SiPM for LHCb SciFi Tracker

SiPM Radiation Workshop,
25.4.-29.4.2022 Cern, Geneva

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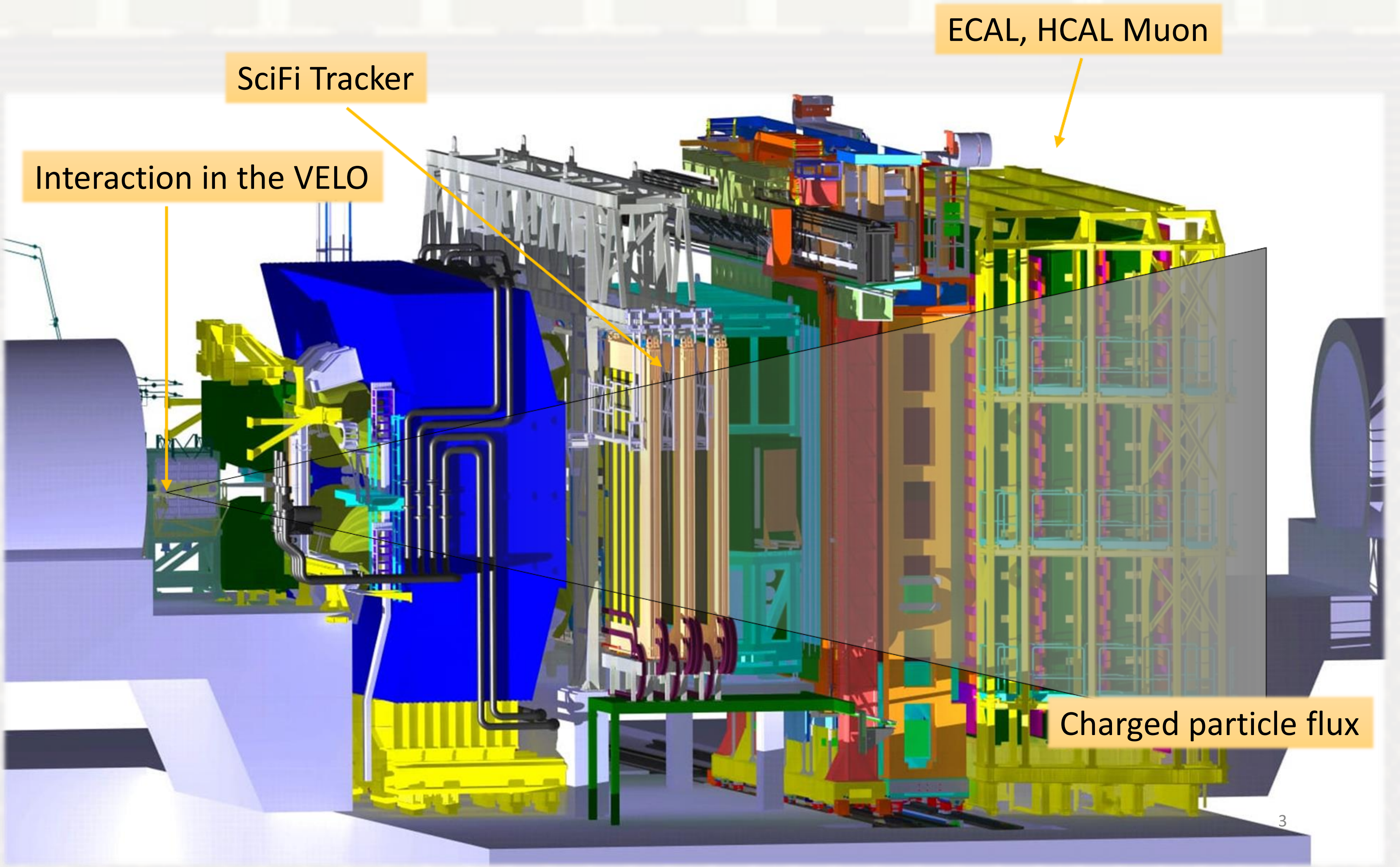
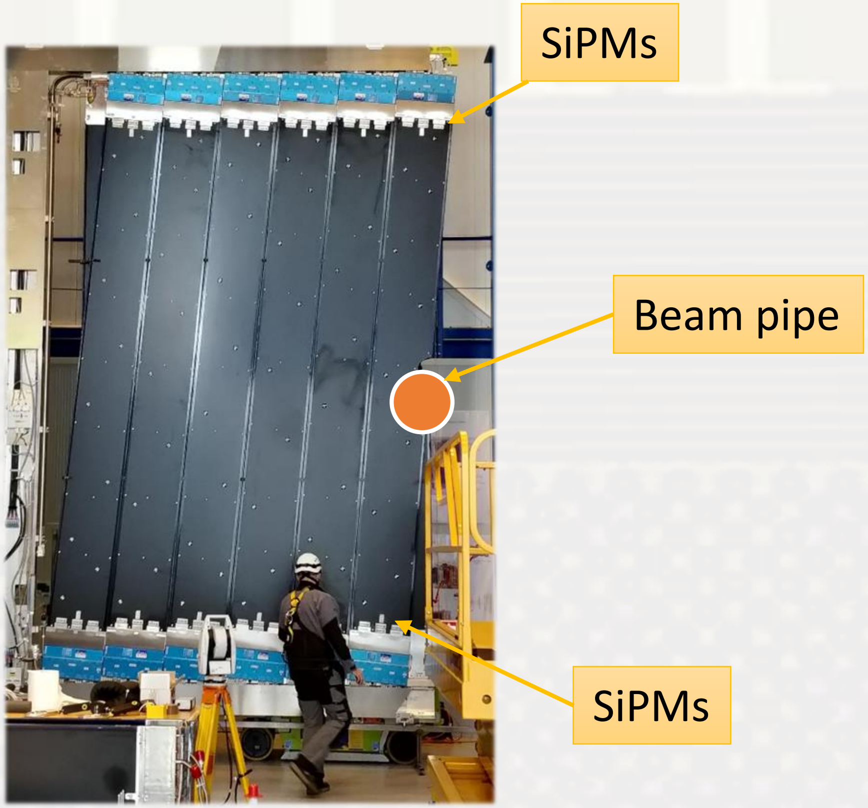
Introduction

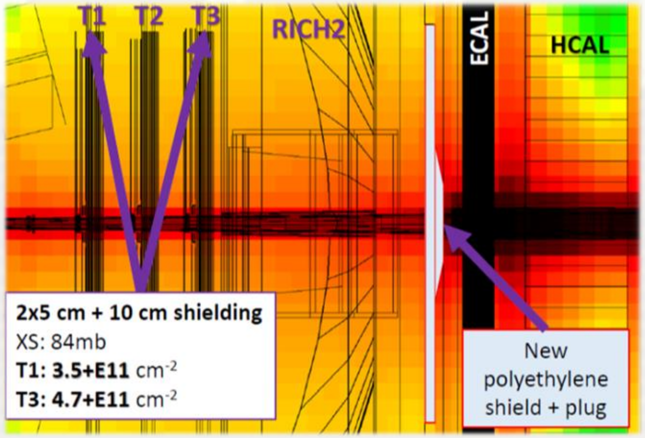
- Radiation environment for the LHCb SciFi Tracker
- Principle of the SciFi and the main requirements for the photo-detector
- Results from neutron irradiation tests, DCR, PDE, gain
- Characterisation of the production of 5500 SiPM arrays (700k channels)
- Development for higher luminosity and higher radiation environment

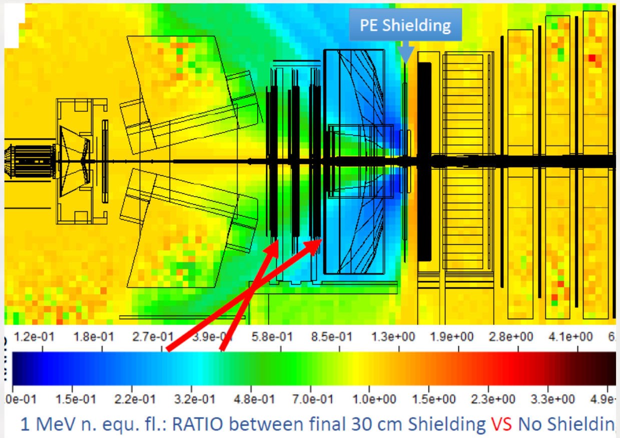
LHCb detector for Run 3



Radiation environment integrated for Run3 assuming an integrated luminosity of 50 fb^{-1}







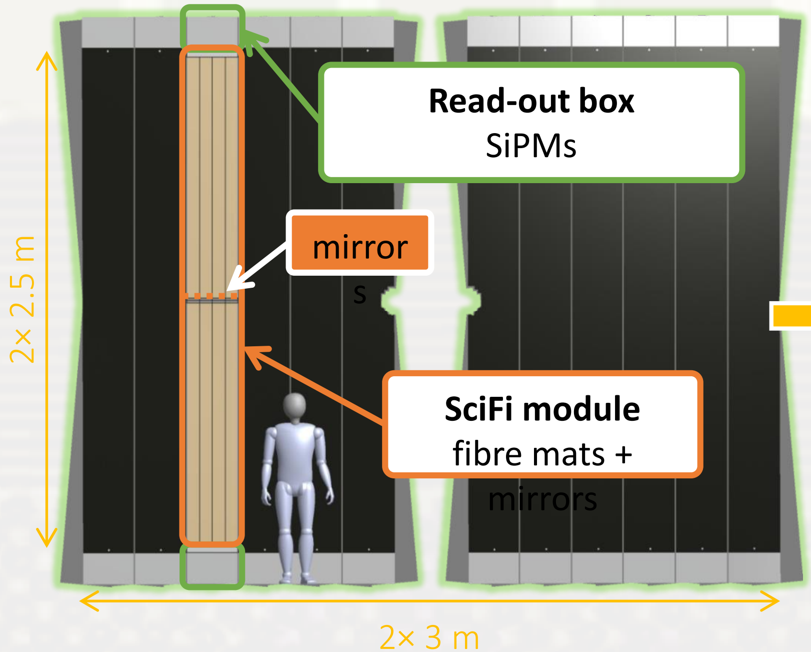
Neutron fluence (highest):
$\Phi = 4.7 \times 10^{11}\, n_{eq}/cm^2$

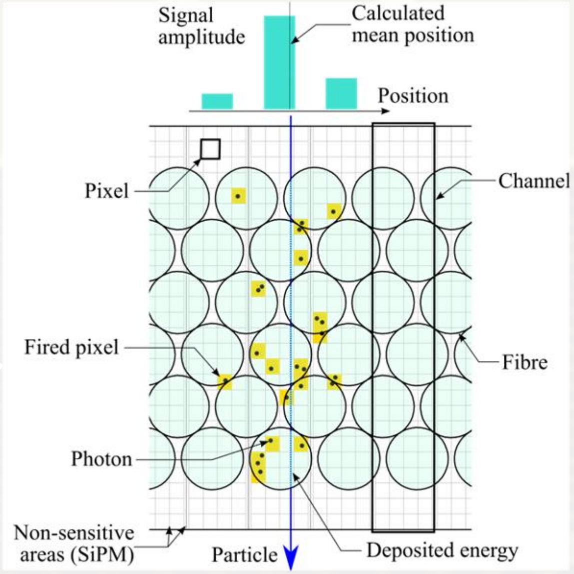
This fluence is a simulated value and takes into account an efficient neutron shield of 10cm upto 30cm thickness (reducing the fluence by a factor 2.5 – 3.4)

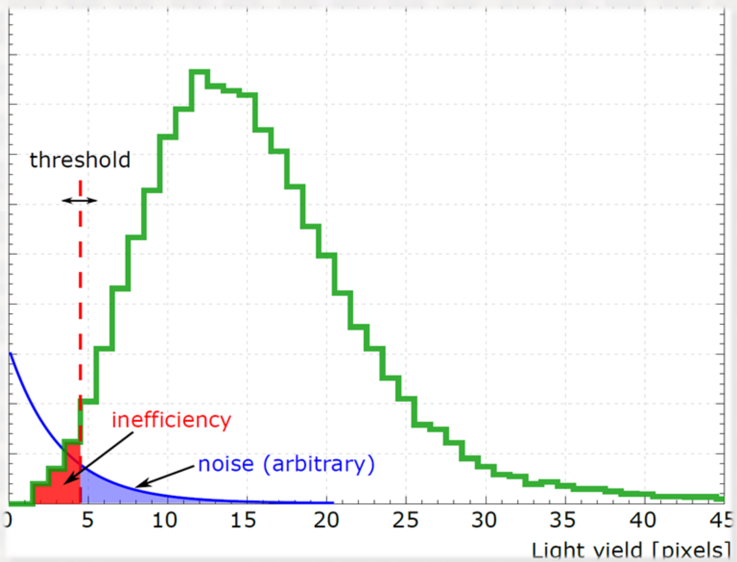
Maximal charged particle induced dose:
D = 100 Gy

Close to the beampipe it is 30kGy but there are no SiPMs (problem for the plastic optical scintillating fibres…)!

SciFi detection principle, requirements







Requirements for the photo-detector:

- Custom geometrical dimension imposed by the SciFi fibre arrangement
- High PDE in blue to green, single photon signal distributed in 2.8 channels in average for a perpendicular track
- Low correlated noise to allow for low noise cut
- Lowest possible DCR after irradiation
- Thin entrance window (max 100µm)
- Low inefficient area between channels and modules, gap less tiling in one direction only

Don't care:

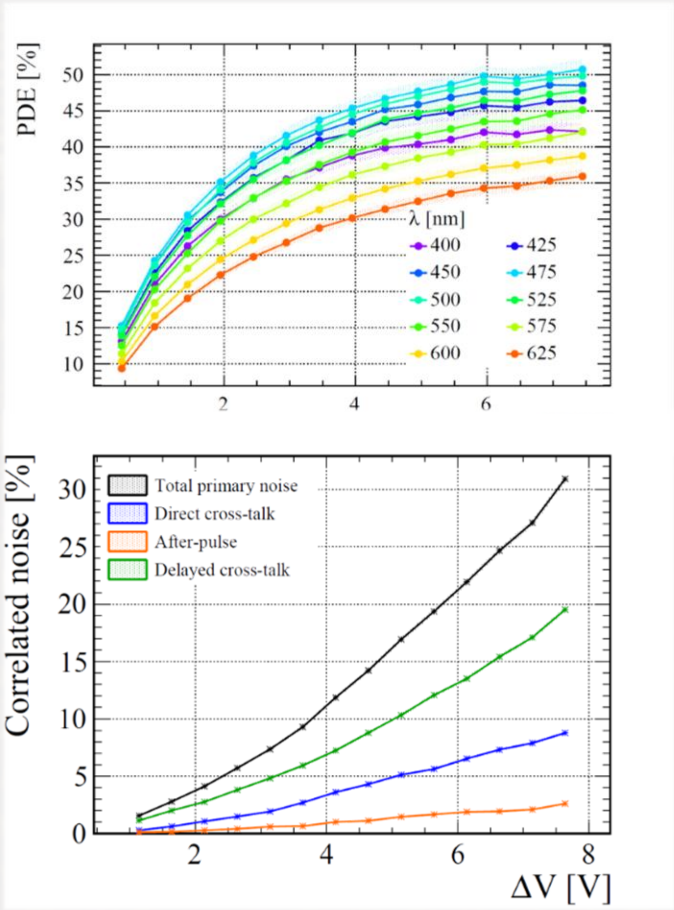
- Gain, dynamic range (100 pixels is sufficient)

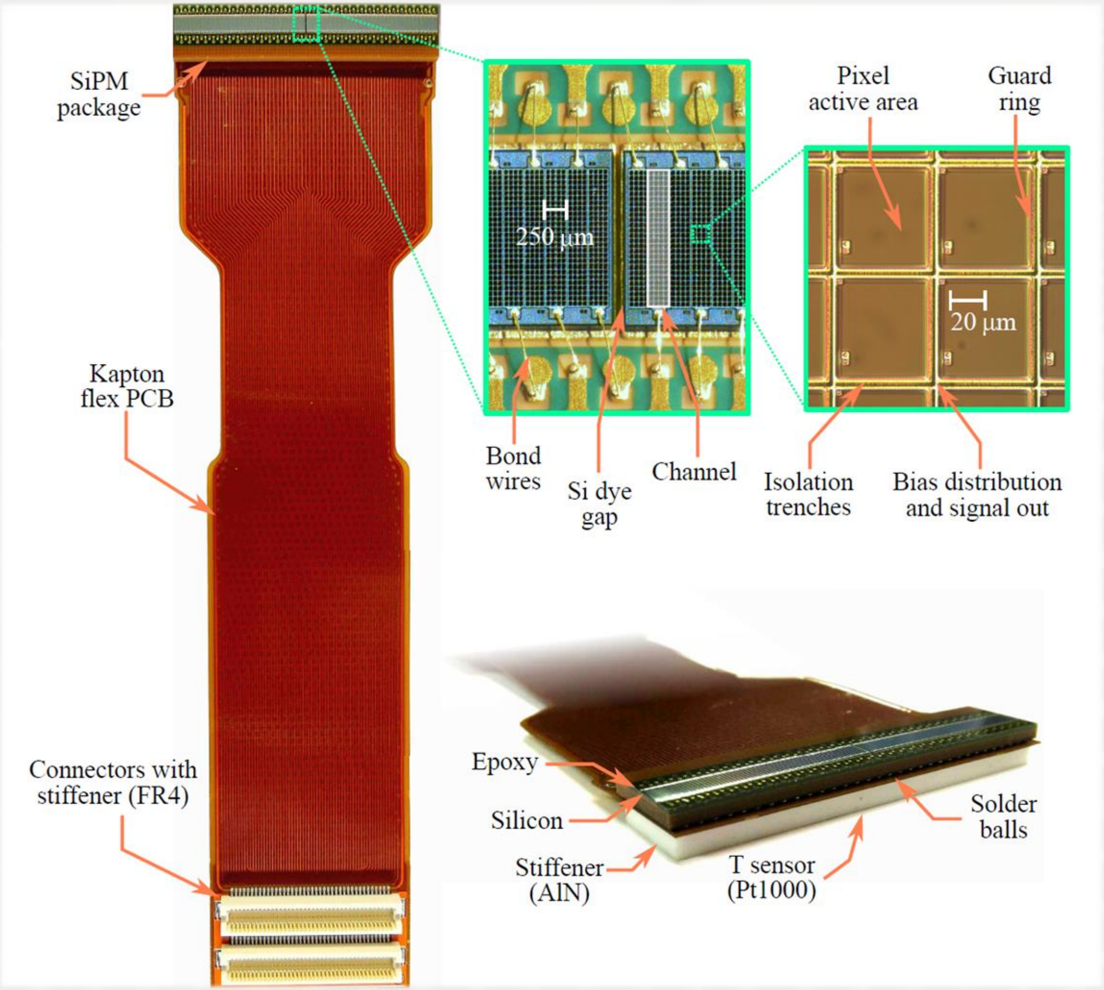
The SiPM array with 128channels (S13552)

Customised SiPM array:

- Large pixels 57.5µm x 62.5µm
- Optical isolation with trenches LTC5
- Fast recovery time 70ns
- Tight cutting and packaging tolerances

32.54 × 1.625 mm²





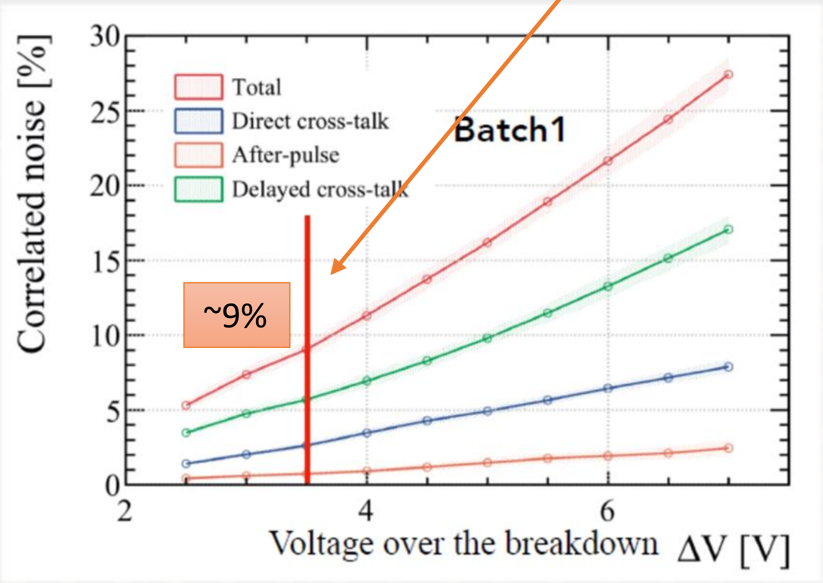
[PhD thesis Olivier Girard](#) [PhD thesis Axel Kuonen](#)

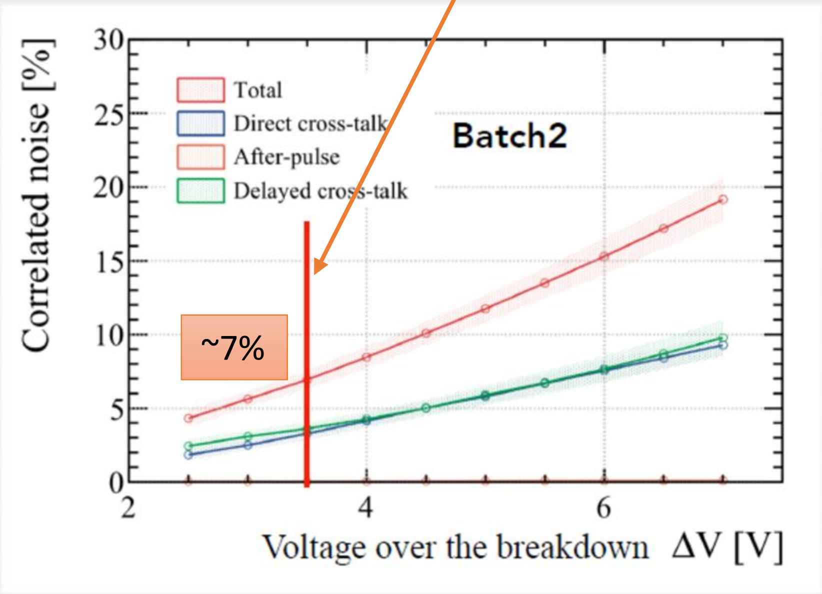
Characterisation of the production batch
Correlated noise

- Higher AP for batch 1
- Higher delayed x-talk for batch 1

Both are within the specification

Low operation voltage to avoid high DCR and high correlated noise!

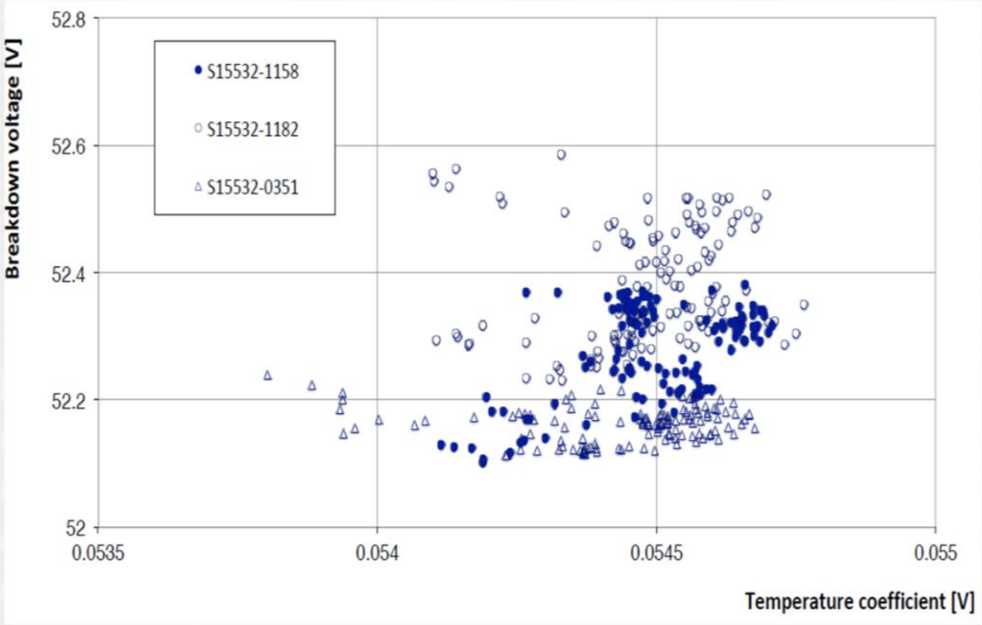




- High PDE and low correlated noise advertised by the SiPM manufacturer are not at the same operation point!
- Pre-production and production batch quite different.

Temperature coefficient

- The specified (silicon only) value is 56mV/K, it seems that there is some difference due to thermal coupling
- For the compensation of the temperature change it is important to take also the package into account. With the integrated temperature sensor it is the best choice to use the temperature coefficient obtained with the this measurement.



- T sensor on module an important luxury and certainly helpful
- Temperature coefficient can change if package is taken into account

Irradiation tests with neutrons (Ljubljana)

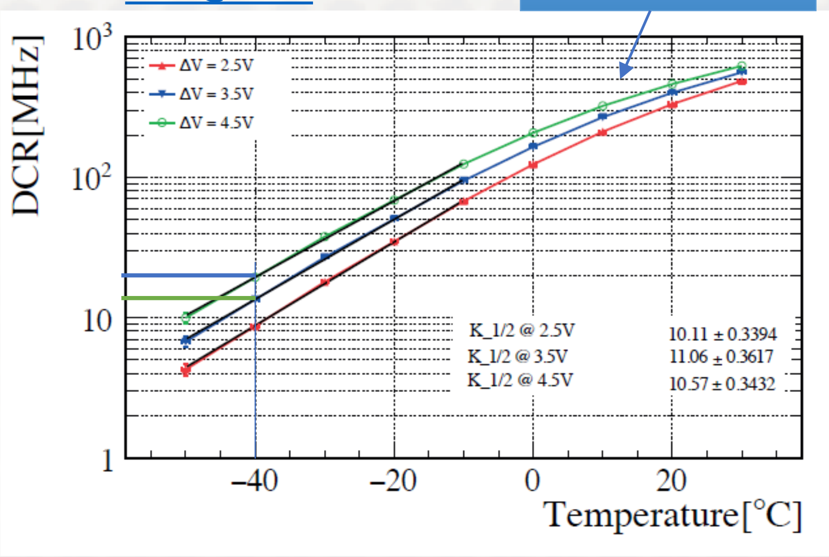
- SiPM area A=0.41mm^2
- Use current measurement with I-V scan
- Measurements are based on average of 128 channels, automated multiplexer
- At high DCR self heating and saturation is observed (104 pixels per channel)

For comparision:
A=1mm^2 , T=-40°C, ΔV=3.5V, p_{tot_cor}=7%, PDE=44%:

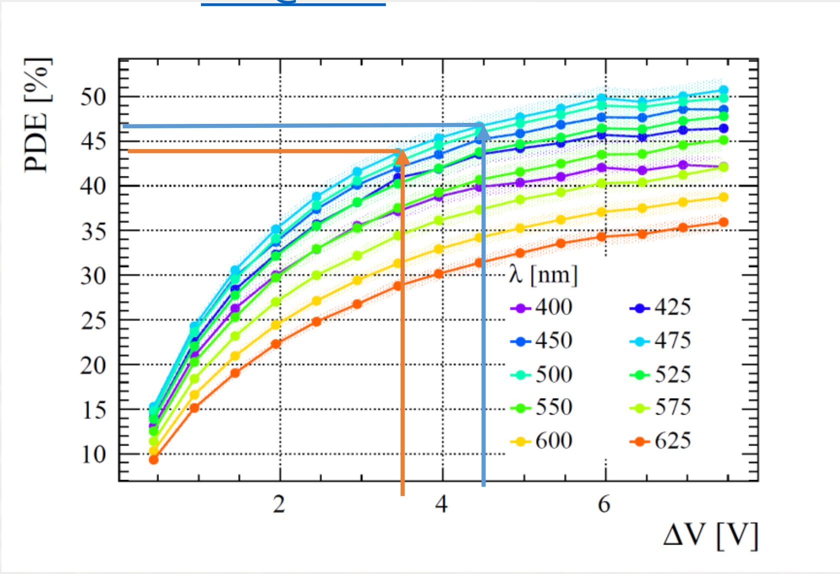
DCR = 34MHz
$K_{1/2}$=10.5K

DCR@3.5V = 14MHz
DCR@4.5V = 20MHz

Saturation due to self heating



Peak PDE@3.5V = 44%
Peak PDE@4.5V = 47%

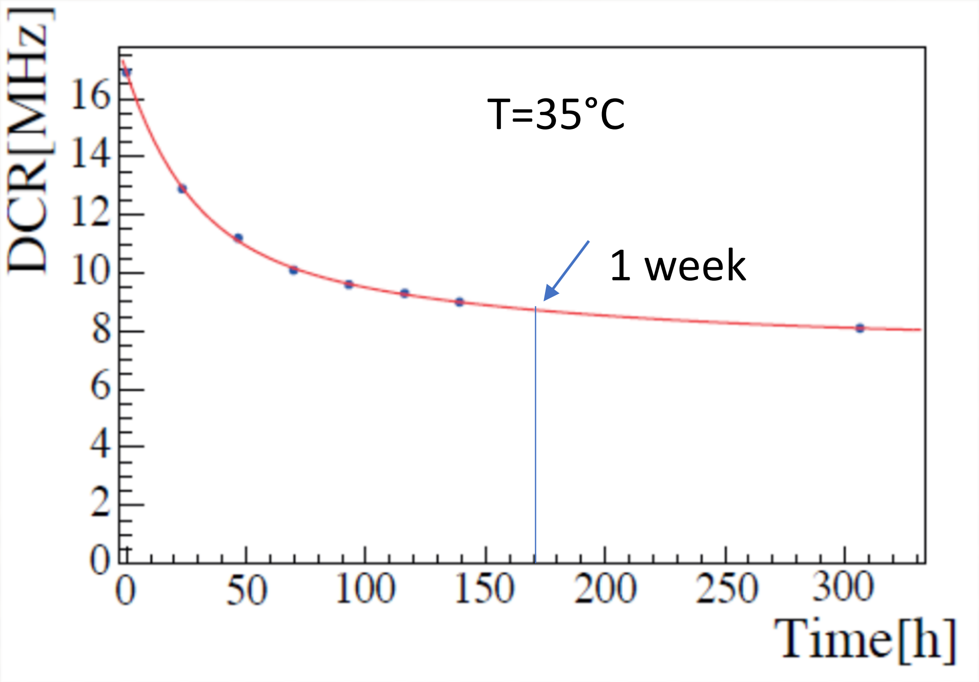


1% dead time with 70ns recovery time @DCR=1.5GHz

DCR=1GHz results in P=26mW, important self heating!

Annealing

- Low temperature annealing test at 35°C over two weeks
- A reduction of a factor 2 is observed.
- Annealing is foreseen in situ for LHCb SciFi Tracker (end of year shutdown of LHC)



To make the irradiation results consistent, annealing was applied before measurements of irradiation effects.

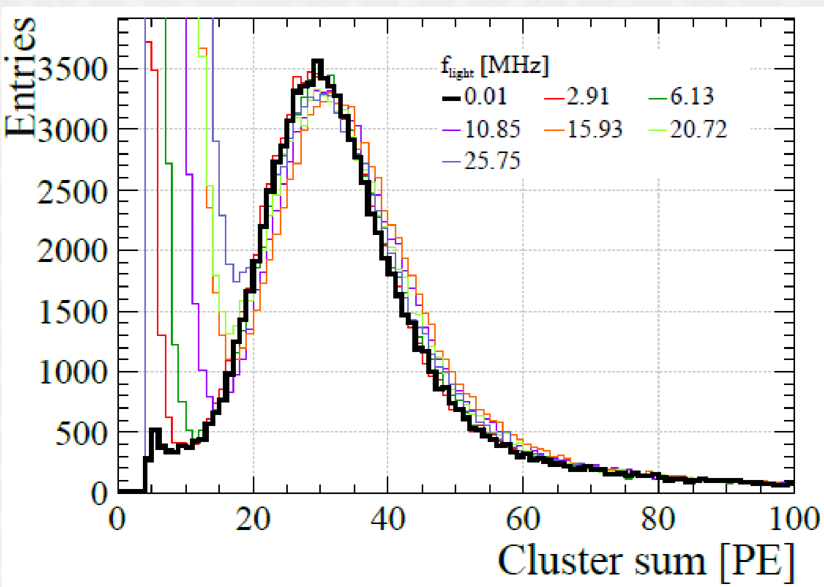
Comparison of the light yield (PDE) between non-irradiated with light and irradiated detectors

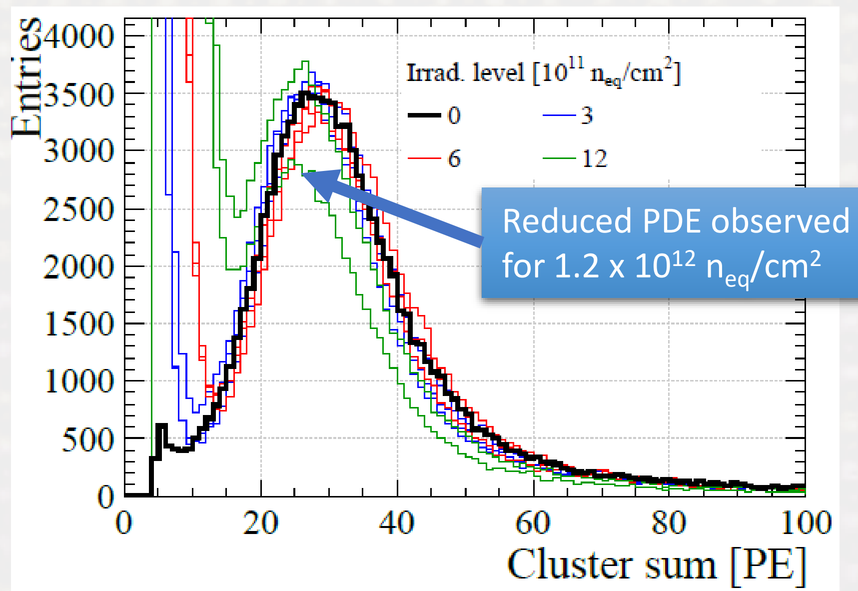
- SciFi module stimulated with mono-energetic electron beam from Sr-90 source
- Light injection system used for “DCR noise generator”
- Light yield measurement with fast readout electronics
- Gain verification with single photon peak amplitude

Repeat the measurement with irradiated samples, same setup at the same DCR

Use light with f_{light}=DCR to test:

- Self heating effects
- Gain change in the amplifier due to saturation and high current to sink



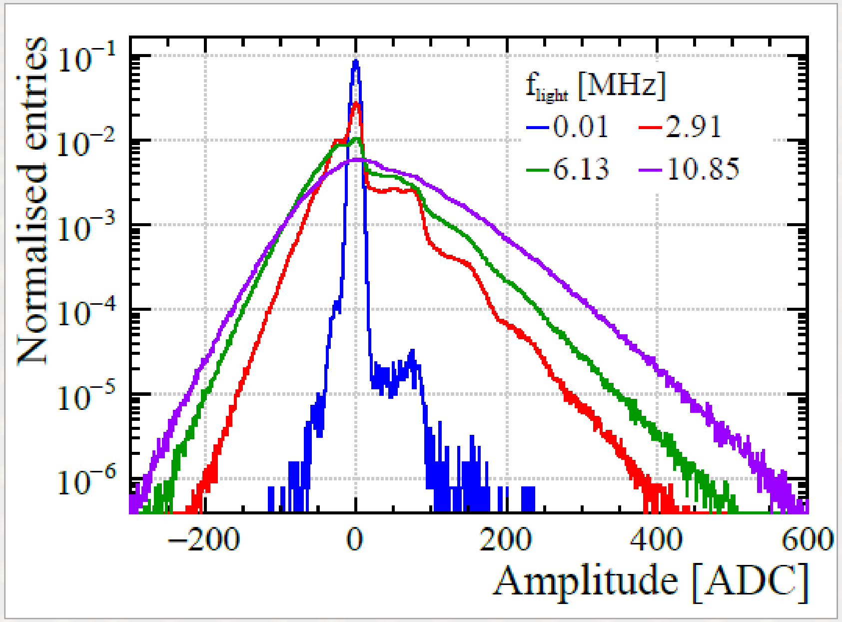


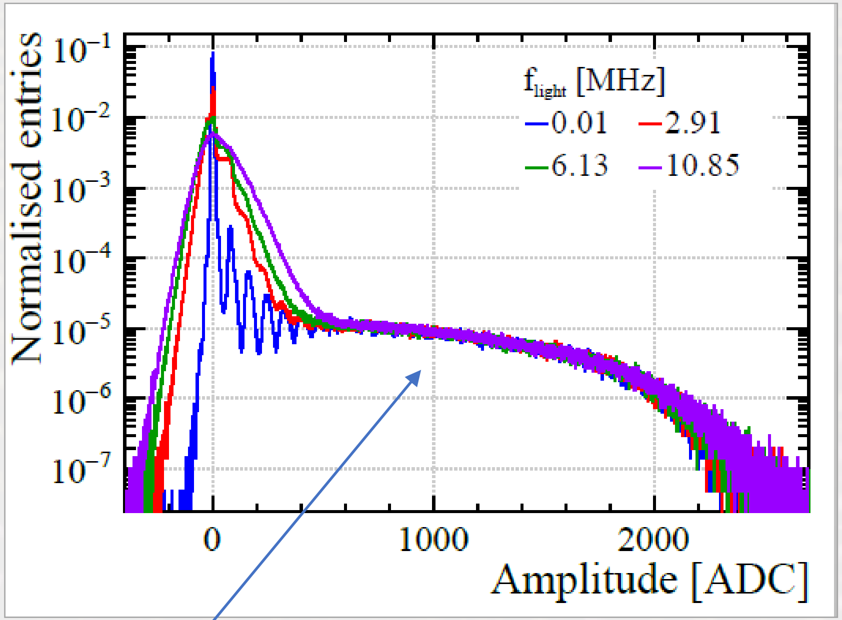
DCR=25MHz/channel results in P=80mW and produces important self heating!

Comparison of the amplitude spectrum

Random light injection at different frequency levels, equivalent to irradiated detectors

Add signal via fibre module, photon-peaks are visible up to 6 MHz

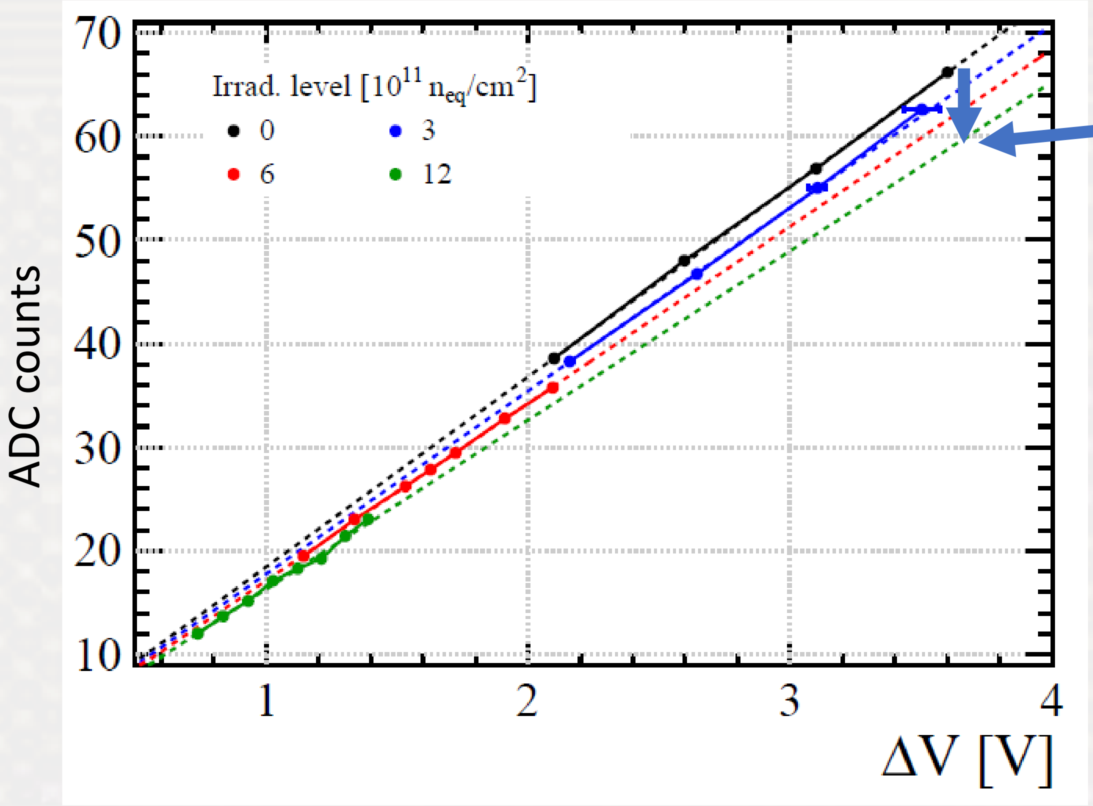




Important region at low number of photons is completely dominated by the DCR. High signal region is unchanged!

Gain at different irradiation levels

The gain was measured based on single photon peak amplitude.
For the highest irradiation level. only a limited over-voltage range could be used.



- Gain reduction is visible in the order of 10% for the highest irradiation level.
- The gain change needs to be taken into account for the PDE measurement!

SiPM production with Hamamatsu and integration into the detector some time line

After the prototype tests, the production of 5500 pieces (25% spares) was started:

- Order date 9.2016 (start)
- Delivery date 5.2017 (500 pieces)
- Delivery date 9.2017 – 2.2018 (5000 pieces)
- Mounted on Kapton flex 7.2018 – 4.2019
- Gluing on cold bar 9.2018 – 6.2020
- Assembly and installation of detector in IP8 5.2019 – 4.2022 (end)

Delivery schedule respected

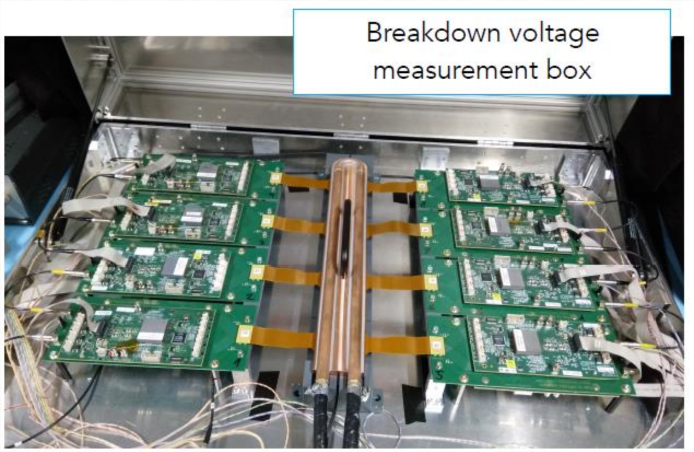
Delay in assembly ~6 month

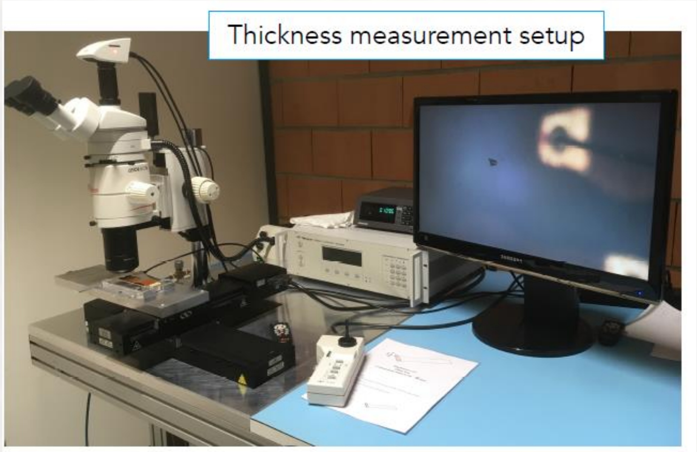
Delay Covid and other reasons 12 month

Summary:
- From the order to the end of assembly 2.5 years.
- From the order to the end of installation 5.5 years!

QA of the SiPM

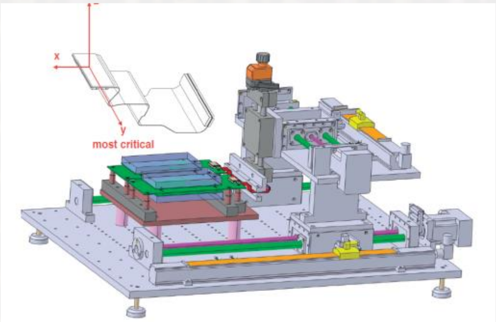
- Sample test of the bare chips without soldering. An adapter has been developed to allow electrical before assembly. (2/500, these detectors are stored without soldering (witness samples). PDE, IV for V_{bd} andR_q, noise analysis
- Partial optical inspection before assembly
- Thermal cycling after assembly (burn in) 3 cycles 80°C to -50°C)
- Electrical testing for shorts and opens after assembly
- Full sample characterisation for V_{bd} , measure 1K channels in one go!
- Full sample measure the total thickness of the detector after assembly
- Full sample optical inspection and cleaning

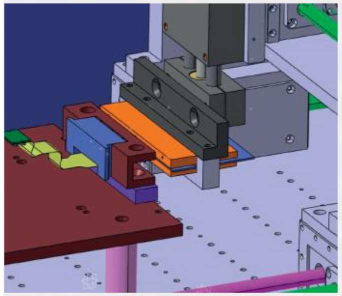
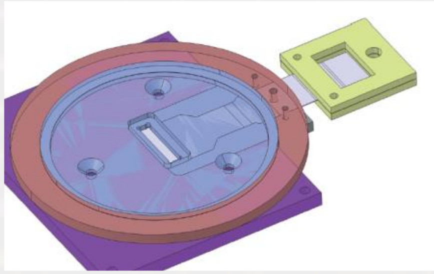
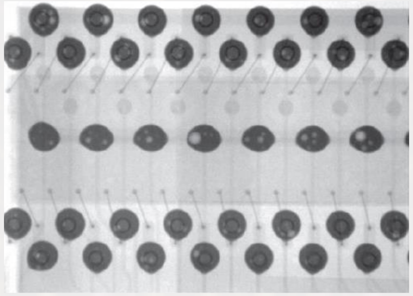




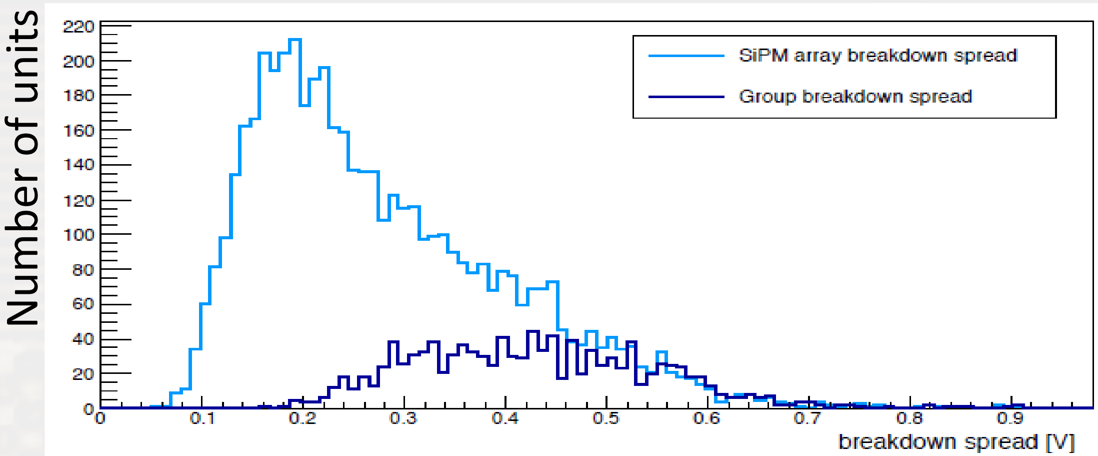
Design tests before production

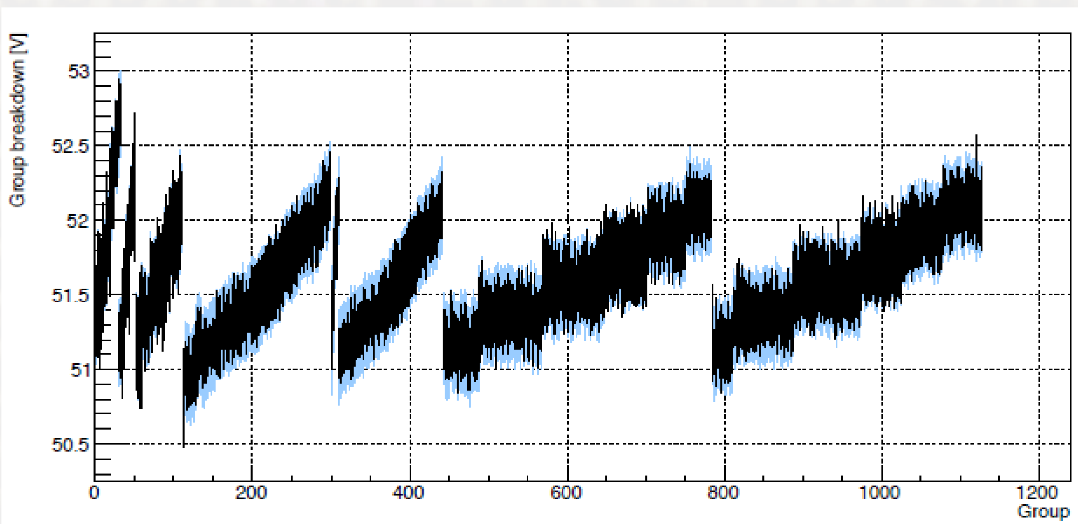
- Vibration test of the Kapton flex PCB, stress test
- Scratch test of the optical surface when the detector is in contact with the fibre mat, pressure test
- Gluing test of the ceramic stiffener
- Thermal cycling test of the assembly (100 cycles 100°C – 55°C)
- Connector reliability test, add glue on connector to reduce stress on solder joints
- X-ray test of the assembly



V_{bd} spread, within one array and within 4 arrays

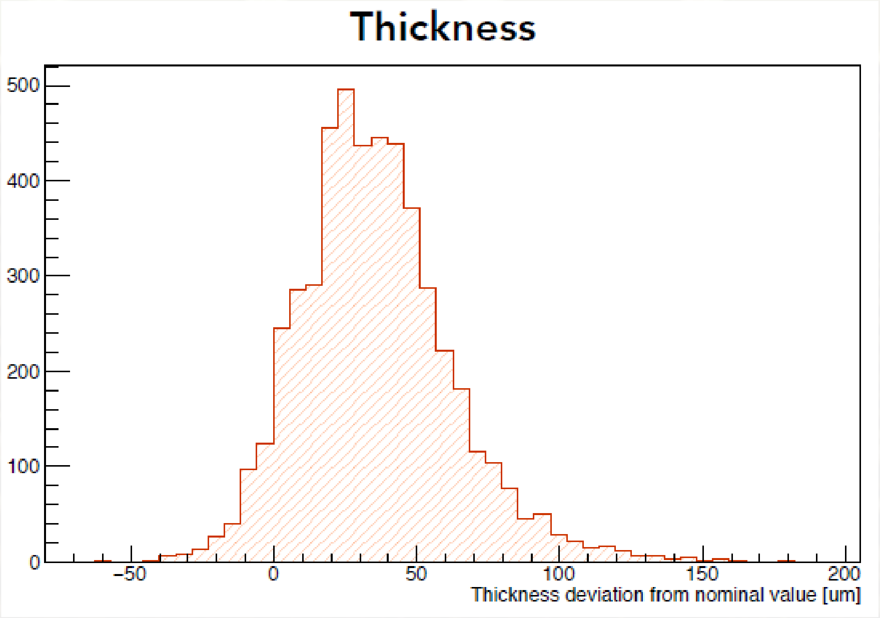




- The spread of Vbd within one array is up to 0.6V
- A maximum of 1V can be compensated by the FE ASIC

- V_{bd} spread over the production is 2V
- Grouping is a lot of work but works

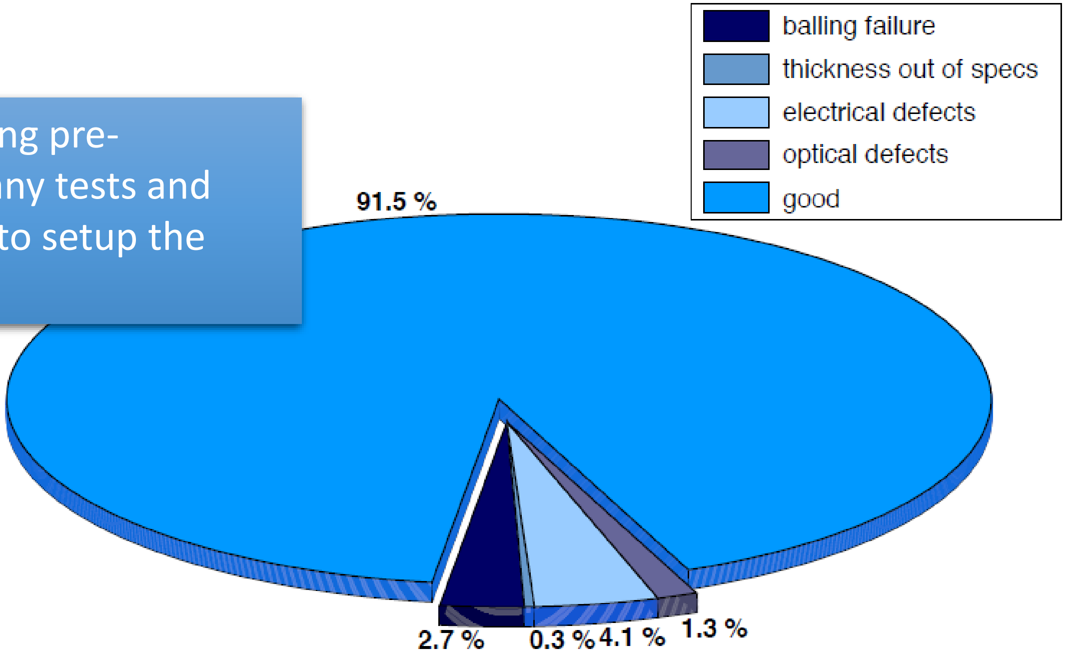
Thickness of assembly



- The large aspect ratio L/W is 32mm/6mm leads to bending (banana shape during reflow)
- Solder and gluing steps introduce variations in thickness important for the optical coupling

SiPM arrays mounted on the cooling pipe

Some statistics: Production yield

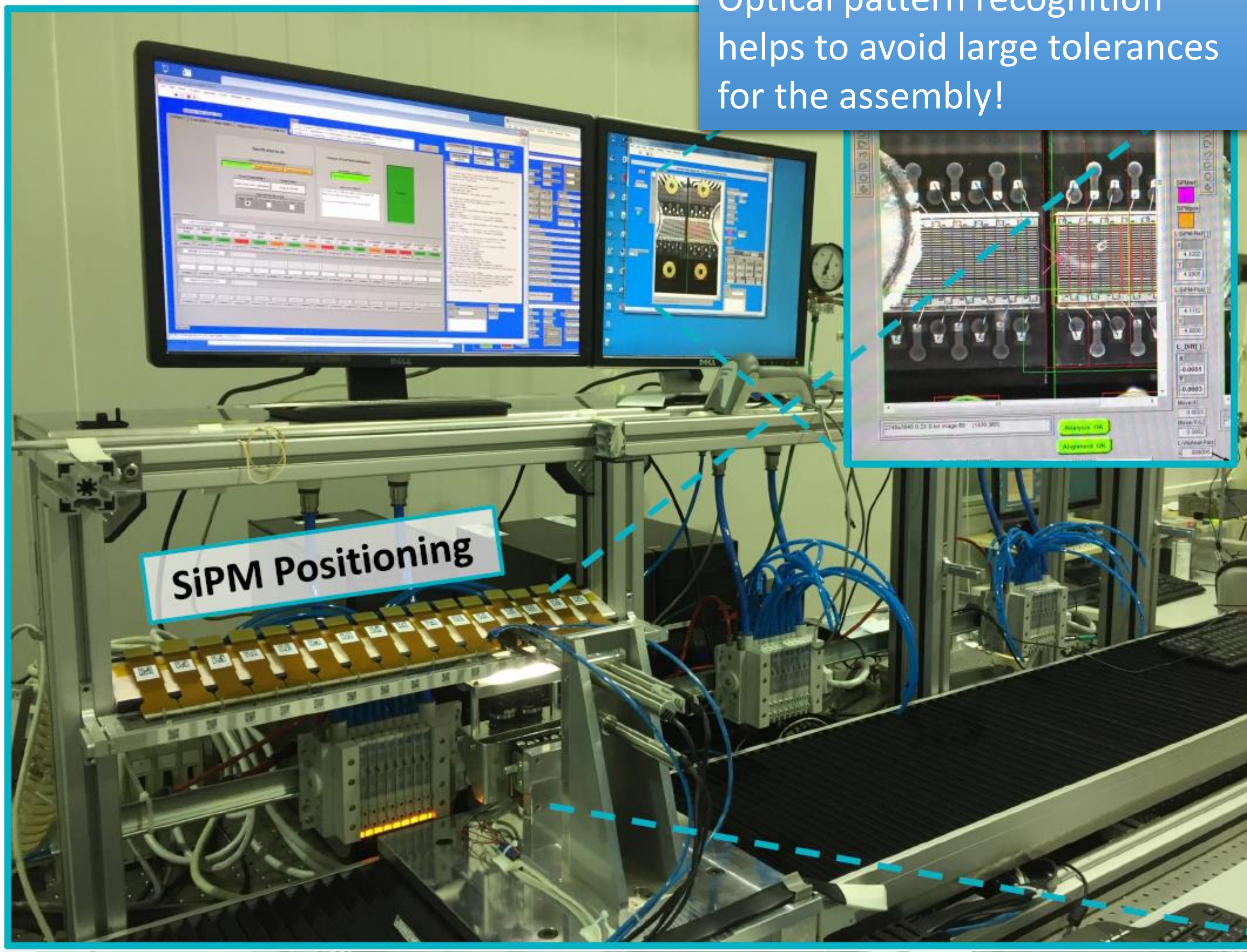


Largest loss during pre-production – many tests and some problems to setup the production!

- 91.5% of final production yield, according to expectations
- The production yield improved from 85% to 99%
- Electrical defects due to connector and balling the major source of failure

Gluing of the SiPM arrays to the cold bar (20µm precision)

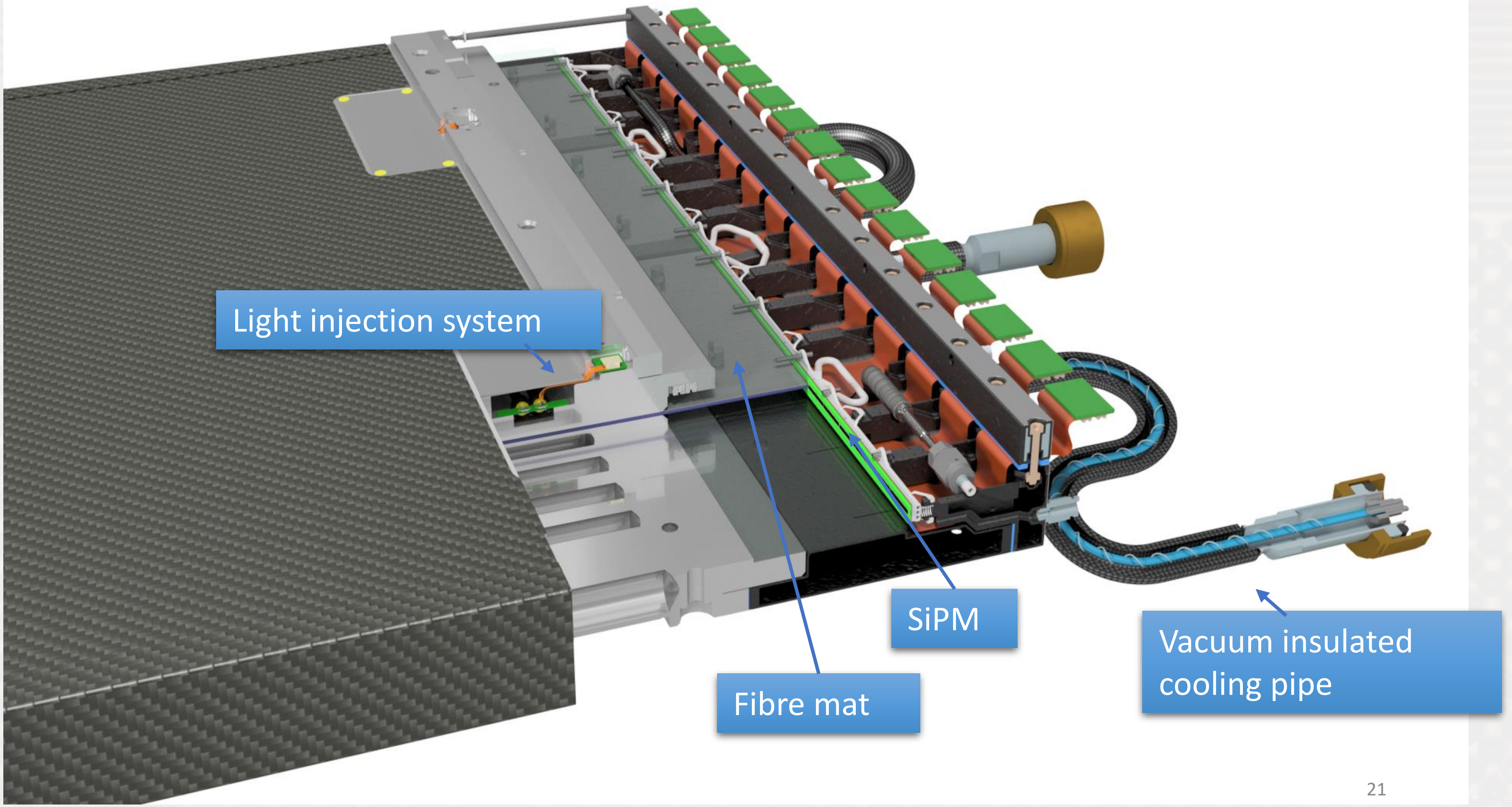
Optical pattern recognition helps to avoid large tolerances for the assembly!



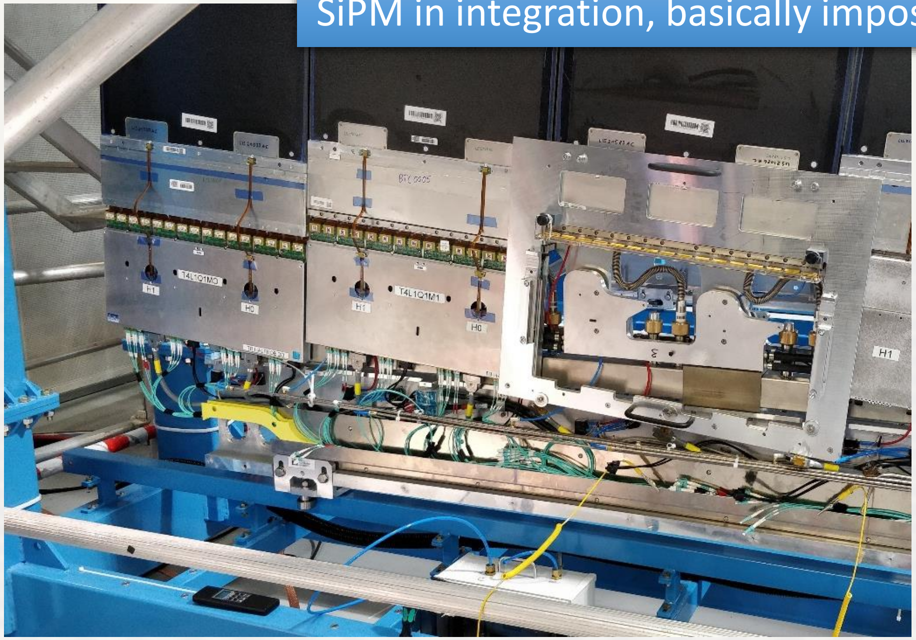
Automated placement

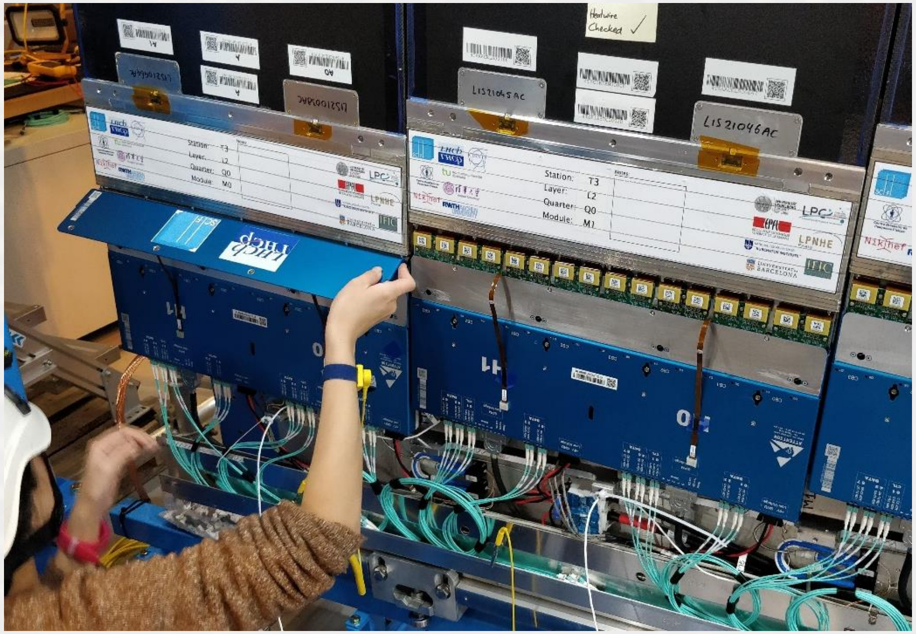
The SiPM integraton into the SciFi detector:

- Light tight
- Air tight (N2 flashed to create over-preassure to avoid humidity
- Cold,T=-40°C specification
- Tight space constraints



SiPM in integration, basically impossible to exchange the SiPMs!





Cooling introduces large complexity for the detector integration

Conclusion: The SiPM array is in the center of the integration, exchanging is impossible!

Development for future LHCb SciFi Tracker

Higher luminosity by a factor 10 is expected, increasing the neutron fluence to the level of: $\Phi = 5 \times 10^{12}$ n_{eq}/cm^2 cooling to lower temperature is required

but

humidity and vapor tightness with conventional foam isolation is not possible beyond T=-40°C

and

decrease the thickness of the fibre layer to reduce cluster size and decrease occupancy

but

less signal requires lower thresholds.

Possible solutions

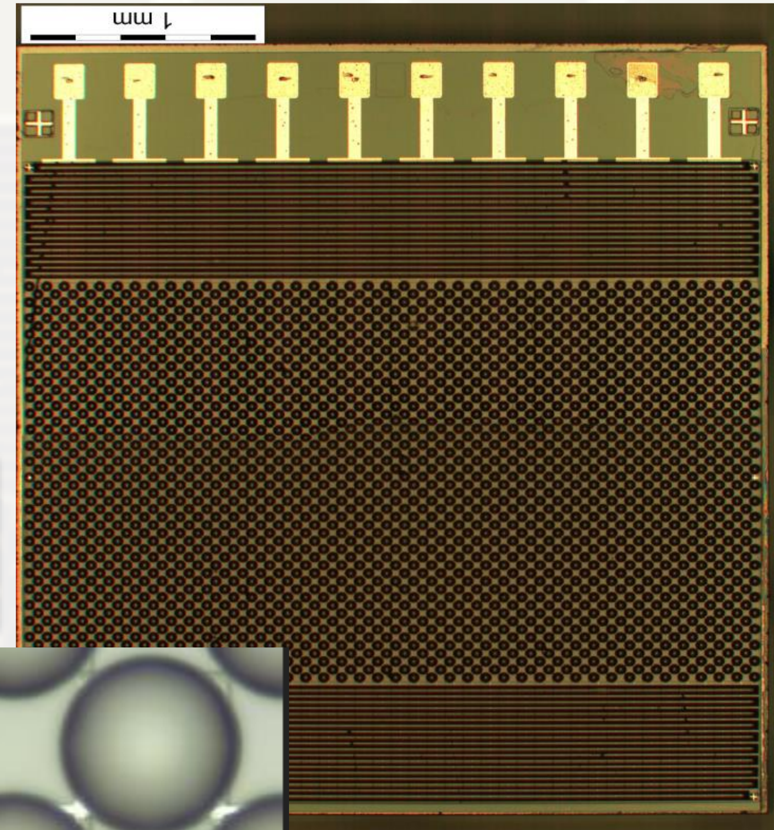
➔R&D on micro-lens enhanced SiPMs to increase signal

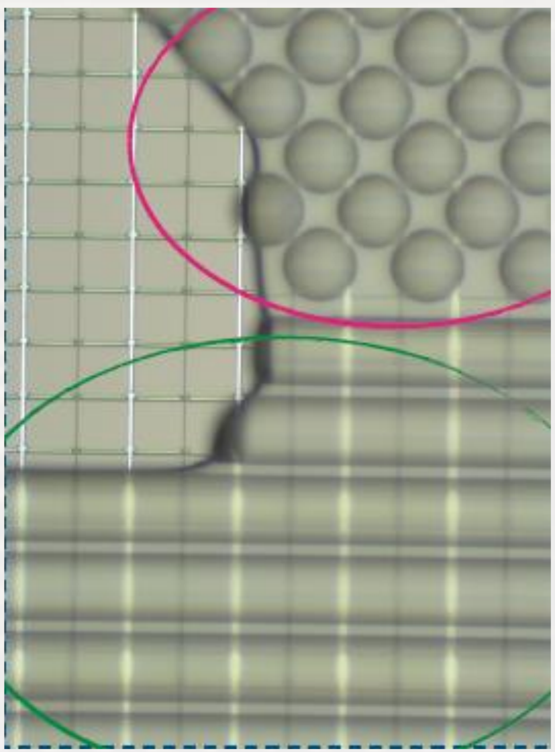
➔Cryogenic cooling for SiPMs at 77K to lower thresholds

Microlens-enhanced SiPM array

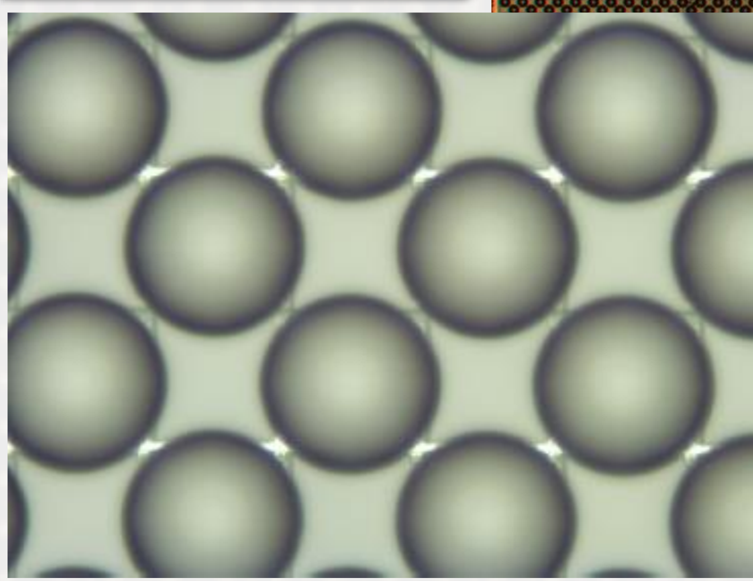
- Two prototype iterations performed on 10 channel SiPM array from FBK
- With a 40µm x 40µm pixel (83% GFF), the improvement expected is ~20% in light yield (15% at low ΔV for the first iteration measured)
- Can also help to operate the SiPM at low ΔV since the light is focused into the center of the pixel

See talk from Carina VCI 2022:





Recovering dead area and avoiding low field region

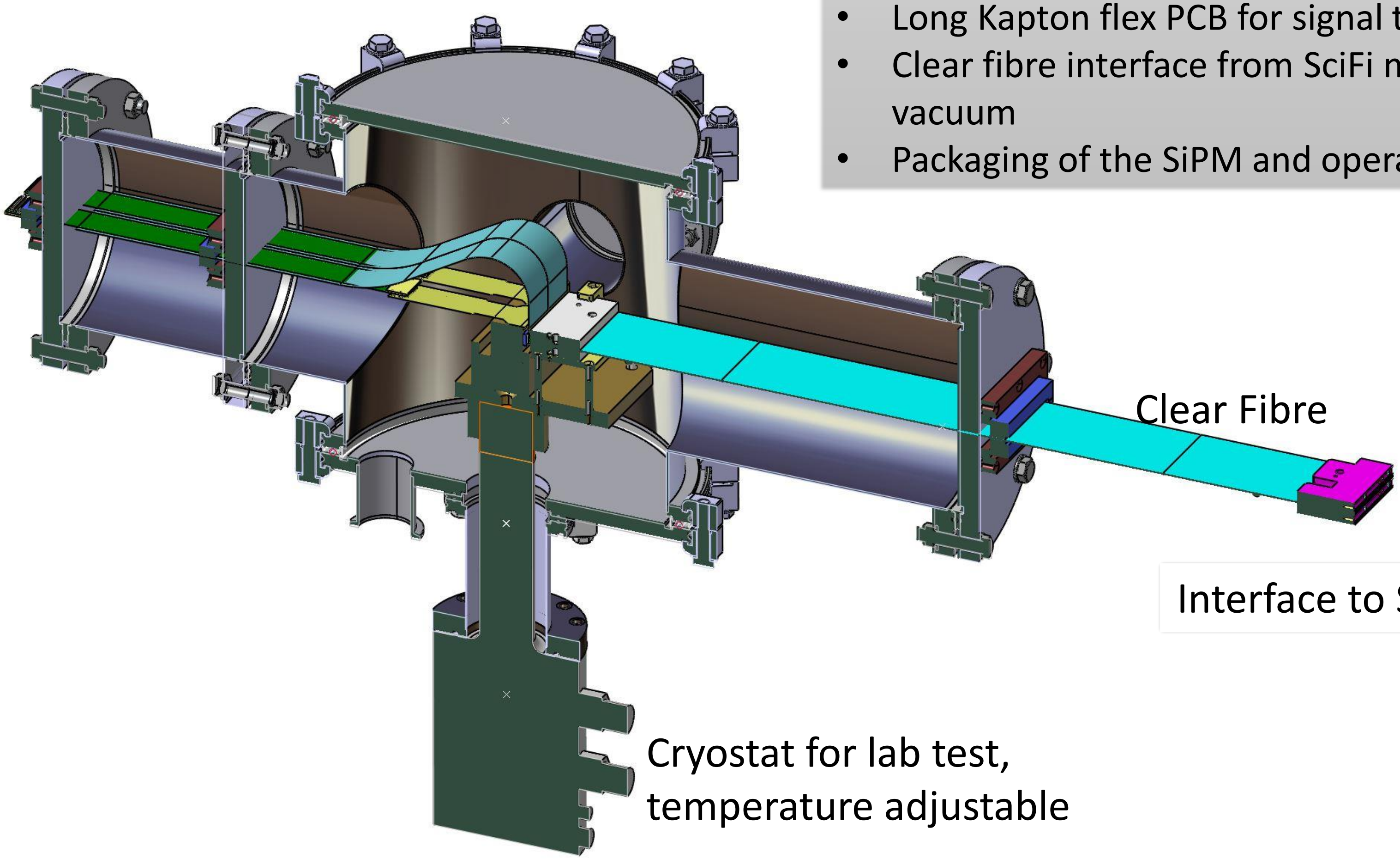


Spherical lenses in the active region and cylindrical outside the light source.

Cryogenic cooling with clear fibre interface

Setup in preparation to evaluate the feasibility of the different parts:

- Long Kapton flex PCB for signal transmission
- Clear fibre interface from SciFi module into the vacuum
- Packaging of the SiPM and operation at 77K



Summary

- Complex project requires long production and integration time
  - 2.5 years production
  - 3.0 years for integration
- Cooling introduces a lot of complexity and the exchange of the SiPM can be impossible which in consequence requires a lot of QA
- Micro-lenses and cooling to 77K are studied to make the SiPM “more radiation hard”
- No significant changes in characteristics of the SiPM observed up to $6 \times 10^{11}\,\mathrm{n_{eq}/cm^2}$ (except DCR) and first indication of reduced PDE and change in gain at $12 \times 10^{11}\,\mathrm{n_{eq}/cm^2}$