Silicon Photomultipliers in the Scintillating Fibre Tracker at the LHCb experiment

SiPM workshop 2019 - Bari

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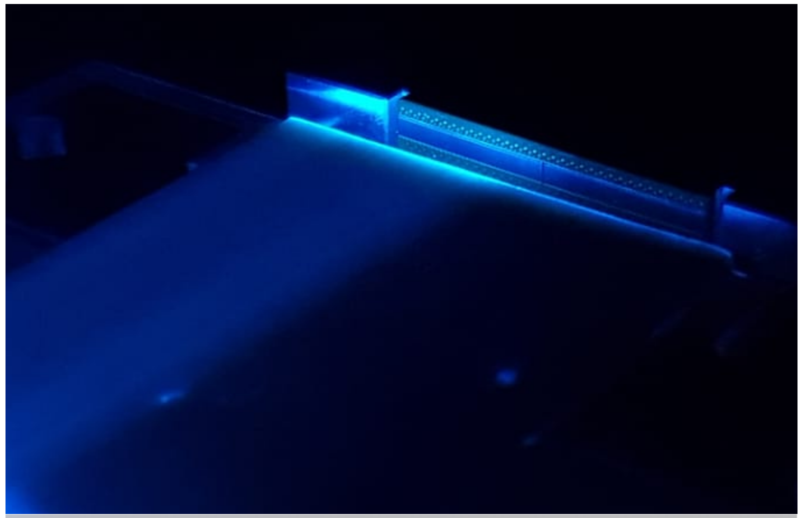
on behalf of the **LHCb - SciFi collaboration**

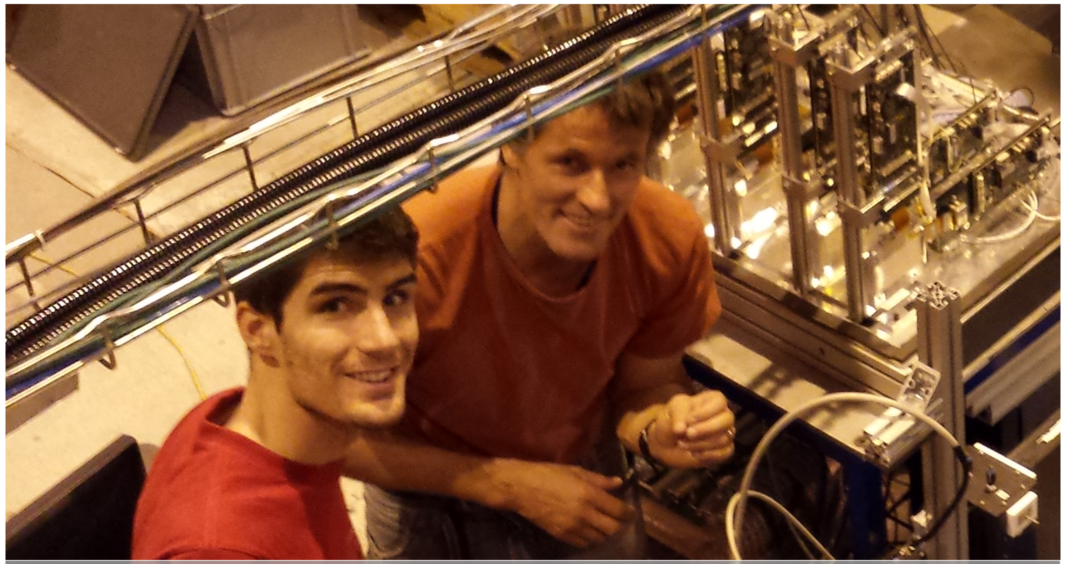
***École Polytechnique Fédérale de Lausanne**

picture credits to Alessandra Longo

Outline

1. LHCb and scintillating fibre (SciFi) tracker upgrade





2. SiPM characterisation

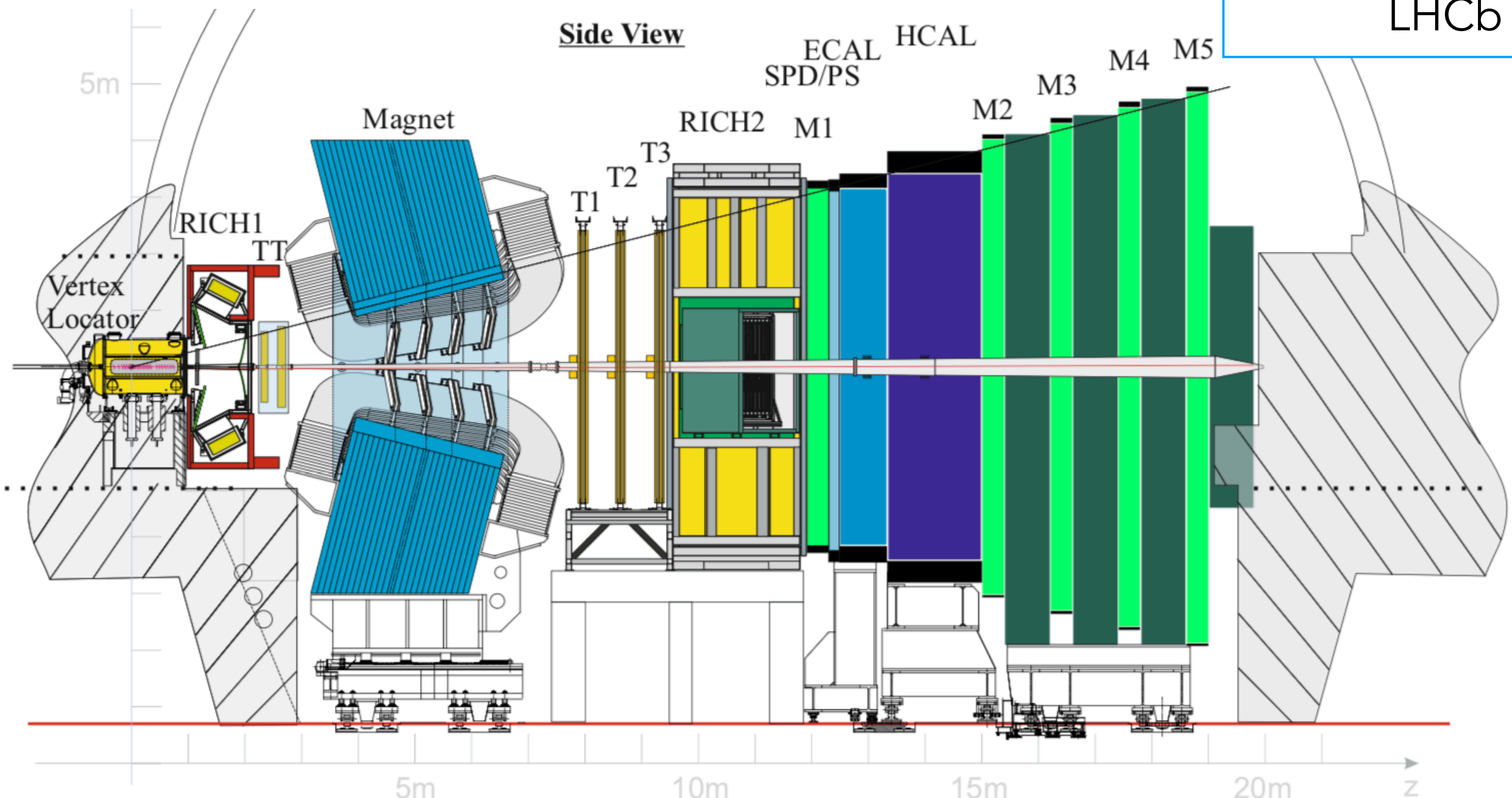
3. SiPM assemblies production

4. Integration and future upgrade

LHCb and scintillating fibre (SciFi) tracker upgrade

LHCb and LHCb upgrade

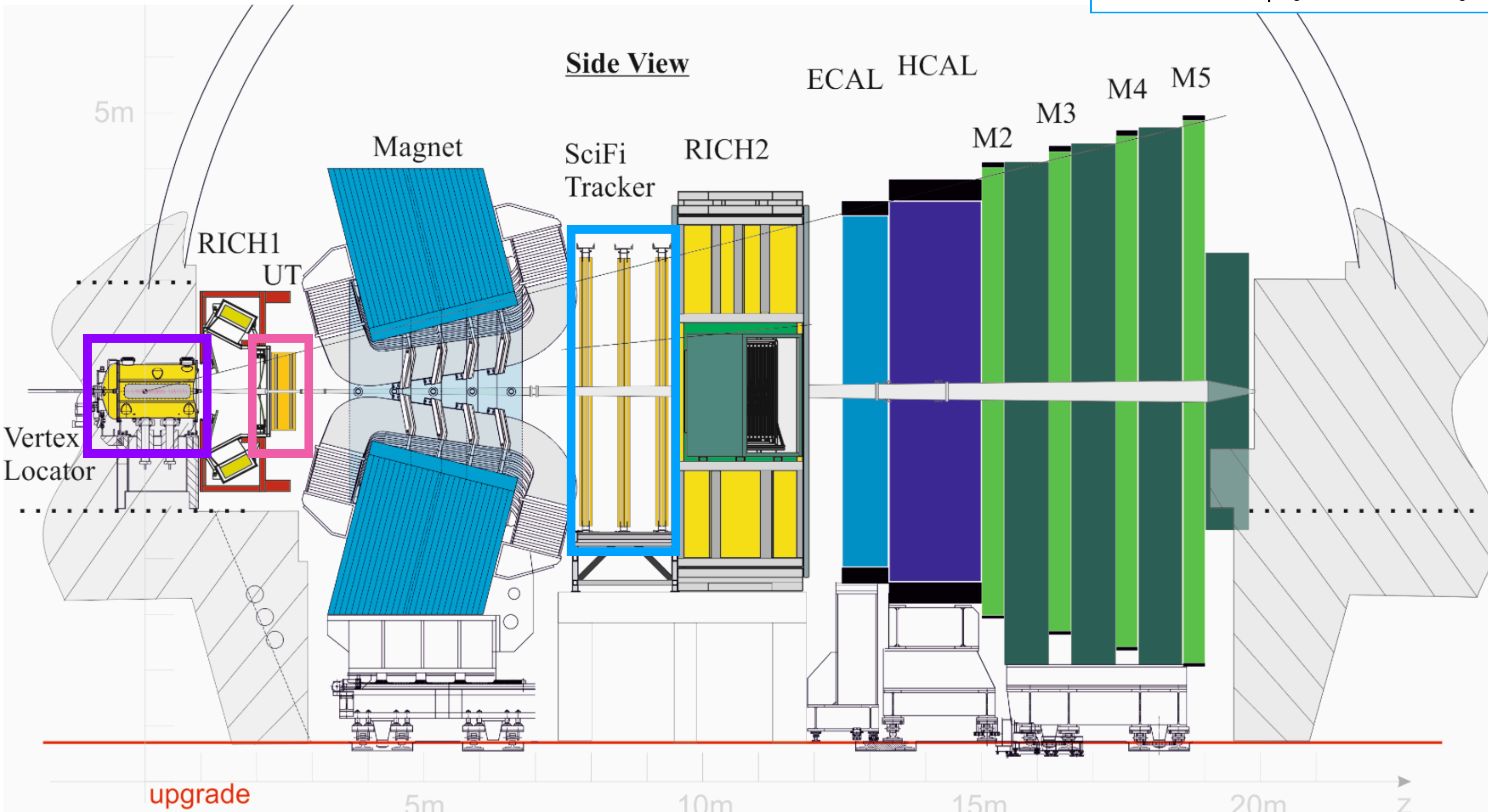
LHCb design



- The LHCb detector is a single-arm forward spectrometer covering $2 < \eta < 5$
- Precision studies decisive to unravel beyond the SM processes at the LHC
- In 2021 **LHCb increases sensitivity** and allows for **new final states**
  - **Raise** the data rate: operational **luminosity** at 2 x 10^{33}/cm^2
  - Raise trigger efficiency: **40 MHz read-out** with software-based trigger
    - replacement of front-end electronics and detector technologies

LHCb tracking upgrade

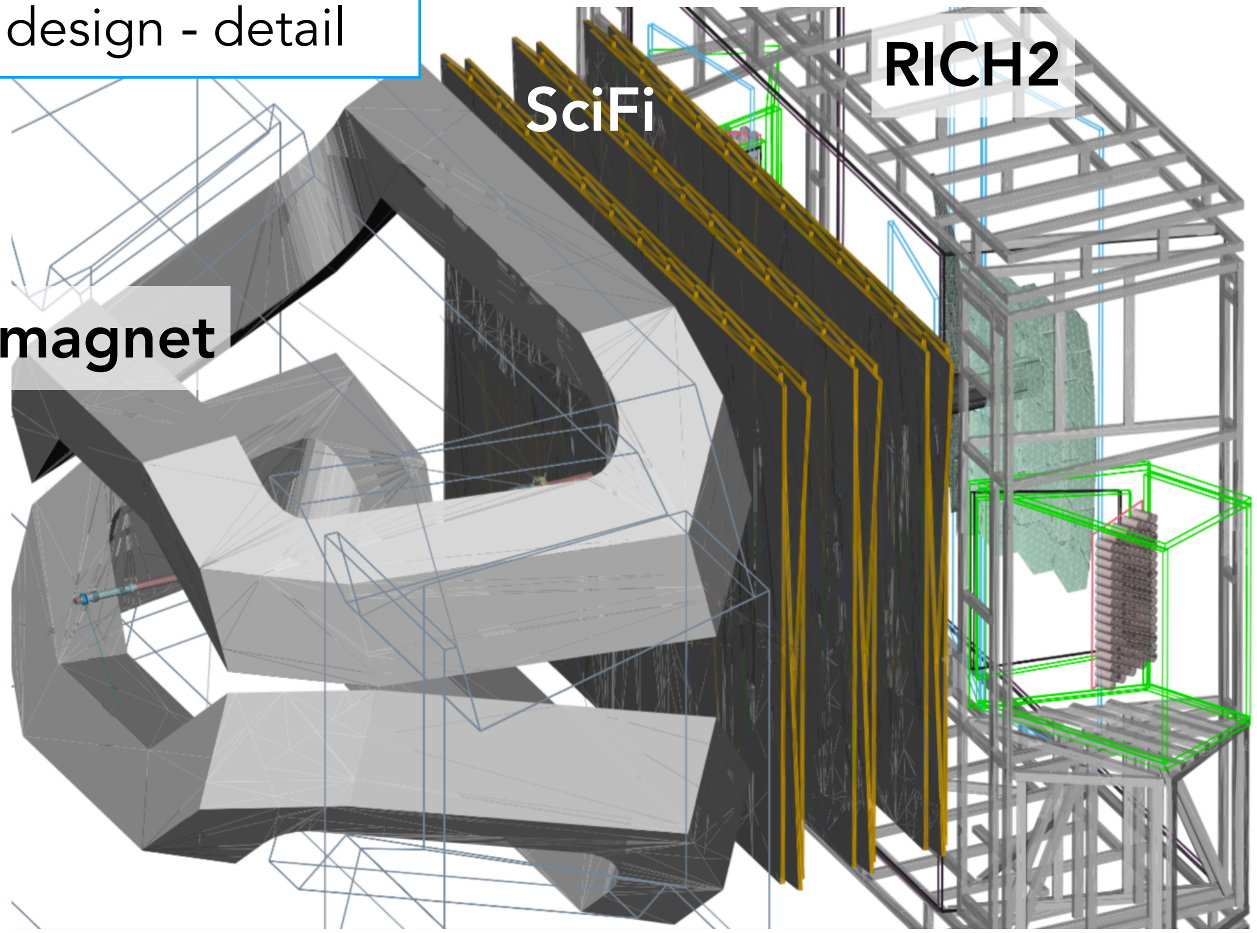
LHCb Upgrade design



- **Vertex Locator (VELO):** silicon micro-strip ➔ silicon pixel detector
- **Upstream Tracker (UT):** silicon micro-strip detector ➔ silicon higher granularity micro-strip detector
- **Scintillating fibre tracker (SciFi):** Silicon microstrip + drift tubes ➔ scintillating fibres and SiPMs

LHCb SciFi tracker requirements

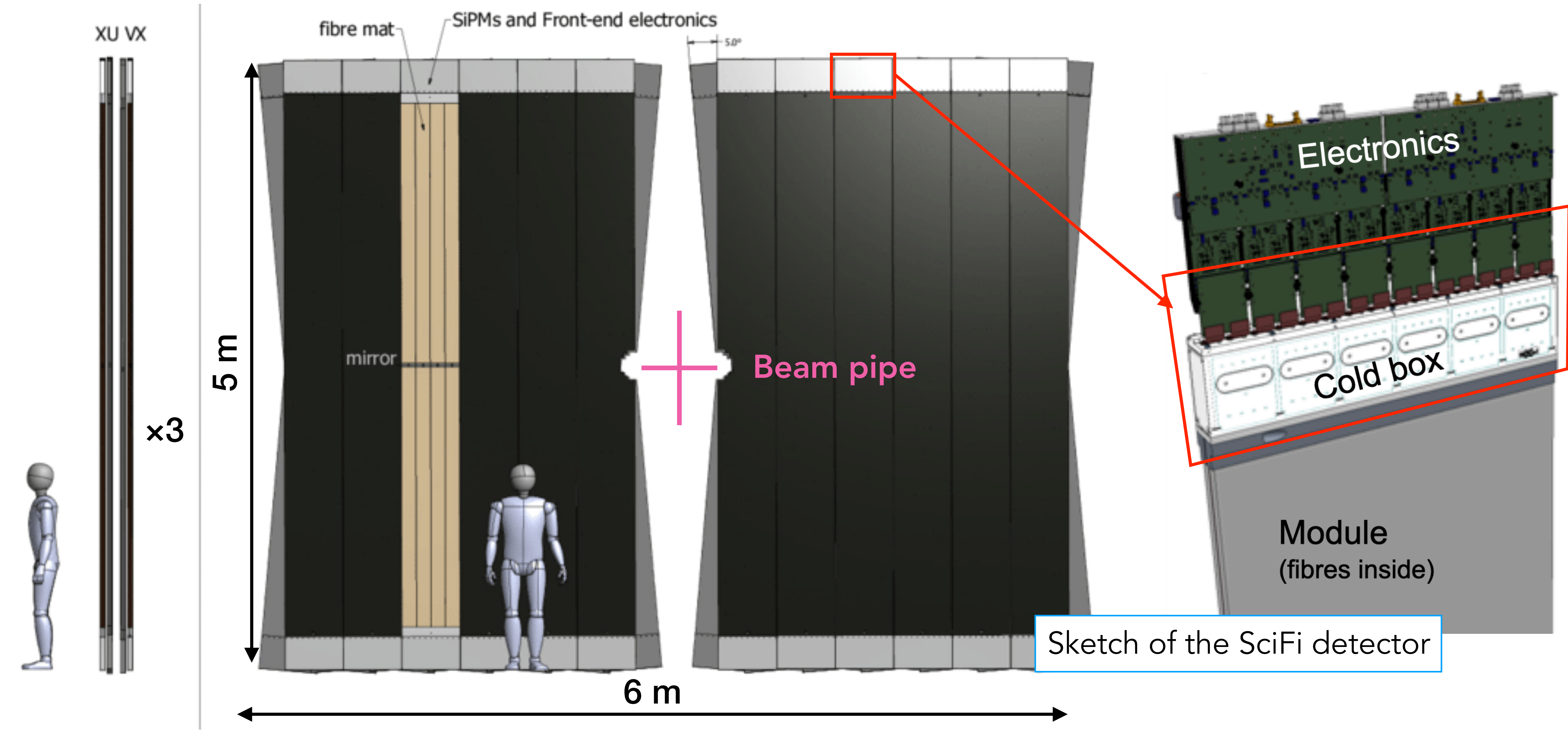
LHCb Upgrade design - detail



SciFi TDR: CERN-LHCC-2014-001

- Replace two technologies with a single one for a total area of 320 m^2
- $X/X_0 \leq 1\%$ per detection layer to limit multiple scattering
- Hit detection efficiency over 98% until the end of the lifetime
- Single hit spatial resolution in the bending plane of the magnet ≤100 μm
- Noise rate at any location < 10% of the signal
- 10 years to collect an integrated luminosity up to 50 fb^{-1}

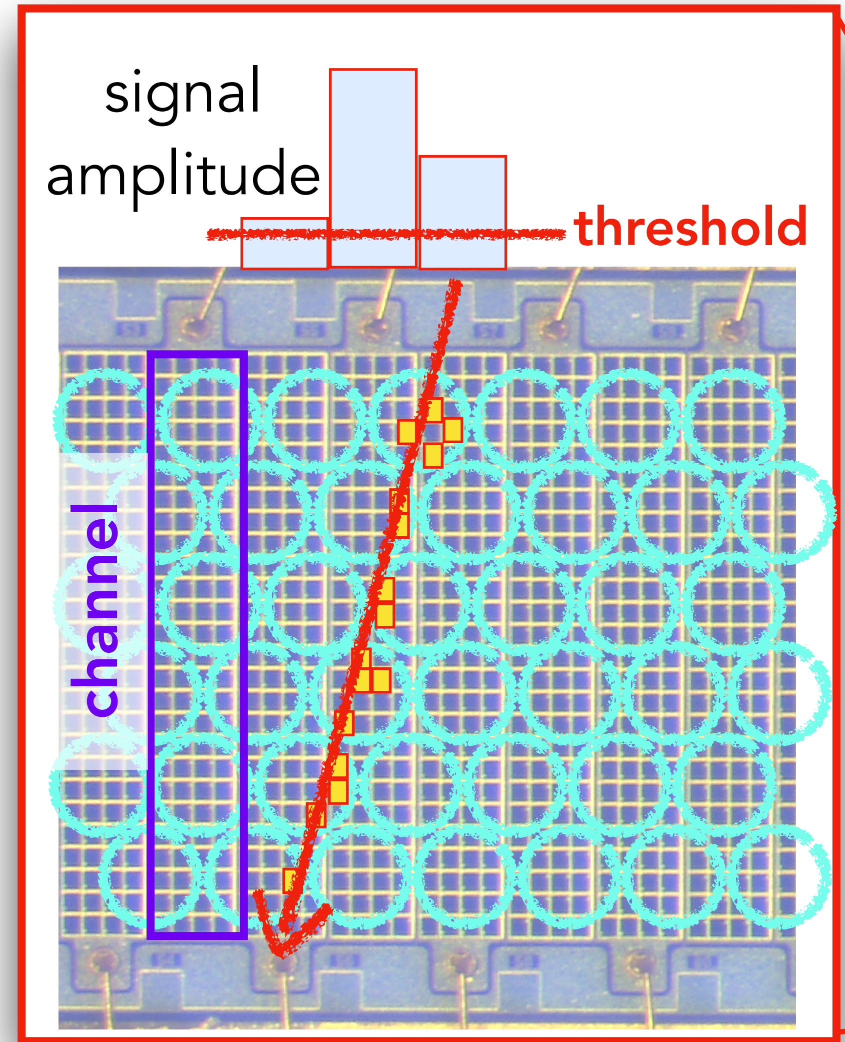
The scintillating fibre (SciFi) tracker



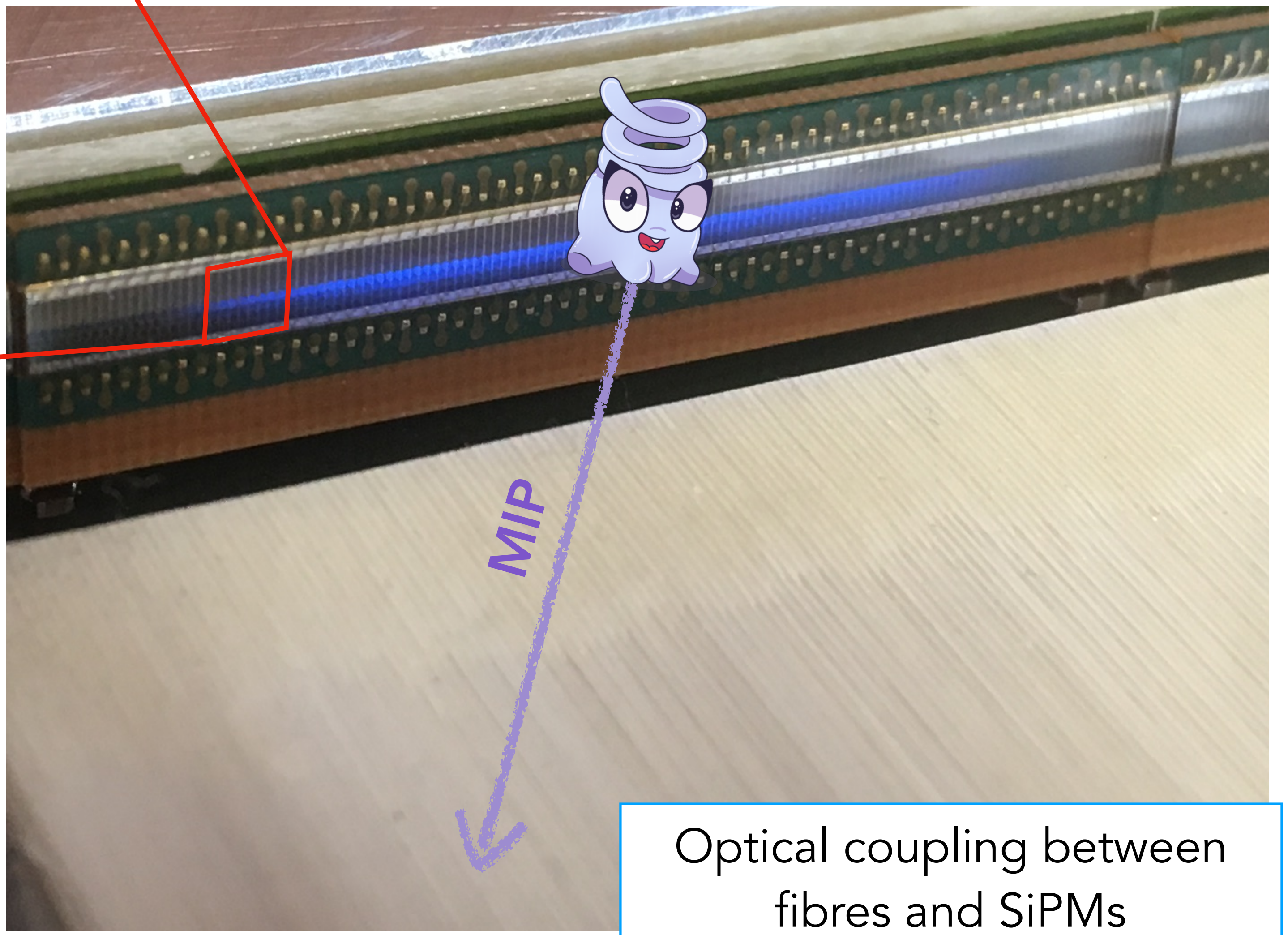
Sketch of the SciFi detector

- 5° stereo angle for ghosts
- 4500 SiPMs (> 500k channels of 250 μm)
- Total fluence at the end of life up to $6 \cdot 10^{11}$ 1MeV n_{eq}/cm^2
    - Cold operation @ -40°C

Working principle



- Ionising particle traversing fibres produces scintillation light
- 10% of the light produced is captured in the fibres
- Fibres staggered wrt channels

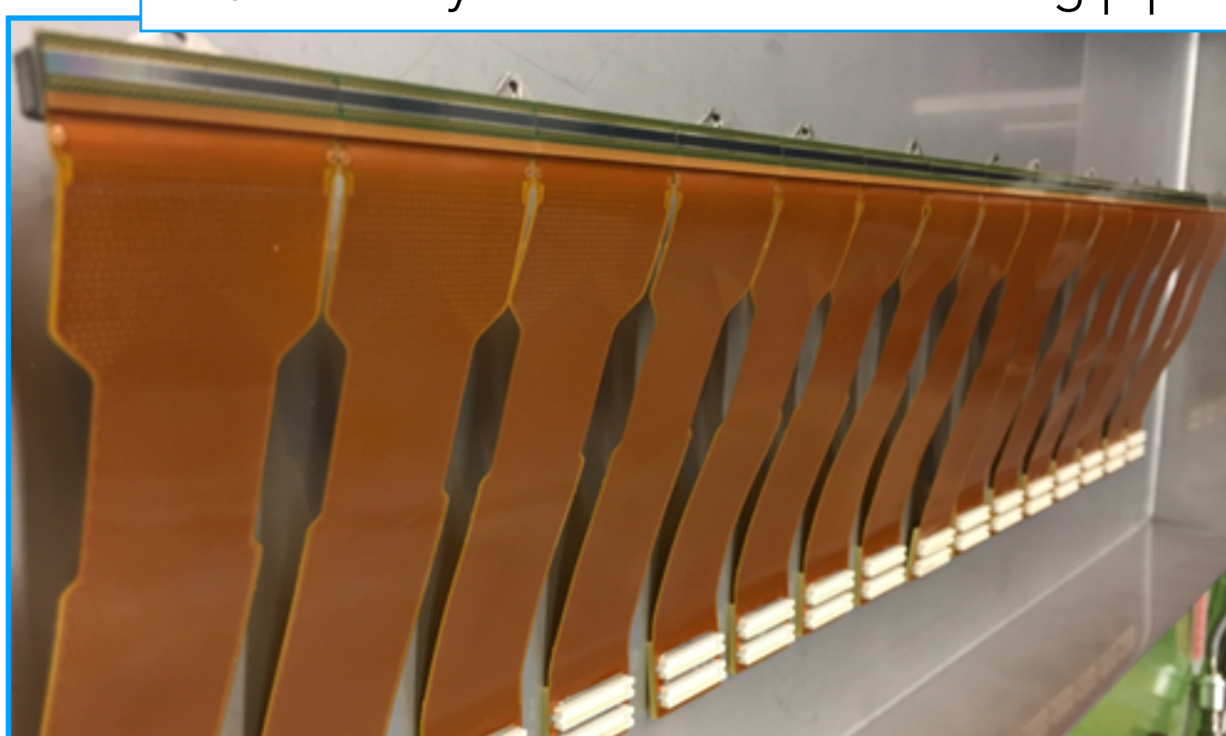


Optical coupling between fibres and SiPMs

- Photons will be detected in 2-3 channels
- Clustering performed with a threshold system

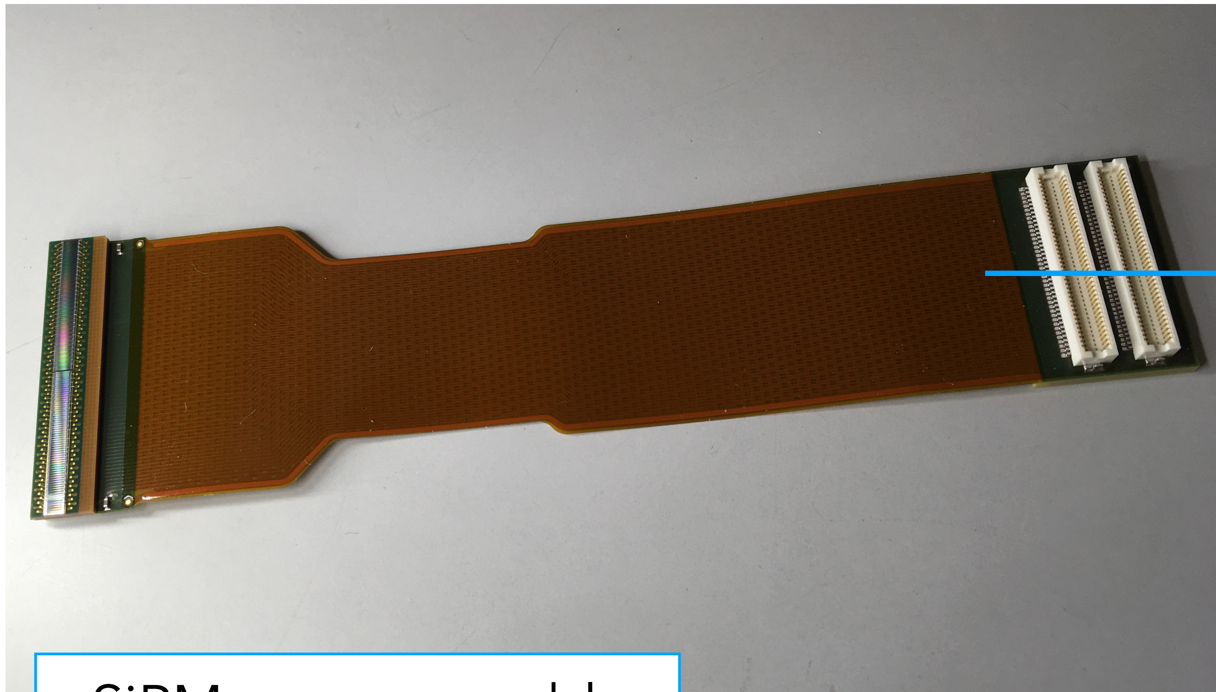
SiPM assemblies modularity

SiPM arrays mounted on the cooling pipe



- **SiPM arrays** will be glued in groups of **16 on a common cooling pipe**
- The distance from the fibres determines the spread of the light in channels (cluster size and occupancy)
  - Thickness uniformity after glueing has to be better than 100 µm
- **One power supply** for group of **four**
  - Breakdown voltage has to be better than 700 mV to allow compensation and insure a uniform response
- **Temperature** will **drop** from -40°C to room temperature on the flex

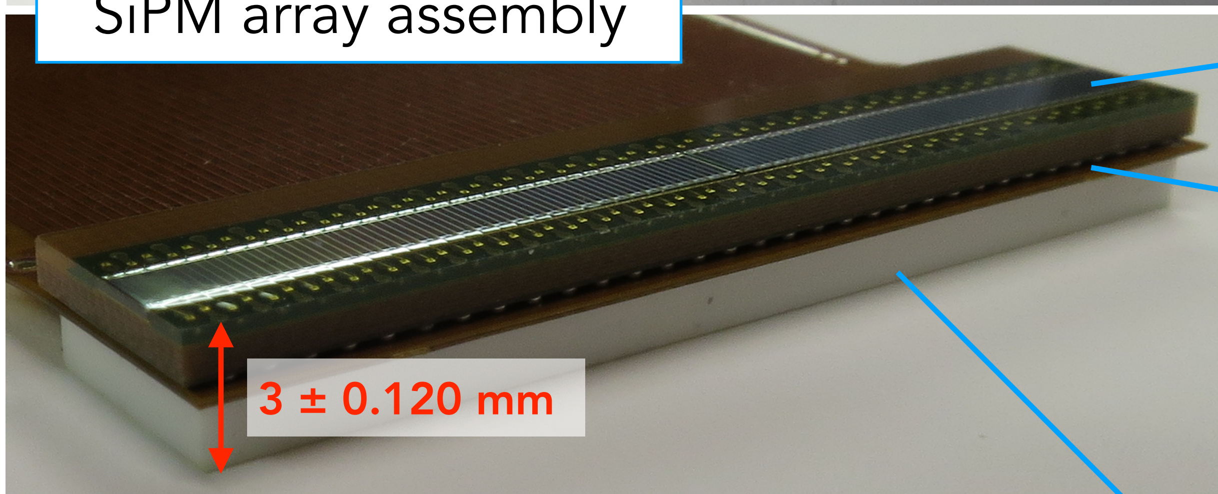
Silicon Photomultiplier assembly



Flex PCB

- Highly flexible
- Capable of dissipating 60°C
- Robust to vibrations during the installation

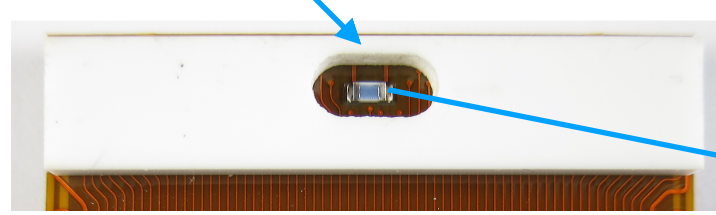
SiPM array assembly



SiPM array Hamamatsu S15532

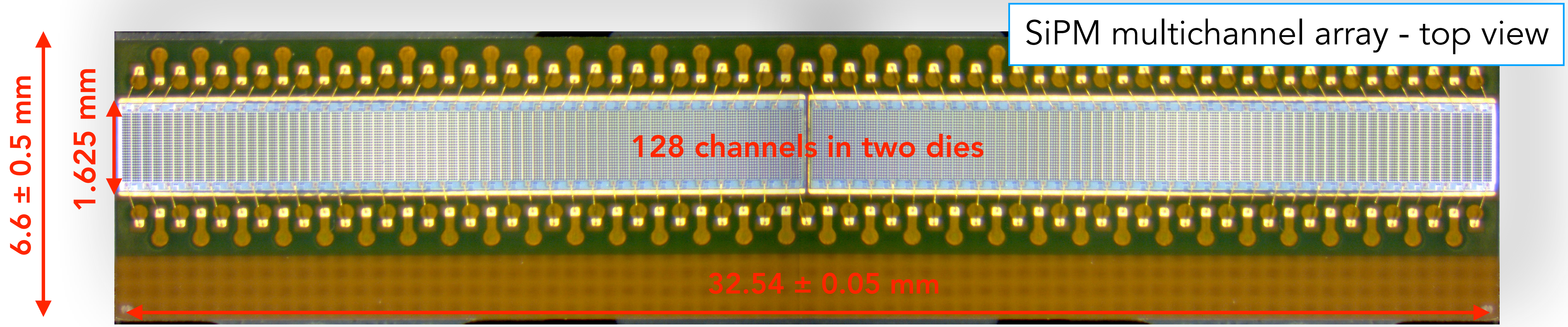
Laser balling

Ceramic stiffener with high conductivity



Temperature sensor: PT1000

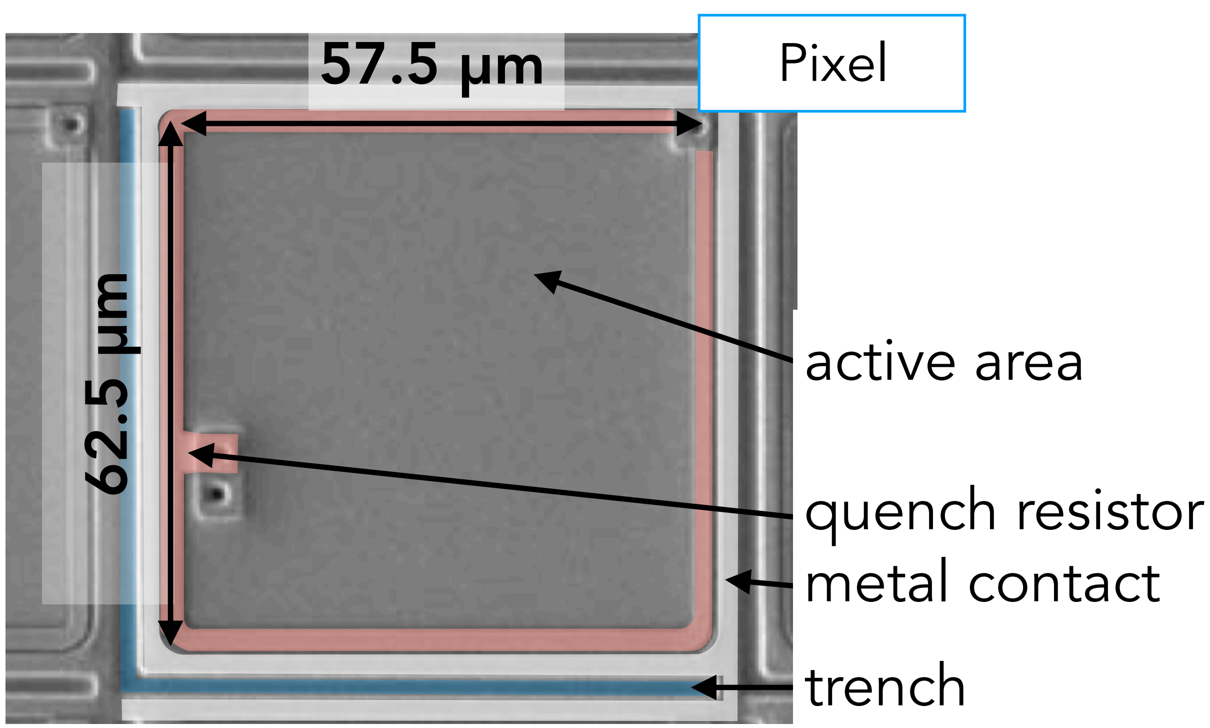
SiPM packaging

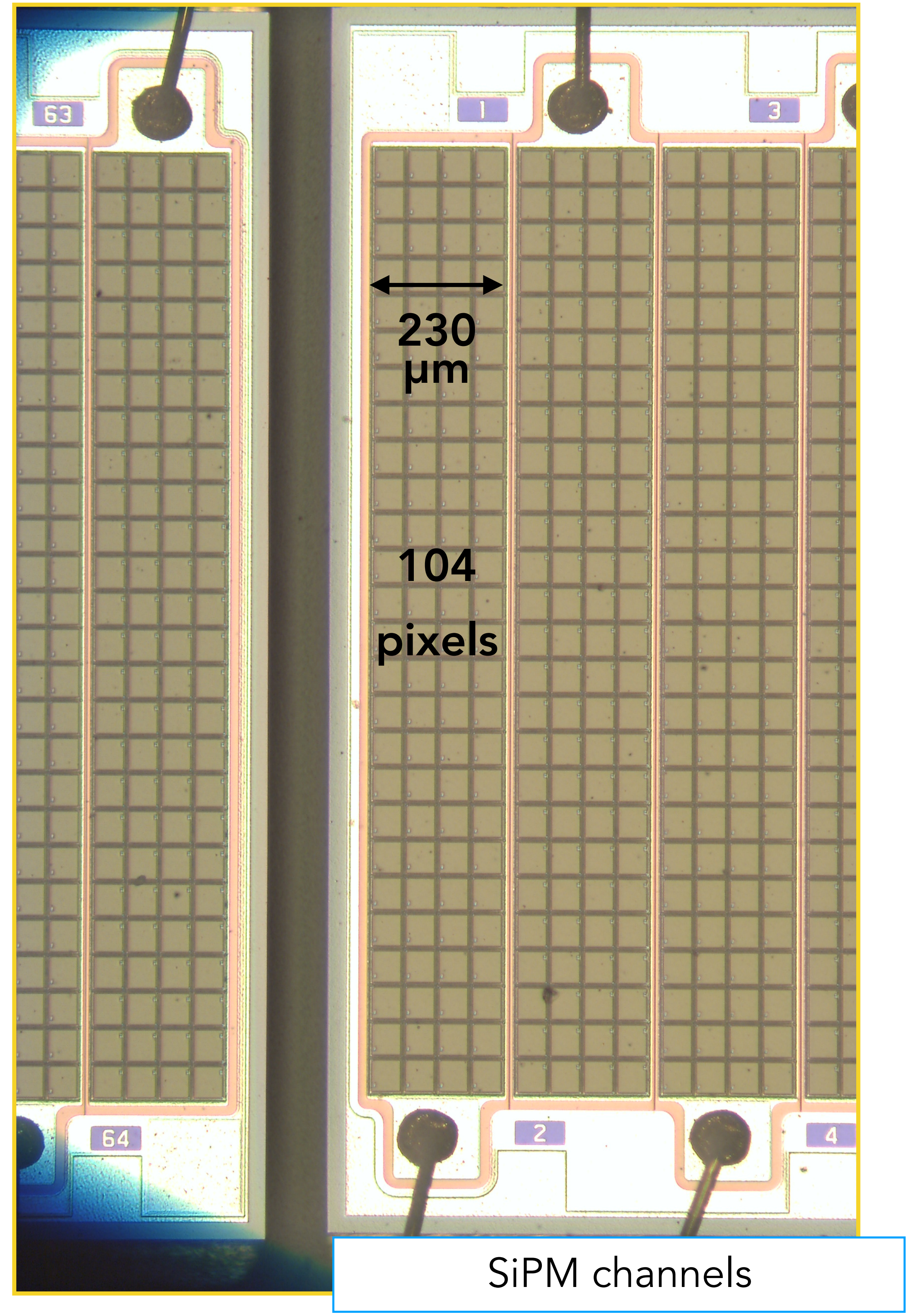


- Balance between aspect ratio to avoid bending and minimum amount of dead regions
- Height of the channel sufficient to cover 6 layers of fibres
- 105 μm entrance window to reduce the light spread
- Channel size ~250 μm

SiPM functional parameters

- Balance between dynamic range and fill factor
- Low correlated noise
    - quench resistor: 510 ± 50 kΩ
    - deep trenches
- Peak sensitivity ~450 nm
- Gain ~ 1.1 x 10^6 e/V



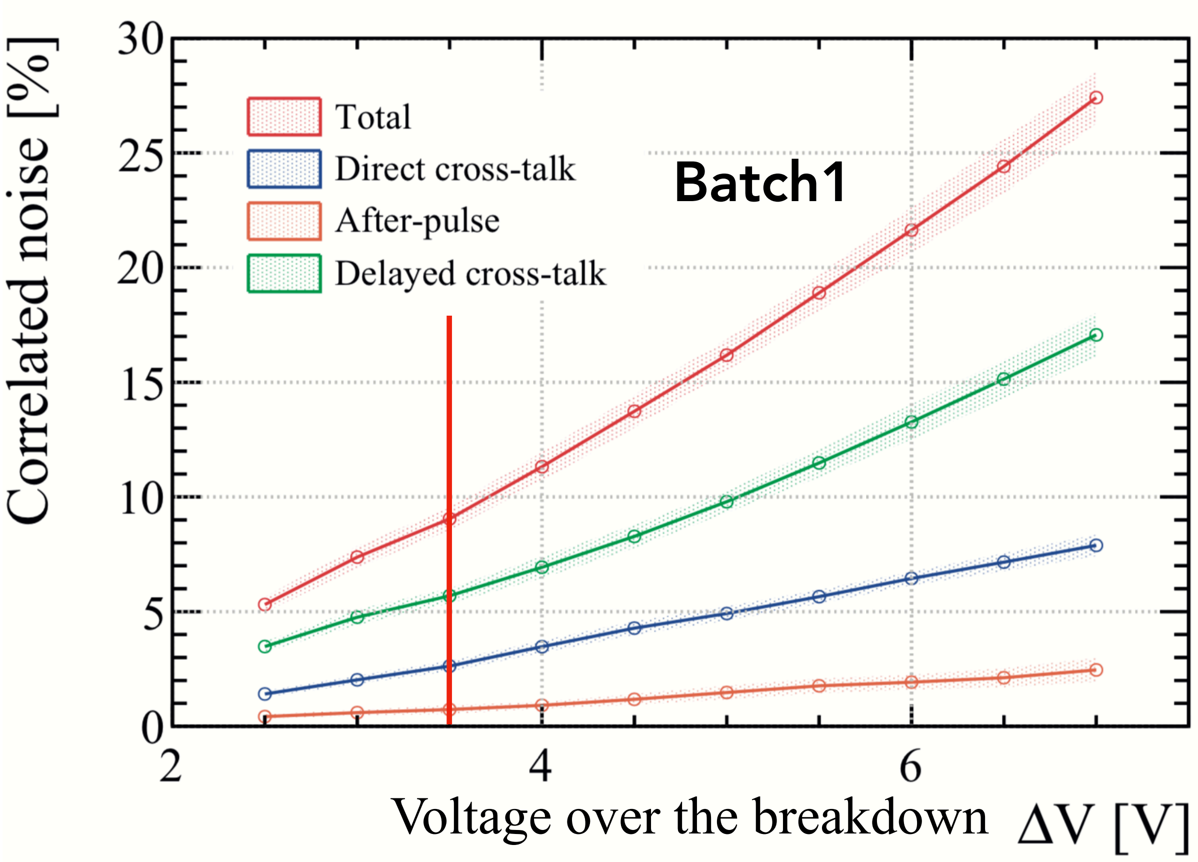


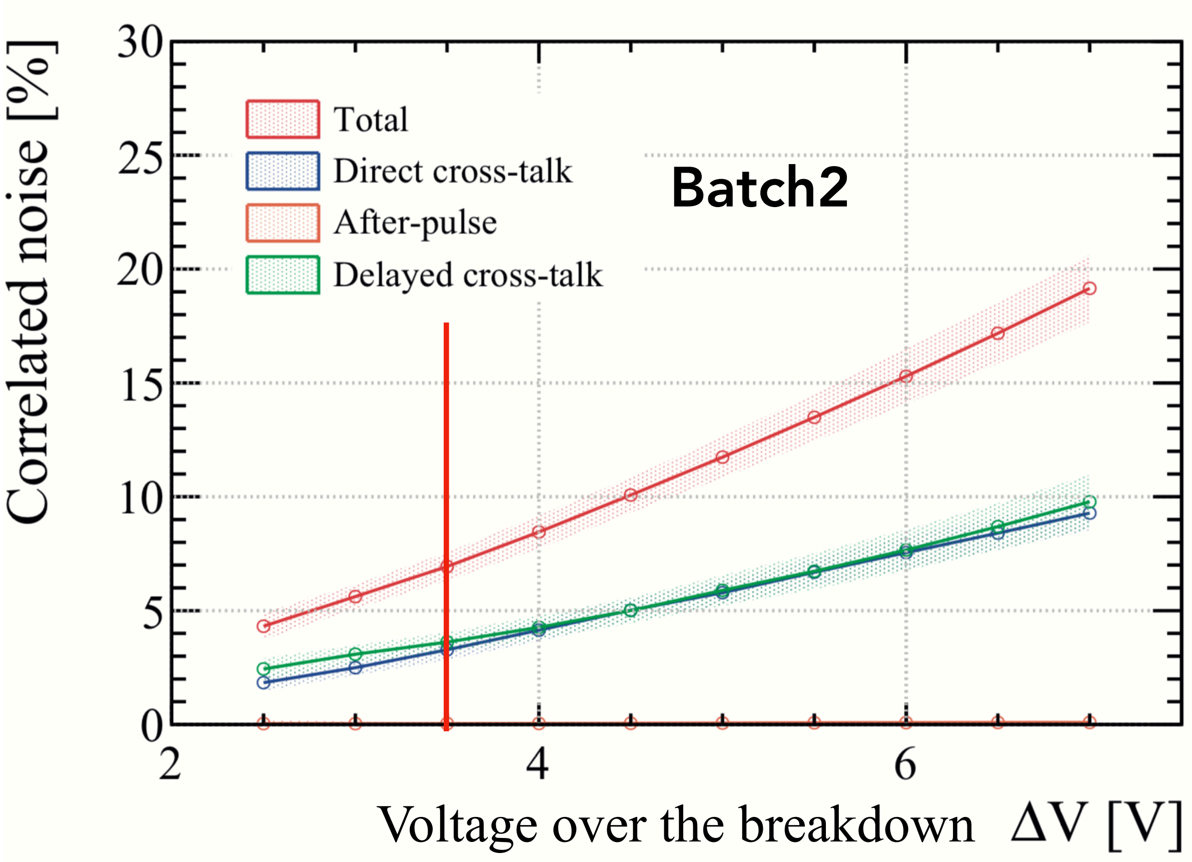
SiPM characterisation

SiPM array and assembly characterisation

- **Mechanical** stress tests
- Long thermal cycles to test **ageing** of the detectors
- **Electrical** and **functional characterisation** (more by Carina Trippl)
- **Irradiation** studies
- **Test beam** campaigns

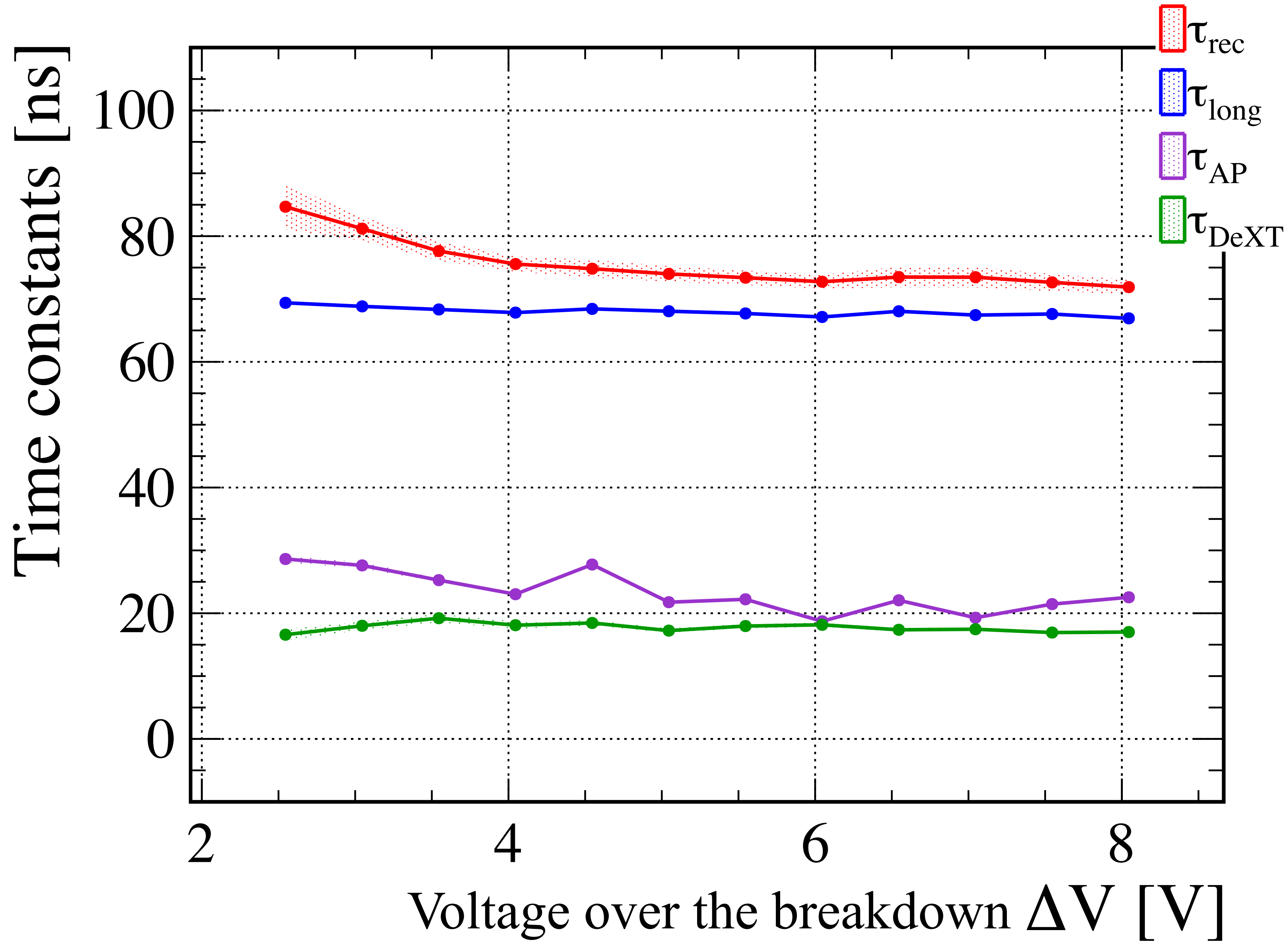
Correlated noise





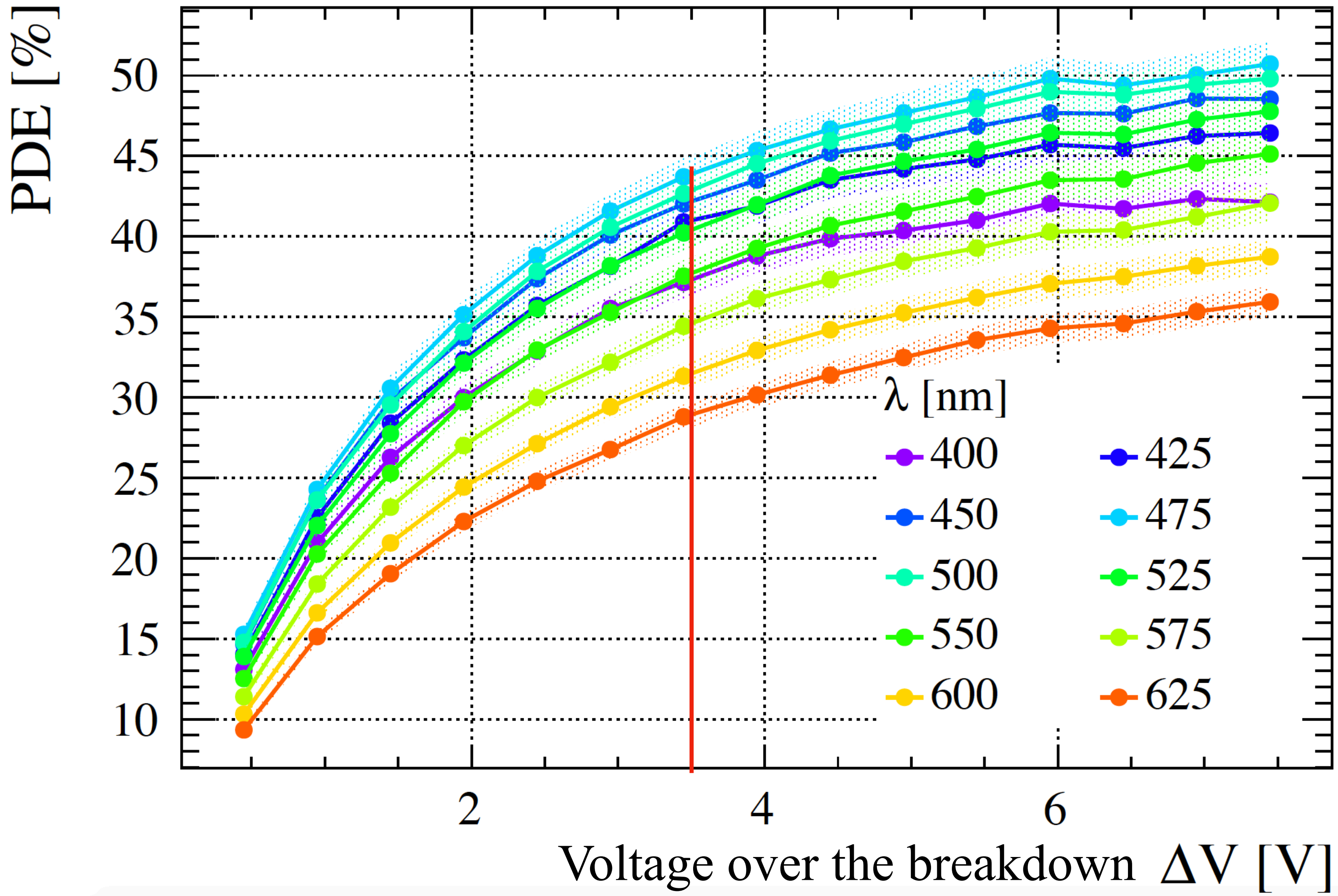
- Correlated noise measured at 22°C
- At benchmark operation point (3.5V overvoltage) lower than 10%
- Batch1 detectors are more noisy, but they correspond to 10% of the production

Time constants



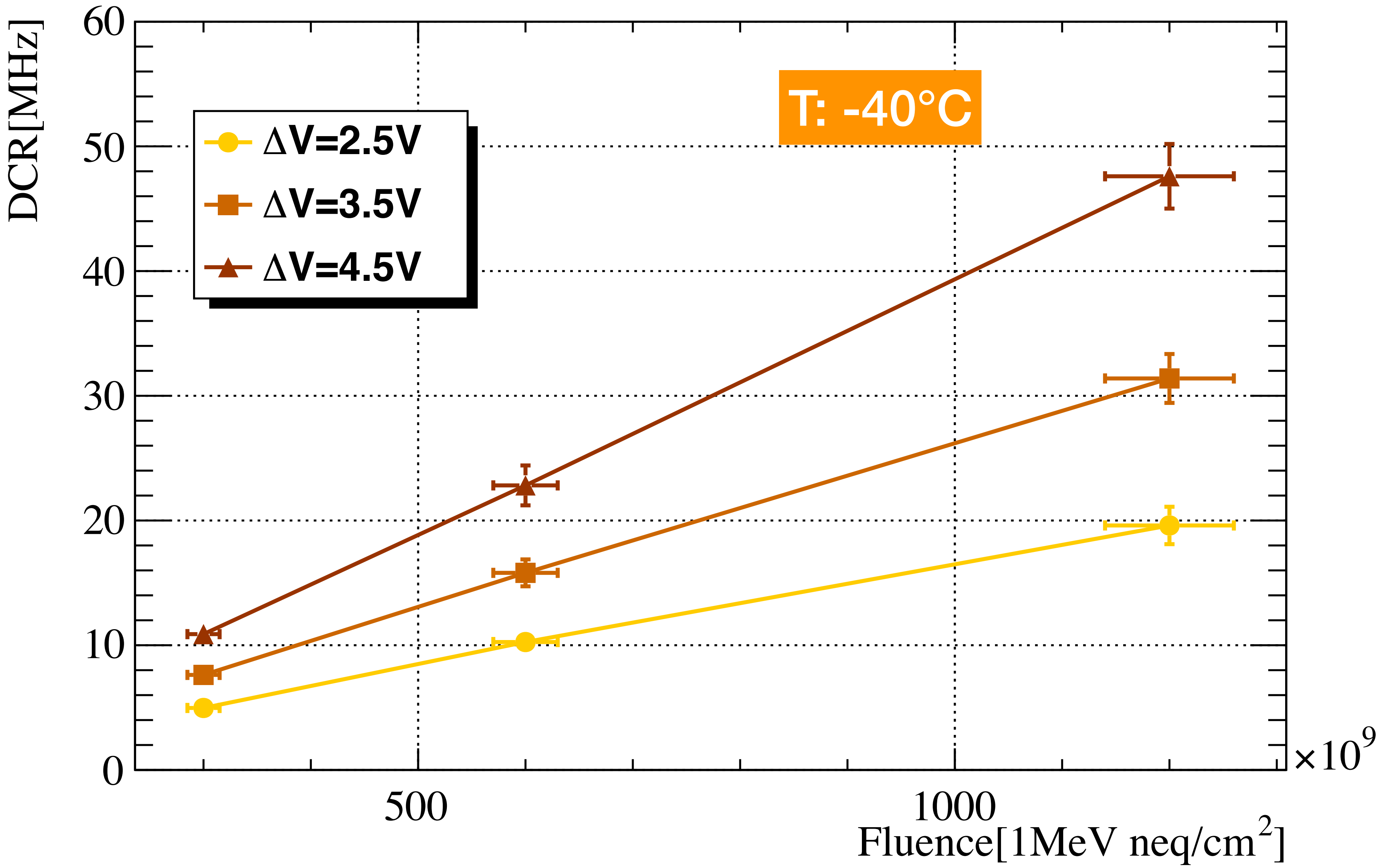
- Recovery time: pixel recovery time constant
- Long component time constant: decay constant measured in single pulse events
- After-pulse and average effective lifetime and delayed cross-talk average effective lifetime: time constants describing the occurrence of a given pulse typology in time

Photo-detection efficiency



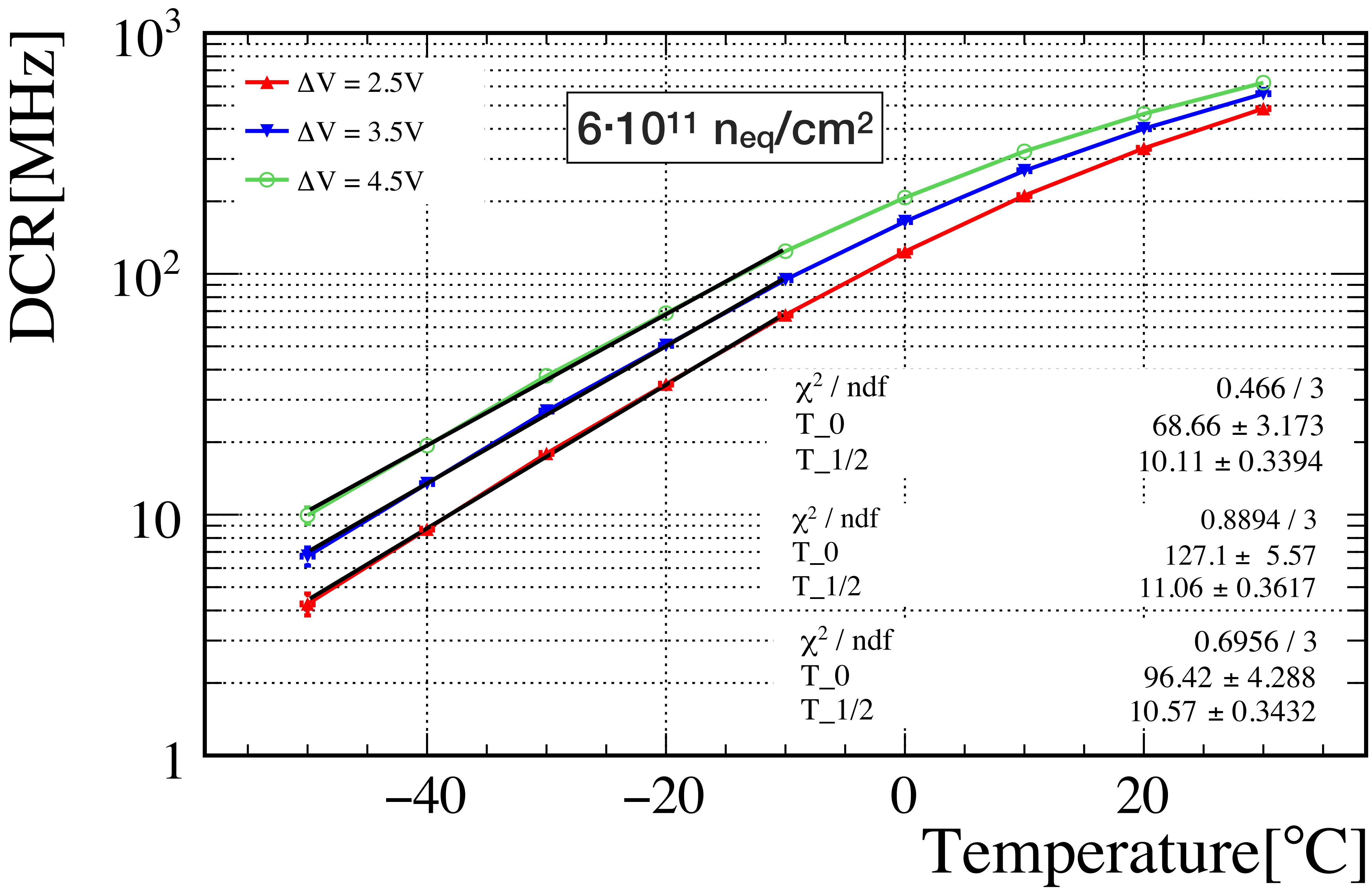
- Assuming an MPV of the energy deposit distribution equal to 12 photo-electrons (expected after irradiation)
- Considering a threshold for noise rejection of 4.5 photo-electrons as noise level
- We have a signal to noise ratio of 2.7

Irradiation effects



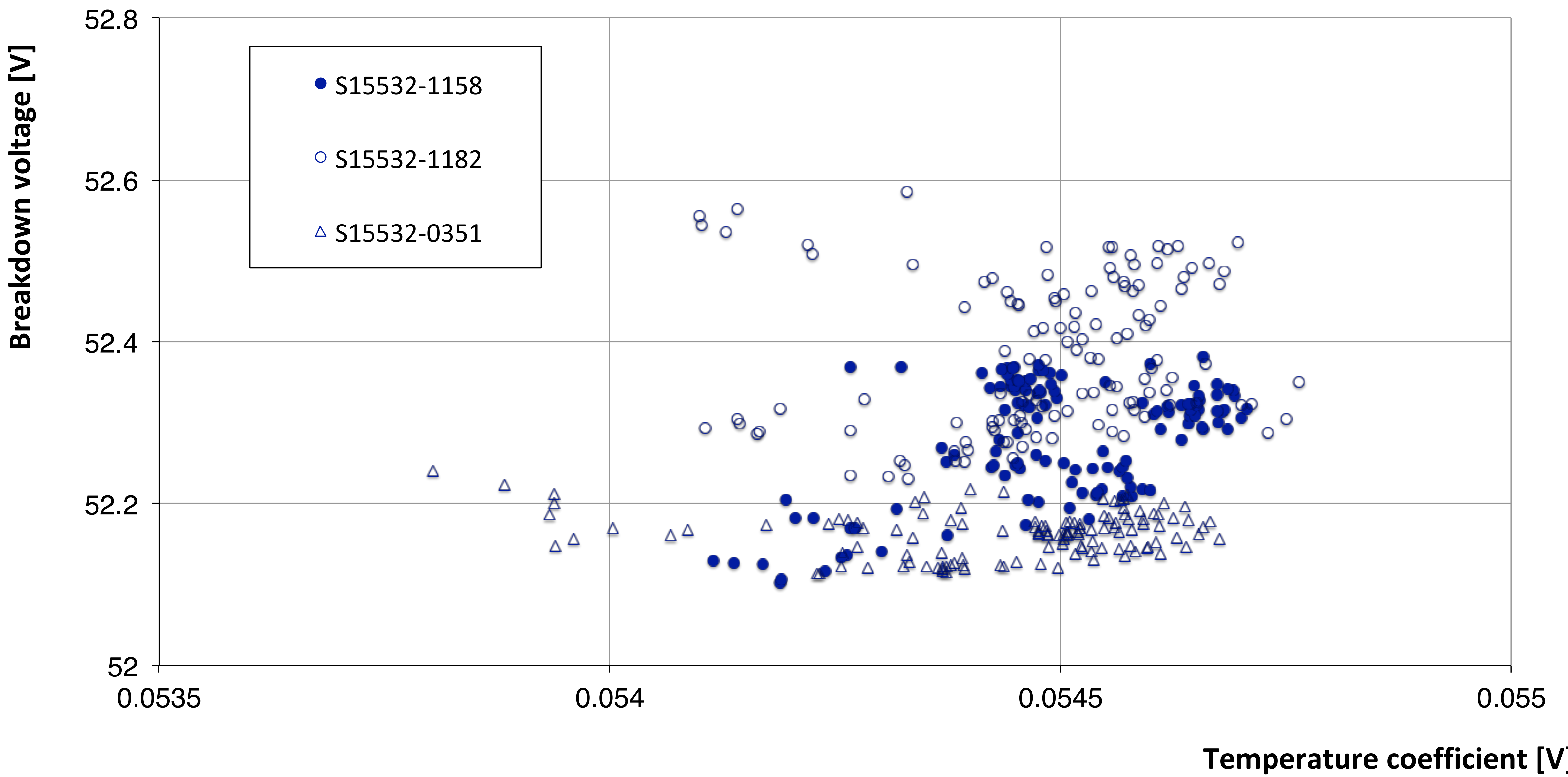
- Dark count rate reaches 14MHz at 3.5V with the expected radiation fluence
- With a recovery time (~70ns), and an occupancy of 4 clusters per event (40MHz), this leads to less than 2% inefficiency

Temperature effect on DCR



- The **DCR is reduced of a factor 2 every 10 degrees** with temperature decrease
- Operation at -40°C avoids **saturation effects**

Other temperature dependencies

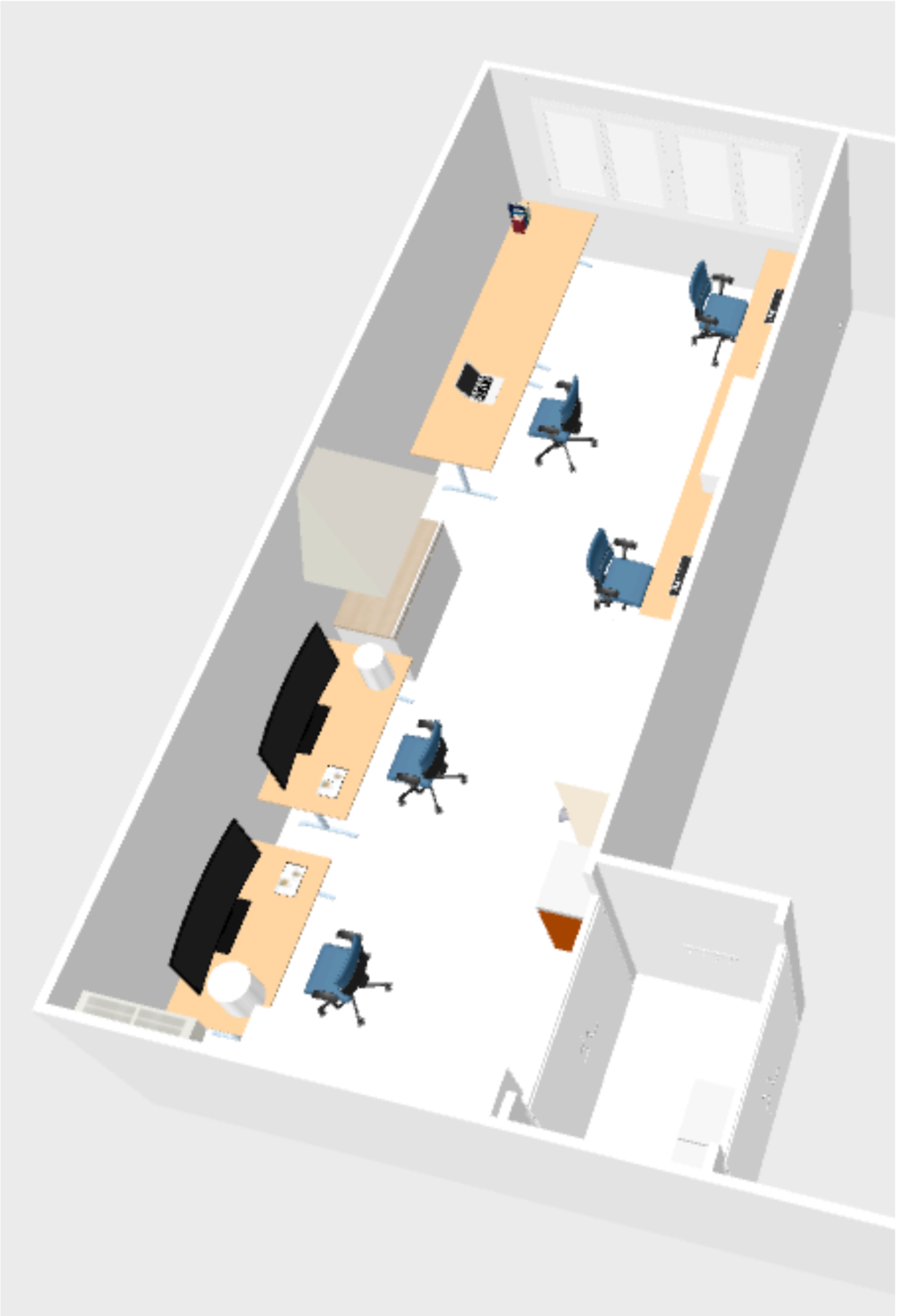


- **Temperature coefficient**: +54 ± 1.5 mV/K
- The **quench resistor** temperature dependence is −3 ± 1 kΩ/K

SiPM assemblies production

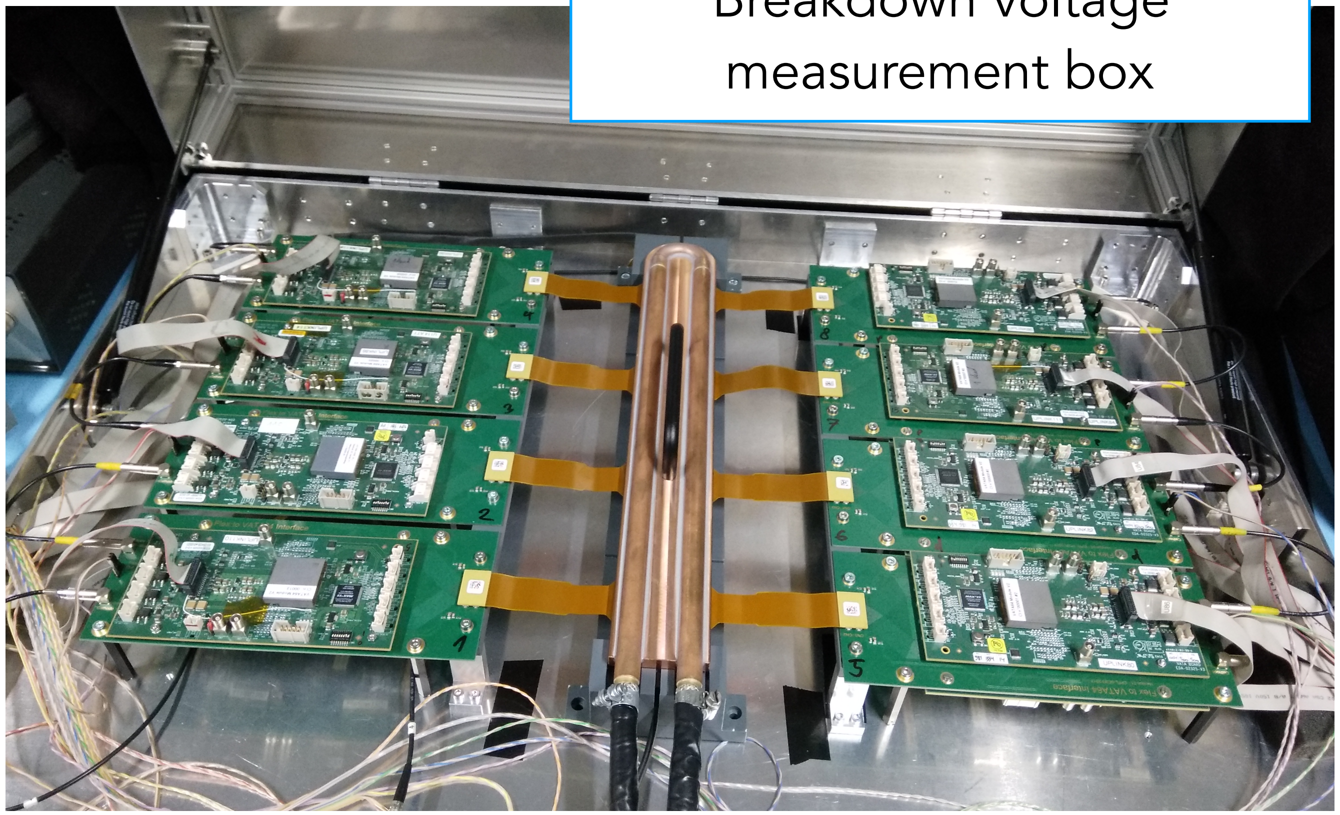
Production and quality assurance

- **Optical inspection** at EPFL on the SiPM **array** package before and after balling
- **Electrical tests** at the assembly partner and thermal cycling to detect and provoke infant mortality
- **Electrical characterisation** of all channels
- **Thickness** measurement at the SiPM side of all assemblies
- **Optical inspection** and cleaning of the final **assembly**
- **Grouping** of the assemblies



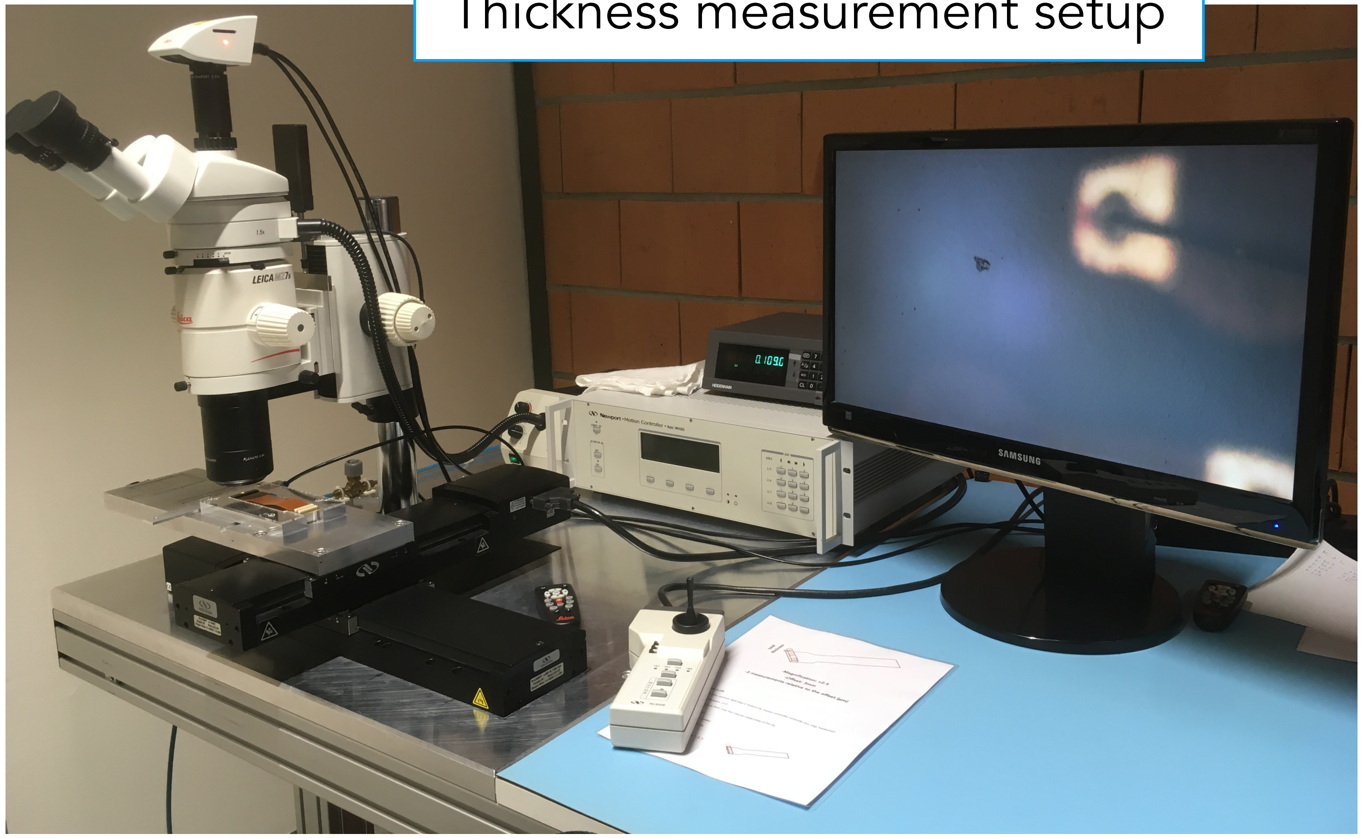
CAD design of grey room

Tests setup



Breakdown voltage measurement box

- Measurement of **breakdown voltage in all channels**
    - grouping purposes
    - not possible with the final read-out!!!
- 1024 channels tested in parallel



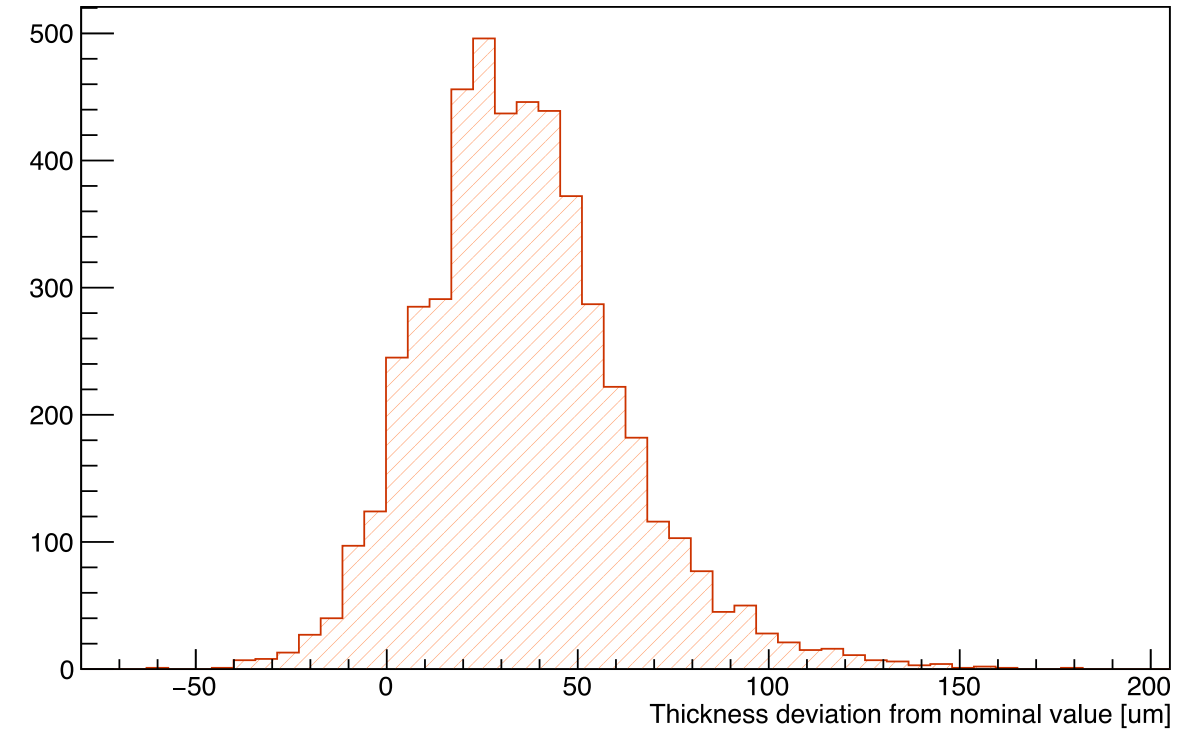
Thickness measurement setup

- **Non invasive** measurement of the **thickness**
- Precision of ± 10 μm

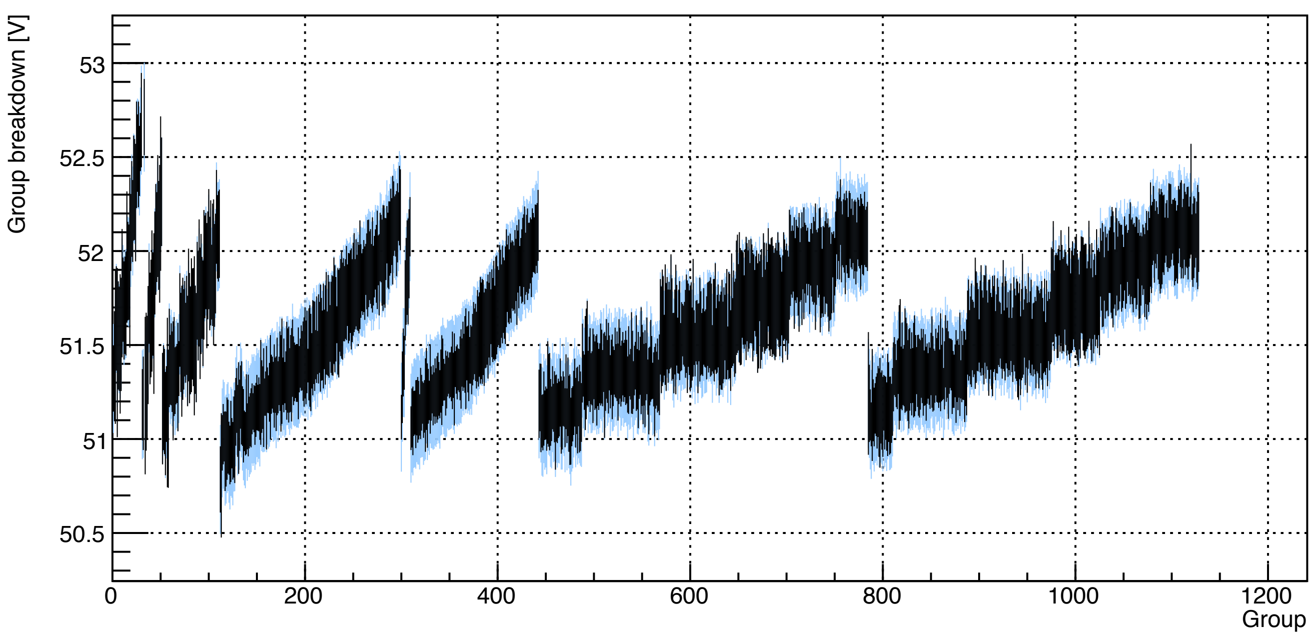
Uniformity

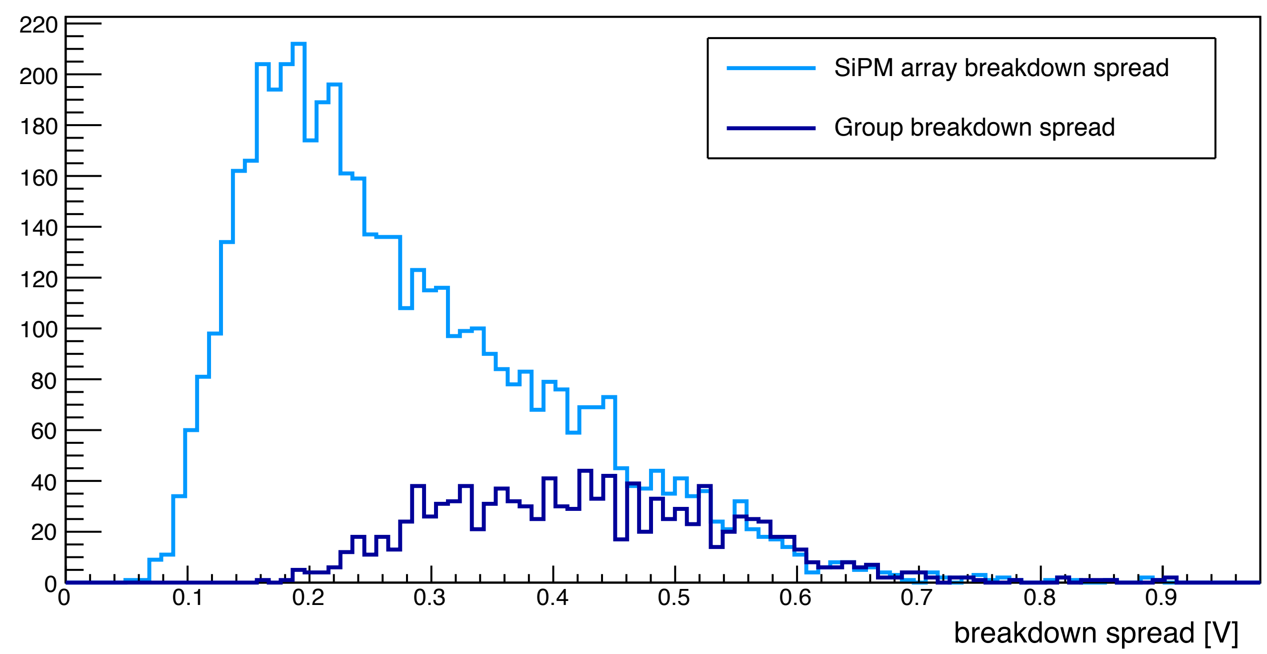
- 1128 groups with thickness variations < 100 μm and total VBD spread < 0.7 V
  - The breakdown spread stays within 0.7 V, most of the times within 0.580 V (full read-out compensation)
  - The max groups spread is compatible with the max single SiPM spread

Thickness

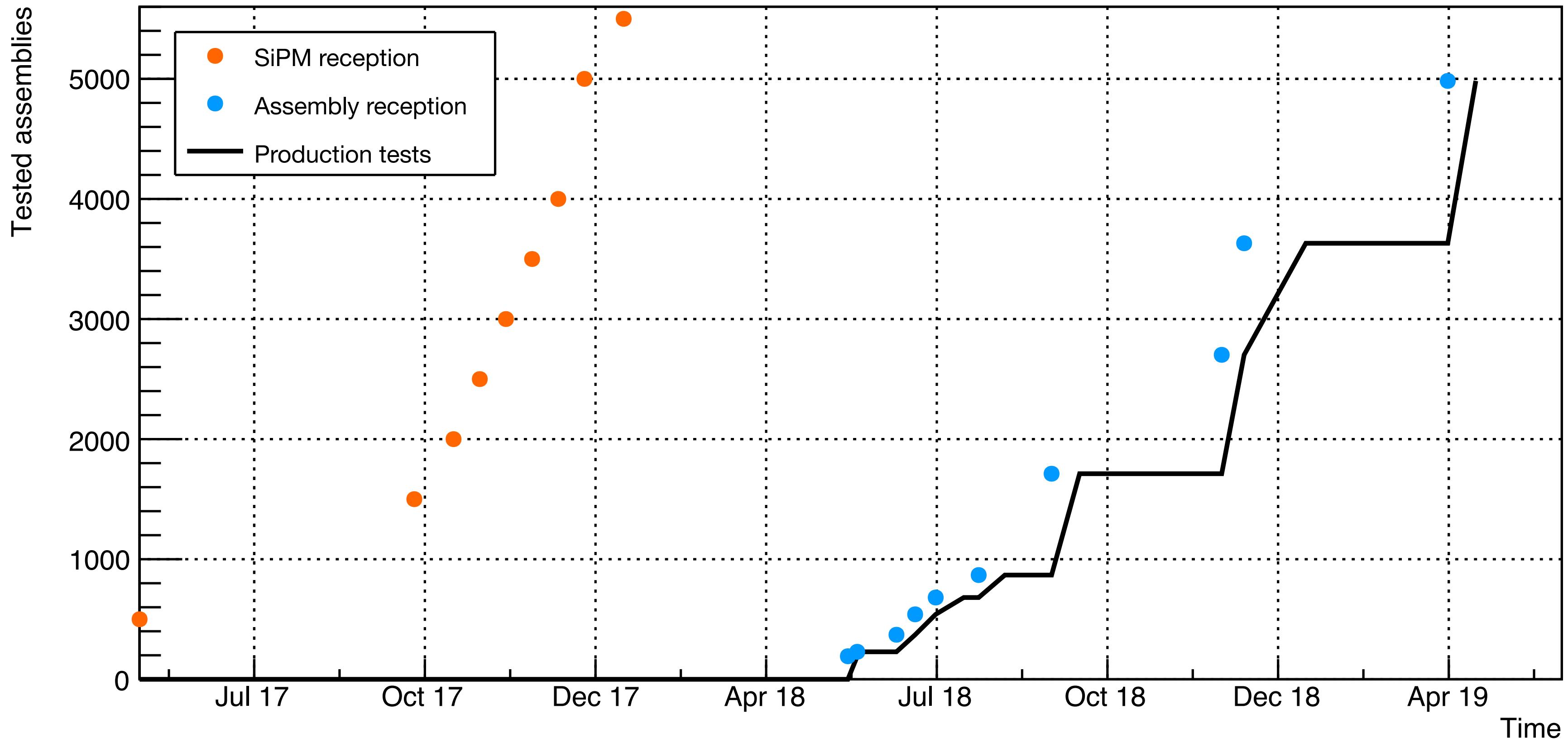


Breakdown voltage



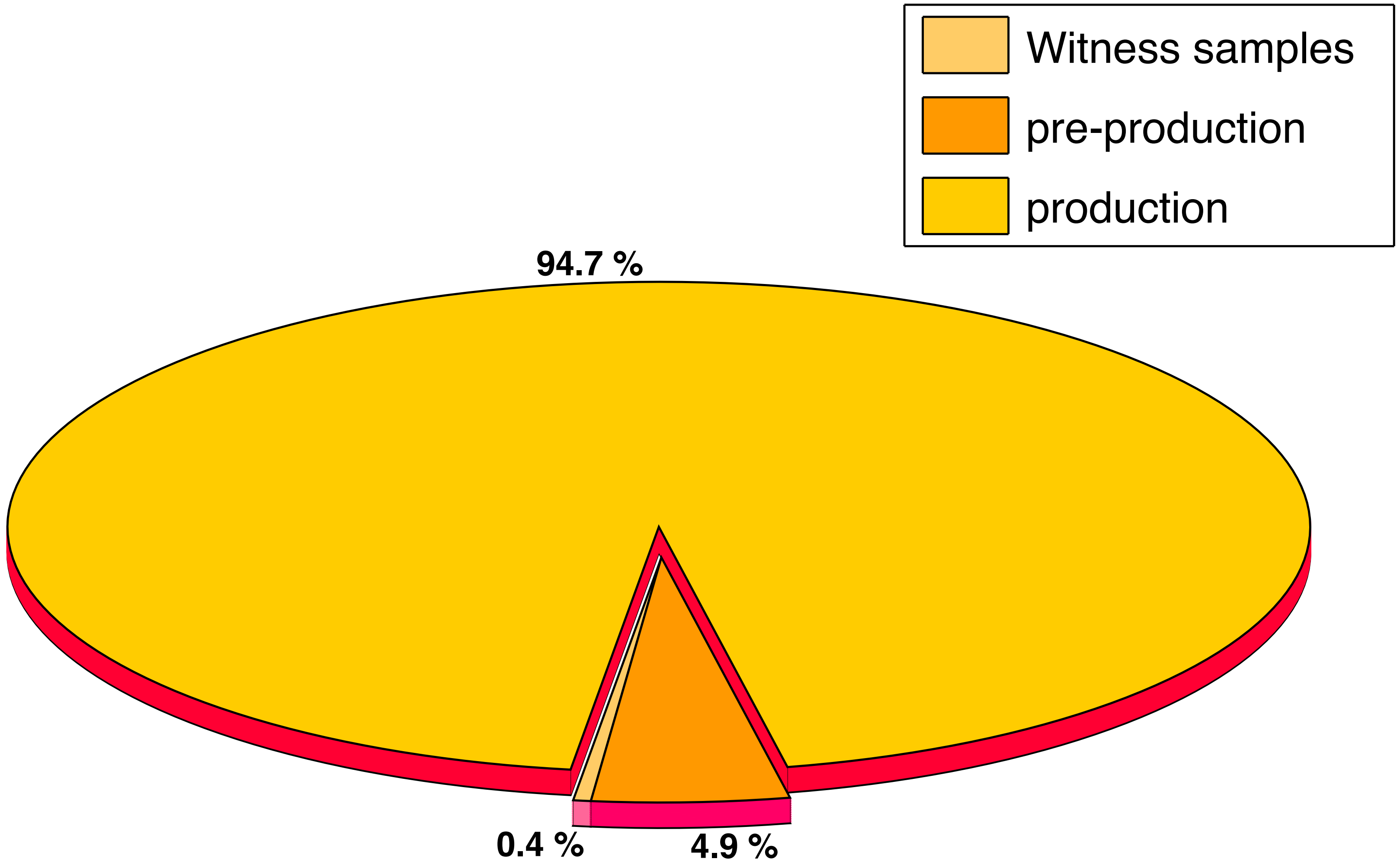


Some statistics: Production trend



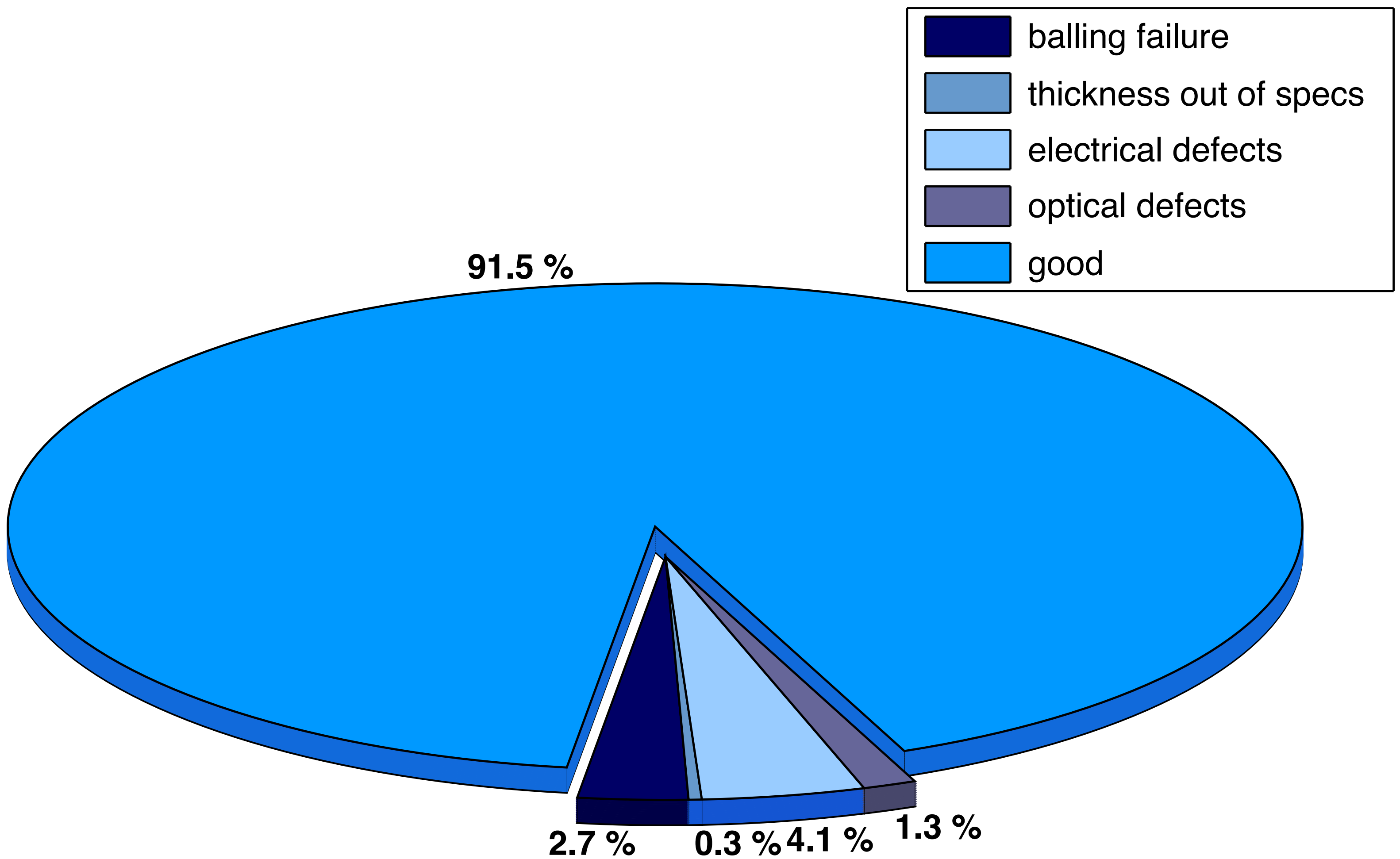
1. Bare SiPMs received and tested
2. Laser balling, optical tests and cleaning
3. Assemblies received and tested
4. Deliveries were following the tests starting from one week after

Some statistics: Detectors employment



- 10% more bare assemblies received
- 0.4% witness samples
- 5% pre-production tests:
  - balling and assembly tests
  - irradiation, glueing and thermal tests, test beams, first cold bars …
- 95% production

Some statistics: Production yield

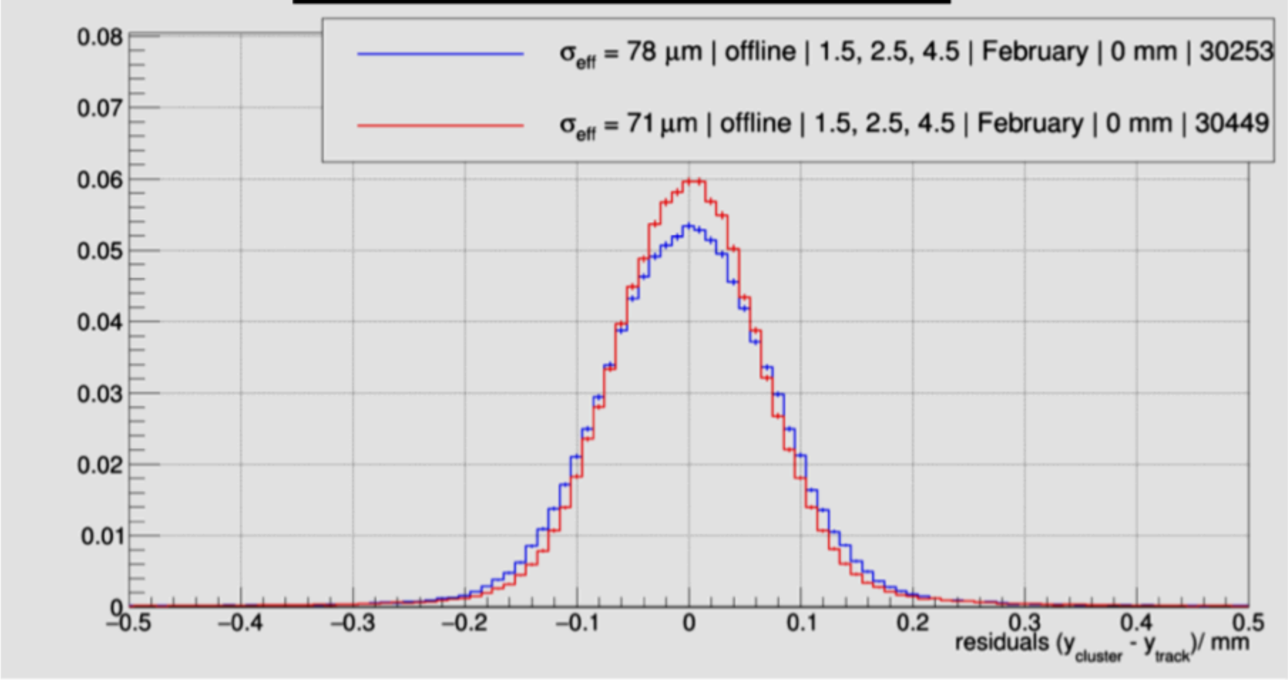


- 91.5% of final production yield, according to expectations
- The production yield improved from 85% to 99%
- Electrical defects due to connector and balling the major source of failure
- Only good SiPMs employed

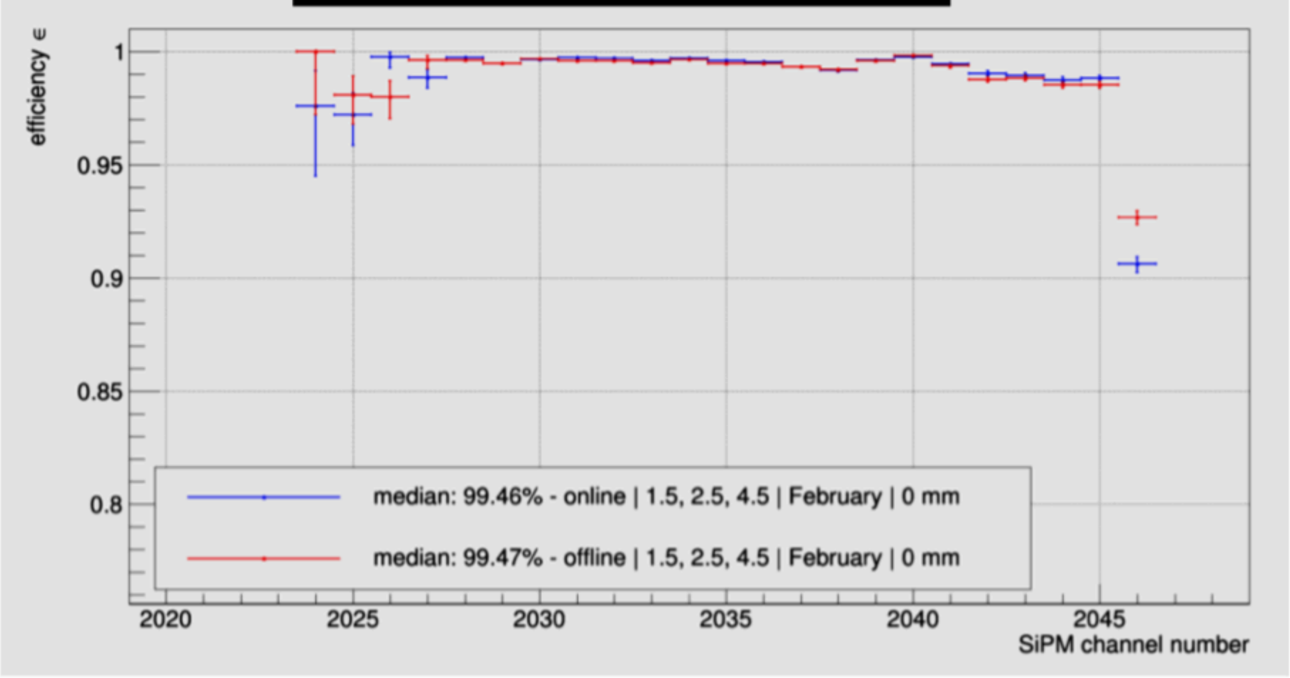
Test beam results

CERN test-beam, July 2018

Single hit resolution: 70-80 µm



Single hit efficiency: 99.5%



- Two final fibre modules tested
- Results in agreement with expectations!!!

From Lukas Gruber - VCI 2019

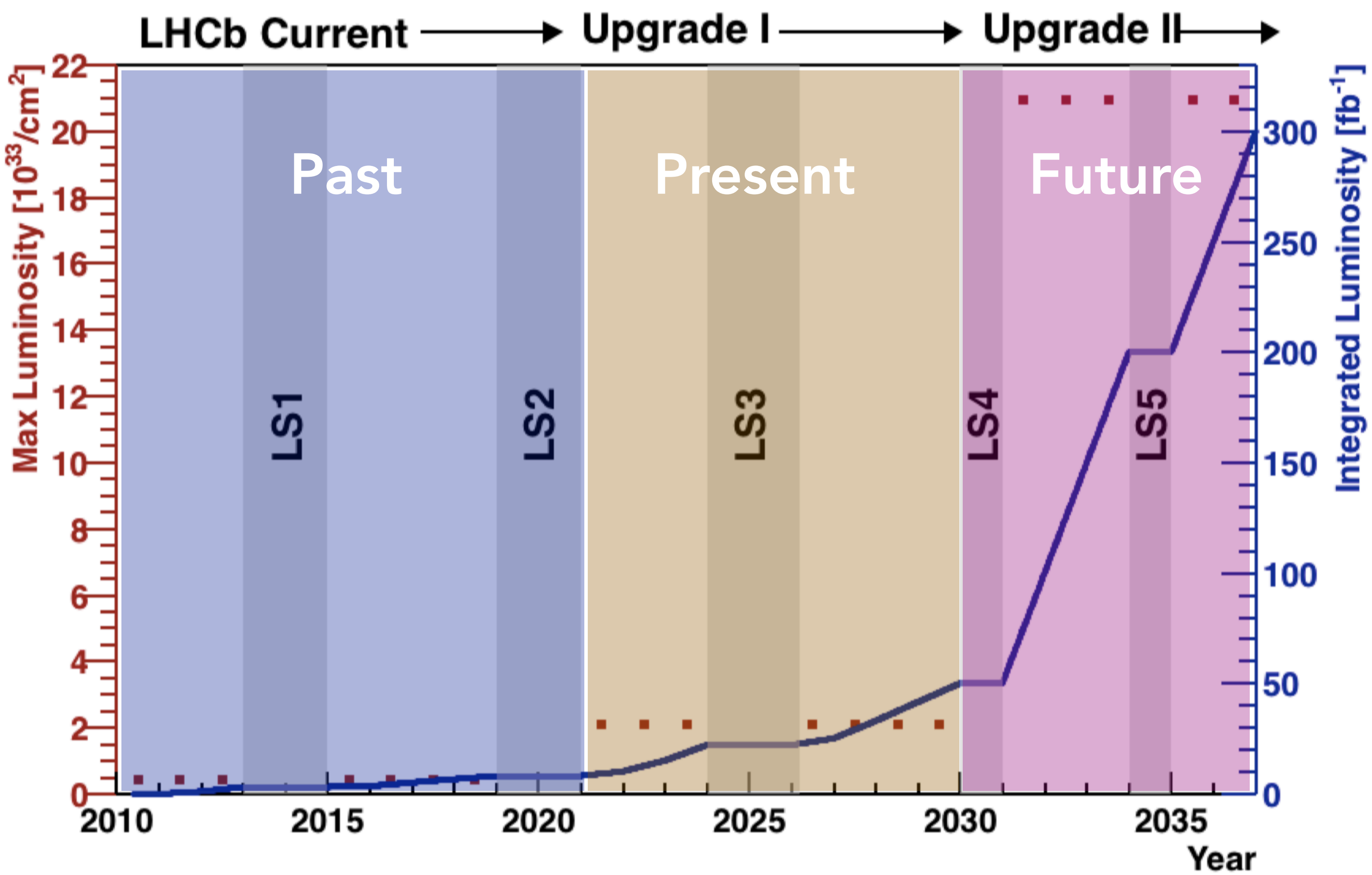
Integration and future upgrade

Integration status

First 1/4 of a sector

- Integration ongoing at CERN
- First read-out test and calibration performed with light injection system

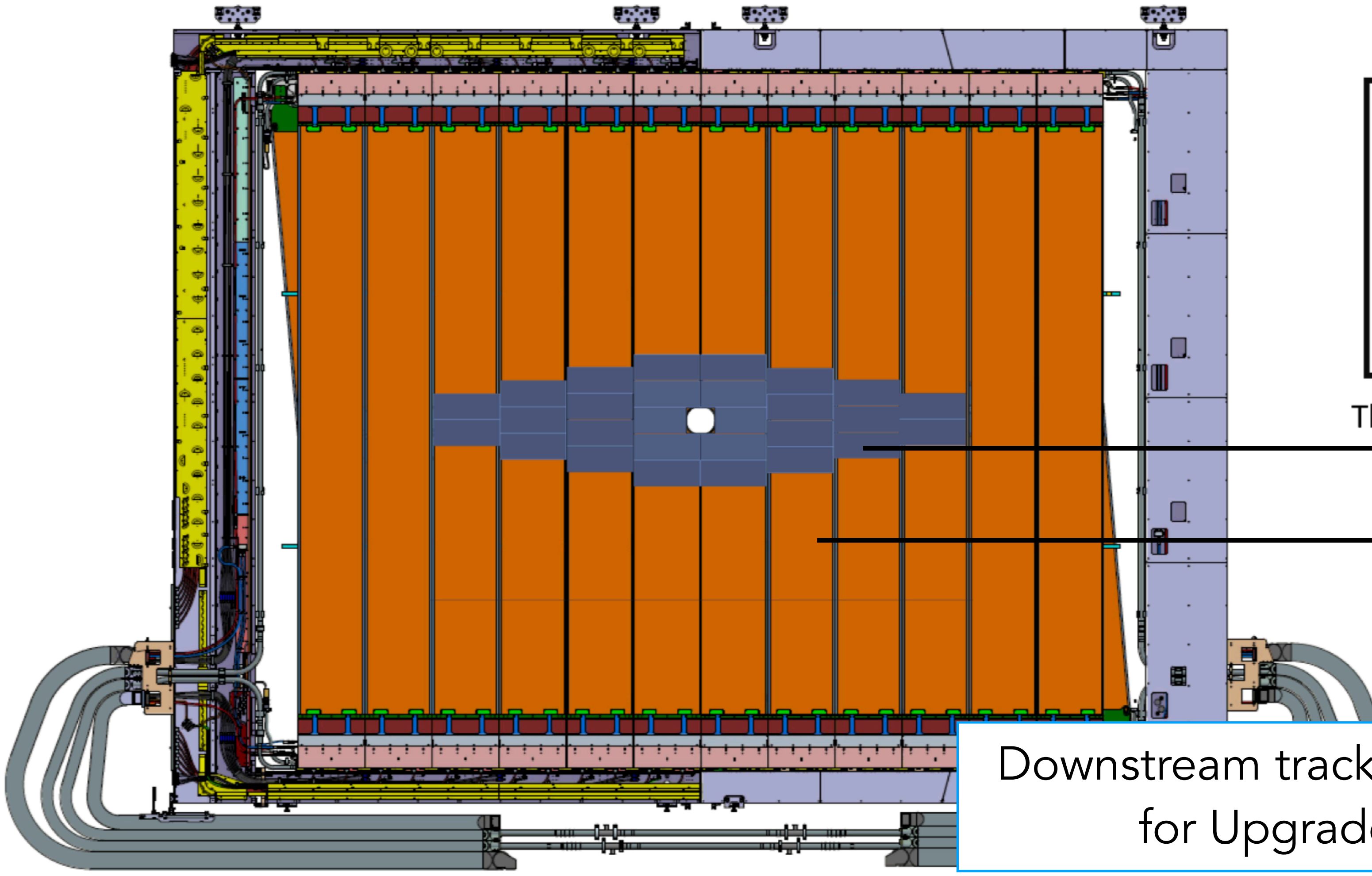
R&D for Upgrade II

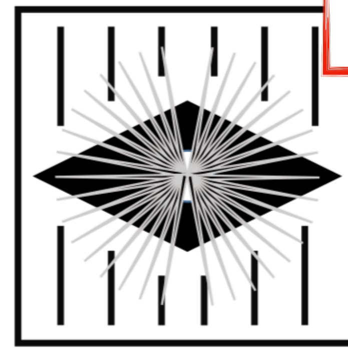


- Factor 10 in instantaneous and integrated luminosity, and irradiation level
- The occupancy increases a factor 10
- Fibres have a logarithmic light yield decrease, will soon have 40% of the light
- A new detector is needed

R&D for Upgrade II

From B. Leverington - SciFi 2 for LHCb Upgrade 2



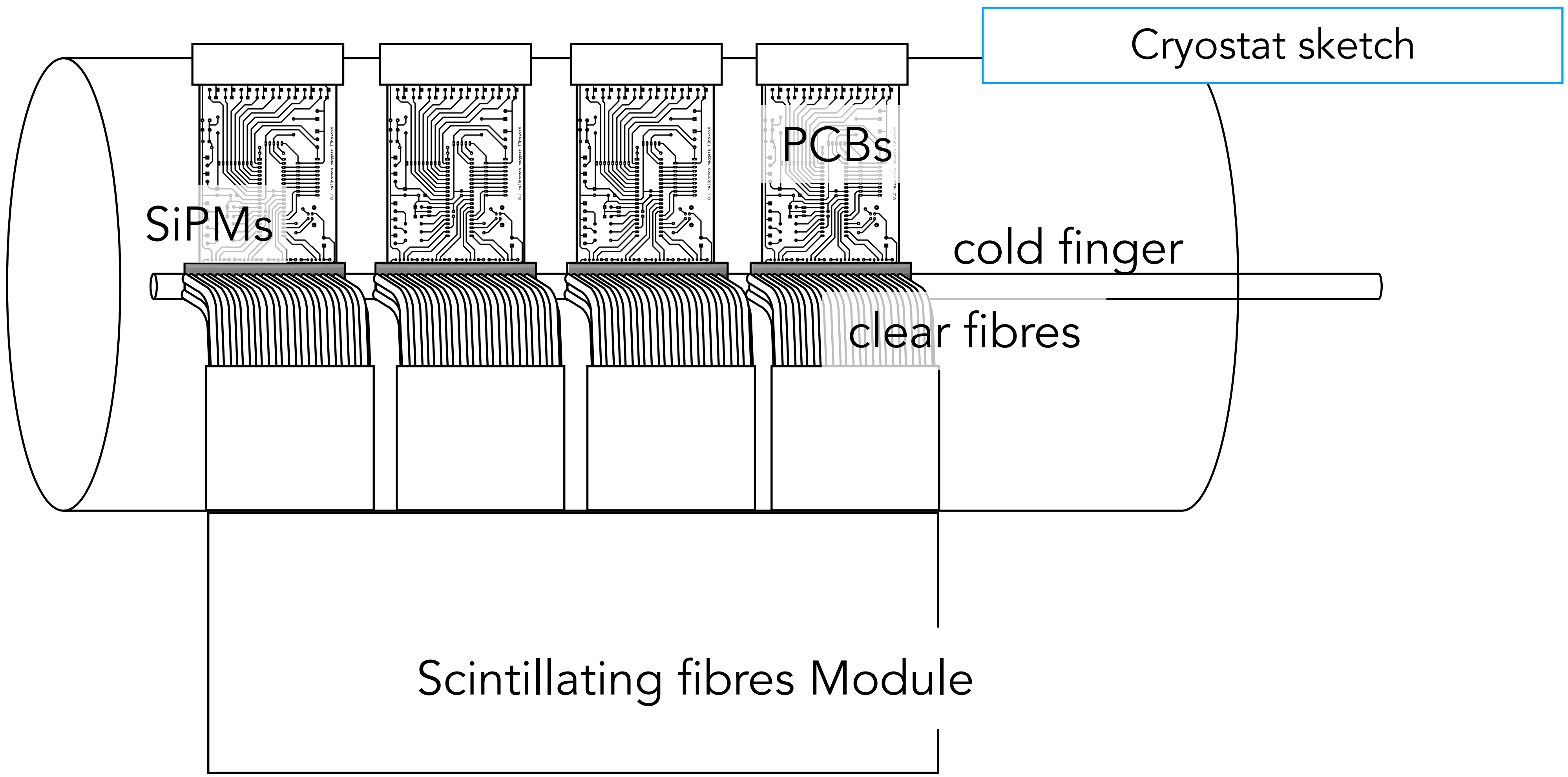


The all-seeing tracker...

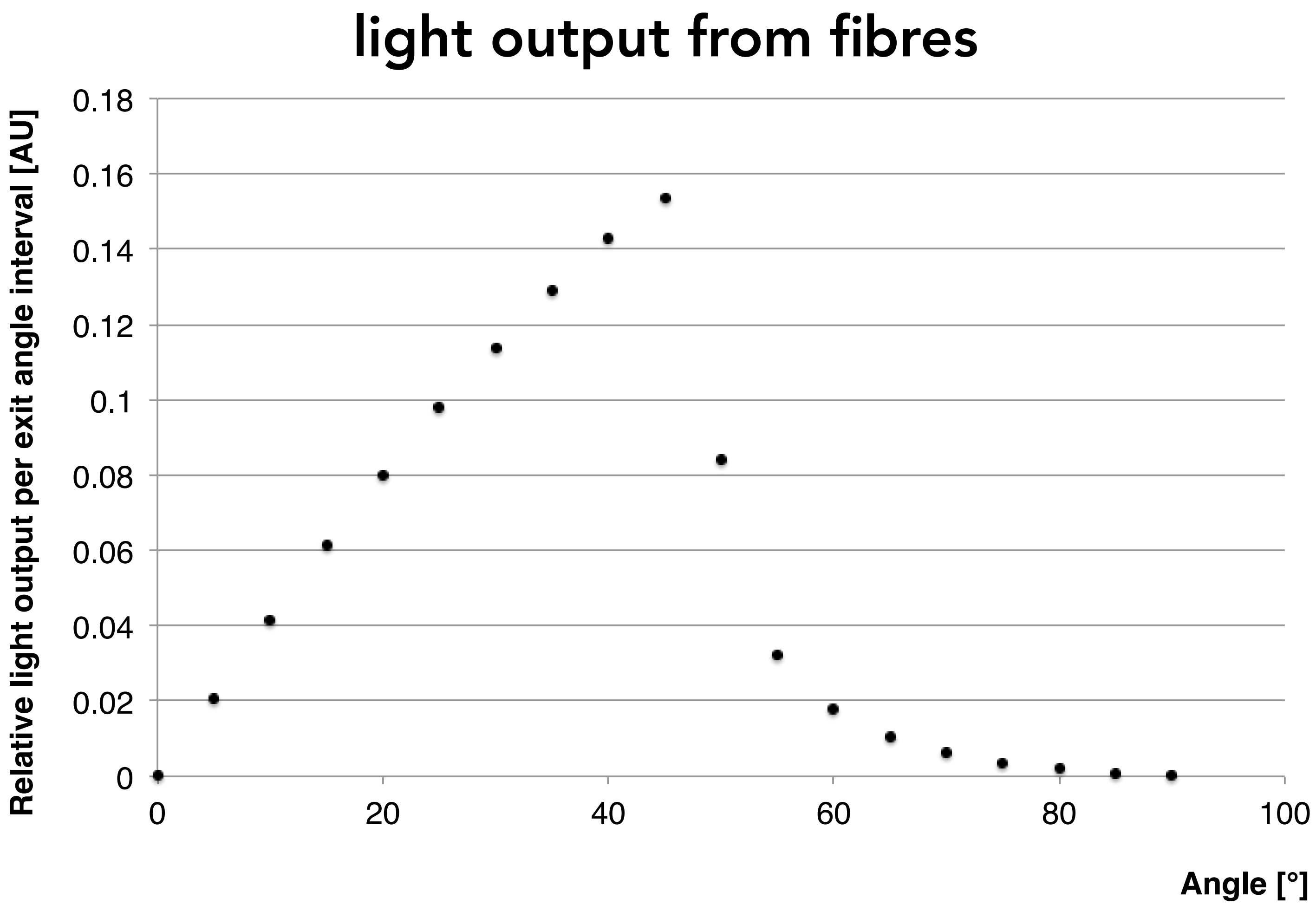
- Length of the fibre modules chosen such to keep 2% occupancy
- Faster fibres under evaluation
- SiPMs need to cope with lower light yield and higher irradiation levels

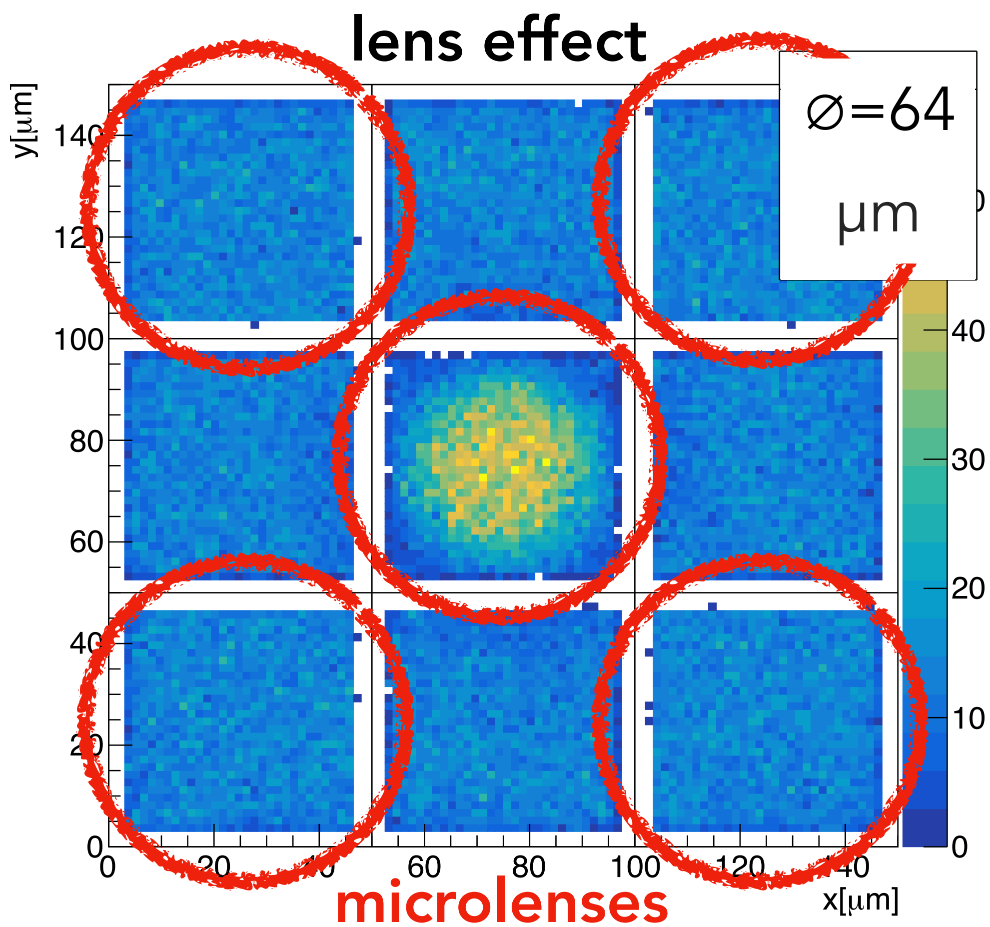
Cryogeny

- Higher irradiation and higher DCR will make impossible to keep the same operation parameters at -40°C
- Liquid nitrogen based, vacuum insulated cryostat, natural light shielded
- Clear fibres interface (0.5 - 1m)
  - ✓ Keep the same modularity
  - ✓ Easy thermalisation and vacuum seal
  - 10% light loss in preliminary tests



Micro-lenses





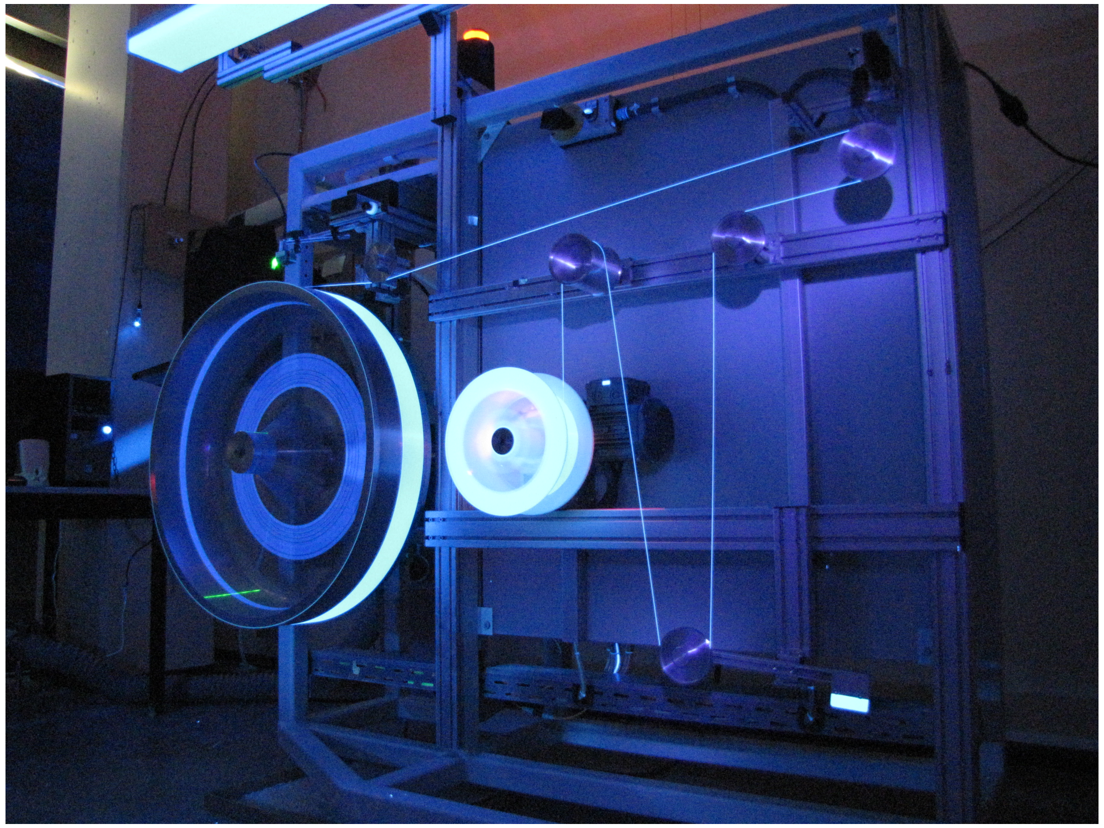
- Given the light output from fibres, an optical focus system can improve the light collection: micro-lenses
- First simulation studies show promising results with a chess-board pattern, capable of recovering all the light loss in the dead areas of the pixels

Conclusions

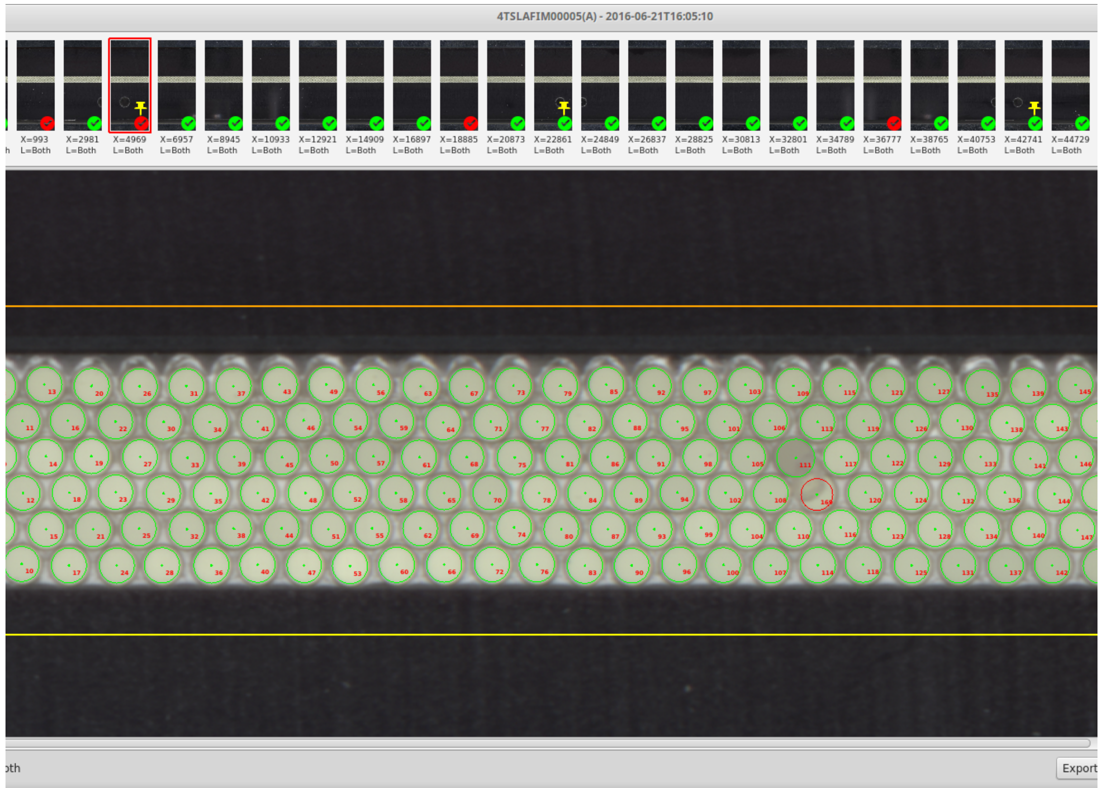
- **4096** fully functional **SiPMs** will be employed **in LHCb** for a large area tracking system together with **scintillating fibres**
- **Characterisation** campaign brought to the choice of an **optimal design**
- **Production and testing** of the assemblies was almost always smooth
  - Lesson learned: delays and unexpected have to be taken into account at every step
- **Operation conditions** must depend on the **irradiation fluencies**
- **Optimisation** of the solutions is the major **goal** now and for the future

Thank you

SciFi fibres production

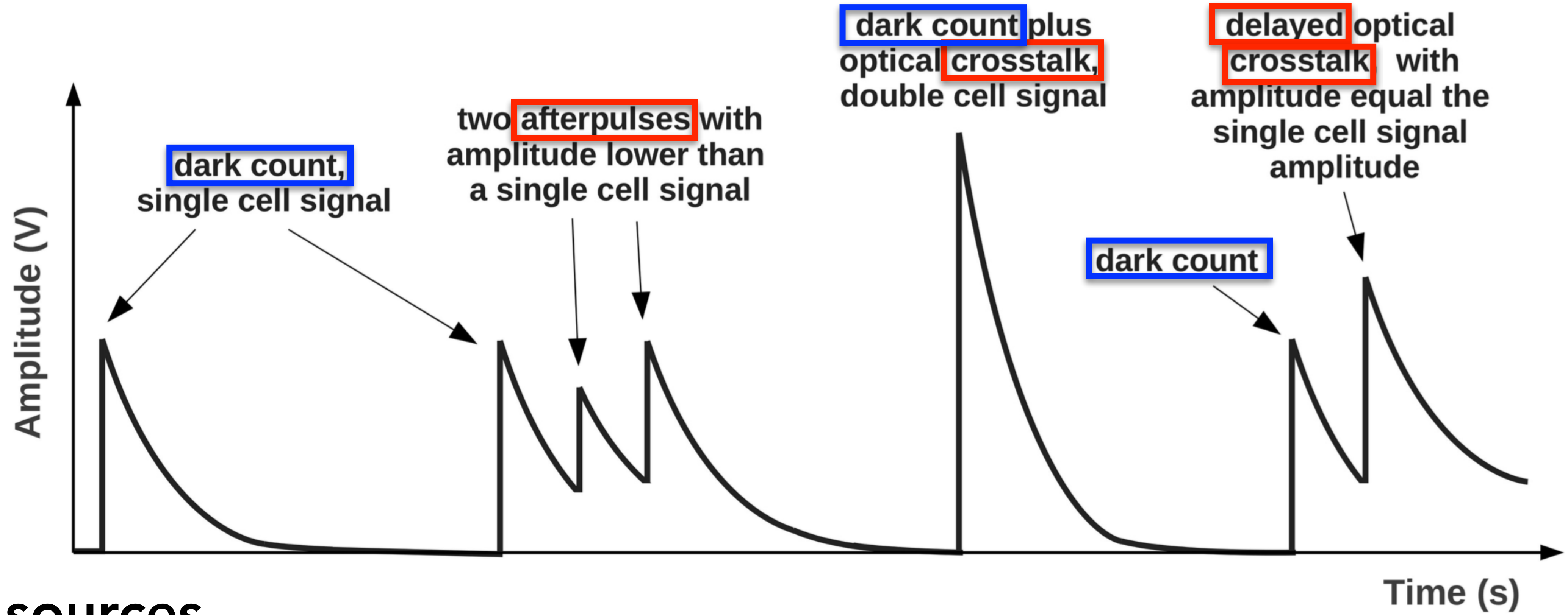


Fibre mattress winding



Fibre mats quality assurance

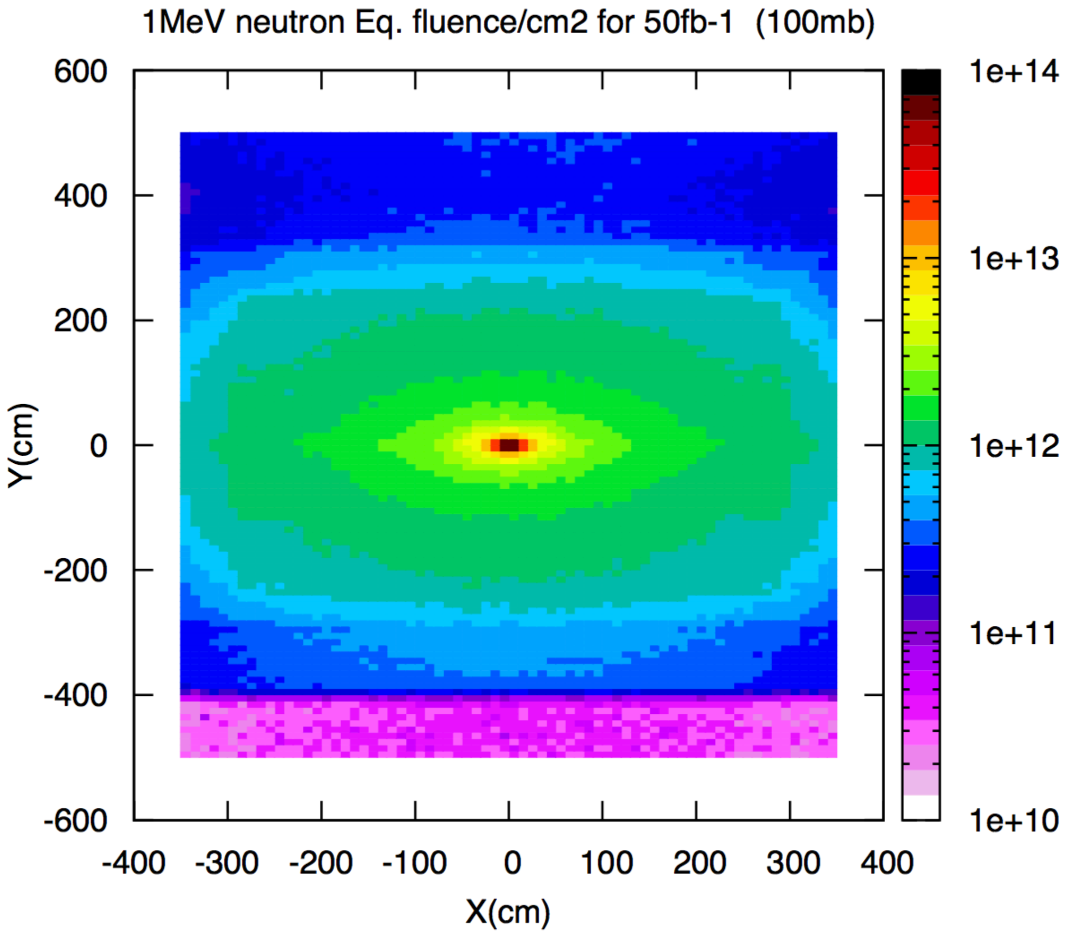
Correlated noise classification



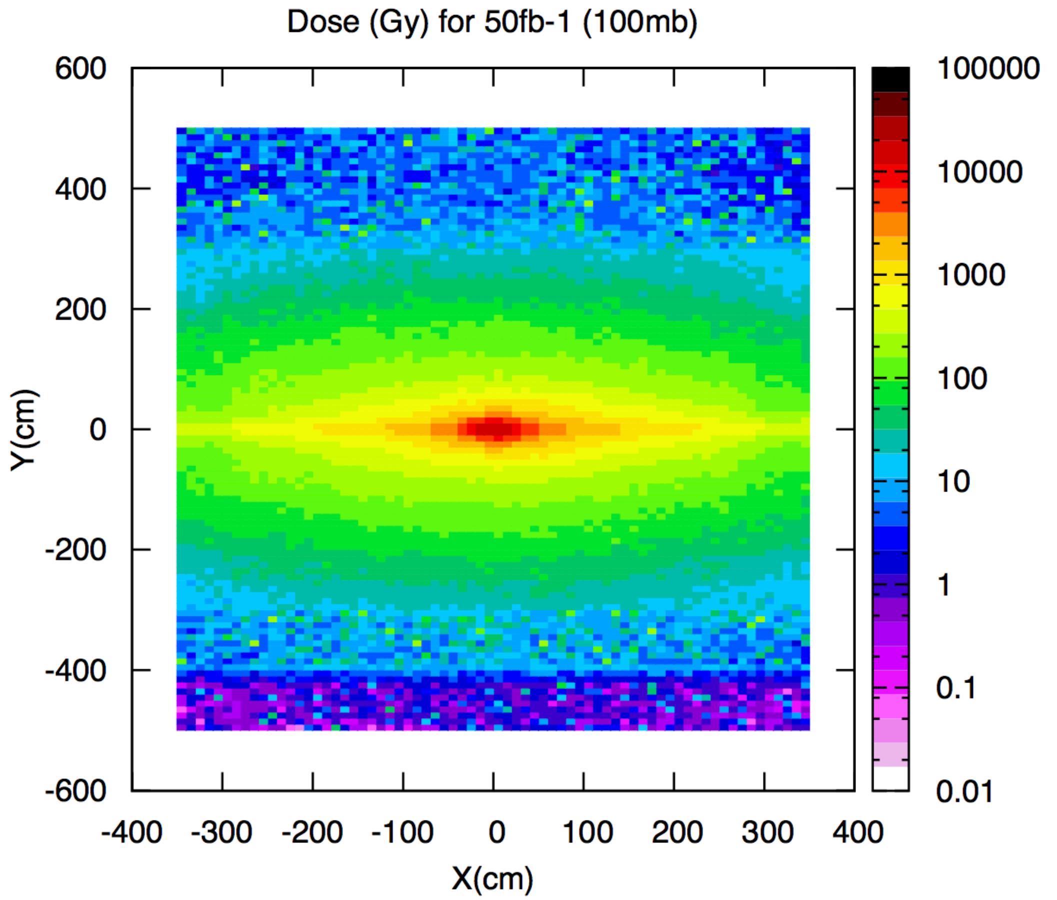
Noise sources

- Dark Counts: thermal / tunnelling generation
- Afterpulse (AP): carriers trapped during the avalanche can produce delayed secondary pulses with amplitude depending on recovery state (~1% @3.5 V for H2017)
- Direct crosstalk (XT): avalanche produced photons, trigger another avalanche in a neighbouring cell instantaneously (~4% @3.5 V for H2017)
- Delayed crosstalk (D-XT): photons create carriers in the vicinity of neighbouring avalanche region triggering a secondary delayed avalanche (~4% @3.5 V for H2017)
- Higher order contributions

Radiation environment

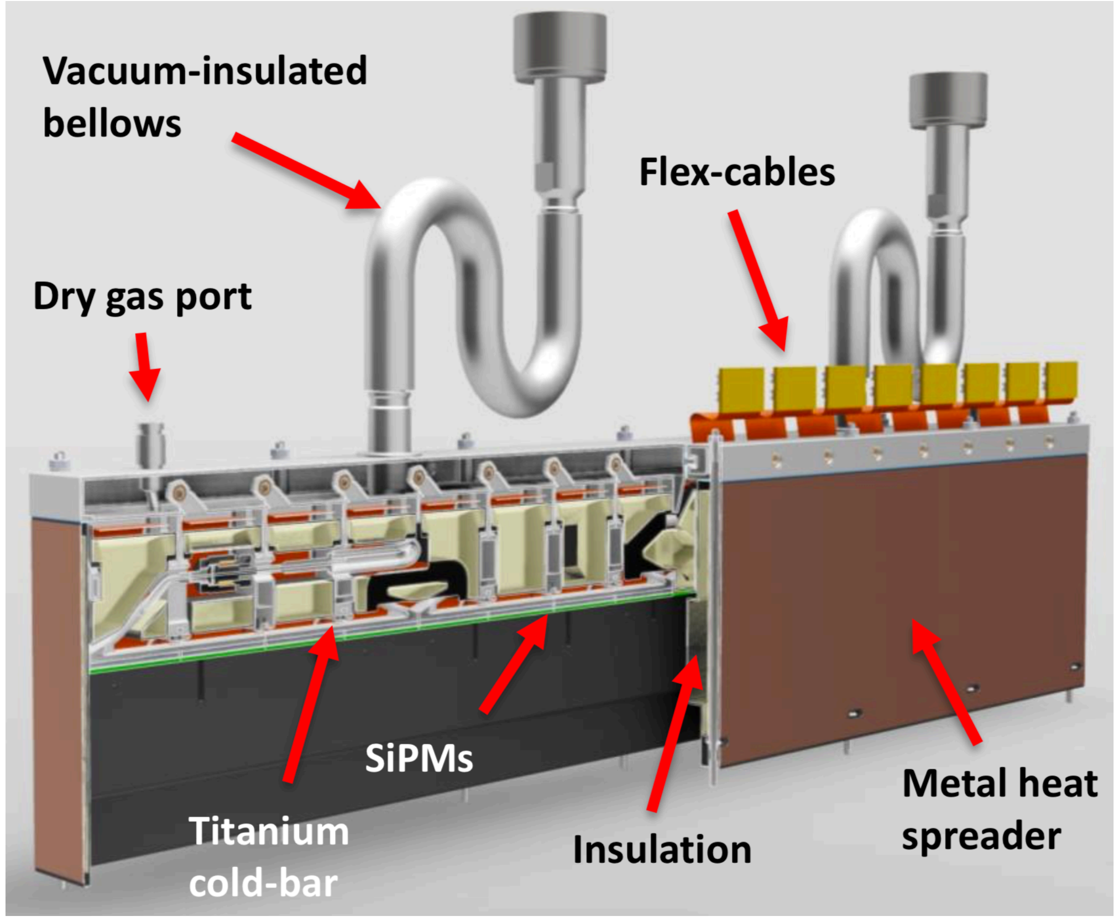


Expected 1-MeV neutron equivalent fluence per cm^2 at z = 783 cm after an integrated luminosity of 50 fb^{-1}



Expected dose in the x-y plane at z = 783 cm after an integrated luminosity of 50 fb^{-1}

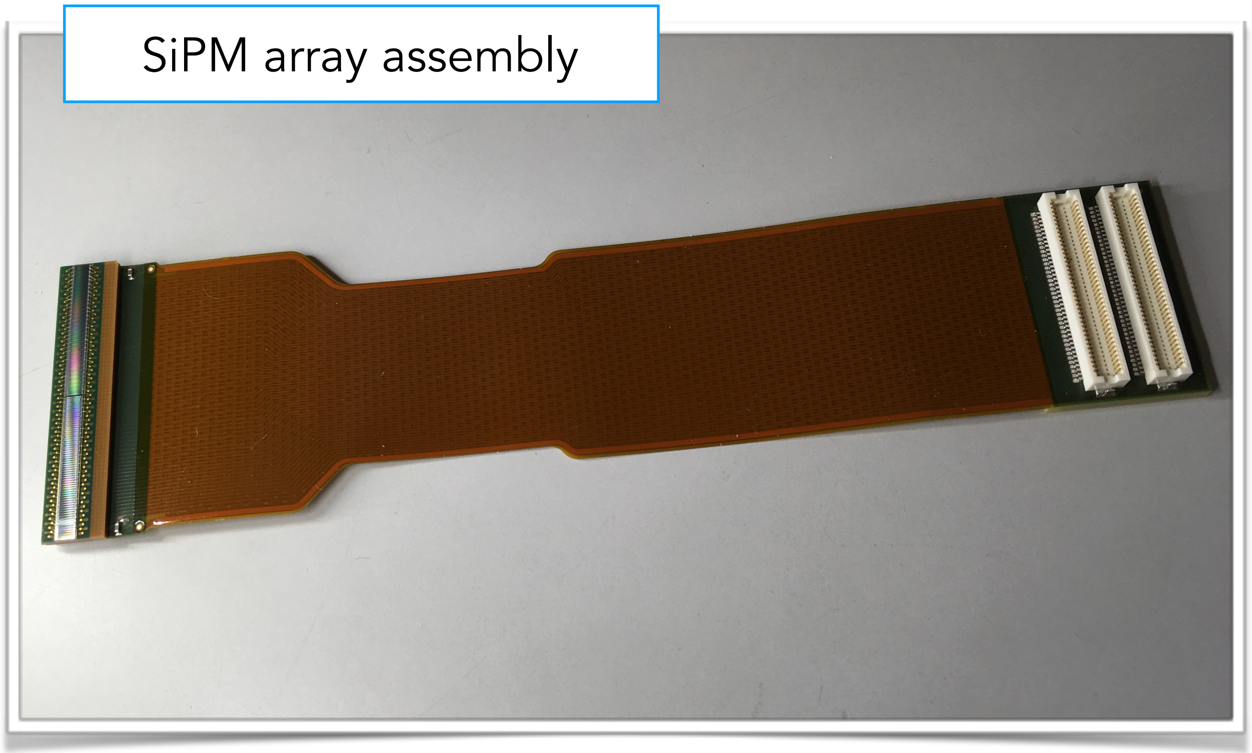
Temperature sensor choice



From Lukas Gruber - VCI 2019

- Cold-box houses 16 **SiPM arrays cooled down to -40**°C
- **Cooling liquid:** monophase 3M Novec 649 (Fluoroketone C6K)
- **Challenges:**
  - thermal insulation
  - humidity management
  - 100 m long transfer lines
- **Total mass flow 7.5 kg/s, total heat load ~ 10 kW**
- Near detector cooling lines are **vacuum insulated**
- Humidity management inside the box with **dry air flushing** (dew point -70 °C)

Flex PCB design

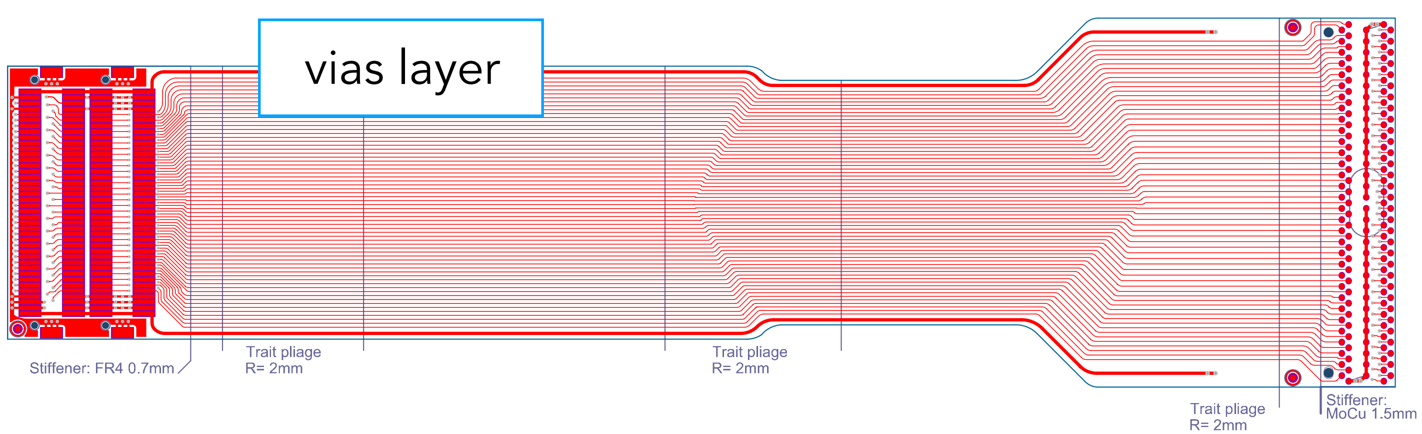


Copper:

- 2 line layers ⟶ - 18 µm
- 1 ground plane ⟶ - 9 µm

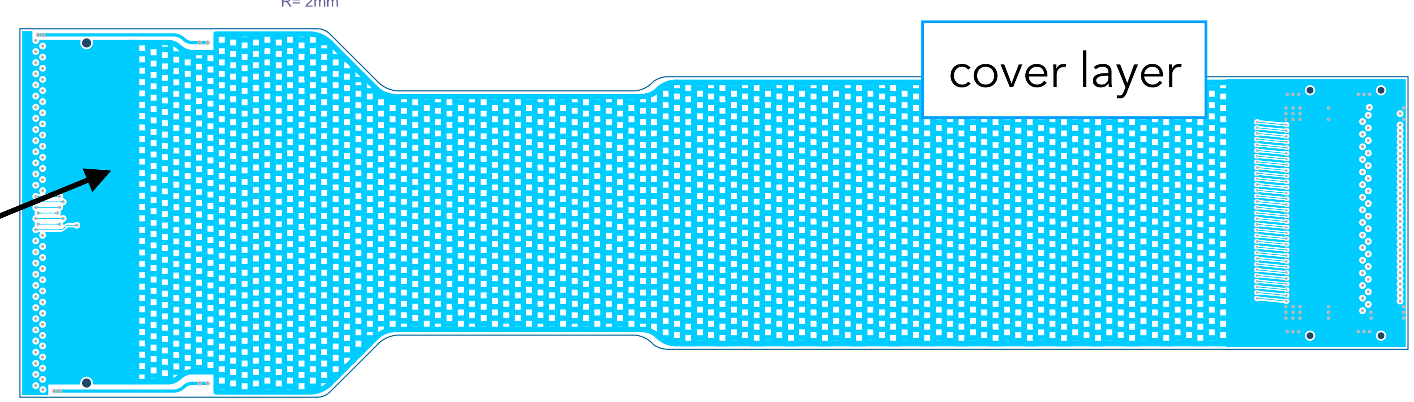
Polymide:

- 3 planes ⟶ - 25,12,25 µm
  - 100% of filled plane
- $R = \dfrac{\text{copper}}{\text{polymide}} = 0.21$



- 16% of filled plane
- 70 µm thick lines, 430 µm pitch

- 80% filled plane
- no thermal barrier



Temperature sensor choice

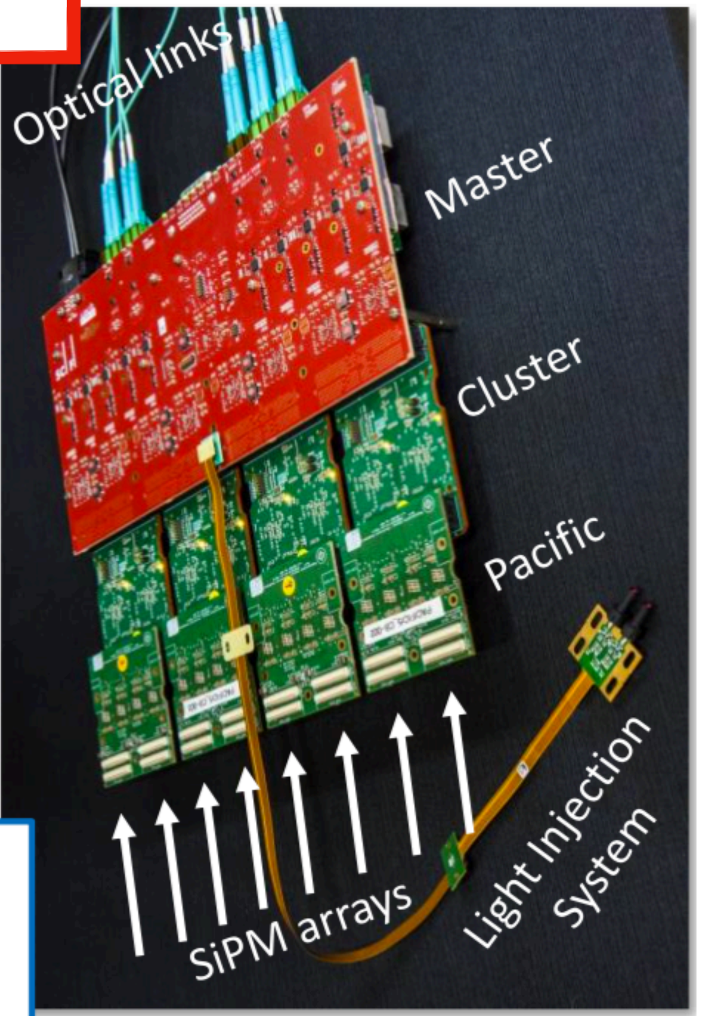
From Lukas Gruber - VCI 2019

Challenges:

- 524k SiPM channels to be read-out at 40 MHz
- High DCR and noise cluster rate due to radiation damage
- SiPM signals with long tails

This requires:

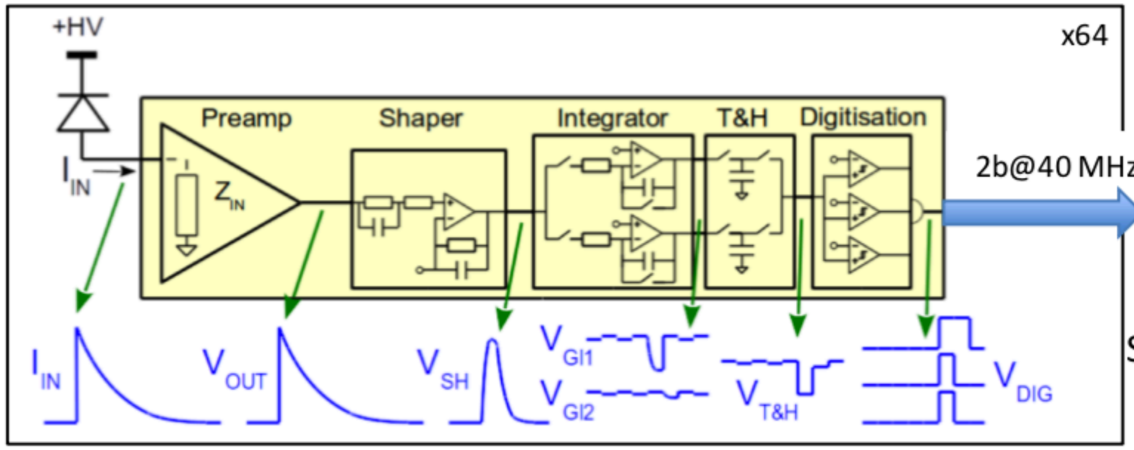
- Low power consumption electronics
- Minimised spillover and dead time (fast shaping and integration)
- Efficient noise rejection, signal digitisation and data processing

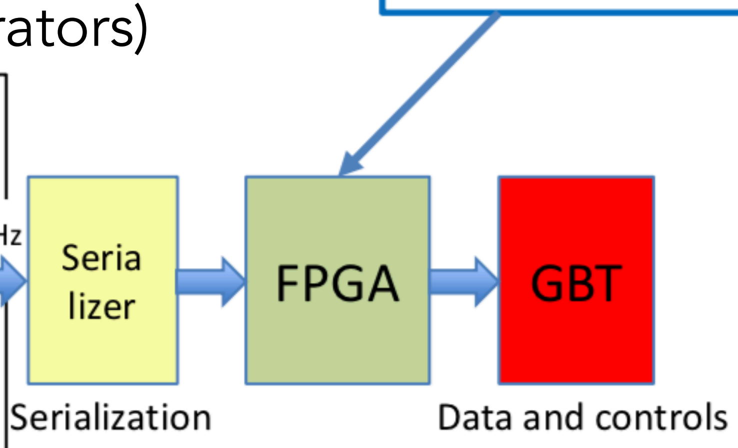


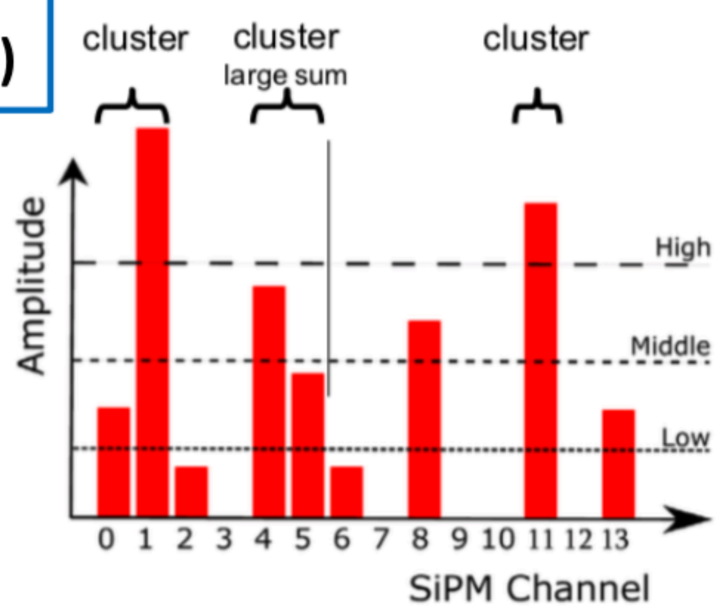
PACIFIC ASIC (custom made for signal digitisation):

- CMOS 130 nm technology
- 64-channel current mode input, 10 mW per channel
- Fast shaping to reduce spillover (10 ns)
- Double gated integrators to avoid dead time (25 ns)
- 2-bit digitization per channel (3 comparators)

Clustering:
~ 14 MHz/channel
< 3 MHz per SiPM array (128 channels)

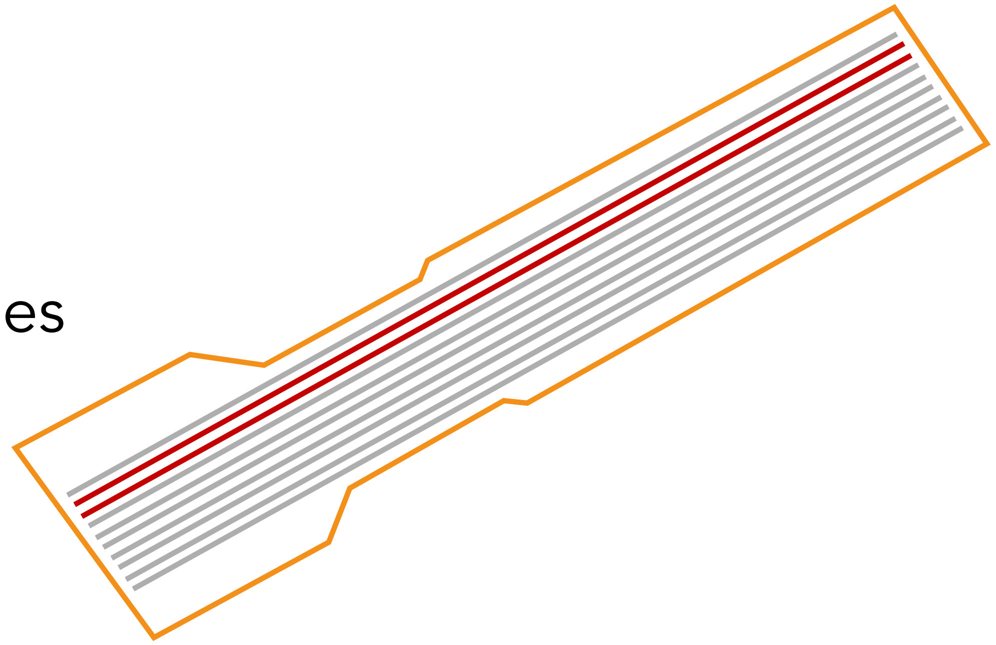






Cross-talk tests

- Testing the cross-talk between two neighbour channels on the flex
  - ✓ one layer for odd, one layer for even channels
- Tests full frequency spectrum (signal from detector)
  - ✓ 8 channel pair tested on 4 detectors from two batches



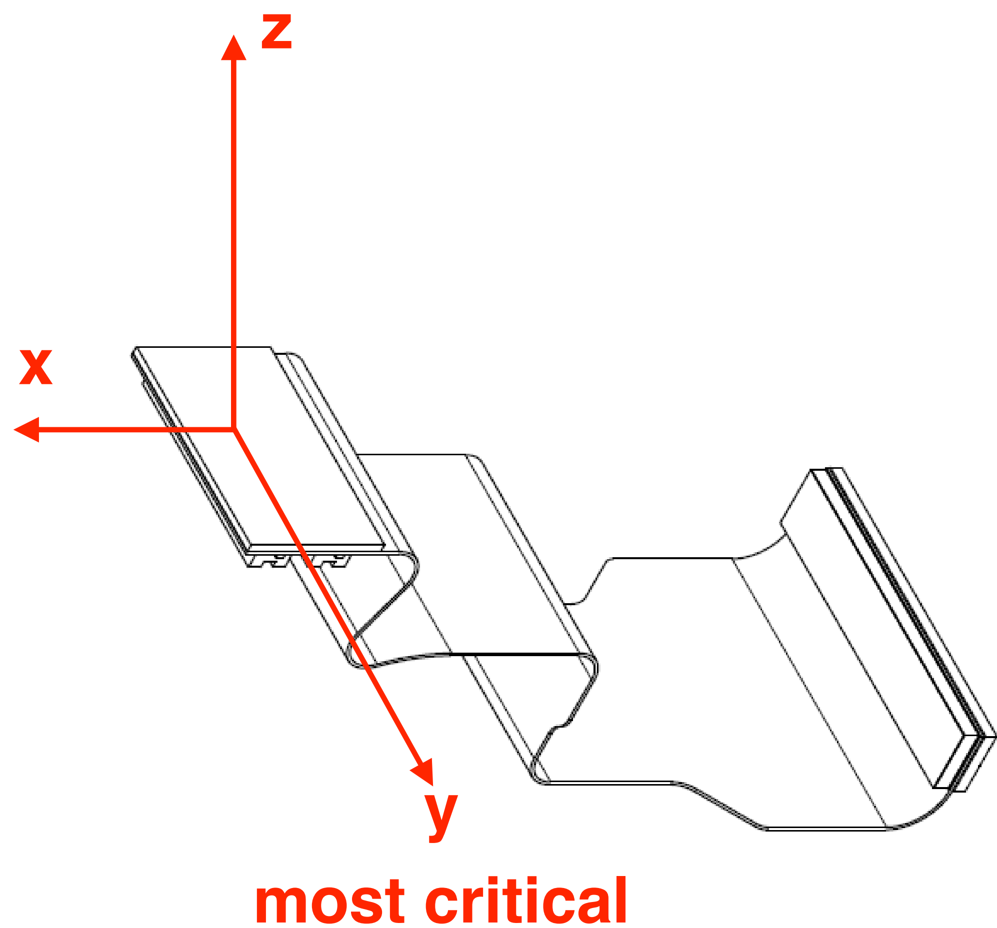
- Test performed @ 3.5 V over-voltage

Bandwidth \ x-talk	mean	sigma
full bandwidth	8.4%	±1.5%
350 MHz	7.7%	±1.6%
200 MHz	7.6%	±1.6%

- Check for light reflected in epoxy:
  - ✓ ~2.3 ‰ for protected detectors

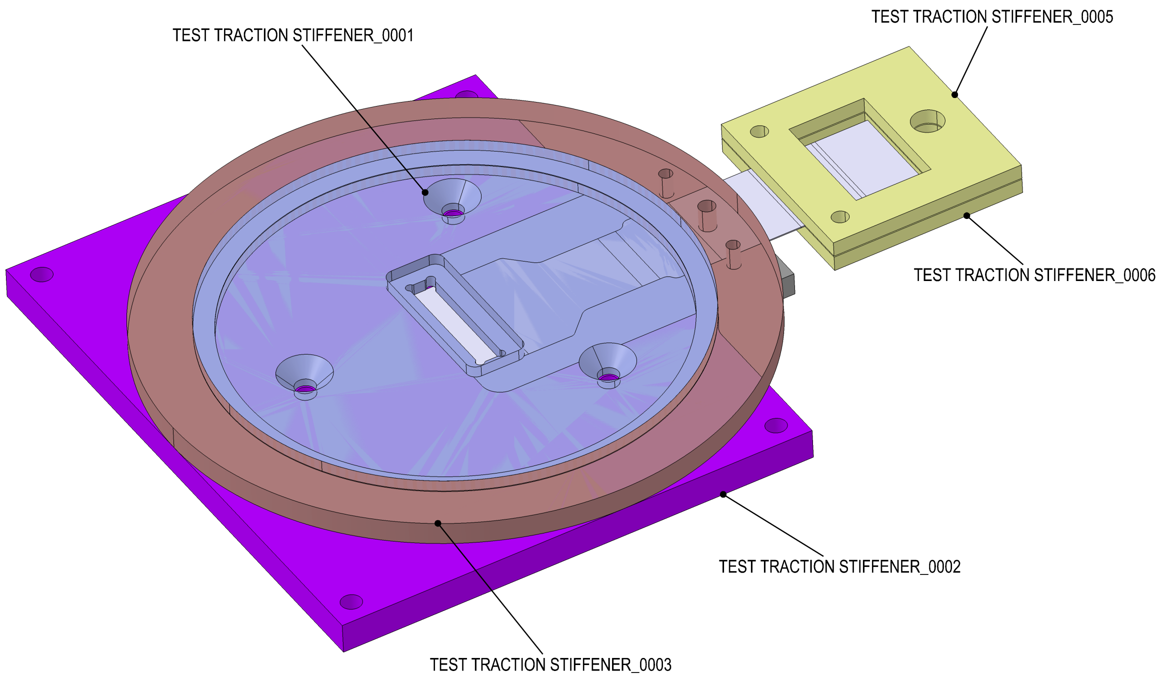
Vibrational tests

- Two flex prototypes tested with 10, 100 and 1000 cycles
  - x = ±1 mm -> no dead or disconnected channel
  - y = ±0.5 mm -> no dead or disconnected channel
  - y = ±1 mm -> broken channels on the flex
  - x/y combined, x = ±1 mm, y = ±0.5 mm -> no dead or disconnected channel
- Two new assembled flex tested with not destructive tests
  - 1000 cycles y = ±0.5 mm -> no dead or disconnected channel
- One prototype tested with crash test
  - y = ±2 mm -> connector visibly disconnected after less than 100 cycles, 50% of channels disconnected, not dead
- z-direction oscillations to be tested



Glue tests

- Testing the strength of the glue under traction and shearing force
- Glue options in production:
  - ✓ Old transfer tape
  - ✓ Epotek 70E-4
  - ✓ Araldite 2031

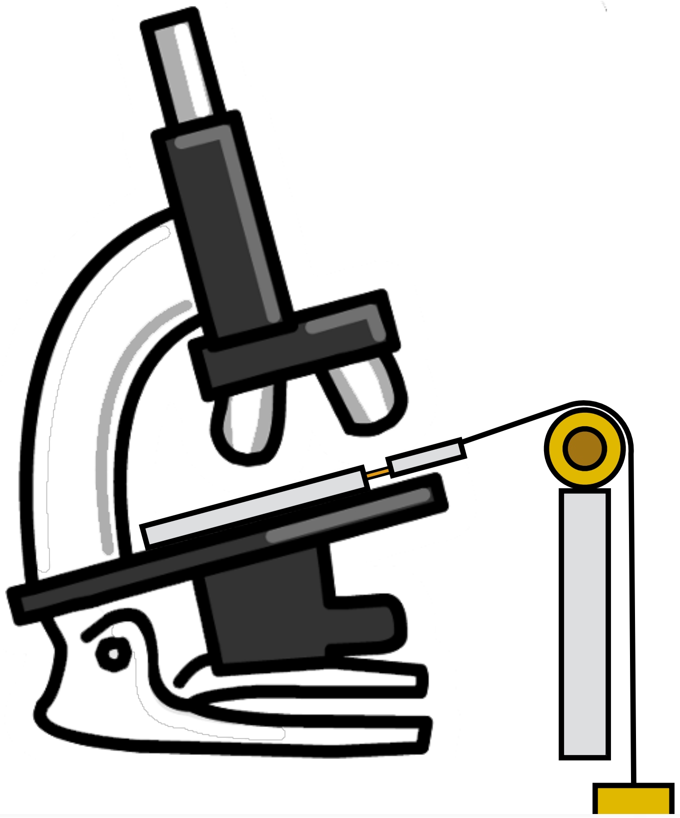


- Results of short test:

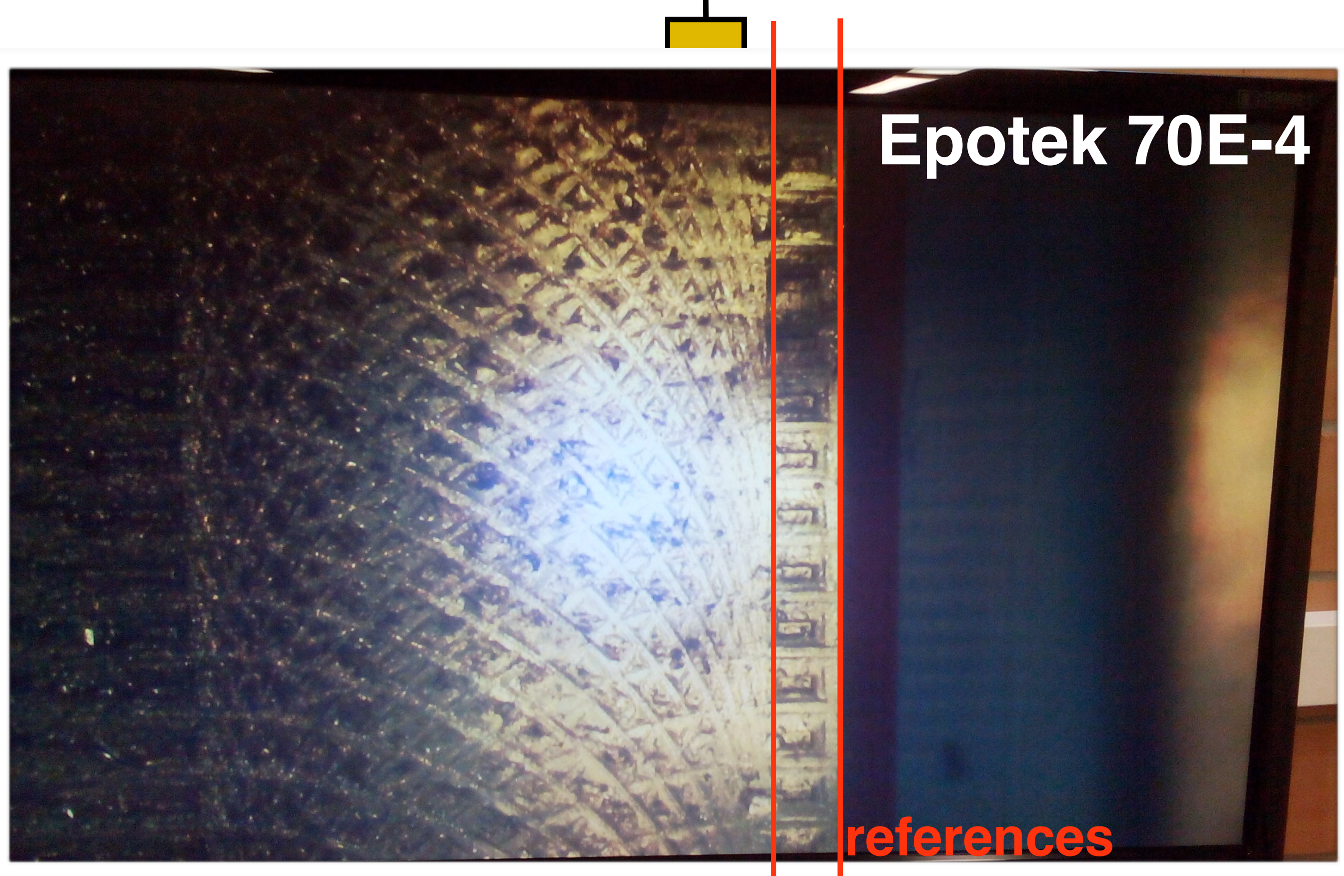
Glue \ Force	Peak traction	Peak shear
Old tape	~7.2 Kg	~1.8 Kg
Epotek 70E-4	No detach > 10 Kg	No detach > 10 Kg
Araldite 2031	No detach > 10 Kg	No detach > 10 Kg

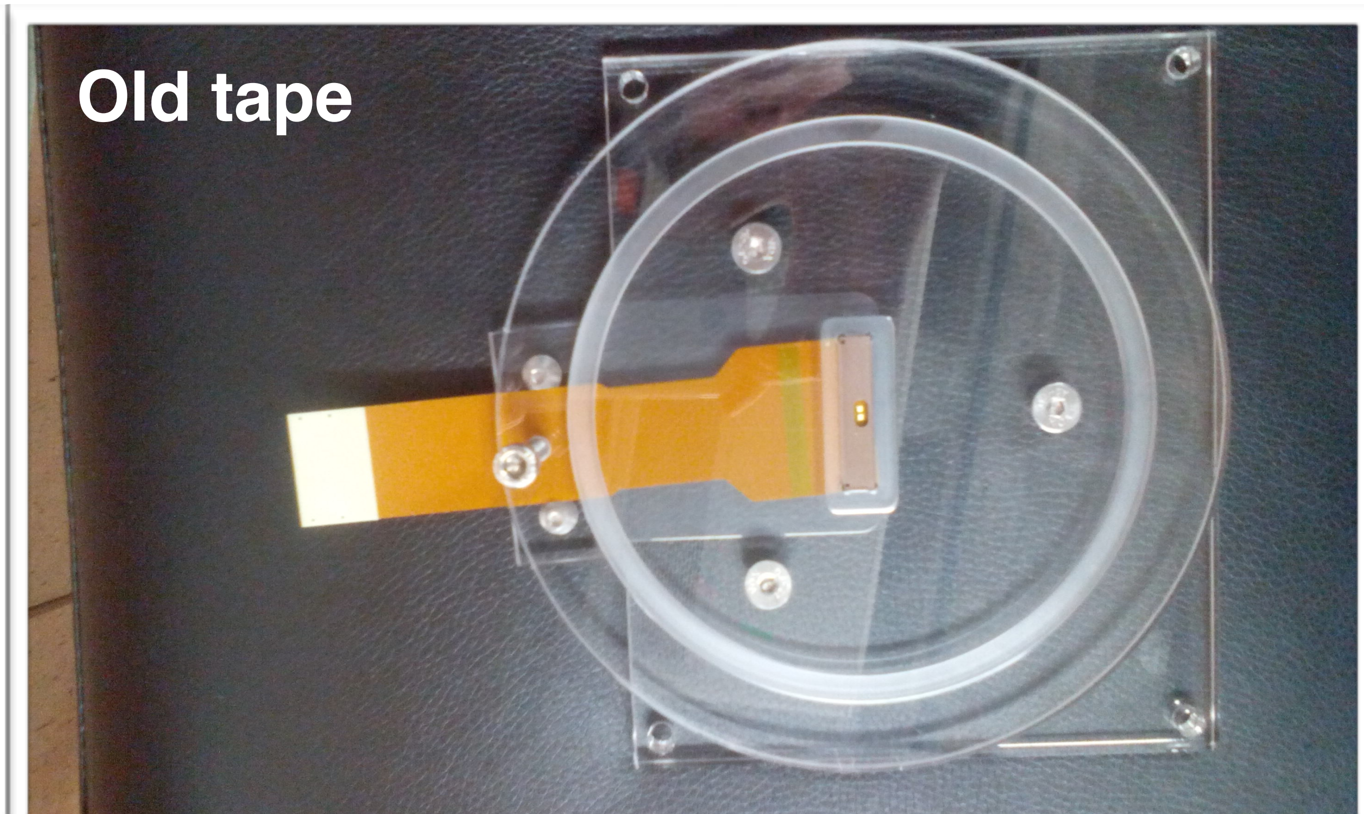
Glue tests

- Results of long test:



Glue \ Force	shear 10 h @ ~0.5 Kg	shear 10 h @ ~1.0 Kg	traction 10h @~2.Kg
Old tape	Visible torsion	————	————
Epotek 70E-4	No torsion	No torsion	No detachment
Araldite 2031	No torsion	No torsion	No detachment





Temperature sensor choice

- Temperature range of operation
- Error on the measurement
- Packaging (optimal: SMD 0603)