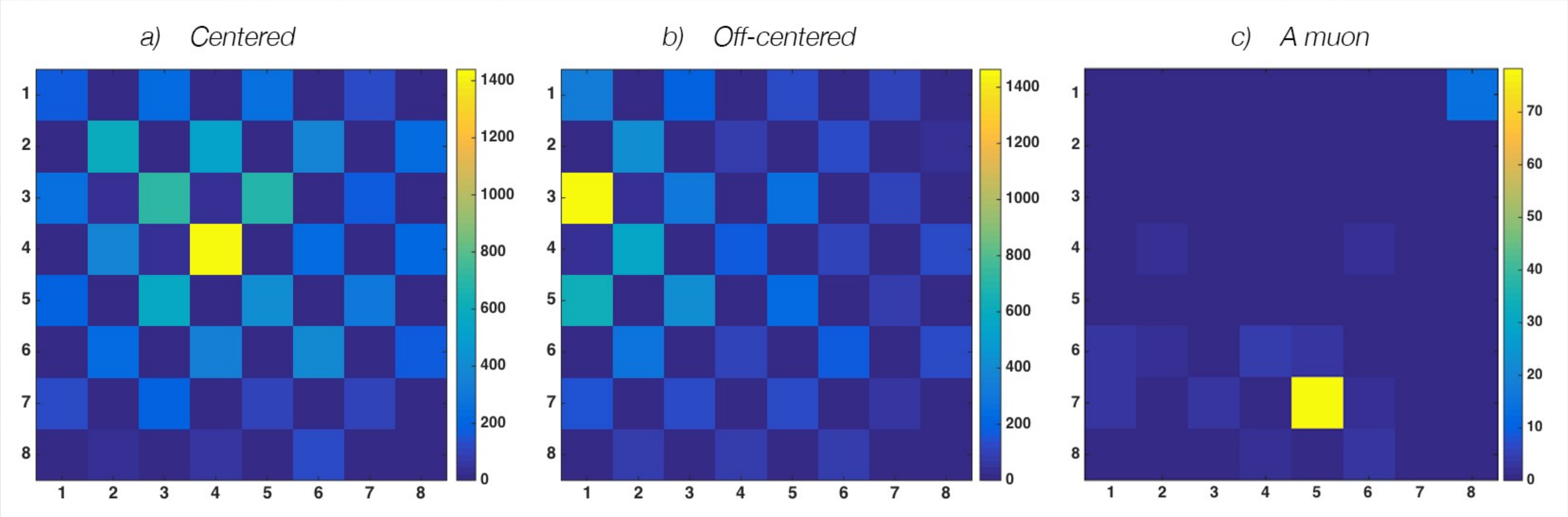
Module 1

- e^+:
  - 20 GeV (> 54.000 events)
  - 40 GeV (> 146.000 events)
  - 60 GeV (> 173.000 events)
- μ^+: 180 GeV (> 100.000 events)

Module 2

- e^+:
  - 20 GeV (> 178.000 events)
  - 40 GeV (> 300.000 events)
  - 60 GeV (420.000 events)
  - 80 GeV (340.000 events)
  - 100 GeV (300.000 events)
- μ^+: 180 GeV (400.000 events)

Exemplary event displays:



40 GeV electron beam

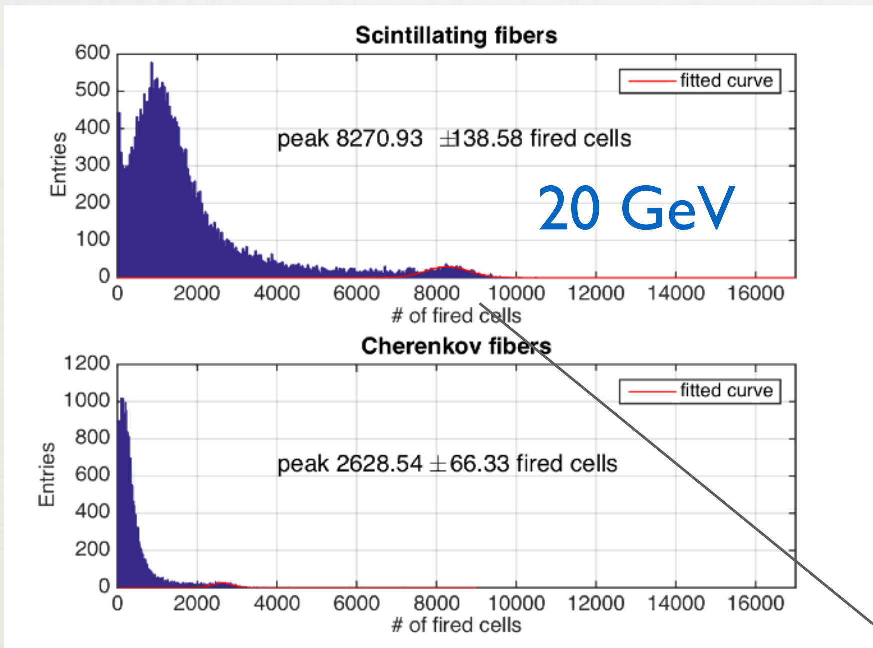
Results from Module I

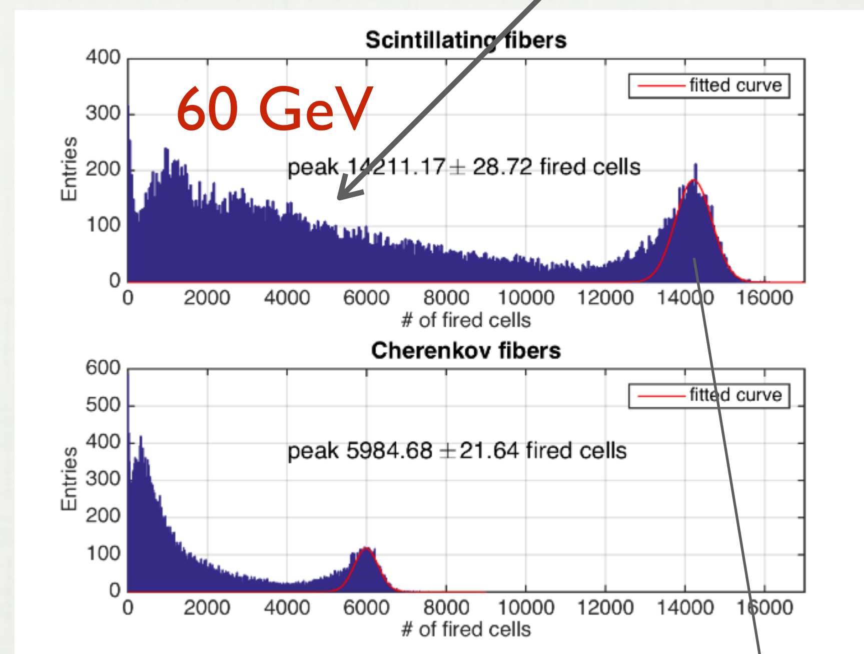
Event selection criteria:

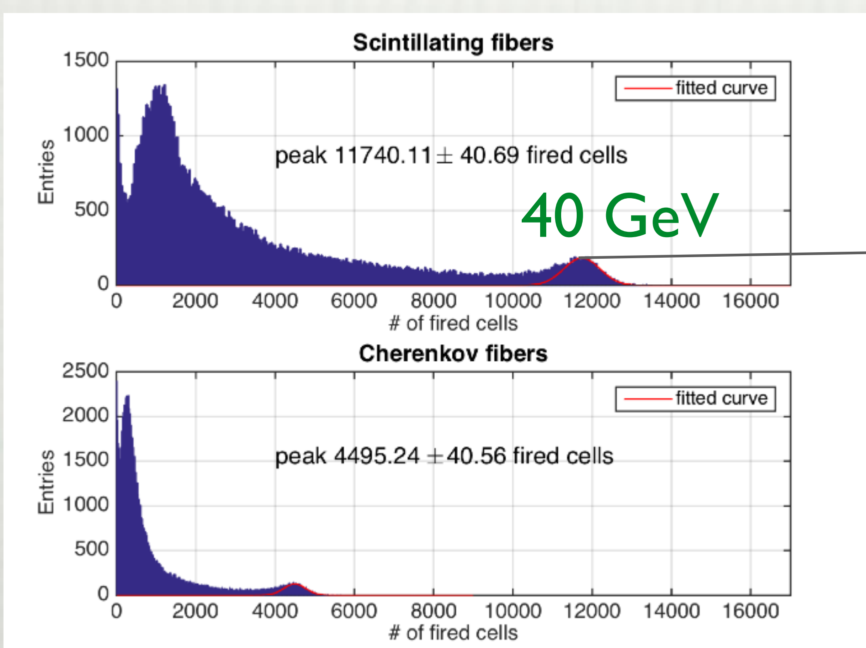
- signal from the array exceeding a 20 cell threshold
- highest signal in the 4x4 core of the array

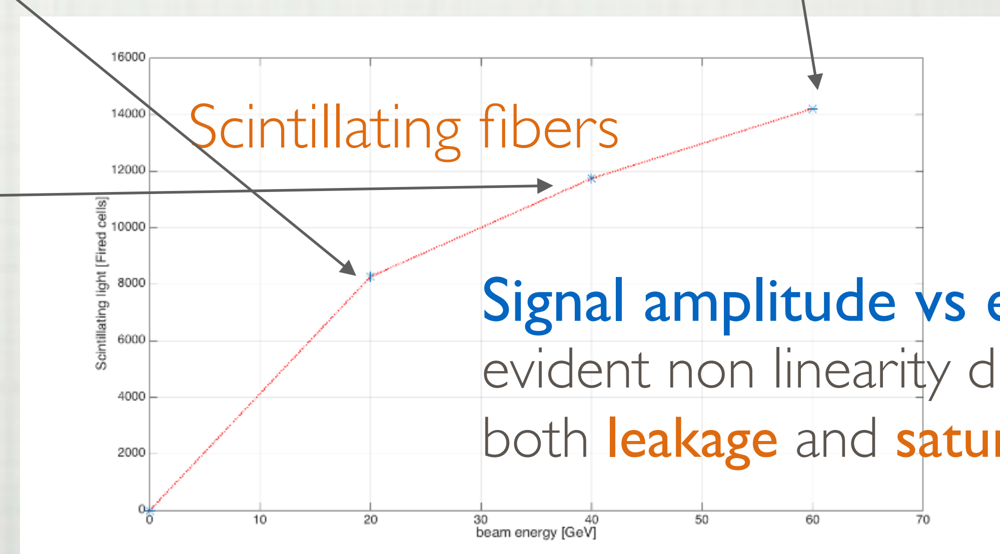
shoulder due to μ's contaminating the beam

Spectra of the Total Signal Amplitude (sum over 32+32 channels)









Signal amplitude vs energy

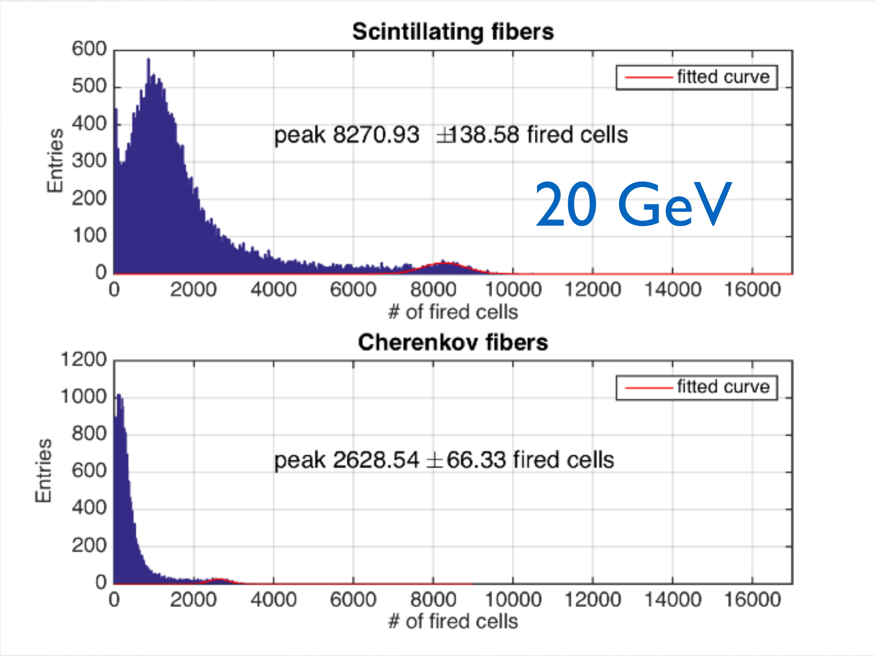
evident non linearity due to both **leakage** and **saturation**

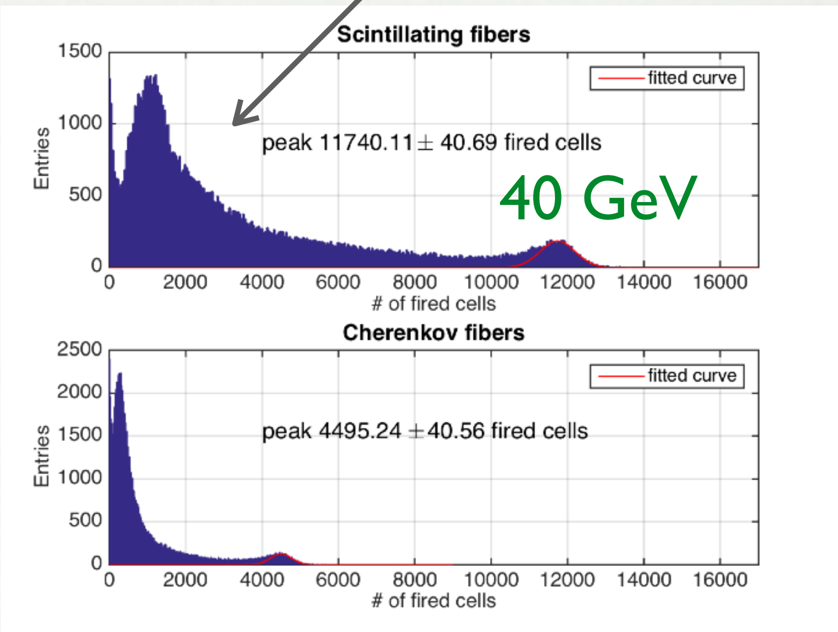
Results from Module I

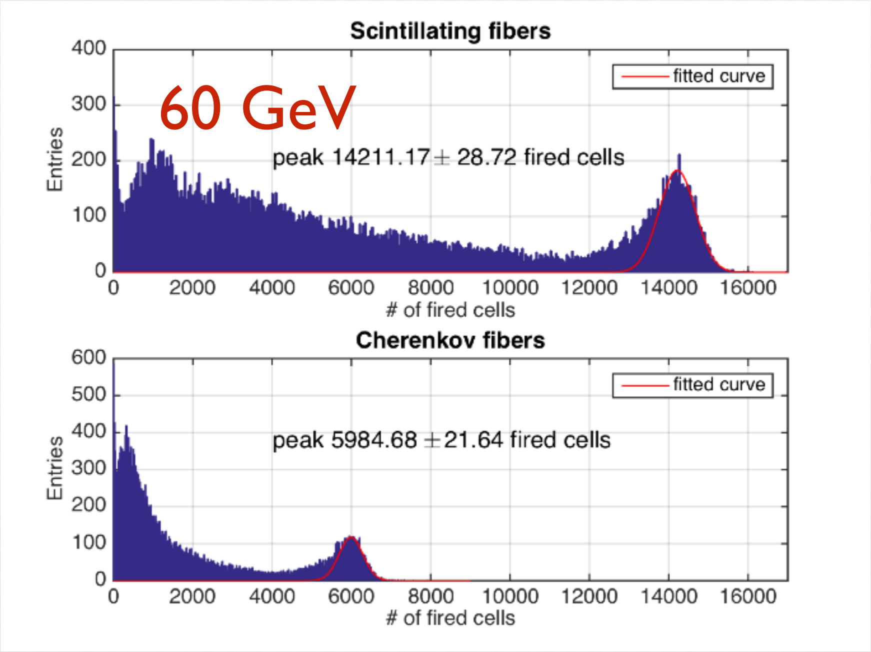
Event selection criteria:

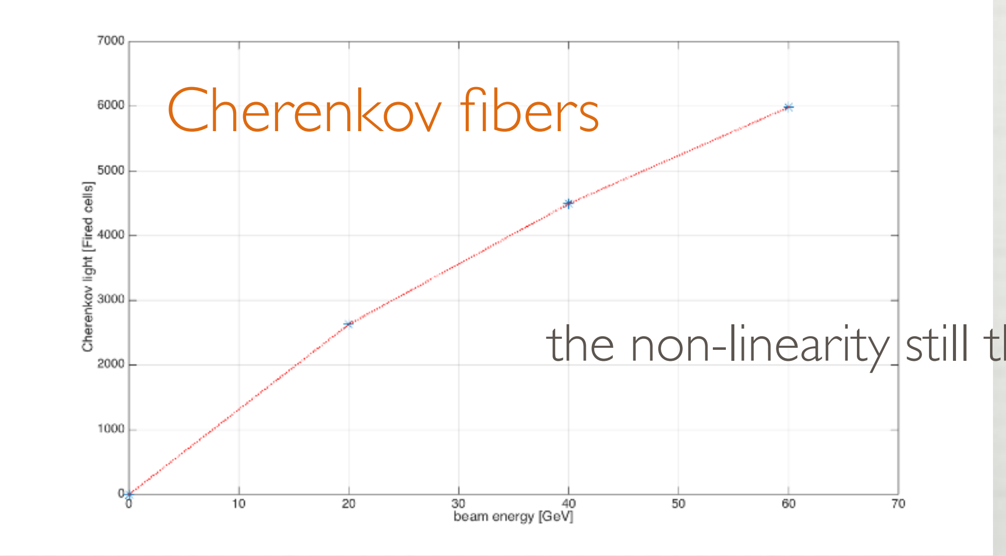
- signal from the array exceeding the 20 cell threshold
- highest signal in the 4x4 core of the array

shoulder due to μ contaminating the beam



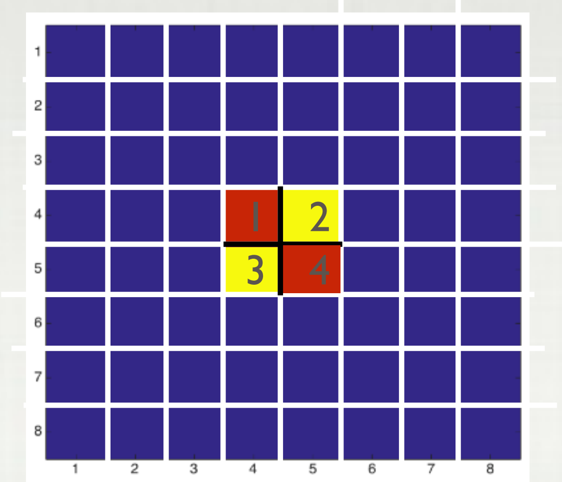




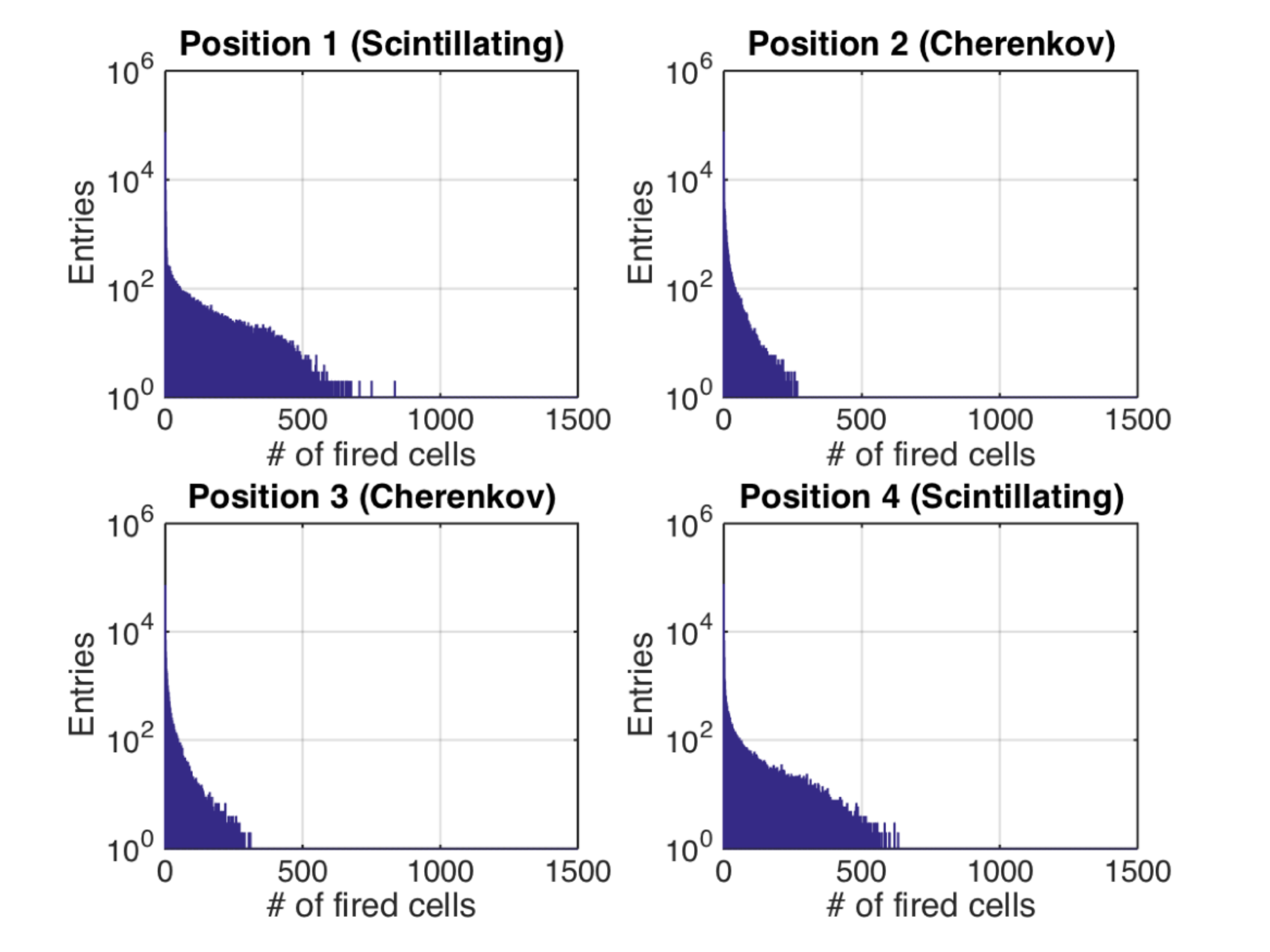


the non-linearity still there

Quantifying the saturation:



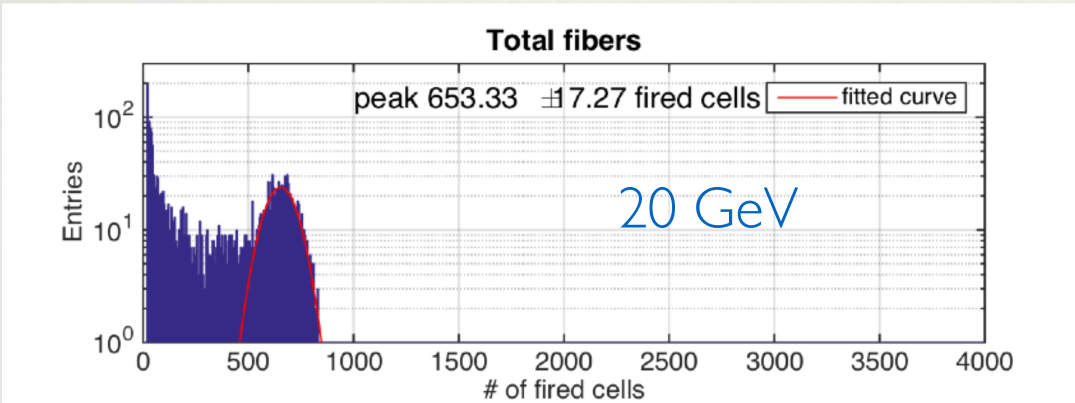
look at spectra of fibres 1-4

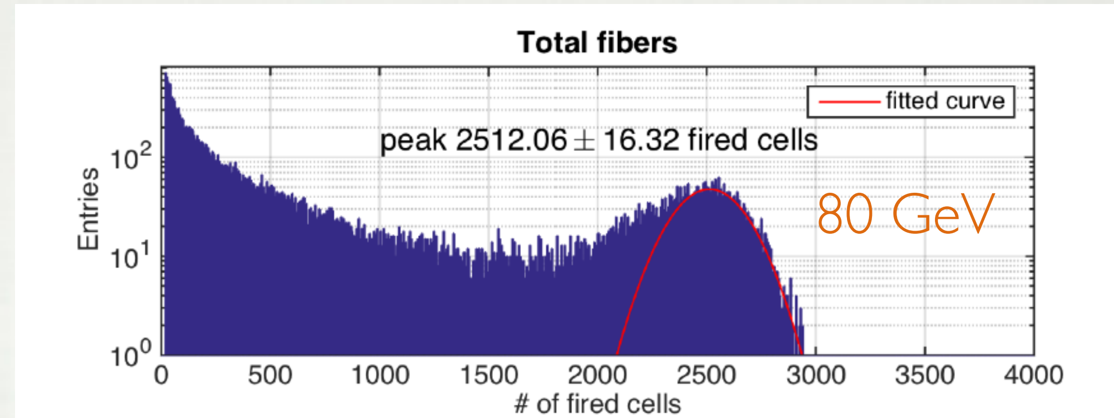


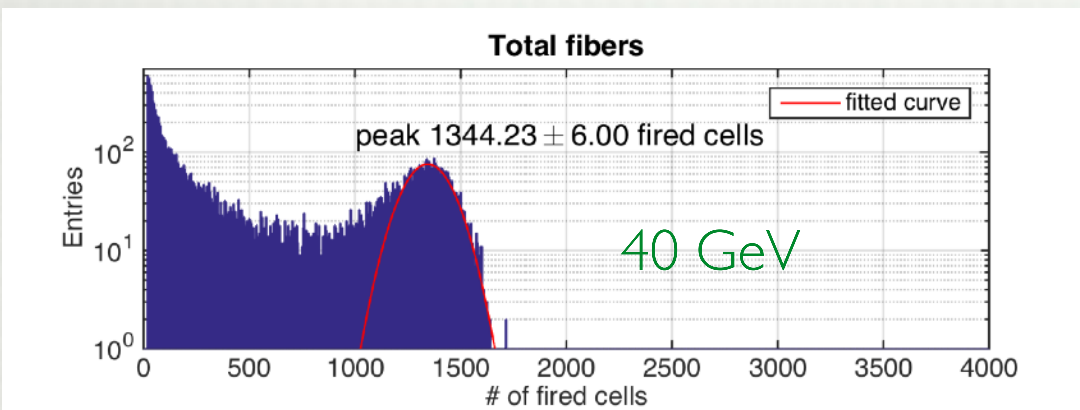
20 GeV

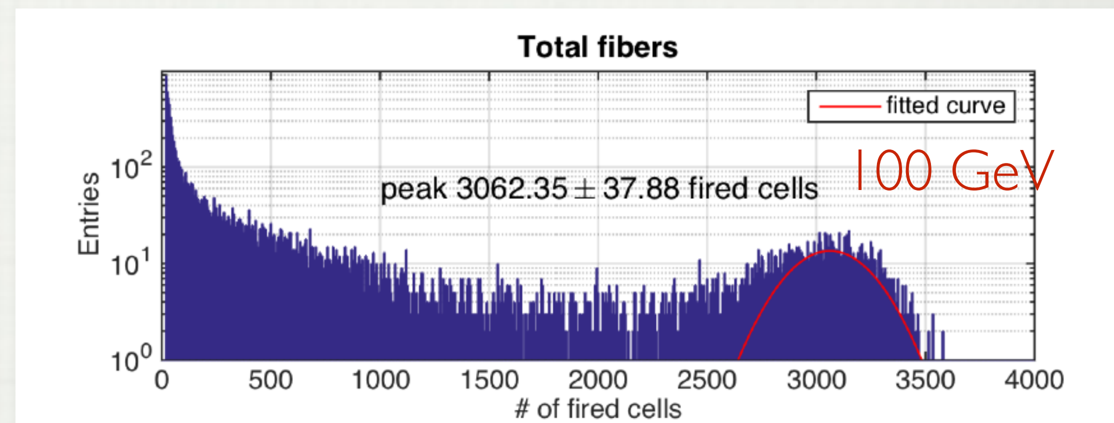
- a sizeable fraction of events shows saturation in the sensors connected to scintillating fibres (well, I see even more cells that I have in the sensor, possibly due to after-pulsing in the 1.8 μs long integration time)
- pixels connected to Cherenkov fibers are "polluted" by the light from the scintillating fibres

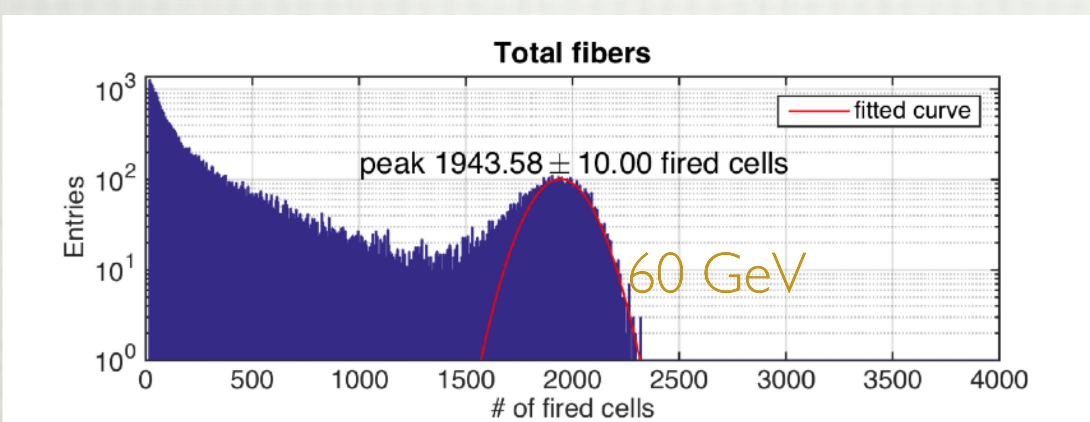
Results from Module 2 [Cherenkov fibres only connected to the SiPM pixels]

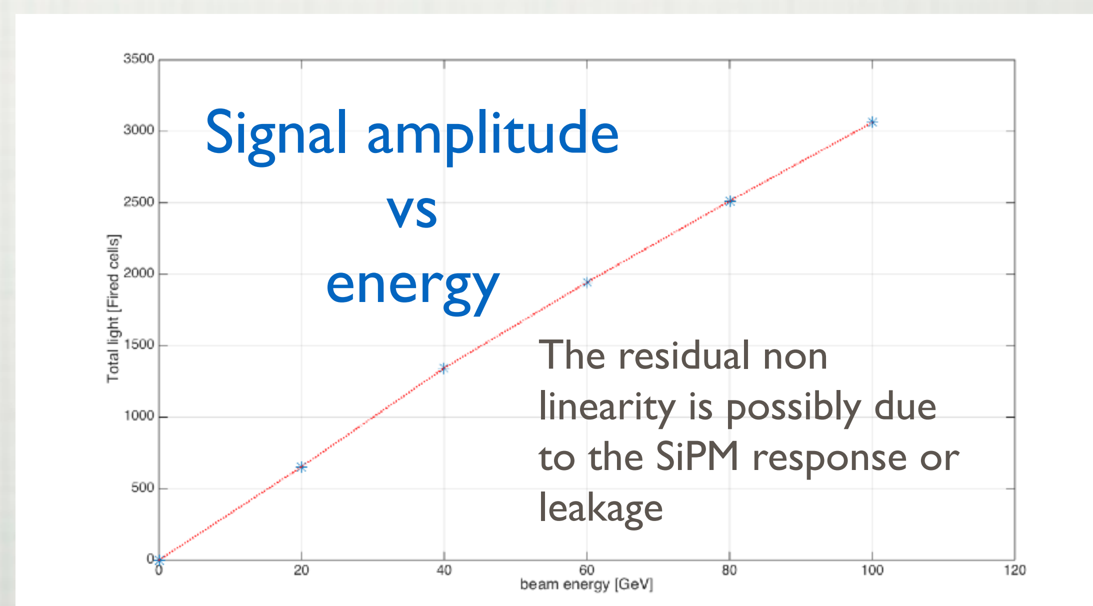




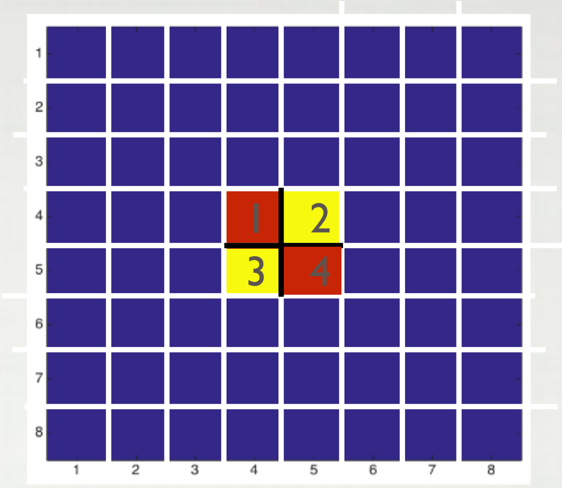


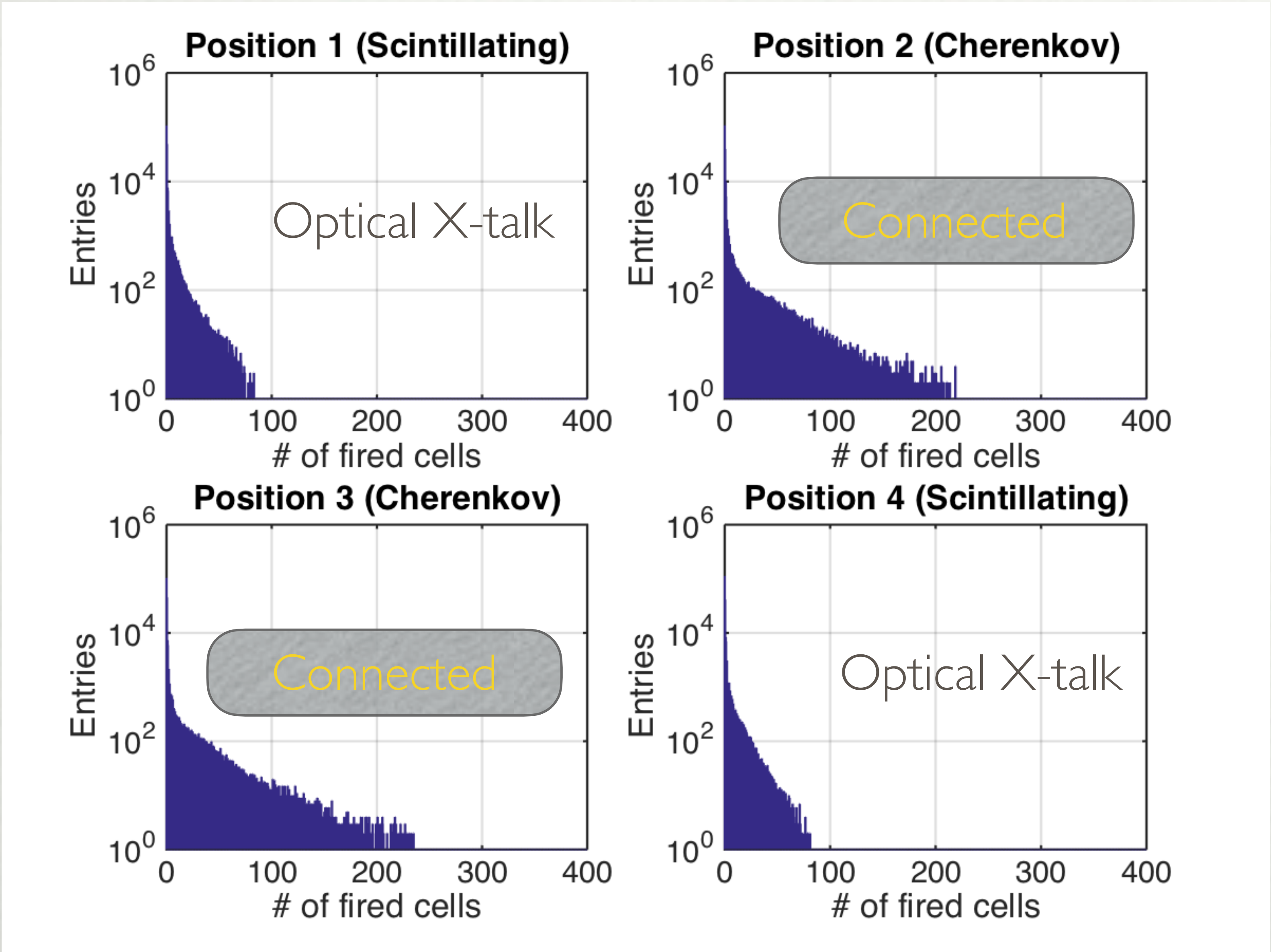






In fact, looking again at single fibre spectra in the core:





- sensors are away from saturation
- however:
  - at 20 GeV the tail of the spectrum ends at ≈ 40 cells, so "single photon sensitivity" and good Photon Detection Efficiency has to be retained
  - SiPM are affected by not linear response well before the saturation*:

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

so the response in this regime shall be handled with care

* [due to their intrinsic and irreducible nature of being granular & operated in Geiger-Mueller regime]

From Module 2, the optical cross talk between neighbouring cells can be measured:

$$X - talk = \frac{\sum_{i=1}^{32} S_i^{scinti}}{\sum_{i=1}^{32} (S_i^{scinti} + S_i^{cherenkov})}$$

leading to these consistent results:

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

telling us we did well but we have to get better….

Conclusions from the 2016 beam test activities:

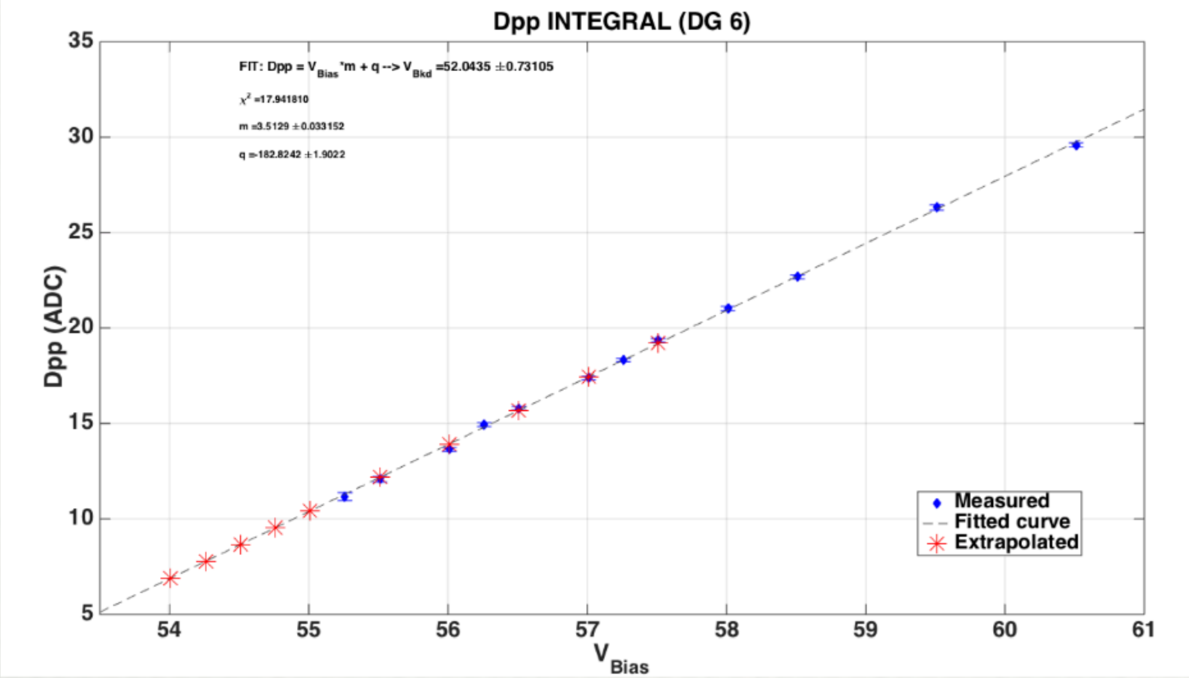
- a dual read-out module was interfaced to a SiPM array, qualified and commissioned on beam :)
- as a proof-of-concept, it was a success. However:
  - the sensor choice & the operating conditions shall be optimised independently for sensors connected to Cherenkov and Scintillating fibres
  - sensors reading out the two kind of fibres shall be decoupled

The two major issues were addressed in the 2017 evolution

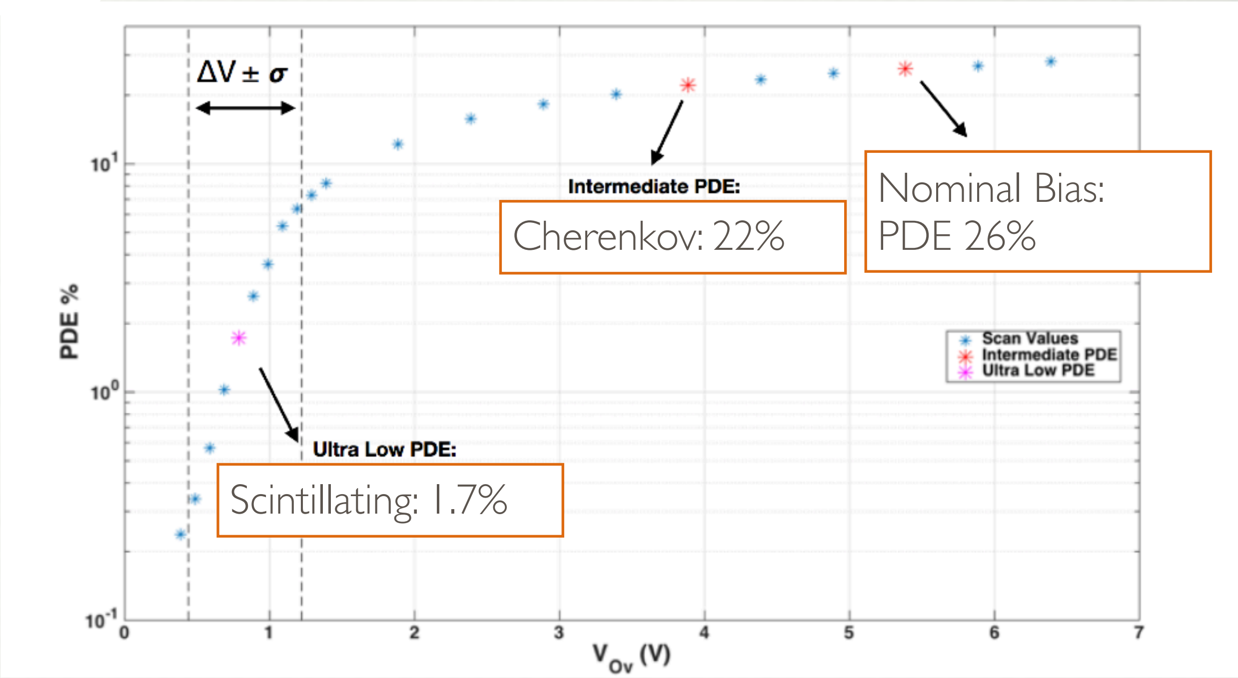
The 2017 sensors:

1. we moved to 25μm pitch

HAMAMATSU S13615-1025	
Sensitive area	1×1 mm^2
Cell pitch	25 μm
No. of pixels	1584
Peak Photon Detection Efficiency	25%
Breakdown voltage V_{br}	53 V
Recommended operational voltage V_{op}	V_{br} + 5V
Gain at V_{op}	7×10^5
Dark Count rate at V_{op}	50 kps
Optical Cross talk at V_{op}	1%



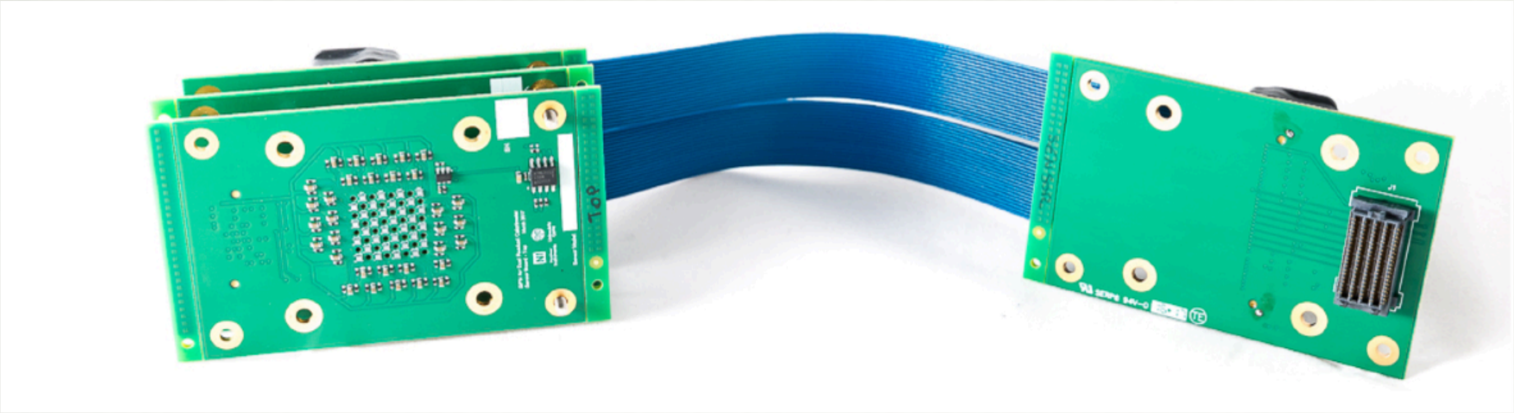
Gain vs voltage

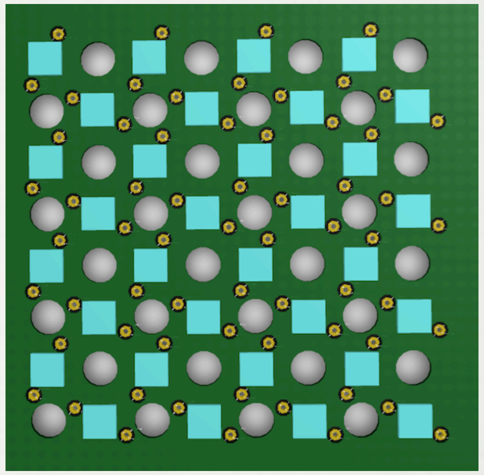


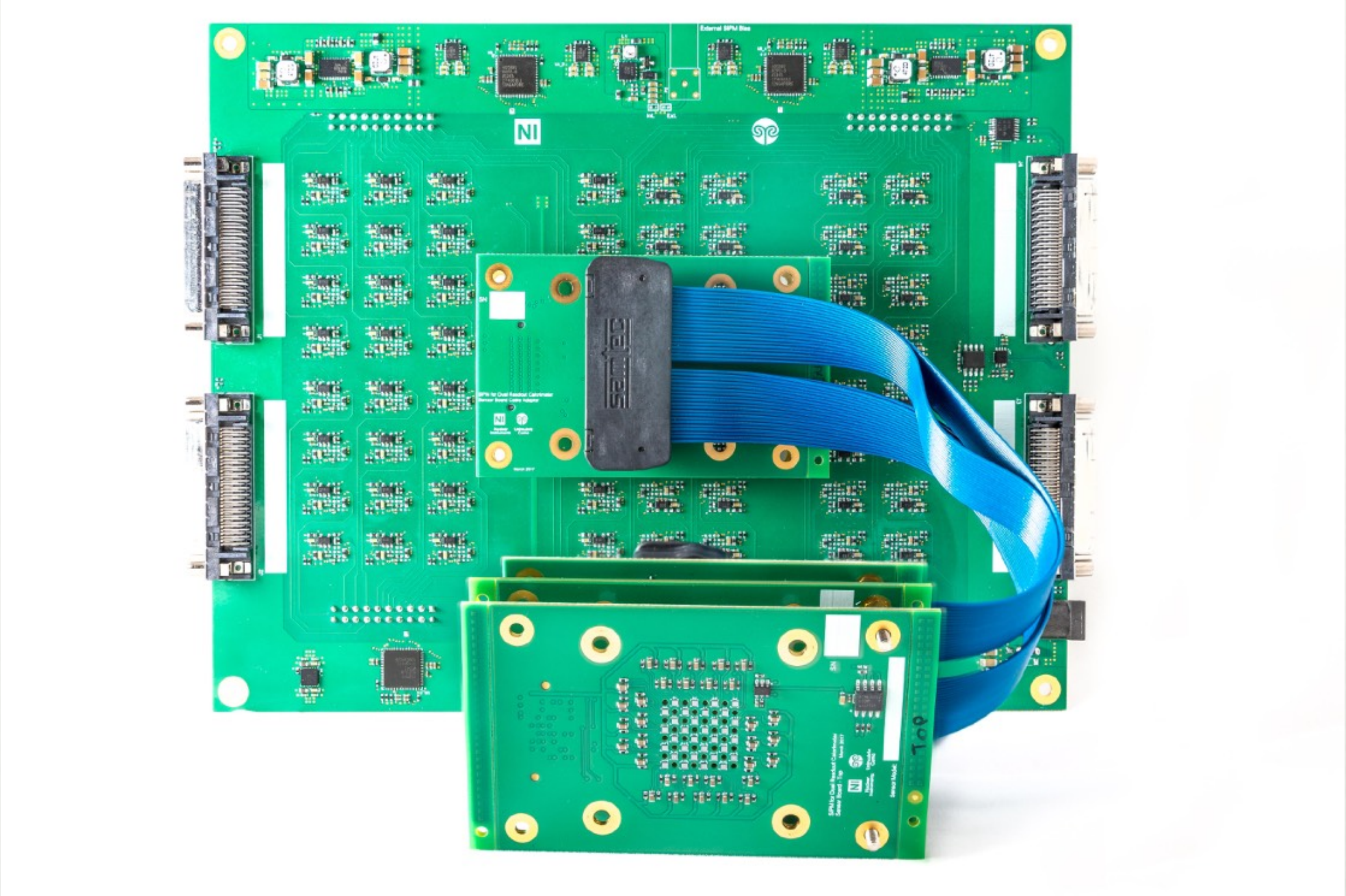
Relative Photon Detection Efficiency vs voltage

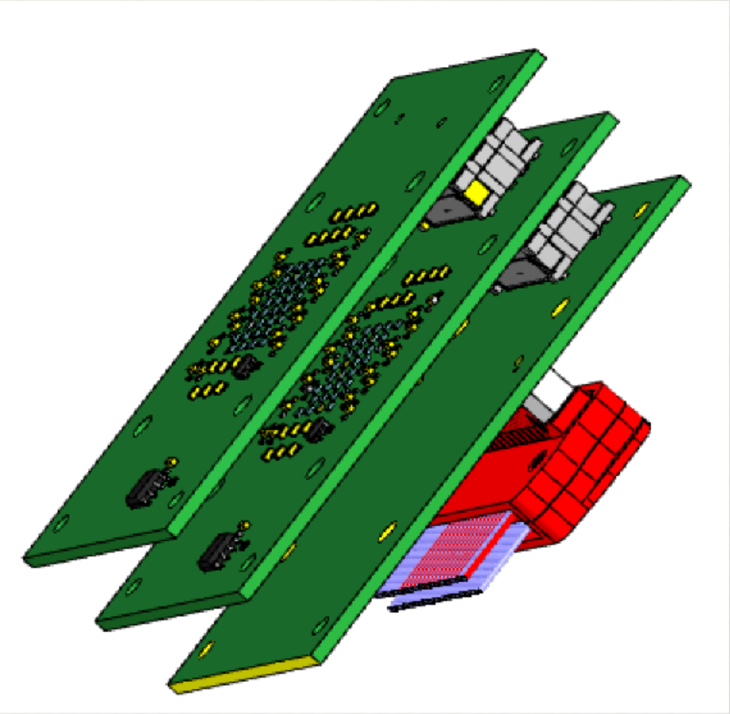
Sensors connected to Scintillating and Cherenkov fibres have been operated at different excess voltage values

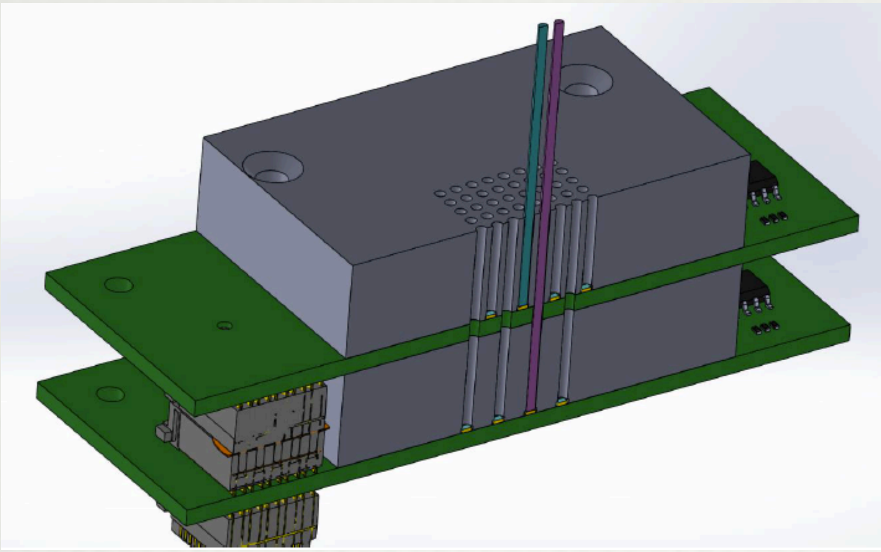
2. we replaced the arrays with an arrangement of 64 individual sensors on a two-tier chessboard-like structure, in order to minimise the optical cross-talk:





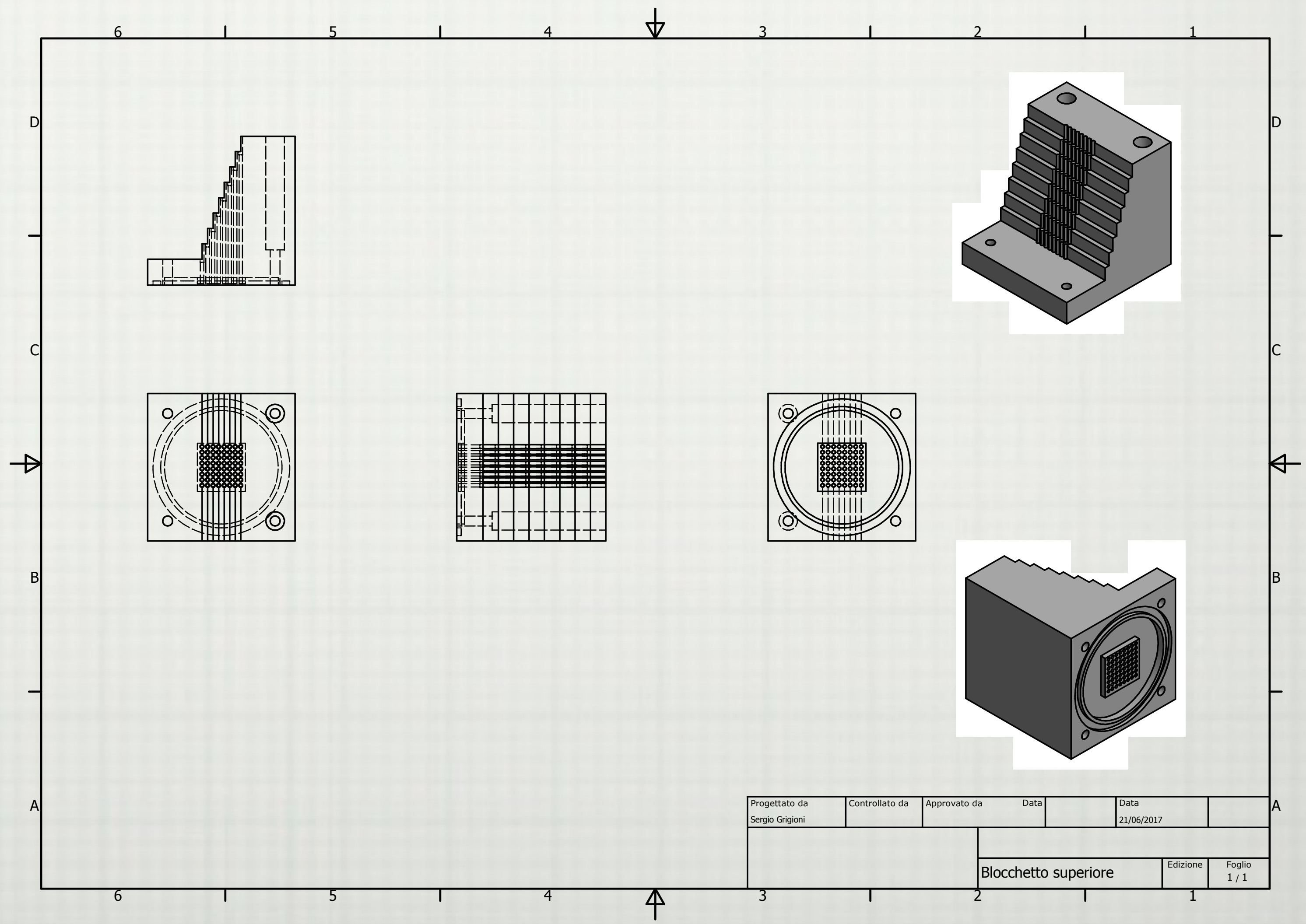






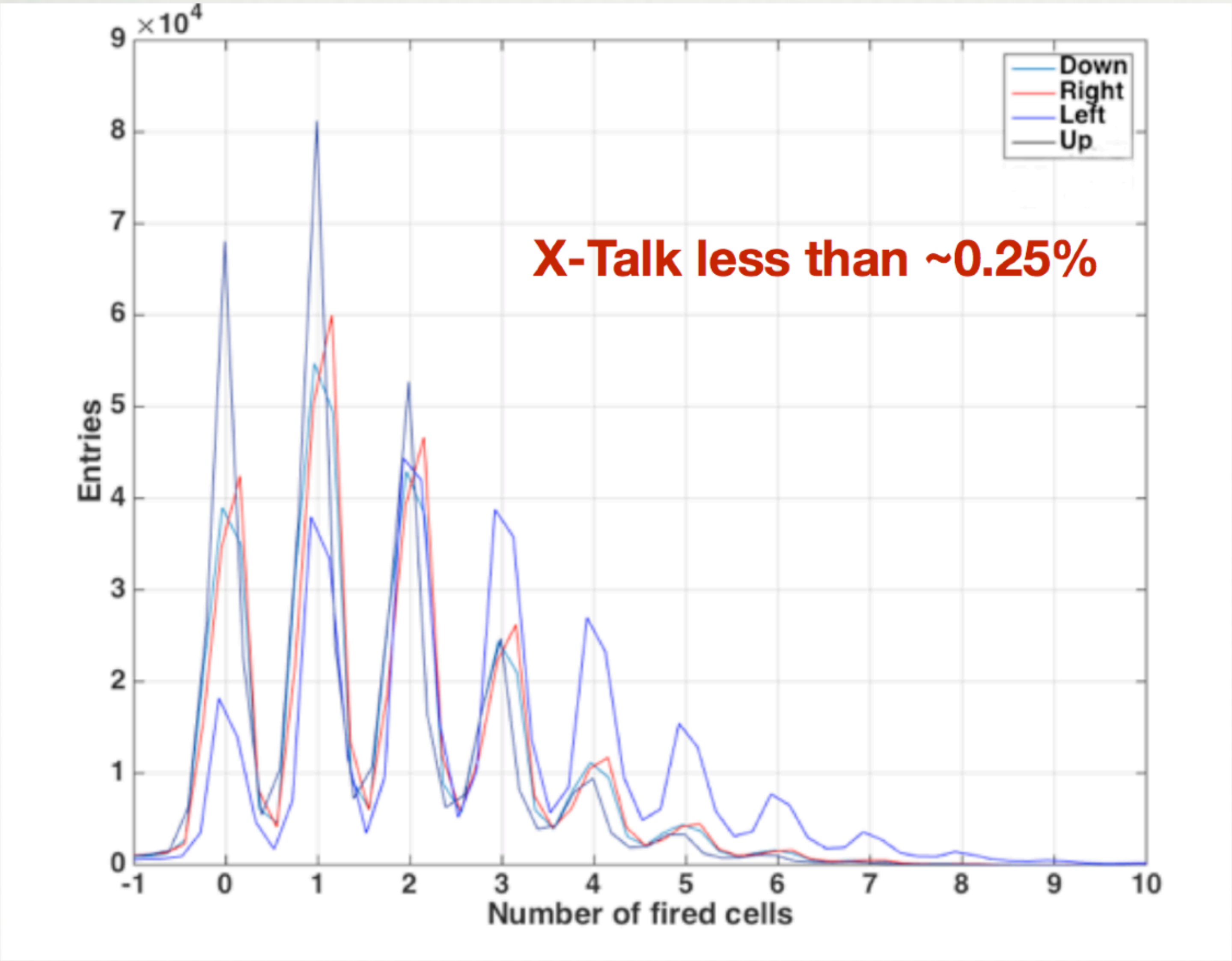
Fibres have been guided through a dedicated "aligner" to sensors on either tier (Tier 1 for Cherenkov fibers, Tier 2 for Scintillating fibres)

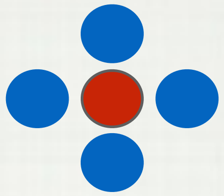
The first sketch



The actual machined piece

The assembly have been tested in the lab, illuminating a scintillating fibre and measuring the light sneaking through and "polluting" the signal on the Cherenkov sensors:





- the central fibre has been illuminated firing about 1000 cells
- the plot shows the illumination profile for the sensor corresponding to the surrounding Cherenkov fibres

=> the Xtalk has been reduced from 25% to 0.25% (upper limit)

July 2017: on beam again

No ps detector

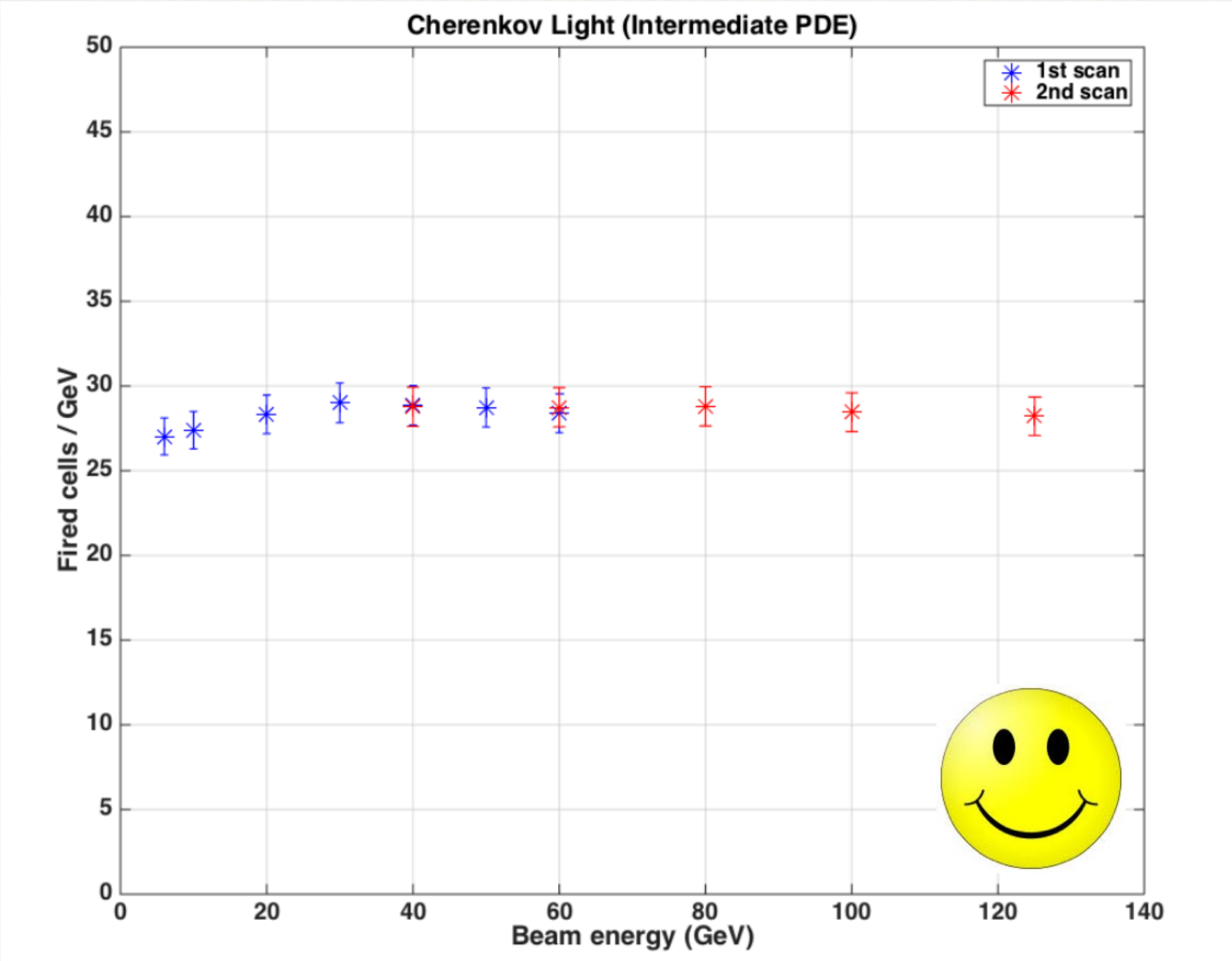
Energy (GeV)	PDE Configuratio	AFE	Detectors	Run numbers	Number of real events	Selected events	T (°C)	Comments
6	Intermediate	3	muon, DWC	12254, 12257	352450	17522	25 24-24.5	**no veto** to increase trg rate, no pedestal (taken 25k
10	Intermediate	3	muon, DWC	12243 12245-12247	190258	24666	25.5 26-26.5	
20	Intermediate	3	muon, DWC	12240-12241	232347	27770	24 24.5-25	stop but no evt loss
30	Intermediate	3	muon, DWC	12238	434973	47610	23.5	
40	Intermediate	3	muon, DWC	12237	469944	11920	23.5-24	
50	Intermediate	3	muon, DWC	12235	470935	2860	24-24.5	
60	Intermediate	3	muon, DWC	12233	468195	99293	24.5-25	

Energy (GeV)	PDE Configuratio	AFE	Detectors	Run numbers	Number of real events		T (°C)	Comments
40	Intermediate	3	muon, DWC, ps	12348	9632	1080	23-23.5	Secondary Beam to 180 GeV
60	Intermediate	3	muon, DWC, ps	12346	10642	1308	23-23.5	Secondary Beam to 180 GeV
80	Intermediate	3	muon, DWC, ps	12347	13480	4014	23-23.5	Secondary Beam to 180 GeV
100	Intermediate	3	muon, DWC, ps	12349	42610	1626	23	Secondary Beam to 180 GeV
125	Intermediate	3	muon, DWC, ps	12350-12352	777205	13684	23 22.5-23	Secondary Beam to 180 GeV **Muons dominated**

A sub-sample of the data we took - **analysis still ongoing, in view of a paper we intend to finalise and submit in January 2018**

A few quasi-final results:

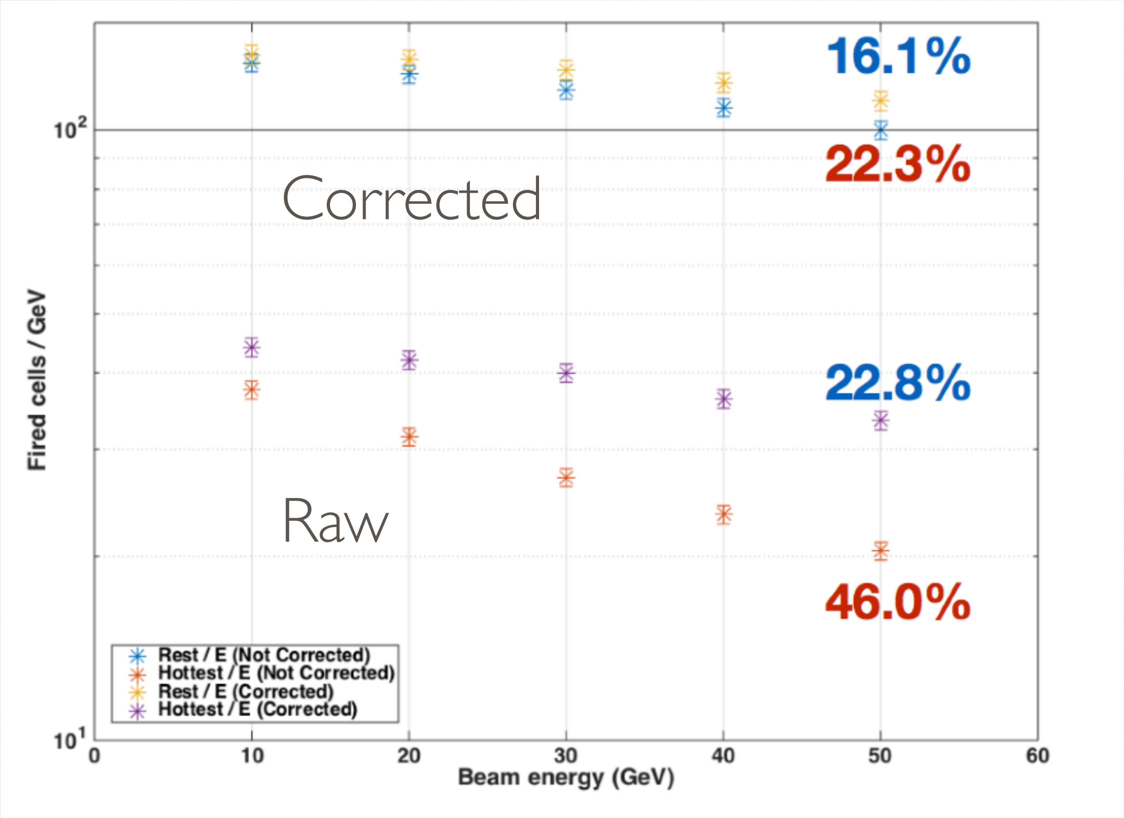
1. Cherenkov fibre response:

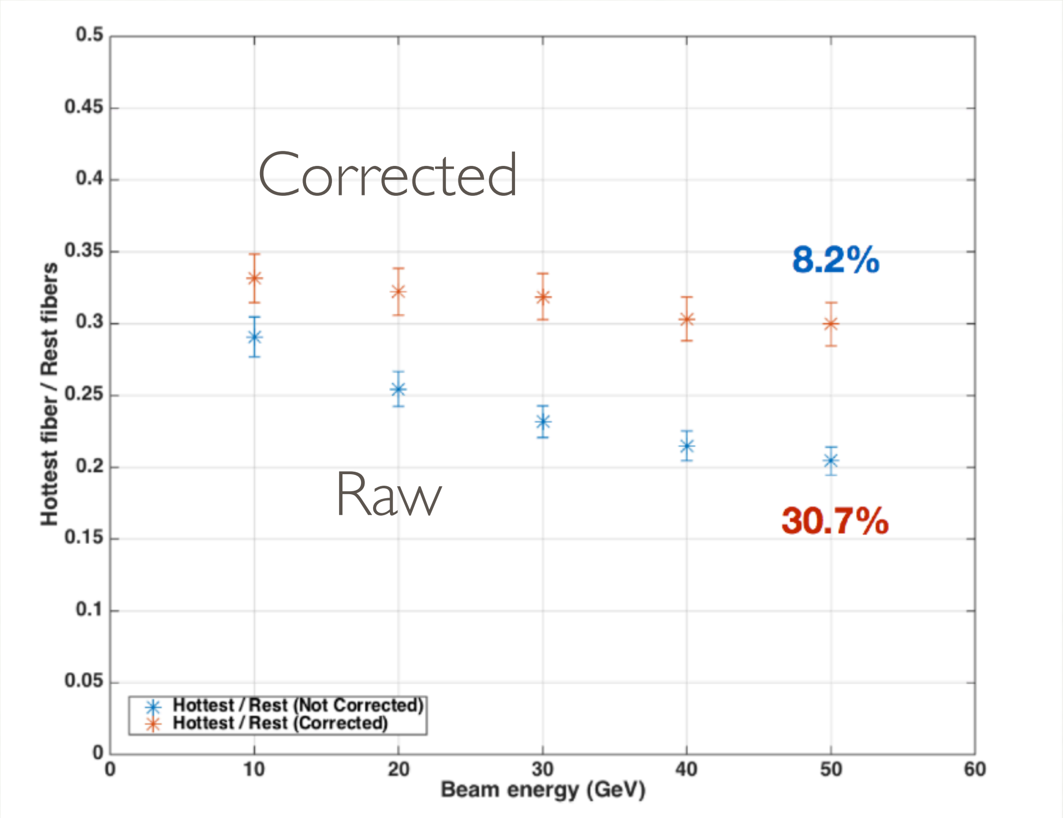


No. of fired cells/beam energy vs Beam Energy
[bias 1.5 below the nominal value (PDE ≈ 22%)

1. Scintillating fibre response:

Ratio between the hottest fibre and the sum over the other 31 fibres vs Beam Energy



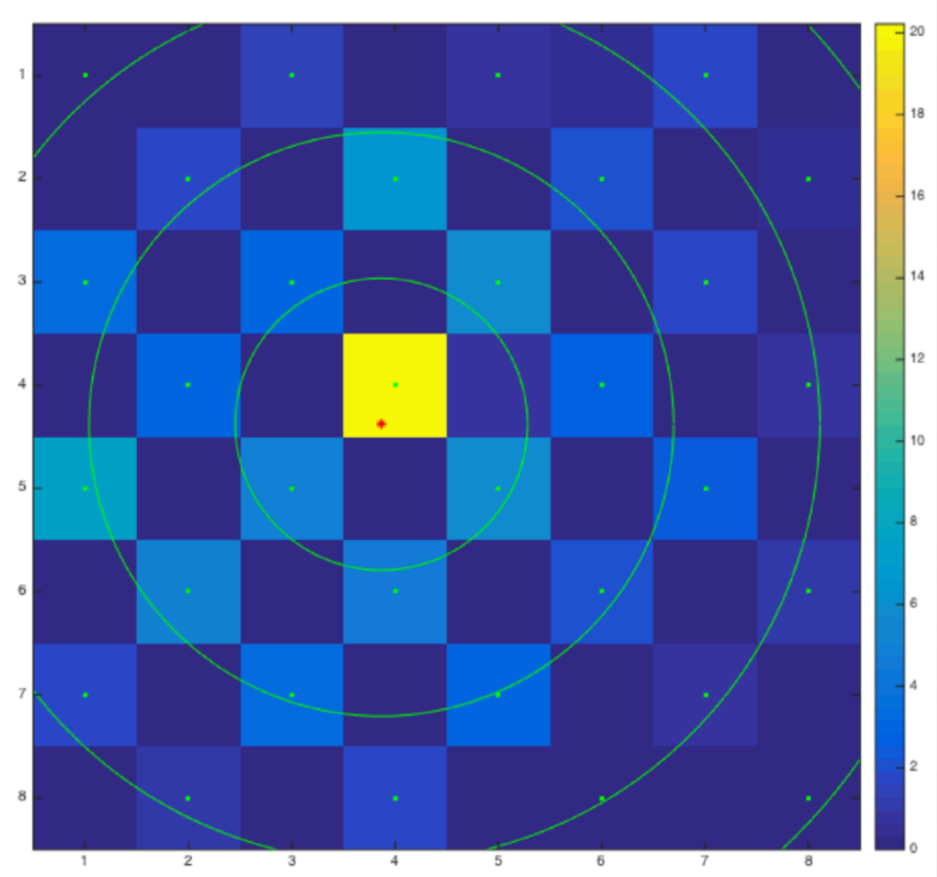


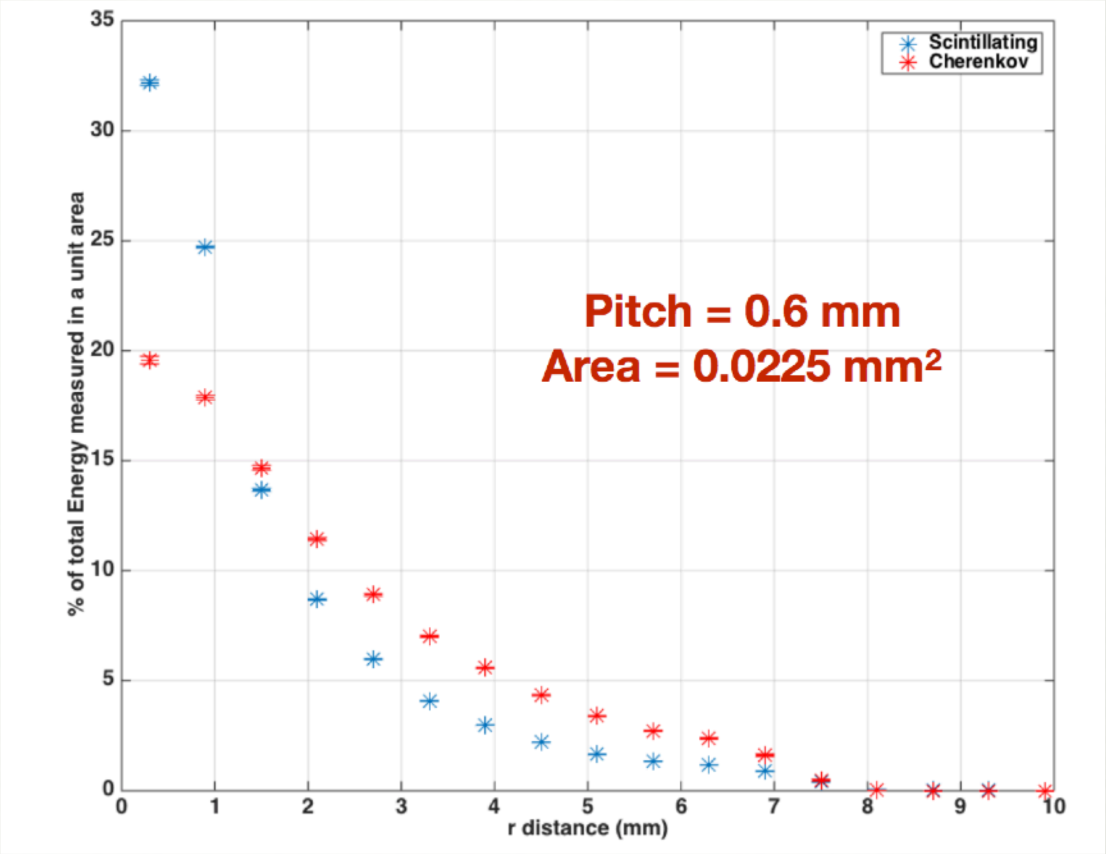
- top data refers to the results after the non-linearity correction:

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

- data taken at a biasing value -5V below the nominal voltage, i.e. ≈0.5V above the breakdown, corresponding to 1.7 % PDE

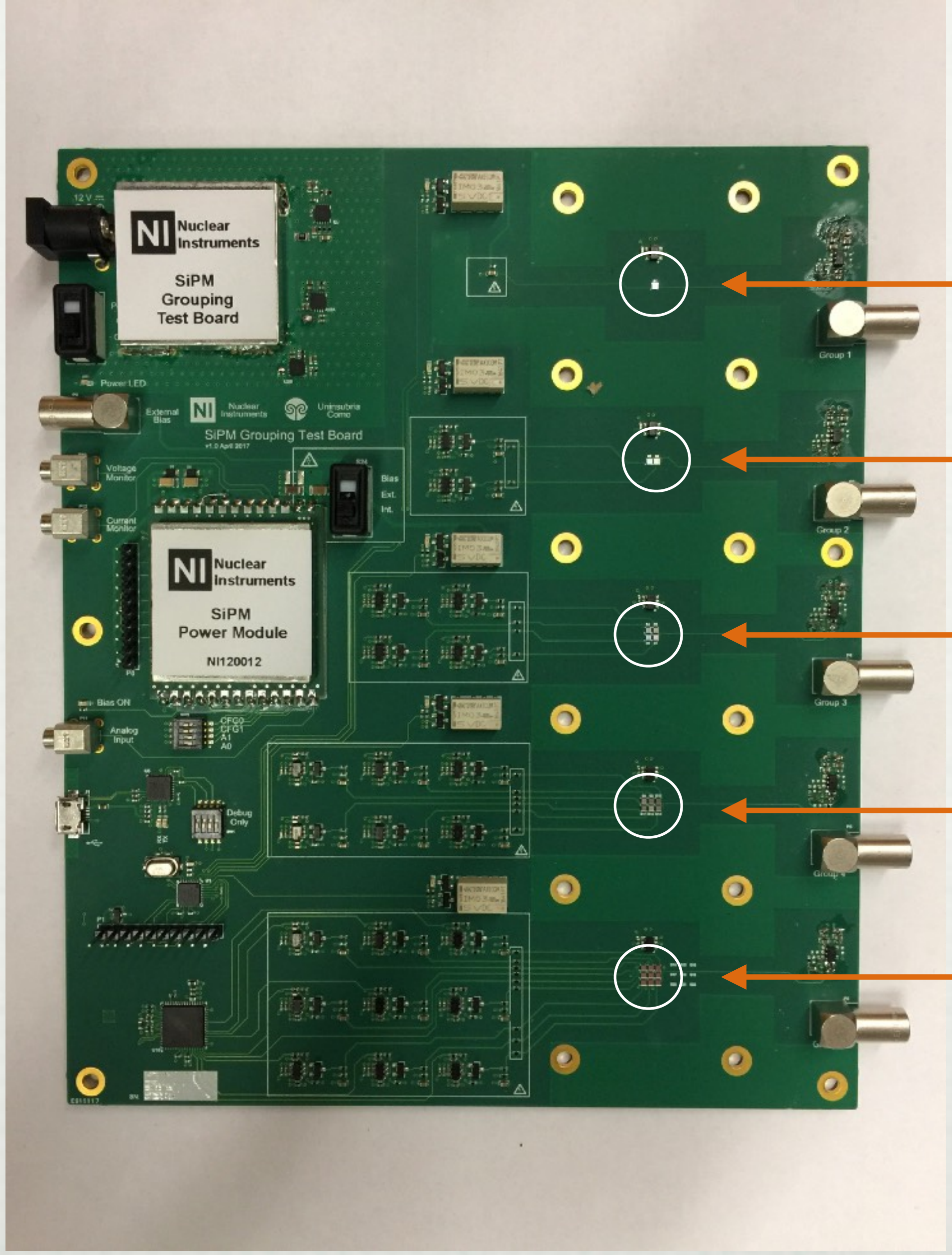
Another ongoing analysis: **study of the radial profile of the shower** (still PRELIMINARY!)





Next steps:

1. study the option of "grouping" the output of more sensors on the same electronics channel while preserving the multi-photon spectrum capability (an invaluable tool for the self-calibration and equalisation of all channels!)



1 sensor

2 sensors

4 sensors

6 sensors

9 sensors

Board designed & produced under the DOE grant to TexasTech

2. Prepare an updated module with 10 micron pitch SiPM (the latest by HAMAMATSU, KETEK and SensL show the multi photon spectrum!)

4. Analyse the currently available ASICs and design a "basic", scalable unit based on an integrated front-end [look at the WeeRoc family, the IDE-AS SiPM chip and a latest development by Carlo Fiorini at PoliMI]