SciFi – A large Scintillating Fibre Tracker for LHCb

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on behalf of the LHCb-SciFi-Collaboration

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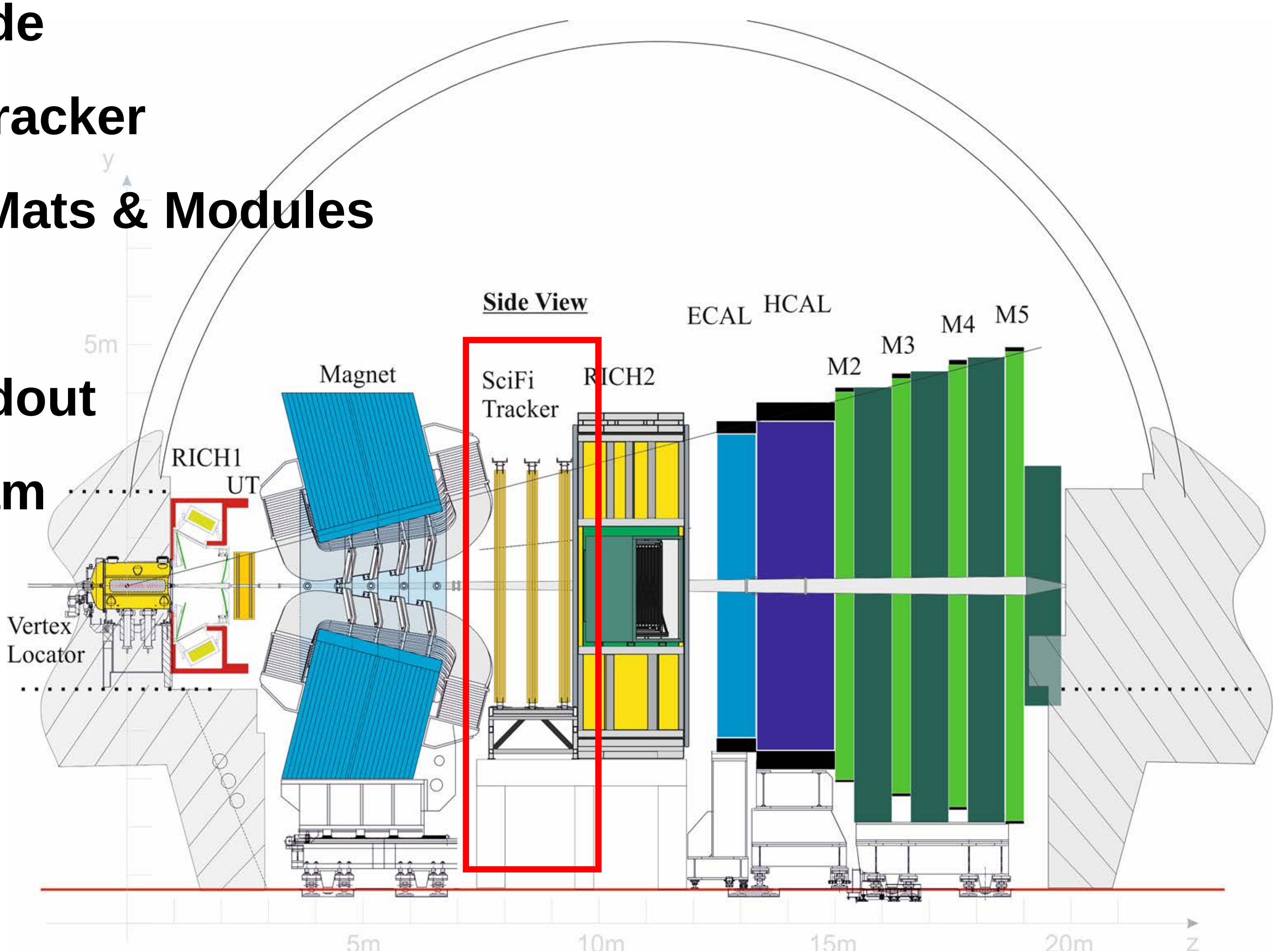
***)** 18 institutes : CBPF (BRA), EPFL (CH), Tsinghua (CN), Aachen, Dortmund, Heidelberg, Rostock (GER), Clermont-Ferrand, LAL, LPNHE (FRA), Nikhef (NL), Warsaw (POL), Kurchatov, ITEP, INR (RUS), Barcelona, Valencia (SPA), CERN

Outline

- **LHCb Upgrade**
- **LHCb SciFi tracker**
  - **Fibres Mats & Modules**
  - **SiPMs**
  - **FE Readout**
  - **Testbeam**

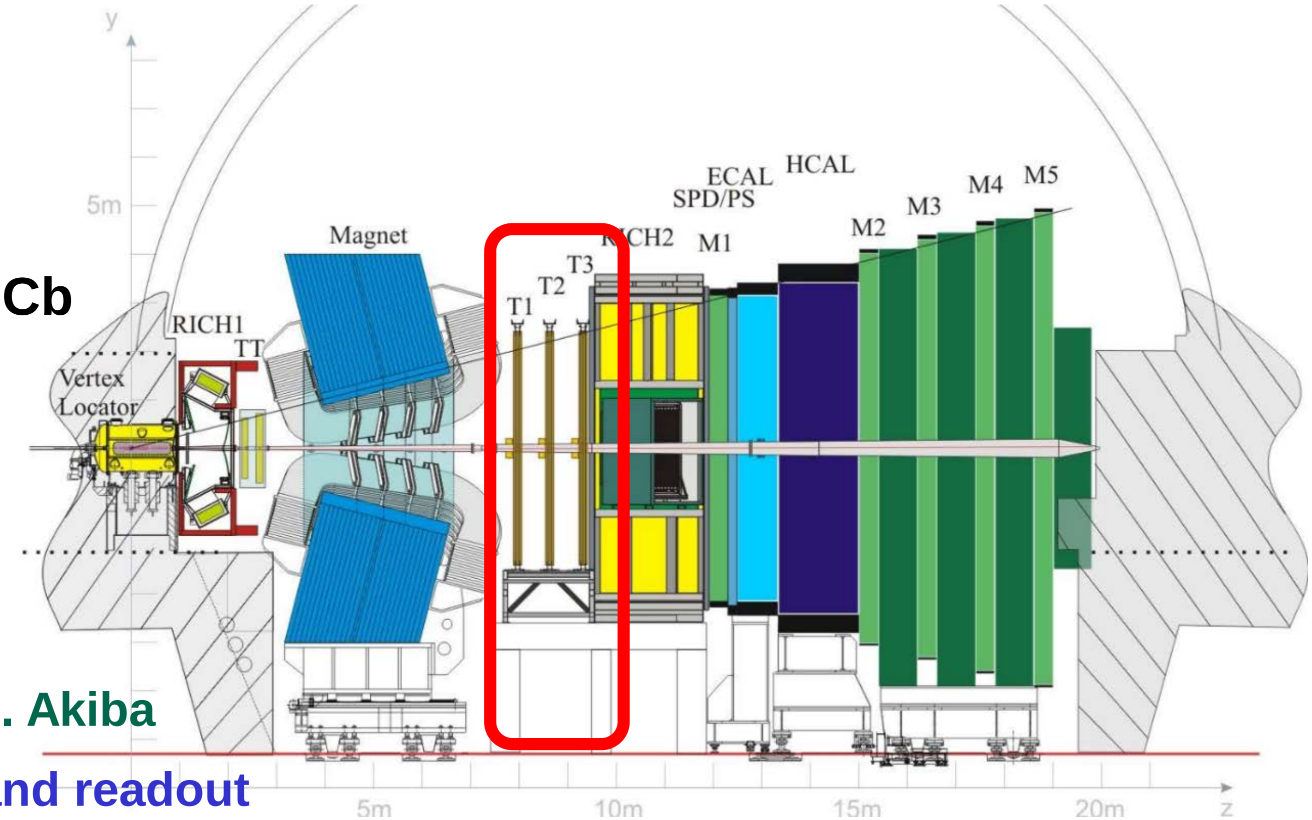


LHCb Detector Upgrade

Motivation: Increase significantly the physics reach, especially for very rare decays

Limitations:
- **1MHz hardware trigger rate**
- **Detector occupancy**

Major tracking upgrade of LHCb (for after LS2, ≥2020, $50fb^{-1}$)



- **DAQ: a 40 MHz full readout**

  → see talk S. Borghi
- **New VELO**

  → see talks K. Hennessy, K.C. Akiba
- **RICH: new photon detectors and readout**
- **Calorimeters: remove SPD/PS and new readout**
- **Muon System: remove M1 and new readout**
- Tracking system: replace TT with new silicon strip detector (UT) and

  IT&OT with SciFi tracker (scintillating fibres with SiPM readout)

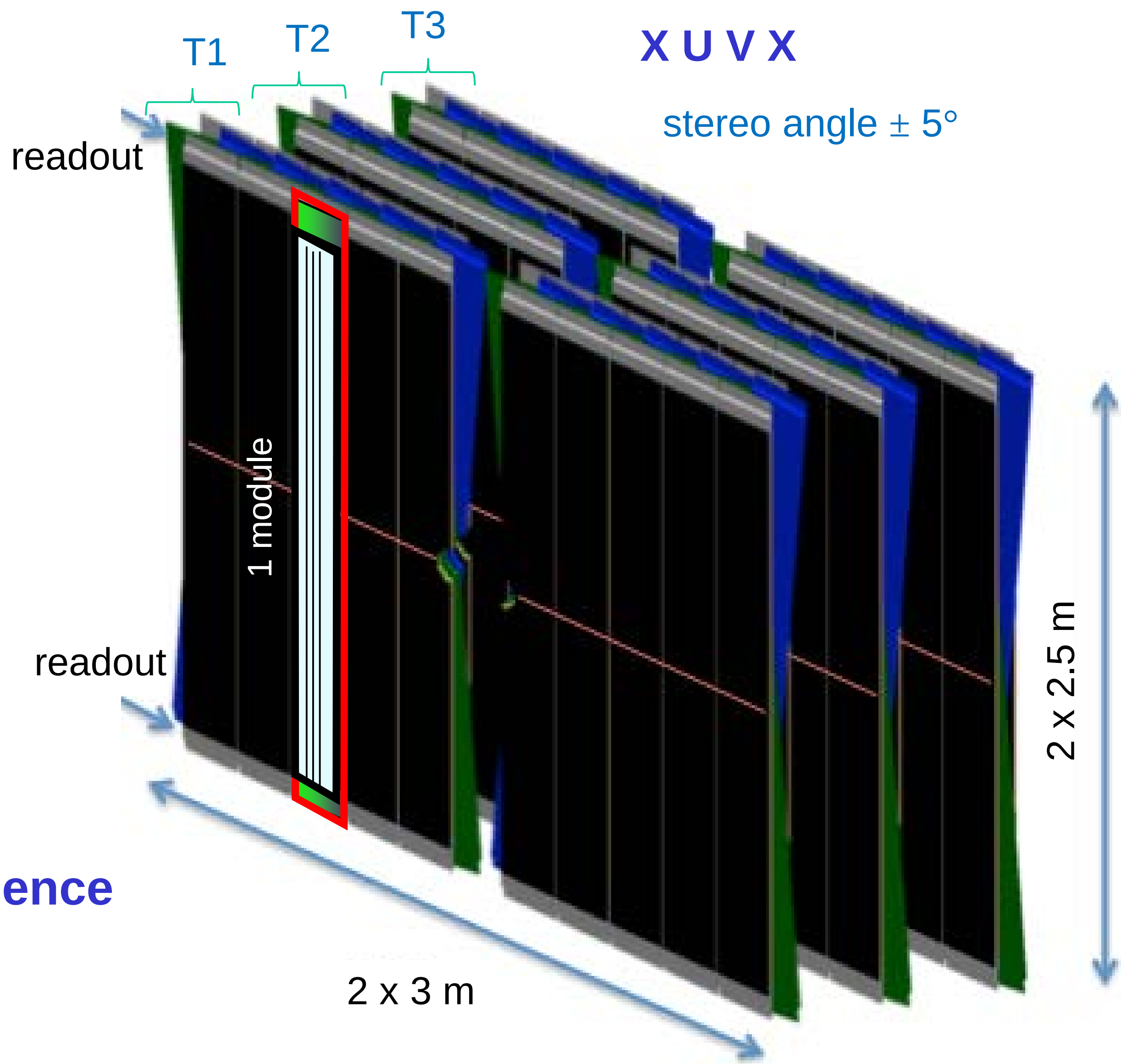
LHCb SciFi Tracker

General layout of the detector geometry:
3 stations with 4 planes each X-U-V-X (stereo angle 5°)

Requirements

- **Hit detection efficiency:**
  single hits ~ 99%
- **Low material budget for single detector layer**
  ~1% X_0
- **Spatial resolution better:**
  100 µm in x-direction
- **40 MHz readout**
  without dead time
- **Radiation environment:**

  Fibres: up to 35 kGy,
  SiPMs: approx. 1· 10^{12} n/cm^2 fluence
  + 100 Gy ionizing dose



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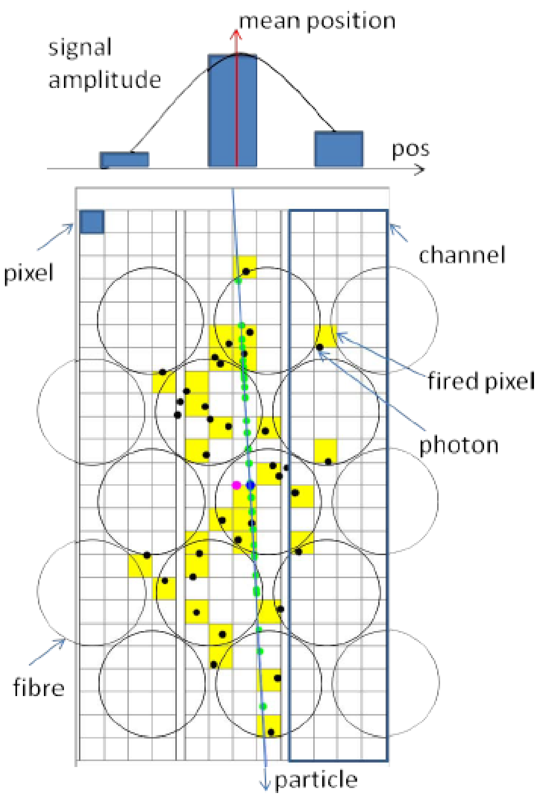
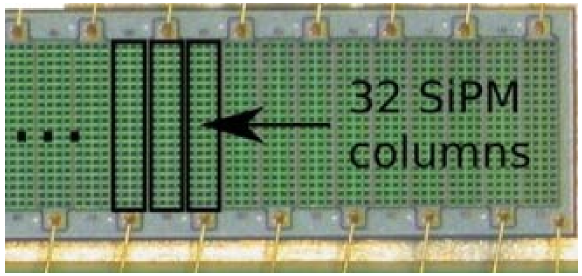
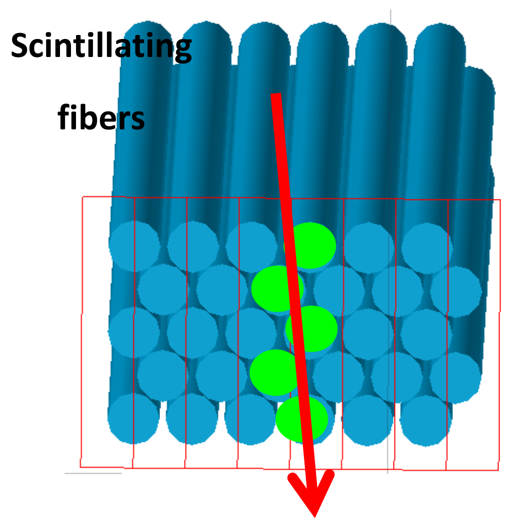
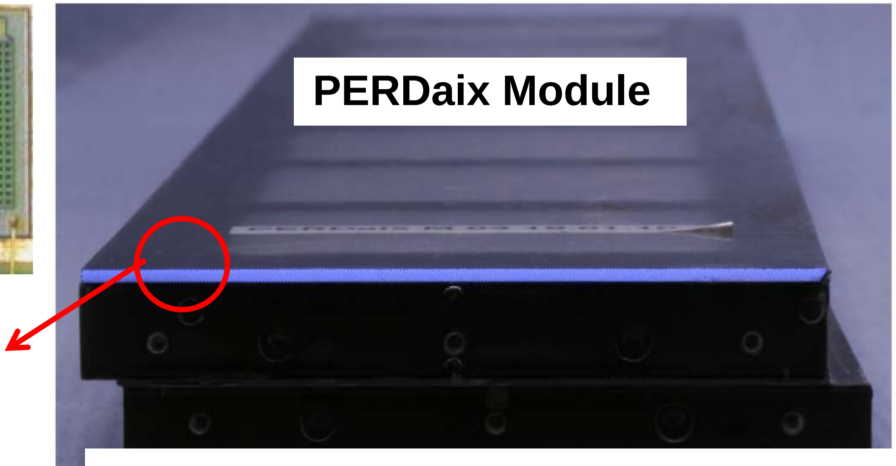
LHCb Scintillating Fibre Tracker: Principle

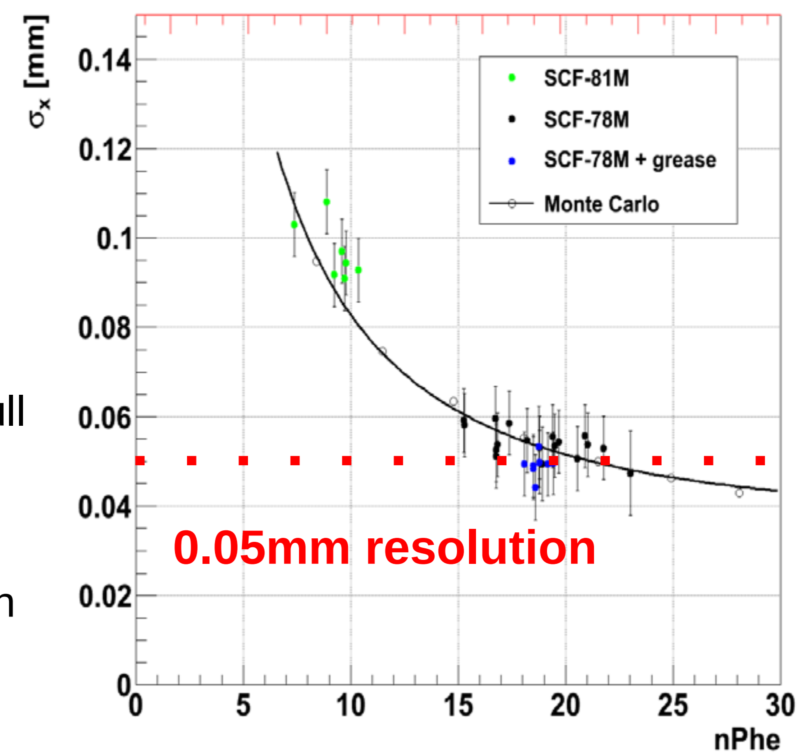








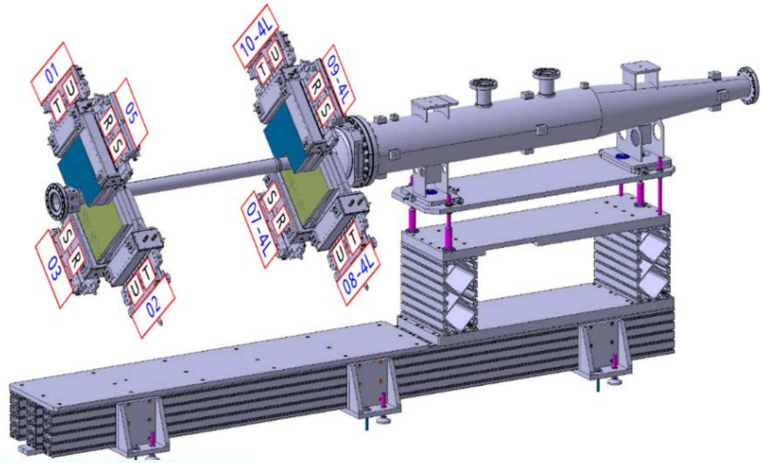
Prototypes with length: 860 mm, width 32 mm or 64 mm

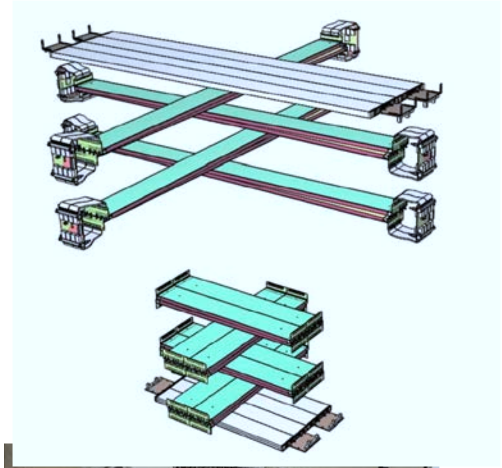


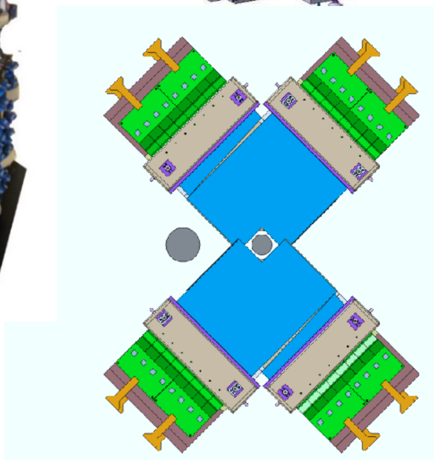
- Staggered layers of Ø250 μm fibres form a fibre mat
- Readout by arrays of SiPMs. 1 SiPM channel extends over the full height of the mat.
- Pitch of SiPM array should be similar to fibre pitch. Light is then spread over few SiPM channels. Centroiding can be used to push the resolution beyond p/sqrt(12).

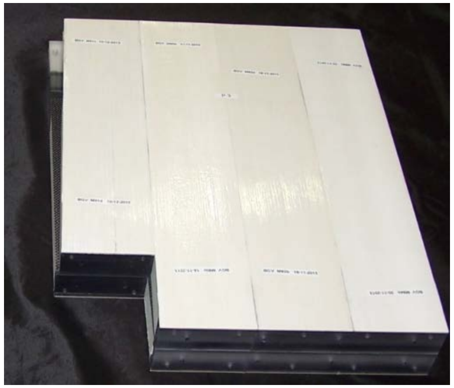
LHCb Scintillating Fibre Tracker: History

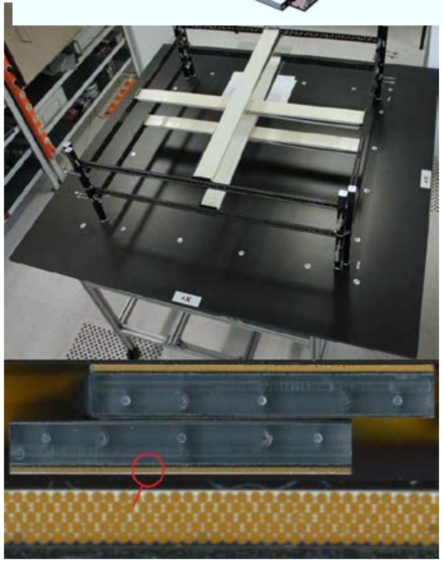
Scintillating Fibres and SiPMs as Photodetectors: The SciFi tracker is following the technology developed by the PERDaix detector (balloon experiment), Beam Gas Vertex (BGV, see talk M. Rihl) Detector and a Muontomograph







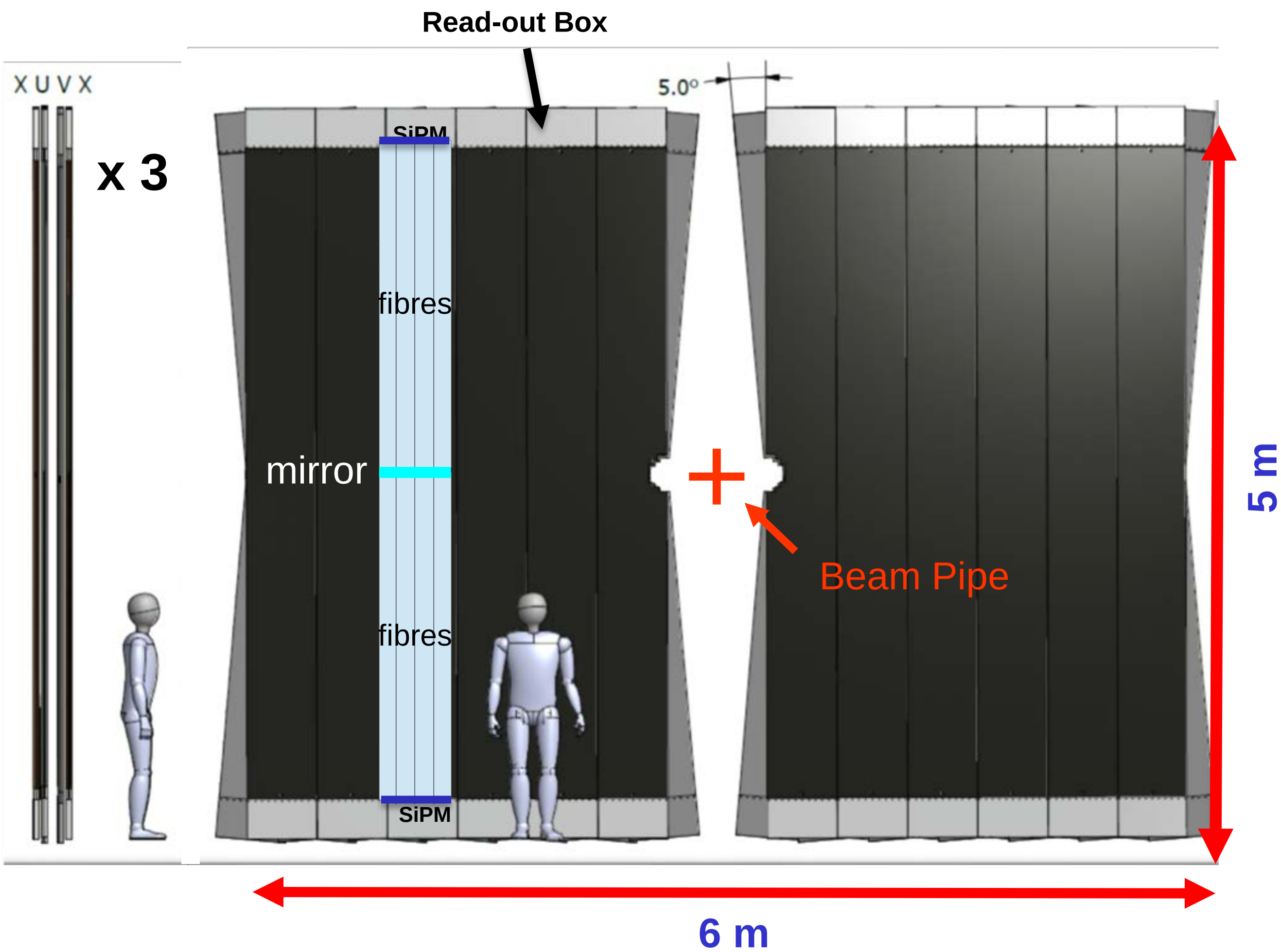




- Fibre Mats: Length: 30cm – 100cm, width: 32-64 mm, Layers:4-5

LHCb SciFi Tracker

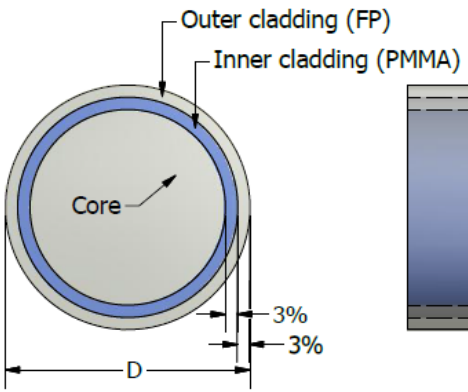
- **144 modules** in 12 layers
- **360 m²** total area
- Module Carriers made out of CF skin and Nomex honeycomb
- **1 Module** consists of **8 fibre mats** (**1152 mats**)
- Fibre mats (**6 layers** per mat) run in vertical direction (L≈ 2 x 2.5m) sandwiched in module carriers (**1.1% X0**),
- Fibres: Ø 250µm, L=2.5m, **total length >10,000 km**)
- Fibres interrupted in mid-plane (y=0) and mirrored
- Read out at top and bottom with SiPM arrays (128 channels, 250 µm pitch)
- 590k SiPM channels
- SiPMs + FE electronics + services in a "Readout Box"

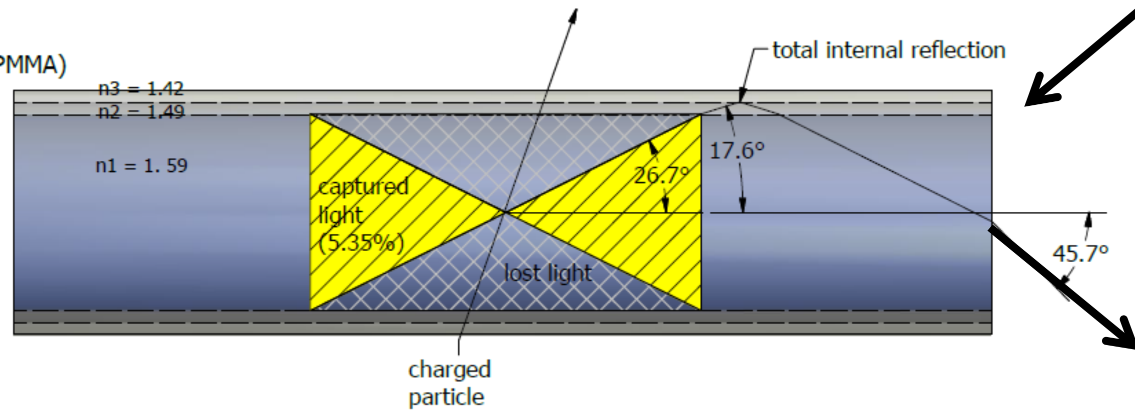


Kuraray SCSF-78MJ fibres: Ø (250 ± 15) µm, 6 fibre layers per mat, each layer with 512 fibres with length 2.5m → 10,000 km fibres

(Scintillator)

Polystyrene core with 2 dyes

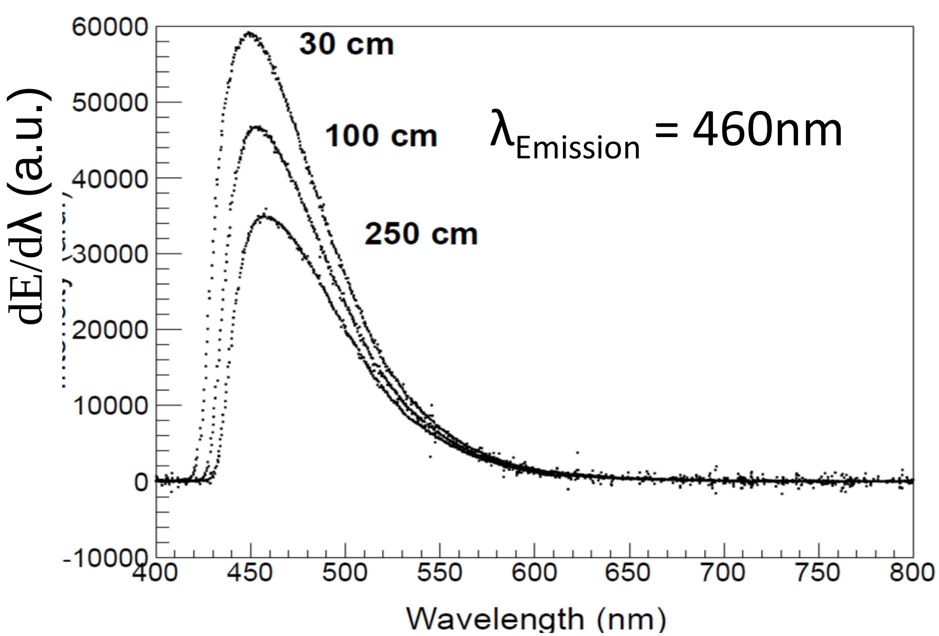




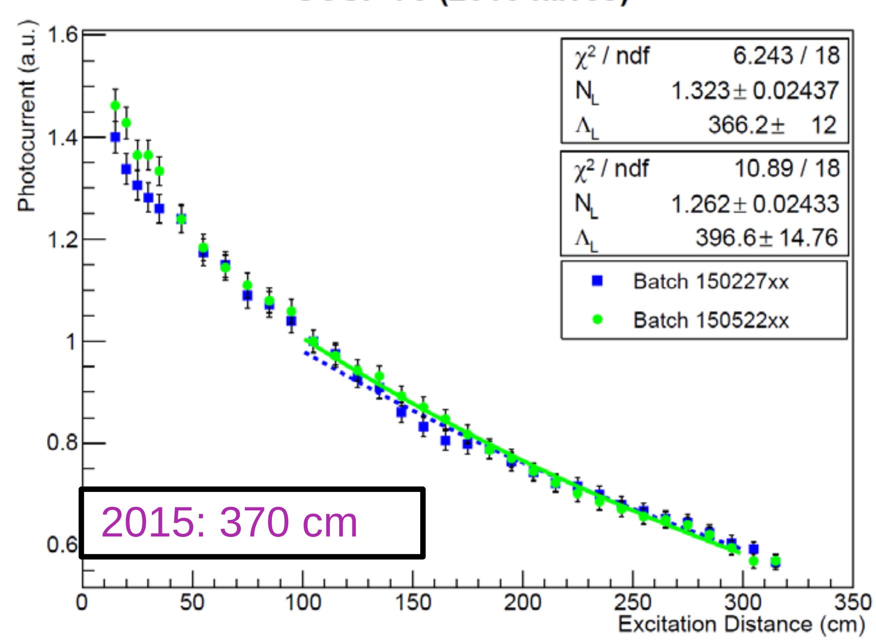
Only a few photons after 2.5m

300 photons per MIP produced (only 5% captured)

SCSF-78MJ



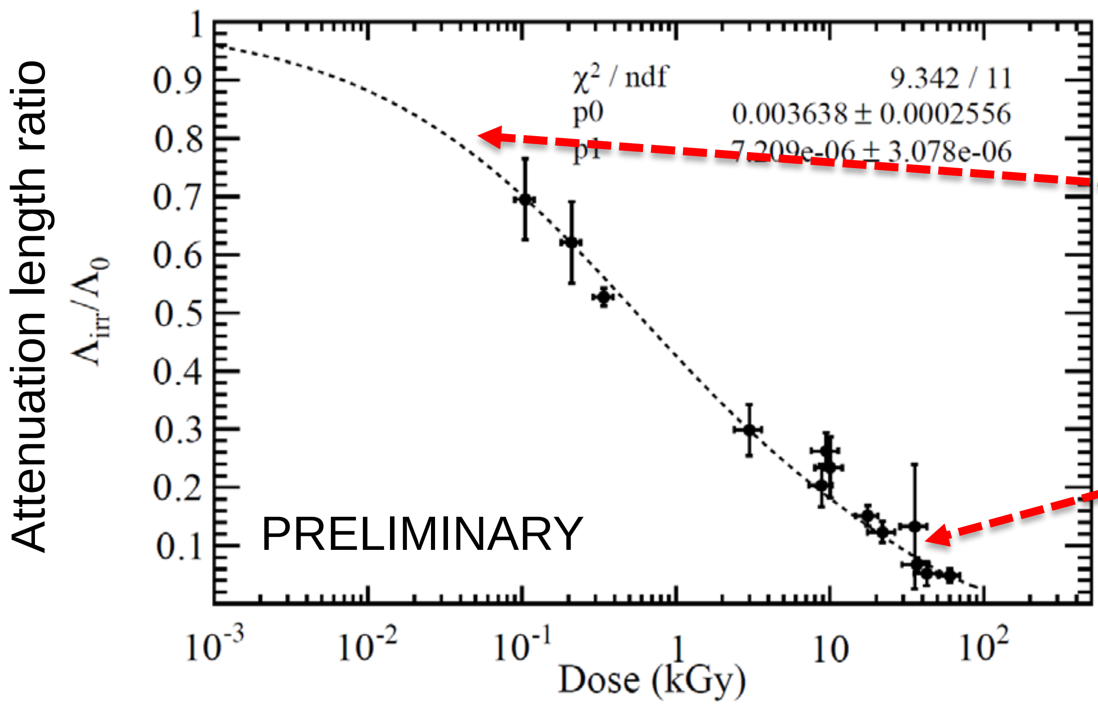
SCSF-78 (2015 fibres)



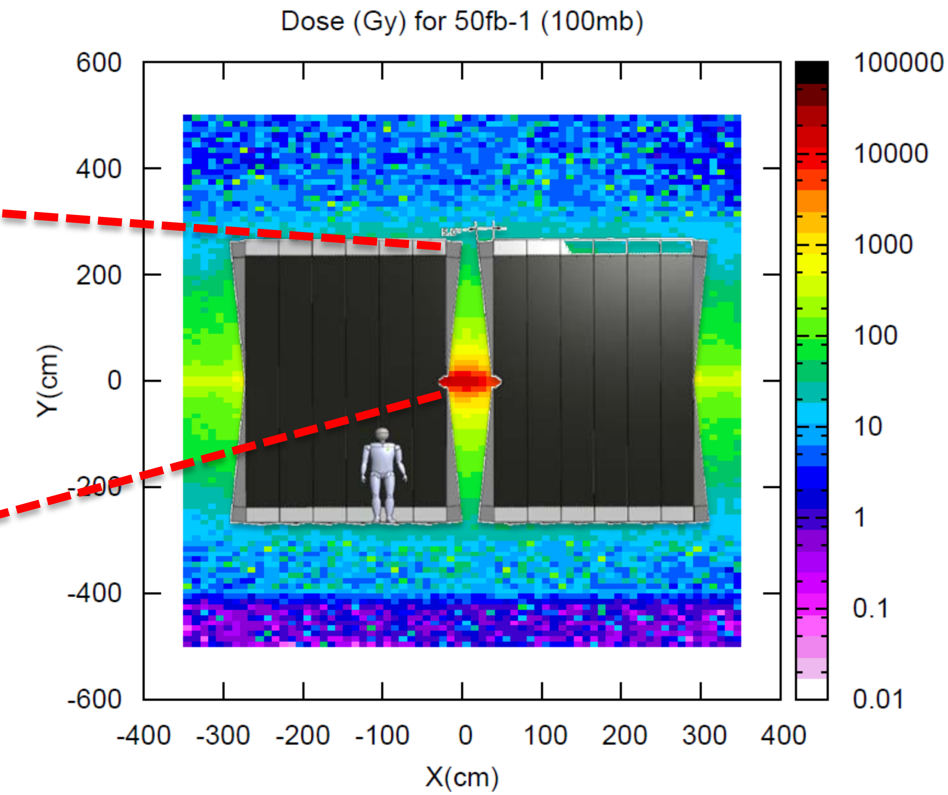
LHCb SciFi Tracker: Scintillating Fibres - Irradiation

Light transmission of scintillating fibre decreases under irradiation, (up to 35 kGy expected near the beam pipe over the upgrade lifetime)

A mix of low dose, low rate xray, gamma and high rate, high dose proton irradiations



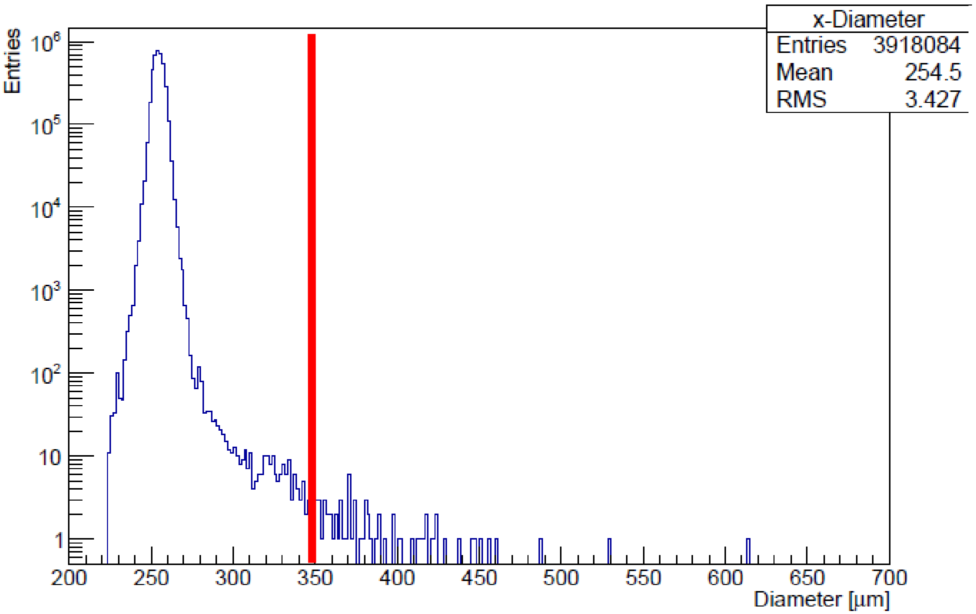
Expected ionizing dose for LHCb Upgrade

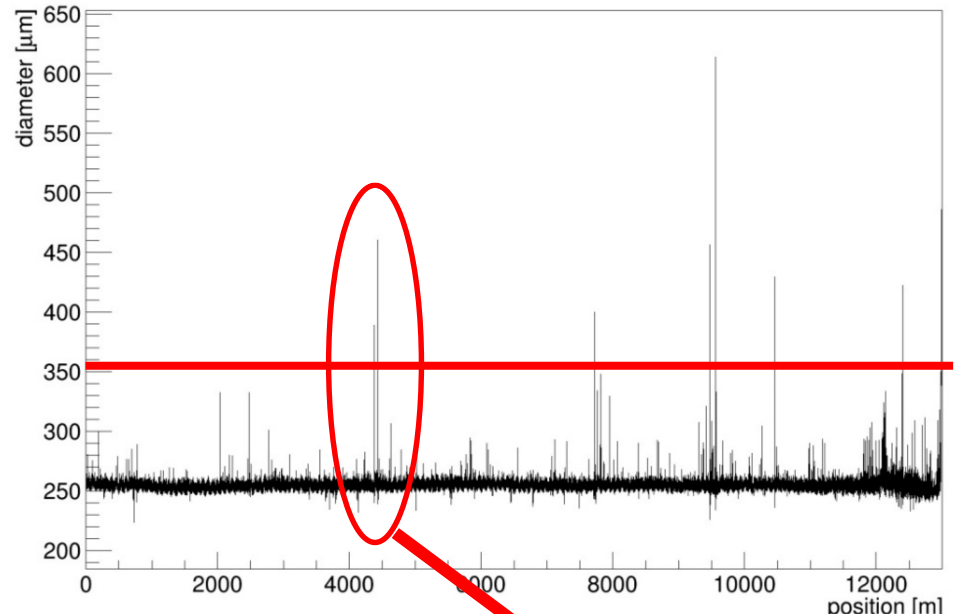


Up to 35 kGy near beam pipe, Down to 60 Gy in SiPM region

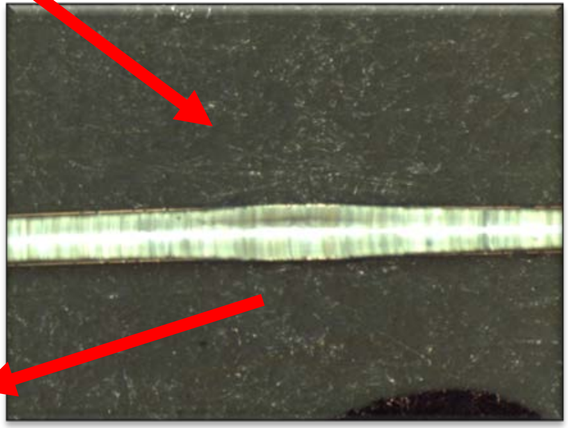
→ Expect a **40%** loss of transmitted light created near the beam pipe **after 10 years**

Measurement of Fibre diameter profile (along fibre)

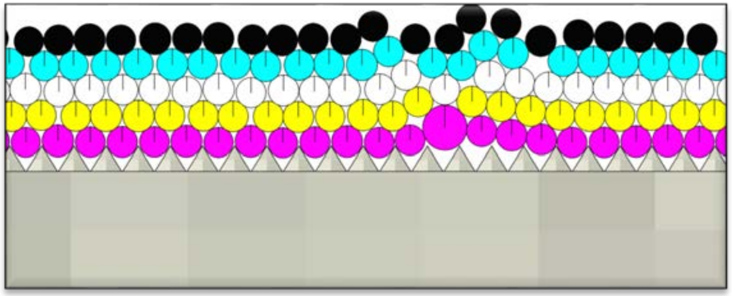




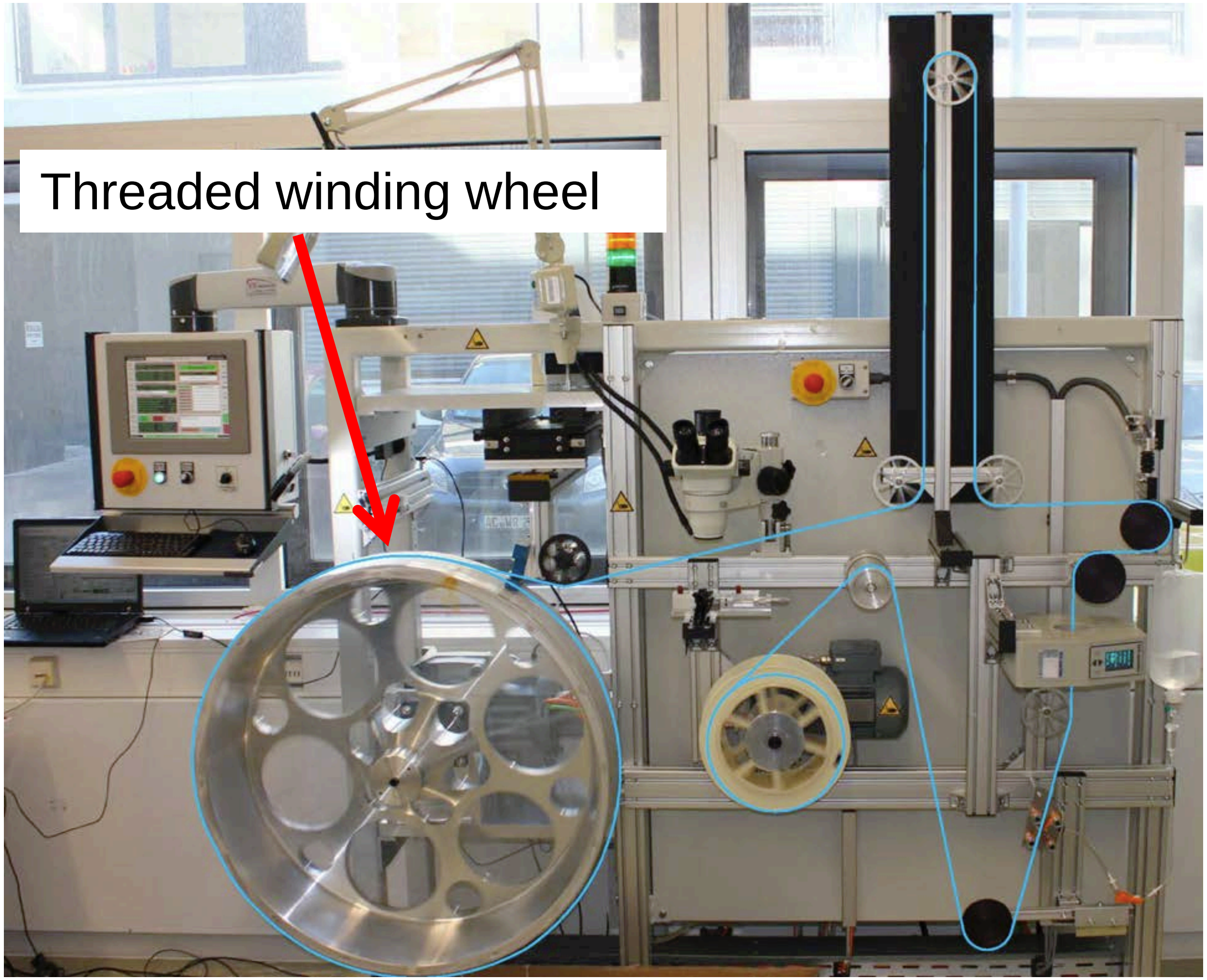
Fibre diameter (250 ± 7) µm,
But bumps appear (diameter >> 300 µm)
≈ 1 per km of fibre = 1 per layer of fibre mat.



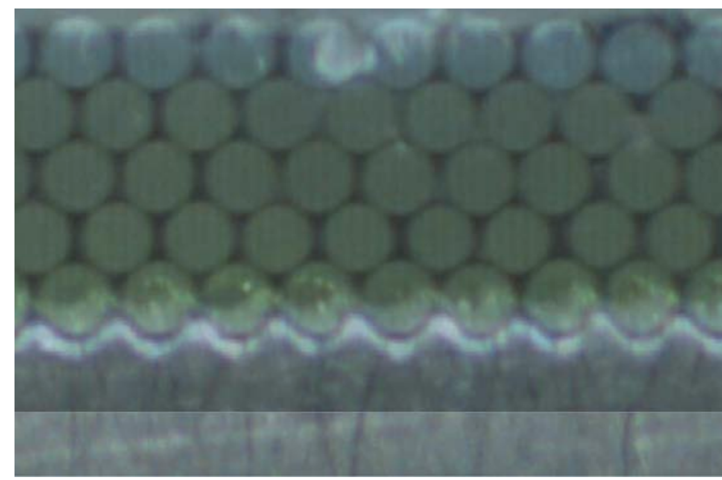
Possible to remove manually during winding process.



LHCb SciFi Tracker: Fibre Mats

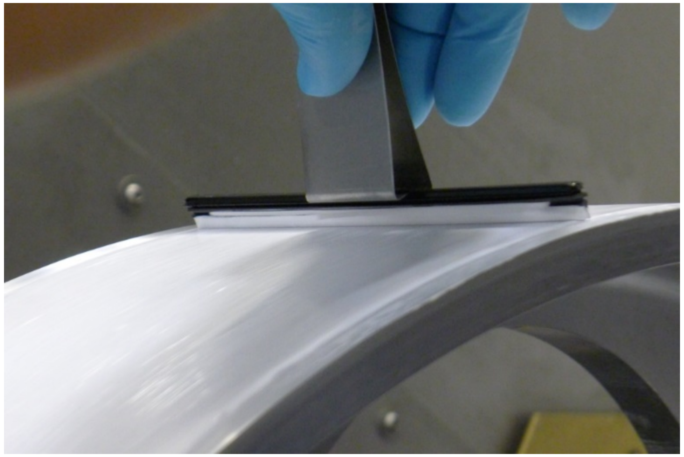


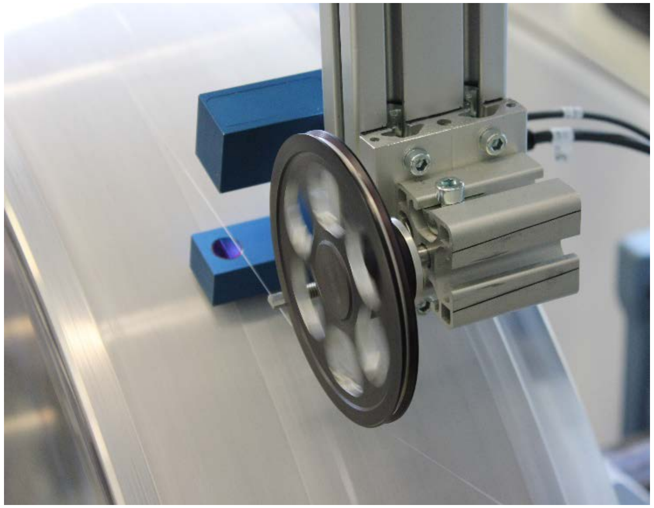
Thread and hole for alignment pin



- First layer is directly wound onto hub,
- following layers are wound into groove-like depressions of preceding layers
- Need about 8km of fibre for one mat of 6 layers 2.5 meters long
  → 10,000 km of fibre in total

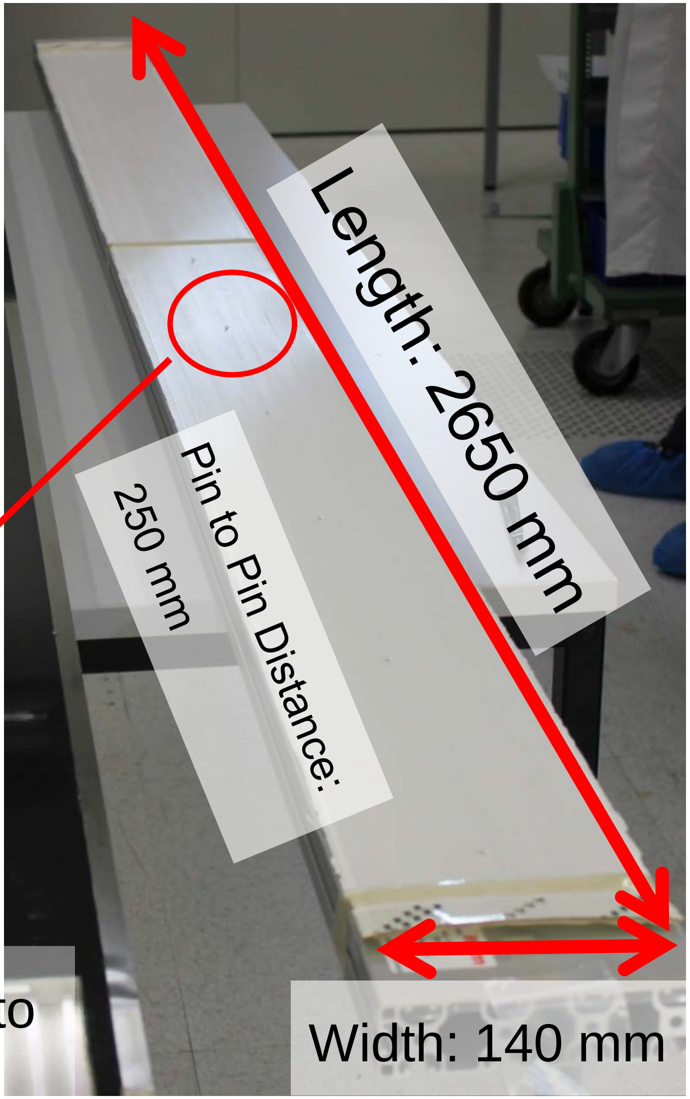
LHCb SciFi Tracker: Fibre Mats





Glue: Epotec 301 + 25% TiO2 (optional)

→ Minimization of crosstalk between adjacent fibers



Pins are bonded to fibre mat on wheel as part of winding to reach a straightness over mat length better than required detector resolution of < 100 µm

LHCb SciFi Tracker: Fibre Mats

Foil lamination of SiFi mat is done to protect fibre mat and to make handling and shipping easier.

5 Production center for fibre mats:

2 in Russia (Kurchatov),

2 in Germany (RWTH Aachen, TU Dortmund)

and 1 in Switzerland (EPFL Lausanne)

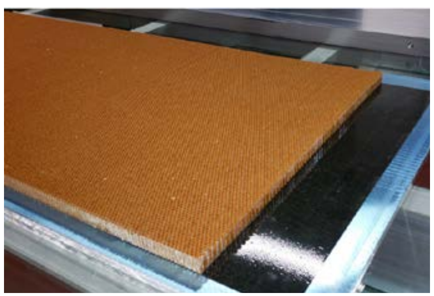
LHCb SciFi Tracker: Fibre Mat Modules:

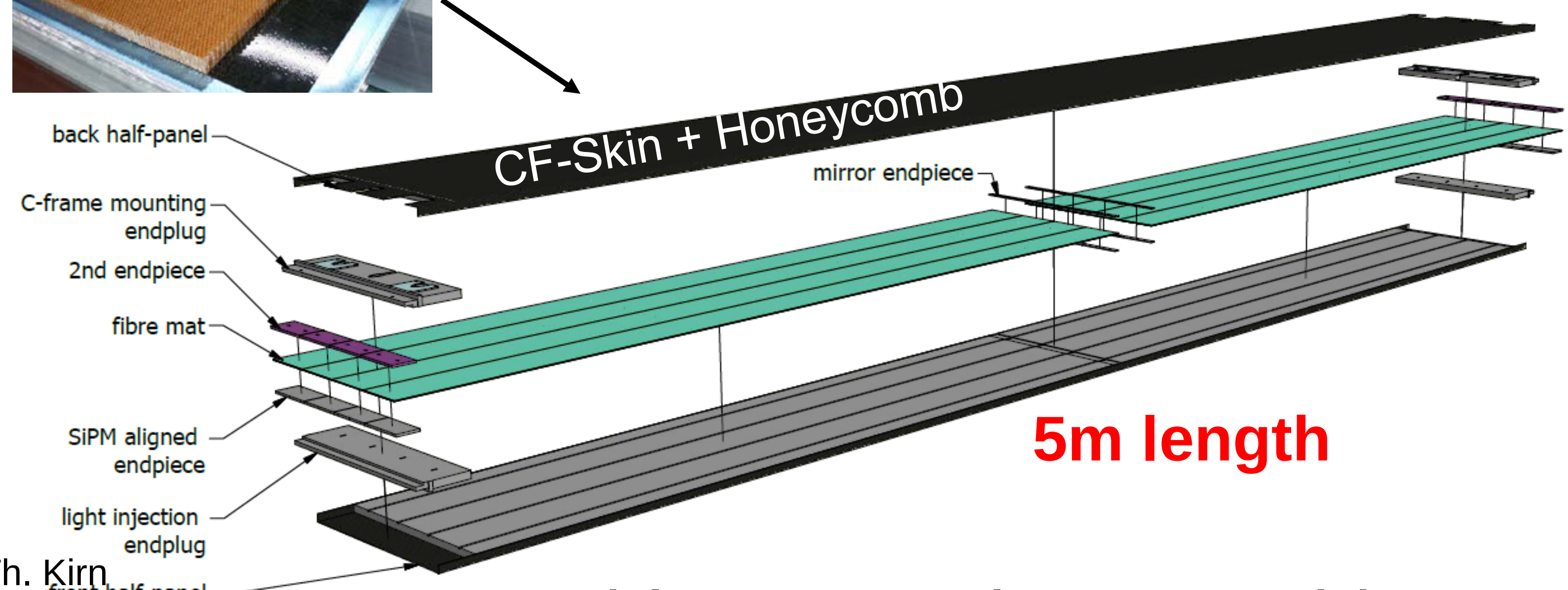
2 Module Center: Heidelberg Universität, NIKHEF Amsterdam

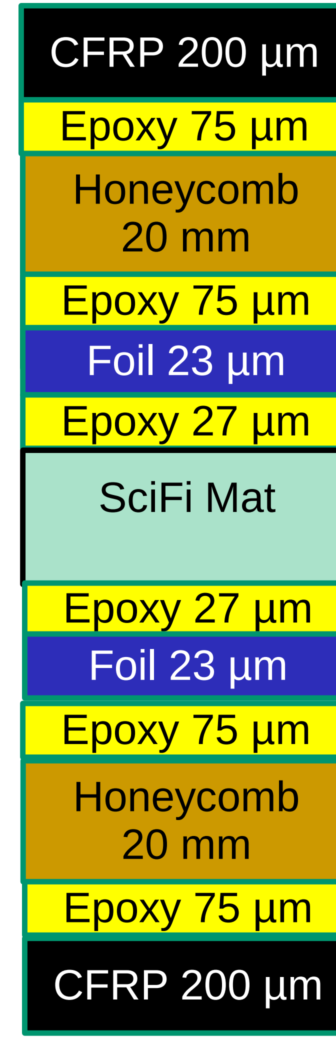
Fibre mats need to be assembled into a module that can be mounted and placed in the LHCb pit

- 8 mats aligned on a precision table
- Bond a carbon fibre + Nomex core structure to make a strong rigid object

→ Precision in time in z-direction better than 300 µm







Material Budget:

1.1% X0

144 Modules, 360 m² total area, 1152 SciFi mats

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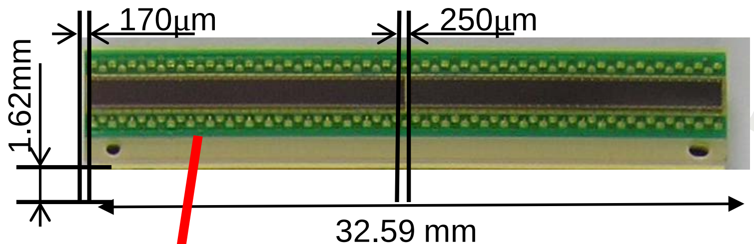
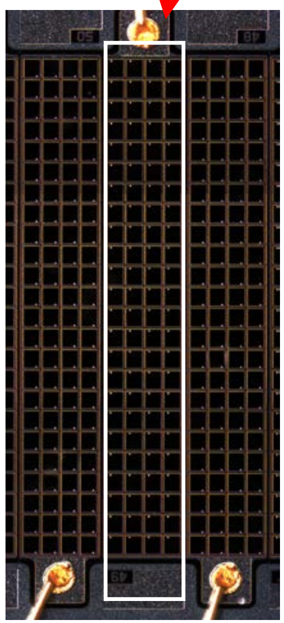
LHCb SciFi Tracker: SiPMs

SiPM arrays, 128-channels (2x 64) with 250 µm gap with very similar dimensions,

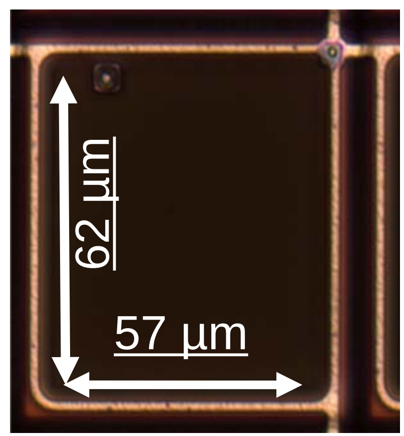
Channel width approximately matches the fibre spacing and diameter

Hamamatsu (Jp)

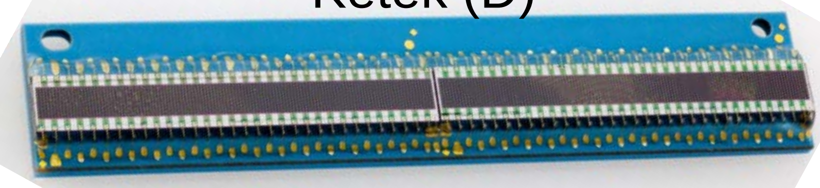




Single pixel



Ketek (D)



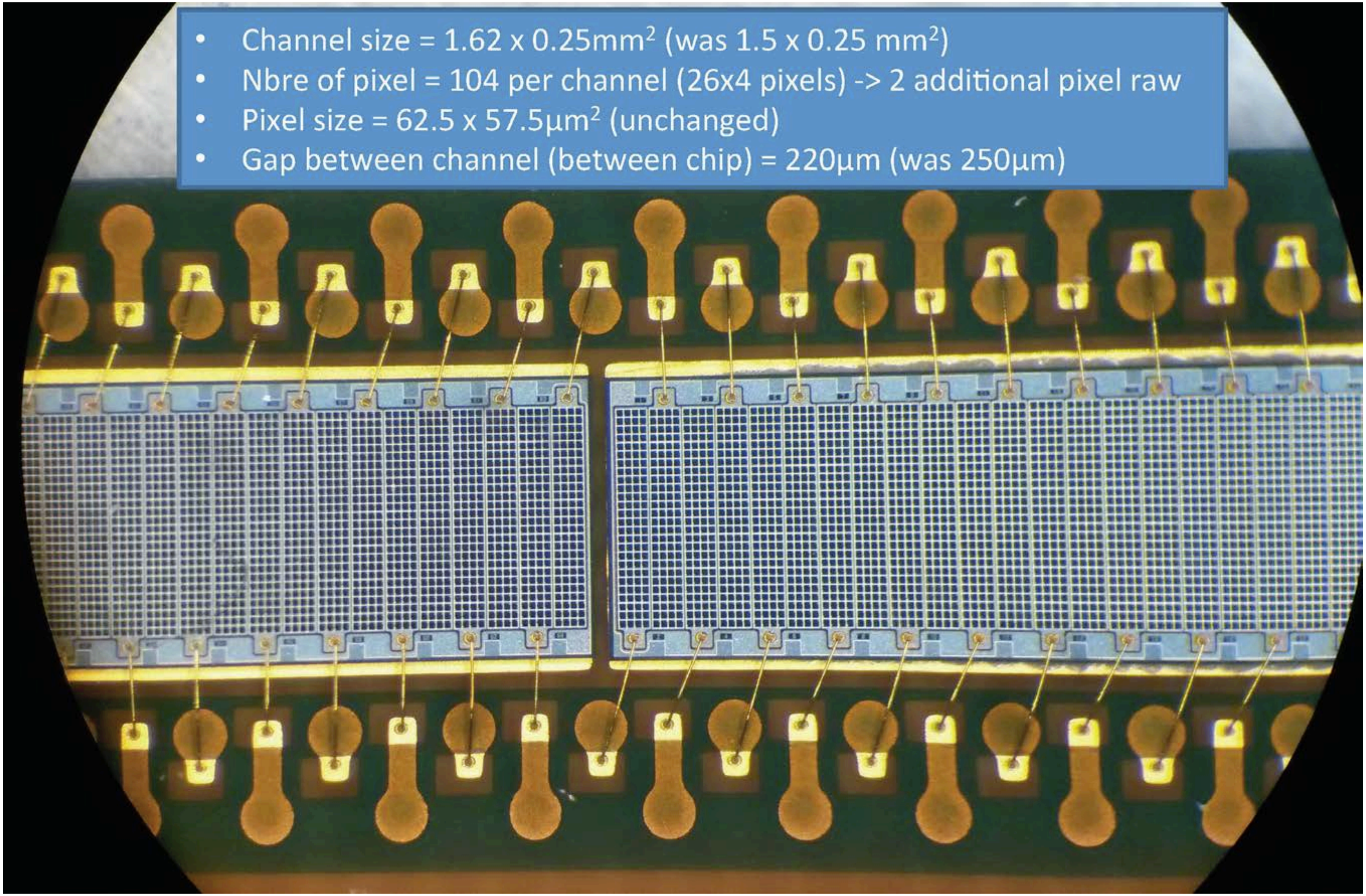
- **High PDE**
- **Low x-talk**
- **Radiation environment**

neutron fluence ≈10^{12} 1MeV neq/cm^2

- **Small temperature dependence**:
- **Small dead regions**
- **Thin entrance window**

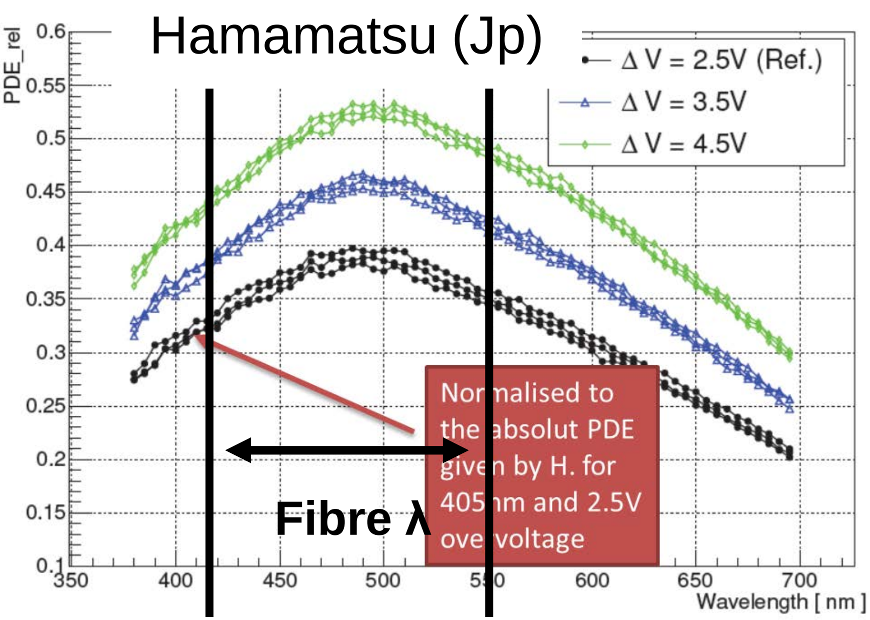
LHCb SciFi Tracker: SiPMs

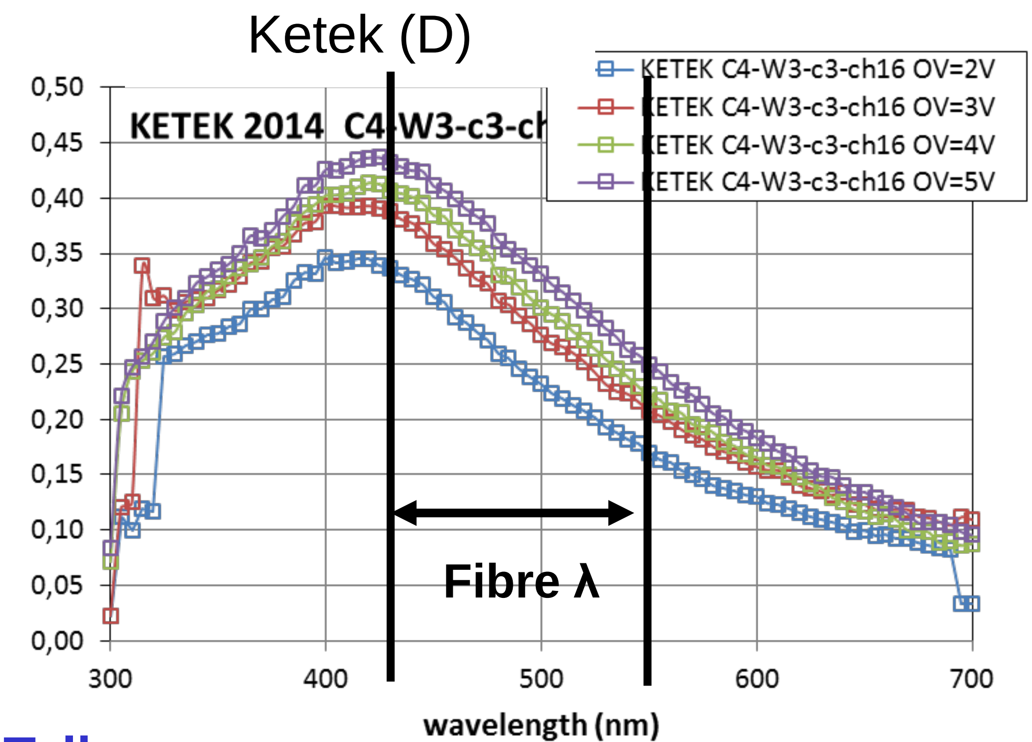
New Hamamatsu 2015 SiPM arrays:



LHCb SciFi Tracker: SiPMs

Photon Detection Efficiency PDE

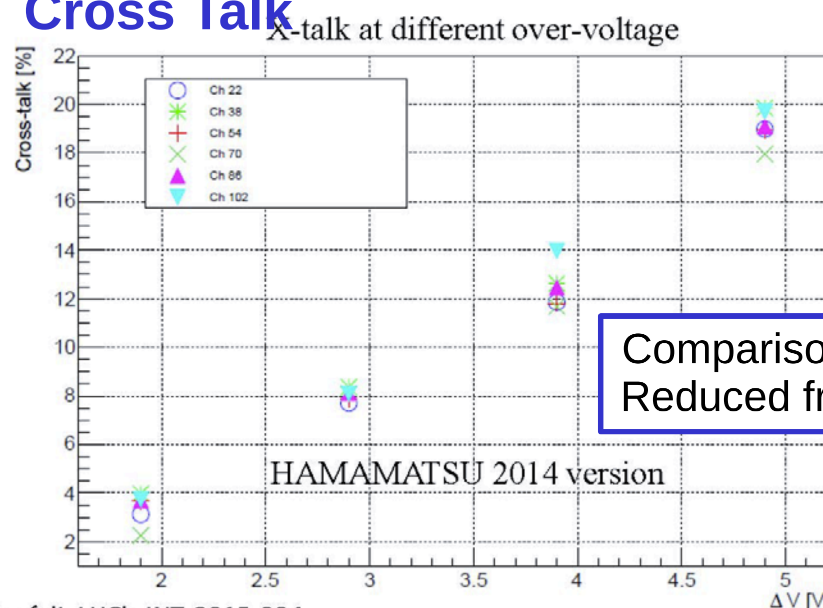




Comparison H2014 & H2015

- PDE(λ) unchanged
- PDE for working point ΔV=3.5V :
  PDE(H2015 @ 3.5 V) = 50 %
  PDE(H2014 @ 3.5 V) = 45 %

Cross Talk

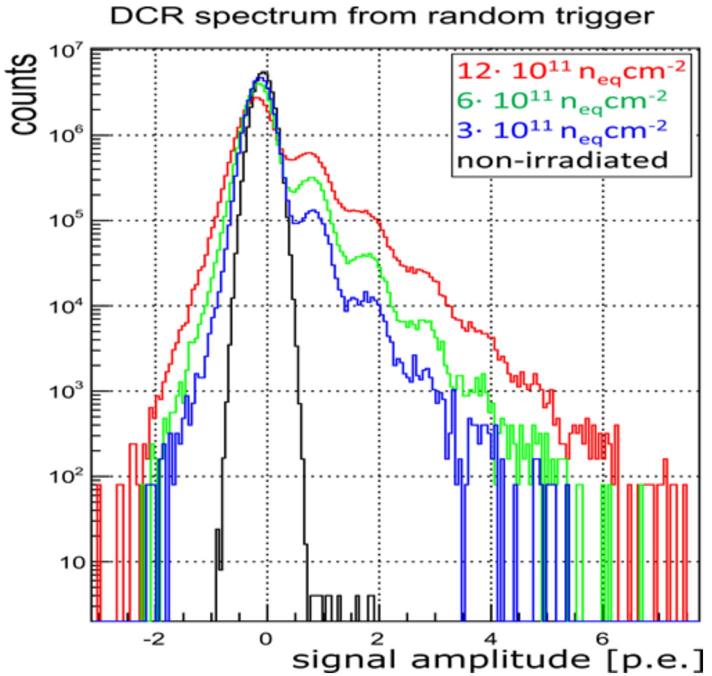


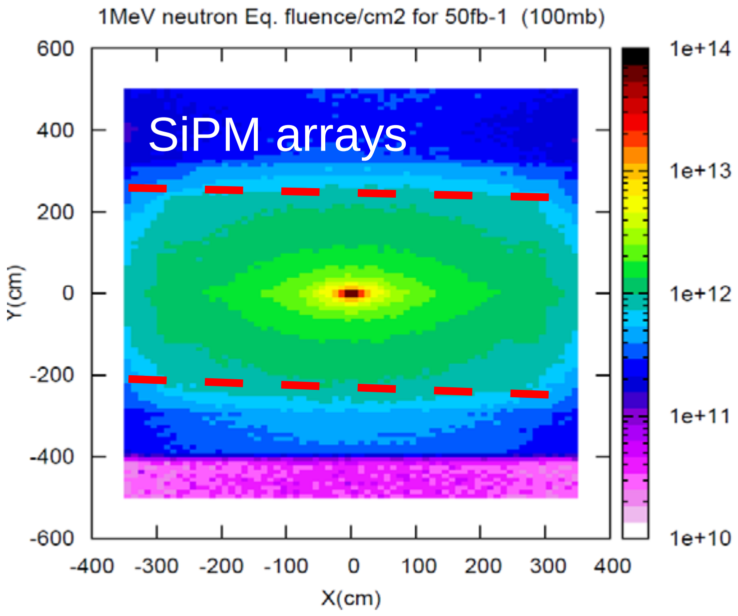
Haefeli, LHCb-INT-2015-004

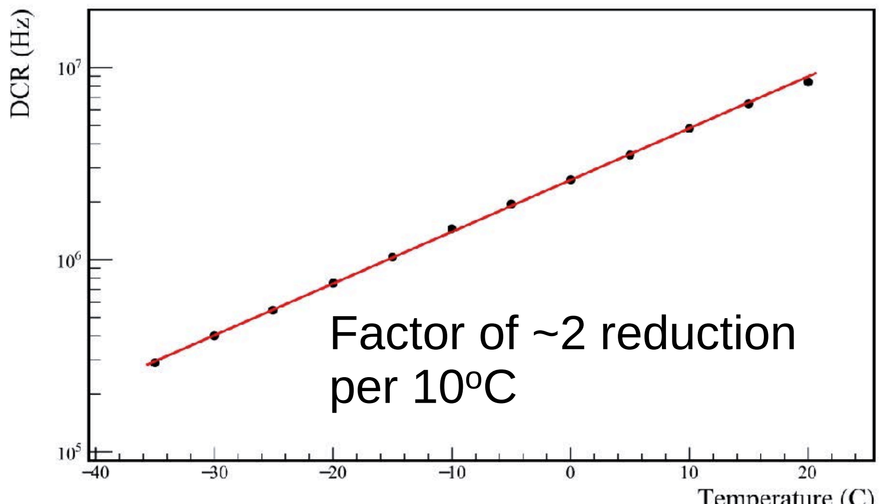
Comparison Xtalk H2014 & H2015
Reduced from 10% to 5% @ 3.5 V

LHCb SciFi Tracker: SiPMs

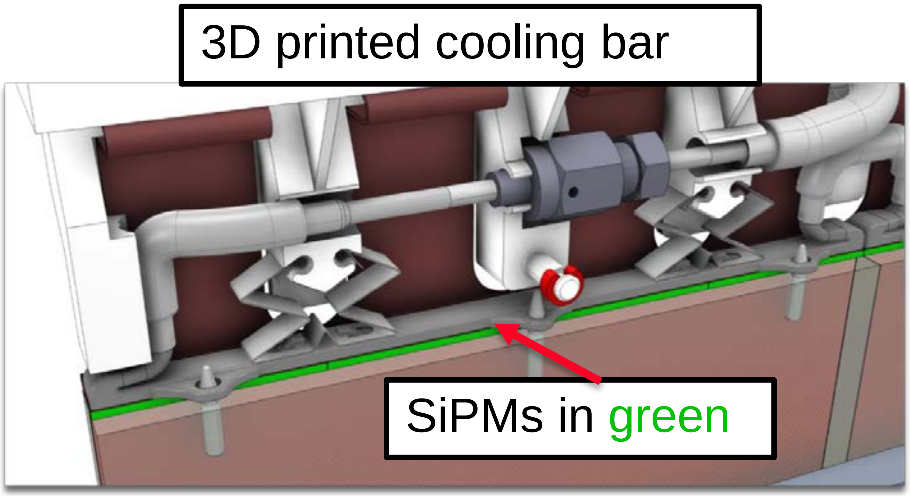
Dark Count Rate



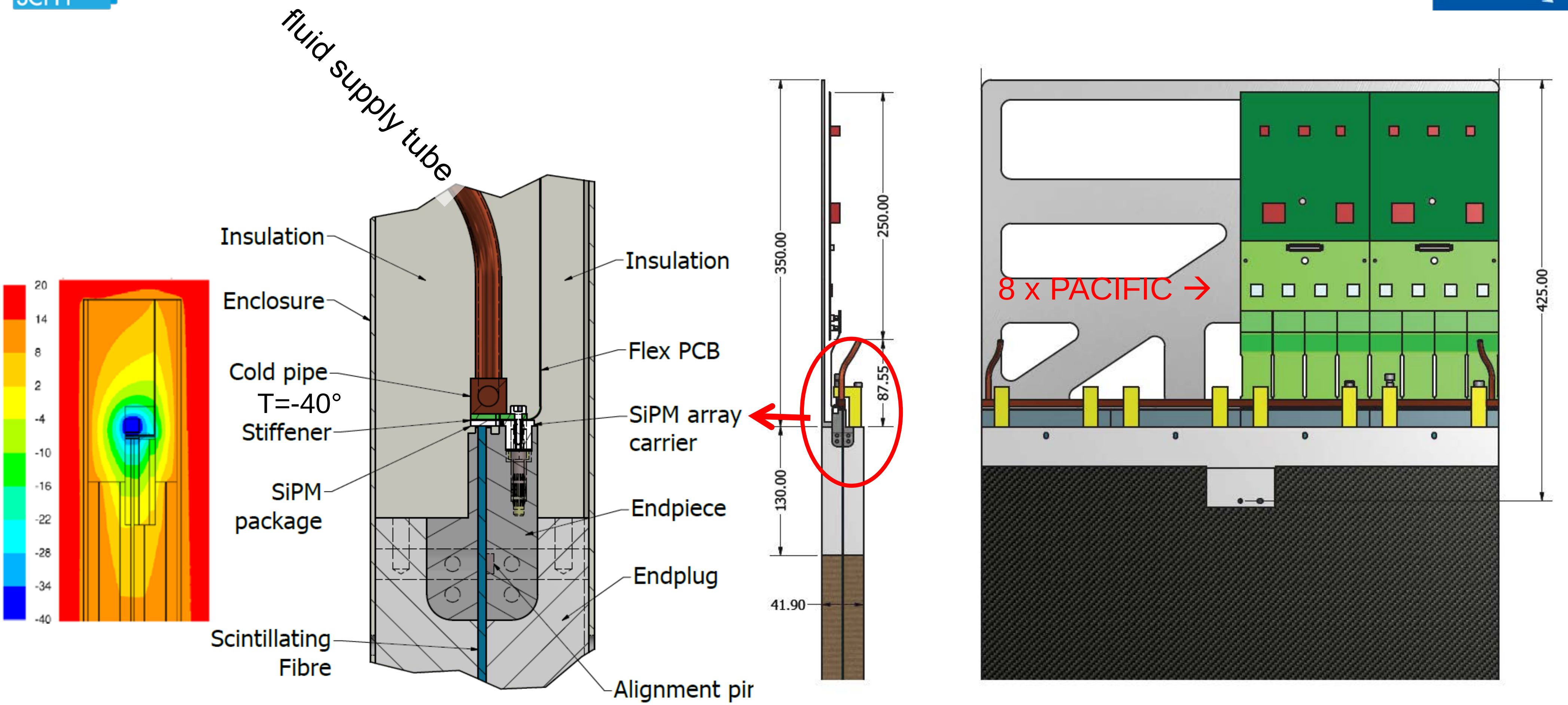




DCR of irradiated single channel SiPM at different temperature



LHCb SciFi tracker: Cooling in Readout Box



- Single phase liquid cooling
- Compact space
- < 20 W thermal load per module
- SiPMs produce little to no heat, box dominated by parasitic heat load
- Issues with condensation and frost need to be dealt with

LHCb SciFi Tracker: Front End Electronics

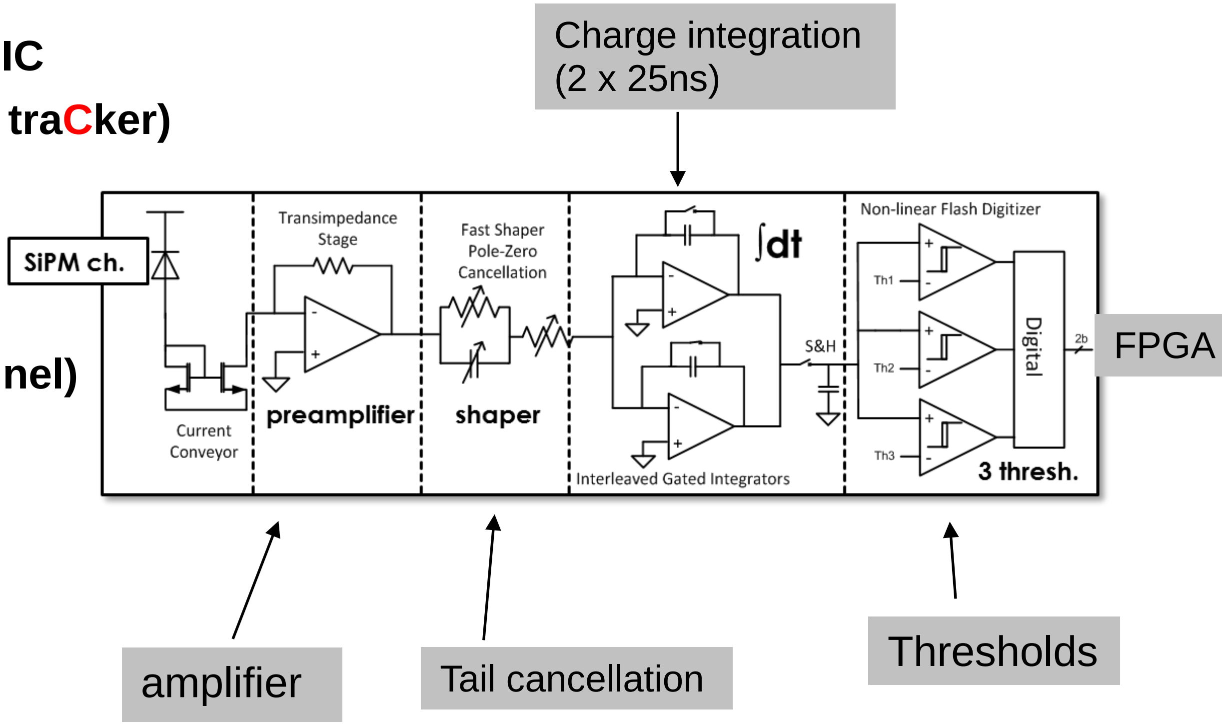
Fast readout with manageable data volume

- Digitizes the 560,000 SiPM signals and forms the cluster and hit positions
- 40 MHz readout rate
- Signal propagation time up to 2.5m · 6ns/m = 15ns → some spill over to next BC
- No adequate (fast, low power) multi-channel ASIC available

LHCb develops its own ASIC, called PACIFIC

(low Power Asic for the sCIntillating FIbre traCker)

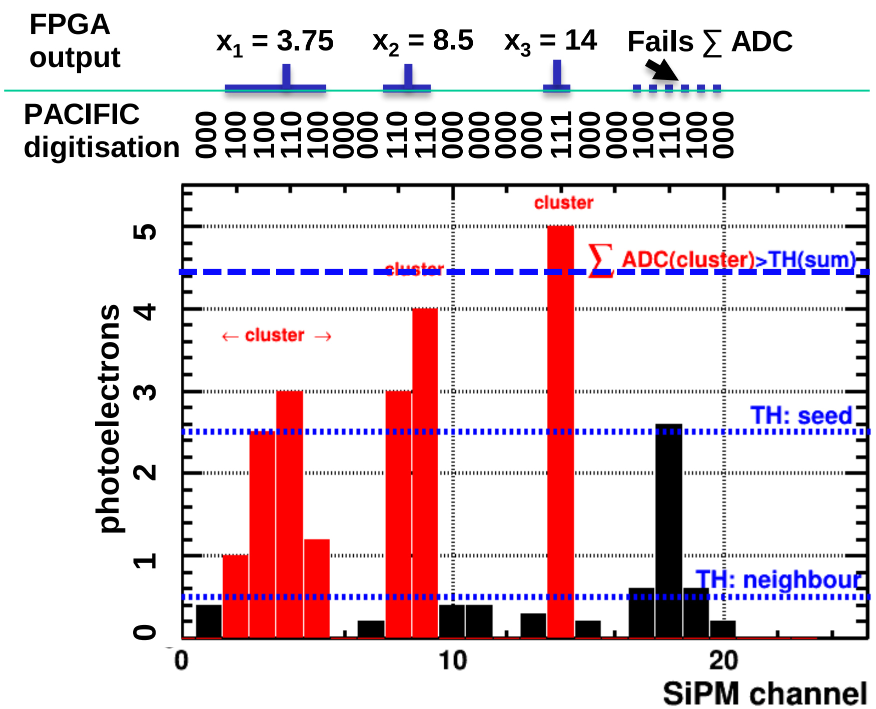
- **TSMC 130 nm**
- **64 channels**
- **2bit/ch digital output**
- **Low power consumption (<10 mW/channel)**
- **Low input impedance:≈ 50Ω**
- **High bandwith:≈ 250 MHz**
- **Fast shaping**
- **Dual gated-integrators (zero dead time)**
- **25 ns peak resolution**

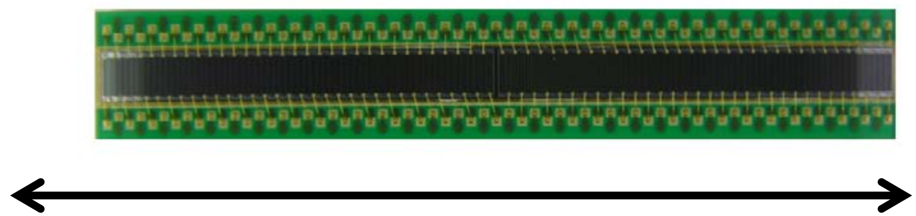


3 hardware thresholds (=2 bits) (seed, neighbour, high) plus a sum threshold (FPGA) are a good compromise between precision (<100 μm), discrimination of noise and data volume.

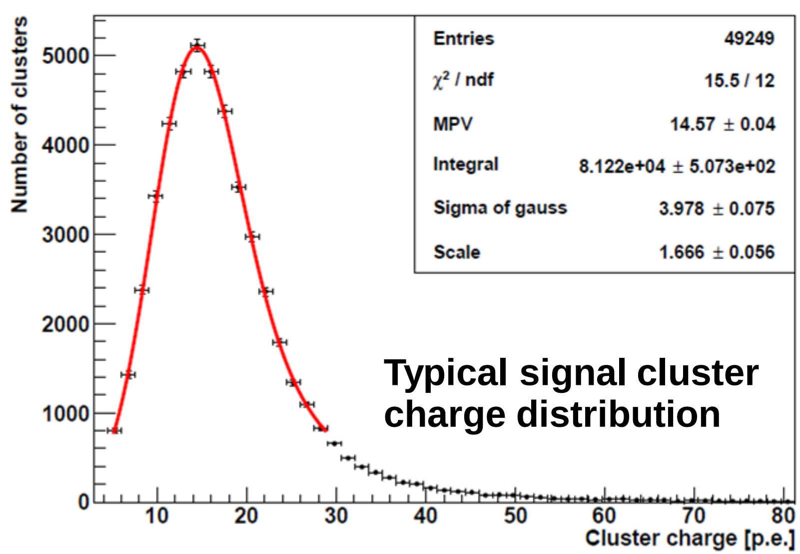
Clusterization FPGA:

- Clustering and threshold
  cuts to reject dark noise clusters
  due to irradiation in the FE electronics
- a balance between thresholds,
  hit efficiency and allowable noise clusters
- Clustering done on an FPGA after
  the PACIFIC;
  hit position output to data acquisition





128 Channel SiPM array



Typical signal cluster charge distribution

LHCb SciFi Tracker: Front End Electronics

Modular Design:

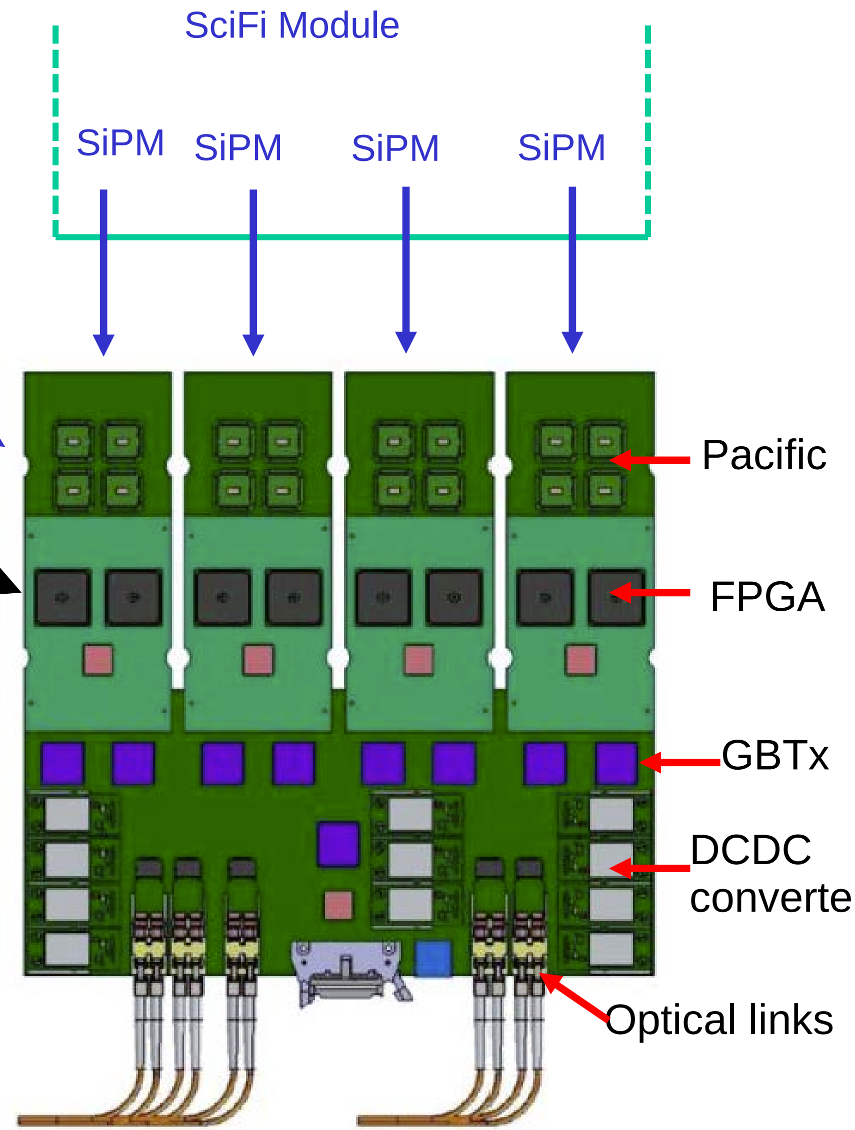
Pacific Board:
Read out 2x SiPM arrays, digitalization

Clusterization Board:
clusterization & zero supression

Efficiently format hit information

Master Board:
Transfer data at high rate via optical link

Generate/distribute
Timing and fast control (TFC),
Experimental slow control (ESC)
clock

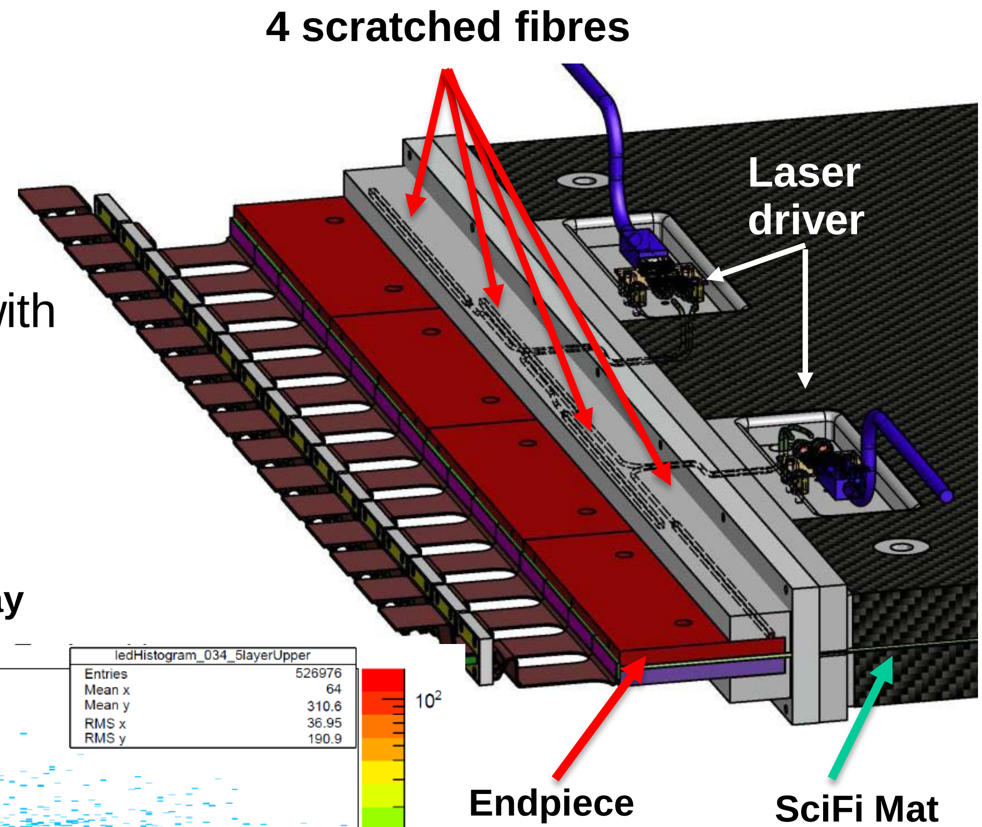


The whole SciFi tracker will generate 47.1 Tb/s data!

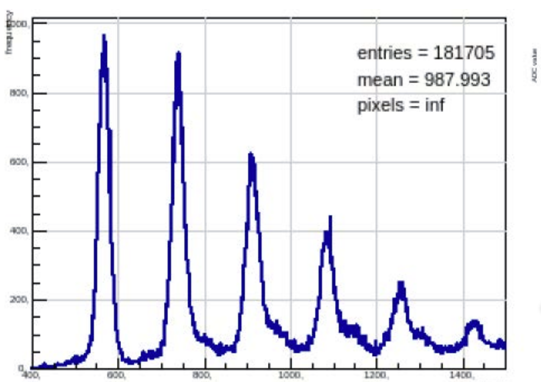
LHCb SciFi Tracker: SiPM Calibration Light Injection System

- Scratched fibre embedded in the module ends
- Shines evenly across the fibre and SiPMs
- Driver
  - Gigabit LASER Driver (GBLD, a radiation tolerant ASIC)
  - Vertical-cavity surface emitting laser (VCSEL) with wavelength of 670 nm

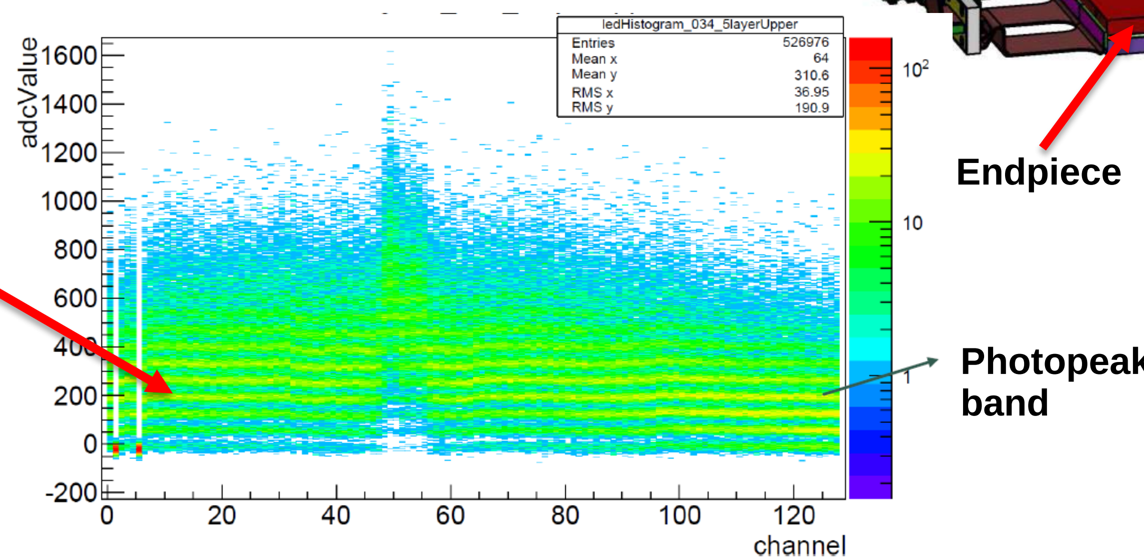
emitted light from Ø1mm fiber



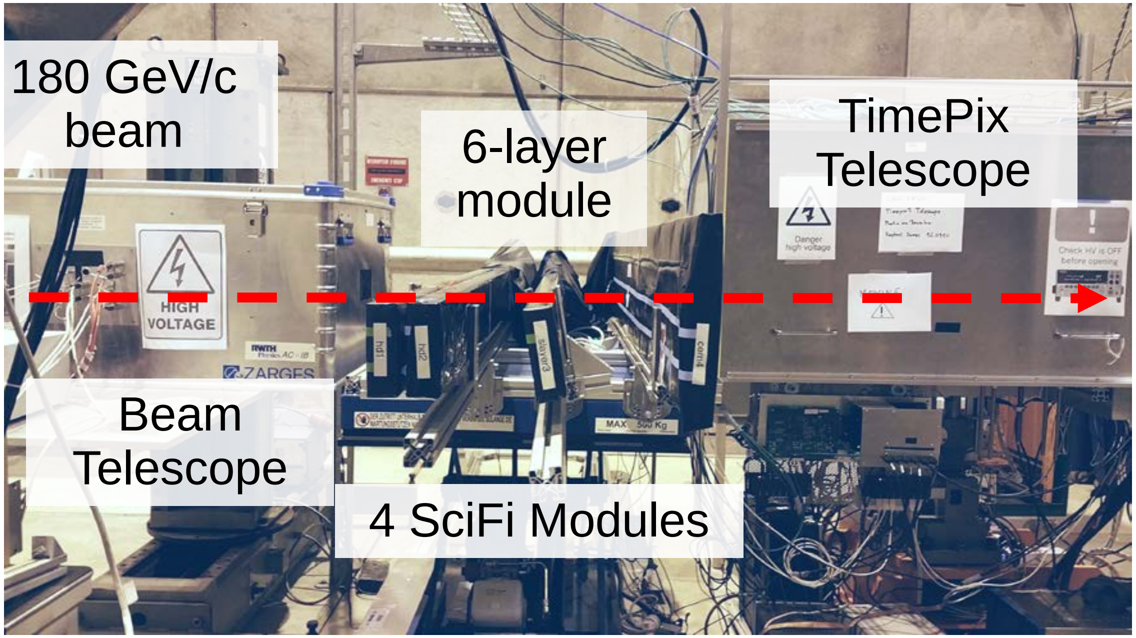
1 SiPM channel



1 SiPM array



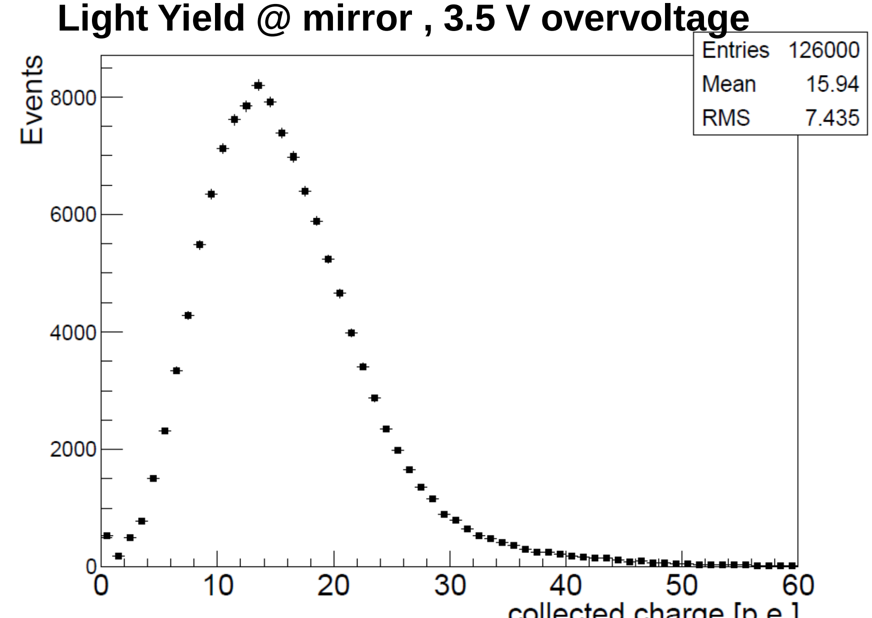
LHCb SciFi Modules: Testbeam 2014/15



6-layer modules:

- **Light yield 16 p.e**. @ 3.5 overvoltage (mirror side)
- **Spatial resolution 70-80 µm** depending on clusterization algorithm
- **Hit efficiency ~ 99%**.

Light Yield @ mirror , 3.5 V overvoltage



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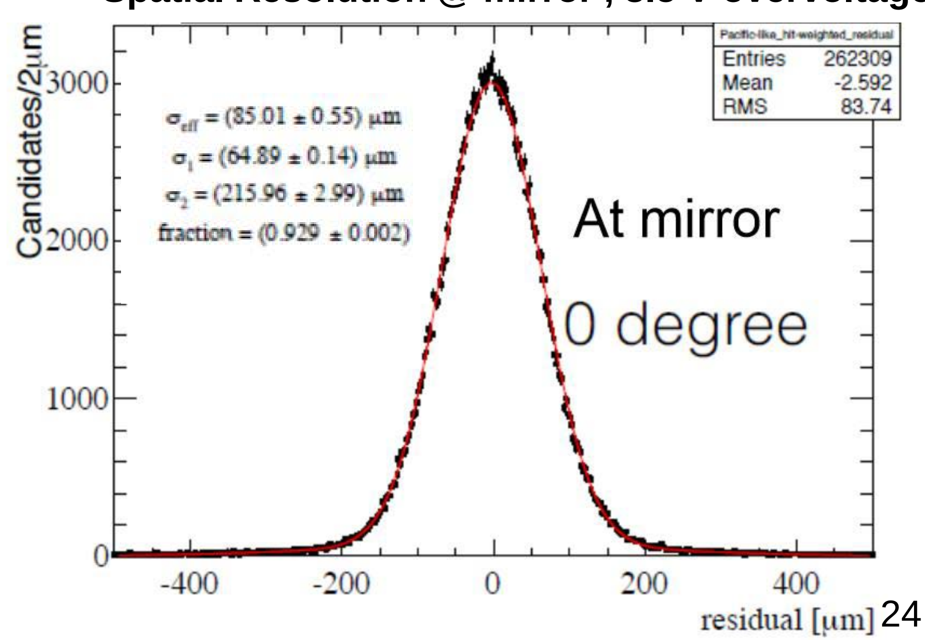
Spatial Resolution @ mirror , 3.5 V overvoltage



LHCb SciFi Tracker: Summary

- Large area high resolution scintillating fibre tracker (360 m^2, 80 µm)
- Photodetectors: Customized multi-channel SiPM arrays
- Scintillating Fibres and SiPMS qualified in LHCb radiation environment
- 64-channel PACIFIC ASIC custom designed
- Modular designed front-end electronics for data processing and transferring, calibration using light injection system
- Testbeam Results: high spatial resolution of 80 µm, hit efficiency 99%
- A close collaboration of 18 institutes in 9 countries
- Production begins in 2016, Installation in 2019, ready for LHC Run 3 from 2021