PIXEL2018
International workshop on Semiconductor Pixel Detectors for Particles and Imaging

Large pixel SiPMs for single photon detection in the new LHCb large area scintillating fibre tracker

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On behalf of LHCb SciFi collaboration

Outline

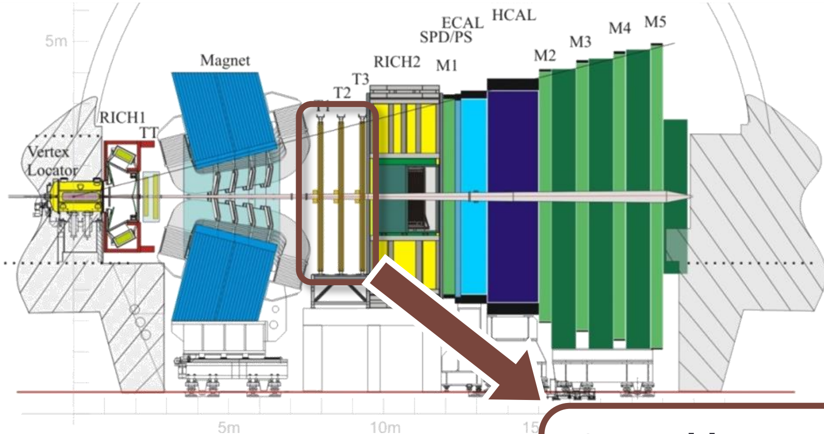
Context
- LHCb and the upgrade
- The SciFi technology

Silicon photomultipliers
- Choices for LHCb

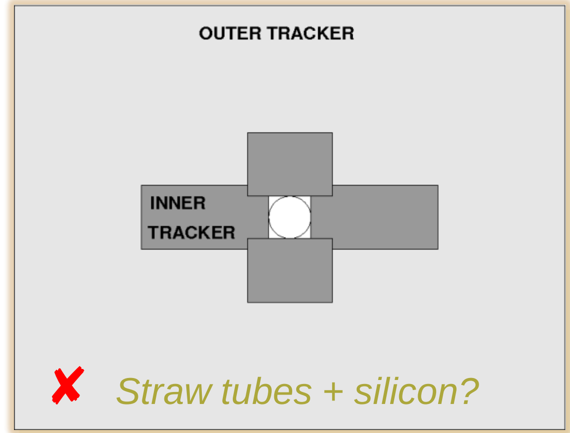
Characterisation of radiation effects
- Random noise
- Detection of low photon signals
- Photon detection efficiency

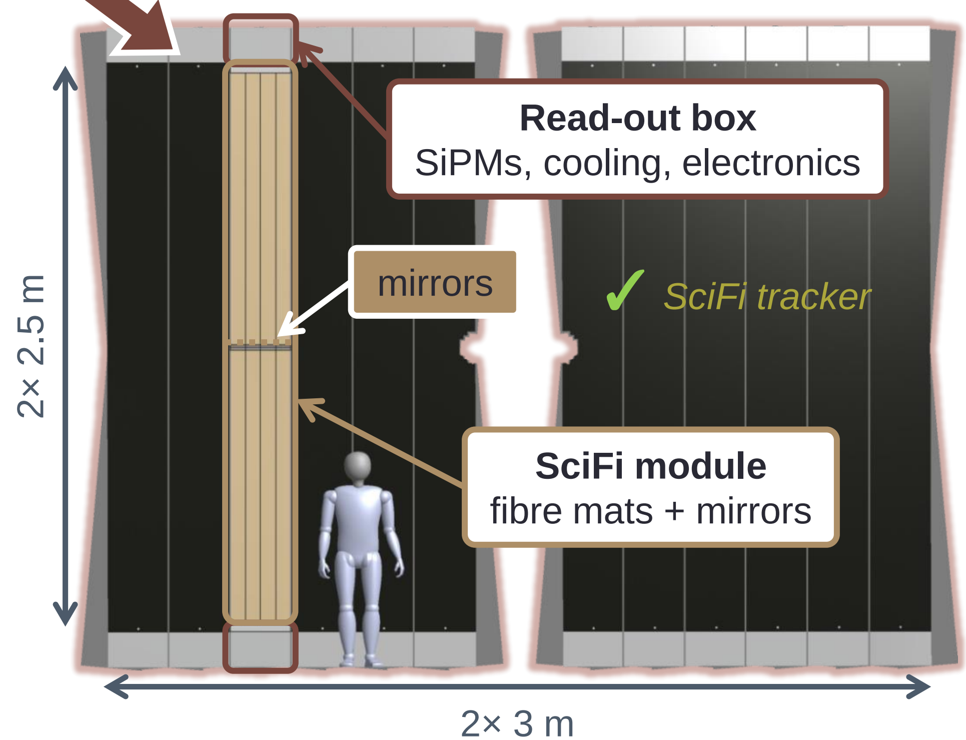
B. Leverington
Module assembly on frame

LHCb SciFi tracker

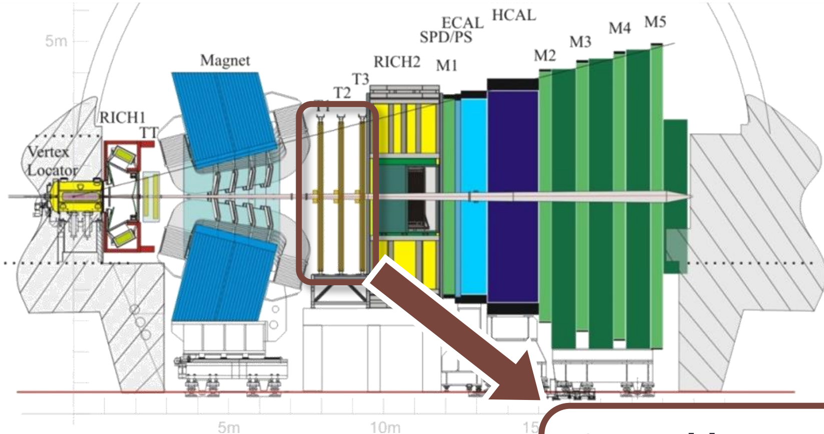


3 Tracking station
12 detection layers
320 m² total area





LHCb SciFi tracker



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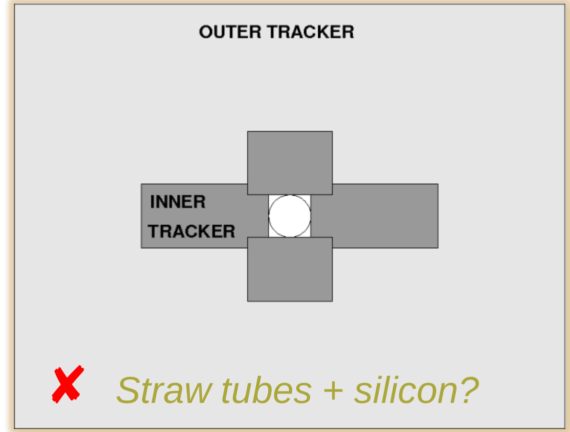

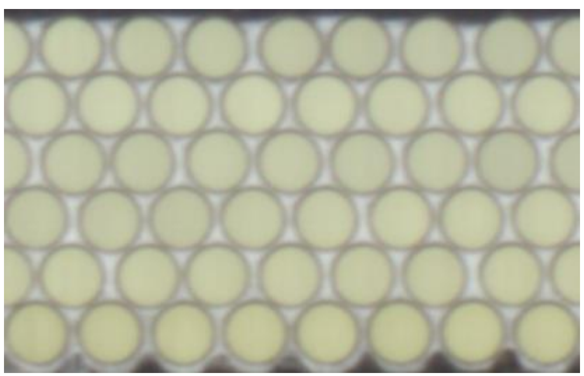

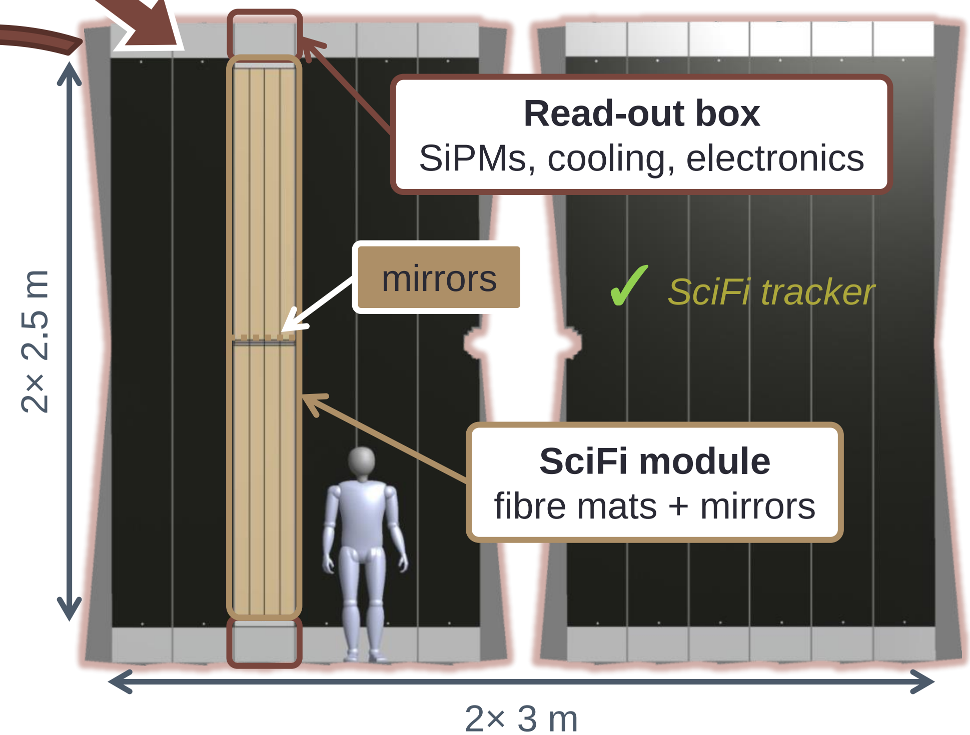

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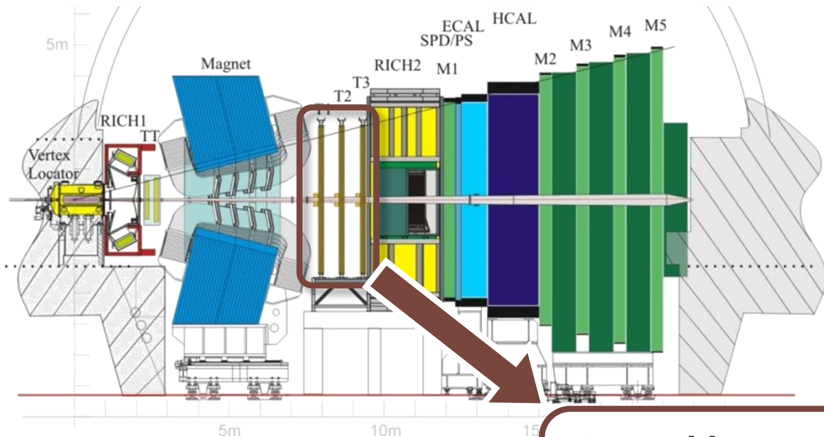

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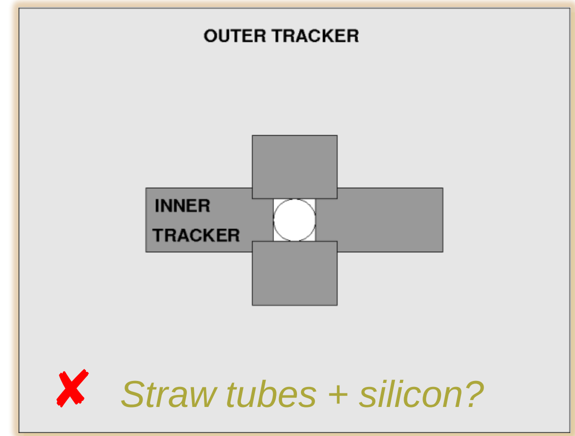
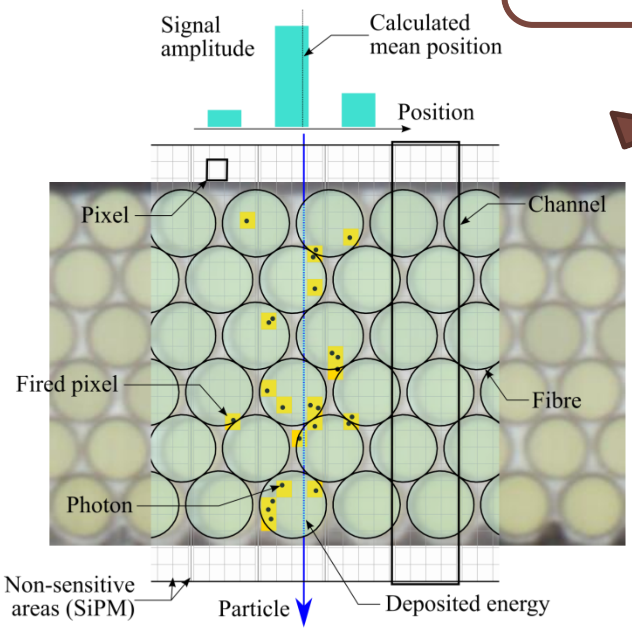
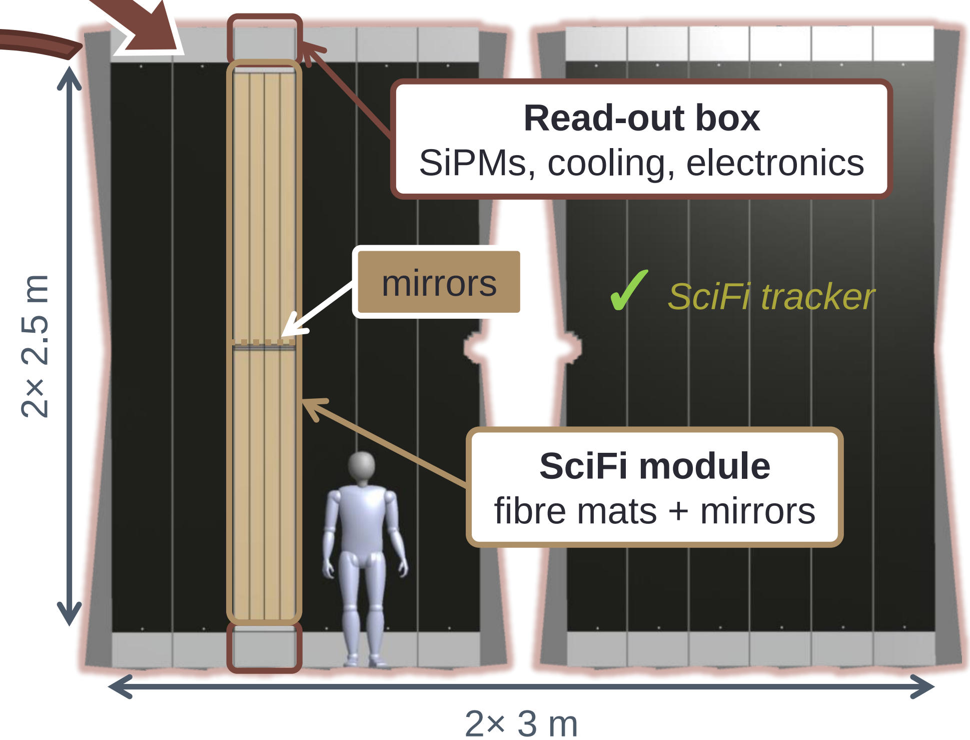


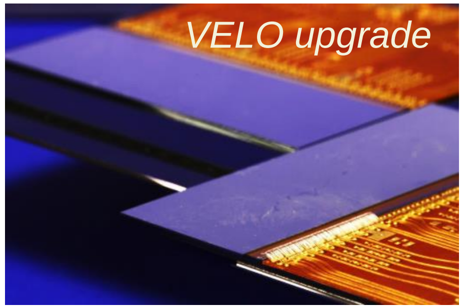




- Fibres: 11'000 km
- SiPMs: 0.2 m², 490k channels

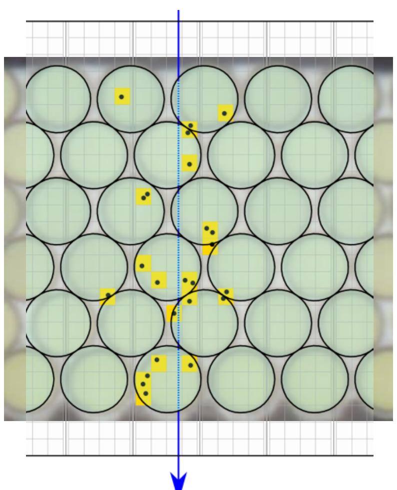
Light detection – challenge

X = 220 µm
X/X_0 = 0.23%



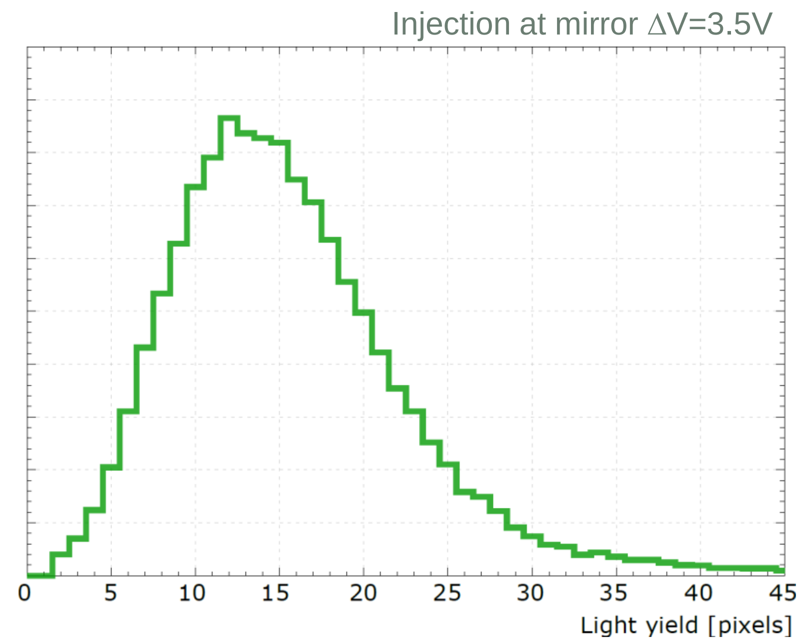
Signal = O(10k) e^-
Noise = O(200) e^-
} Collected on 1 pixel

X = 1.35 mm
X/X_0 = 0.41%



Signal =

Energy deposit
× scint. light yield
× light capture
× light attenuation
× photon det. eff.



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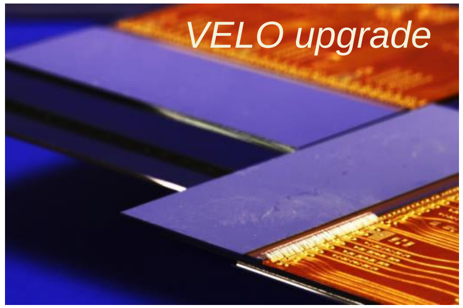

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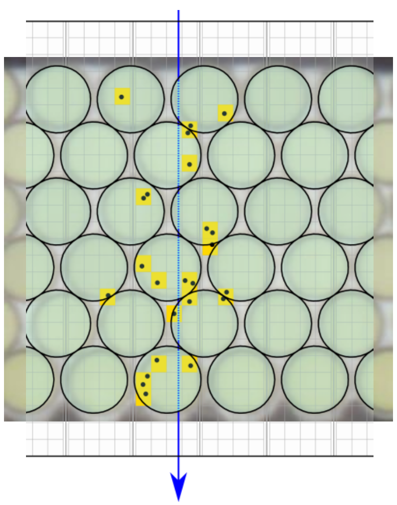

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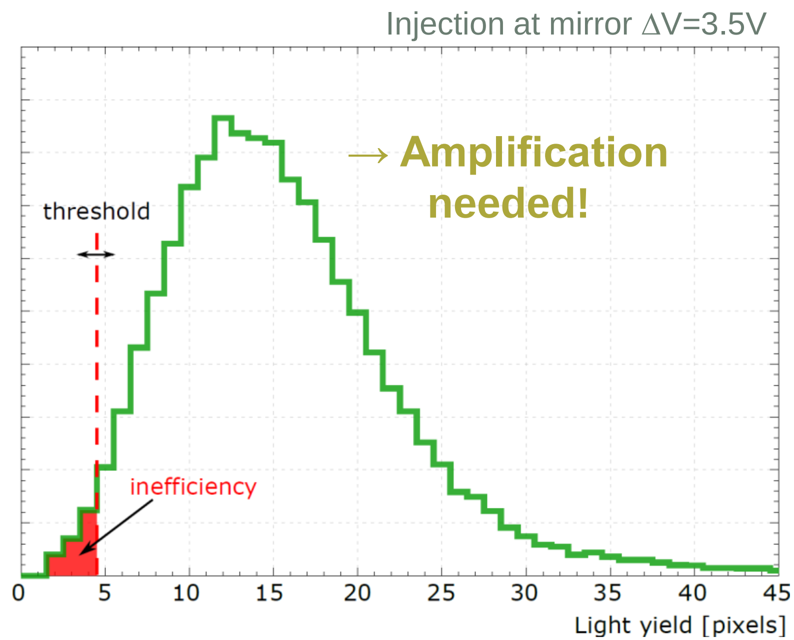

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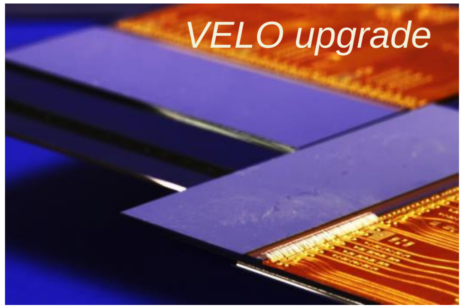

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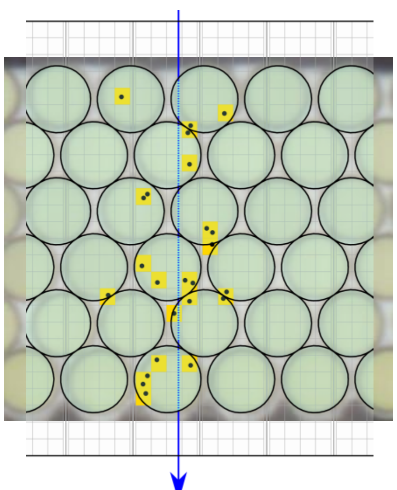

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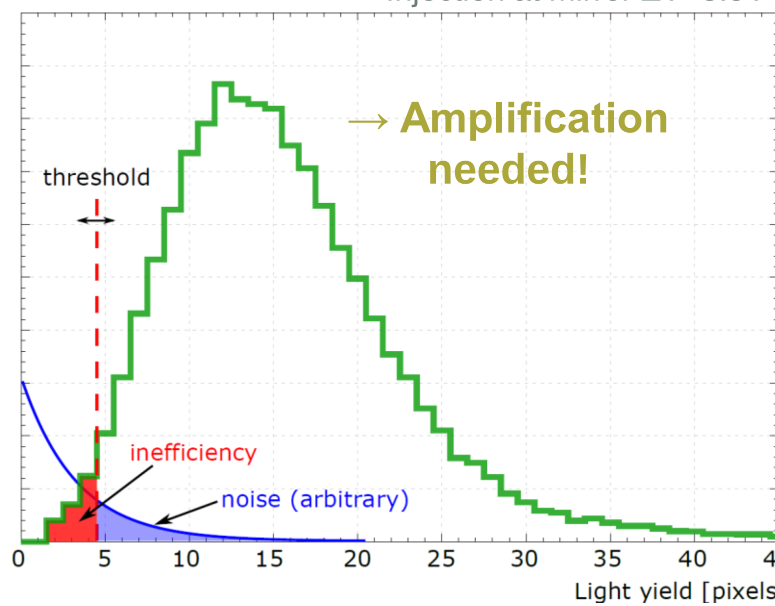
Noise

Collected from 2-3 ch.
= 2-3 × 104 pixels

Injection at mirror ΔV=3.5V



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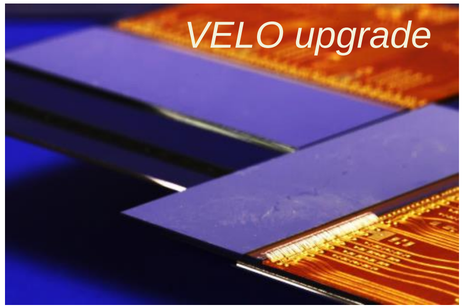

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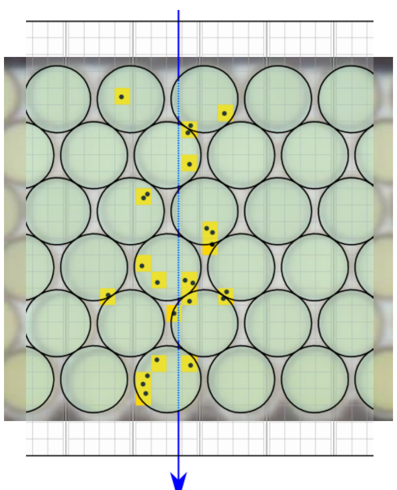

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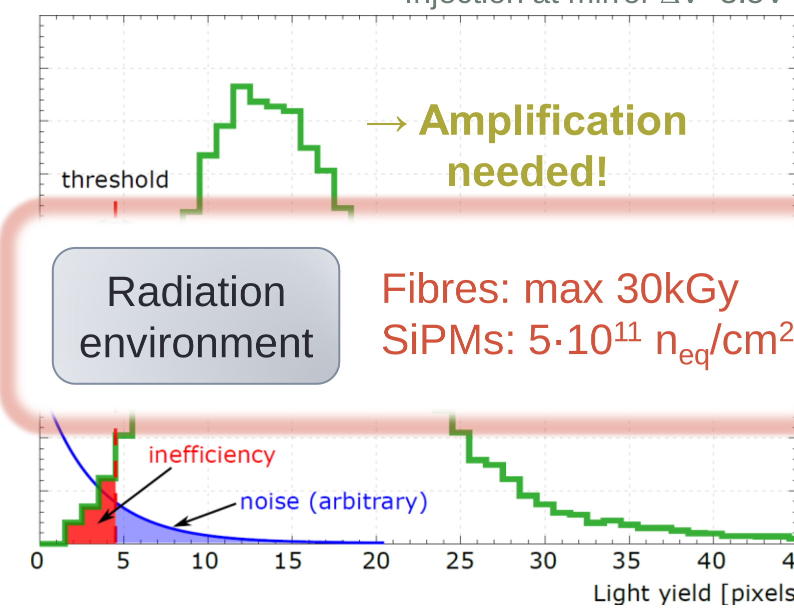


→ **Amplification needed!**

Radiation environment

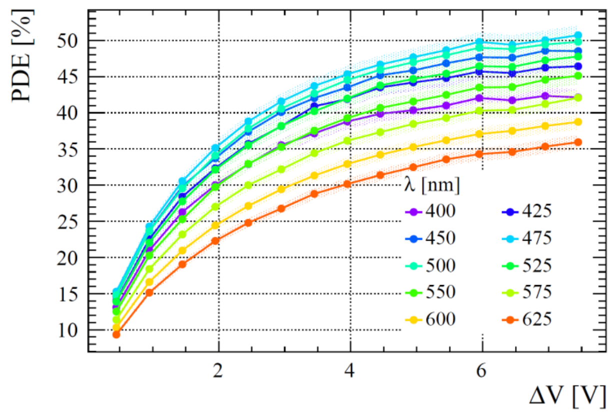
Fibres: max 30kGy
SiPMs: $5 \cdot 10^{11}\ n_{eq}/cm^2$

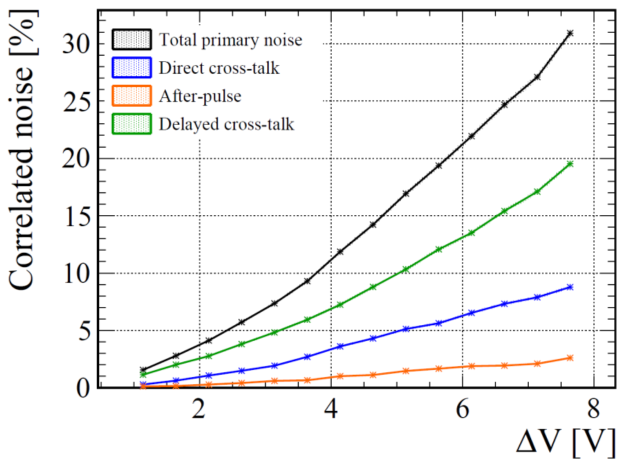
SiPM for the SciFi tracker

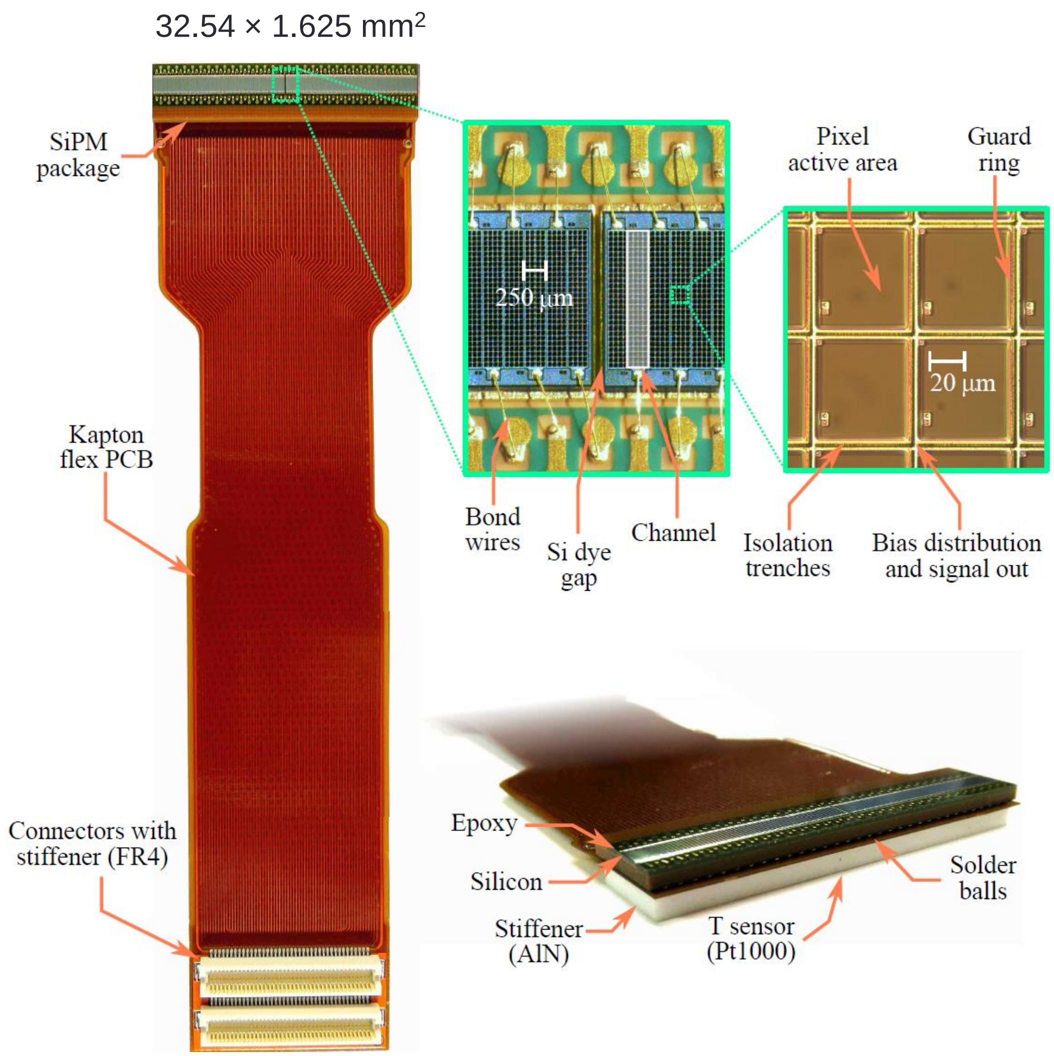
Customised SiPM array produced by Hamamatsu (S13552)

Design choices:

- Large pixels
- Opaque trenches
- Adjusted quenching resistor



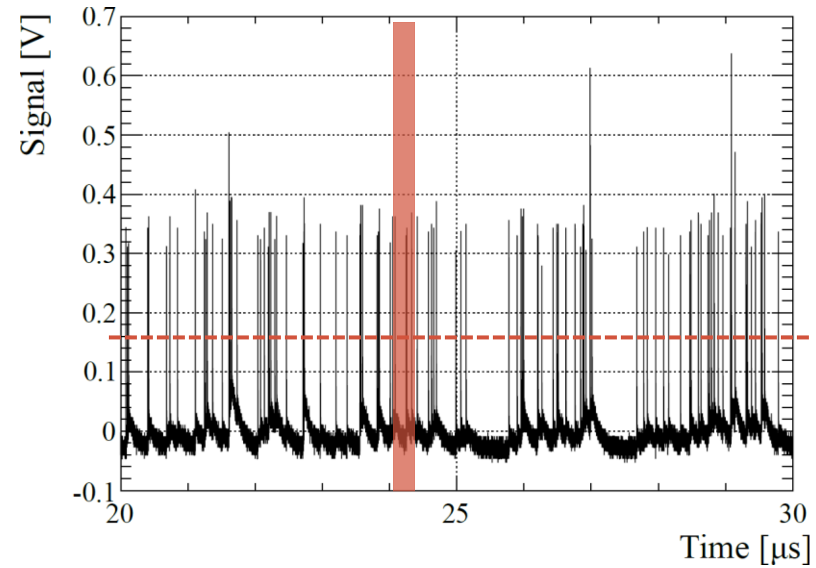


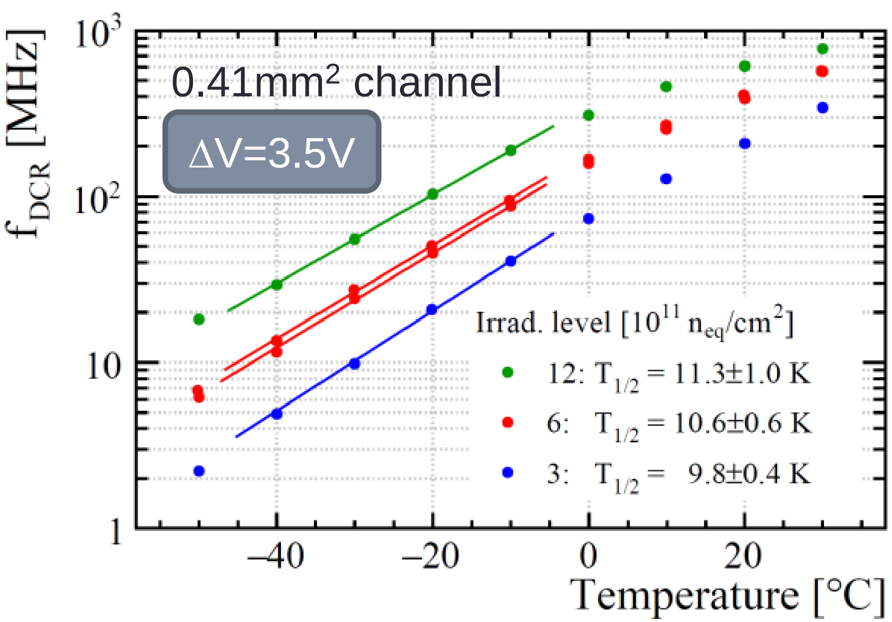


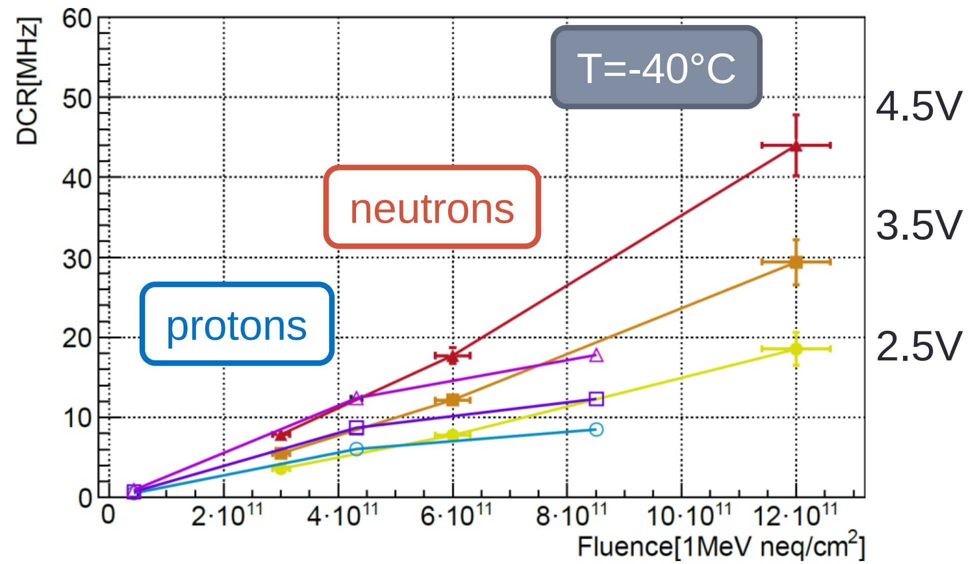
Dark count rate and effect of irradiation

Random noise – Dark count rate (DCR)

- Thermally-generated e-h pair ~100 kHz/mm²
- Increased by irradiation 30’000×
  - ☒ Overlap of pulses (high signals)
  - ☑ **Cooling** (÷2 per 10°C)
  - ☑ **Short integration time**
  - ☑ **Clustering**





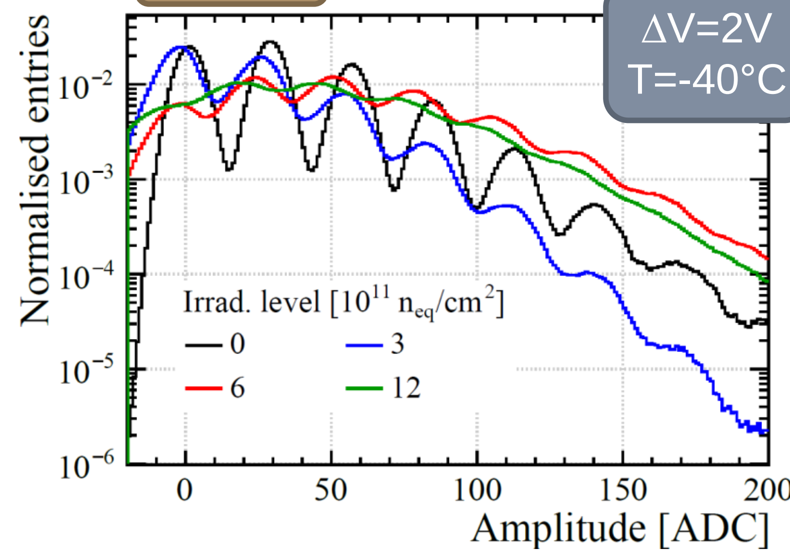


Sensitivity for low-light signals after irradiation

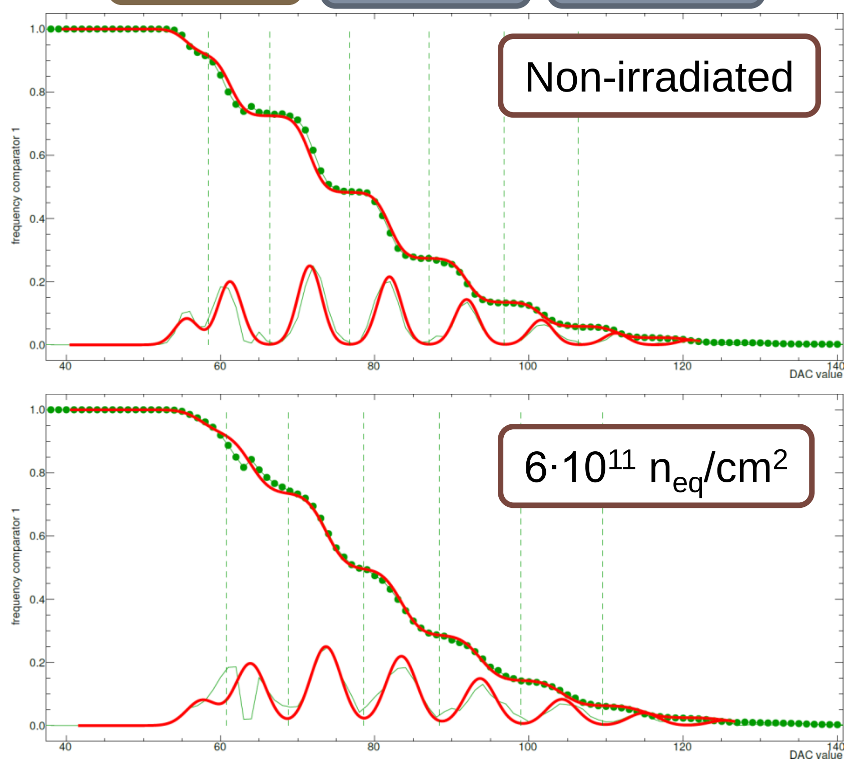
Low light spectrum

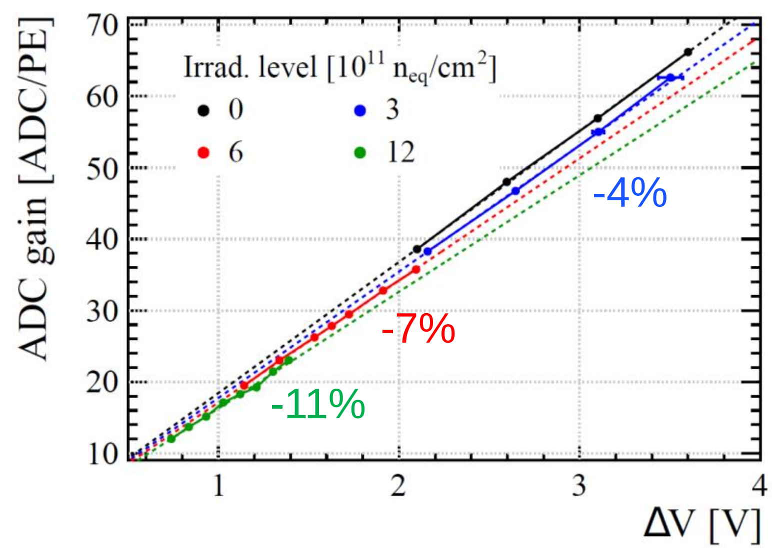
- Gain measurement
- Compensation for effects in the electronics due to the high dark current

SPIROC

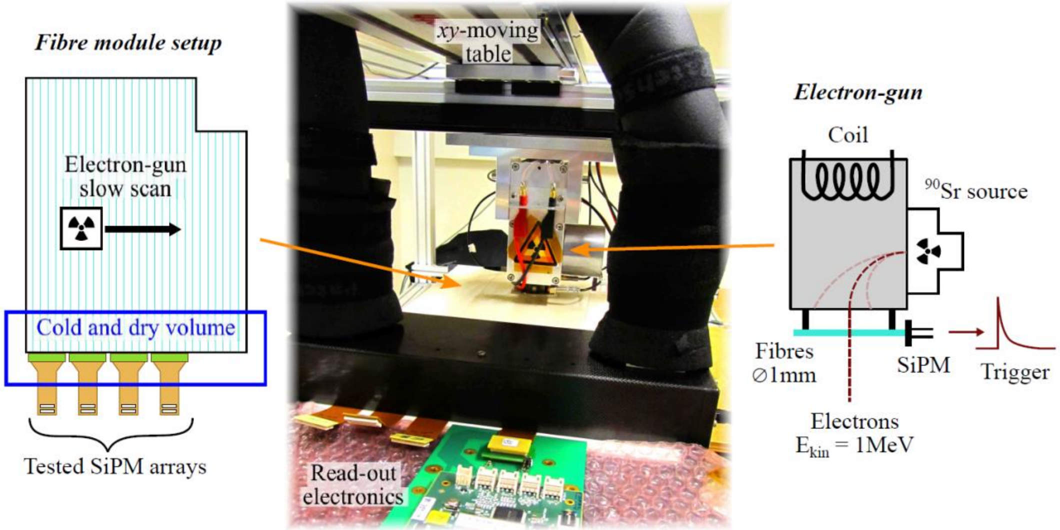


PACIFIC T=-40°C ΔV=3.5V





Light yield with irradiated SiPMs



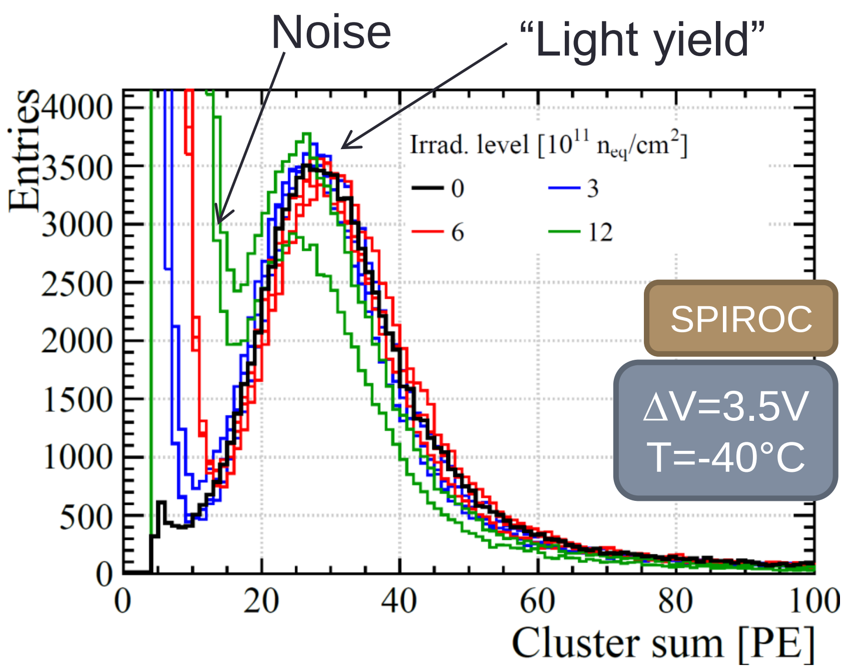
Electron injection in the fibres

- Comparative photon detection efficiency

Measurement

- Correction for DCR contribution
- 5% measurement uncertainty
- Light yield variation observed:

±4% up to $6{\cdot}10^{11}\ n_{eq}/cm^2$



Conclusion & outlook

SciFi technology

- Cost-efficient solution to cover large surface with good spatial resolution (<100 μm for 2.5 m, better for small size)
- Particularly interesting for applications with no radiations
- Can provide timing information ~0.5 ns

How can we make the SciFi technology radiation-harder?

Photodetector:

- SiPMs: improve structure and implementation
- Use a pixel sensor with amplification for visible light detection?
- Improve light collection: microlenses

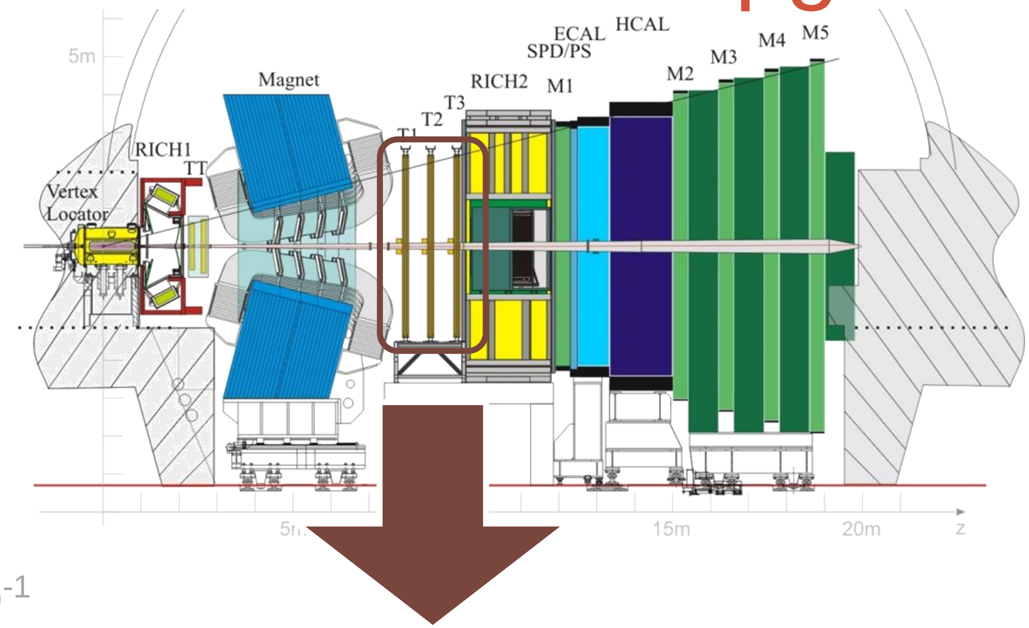
Fibre:

- Improve scintillation light yield in the green, reduce attenuation and improve radiation hardness
- Light transport outside the radiation environment with clear interface with optical fibre?

Backup

LHCb & the SciFi tracker

LHCb upgrade



Timescale during LS2 in 2019-2020

Goal extend physics reach with:

- Higher luminosity (5×)
- Better trigger efficiency for a wide range of decay channels
- Design for 50 fb^{-1} integrated luminosity Run1+2 (2011-now): 7 fb^{-1}

Detector changes

- 40 MHz read-out + flexible trigger (in software)
- Detector hardware: cope with increased occupancy and read-out rate

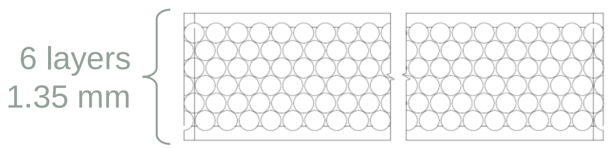
Downstream tracker is replaced:

silicon strips (IT) + straw tubes (OT) → **scintillating fibre (SciFi) tracker modules**

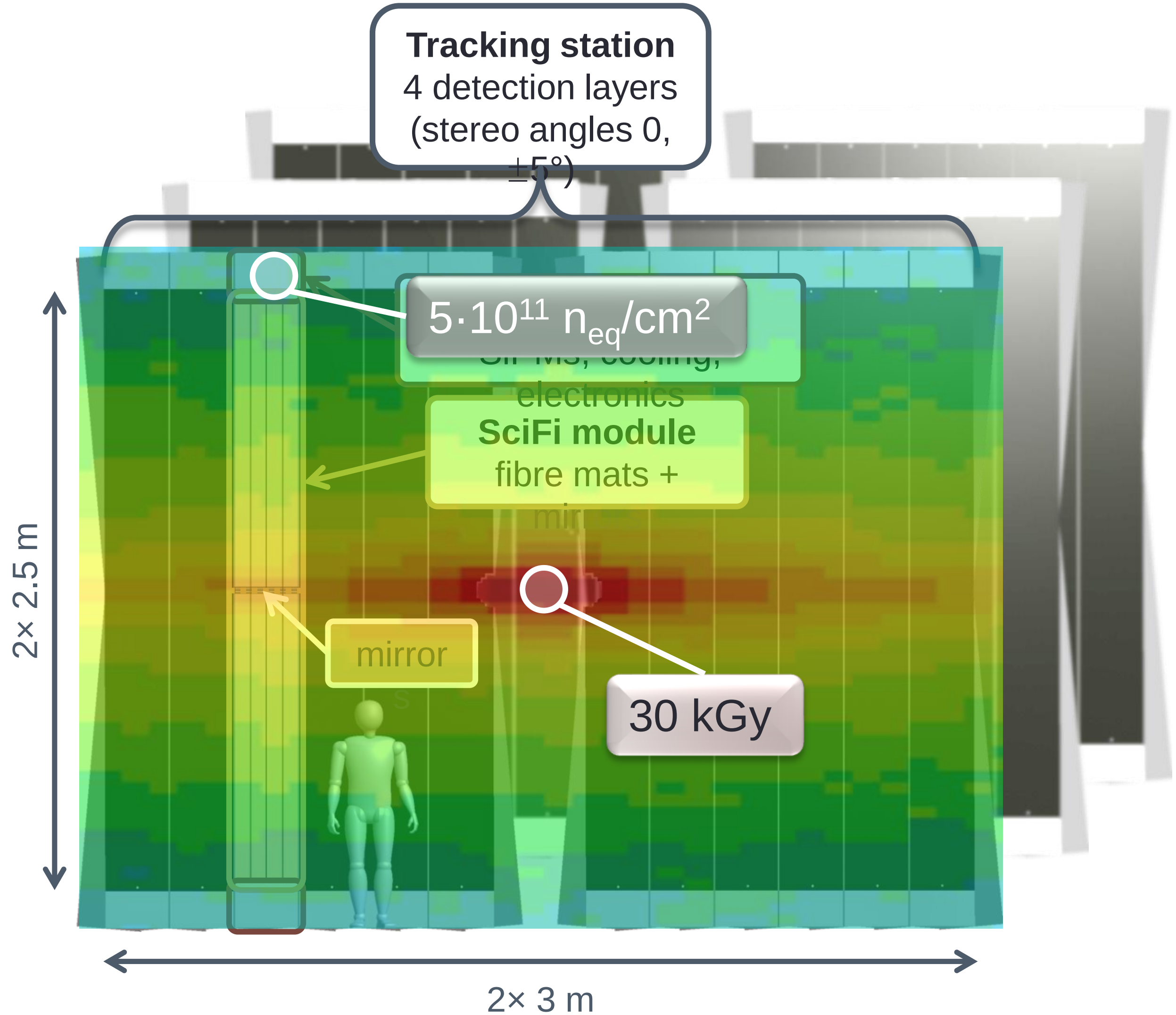
- ❑ *High hit detection efficiency*
- ❑ *Fine granularity*
- ❑ *Low mass (homogenous distribution)*

SciFi tracker

- Total area of 320 m^2
- 11’000 km fibres (∅250 μm) arranged in mats

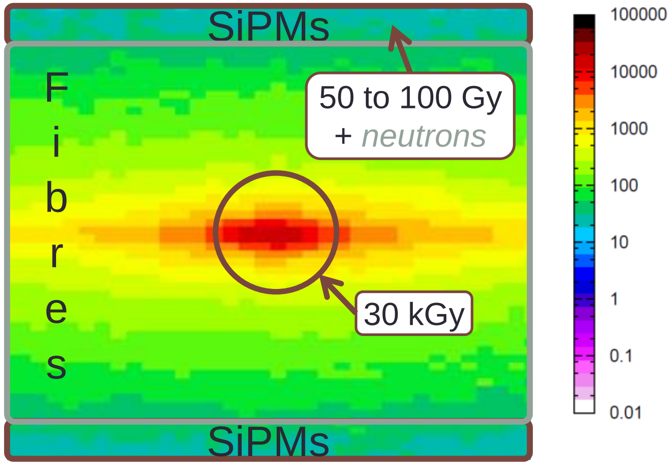


- 4000 multi-channel Silicon PhotoMultipliers (SiPMs) for a total of 524k read-out channels

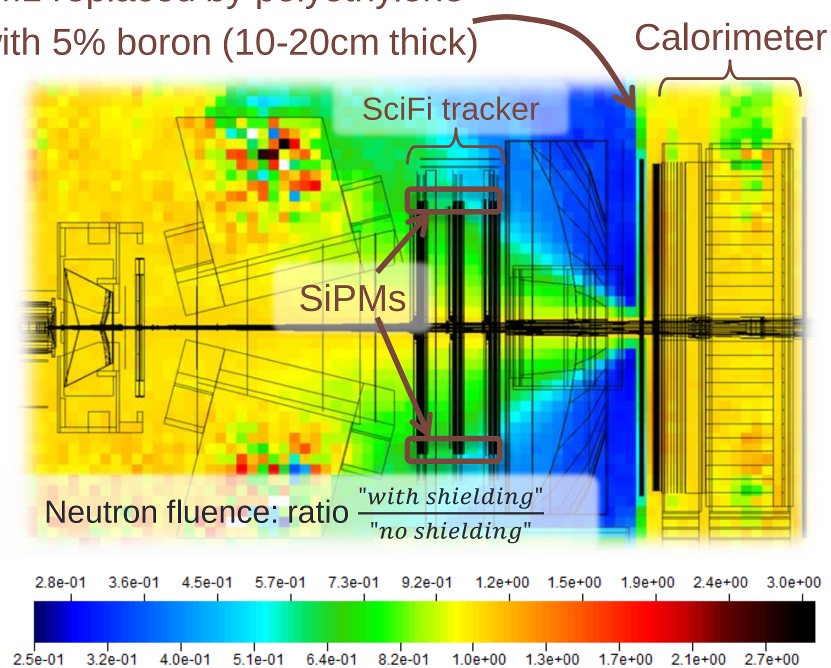


Radiation environment

Total ionising dose at the end of the lifetime of the SciFi tracker [Gy]



M1 replaced by polyethylene with 5% boron (10-20cm thick)



Simulation of the cumulated radiation after the design integrated luminosity (50 fb^{-1})

Fibres:

- In the central region: 30 kGy

SiPMs:

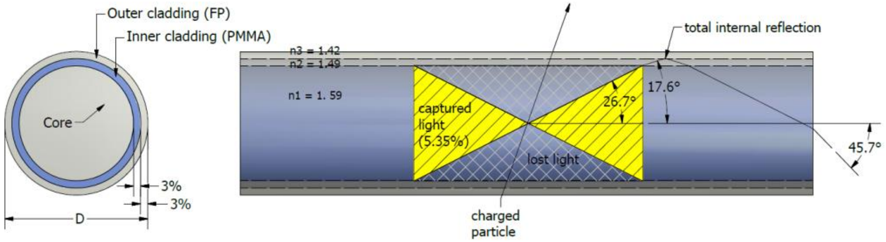
- Dominated by neutrons
- Neutron shielding between SciFi tracker and calorimeter
  - Fluence expected: $5 \cdot 10^{11}\, n_{eq}/cm^2$

Effect on the performance:

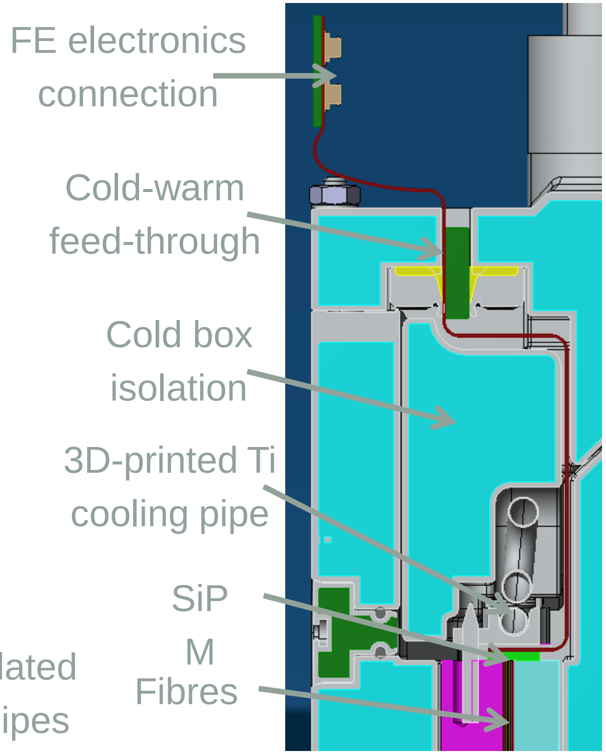
- Reduced transparency of the fibres
- Increase in SiPM noise

SciFi tracker

Kuraray SCSF-78MJ blue emitting fibre

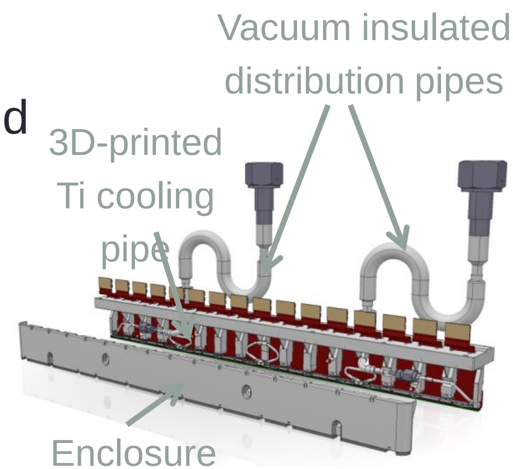


Cold box cross-section



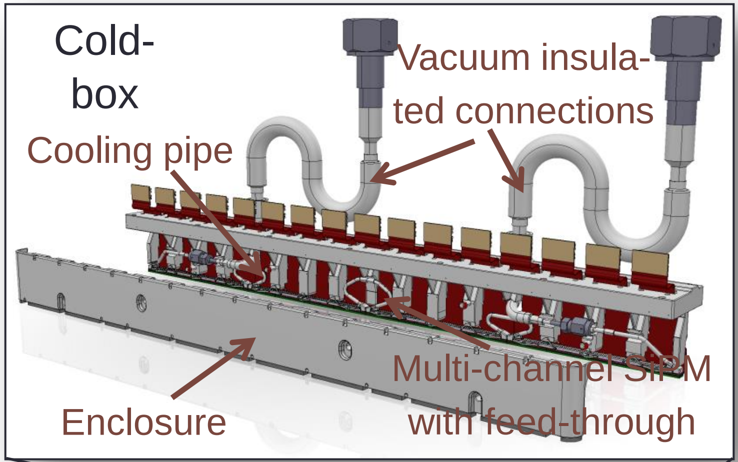
Challenges and design choices:

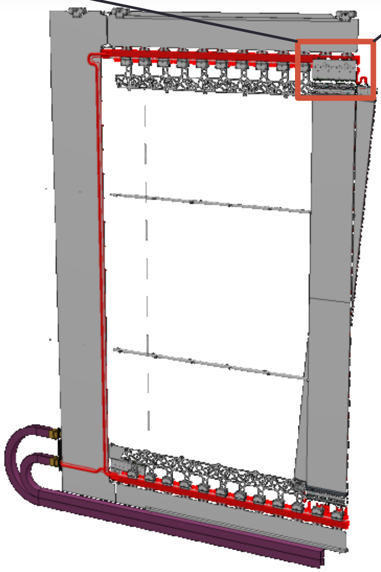
- Signal time spread: scintillator decay time and light transport
- Attenuation length: ~ size
- Large size: flatness and mechanical stability with low material budget
- Radiation environment (fibres and SiPMs): detection efficiency
- SiPM cooling (-40°C)



Integration of SiPMs in LHCb SciFi

- SiPM gluing to cooling pipe and optical alignment
- 3D printed Ti cooling pipe with alignment pins, thermal expansion and isolation are the main challenges
- Integration into a vapour tight cooling enclosure, vacuum insulated cooling pipes
- Cooling with single phase liquid chiller (Novec or C_6F_{14})
- Front-end electronics with custom read-out chip (Pacific)
  - Zero suppression (clusterisation) based on 3 threshold sampling
- Optical transmission, zero suppression on FPGA and GBT transmission
- Common off detector electronics TELL40

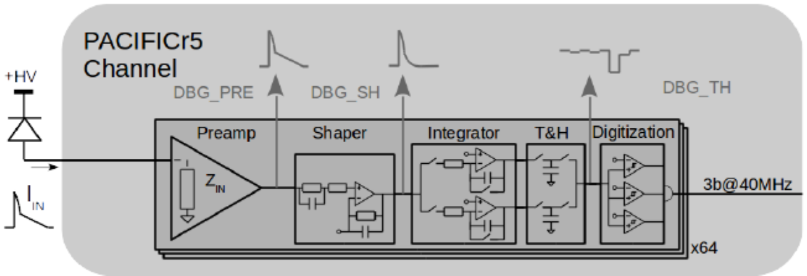


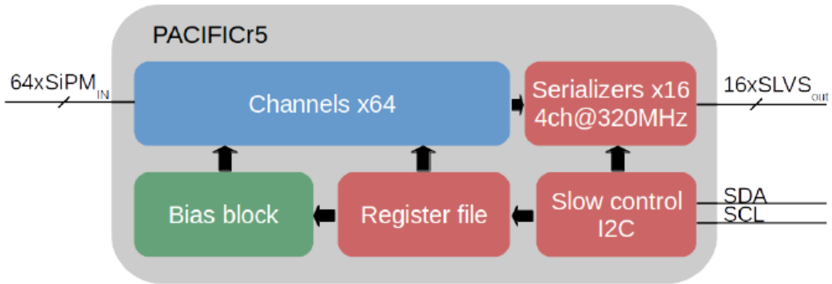


IEEE NSS MIC 2017

PACIFIC

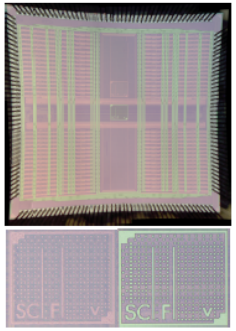
Low Power ASIC for the SCIntillator FIbres traCker





Channel processing chain:

- High bandwidth current input.
- Anode voltage control.
- Fast Shaper for tail adjustment.
- Double interleaved gated integrator.
- Track and hold.
- Digitization with 3 hysteresis comparators.
- Serialization and slow control (std cells).



4x3.85mm^2

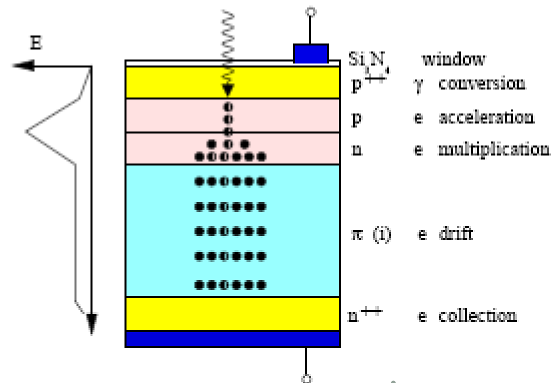
BGA package
$12 \times 12mm^2$ 196pins

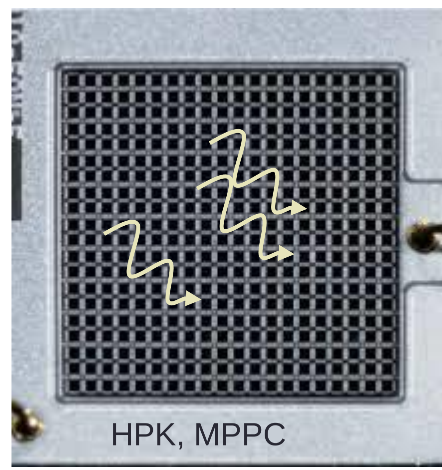
Backup
SiPM

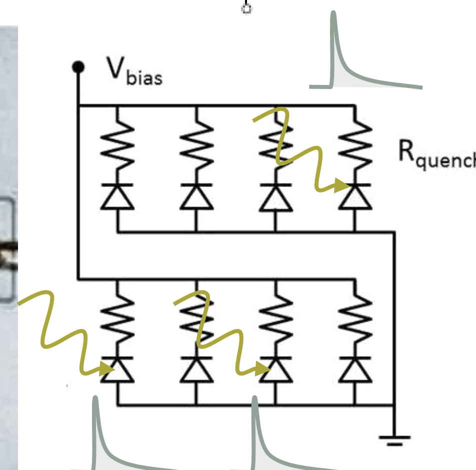
Silicon photomultipliers – working principle

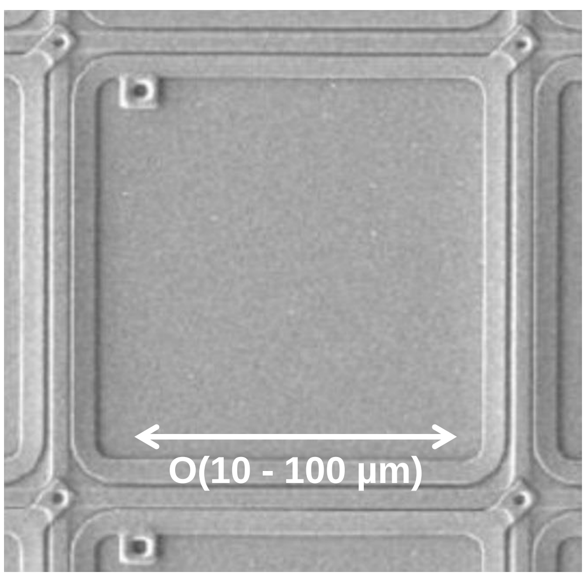
Based on avalanche photodiodes in GM-mode

- Internal amplification (gain ~10^6) through impact ionisation
- Operated above the breakdown voltage V_{BD} (GM-APD)
- Quenching circuit (ex. R_Q) and cell recovery
- Photon counting: array of GM-APDs in parallel
- Photon detection efficiency
  - PDE = QE(λ) × FF × $P_{01}(\Delta V)$

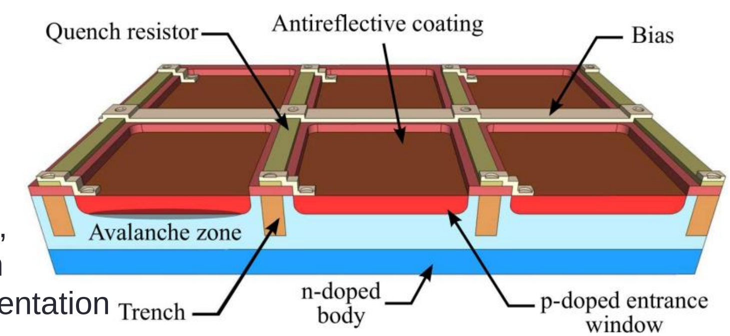



HPK, MPPC





HPK, thin metal film R_Q

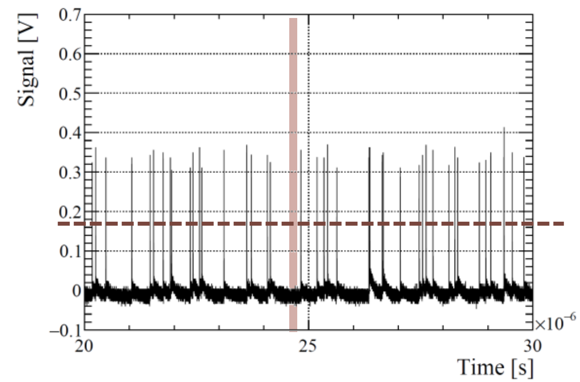


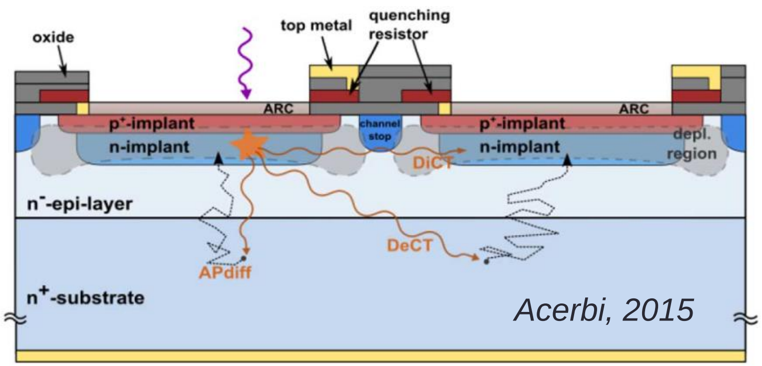
KETEK, Custom implementation

Noise sources

Random noise – Dark count rate (DCR)

- Thermally-generated e-h pair ~100 kHz/mm^2
- Increased by irradiation 30’000×
  - ☒ Overlap of pulses (high signals)
  - ☑ Reduced by cooling (÷2 per 10°C) and short integration time window

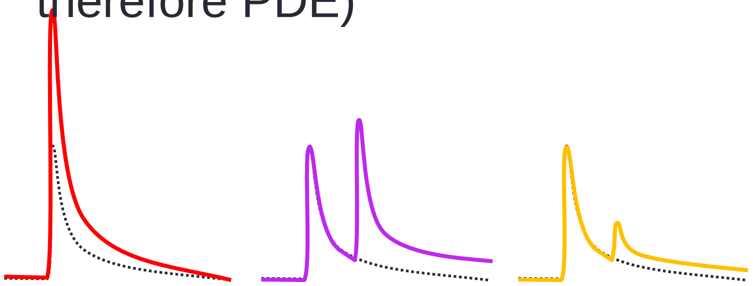




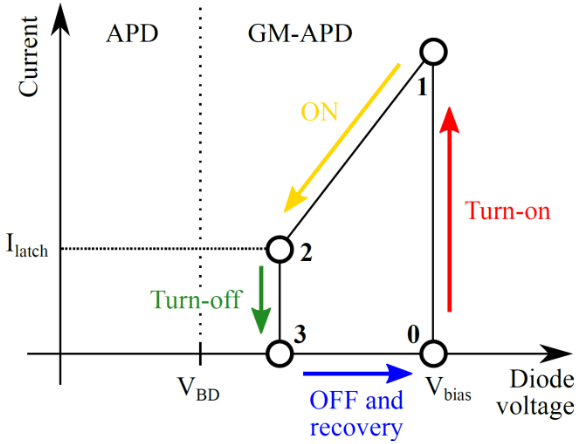
Acerbi, 2015

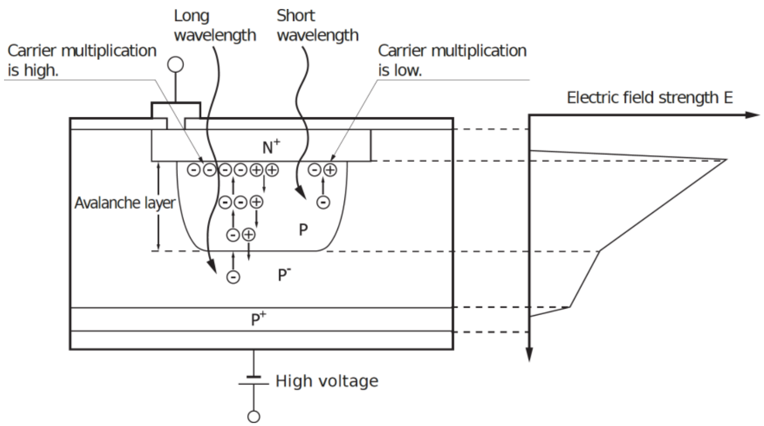
Correlated noise

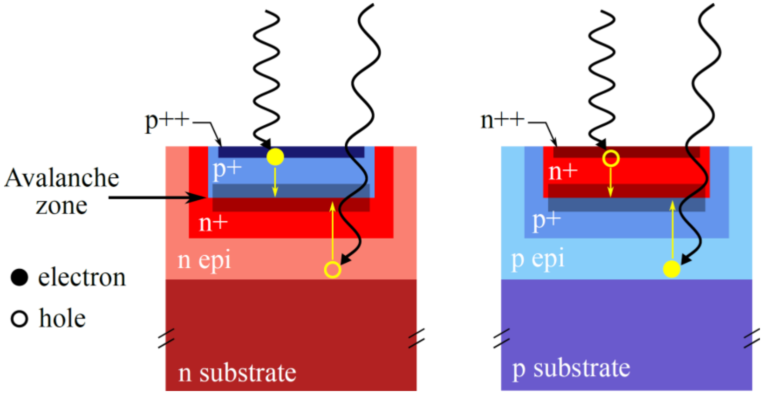
- Avalanches generated ~simultaneously
- DiXT, DeXT, AP
- ☒ Limits the operation range (and therefore PDE)

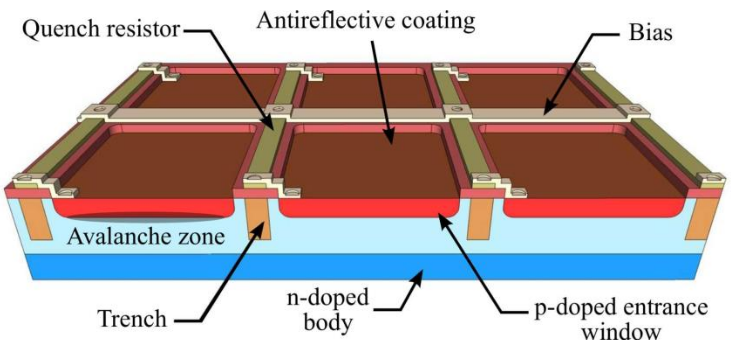


Working principle bonus



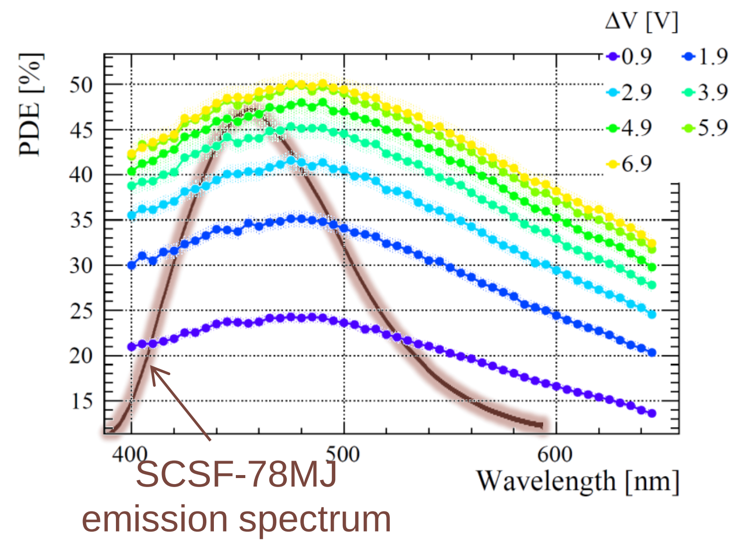


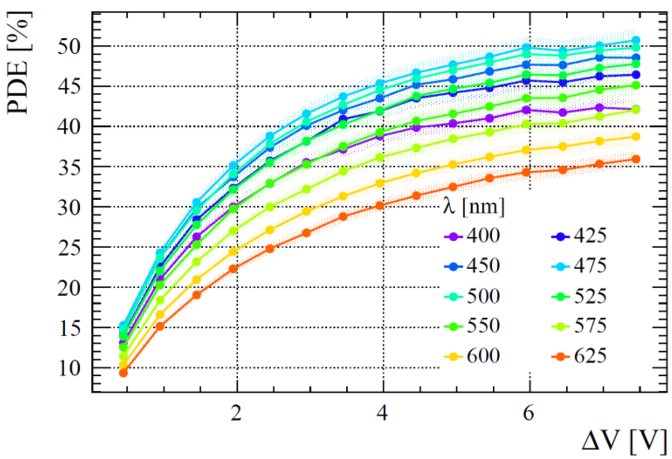




Photon detection efficiency

- Calibration using a photodiode
- Two independent methods: SiPM current and pulse frequency under illumination
- Accurate corrections for correlated noise (and dark)
- Estimated uncertainty on PDE: 6.0% / 3.5%





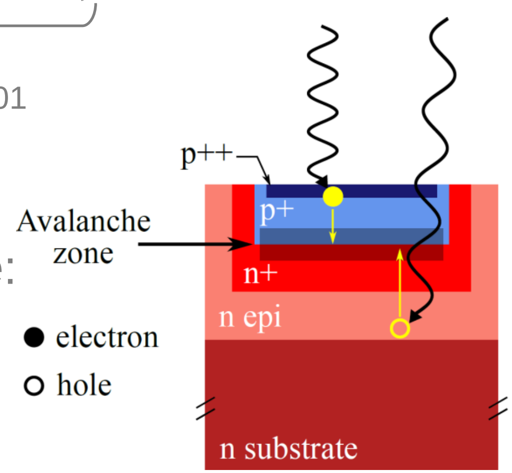
$$\mathrm{PDE}(\Delta V) = b \cdot \underbrace{\left(1 - e^{-\Delta V/a}\right)}_{P_{01}}$$

b: QE·FF

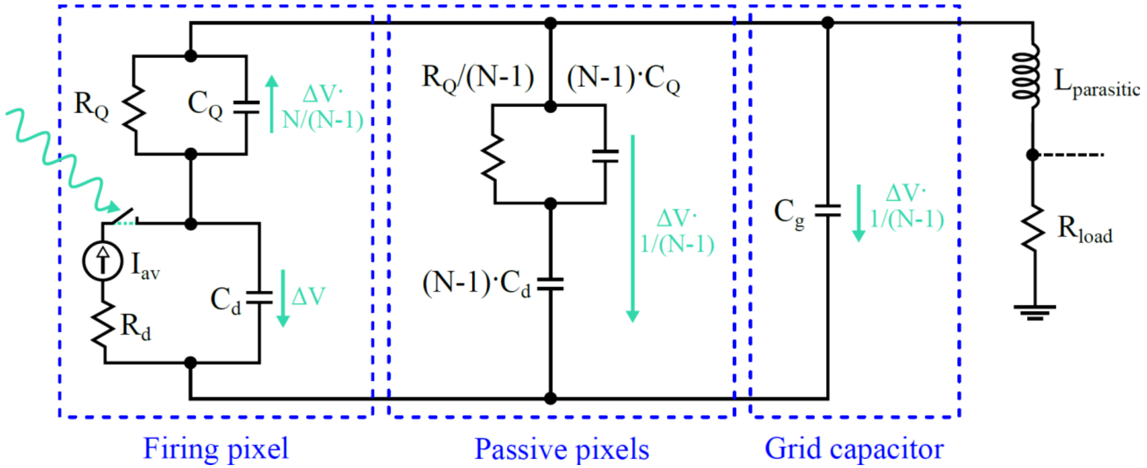
~50% @ peak

For *p*-on-*n* structure:

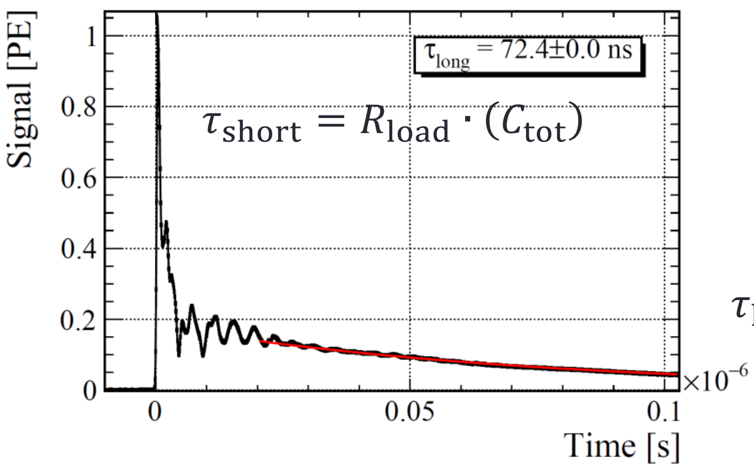
$a(\lambda) > a(\lambda)$



SiPM electrical model



$$\tau_{\mathrm{d}} = R_{\mathrm{d}} \cdot (C_{\mathrm{d}} + C_{\mathrm{Q}})$$



$$\tau_{\mathrm{short}} = R_{\mathrm{load}} \cdot (C_{\mathrm{tot}})$$

$$\tau_{\mathrm{long}} = R_{\mathrm{Q}} \cdot (C_{\mathrm{d}} + C_{\mathrm{Q}})$$

Backup

SiPM characterisation

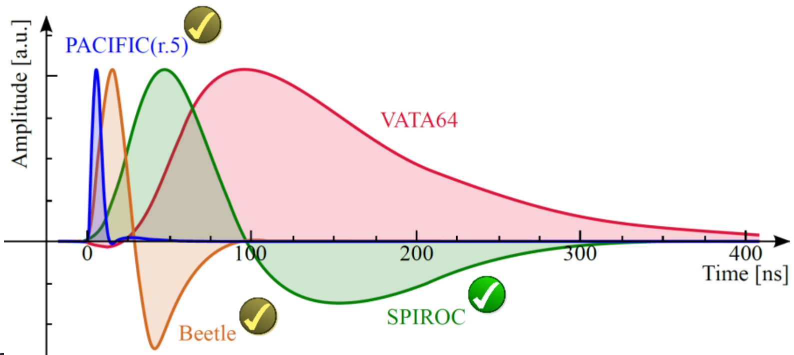
Measurement setups

Single-channel based setups

- Fast preamplifier and oscilloscope — Pulse shape ✓ | Correlated noise ✓ | PDE | Gain
- IV scan (ev. with multiplexer) — V_{BD} ✓ | DCR ✓ | R_Q ✓

Multichannel arrays

- Use integrated front-end ASICs
- Signal is integrated and/or shaped

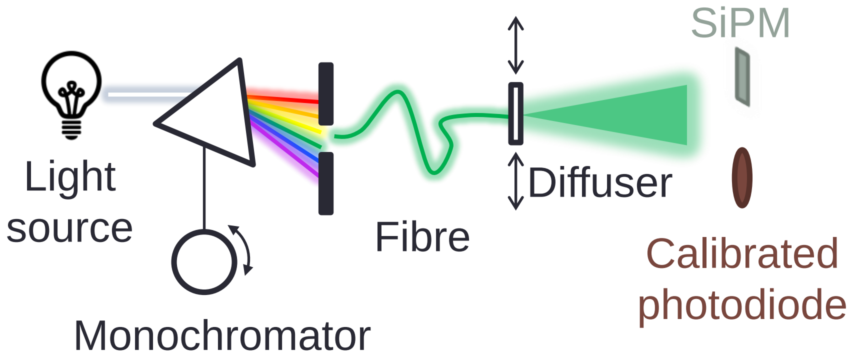


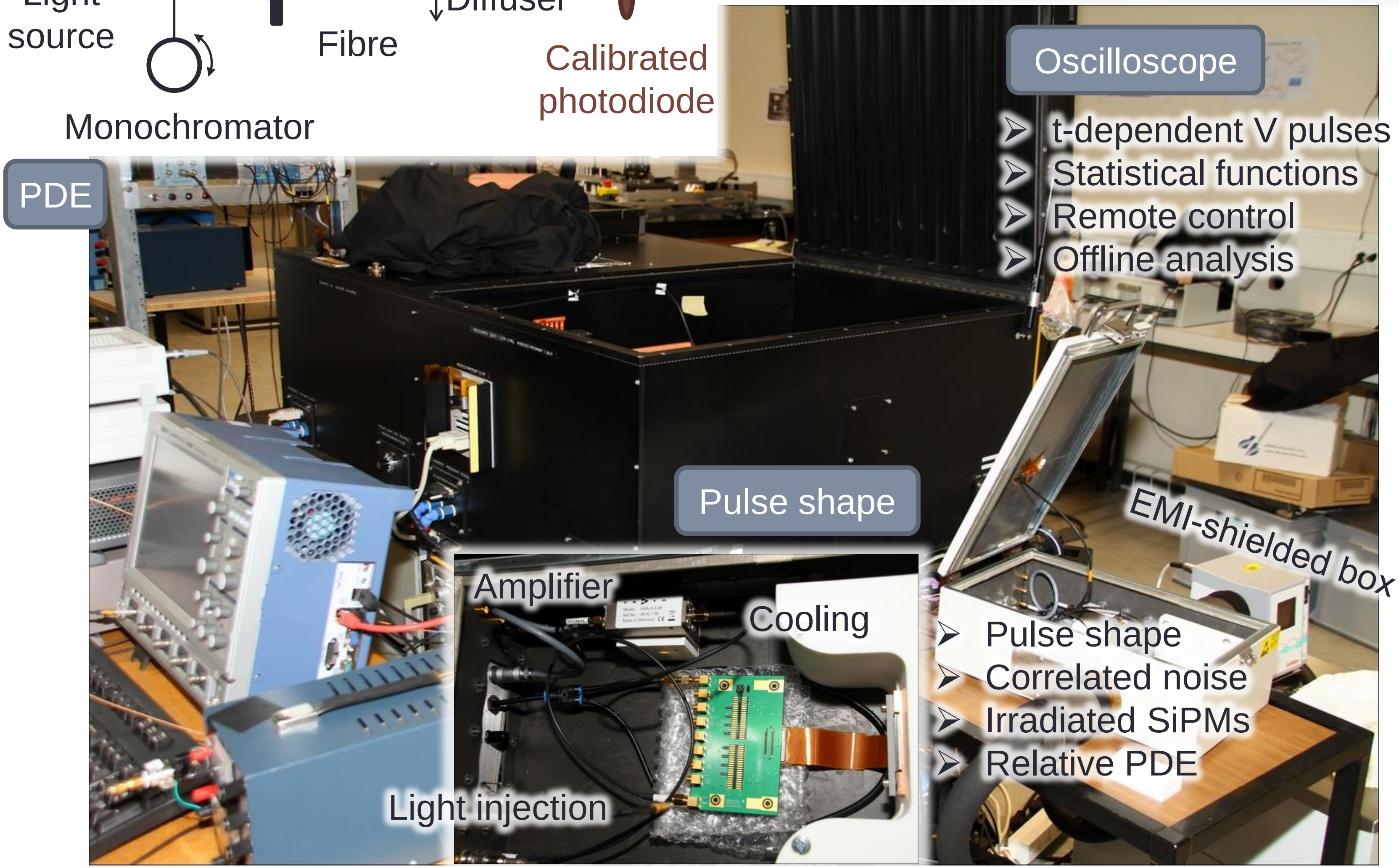
- Pulsed light injection — V_{BD} ✓ | Gain ✓
- Fibre mat and electron-gun — PDE ✓ | Gain | NCR ✓

Suitable for irradiated SiPMs (up to 10^{12} 1MeV n_{eq}/cm^2)

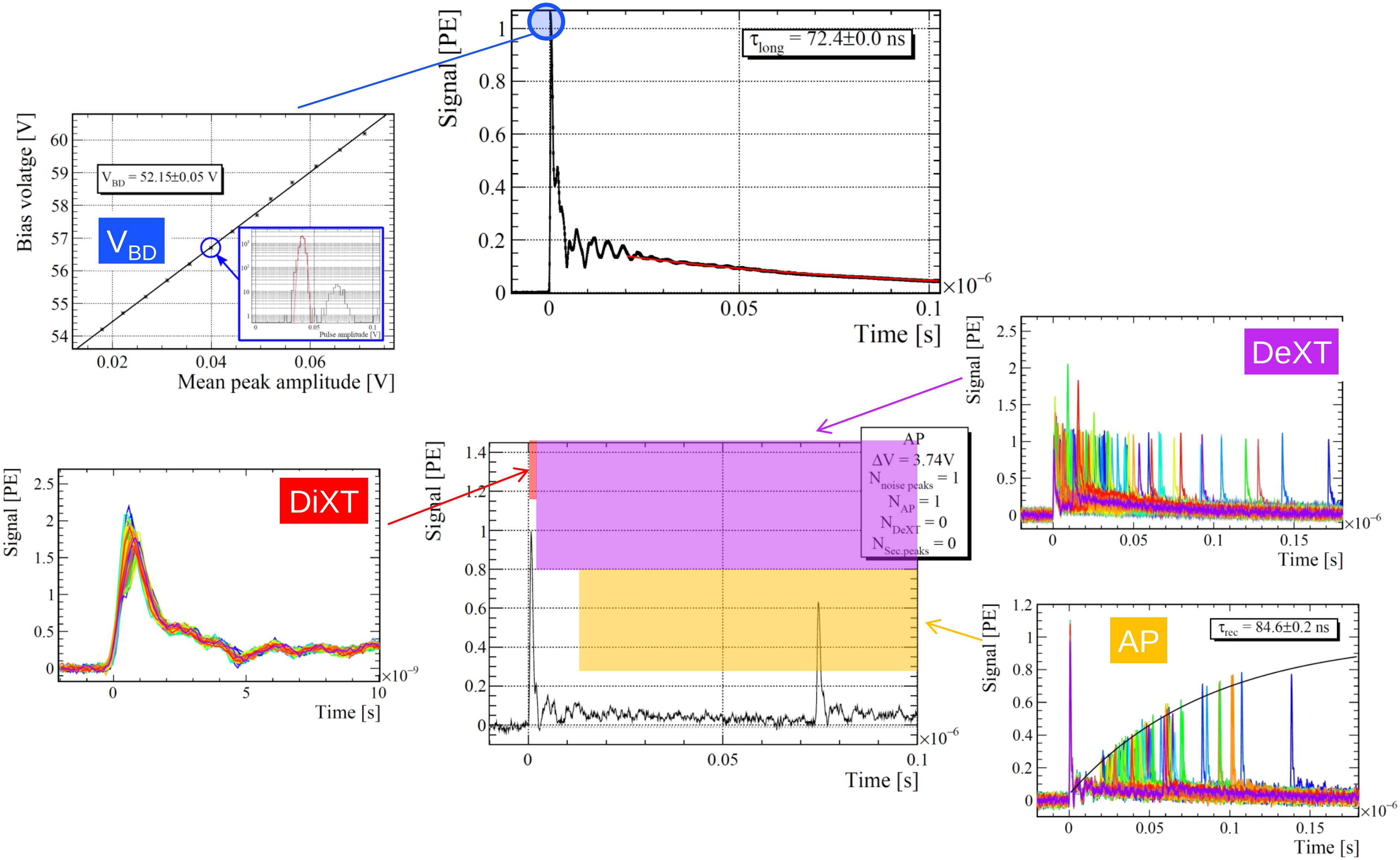
Oscilloscope setup

Measurements on single channel

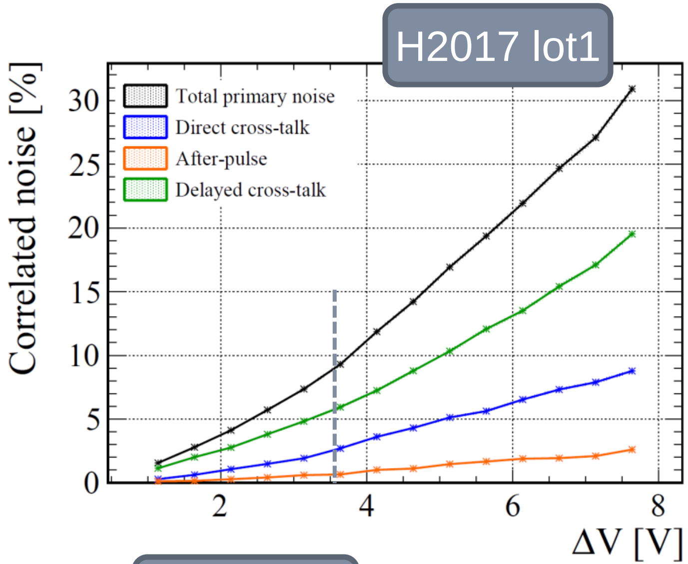


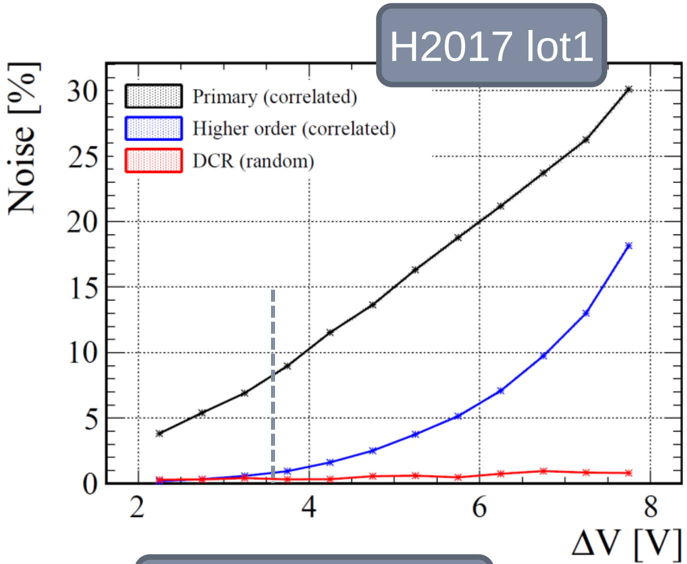


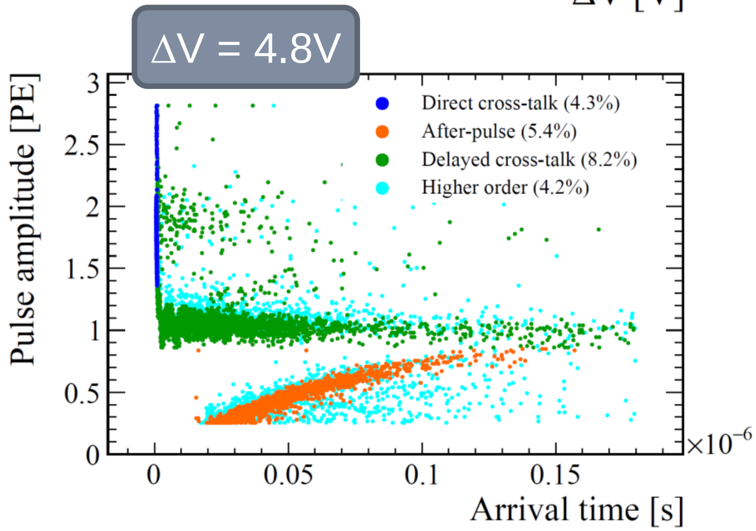
Pulse shape and correlated noise

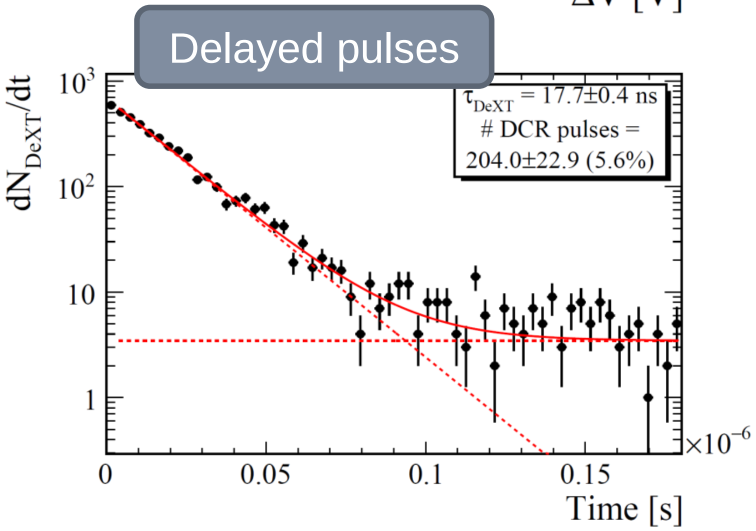


Correlated noise – H2017





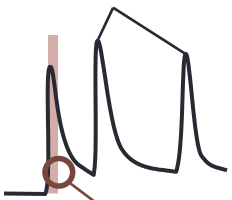




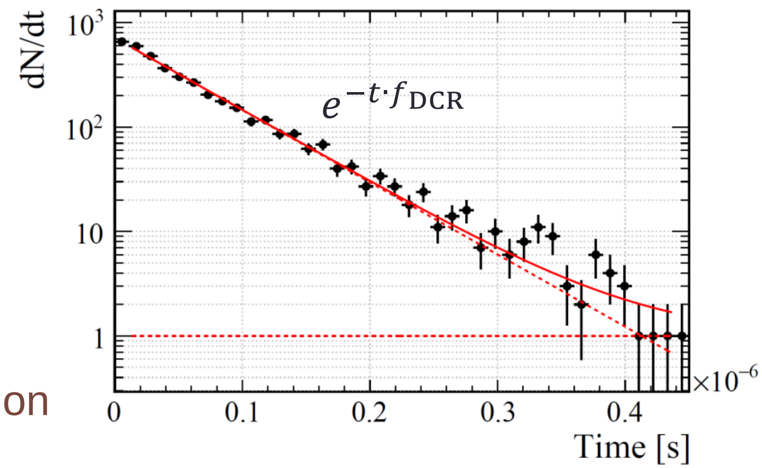
Waveform analysis – irradiated detectors

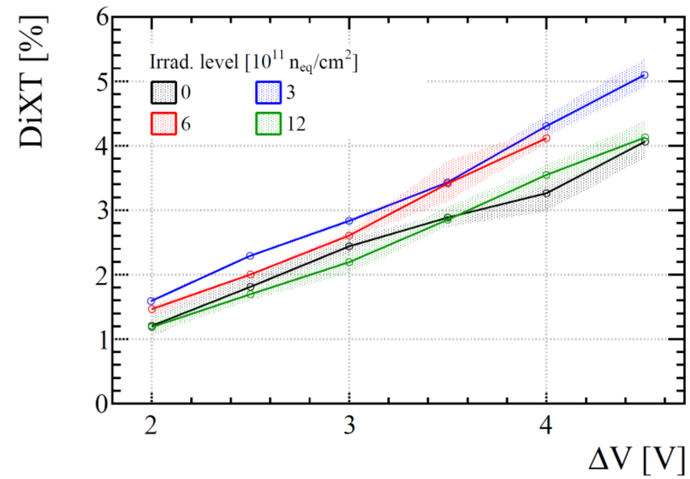
DiXT

High DCR

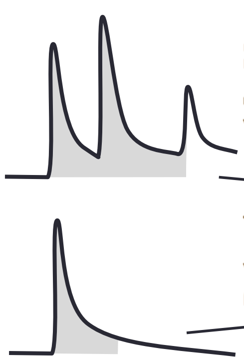


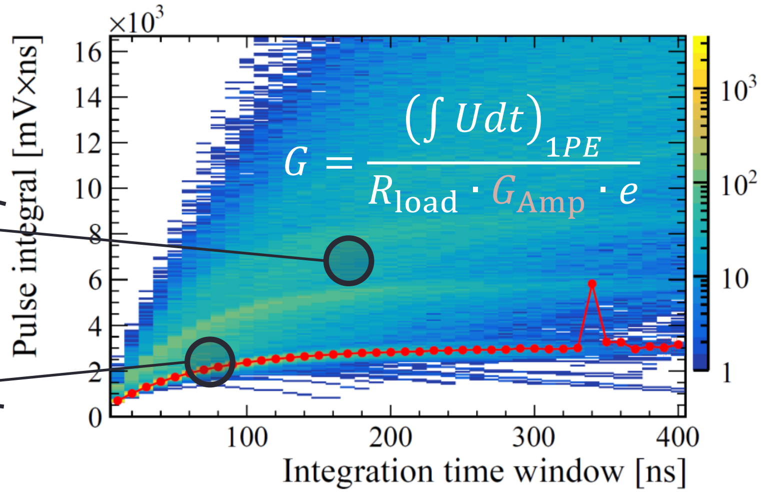
DiXT detection

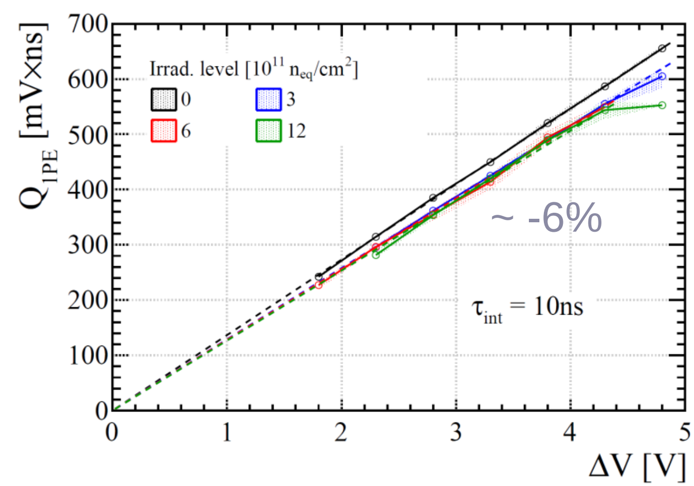


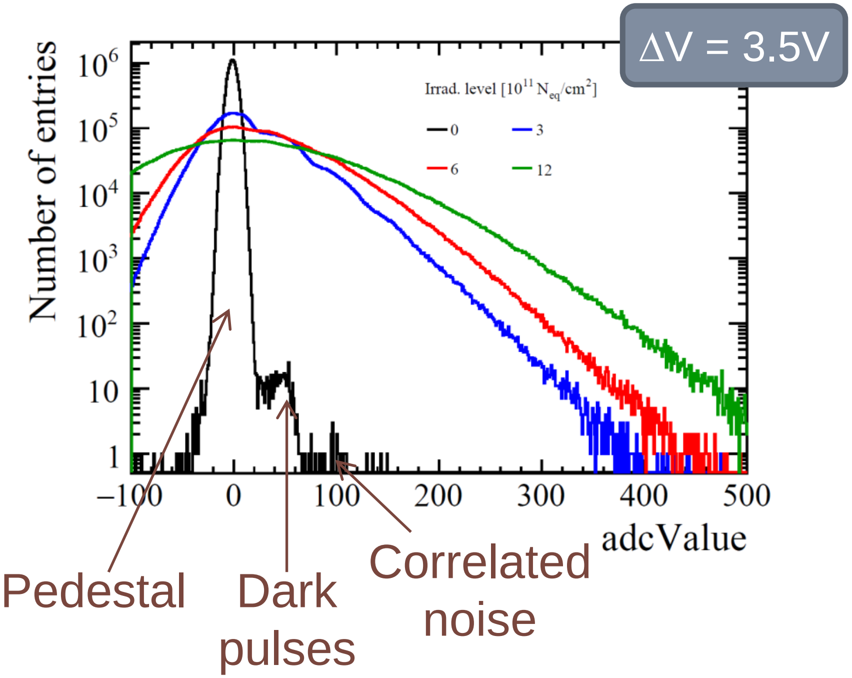


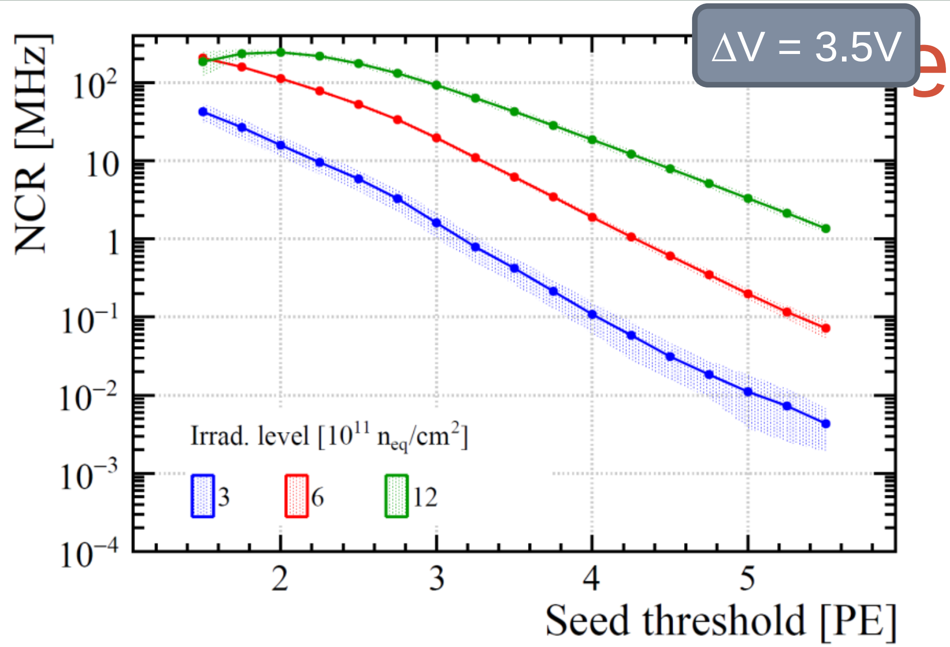
Relative gain

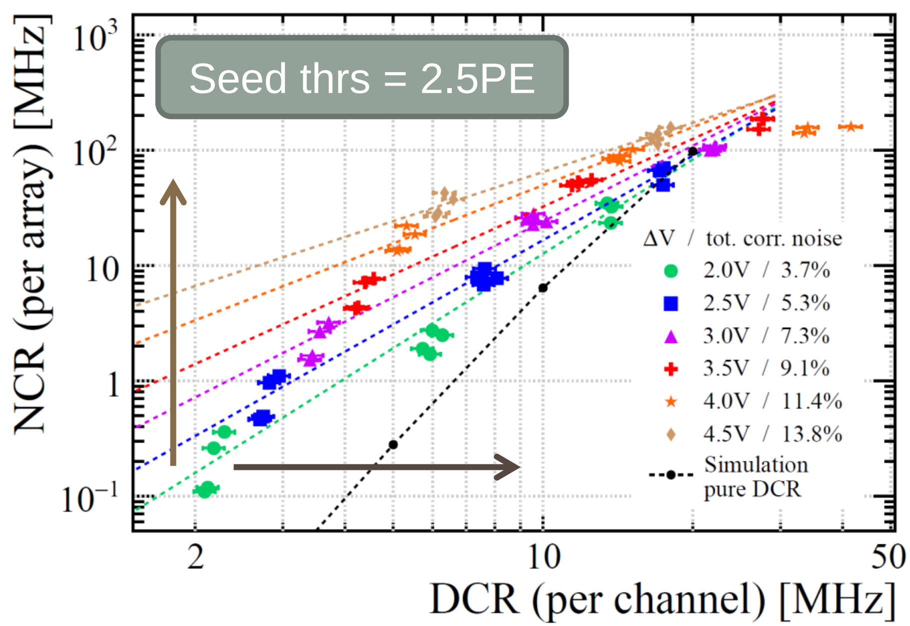






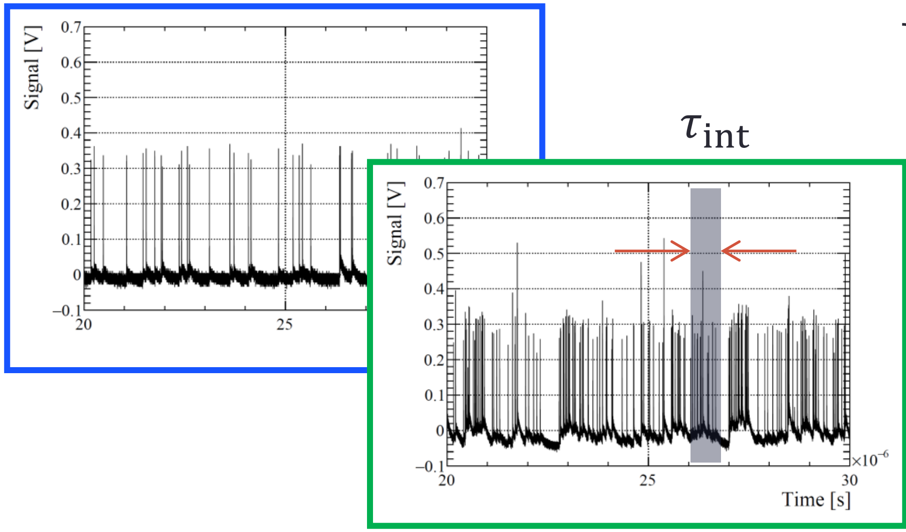






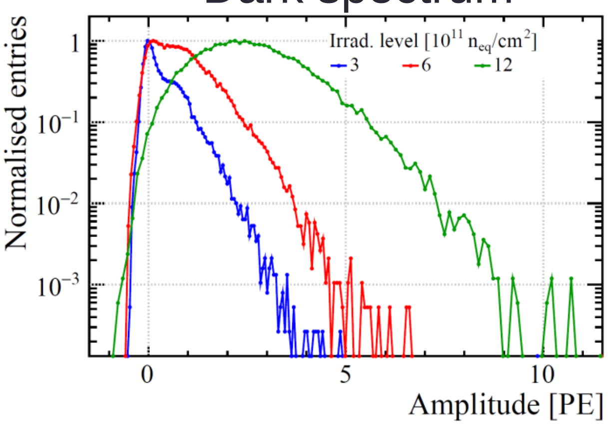
- NCR computed for 128-channel array read out at 40MHz
- Strong dependence on the electronics shaping (here: **SPIROC**)
- Contributions from random pulse overlap and correlated noise

Noise cluster rate – simulation

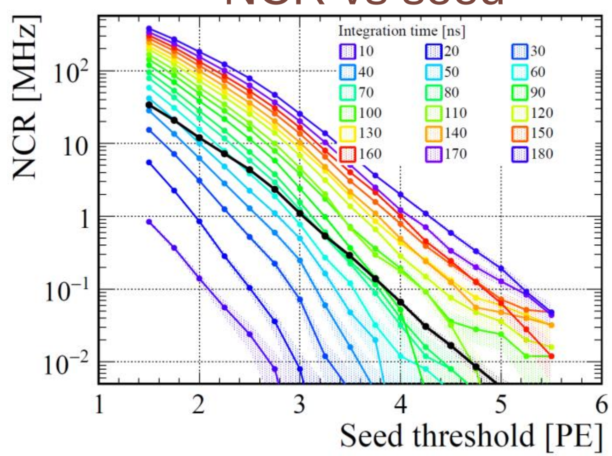


- Long waveforms acquired on the oscilloscope
- Numerical integration by sections of length τ_{int}
- Simulation of 128-channel array
- Clustering: measurement of NCR as a function of τ_{int}
- Values in the range expected from measurement with PACIFIC

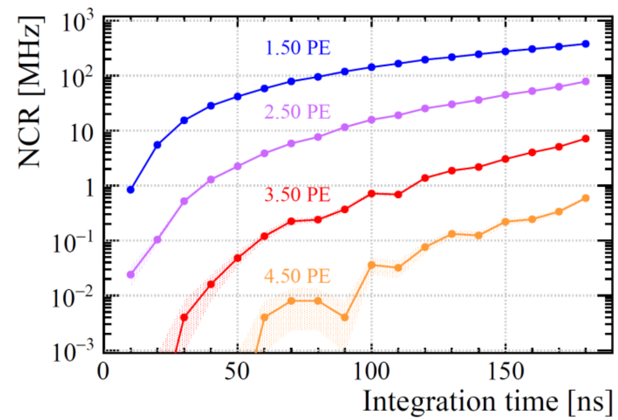
Dark spectrum



NCR vs seed



NCR vs τ_{int}

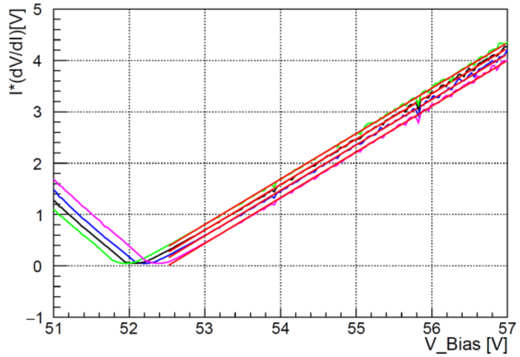


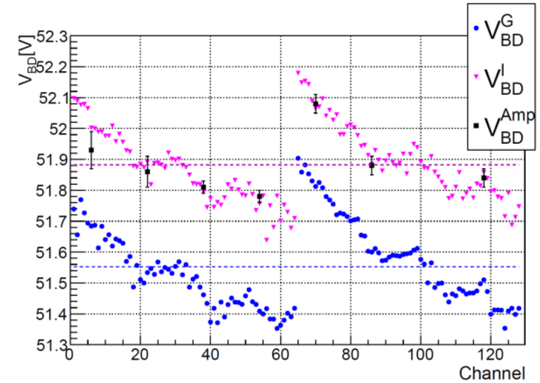
Dark count rate after irradiation

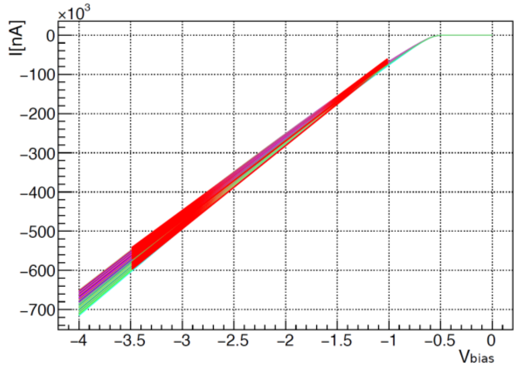
- Fast, simple and robust
- V_{BD}: $I(V_{\text{bias}}) = \alpha \cdot (V_{\text{bias}} - V_{\text{BD}})^{\varepsilon}$

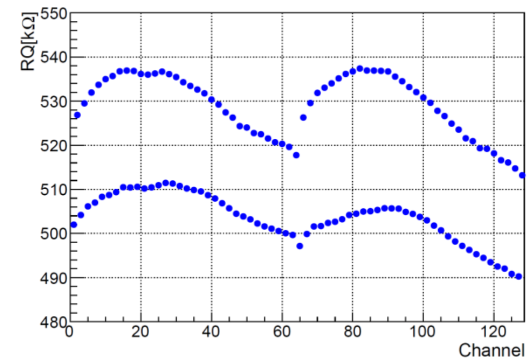
$$\Rightarrow \left[\frac{\mathrm{d}\ln(I)}{\mathrm{d}V_{\text{bias}}}\right]^{-1} \propto \Delta V$$

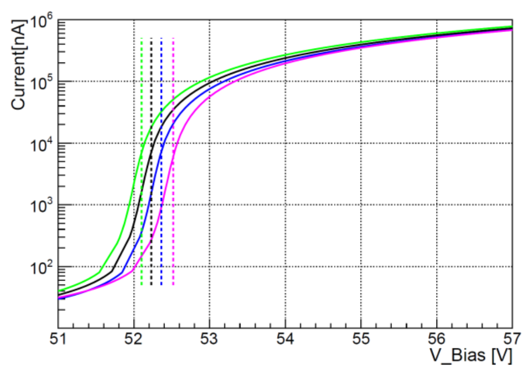
- $R_Q(T)$ for scan in forward bias region
- DCR(ΔV, T)

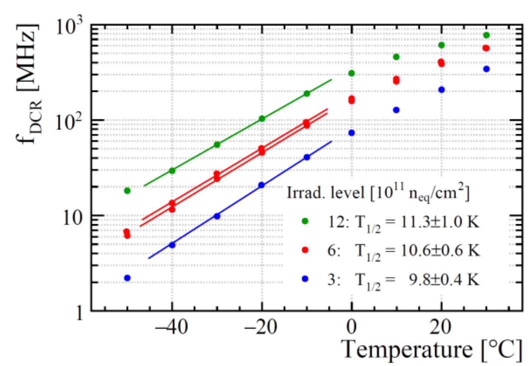












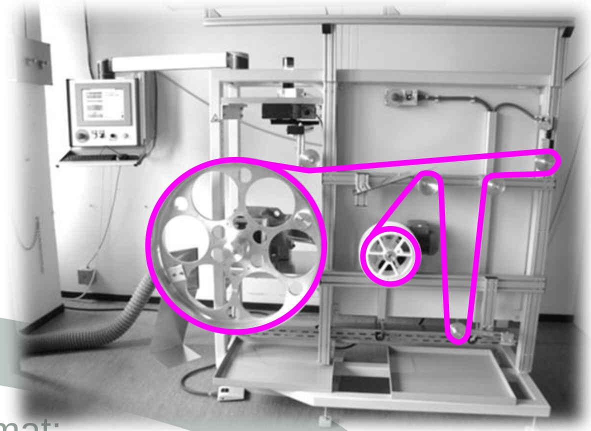
Backup

SciFi tracker fabrication

Fibre tracker production

1. Fibre QA
- Optical properties
- Mechanical

2. Mat
- Custom machine
- Total of 1200 mats
- Four production centres (including EPFL)
- High quality mat: 2.5 m × 13 cm, 6 fibre layers



Related posters:

P. Hopchev, *Production and quality assurance of scintillating fibre modules for the LHCb upgrade*.

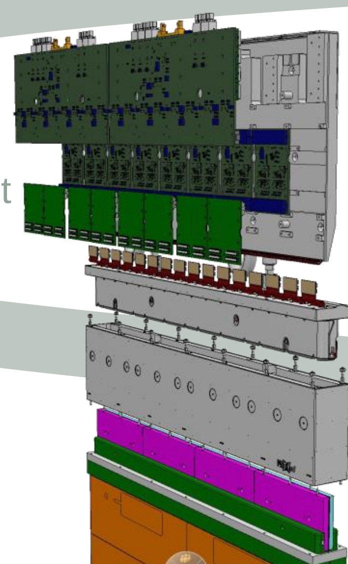
3. Mat
- Uniform light yield (β-source)
- Optical scanner

SiPMs (EPFL)

Cooling

FE electronics

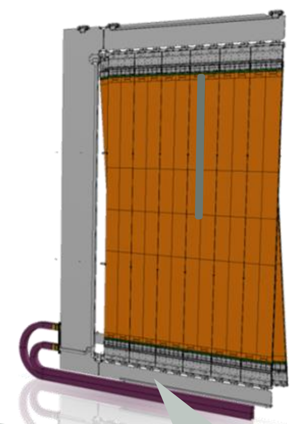
4. Module
- Special modules with beam pipe cut out
- Rigidity: honeycomb panels
- 5 m × 53 cm



Infrastructure

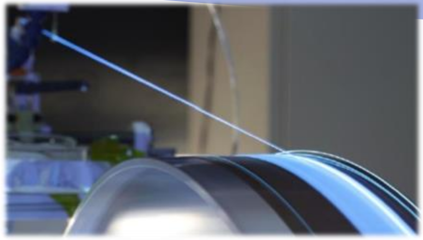
Frames

5. Integration in
- Cabling
- Cooling distribution
- Neutron shield



Mat production steps

1. **Winding**

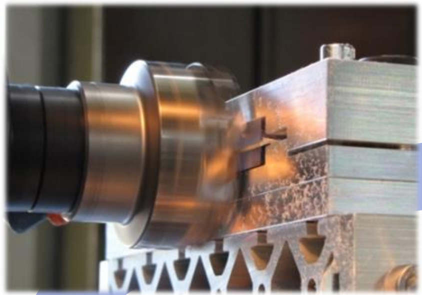


2. **Glue curing** with wheel rotating for 12h in an area with controlled humidity and temperature

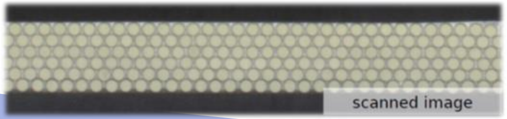
3. **Cutting and unforming**

4. **Foil lamination** with black 25 μm thick capton foil (both sides, ensures light tightness) and **end piece glueing**

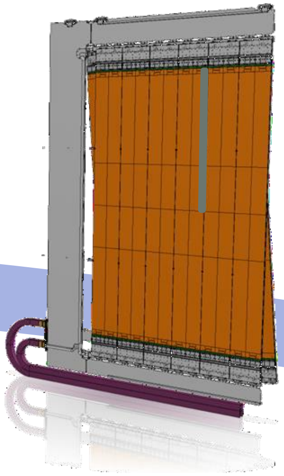
5. **Optical cut** with a milling machine (polishing with a diamond head)



6. **Mirror glueing**



7. **QA tests** with optical scanner and β-source (light yield homogeneity)



8. **Delivery** to Heidelberg and Nikhef for module assembly + integration of SiPMs, cooling and FE electronics

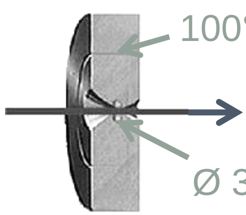
QA for Scintillating fibres

Fibres are produced by Kuraray (300 km every two weeks) and delivered at CERN where quality assurance tests are performed.

Goal of QA:

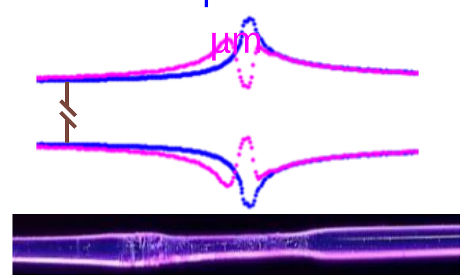
1. Acceptance test regarding optical and scintillation properties:
   - Attenuation length with UV LEDs
   - Scintillation yield with beta source
   - Irradiation tests with X-ray source
2. Removal of fibre sections out of mechanical specification ensuring high quality fibre mat production
   - Fibre defects (large diameter fluctuation) «bump» identified with laser micrometer scanner
   - Bump shrinking with heating element or cutting

Bump shrinking is fully automatic and it preserves fibre strength, cladding and 85% light transmission.

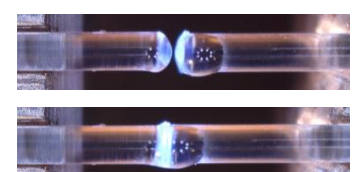


Example:

Before 415 µm → After 337 µm



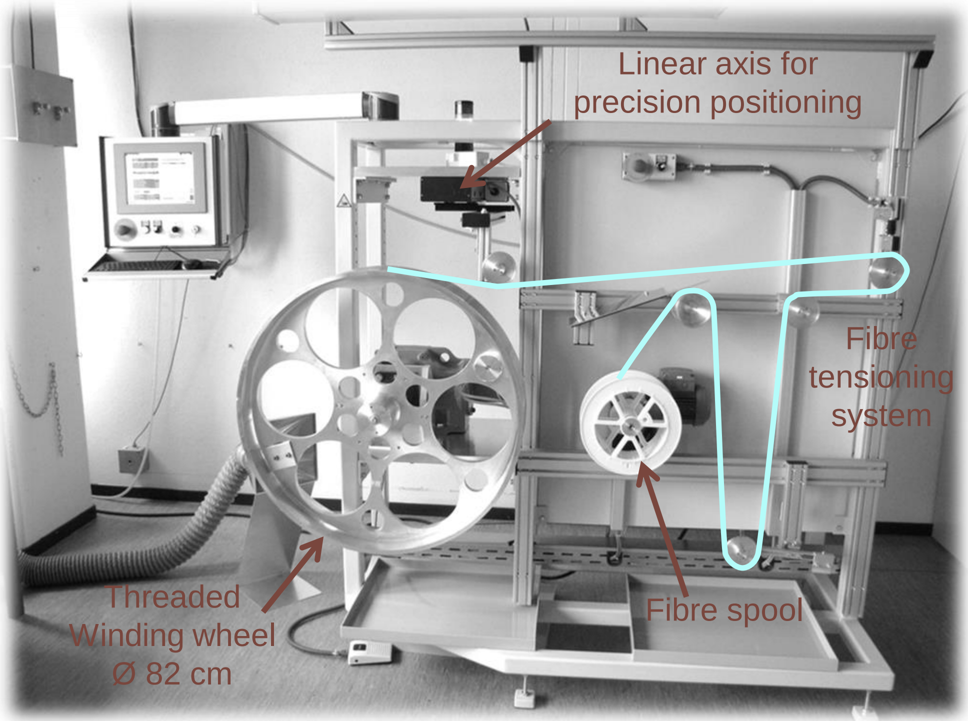
Fiber Bumps larger than 500 µm must be cut away and the fibre re-glued (~15 min, 1-2×/spool).



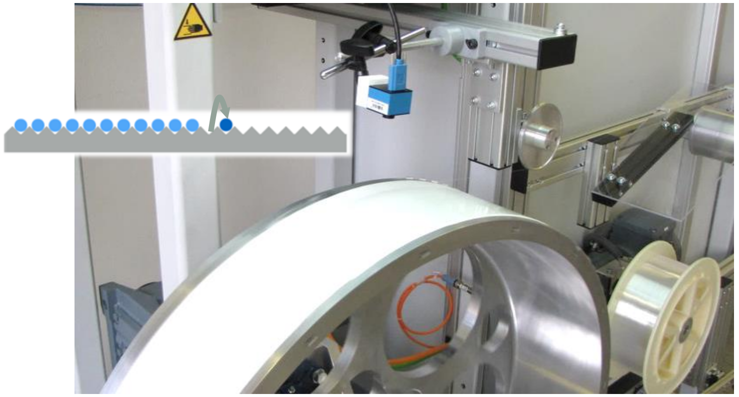
~**1200 mats** required for the SciFi tracker
Aimed production rate: 4 mats/week/site

Fibre mat winding

- Four production centres: RWTH Aachen and TU Dortmund (DE), EPFL (CH) and Kurchatov Institute (RU)
- Custom winding machine produced by an industrial company (one per winding centre)
- Fibre mat of 2.5 m length × 13 cm width, 6 fibre layers with a total of 7 km of fibres
- Mat winding takes 4h (1 per day)



Visual monitoring to detect fibre jumps

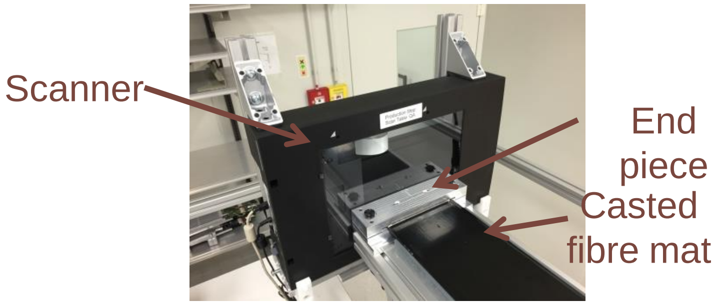


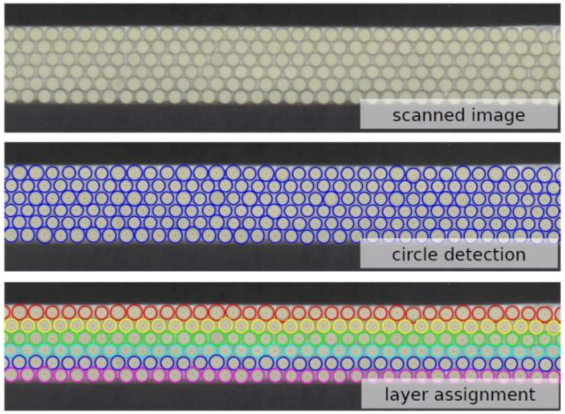
Alignment pin groove in the wheel, filled with glue during winding, allows precision positioning at later production steps

Mat quality controls

Mat transverse geometry:

- Checks for distorted or missing fibres with an automated optical scanning and fibre detection





Mat response uniformity:

- Measurement of light yield with an electron source