# LHCb SciFi

## The new Fibre Tracker for LHCb

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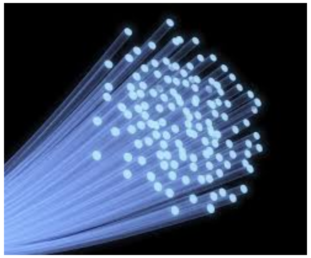
CERN PH/DT

ECFA High Luminosity LHC Experiments Workshop - 2014

**The LHCb SciFi project:** Brazil (CBPF) - China (Tsinghua) - France (LPC, LAL, LPNHE) - Germany (Aachen, Dortmund, Heidelberg, Rostock) - Netherlands (Nikhef) - Poland (Warsaw) - Russia (PNPI, ITEP, INR, IHEP, NRC KI) - Spain (Barcelona, Valencia) - Switzerland (CERN, EPFL) - UK (Imperial College)

# Scintillating fibre tracking: more than 30 years of history in HEP

- UA2 upgrade, CHORUS, D0, ATLAS ALFA + many smaller scale experiments
- high geometrical flexibility (planar, barrel, …) and in principle "edgeless"
- good tracking performance ($\sigma_{hit} < 100\ \mu m$), potentially high speed
- very low and uniform material budget



R.C. Ruchti
Annual Review of Nuclear
and Particle Science, 1996

# Evolution of optical readout technology

- image intensifiers (II) + CCD → (MA)PMT/HPD → VLPC → SiPM
- very fast (LHC speed) readout is now possible

# Unfortunately little progress in

- scintillating fibres: few suppliers, limitations in light yield, attenuation length, rad. hardness
- assembly technologies: no company produces high quality fibre mats

→ **building a SciFi tracker is a labour-intense adventure**

# Outline

- **The LHCb SciFi Tracker**
- **The main challenges**
    - Fibres with high light yield and long attenuation length
    - Building large-size detector modules
    - Radiation damage to scintillating fibres
    - Optimised SiPM detectors and their radiation hardness
    - Fast readout with manageable data volume
    - Integration (incl. operation at -40 °C)

Reminder:

# LHCb upgrade for running after LS2 (≥2020, 50fb$^{-1}$)

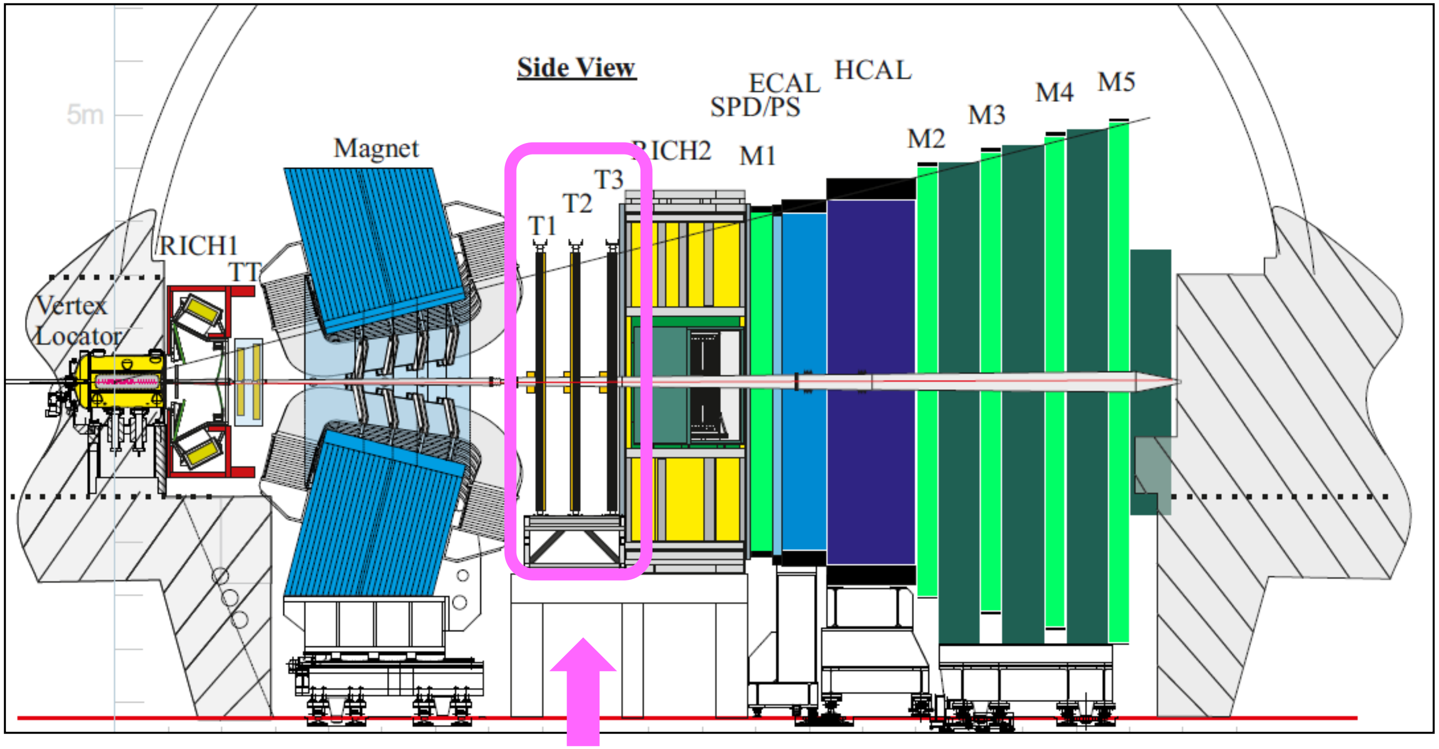
(see talk by G. Passaleva, yesterday)

The current

- Outer Tracker (OT) = Straw tube gas detectors (Ø 4.9 mm)
- Inner Tracker (IT) = Silicon μstrips (pitch = 200 μm)

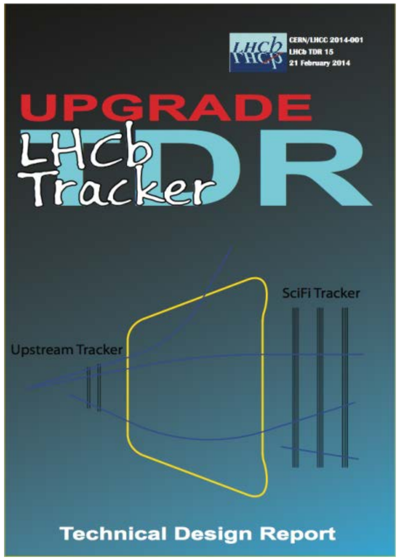
will be replaced by a single fast and light technology:

**SciFi tracker = scintillating fibres with SiPM readout.**



IT + OT → SciFi

Current LHCb


CERN/LHCC 2014-001
LHCb TDR 15
21 February 2014

UPGRADE
LHCb Tracker TDR

Technical Design Report

LHCb Tracker Upgrade TDR
CERN/LHCC 2014-001
LHCb TDR 15

# Main requirements on the SciFi tracker

## Detector intrinsic performance: measure x,x' (y,y') with

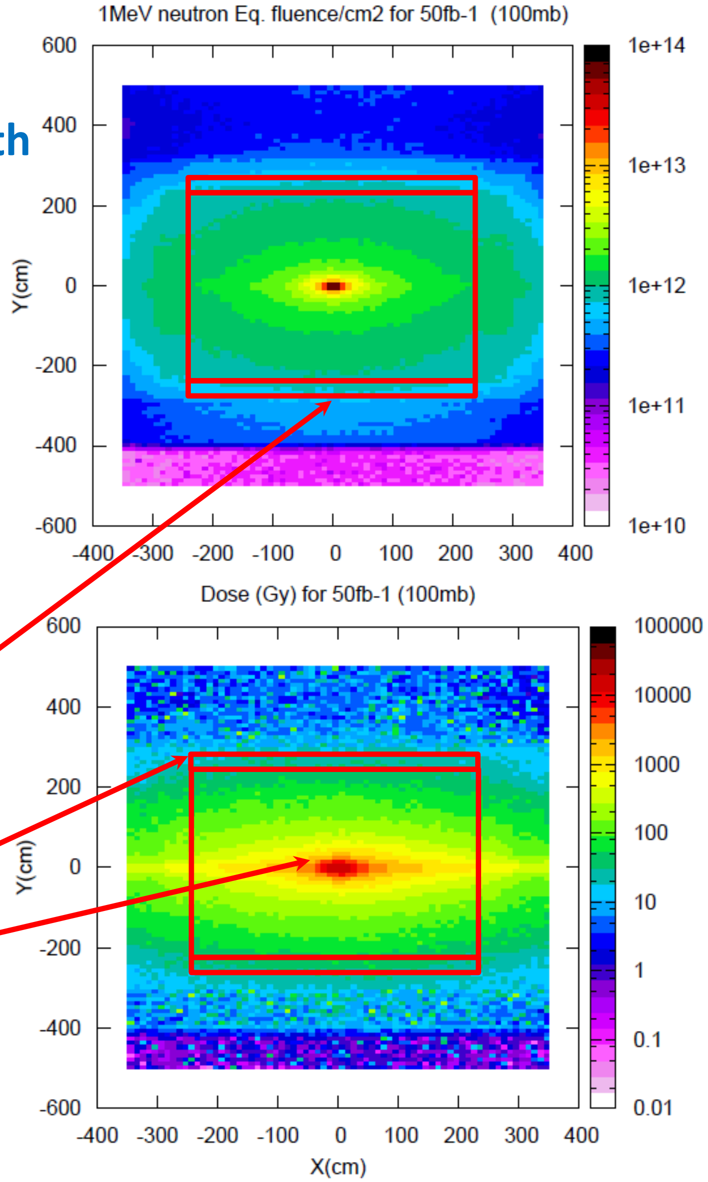
- high hit efficiency(~99%)
- low noise cluster rate (<10% of signal at any location)
- $\sigma_x < 100\mu m$ (bending plane)
- $X/X_0 \leq 1\%$ per detection layer

## Constraints

- 40MHz readout
- geometrical coverage: 6(x) × 5(y) $m^2$
- fit in between magnet and RICH2 ($\Delta z$ ~ 170 cm)
- radiation environment:
  - $\leq 10^{12}$ 1MeV $n_{eq}$ / $cm^2$ at the location of the photo-detectors
  - ≤ 80Gy at the location of the photo-detectors
  - ≤ 35kGy peak dose for the scintillating fibres

→**low temperature operation of photodetectors**

LHCb FLUKA simulation



# Technology: Fibres and photodetectors

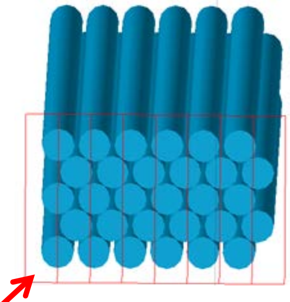
The SciFi tracker is following the technology developed by the Aachen group for the **PERDaix detector** (prototype balloon experiment)

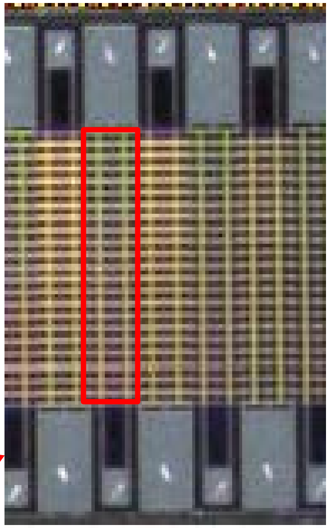
B. Beischer et al., A 622 (2010) 542–554
G.R. Yearwood, PhD thesis, Aachen, 2013

PERDaix: 32 mm wide bi-layer module in stereo geometry.

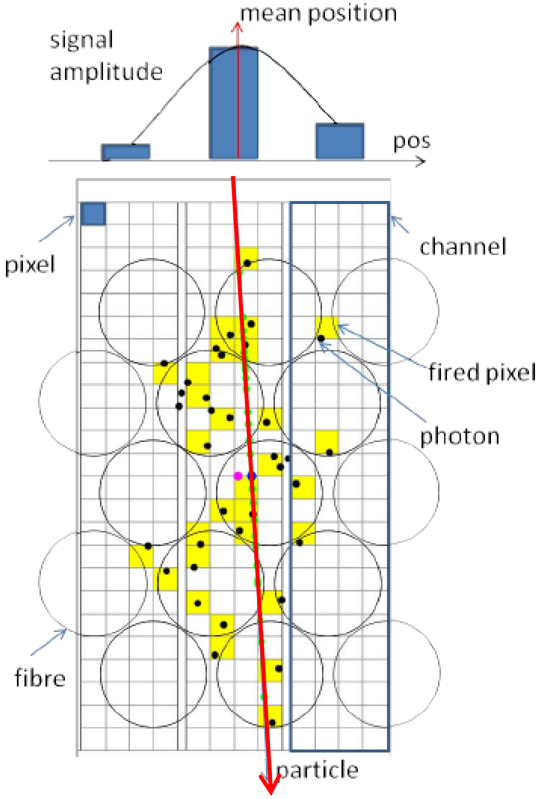
4 64-ch. SiPM arrays

- Readout by arrays of SiPMs. 1 SiPM channel has the similar width as fibre pitch (~250 µm) and extends over the full height of the mat (~1.5 mm).





- 5 staggered layers of Ø250 µm fibres form a ribbon (or mat)



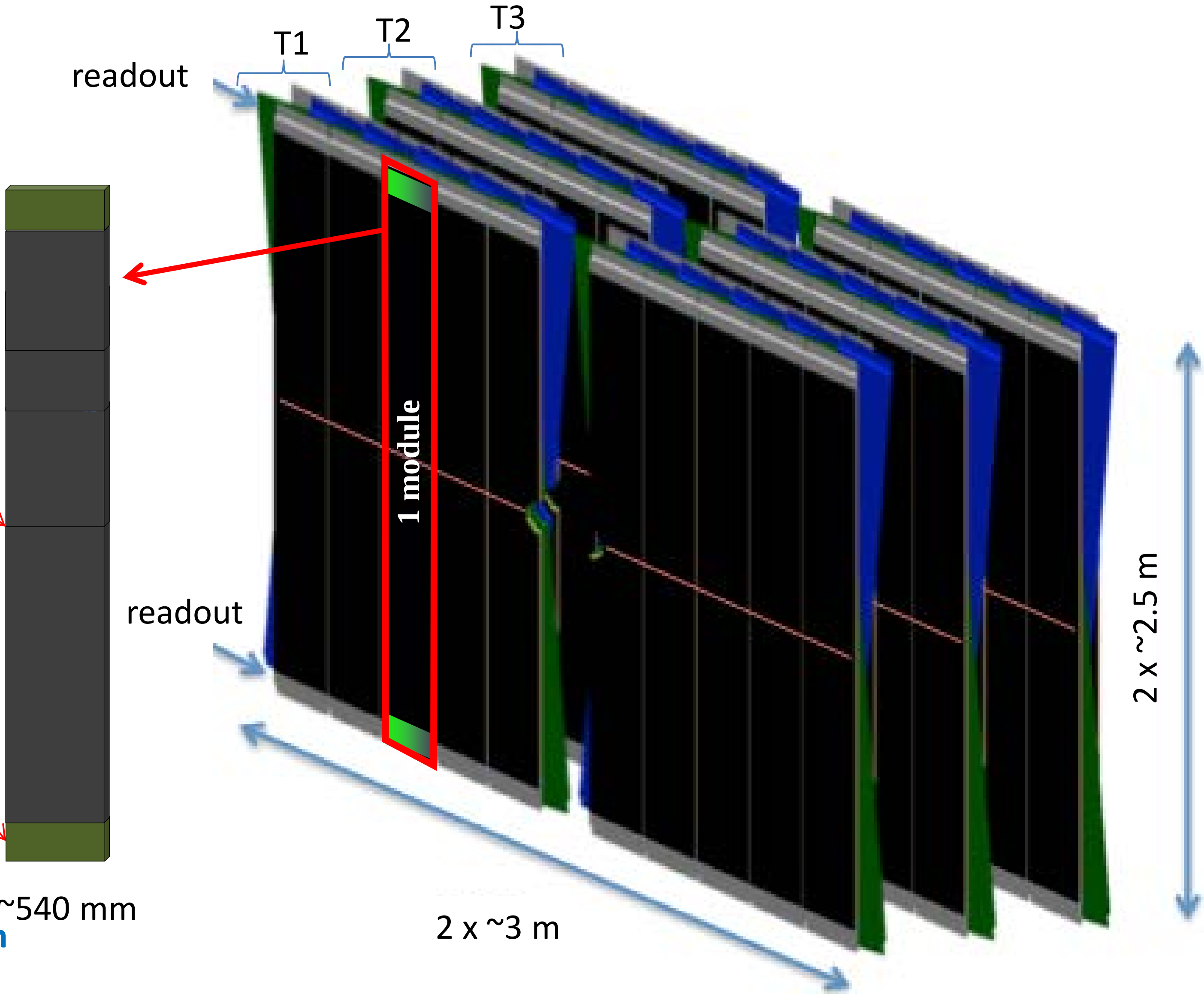
- Hits consist of clusters with typical size ~ 2.
- Allows for good resolution from COG and suppression of noise (= single hit pixel in 1 channel).

# General layout of the detector

## 3 stations with 4 planes each X-U-V-X, stereo angle ± 5° (prel.)

- 10 or 12 (almost) identical modules per detection plane
- fibre ribbons (mats) run in vertical direction.
- fibres interrupted in mid-plane (y=0) and mirrored
- fibres read out at top and bottom
- photodetectors + FE electronics + services in a "Readout Box"
- Very light and uniform material distribution

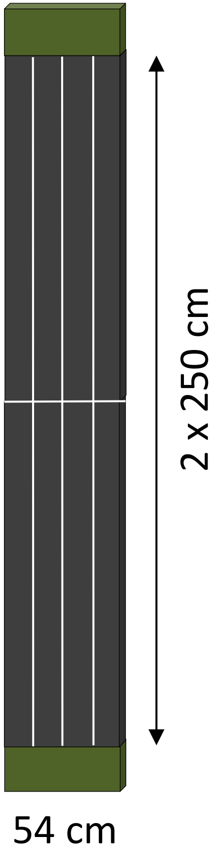
**$X/X_0$ = 2.6% per station**



# Main specifications of the SciFi tracker

| item | specs |
|---|---|
| Scint. fibre | 0.25 mm Ø, double cladded, blue emitting. Baseline SCSF-78 MJ |
| Photodetector | SiPM array, 128 ch., pitch 0.25 mm |
| Module dimensions | (2 x 250) x 54 cm, 40 mm thick, one end mirrored |
| Active surface | ~360 $m^2$ |
| Radiation | Non-uniform, up to 30 kGy, $10^{12}$ n/$cm^2$ |
| Readout | 3-thresholds, clustered, 40 MHz |
| Environment | SiPM at -40°C, rest at ambient T |

SciFi module

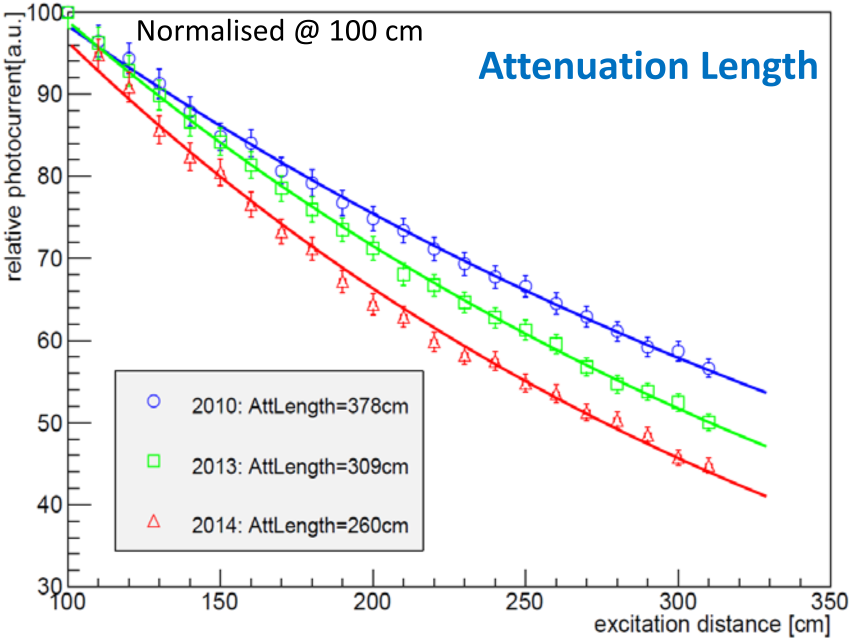


**Some rough numbers**

- 3 M fibres (2.5 m long)
- Total fibre length ~10,000 km of fibres (+ spares)
- 600 000 readout channels

# Challenge 1: Fibres with long attenuation length and high light yield

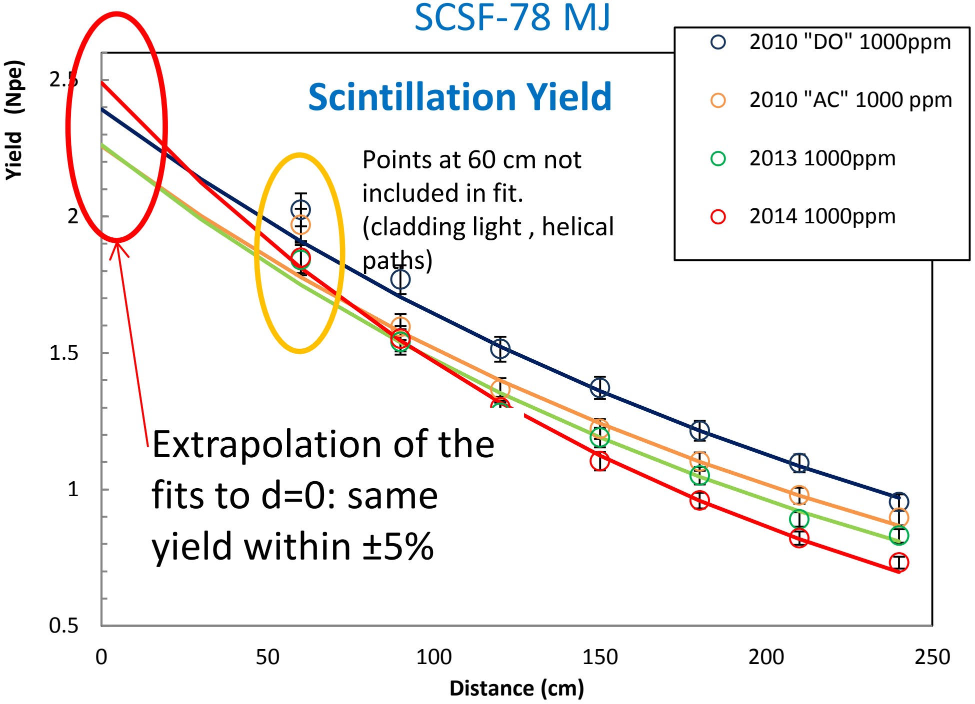
SCSF-78 MJ



Normalised @ 100 cm

**Attenuation Length**

SCSF-78 MJ



**Scintillation Yield**

Points at 60 cm not included in fit. (cladding light , helical paths)

Extrapolation of the fits to d=0: same yield within ±5%

We are currently observing attenuation lengths which are lower than for fibres bought in 2010.

The scintillation yields appear to be ~OK.

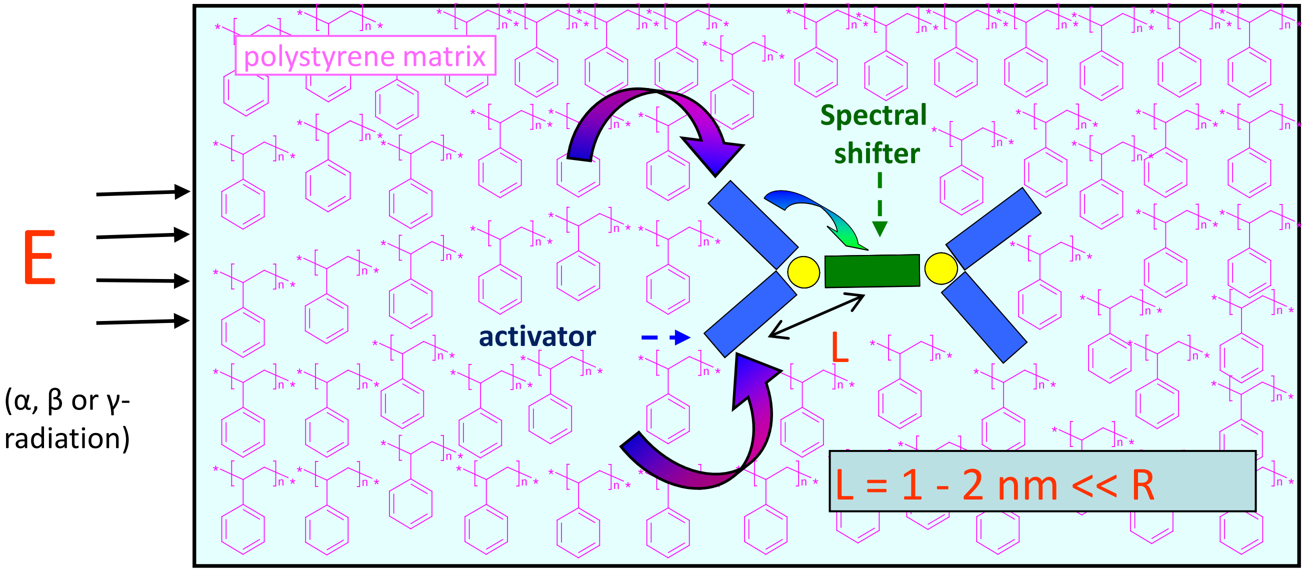
Possible causes identified at recent meeting with supplier. Expect improved batch in few weeks.
We aim for $\Lambda_{att}$ **> 3.5 m**

## We are also exploring a new scintillation material

S.A. Ponomarenko, Nature Scientific Report, 8 Oct 2014, doi:10.1038/srep06549

(Institute of Synthetic Polymeric Materials, Russia, S. Ponomarenko)

## Nanostructured Organosilicon luminophores (NOLs)



*Patent RU* 2380726 (2010)

- Material is highly interesting for **inner region of SciFi tracker** (strong 'natural' attenuation + high ionising dose).
- A fibre supplier and ISPM have started to collaborate on the development of NOL based fibres. We expect **first samples in about 1 month**.

Chemical coupling of activator and WLS molecules increases scintillation yield.

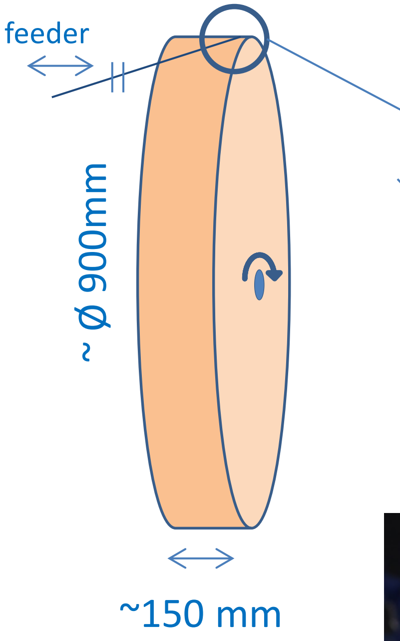
Light output is 90-120% of that of anthracene ,
i.e. **50% higher** than in standard plastic scintillator (like BC-408).

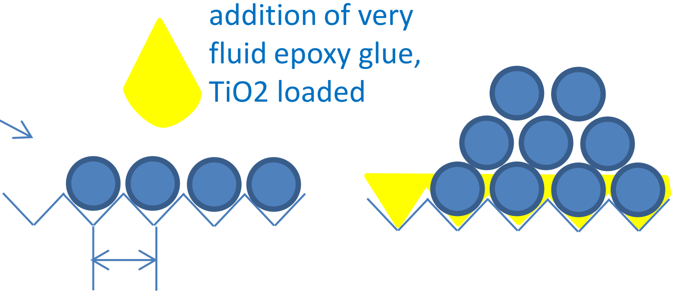
So far only tested on scintillator tiles, not on fibres!

Radiation hardness ? To be tested!

# Challenge 2: Geometrical precision

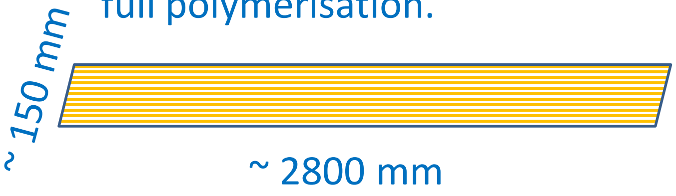
Fibre mats are produced by winding fibres, layer by layer, on a fine-pitch threaded wheel



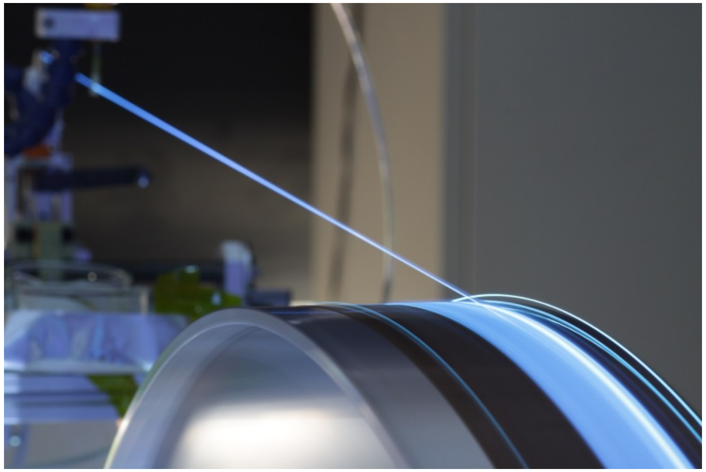


addition of very fluid epoxy glue, TiO2 loaded

After partial polymerisation, the mat is cut and flattened for full polymerisation.



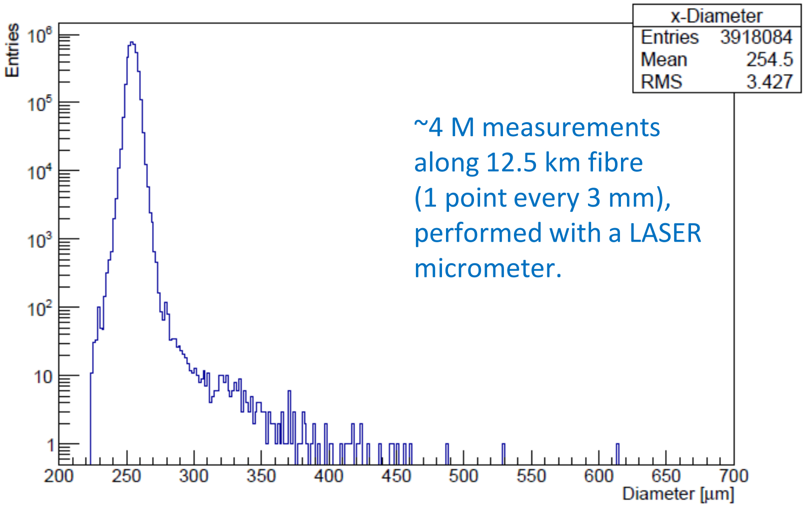
Fibre winding (at Univ. of Dortmund)
Dedicated machine, in-house production



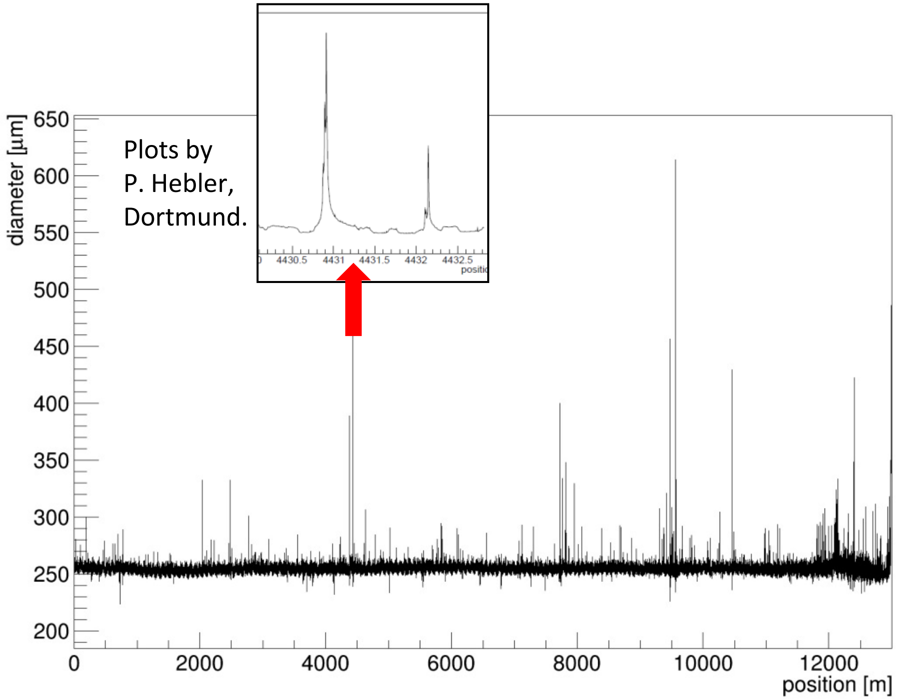
Test winding (at Univ. of Aachen)
Use of a large CNC lathe.

# An important parameter: Fibre diameter (non-)uniformity

Over 99.9% of the length, the fibre diameter is within 250 ± few μm



~4 M measurements along 12.5 km fibre (1 point every 3 mm), performed with a LASER micrometer.

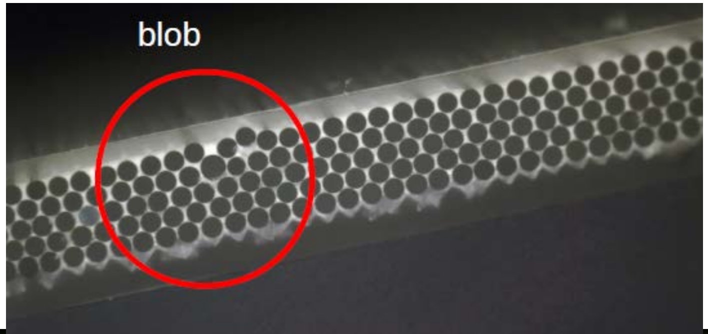


Plots by P. Hebler, Dortmund.

However, typically once per km, the fibre diameter increases beyond acceptable limits (~300 μm).

**Bump** problem addressed together with supplier. Expect improvement in coming few months.

Bumps distort local winding pattern.

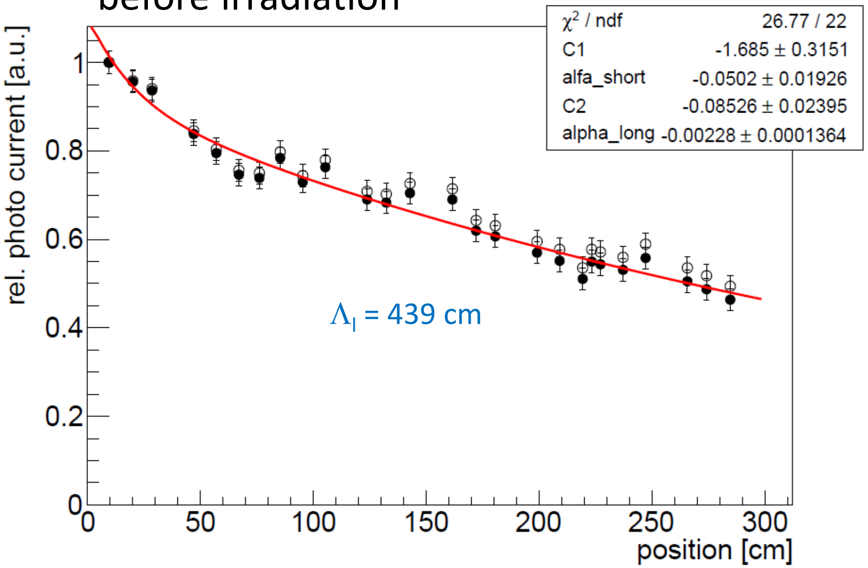


Occasional bumps can in principle be eliminated during winding, but this is time consuming.

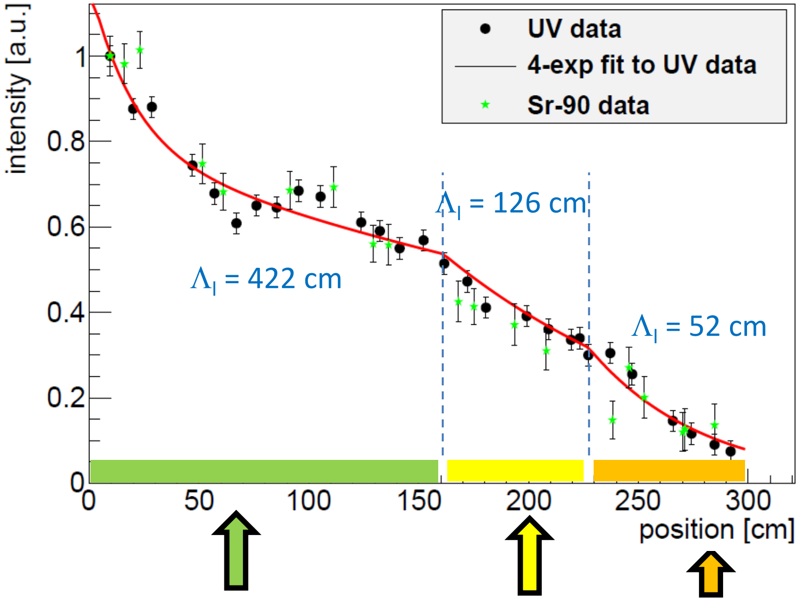
# Challenge 3: Radiation damage to scintillating fibres

- Complex subject. Literature relatively poor and contradictory → We perform our own irradiation tests under conditions which come close to the ones met in the experiment.
- Ionising radiation degrades transparency of polystyrene core (shorter att. length), but doesn't affect scintillation + WLS mechanism.
- Example: LHCb irradiation test (2012)
  - 3 m long SCSF-78 fibres (Ø 0.25 mm), embedded in glue (EPOTEK H301-2)
  - irradiated at CERN PS with 24 GeV protons (+ background of $5\cdot10^{12}$ n/cm2)

before irradiation



after irradiation

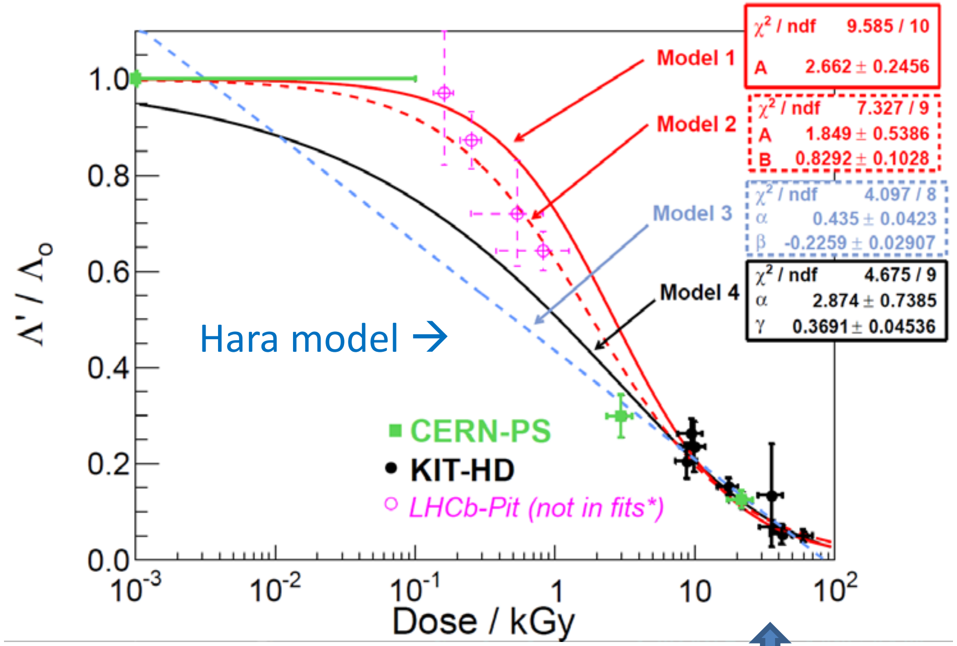


0 kGy

3 kGy
at 6.25 Gy/s

22 kGy
at 1.4 Gy/s

# More irradiations were performed at KIT (Karlsruhe) 10 MeV protons and in-situ in LHCb cavern.



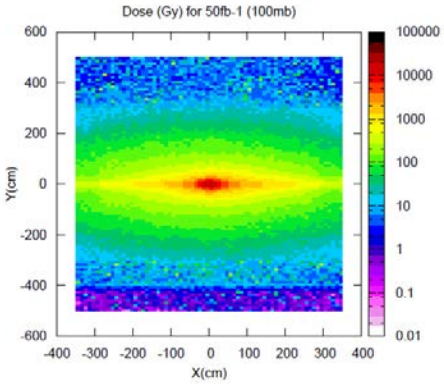
There is no well-established model to describe $\Lambda(D)/\Lambda_0$ = f(Dose)

Hara model: $\Lambda(D)/\Lambda(0) = \alpha + \beta \log(D)$

K. Hara et al., NIM A411 (1998), no. 1 31 .

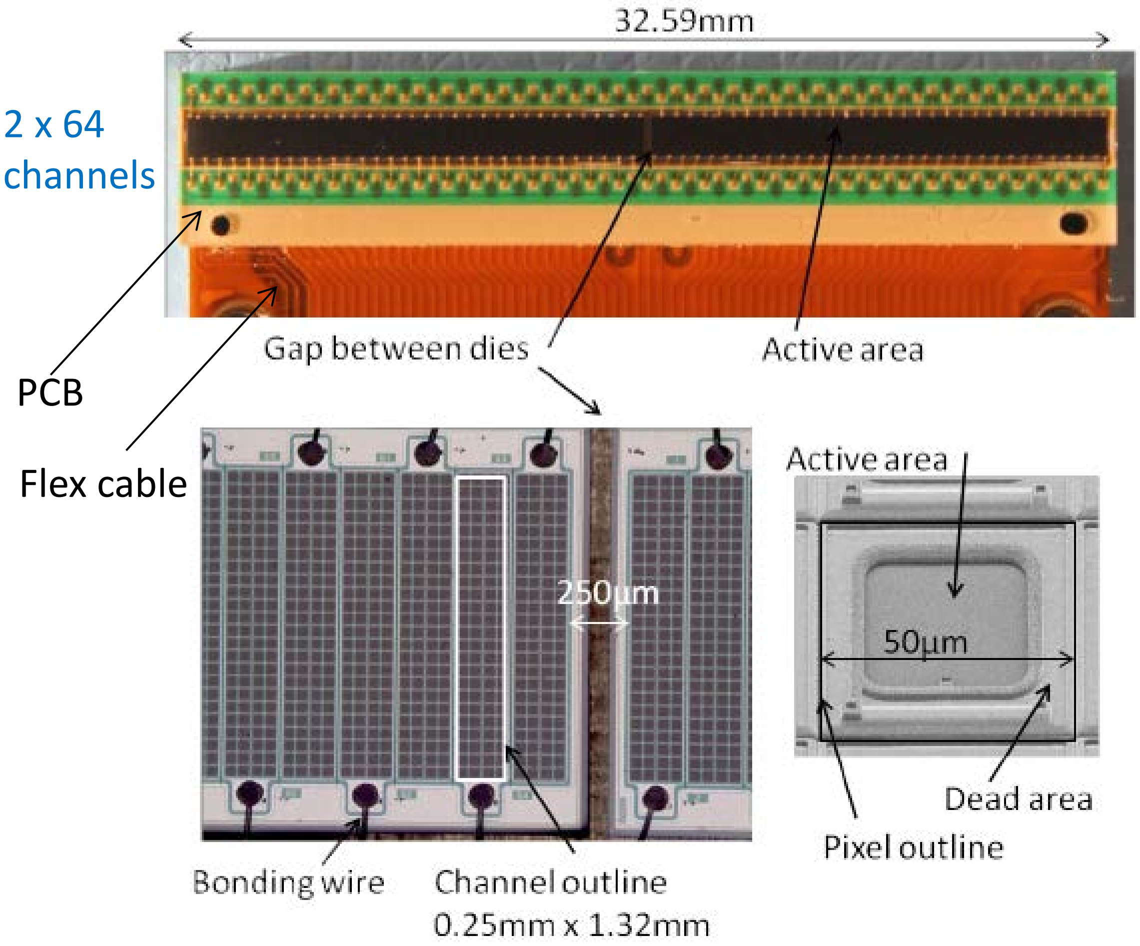
describes our high dose data well, but has some weaknesses (can't include D=0, can become negative)

We are currently preparing several low-dose (1 kGy) irradiations to improve data situation.



$\oplus \quad \Lambda(D) \quad \rightarrow$ Max. signal loss in region around beam pipe (35 kGy) of 27%

# Challenge 4: Optimised SiPM detectors and their radiation hardness



We co-develop with **Hamamatsu (JP)** and **KETEK (DE)** 128-channels SiPM arrays, with very similar dimensions.

**Photon detection efficiency**

$PDE = QE \cdot \varepsilon_{geom} \cdot \varepsilon_{avalanche}$

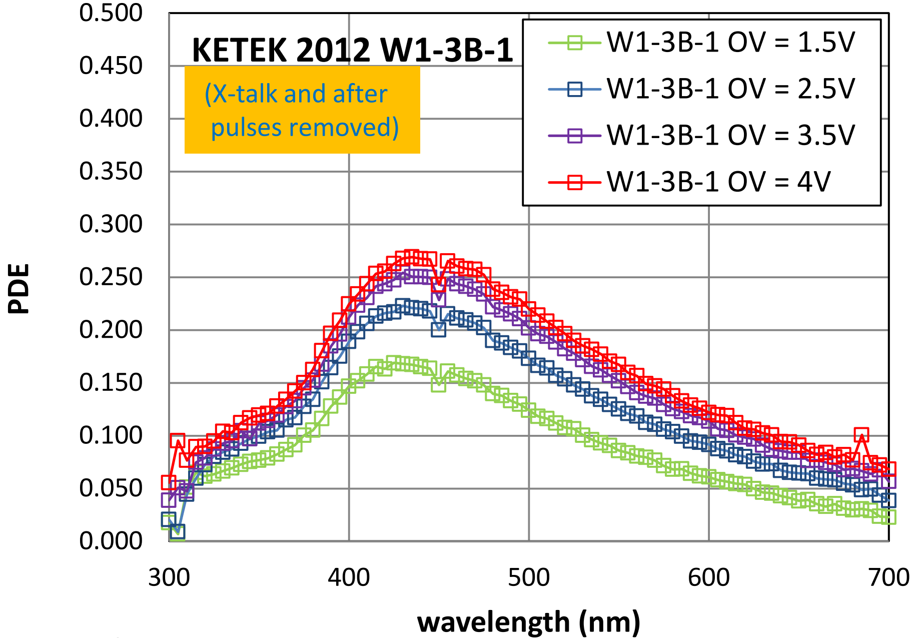
↓

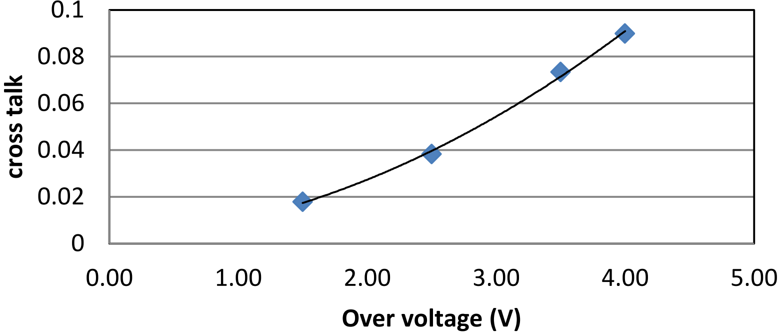
$=f(OV)$

- $\varepsilon_{geom}$ can be optimised by increasing the pixel size.
- $\varepsilon_{avalanche}$ can be increased by higher OV.
- Both effects must be counter-acted by efficient trenches to control pixel-to-pixel cross-talk.

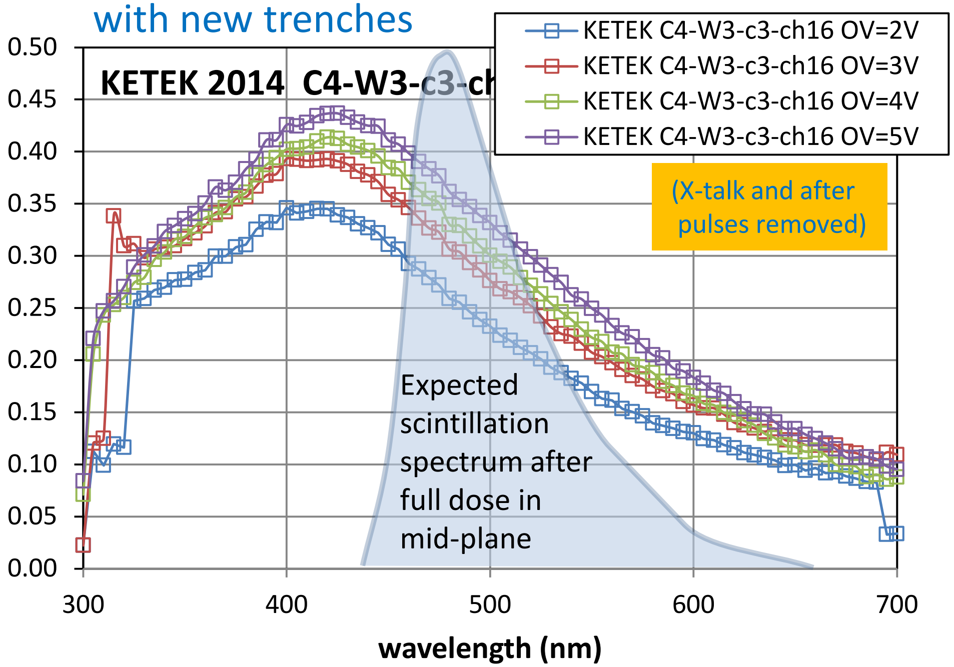
# PDE and cross talk measurements at CERN and EPFL

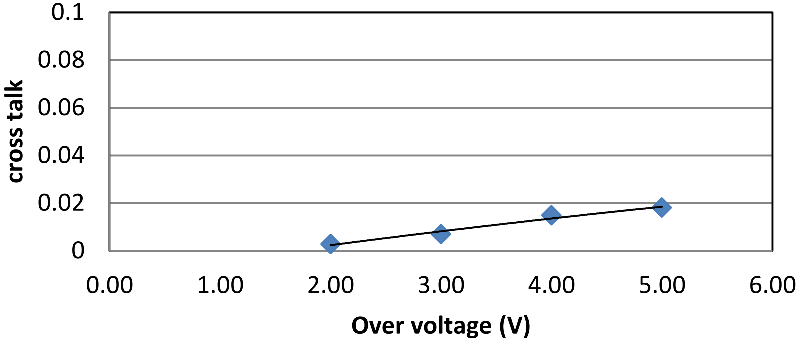
## with trenches





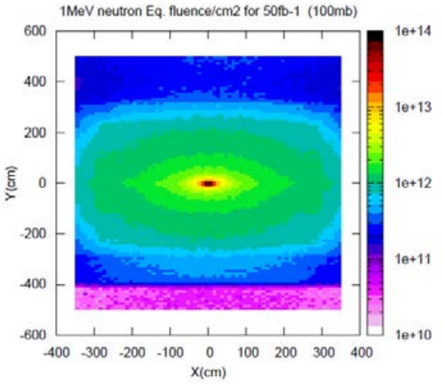
## with new trenches



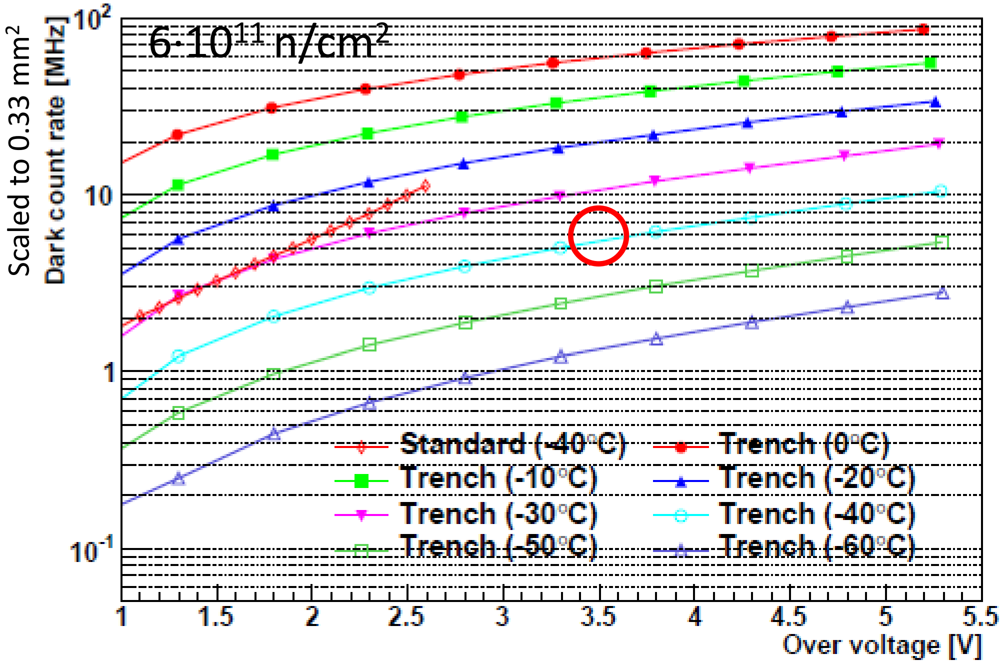


Received very recently also new Hamamatsu devices (under test)!

# The SiPMs suffer mainly from the neutrons (NIEL)



- The SiPMs are exposed to $1.2 \cdot 10^{12}$ $n_{1Mev.eq.}$ /cm$^2$ (50 fb$^{-1}$)
- A detailed FLUKA simulation showed that shielding (Polyethylene with 5% Boron) can halve this fluence → tests so far done for $6 \cdot 10^{11}$/cm$^2$ .
- The SiPMs need to be cooled. Our default working point is -40°C. Noise reduced by factor ~64.



Hamamatsu 2013 technology (single channel devices)

- Dark counts are primary noise source.
- Keep pixel-to-pixel cross-talk low → avoid double-noise hits (which can seed noise clusters)

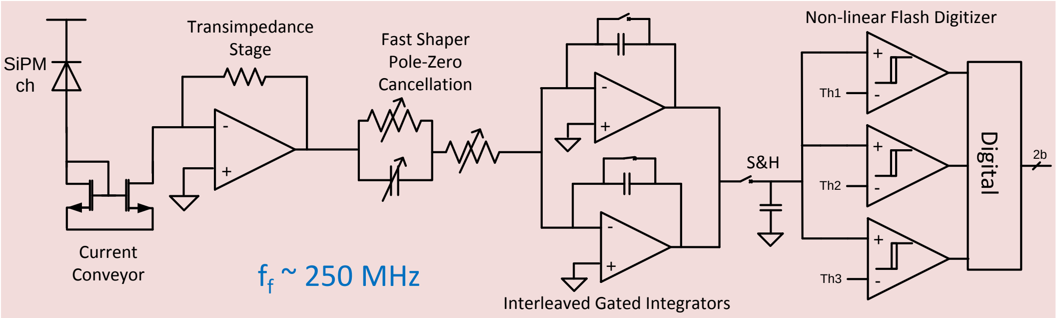
# Challenge 5: Fast readout with manageable data volume

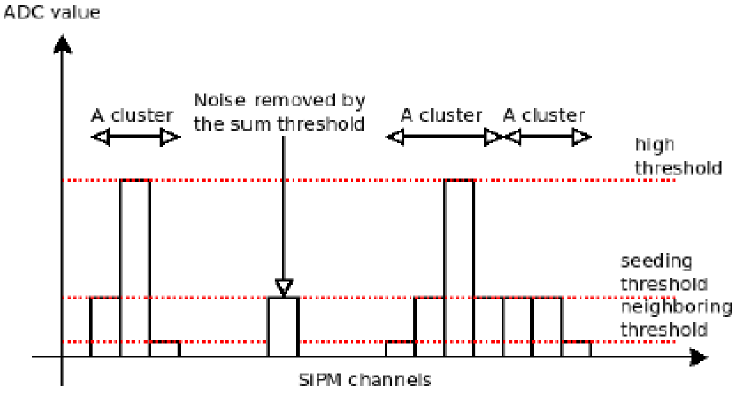
- ~0.6 M channels
- 40 MHz readout rate
- Signal propagation time up to 5m · 6ns/m = 30ns → some spill over to next BC
- No adequate (fast, low power) multi-channel ASIC available

**LHCb develops its own ASIC, called PACIFIC, with 64 channels** (130 nm CMOS, TSMC)

P ~ 8 mW/channel

$Z_{in}$ ~20-40 Ω





**3 hardware thresholds (=2 bits)**

- **seed**
- **neighbour**
- **high**

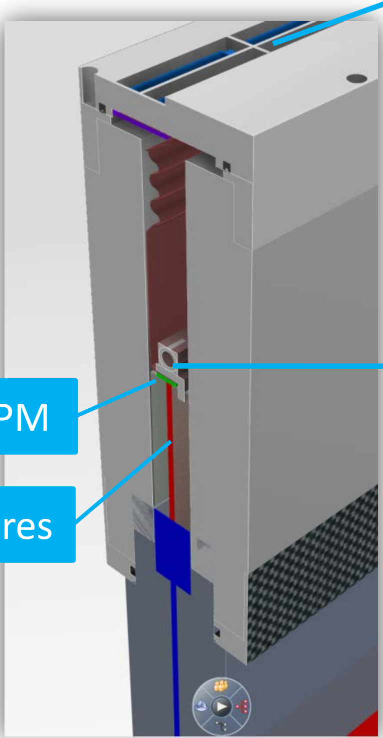
**plus a sum threshold (FPGA)** are a good compromise between precision (<100 μm), discrimination of noise and data volume.

Compared to analog (6 bit) readout, expect resolution to degrade from ~50 to 60 μm. Marginal impact on p-resolution.

# Challenge 6: Integration (incl. operation at -40 °C)

The principal integration element is the Read Out Box (ROB) at the end of every module.

- Ensure precise optical coupling of cold SiPMs to fibres
- House warm electronics
- Ensure gas & light tightness and insulation.
- Couple to mechanical frame structure.



Hybrid connectors

SiPM cooling pipes

Mounting flange

Cooling pipe

Insulation
(Rohacell with
Mylar µ alu layer)

SiPM

fibres

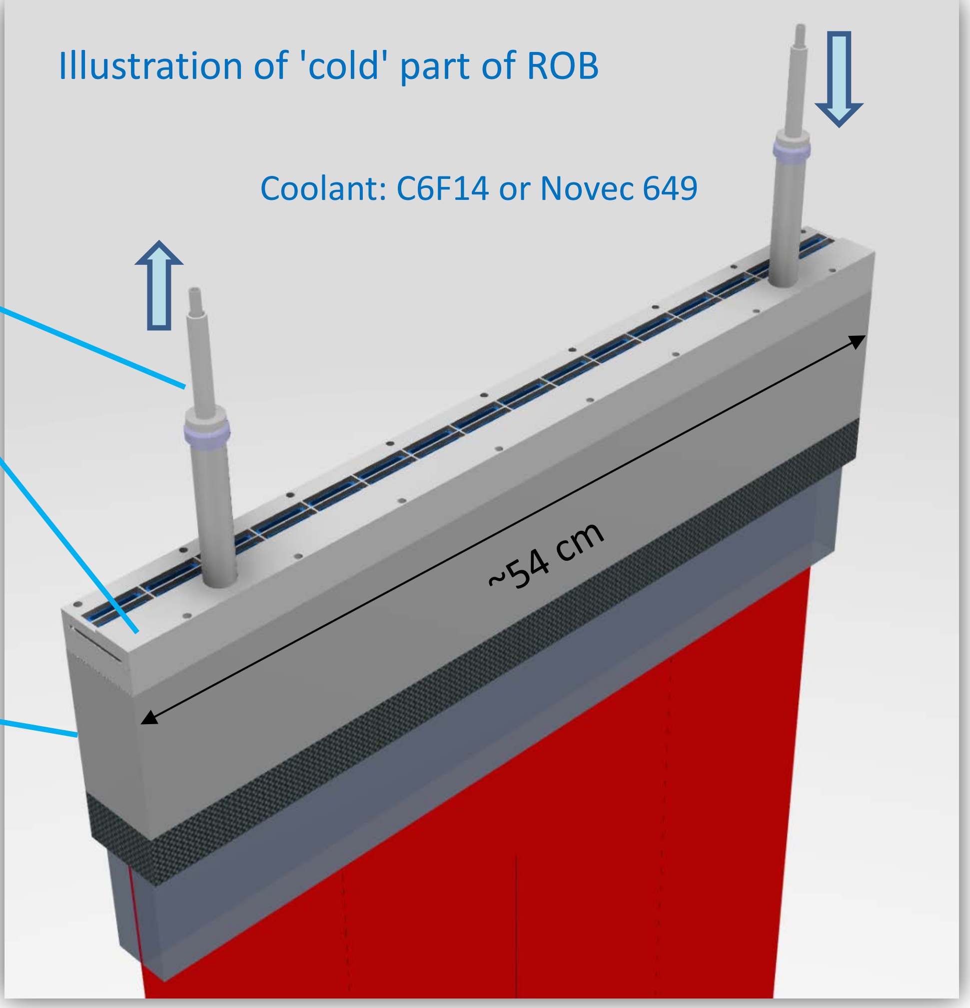


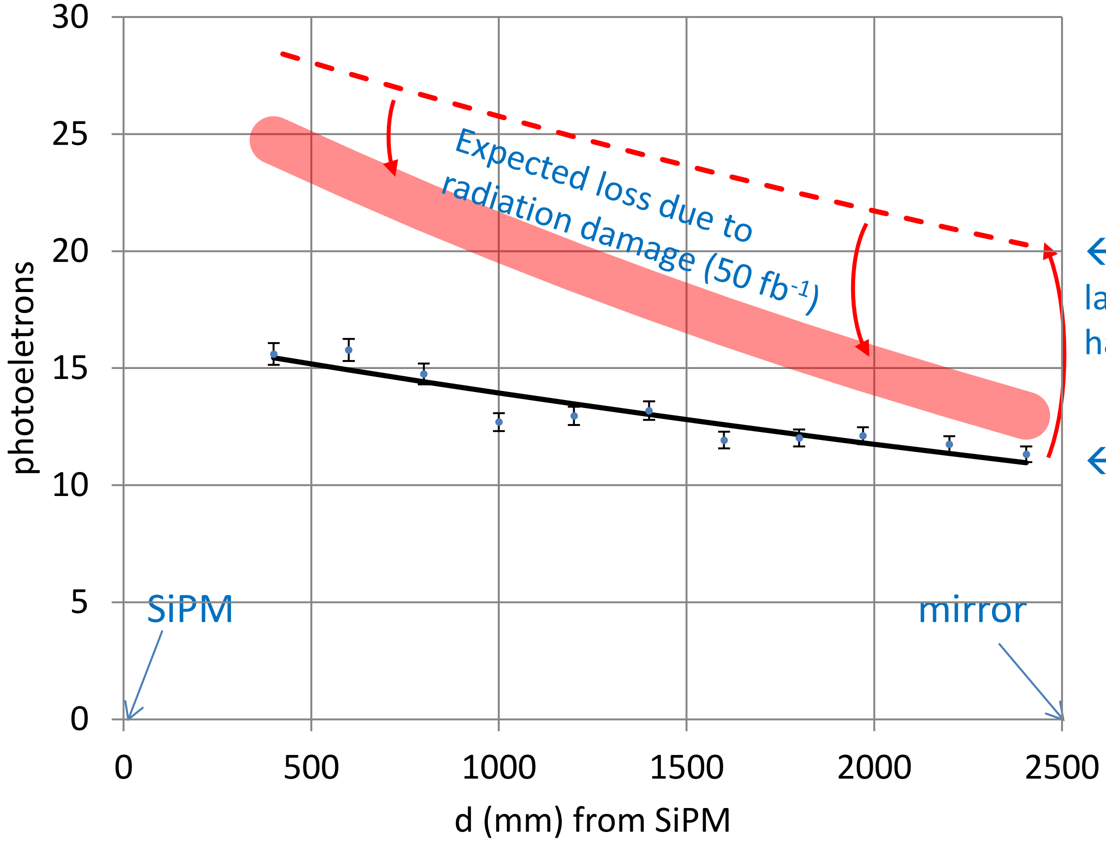
Illustration of 'cold' part of ROB

Coolant: C6F14 or Novec 649

Heat load / ROB
~ 20 W

# Where do we stand and what can we expect?

Non-irradiated 2.5 m long 5-layer mat + 2011 technology SiPM array, measured with 1.5 MeV e$^-$ in lab (from energy filtered Sr-90 source).



Expected loss due to radiation damage (50 fb$^{-1}$)

← expected gain from non-irradiated 6-layer mat, 2014 SiPM technology, H.E. hadrons

← measured in lab (Sr-90 e$^-$) in 2013

We expect this performance to be sufficient to guarantee 98-99% hit efficiency anywhere and after full radiation dose.

**We just had 1 week of successful test beam at CERN H8. Full size fibre mats + latest SiPM technology. Analysis in progress.**

# Status and Outlook

| | |
|---|---|
| **Fibre modules** | Learned how to make **13 cm wide and >2.5 m long fibre mats**. Current focus: machining and precision assembly of mats on panels. Several fibre mats successfully tested in H8 (1 week ago). |
| **SiPMs** | 128-ch. SiPM arrays from KETEK successfully tested, but packaging needs to be improved. **Increased PDE and(!) reduced XT.**<br>New arrays from Hamamatsu just arrived, but already used in beam. |
| **RO electronics** | **Single channel of PACIFIC successfully tested**. 8-channel version fabricated, but had a minor design flaw. Full scale (64 ch.) prototype ASIC in 2015. |
| **Design** | Efforts for overall detector design, Readout Box, mechanics now in full swing. Lots of challenges like beam pipe hole, cooling (insulation, condensation). |
| **Production** | Starting to prepare tooling, logistics and QA. Mass production of fibre mats and modules will require sustained efforts (4 winding centres) and tight quality control. |

**→ Start of fibre mat and module production around end 2015.**
**→ Detector to be ready for installation around mid 2018.**