# Large Area Tracking Systems
# Based on Scintillating Fibres Read Out by SiPMs

# The new Fibre Tracker for LHCb

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INFIERI Summer School 2014

# Outline

- Basics of scintillating fibres
- Tracking with scintillating fibres. Pros and cons.
- A bit of history
- Short recap of SiPM technology
- The LHCb SciFi Tracker
- LHCb SciFi R&D: Challenges, strategies, status

# Basics of scintillating fibres

# Basics of scintillating fibres

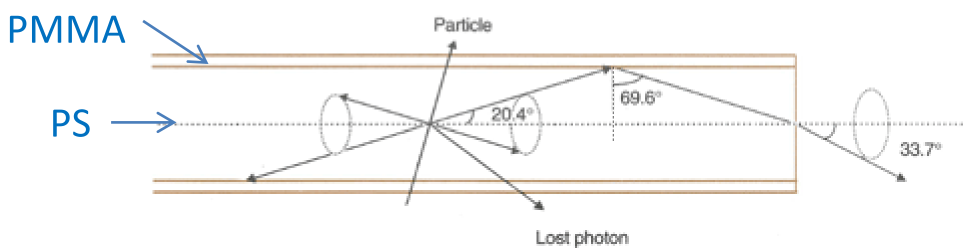
- Scintillating fibre = Polystyrene (PS) core + plexiglass (PMMA) cladding + O(1000 ppm) dopants

  n ~ 1.59           n ~ 1.49

Typical dimensions:

- core ~ mm
- 3% of core (~ 10 μm)

$$\theta_{crit} = \text{asin}\left(\frac{1.49}{1.59}\right) = 69.6°$$

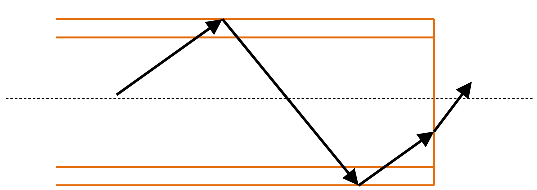


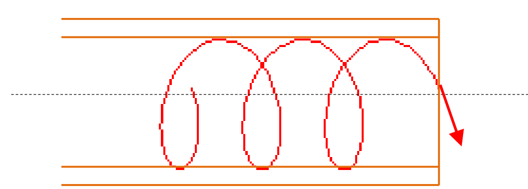

Assuming isotropic emission of scintillation light in a round fibre, the trapping fraction is

$$\varepsilon_{trap} \geq \frac{1}{4\pi}\int_0^{20.4°} 2\pi\, sin\theta d\theta = 3.1\%$$ (per side)

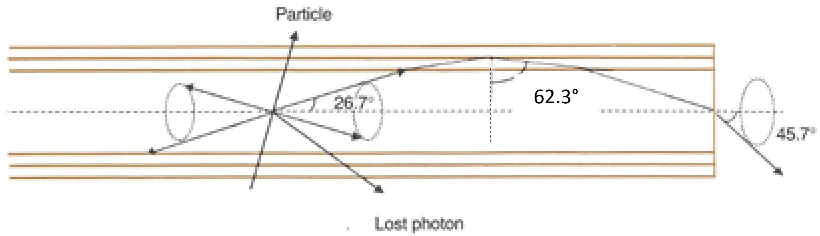
- Why "≥" ? 3.1% corresponds to meridional modes only, i.e. rays which cross the fibre axis and which are reflected at the core/cladding boundary.

In addition there are 'cladding rays' and helical paths. They usually survive only over short distances.





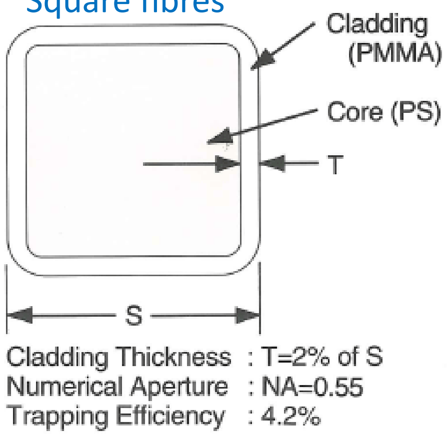
- Double cladded fibres make use of an extra layer of a fluorinated polymer with lower refractive index (n = 1.42) (CERN RD7 / Kuraray 1990). This is still state-of-the art!



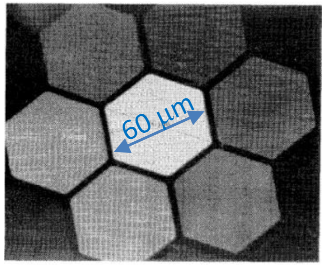

$$\varepsilon_{trap} \geq \frac{1}{4\pi}\int_0^{26.7°} 2\pi\, sin\theta d\theta = 5.4\%$$

- Scintillating fibres exist also in other geometries and flavours

Square fibres

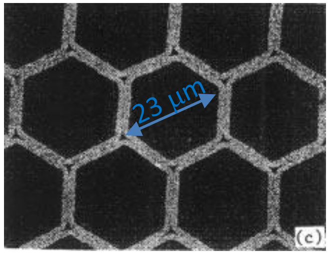



hexagonal fibres



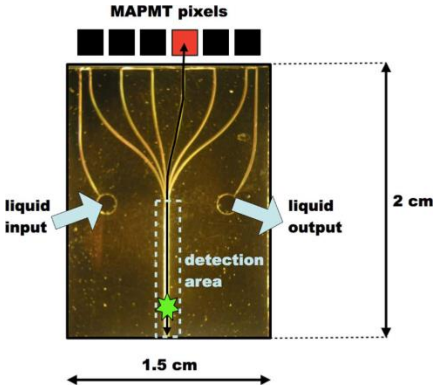

C.D. Ambrosio et al., NIM A 325 (1993), 161

glass capillaries with liquid scintillator




Annis P, et al. NIM A367 (1995) 377

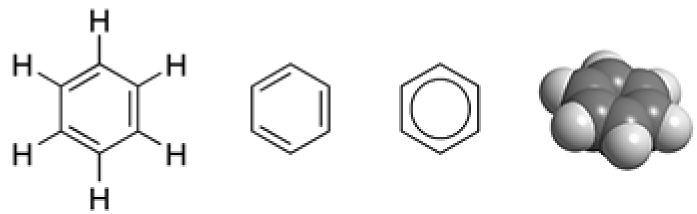
Micro-fluidic detector study

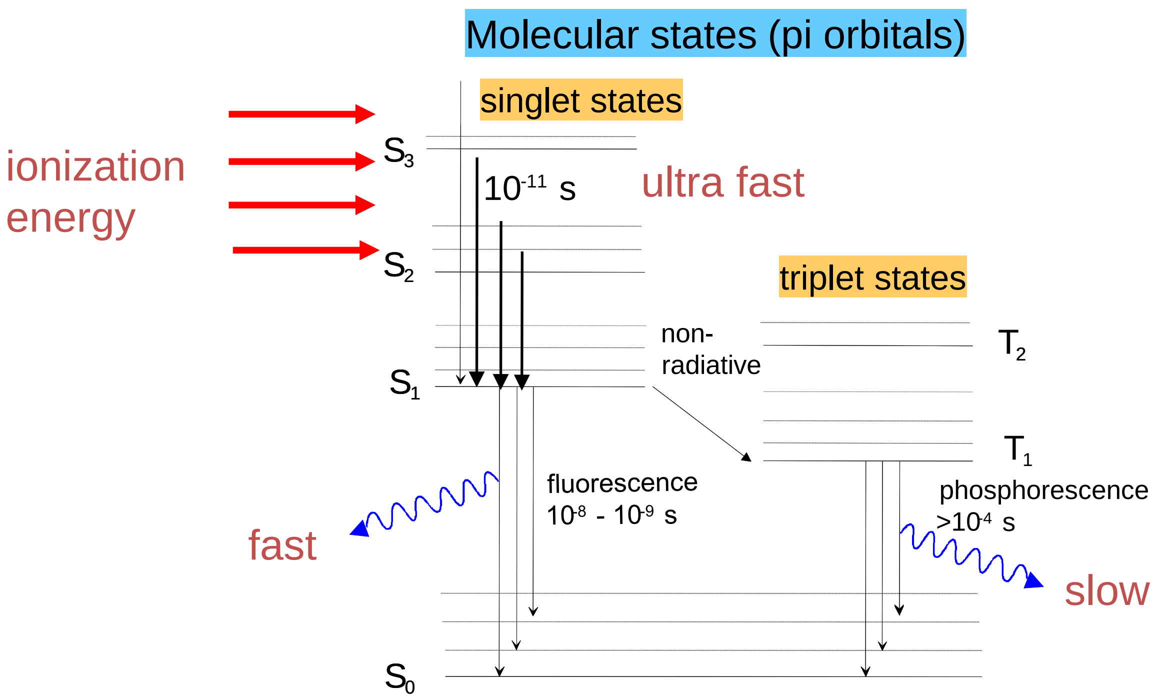



A. Mapelli et al., IEEE TNS 58, NO. 3, JUNE 2011

## Scintillation in organic materials

- The organic scintillation mechanism is based on the pi-electrons (molecular orbitals) of the benzene ring ($C_6H_6$).



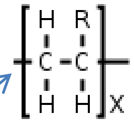




**Organic scintillators exist as**

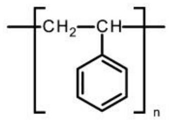
- Crystals (anthracene)
- Liquids (solutions)
- Plastics (polymerized solutions)

Organic scintillators are fast. Scintillation light decay time ~ few ns.

In HEP, we use mainly

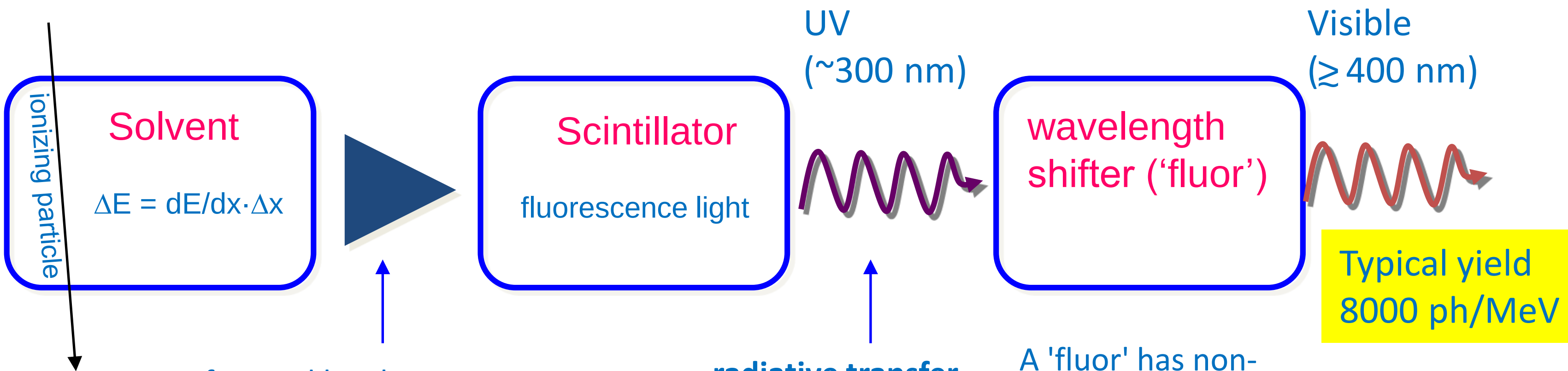


Polyvinlyltoluene (PVT) ==> plastic scintillator tiles



**Polystyrene (PS) ==> scintillating fibres**

In pure form, both PVT and PS, have a very low scintillation yield.
One adds therefore dopants in ‰ - % concentrations.




fast and local energy transfer via non-radiative dipole-dipole interactions. **Förster transfer.**

**radiative transfer**

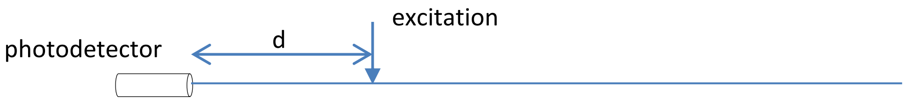
A 'fluor' has non-overlapping absorption and emission spectra. The energy/wavelength difference is called **Stokes shift**

(Producers normally don't disclose the details about the additives and their concentrations.)

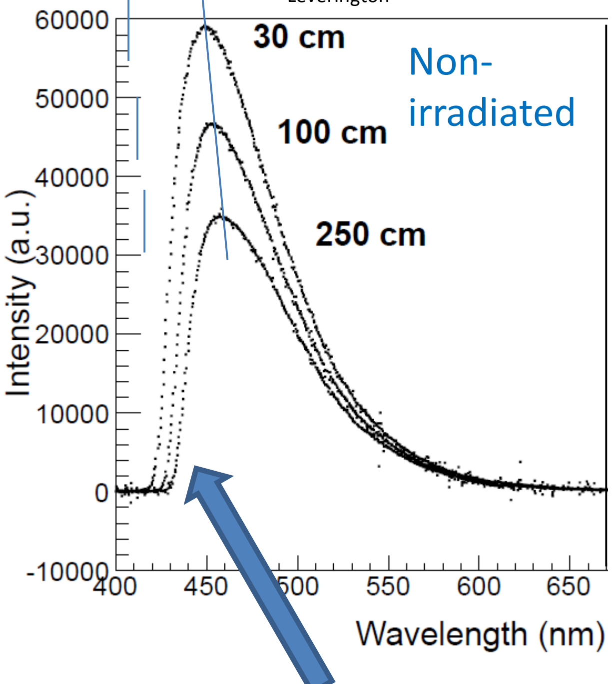
# Emission spectrum of Kuraray SCSF-78 fibre

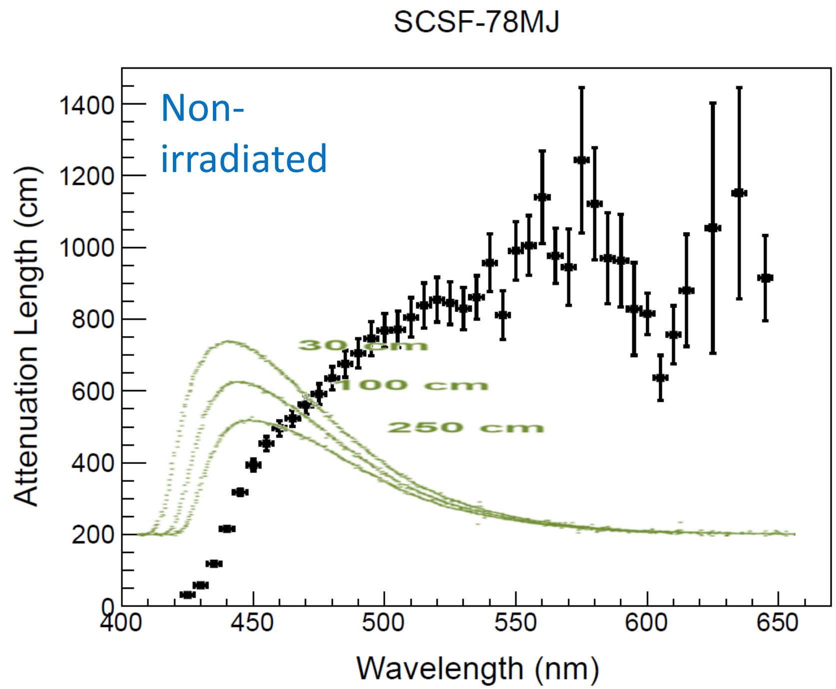
(baseline for LHCb Tracker TDR)

## as function of distance from excitation point




Tracker TDR, measurement by B. Leverington



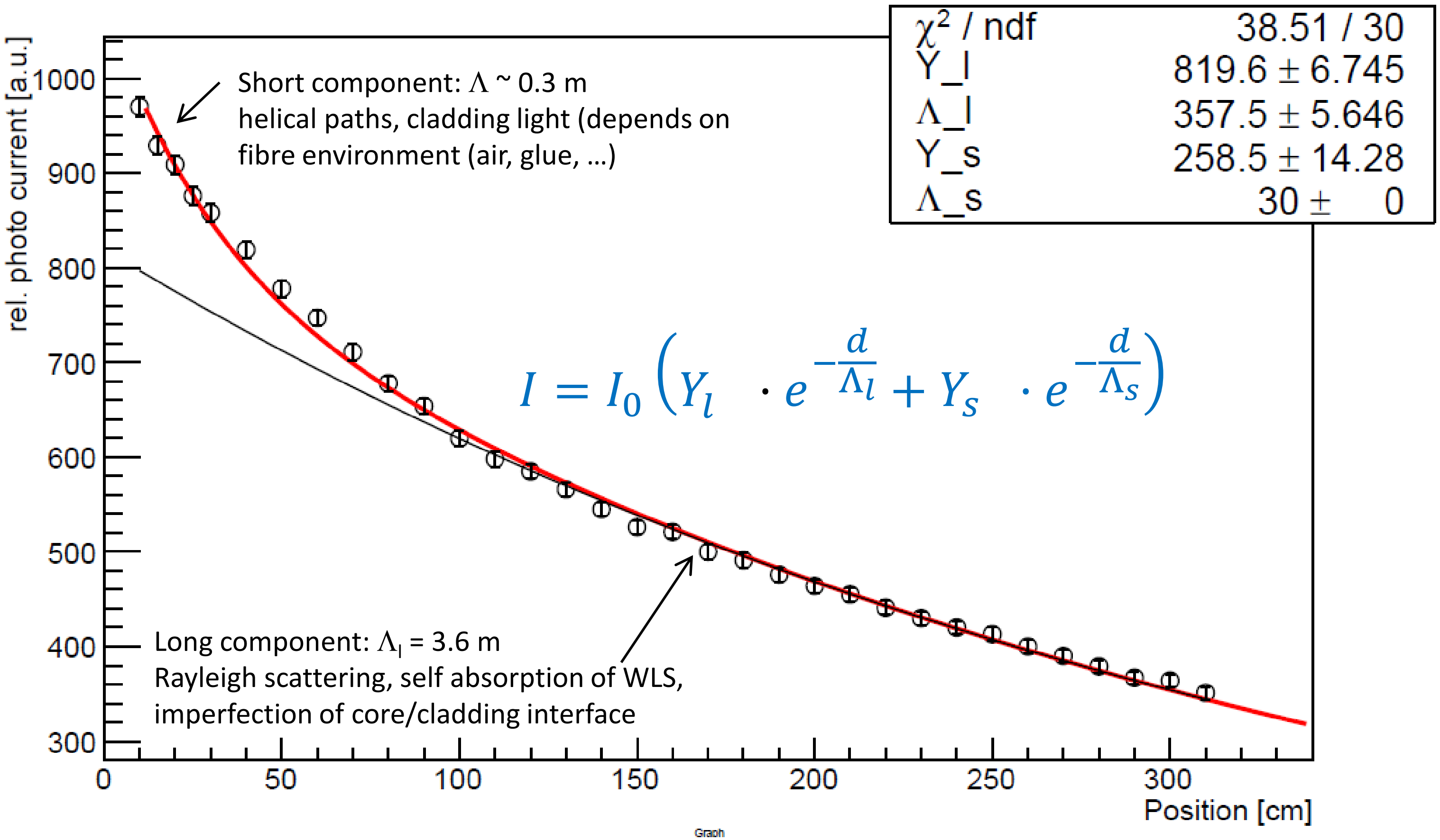




- Light is attenuated during propagation
- Blue light is stronger absorbed than green and red

$$I = I_0 \cdot e^{-\frac{d}{\Lambda}}$$

$\Lambda(\lambda)$ attenuation length

## Attenuation in a 3.5 m long SCSF-78 fibre (Ø 0.25 mm) in air, averaged over emission spectrum




$$I = I_0\left(Y_l \cdot e^{-\frac{d}{\Lambda_l}} + Y_s \cdot e^{-\frac{d}{\Lambda_s}}\right)$$

# Radiation damage of scintillating plastic fibres

C. Zorn, A pedestrian's guide to radiation damage in plastic scintillators,
Nuclear Physics B - Proceedings Supplements 32 (1993), no. 0 377

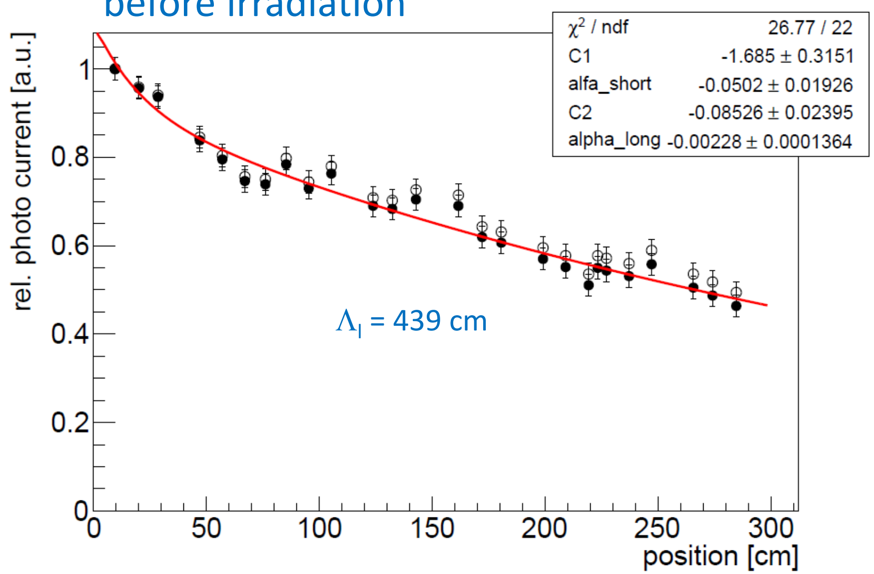
- Mainly studied in the 1990ies, but often poor dosimetry and not very well documented.
- Literature gives partly contradictory results / interpretations (impact of radiation type, dose rate, environment).
- Agreement that the main effect of ionizing radiation is a **degradation of the transparency of the core material** (PS), while scintillation yield and spectrum are unaffected.
- Radiation leads to the formation of radicals in the fibre which act as colour centres. Those can in principle react with oxygen and anneal. **Environmental parameters** may therefore play a role.
- Viability of a fibre depends crucially on its length and the dose distribution along the fibre in the specific application.

**→ Irradiation tests should therefore be performed under conditions which resemble as much as possible the ones met in the experiment.**

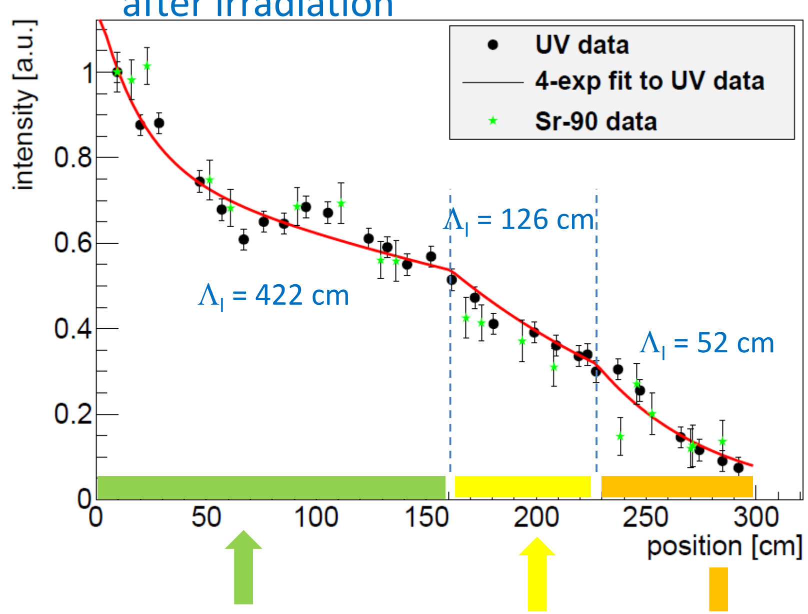
# Example: LHCb irradiation test (2012)

- 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 $5 \cdot 10^{12}$ n/cm2)

before irradiation




after irradiation

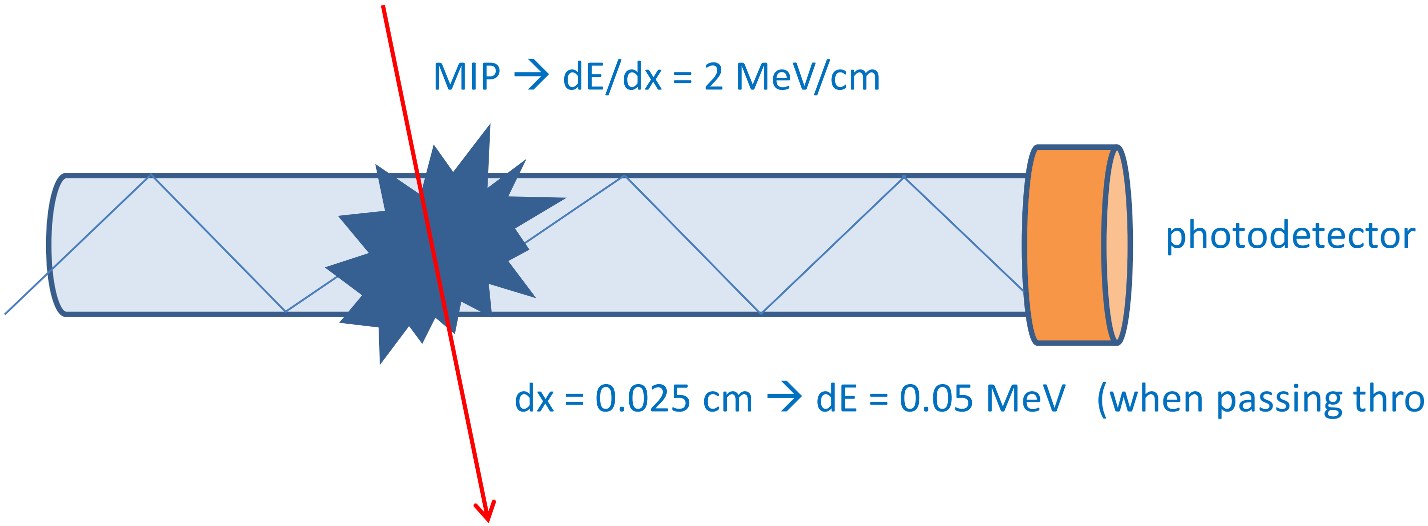



0 kGy

3 kGy
at 6.25 Gy/s

22 kGy
at 1.4 Gy/s

Back-of-the-envelope estimate of photoelectric yield in a 0.25 mm double cladded fibre, 1 m from photodetector. Non-irradiated.




dx = 0.025 cm → dE = 0.05 MeV (when passing through axis … optimistic!)

- Scintillation yield: $dY_\gamma/dE$ = 8000 ph / MeV → $Y_\gamma$ = 400
- Trapping inside fibre (1 hemisphere): 5.4% → $Y_\gamma \sim 20$
- Attenuation losses over 1 m: 22% → $Y_\gamma \sim 16$
- Efficiency of photodetector (typ. PMT): 25% → $Y_{p.e.} \sim 4$

→ Need more traversed fibre thickness
→ Need higher photodetector efficiency
→ Need to recover light in the second hemisphere

## A tracker serves to detect particles with

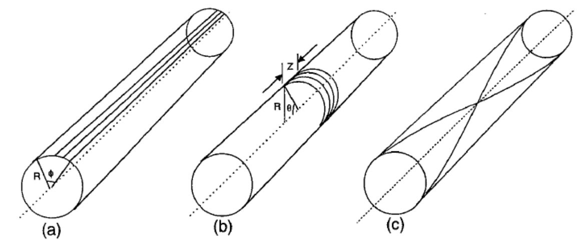
- high efficiency → enough light, low threshold
- good spatial resolution → fibre diameter, readout geometry, mechanical precision

**In addition…**

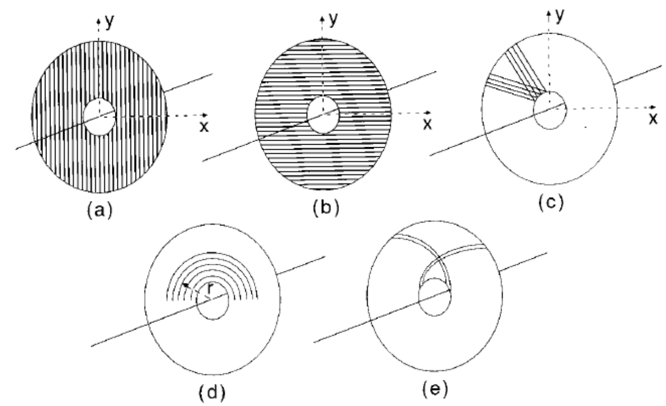
- it should give no/few false hits (ghosts) → low noise
- It should have low mass
- It should survive the radiation damage
- It should be affordable
- LHCb specific: it should allow for fast readout rate (40 MHz)

# Tracking with scintillating fibres -

# Pros and Cons




- ✚ **flexible in shape** (planar, cylindrical) and size
- ✚ **light weight** ($X_0$ (PS) = 42.4 cm, 1 mm fibre = 0.25% $X_0$)
- ✚ fibres generate and transport optical signal → the active region can consist of active material only (almost☺)
- ✚ the **material distribution** can be **very uniform**
- ✚ **fast signal** (ns decay times)
- ✚/▬ medium resolution, O(50 µm)
- ▬ quite **small signals** (few p.e.)
- ▬ **limited radiation hardness**
- ▬ **cumbersome production** (no company delivers high precision fibre layers).




*R.C. Ruchti, Annu. Rev. Nucl. Part. Sci. 1996. 46:281–319*

# A bit of history

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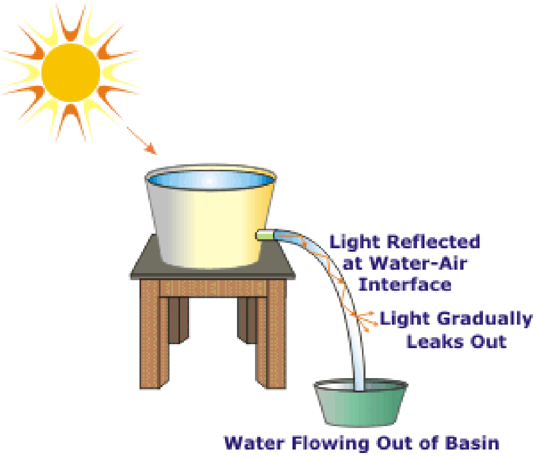
Jean-Daniel Colladon, a 38-year-old Swiss professor at University of Geneva, demonstrated (by accident) light guiding or total internal reflection for the first time in 1841.




**Filament Scintillation Counter***

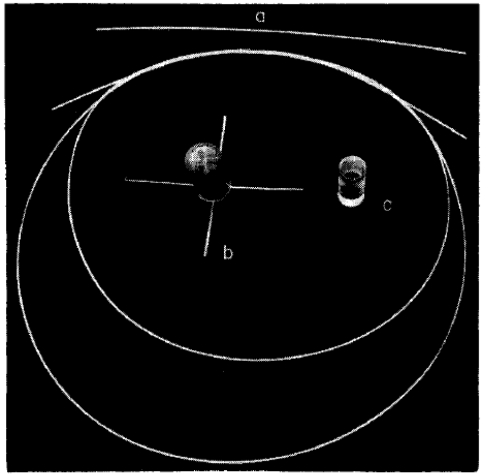
George T. Reynolds and P. E. Condon

*Palmer Physical Laboratory, Princeton University, Princeton, New Jersey*

Rev. Sci. Instrum. 28, 1098 (1957);

The above result indicates that a minimum ionizing particle passing through a filament of 1-mm diameter (index of refraction 1.58) would, on the average, result in 110 photons appearing at the end of the filament,

…… . Viewed with image intensifier tubes currently being developed,[3,4] these filaments would provide a solid scintillation chamber capable of fast timing and good space resolution



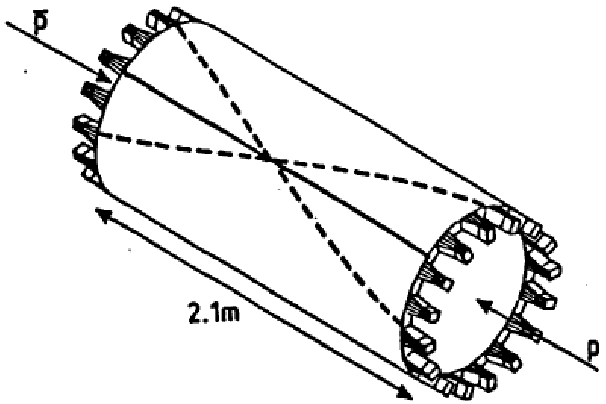

First (?) non-cladded scintillating plastic fibre.

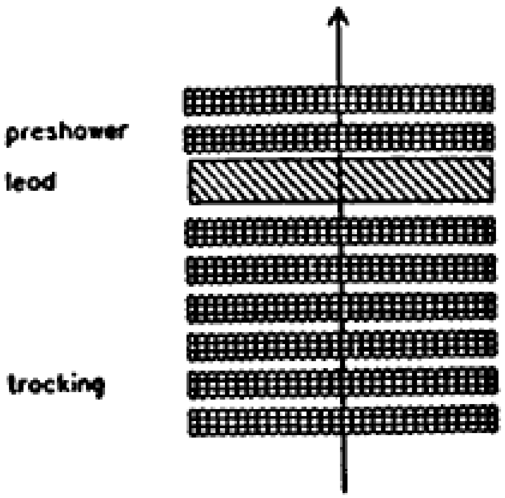
Upgrade of the **UA2** experiment (1985-87).

J. Alitti et al. , NIM A 273 (1988) 135

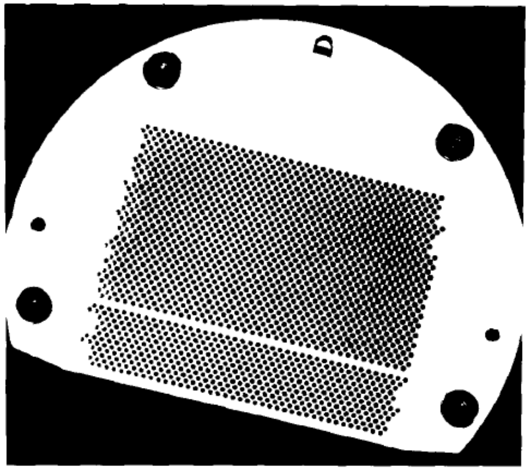
The first major collider application of scintillating fibre tracking technology.

- Outer tracking and pre-shower measurement for electron identification.
- **60,000** single-clad, blue-emitting scintillating fibres of **1 mm in diameter** and 2.1 m long
- developed and produced (!) at Saclay. $\Lambda$ > 1.5 m.
- Light propagates to 32 collector plates which are readout by **32 image-intensified CCDs** (32000 pixels each).

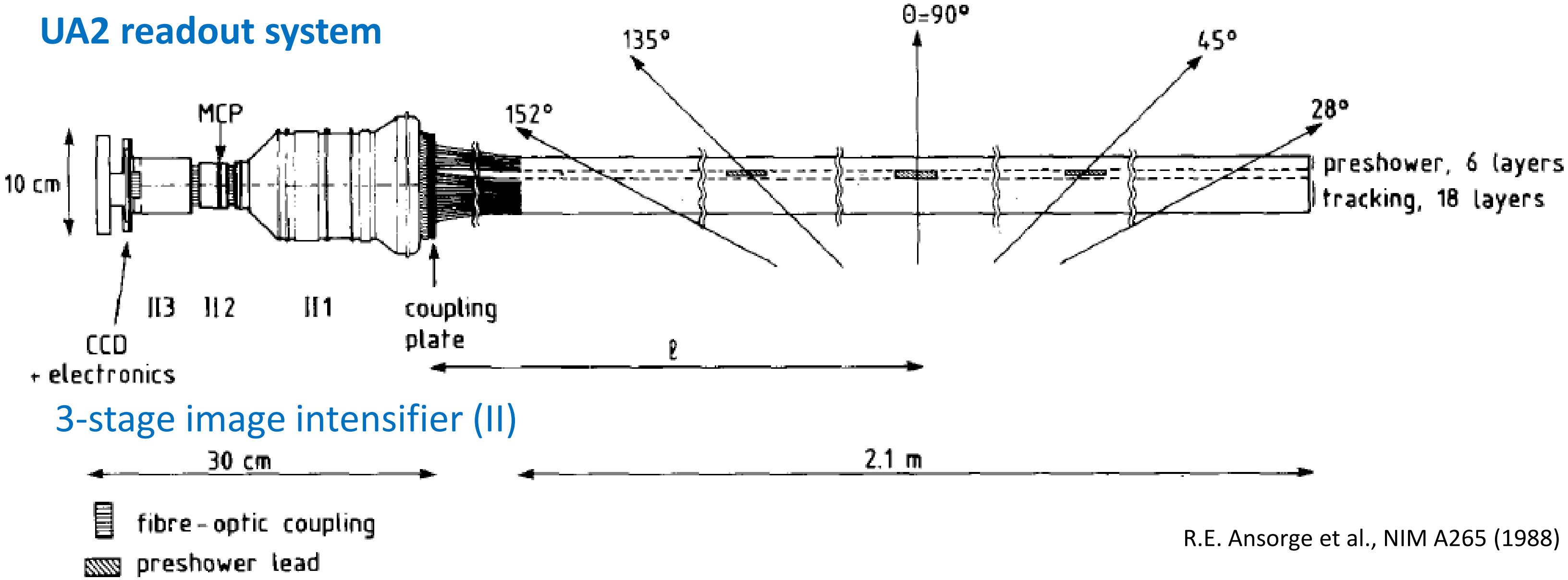



collector plate

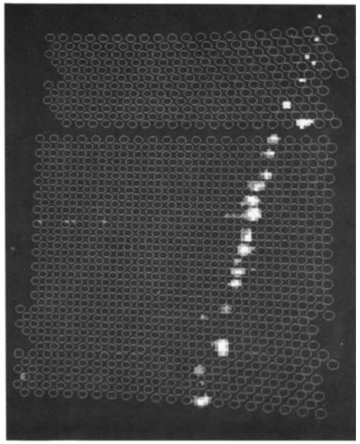


## UA2 readout system




3-stage image intensifier (II)

R.E. Ansorge et al., NIM A265 (1988) 33-49



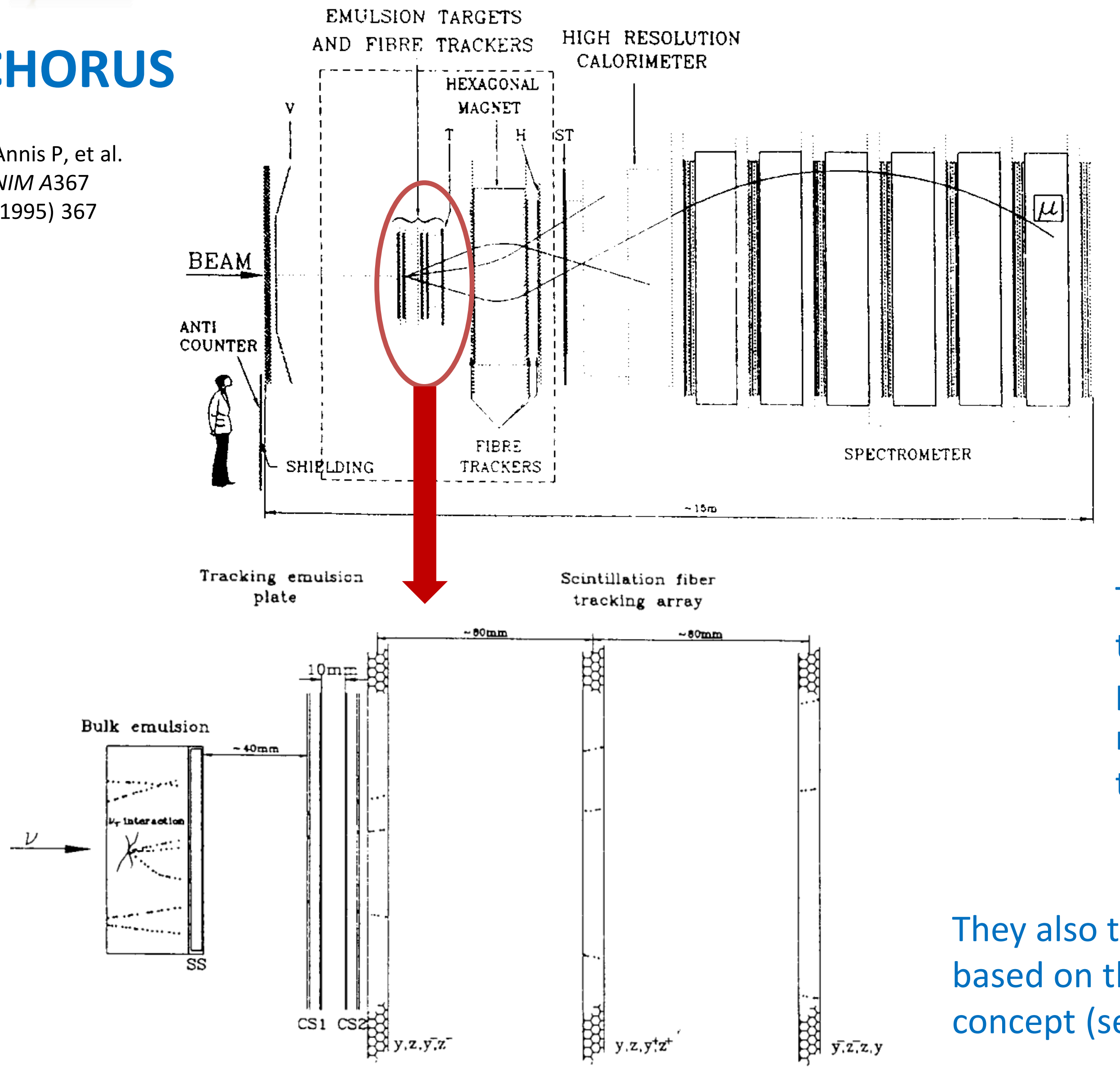
CCD image (circles show calculated fibre positions)

### Performance

- 2.8 p.e. per fibre (1mm)
- Single fibre efficiency: >91%
- $\sigma_{hit}$ = 0.35 mm, $\sigma_{track}$ = 0.2 mm
- Readout time ~10 ms

# CHORUS

Annis P, et al.
*NIM A*367
(1995) 367



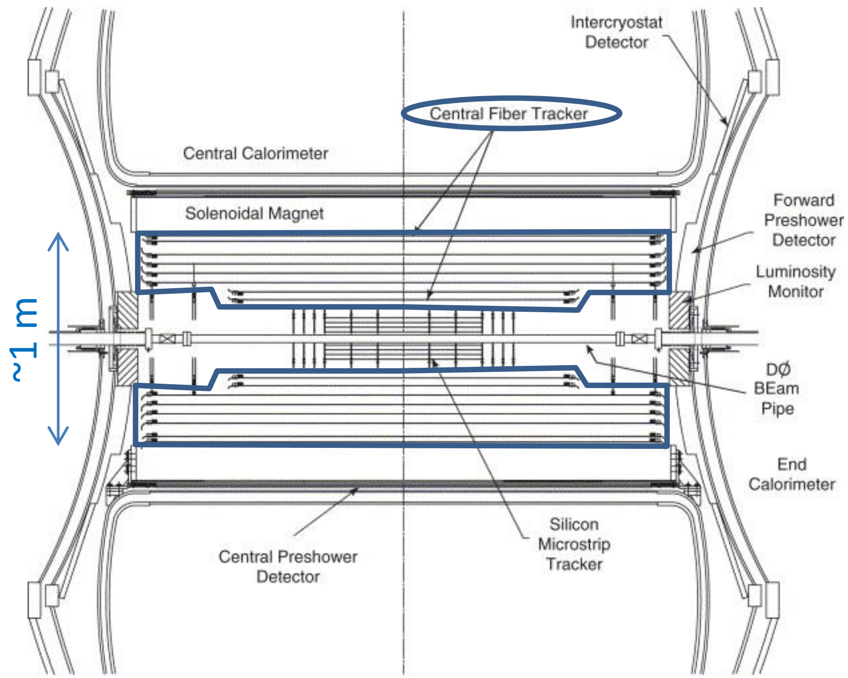

- $10^6$ scintillating fibres of Ø 500 µm
- 58 image-intensifier chains + CCD,
- similar to UA2.

The scintillating fibre-tracking layers provide pre-localisation of the regions to be scanned in the emulsion.

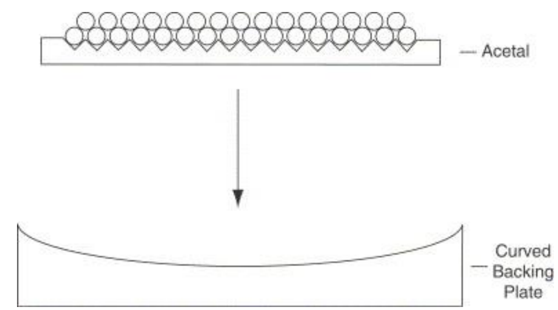
They also tested a micro-vertex tracker based on the liquid-in-capillary concept (see photo on slide 5).

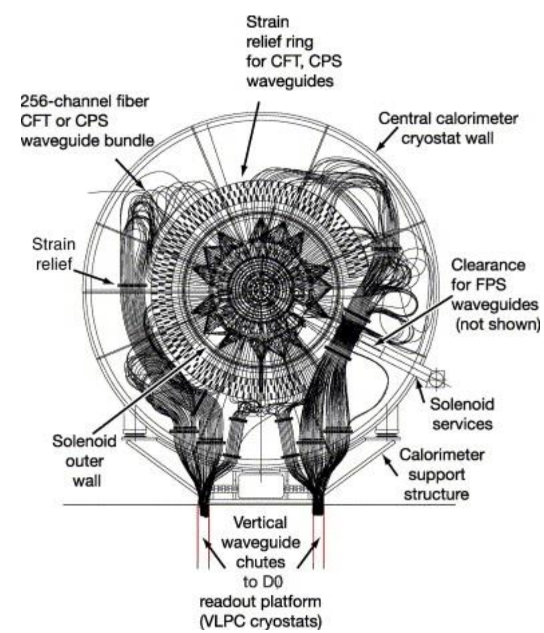
## DØ The upgraded DØ detector comprises a 80,000-channel central fiber tracker (CFT).

V.M. Abazov et al, A 565 (2006) 463–537



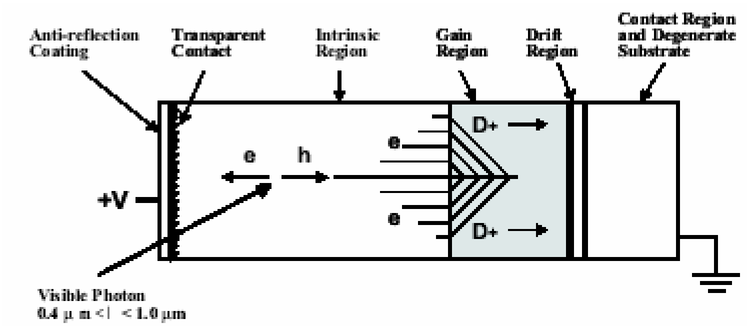

Ø 835 μm fibres are arranged in 'Doublet' structure



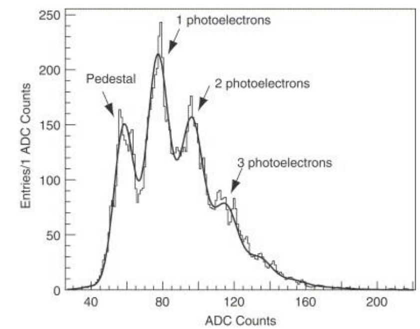

- 8 concentric layers (axial + stereo)
- $L_{fibre}$ ~ 2 m + O(10)m clear waveguide
- Total = 200 km of scintillating and 800 km of clear fibres

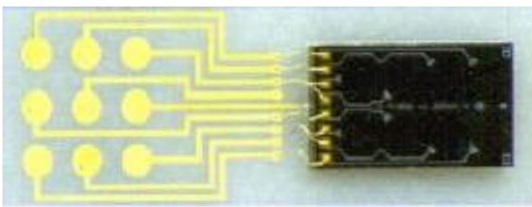
# Very innovative readout in D0: Visible Light Photon Counters (VLPC)



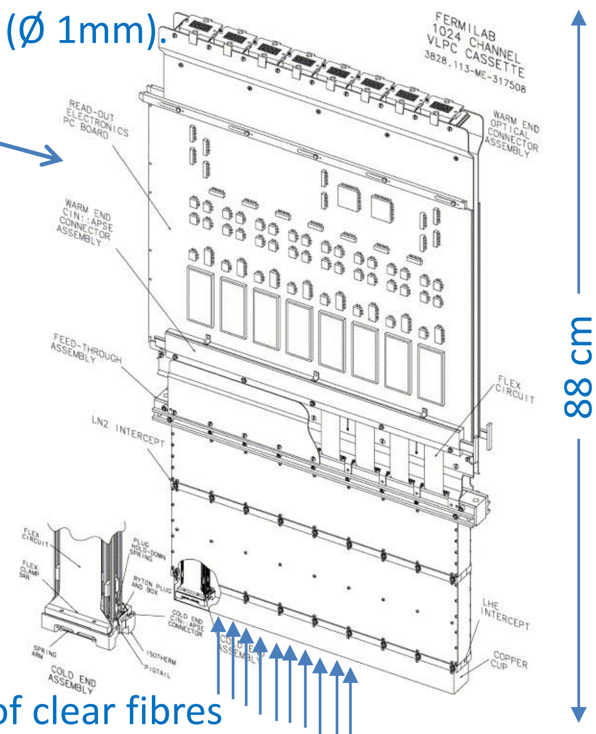

Si:As avalanche photodetector
Very high QE: ~ 75%
High gain: ~40.000
! Needs to be operated at 9 k!

LED calibration spectrum



D0 used chips with 8 VLPCs (Ø 1mm).
128 chips fit in a cassette




## Performance (partly from test stand)

B. Baumbaugh et al. IEEE TNS 43, NO. **3,** JUNE 1996

- Yield: ~10 pe / fibre
- Hit efficiency: 99.5%
- Doublet hit resolution: 100 μm
- Fast readout: CFT contributes to the L1 trigger (every 132 ns)

Same technology is also used in the MICE experiment http://mice.iit.edu/

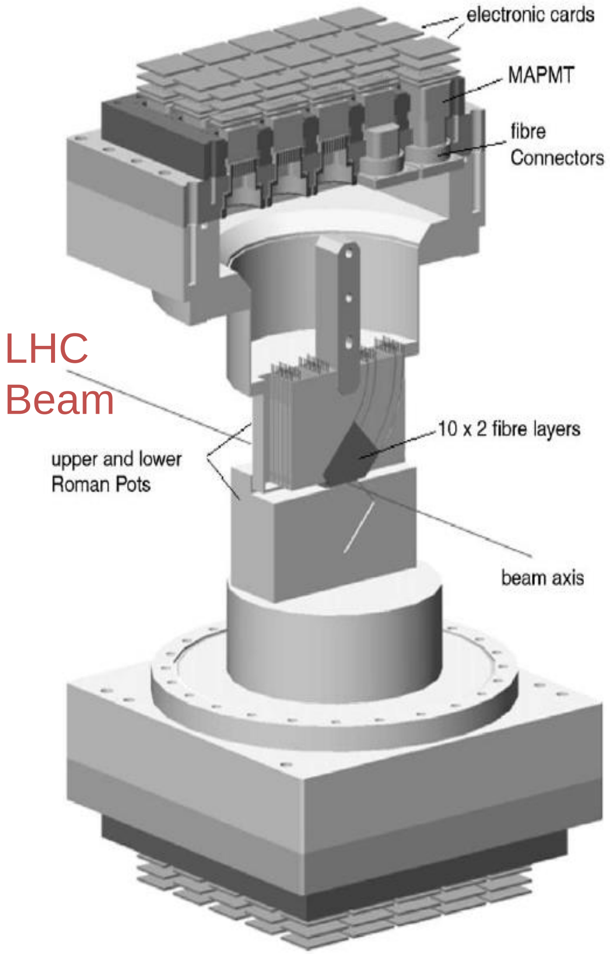
Bundles of clear fibres

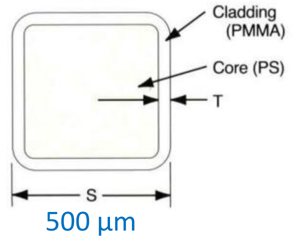
# ATLAS ALFA

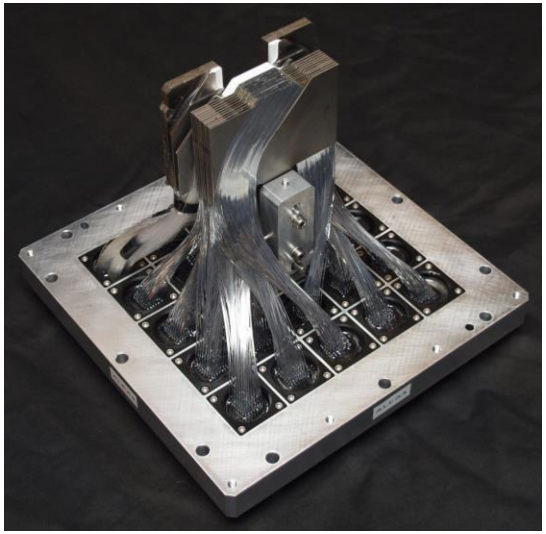
S. Ask et al., NIM A 568 (2006) 588–600
S. Jakobsen, PhD thesis, NBI Copenhagen, 2013

Forward detector in Roman Pots for luminosity and $\sigma_{tot}$(pp) measurement

4 RP stations are located at ±240 m from ATLAS in LHC tunnel



- Scint. fibres chosen because they are sensitive up to the very edge (no guard ring like in Si detectors).
- Total ~11.000 fibres, 500 µm squared, ~35 cm long, aluminized for reduced cross-talk.
- UV geometry with 2x10 staggered layers. Active area is only about 3 x 3 cm2.
- Readout (at 40 MHz) by 184 Multi-anode (64 ch.) PMTs.

**Performance:**

- Yield: ~4 pe / fibre
- Track resolution: ~25 µm

# A short recap of SiPM technology

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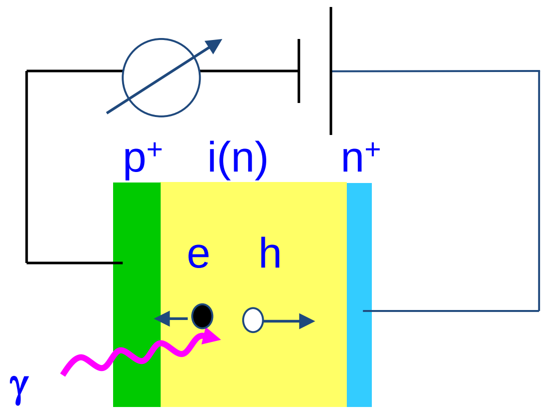
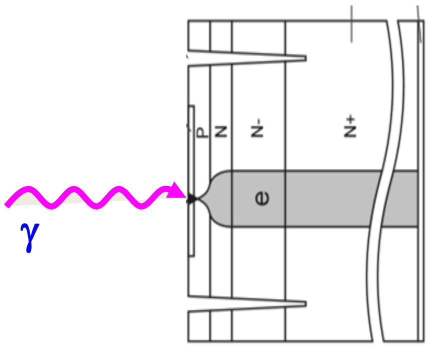
### PIN photodiode




- $U_{bias}$ = small (or even 0)
- No charge gain (G=1)
- High QE (~80%)

Used in calorimetry (1980-2000), e.g. L3

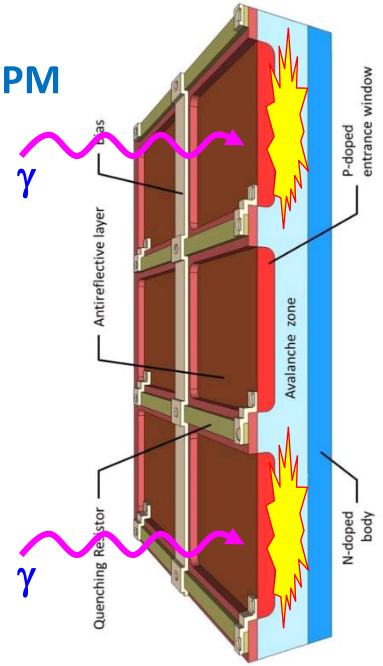
### Avalanche Photodiode (APD)




- $U_{bias}$ = few 100 V
- Avalanche, self terminating
- Charge gain G ~ few 100
- Excess noise, increasing with G
- $\Delta G$ = 3.1%/V and -2.4 %/K
- High QE (~80%)

Used e.g. in CMS ECAL

### SiPM



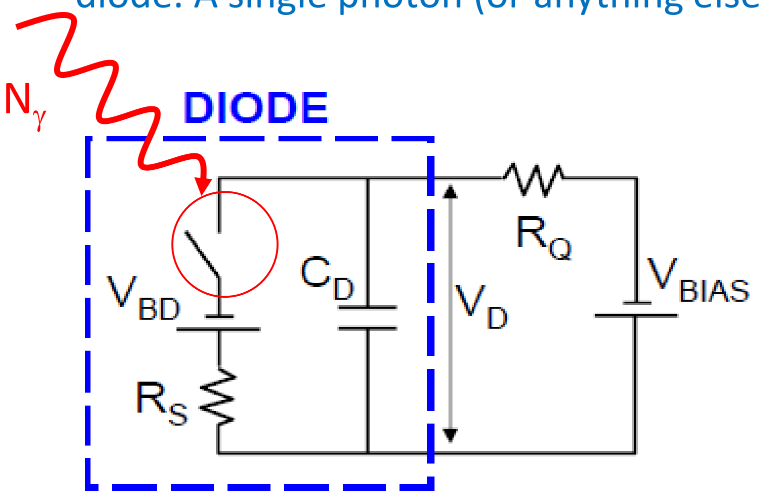

Multi-pixel array of APD

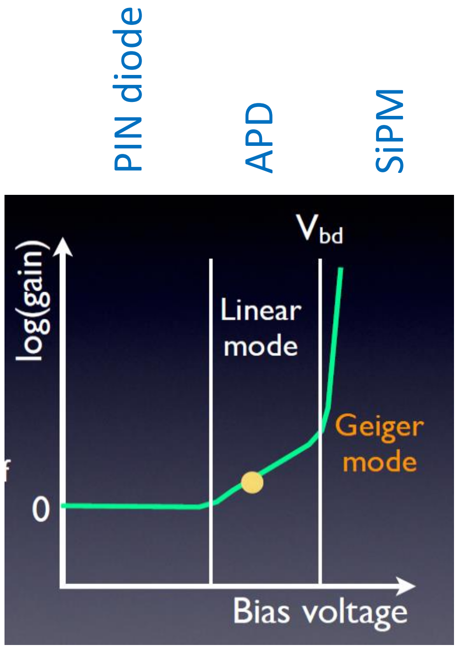
- operated in Geiger mode, i.e. above break down
- with quenching
- G ~ $10^6$ - $10^7$

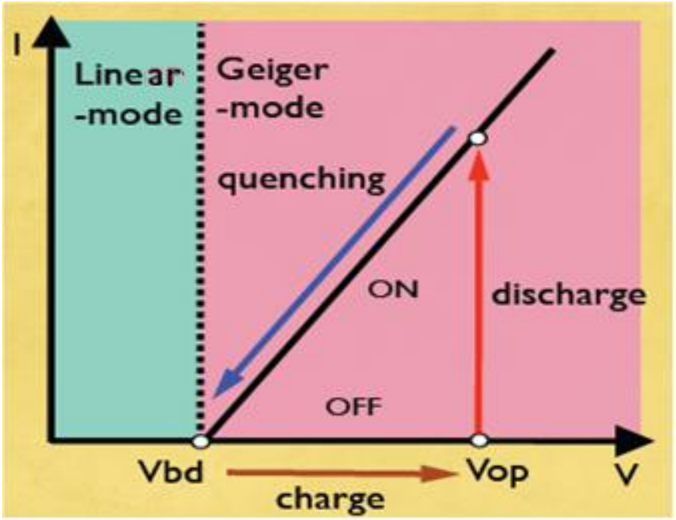
All these devices are immune to magnetic fields !

**How to obtain higher gain (= single photon detection) without suffering from excessive noise ?**

- Operate APD cells in Geiger mode (= full discharge), however with (passive/active) **quenching**.
- Photon conversion + avalanche short circuit the diode. A single photon (or anything else) is sufficient!



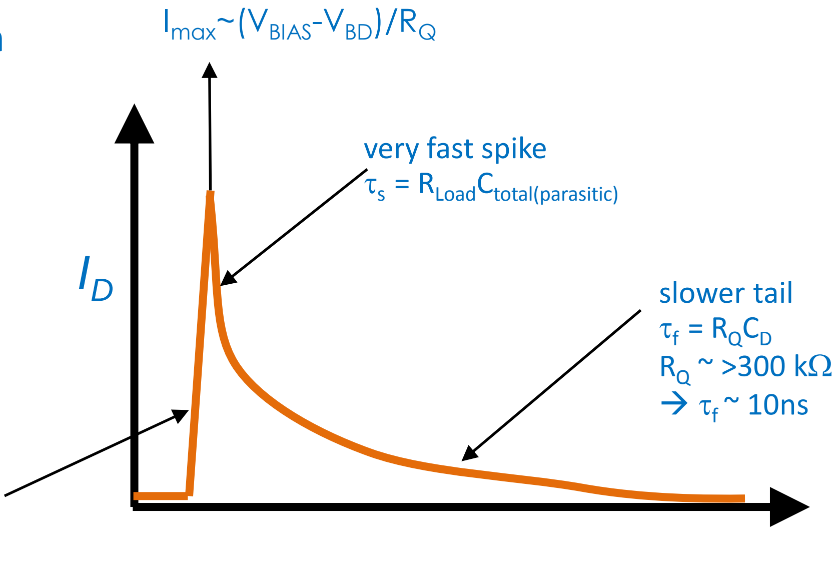



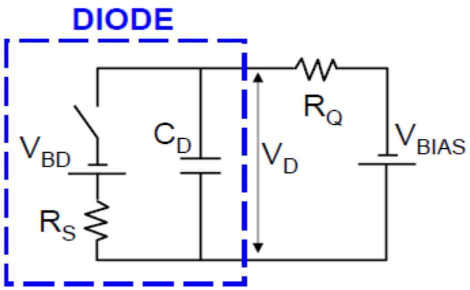




- A single-cell GM-APD is just a **binary** device (=switch).
- Info on $N_\gamma$ is lost in the Geiger avalanche.
- It will become more interesting when we combine many cells in one device …

# Signal characteristics and Gain of a single SiPM cell

The avalanche formation is intrinsically very fast, because confined to a small space (~µm)



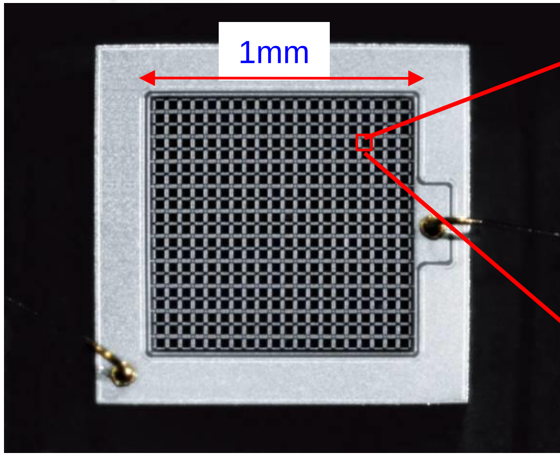




$$Gain = Q / e = \underbrace{(V_{BIAS}-V_{BD})}_{\Delta V \text{ (overvoltage)}} C_D / e$$

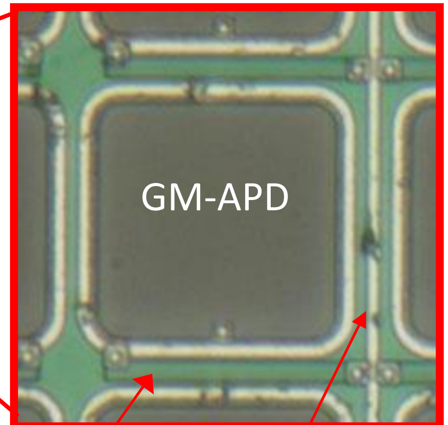
$C_D$ scales with cell surface (and inversely with the thickness of the avalanche region)

- G ~ $10^5$ -$10^7$ at rel. low bias voltage (<100 V)
- dG/dT and dG/dV similarly critical as for APD.

100 – several 10000 pix / mm$^2$




Sizes up to 6×6 mm$^2$ now standard.




quench resistor

bias bus

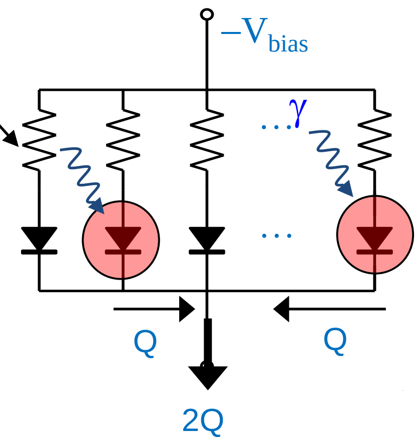
Only part of surface is photosensitive!

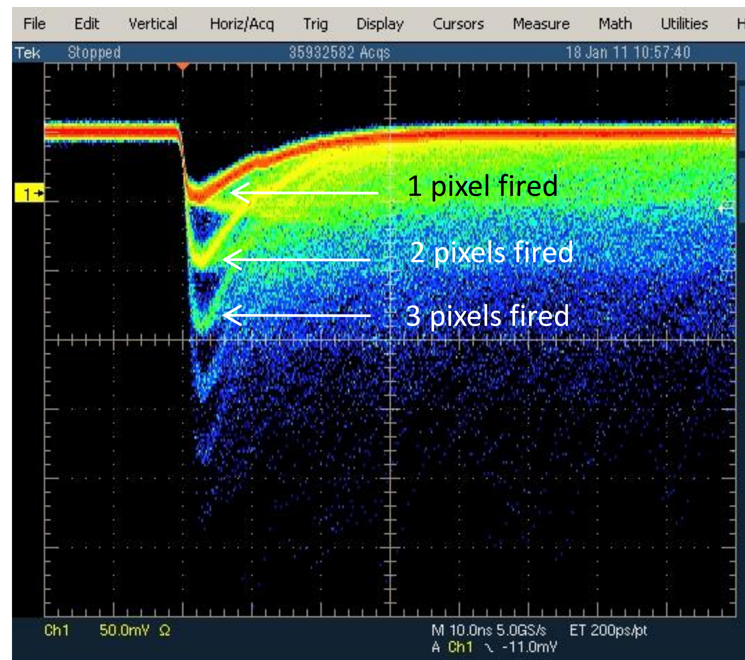
**Photon detection efficiency**

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

=f(OV)

Quench resistors



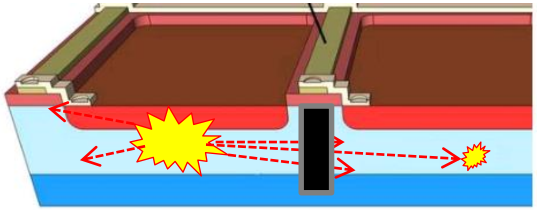

- 1 GM-APD is a binary device.
- The operation of many GM-APDs in parallel leads to a quasi-analog detector with photon counting properties.

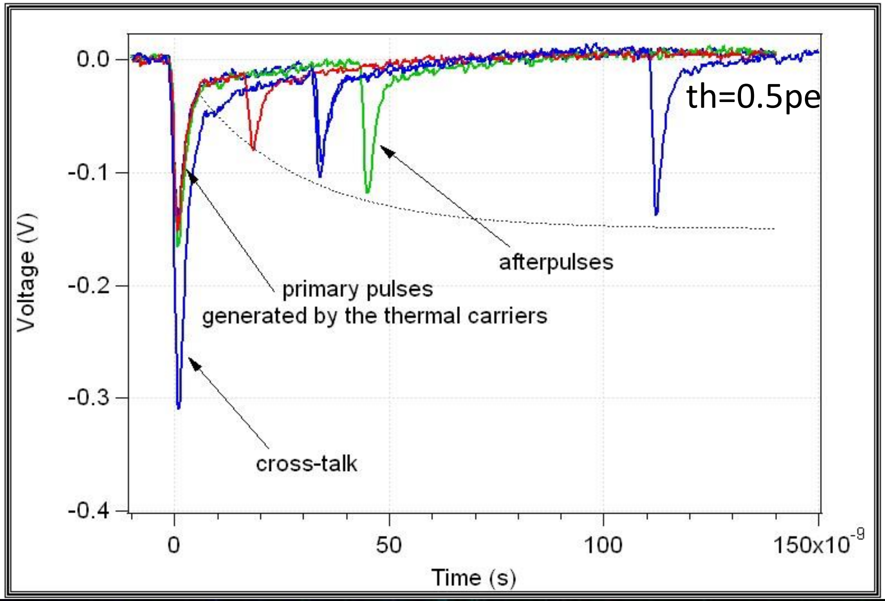
# The 'dark' side of the SiPM detector

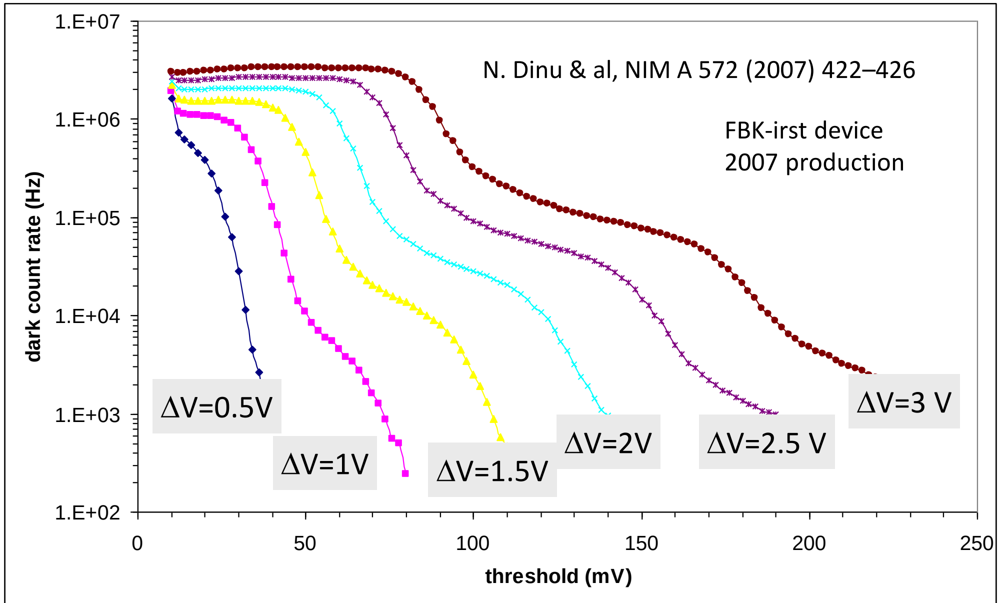
- **Thermal/tunneling** : thermal/ tunneling carrier generation in the bulk or in the surface depleted region around the junction
- **After-pulses :** carriers trapped during the avalanche discharging and then released triggering a new avalanche during a period of several 100 ns after the breakdown
- **Optical cross-talk:** $10^5$ carriers in an avalanche plasma emit on average 3 photons with an energy higher than 1.14 eV (A. Lacaita et al. IEEE TED 1993). These photons can trigger an avalanche in an adjacent μcell.

→ **Limit gain, increase threshold**

→ **add trenches btw μcells**



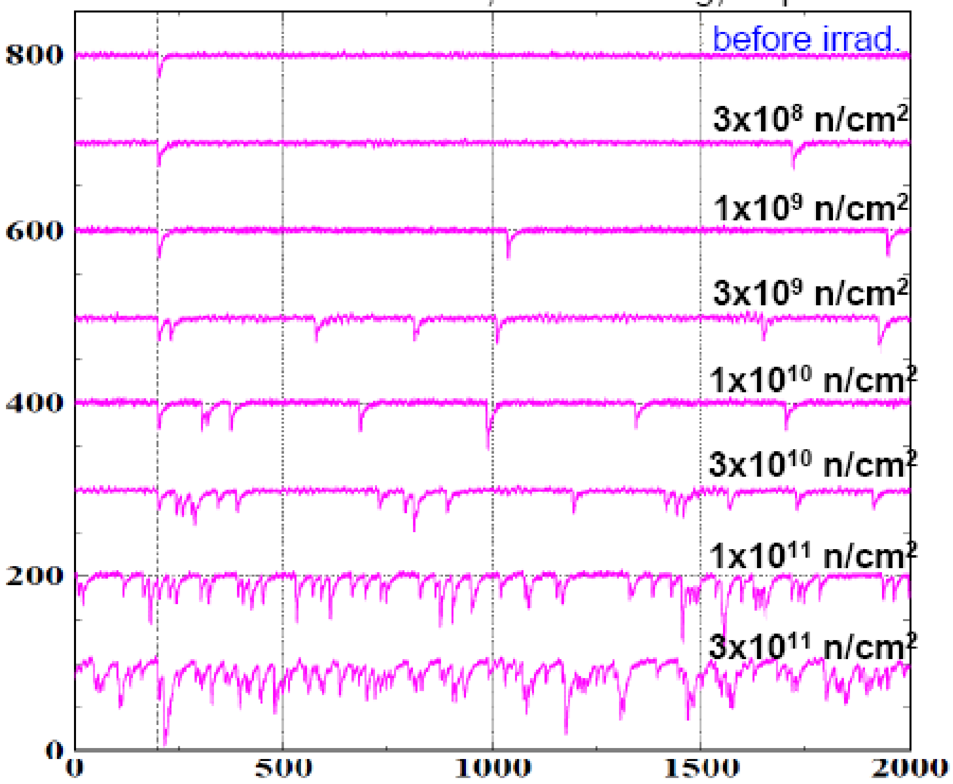


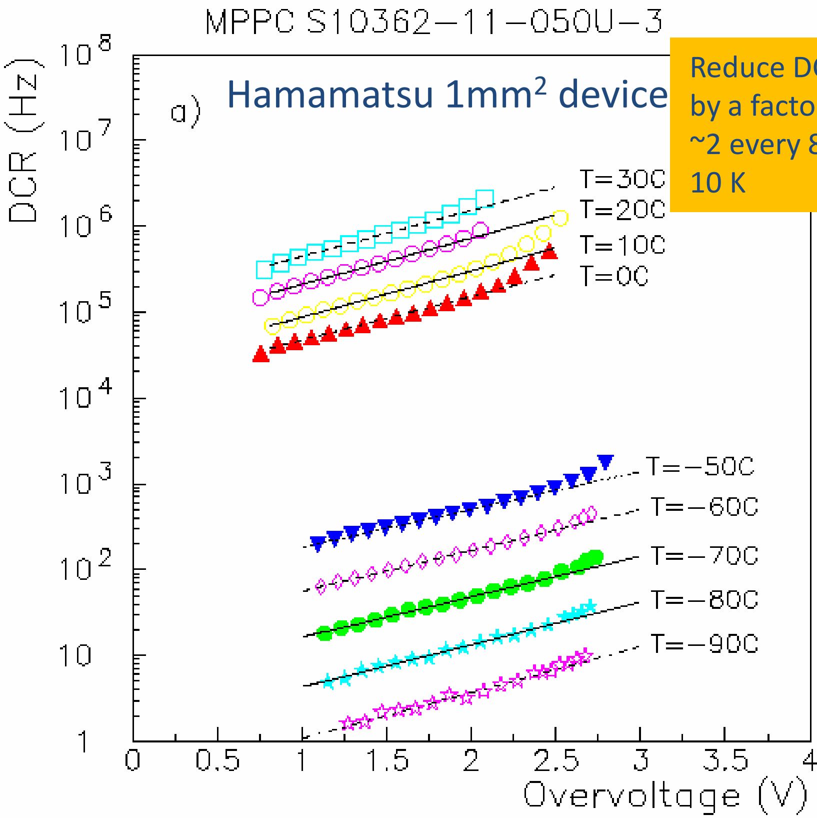
In addition… as for every Si detector, radiation damage is an issue. Linear increase of dark noise rate (DCR) with n-fluence. No other serious effects.

$DCR \sim \Phi_{n,1MeV\ eq.}$ $I_{dark} = e \cdot G \cdot DCR$

I.Nakamura, JPS meeting, Sep. 2008




Fortunately cooling helps!




Reduce DCR by a factor ~2 every 8-10 K

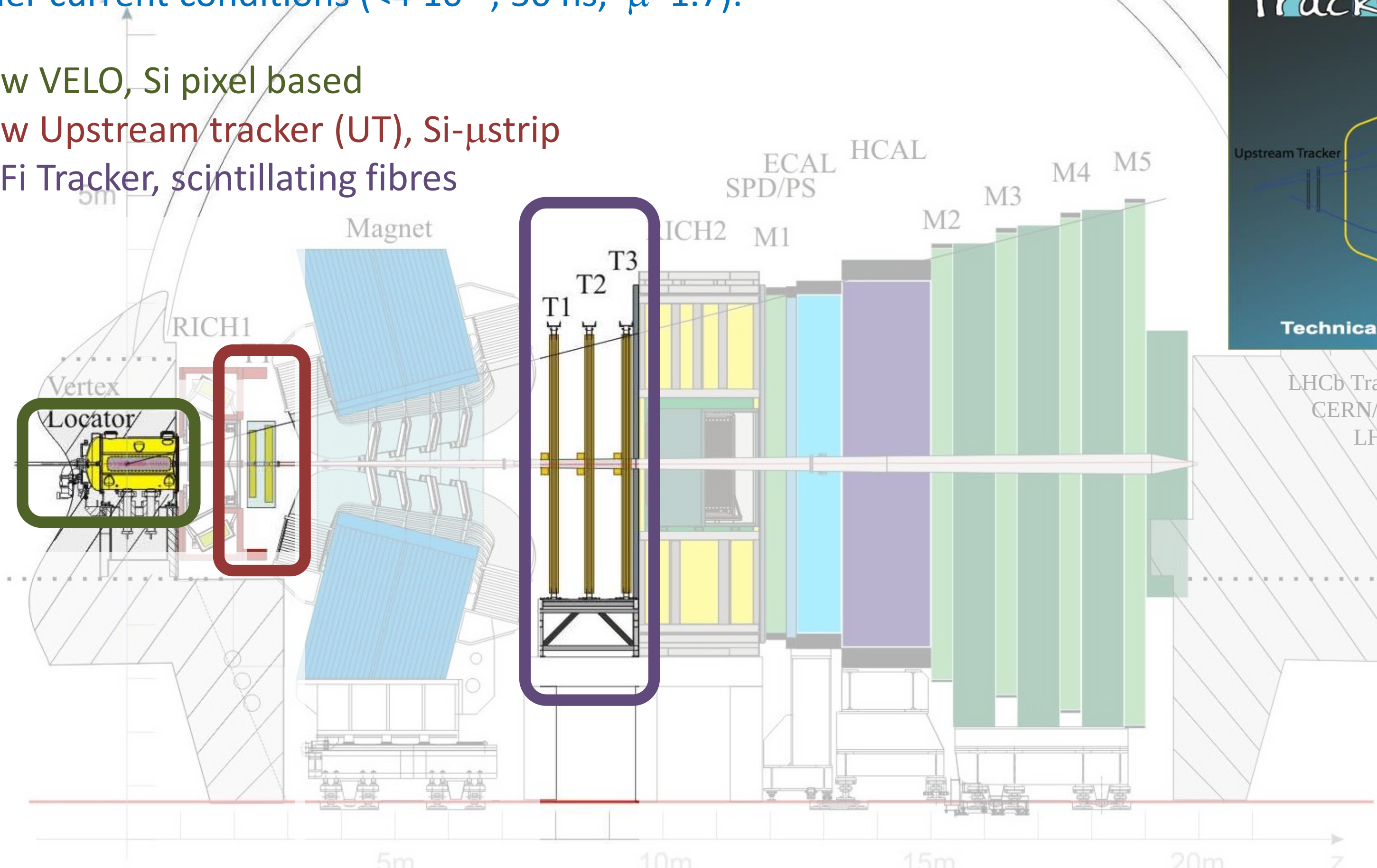
N. Dinu et al., NSS *Conf Record (NSS/MIC), 2010 IEEE*, vol., no., pp.215-219,

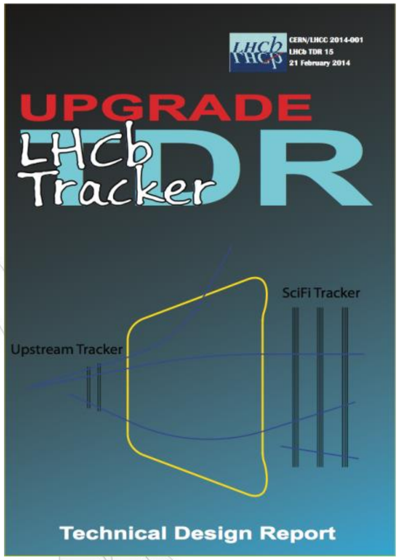
# The LHCb SciFi Tracker

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

Aim for the same performance at high luminosity ($2\cdot10^{33}$ $cm^{-2}s^{-1}$, 25 ns, $\nu$ =7.6) as under current conditions (<$4\cdot10^{32}$, 50 ns, $\mu$=1.7).

- New VELO, Si pixel based
- New Upstream tracker (UT), Si-$\mu$strip
- SciFi Tracker, scintillating fibres




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

# Main requirements

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

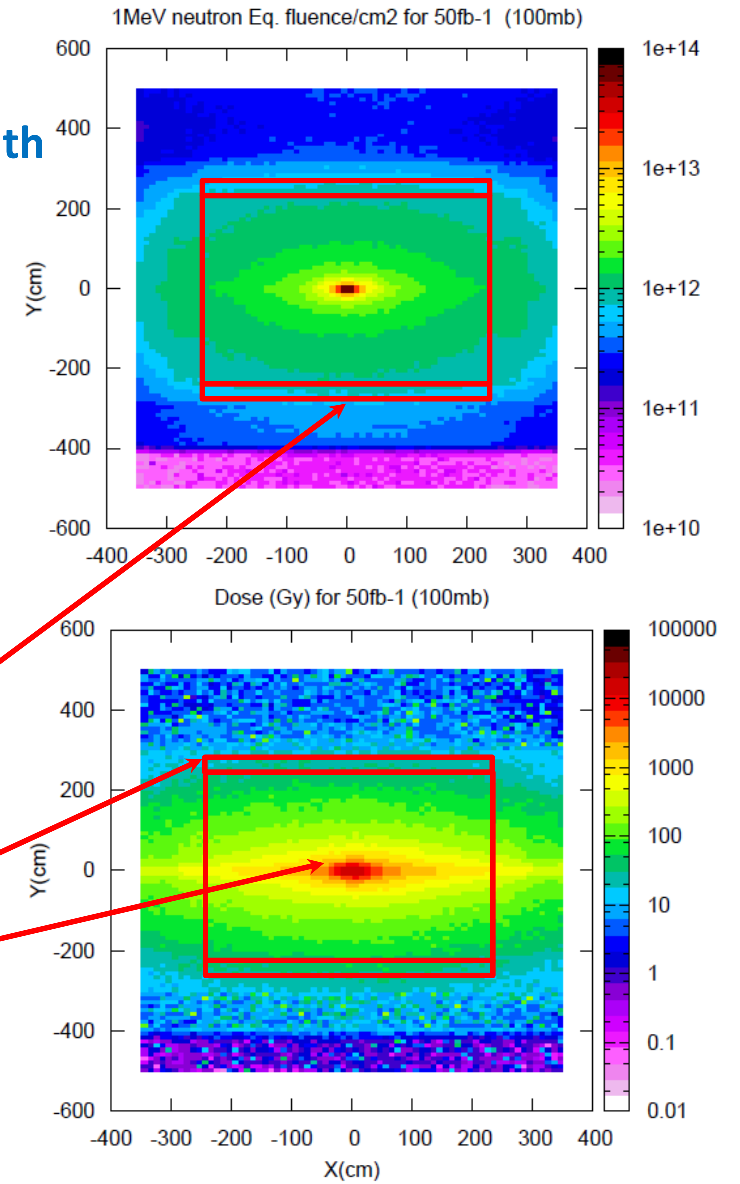
- high hit efficiency(~99%)
- low noise cluster rate (<10% of signal at any location)
- $\sigma_x$ < 100µm (bending plane)
- $X/X_0 \leq 1\%$ per detection layer

## Constraints

- 40MHz readout
- geometrical coverage: 6(x) x 5(y) $m^2$
- fit in between magnet and RICH2
- 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

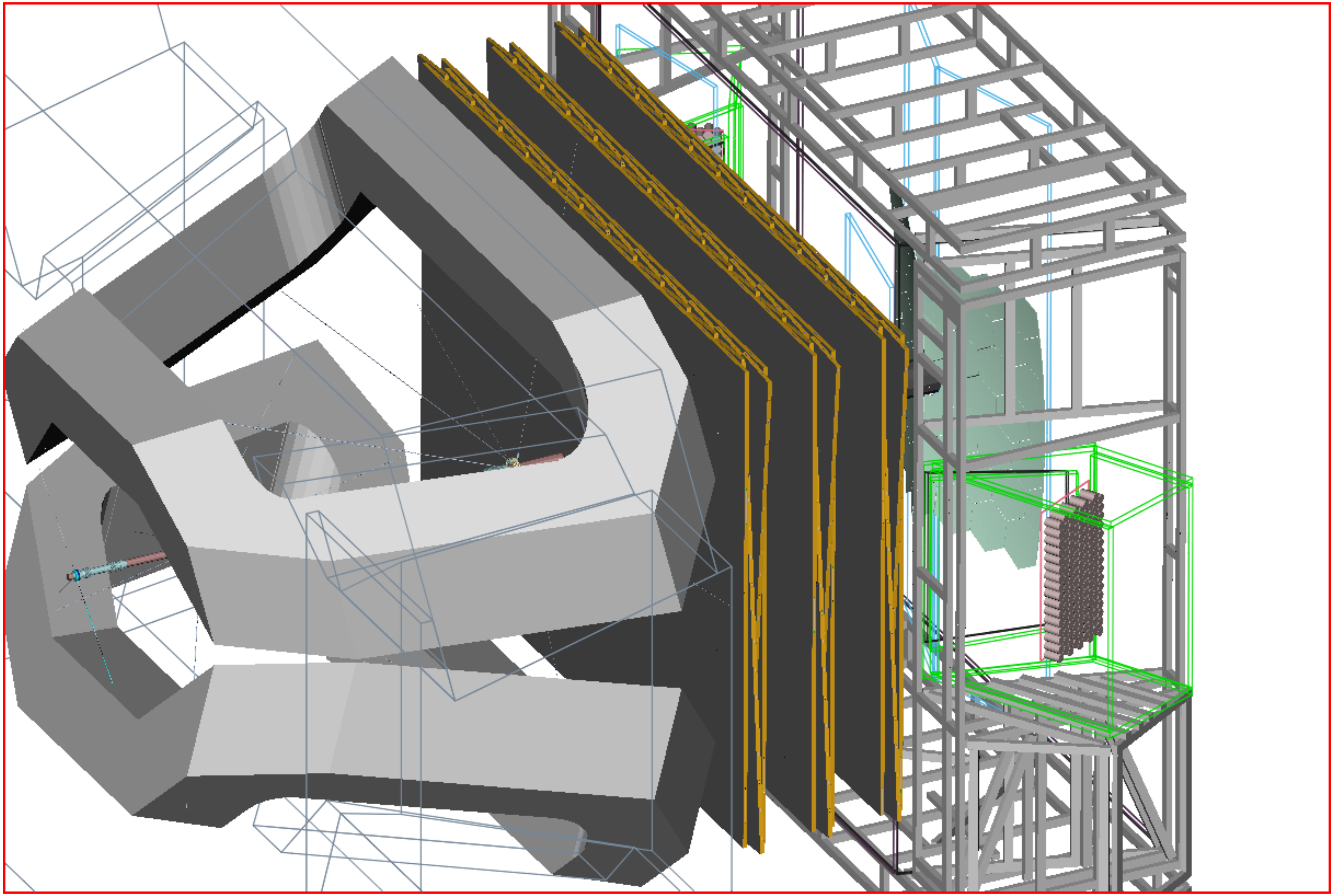
**→low temperature operation of photodetectors**

LHCb FLUKA simulation

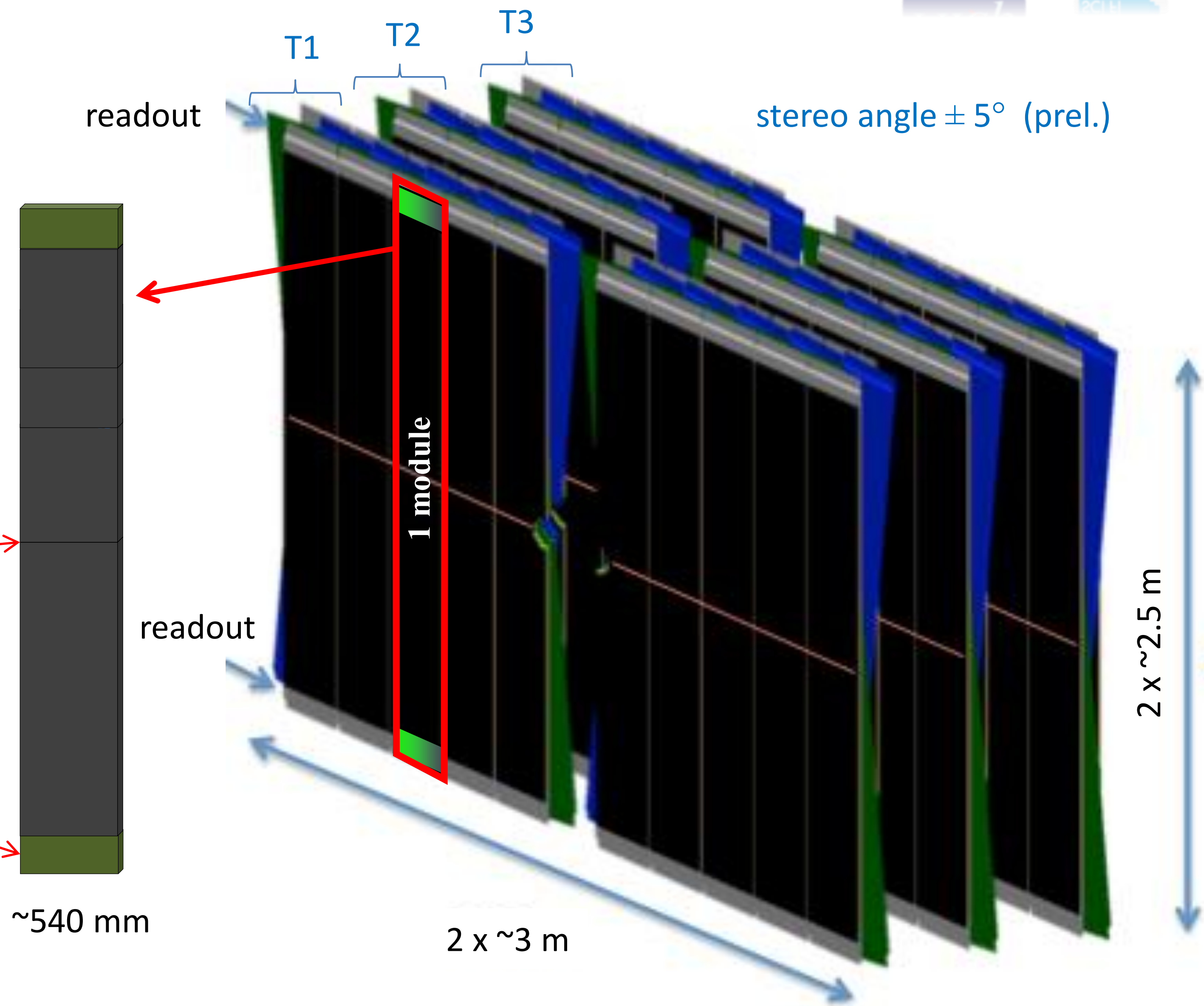


## General layout of the detector geometry:

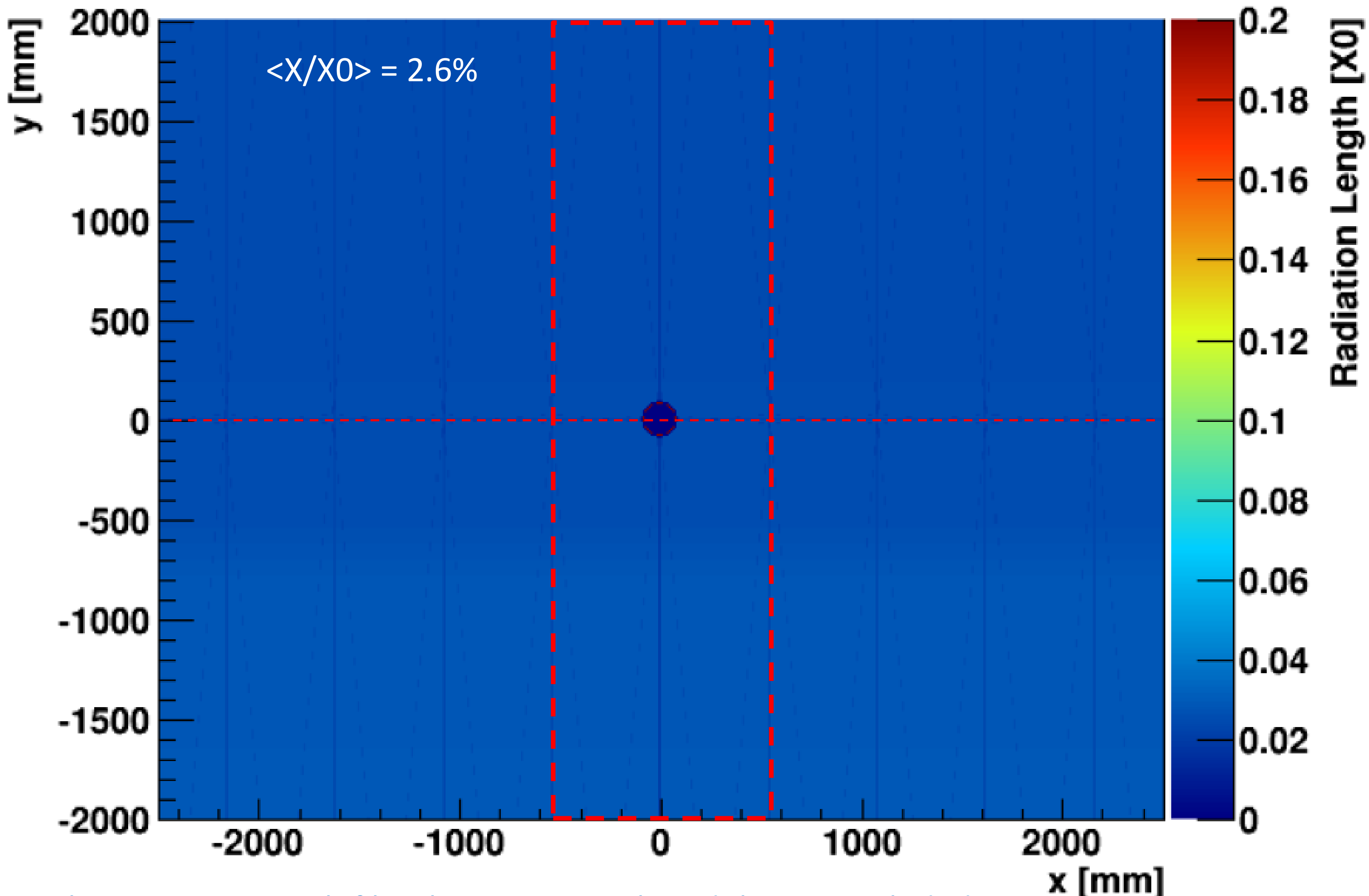
3 stations with 4 planes each X-U-V-X



- 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”



## Material distribution $X/X_0$ of station T1 (with 4 planes X-U-V-X)



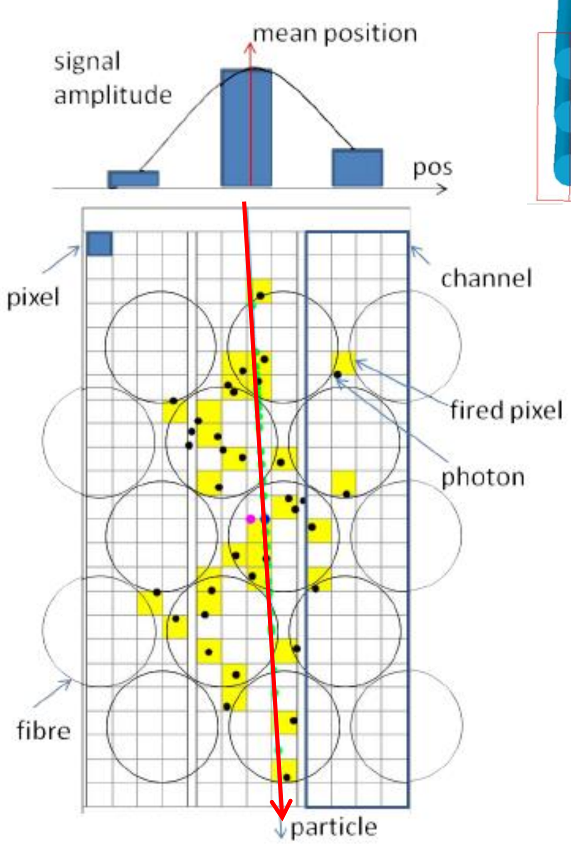

Plot is a bit optimistic: 6th fibre layer in central modules not included

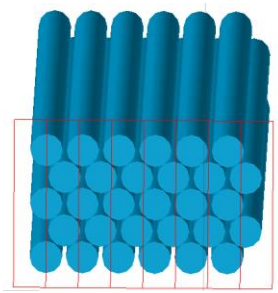
Fibre end pieces in midplane (y=0) not included

# 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: 860 mm (L) x 32 mm (W) bi-layer module in stereo geometry.

- 5 staggered layers of Ø250 μm fibres form a ribbon (or 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).
- Hits consist of clusters with typical size = 2. This is an efficient approach to suppress noise hits (=single pixels in 1 channel).

M = 40 kg
$P_{el.}$ = 60 W

**Main physics purpose:**
Measurement of the parameter $\phi_0$ which describes the modulation of the cosmic ray flux due to the solar wind.
(The magnetic fields modulate the interstellar cosmic ray flux)

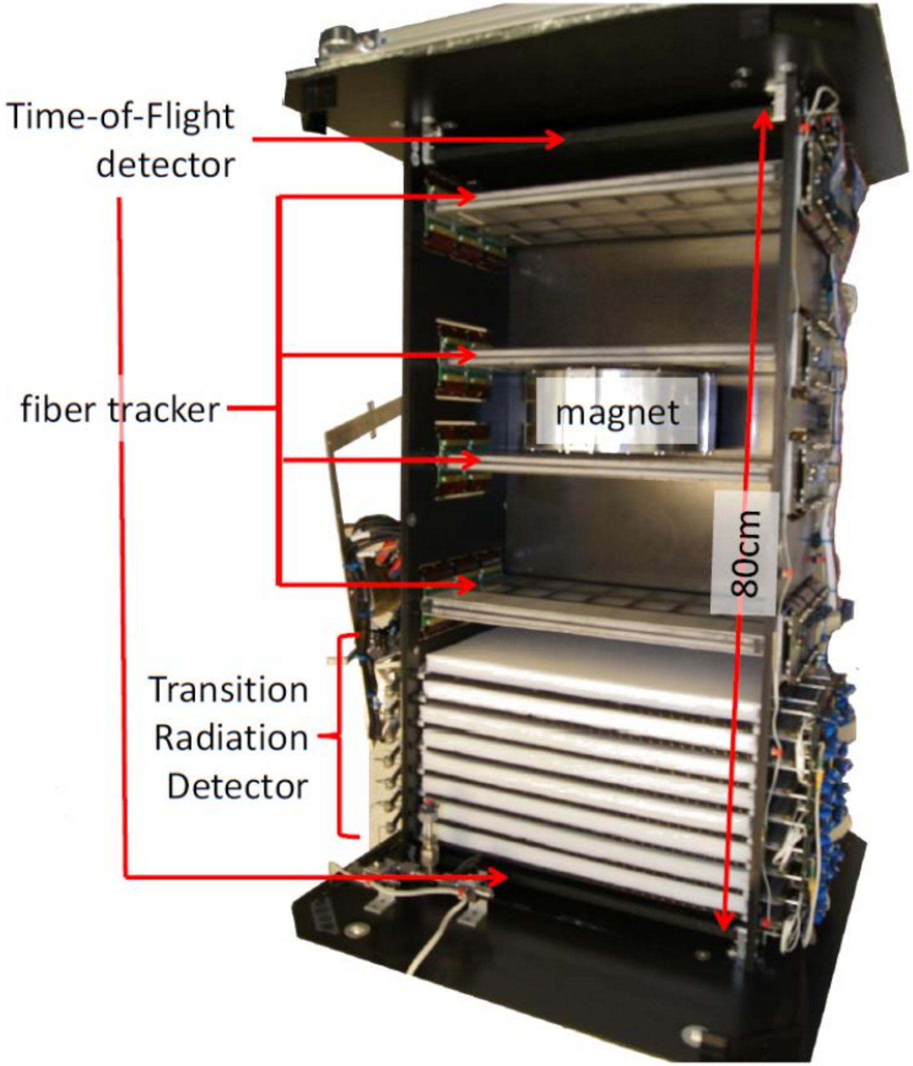
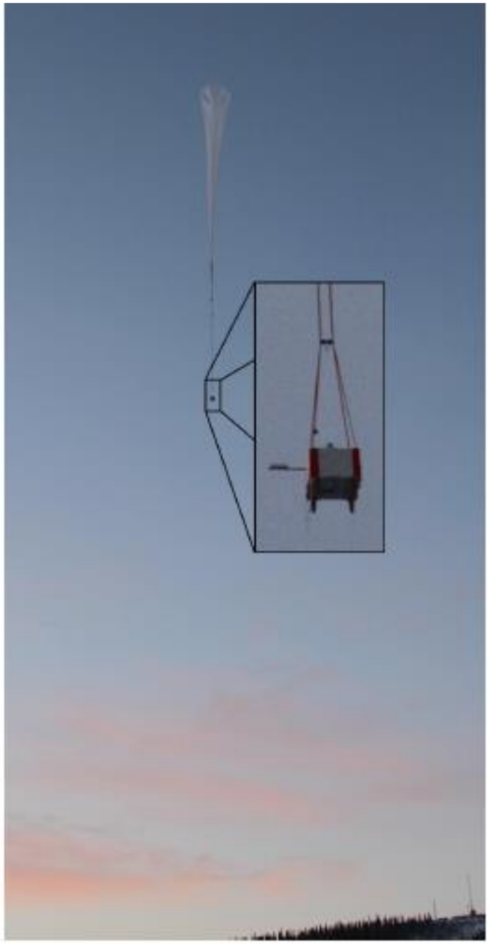



*Figure 2. A photograph of the PERDaix detector.*

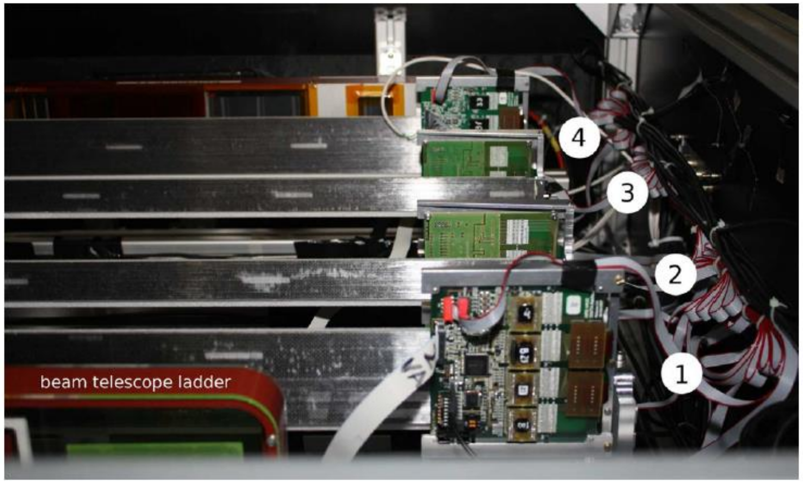
R. Greim et al., *Proc. '20th ESA Symposium on European Rocket and Balloon Programmes and Related Research' Hyère, France, 22–26 May 2011 (ESA SP-700, October 2011)*

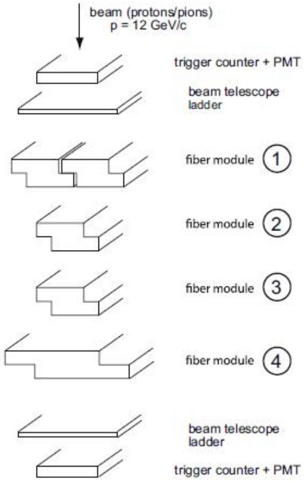
(a) The launch vehicle carrying the gondola with the experiments before the BEXUS-11 launch

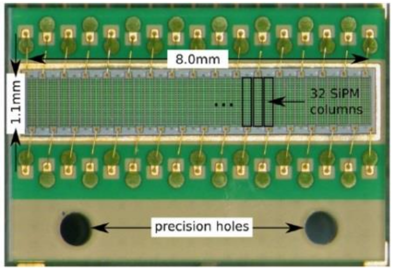


(b) BEXUS-11 carrying PERDaix into the stratosphere

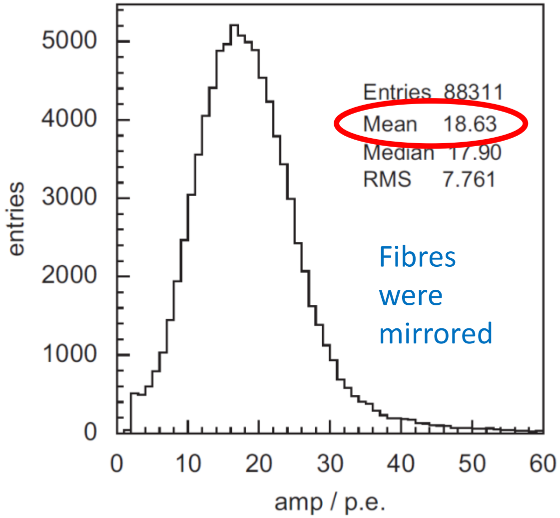
# Some PERDaix test beam results (CERN T9, 2009)

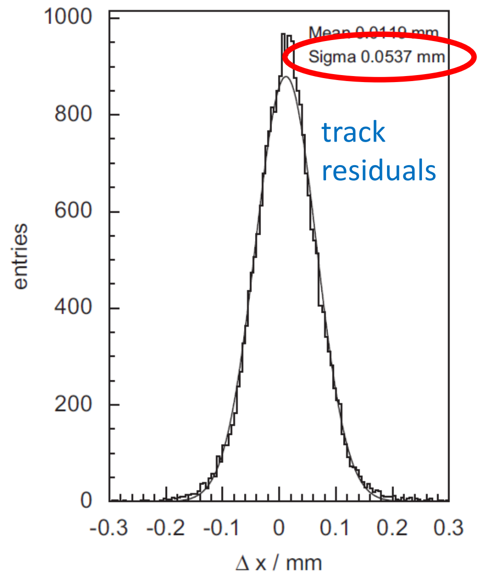


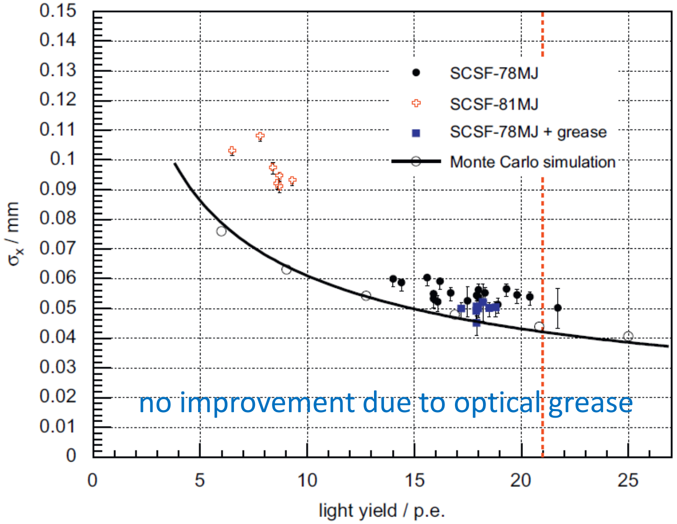




- 32 channel SiPM array from Hamamatsu.
- Readout by IDEAS VA_32 ($\tau_s$=75 ns) + 12 bit ADC



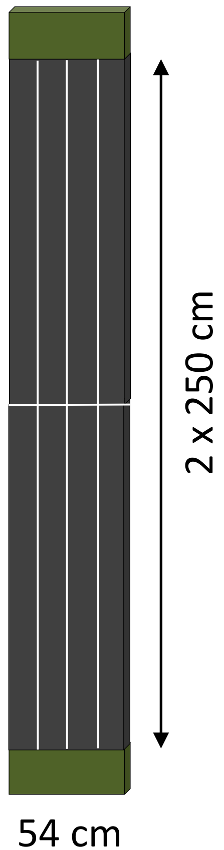



# LHCb SciFi module design

### What is different from PERDaix?

| | PERDaix | LHCb SciFi |
|---|---|---|
| **Module length** | 39.5 / 86 cm | 2 x 250 cm |
| **Detector surface** | 0.25 $m^2$ | ~360 $m^2$ |
| **Radiation** | none | $10^4$ Gy, $10^{12}$ n/cm2 |
| **Multiplicity** | 1 | A few hundred |
| **Readout** | rel. slow | 40 MHz |

SciFi module

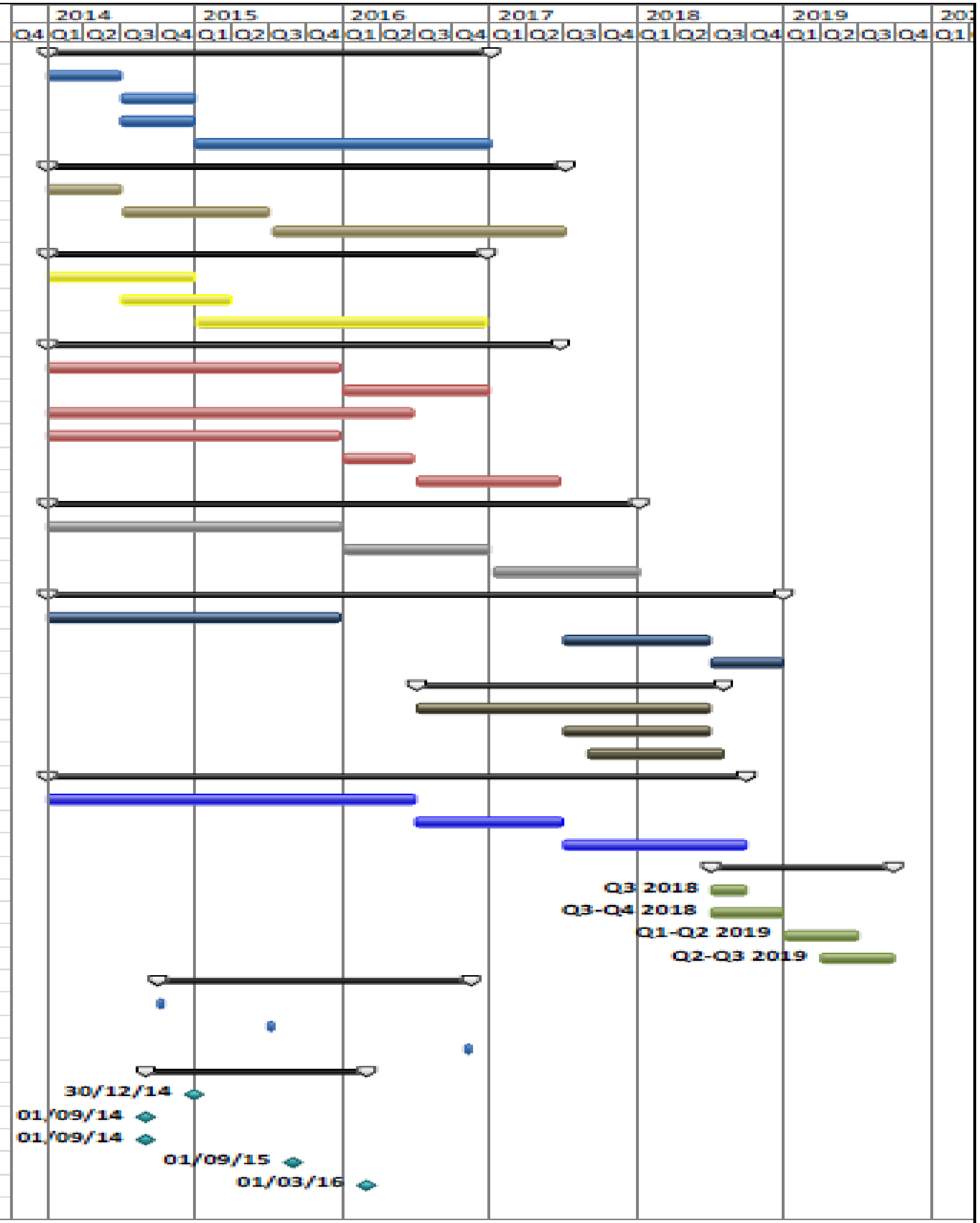



### LHCb SciFi main design parameters

- Round double cladded fibres of Ø250 μm, L = 2500 mm, mirrored
- 13 cm wide fibre mats made of 5 (or 6) staggered layers.
- 4 mats are assembled on the same support structure and form a 54 cm wide module.
- Readout by arrays of SiPMs. 128 channels. Pitch of SiPM = 250 μm.

➔ >10,000 km of fibres

| ID | Task Name |
|---|---|
| 1 | **Scint. Fibres** |
| 2 | Consolidation Radiation Hardness |
| 3 | Qualification supplier(s) |
| 4 | Develop QA benches/procedures |
| 5 | Procurement |
| 6 | **Fibre Mats and Panels** |
| 7 | Finalise design |
| 8 | Copies of tooling |
| 9 | Production |
| 10 | **SiPM** |
| 11 | Design optimisation |
| 12 | Develop test stands |
| 13 | Procurement / Testing |
| 14 | **Front End Electronics** |
| 15 | ASIC design / iterations |
| 16 | ASIC procurement |
| 17 | PCB design |
| 18 | Back End design |
| 19 | FPGA procurement |
| 20 | PCB procurement & loading |
| 21 | **Read Out Box** |
| 22 | Design / prototyping |
| 23 | Procurement components |
| 24 | ROB assembly, loading & testing |
| 25 | **SiPM Cooling** |
| 26 | Prototyping |
| 27 | Procurement |
| 28 | Installation infrastructure (cavern) |
| 29 | **Module Assembly** |
| 30 | Module assembly (incl. mirroring) |
| 31 | Integration of ROB |
| 32 | Module testing |
| 33 | **Detector Station Mechanics** |
| 34 | Design |
| 35 | Construction |
| 36 | C-frame loading |
| 37 | Installation |
| 38 | OT dismantling |
| 39 | Infrastructure preparation |
| 40 | SciFi Installation |
| 41 | Commissioning |
| 42 | **Test beams** |
| 43 | TB components |
| 44 | TB mini system |
| 45 | TB full module |
| 46 | **Milestones and Reviews** |
| 47 | Module 0 |
| 48 | EDR SiPM |
| 49 | EDR Fibres |
| 50 | EDR FE electronics |
| 51 | EDR Mechanics |
| 52 | |



# SciFi Tracker: ~20 participating institutes

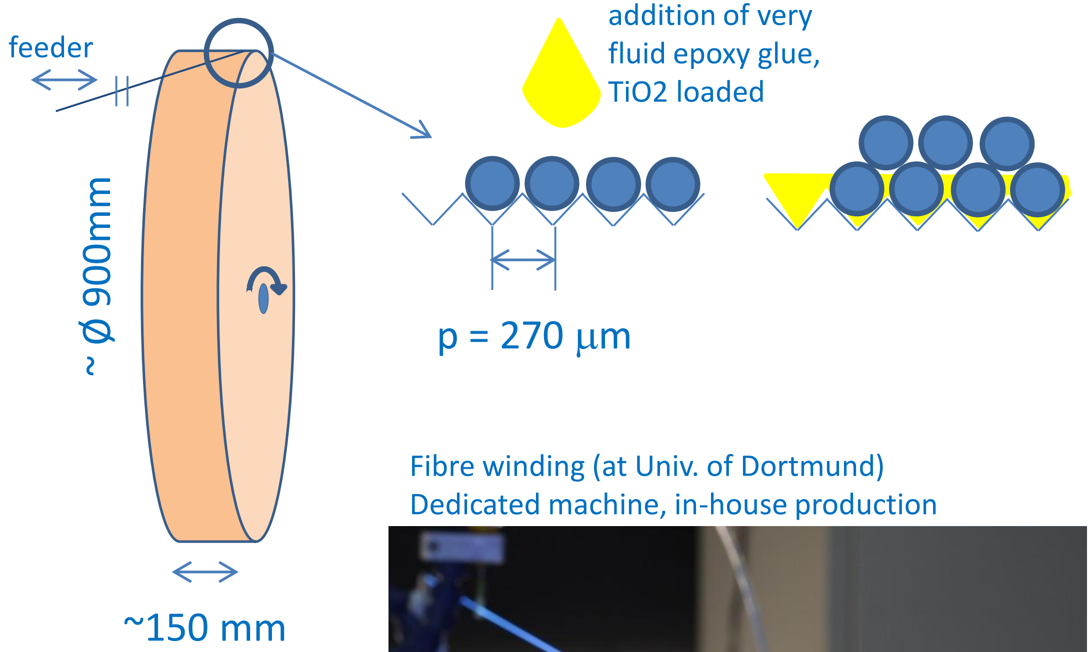
- Brasil (CBPF)
- China (Tsinghua)
- France (LPC, LAL, LPNHE)
- Germany (Aachen, Dortmund, Heidelberg, Rostock)
- Netherlands (Nikhef)
- Poland (Warsaw)
- Russia (PNPI, ITEP, INR, IHEP, NRC KI)
- Spain (Barcelona, Valencia)
- Switzerland (CERN, EPFL)
- UK (Imperial College)

# LHCb SciFi R&D: Challenges, strategies, status

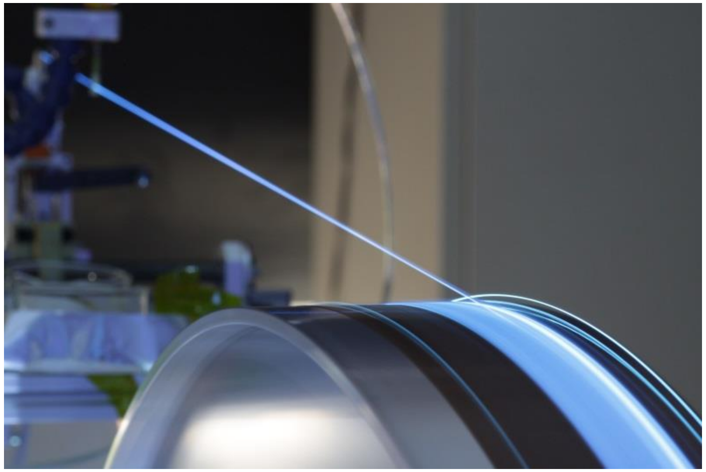
- Geometrical precision
- Get enough light
- Fast readout with manageable data volume
- Survive the radiation
- Optimize detection efficiency vs ghost rate

## Geometrical precision

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



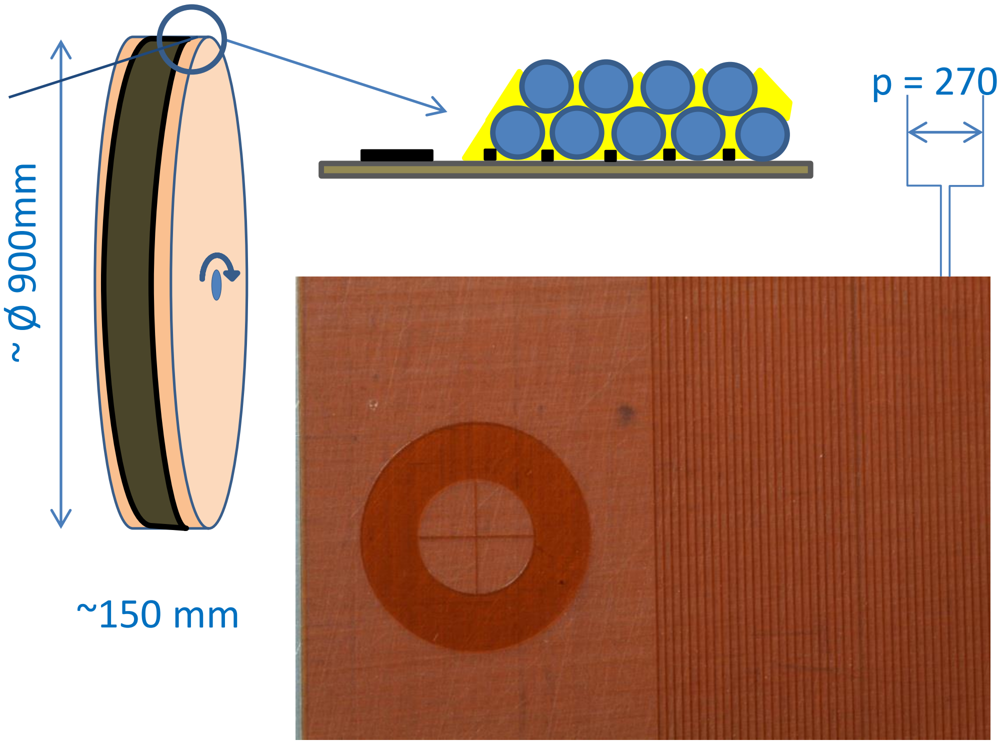

Fibre winding (at Univ. of Dortmund)
Dedicated machine, in-house production



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

# Geometrical precision

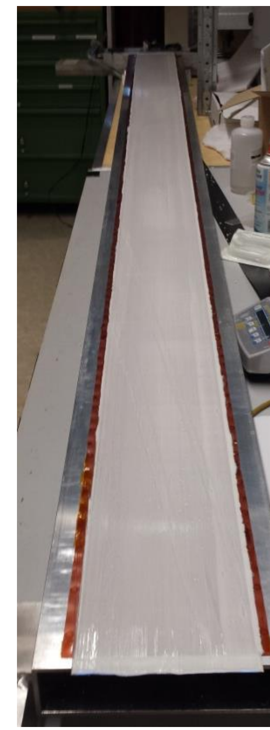
- Alternative technique: replace thread by a kapton film, structured with coverlay(© Dupont). PCB technique, R. de Oliveira.




Kapton film becomes part of fibre mat.
Allows use of precise alignment marks.

3 m long and 16 cm wide Kapton film used for a full-size 6 layer mat (march 2014).

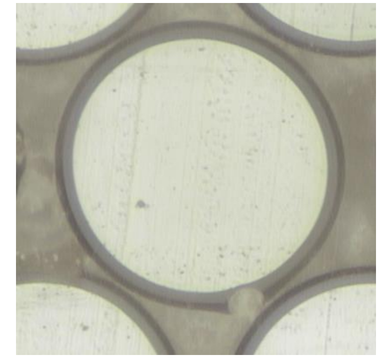
Inspection at CERN

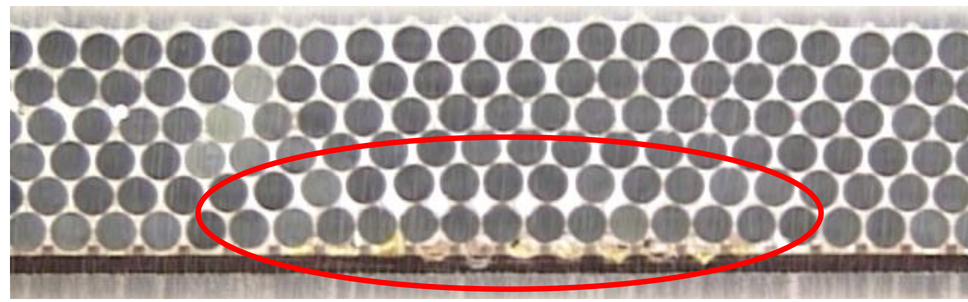


After winding at Univ. Dortmund

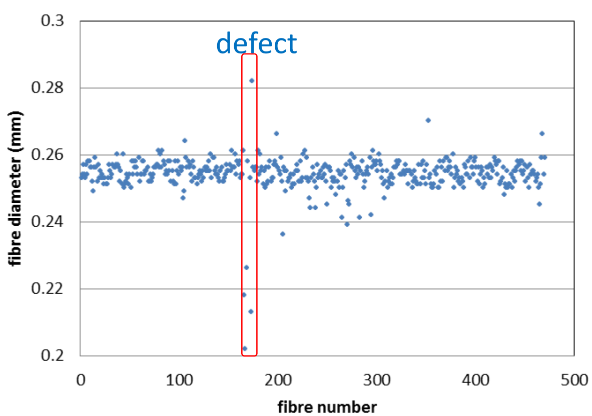
# Scan of fibre mat end faces (after cut with diamond tool)

Optical 3D coordinate measurement machine (CMM) in PH/DT bond lab.

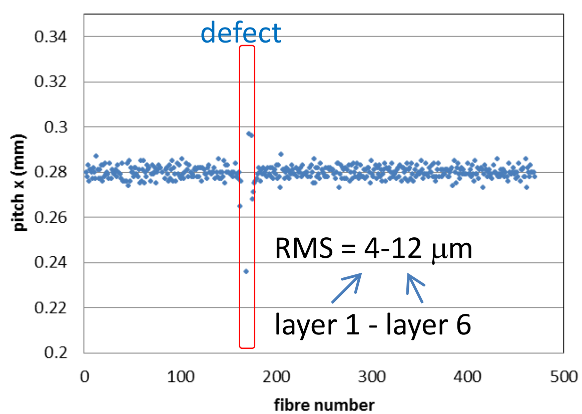





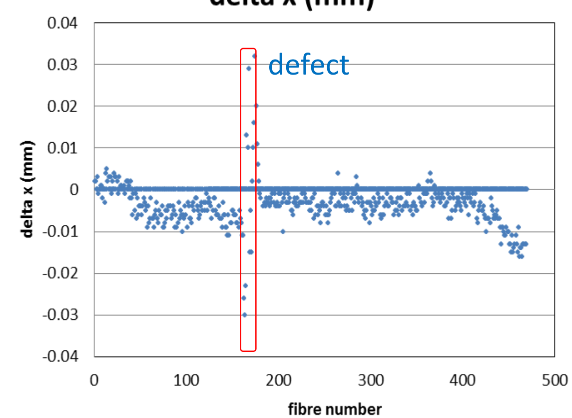
**fibre diameter (mm)**




**pitch x (mm)**



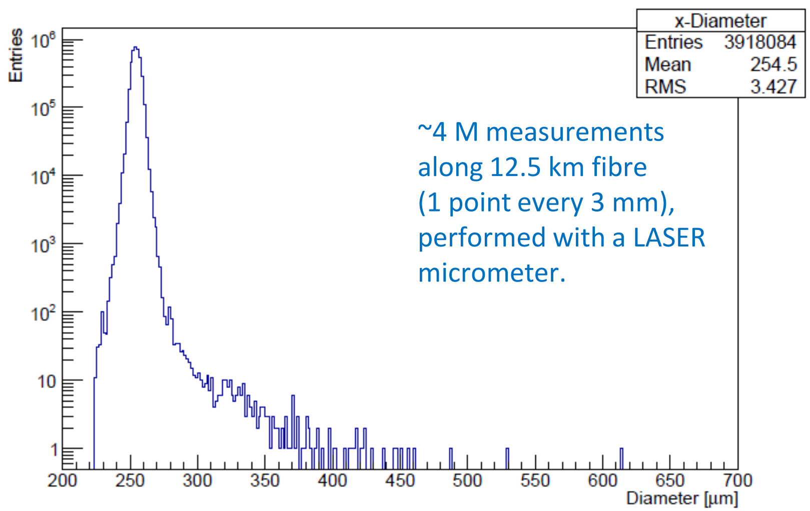

**delta x (mm)**

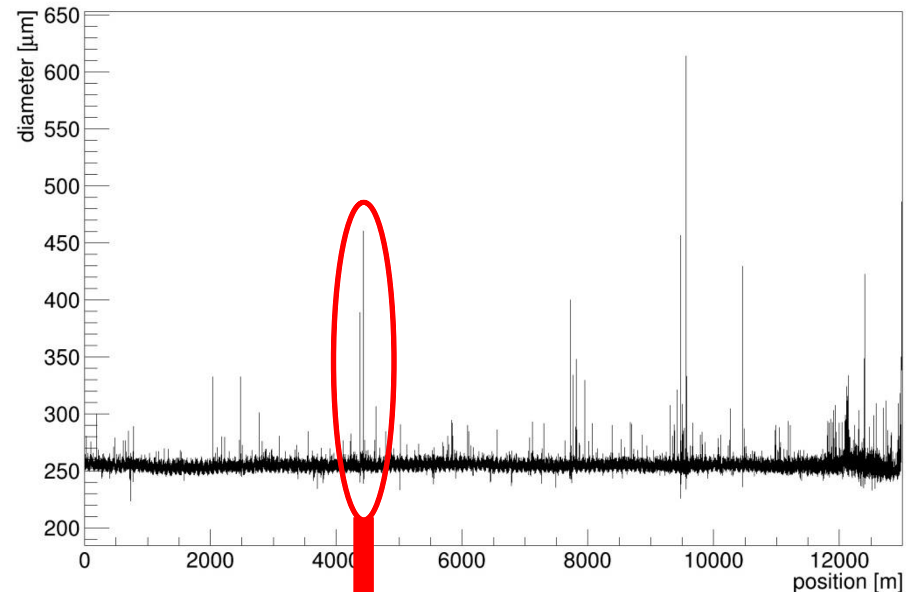


# An important parameter: Fibre diameter profile (along fibre)

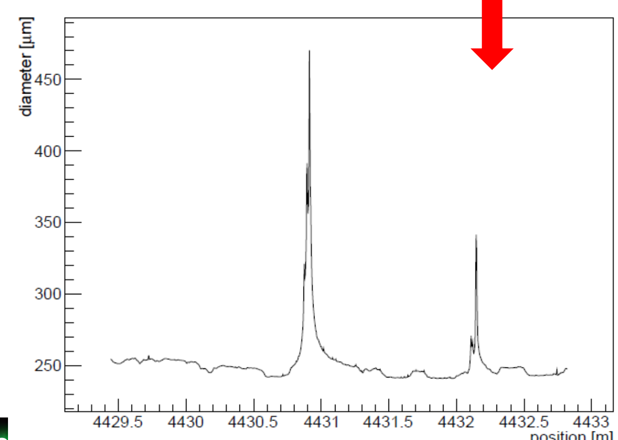
Plots by P. Hebler, Dortmund.

Over 99% of the length, the fibre diameter is within 250 ± few μm




However, typically once per km, the fibre diameter increases beyond acceptable limits (300 μm). Problem worked on by producer but not fully understood.




These sections are manually removed during winding process, at the position where the mat is anyway cut. Costs time (5') but no performance.

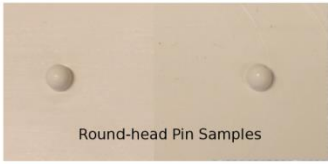
# Maintaining the intrinsic fibre precision when building a full detector

Require overall precision and stability: O(100 μm)

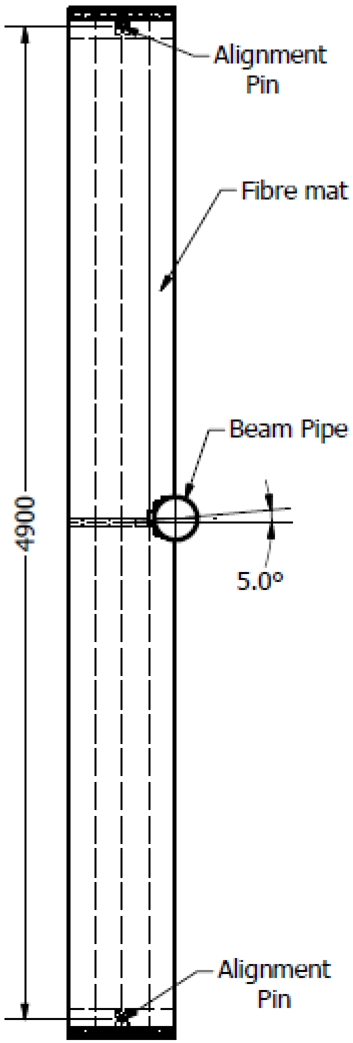
- Quite non-trivial! Subject of current studies.
- Good ideas and promising results on prototype level exist.

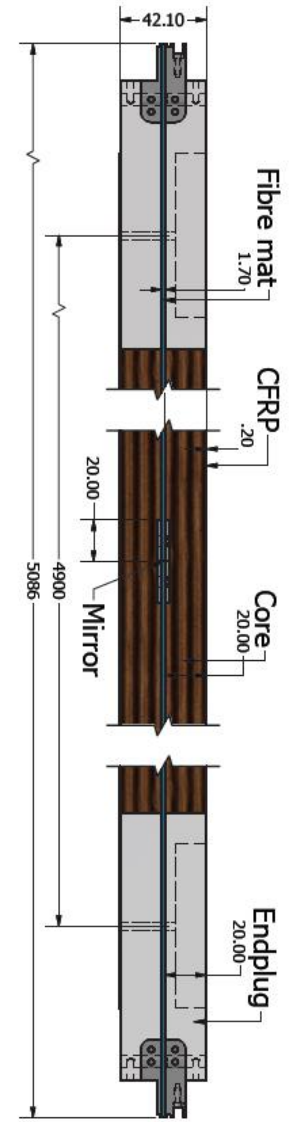
**Alignment chain:**

- Fibres inside mat → thread / coverlay
- Sides and end faces of mats need to be cut → rely on epoxy-pins on backside of mat (or markers on coverlay).

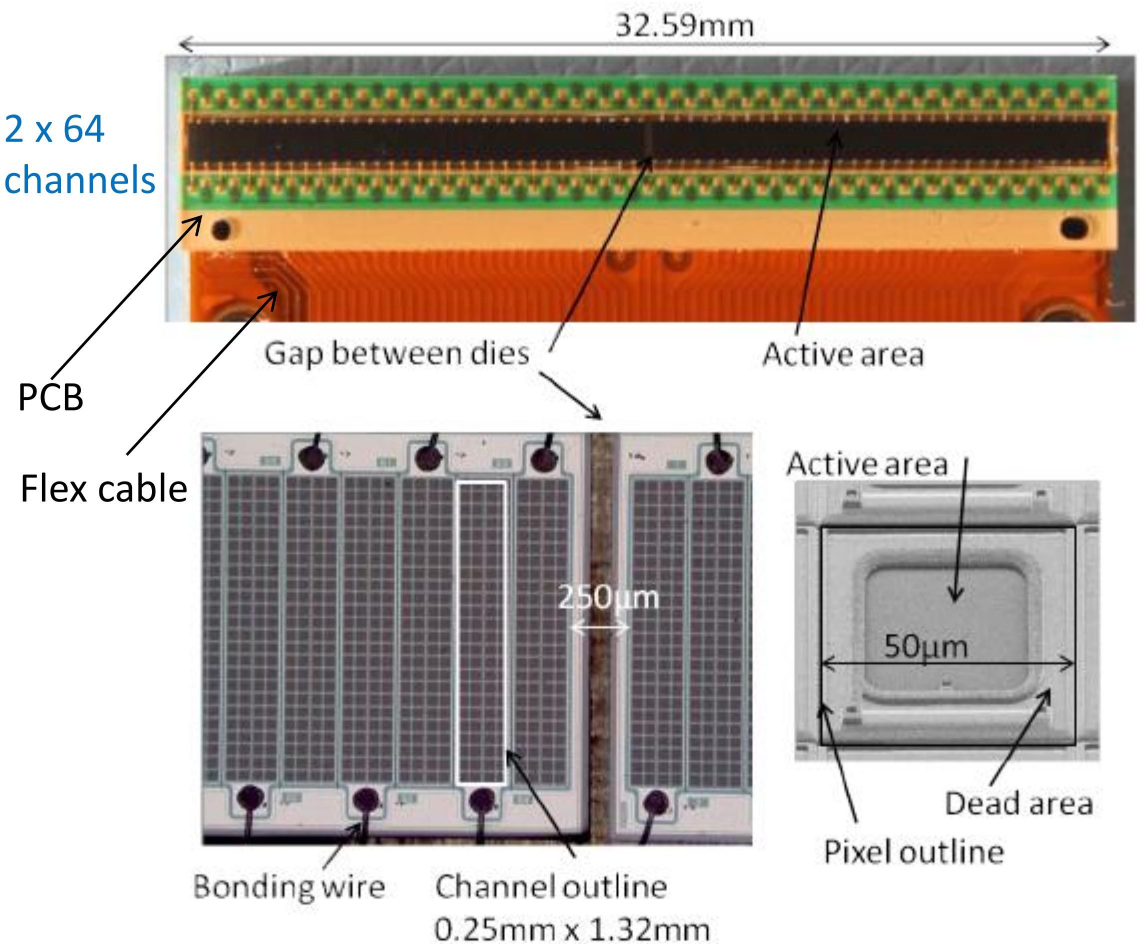



- Mount mats on support panels → rely on epoxy pins or mat precision
- Mount support panels in C-frames → alignment pins.
- Offline alignment ☺



# Get enough light → maximise  PDE of SiPM




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

**Photon detection efficiency**

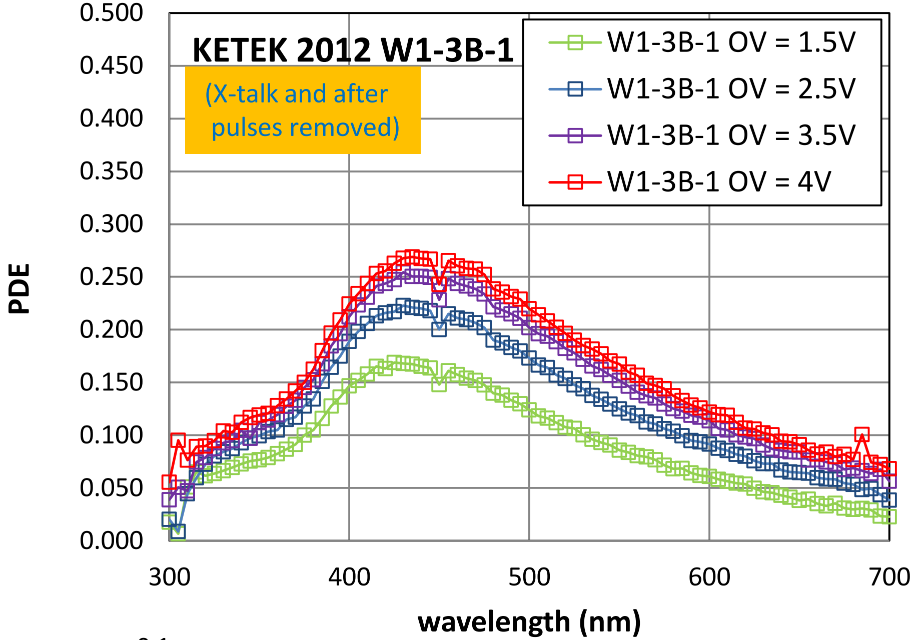
$$PDE = QE \cdot \varepsilon_{geom} \cdot \varepsilon_{avalanche}$$

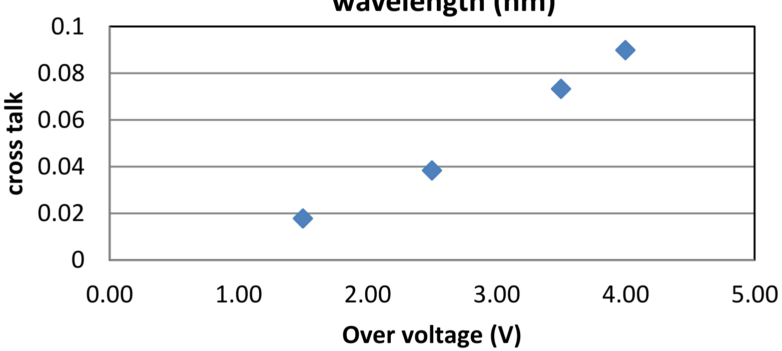
$\varepsilon_{avalanche}$ ↓ $=f(OV)$

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

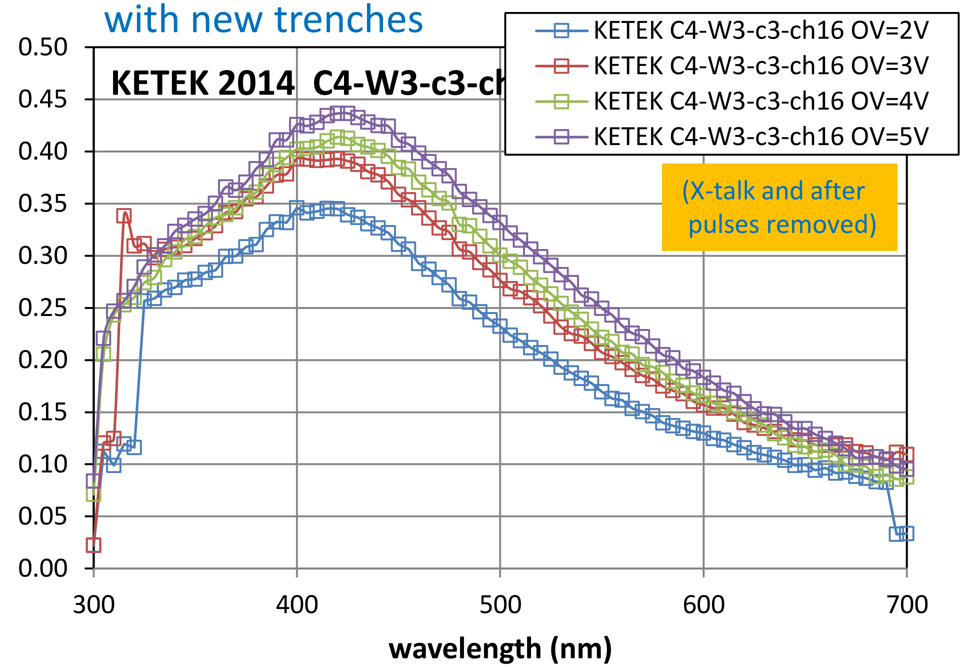
# PDE and cross talk measurements at CERN and EPFL

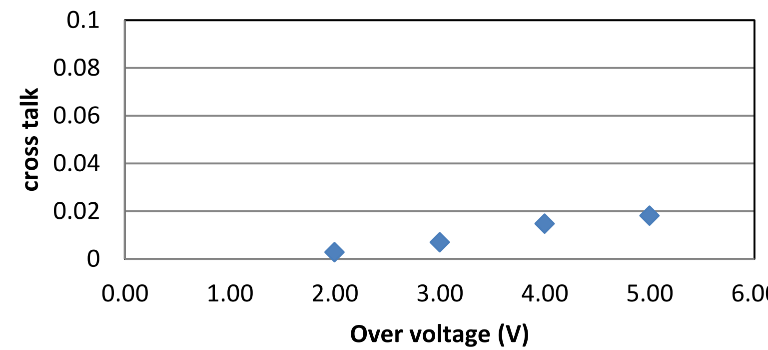
## with trenches



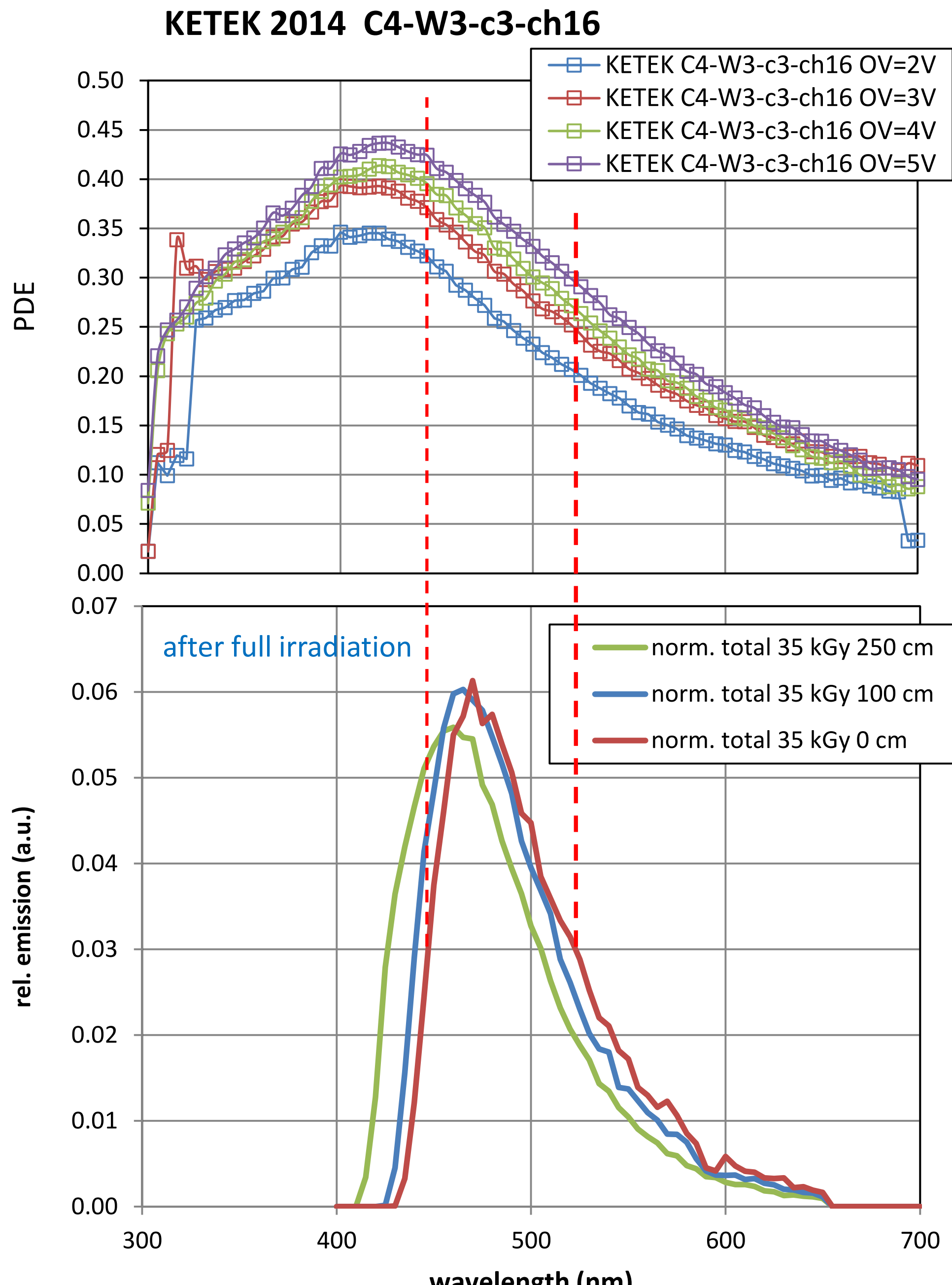

## with new trenches




Expect also new Hamamatsu devices in few weeks!

Matching between KETEK PDE and scintillation spectrum (after irradiation) isn't perfect yet.




Close to SiPM

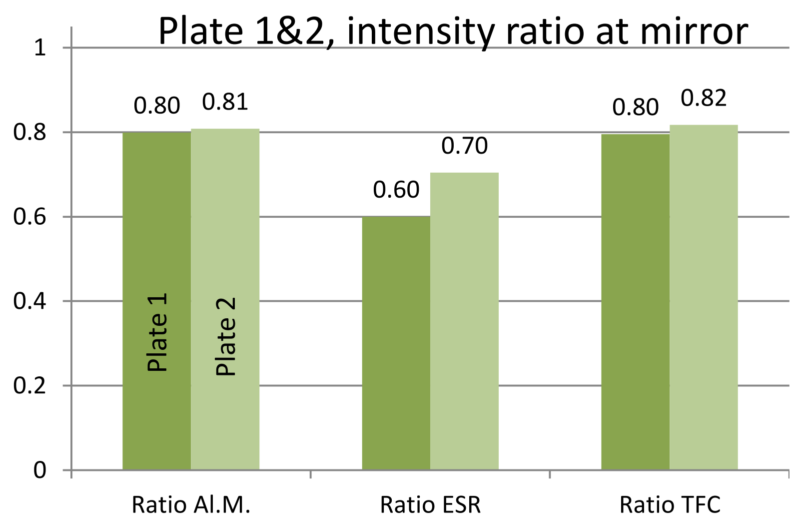
Mid plane

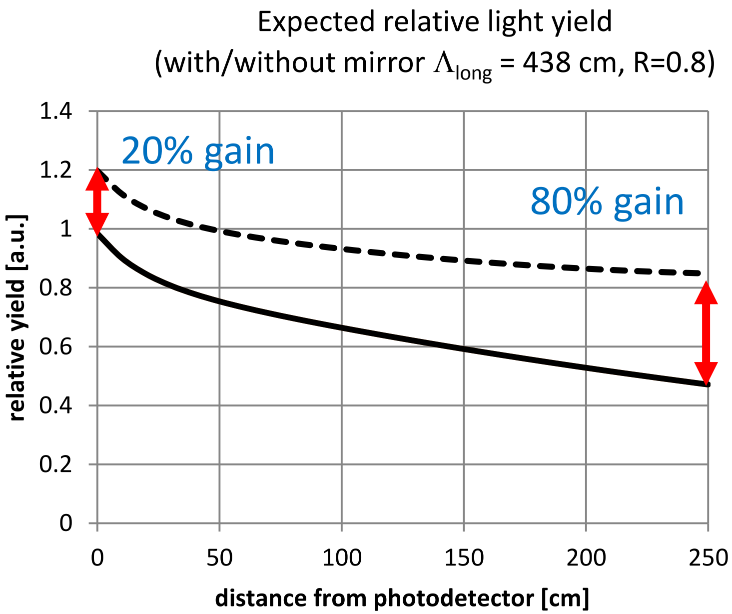
# Get enough light → produce high quality mirror at non-read fibre end

50% of the scintillation light is emitted in the wrong hemisphere.

We studied three different mirror technologies
- Aluminised mylar foil
- 3M Extended Specular Reflectance (ESR) foil
- Aluminium thin film coating (TFC)

and measured the intensity gain (mirror/no mirror*)

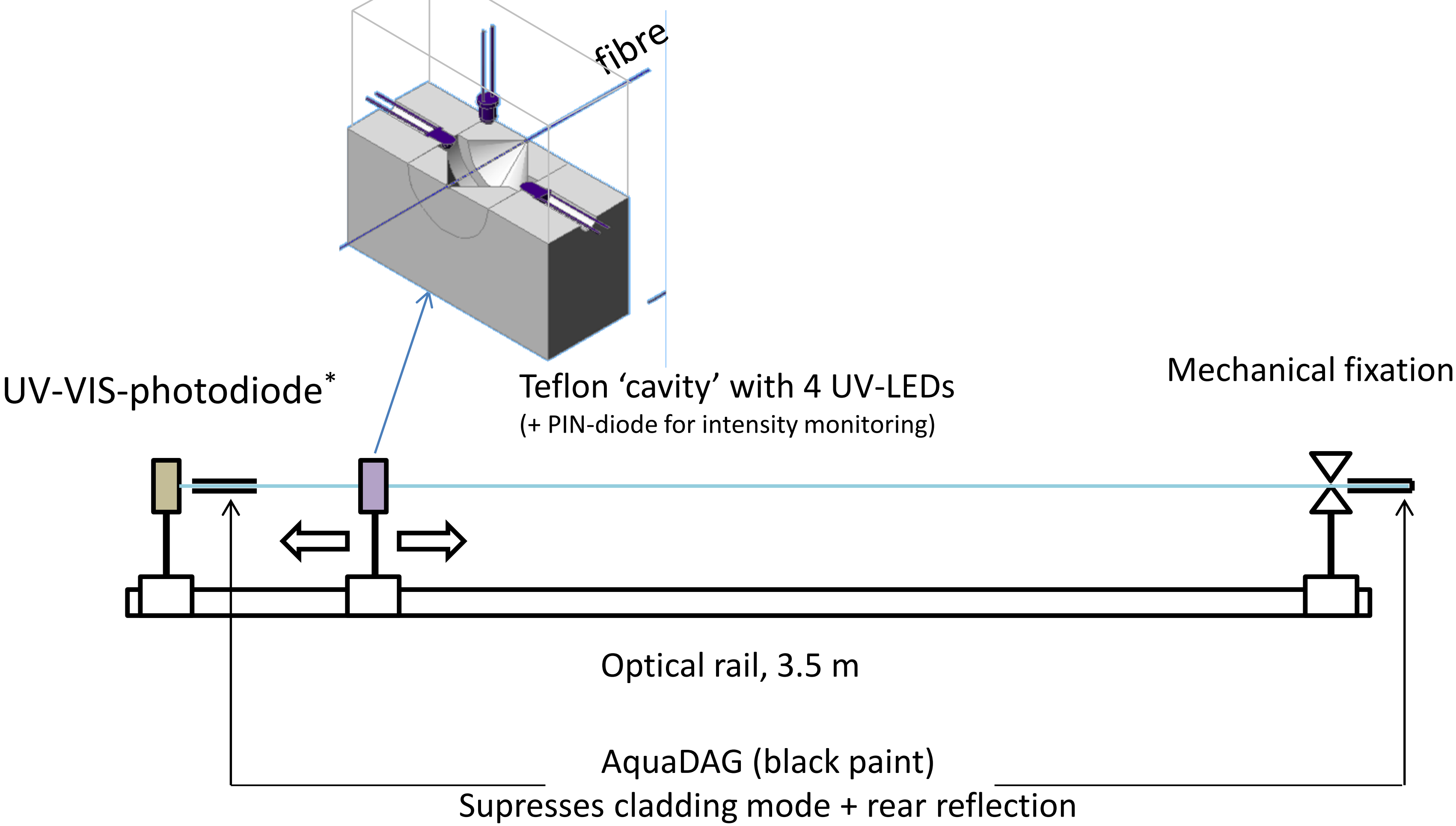



It remains unclear why ESR results are so low. Would have expected ≥ Al. Mylar.
We checked for possible influence of angle of incidence as well as glue type. No change.

# Get enough light → maximise fibre attenuation length

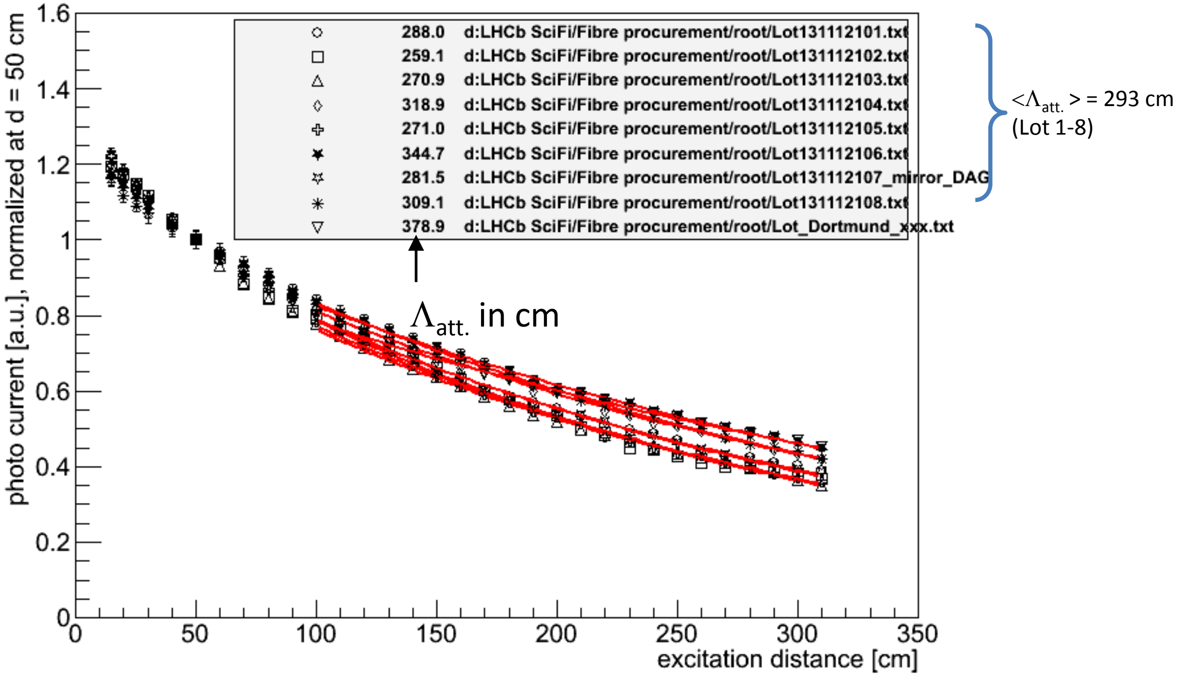
CERN set-up for measurement of attenuation length




*May be replaced by a SiPM, to have correct sensitivity characteristics.

# Measurements of 8 spools + older Dortmund sample (unknown Lot no.)

KURARAY SCSF-78, 250 μm, double cladded)




We are currently investigating with Kuraray whether lower or higher concentrations of dopants have a sizable impact on $\Lambda$ or whether we have to live with $\Lambda$~3-4 m.

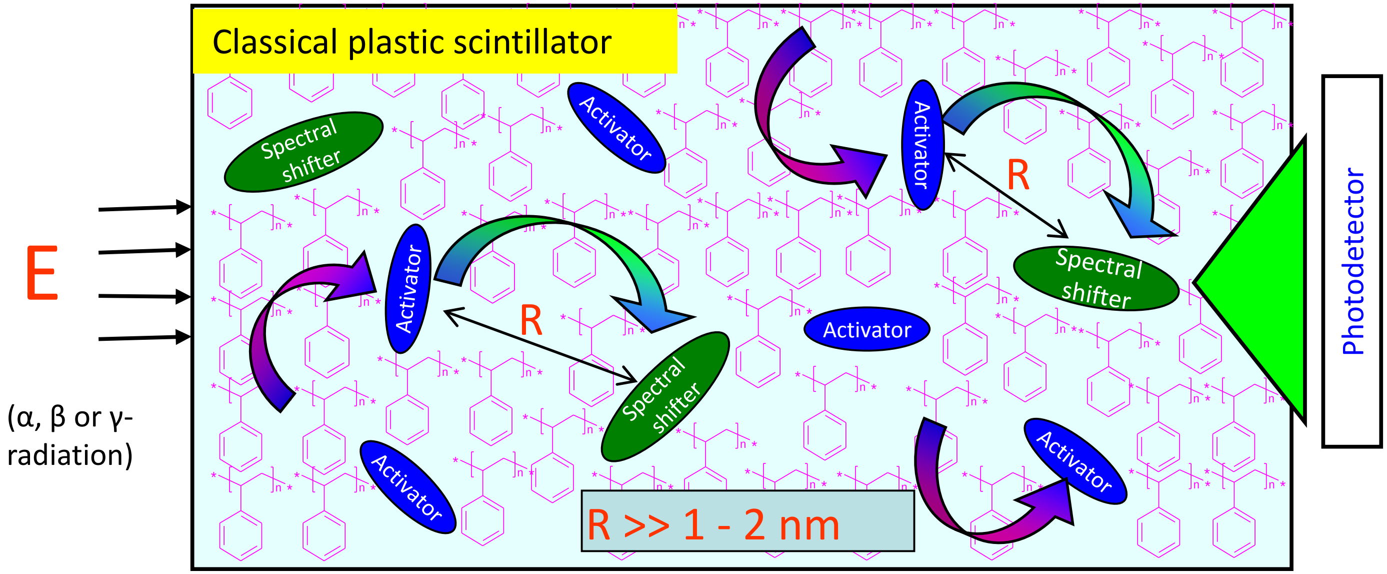
Side remark: We are also maintaining / building up relations to 2 other potential fibre producers: Saint-Gobain (Bicron), ELJEN Technologies (new in the SciFi market).

## A new but still unproven approach for scintillating fibres:

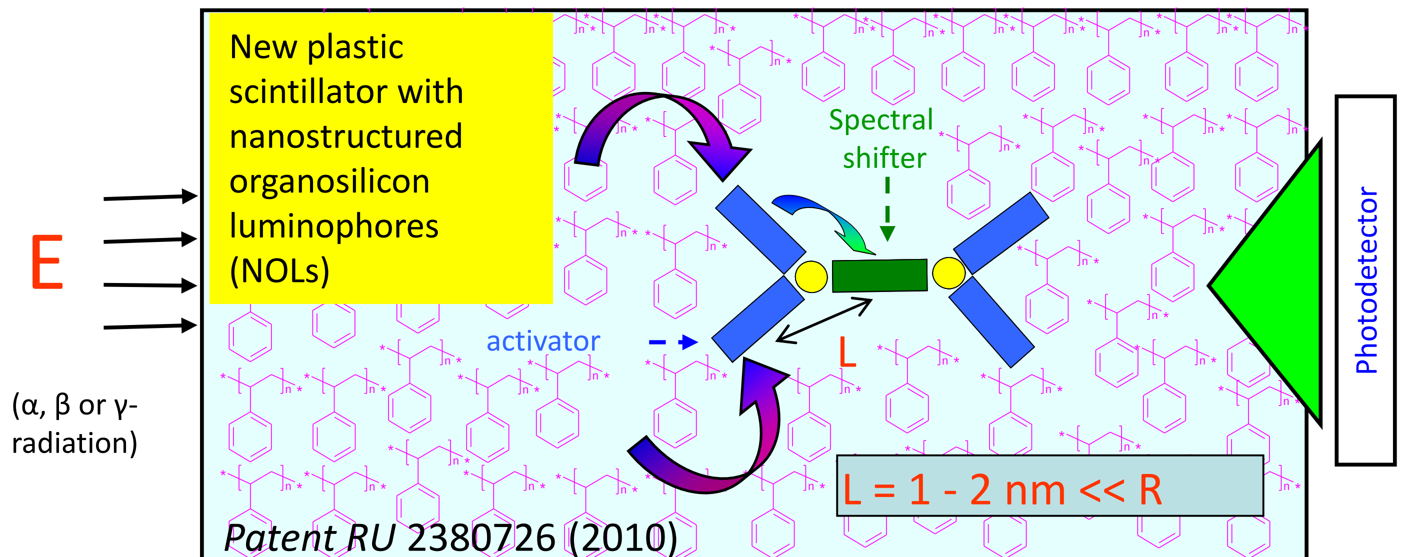
# Nanostructured organosilicon luminophores (NOLs)

S.A. Ponomarenko *et al.* , *Enikolopov Institute of Synthetic Polymer Materials, Russian Academy of Sciences*

Activator = Scintillator
(see slide 7)



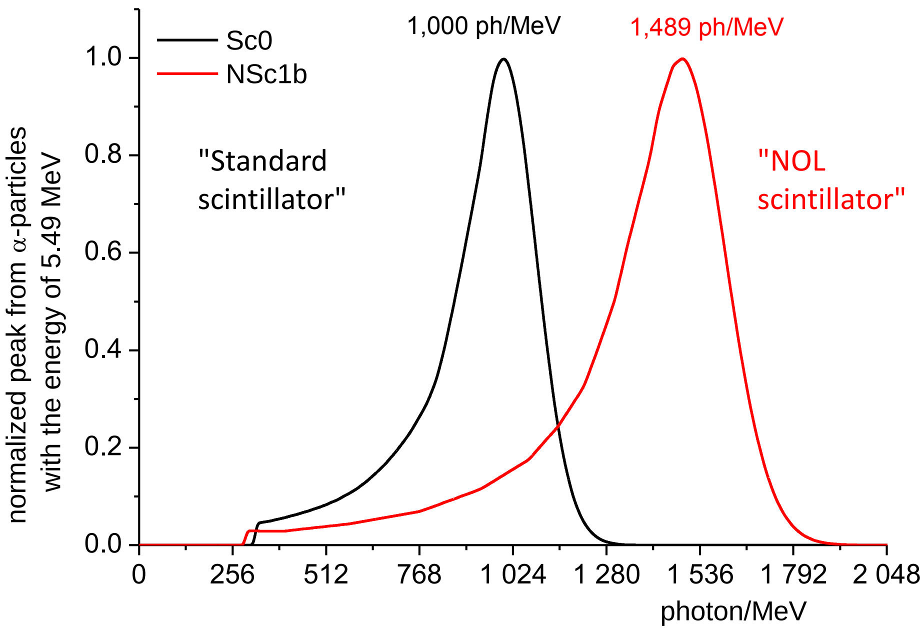

Light output is 45-65% relative to the anthracene standard.



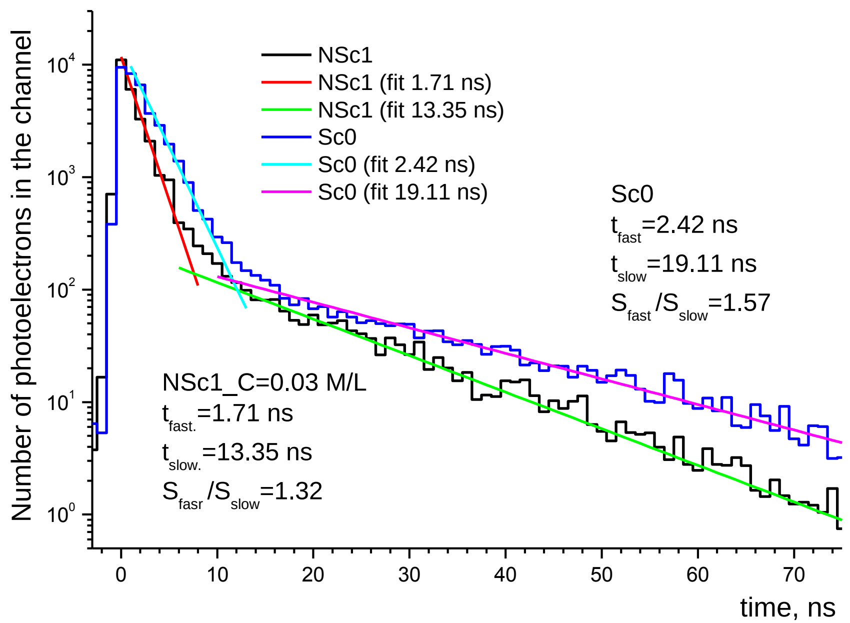

Light output is 90-120% relative to the anthracene standard.

# Measurements on scintillator tiles

Comparison of light yield from 5.49 MeV α particles




Comparison of scintillation decay time



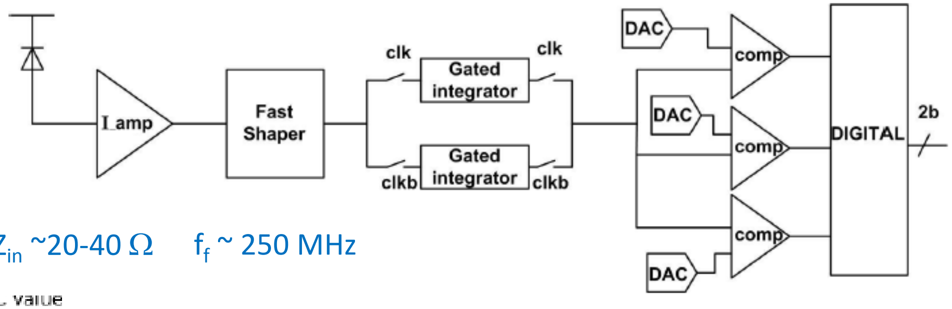

S.A. Ponomarenko *et al.*, *Enikolopov Institute of Synthetic Polymer Materials, Russian Academy of Sciences*

- Potentially very interesting!
- How will the material behave in fibre geometry ?
- Radiation hardness ?

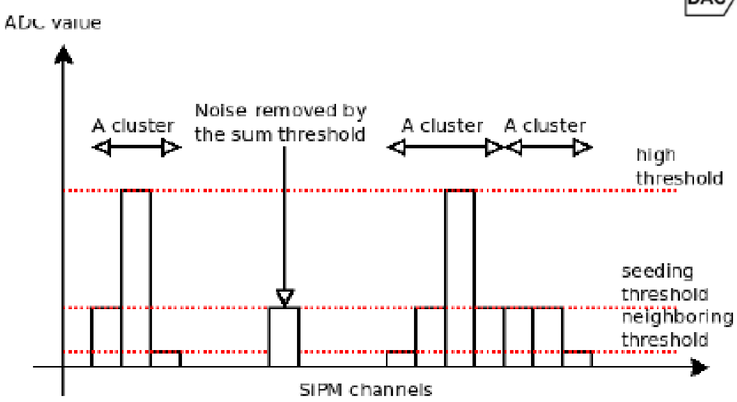
# Fast readout with manageable data volume

- ~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 128 (or 64) channels** (130 nm CMOS)




$Z_{in}$ ~20-40 Ω    $f_f$ ~ 250 MHz

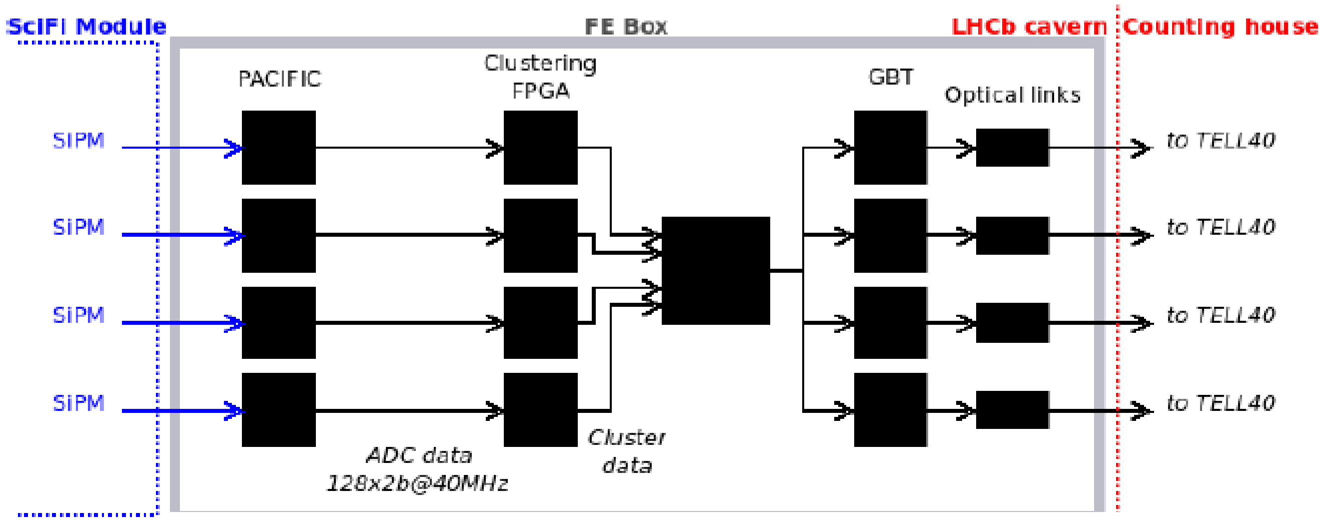



**3 hardware thresholds (=2 bits)**

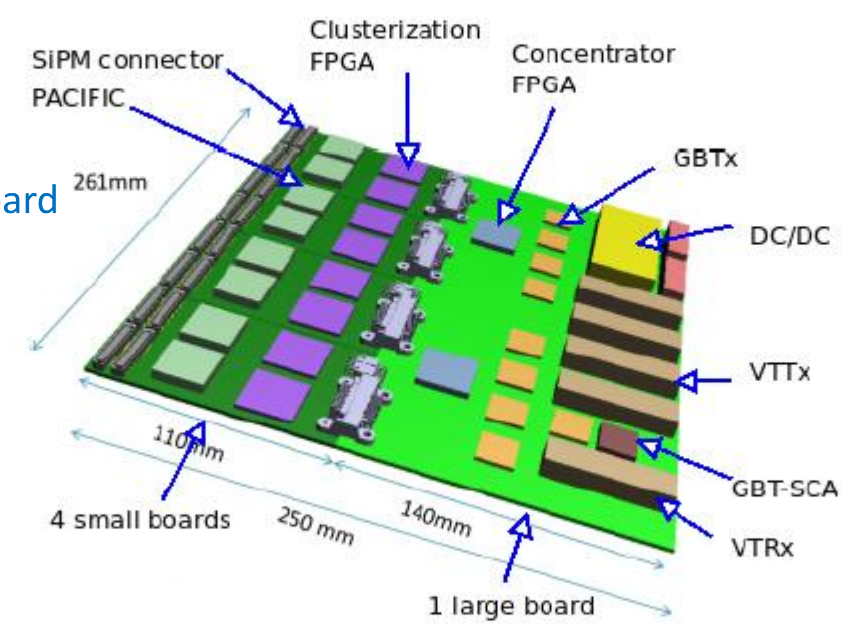
- **seed**
- **neighbour**
- **high**

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

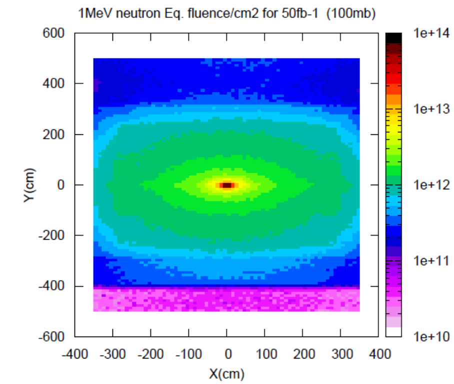
Compared to analog (6 bit) readout, expect resolution to degrade from ~50 to 60 μm. Marginal impact on p-resolution.




Current layout of motherboard
For 8 x 128 channels.

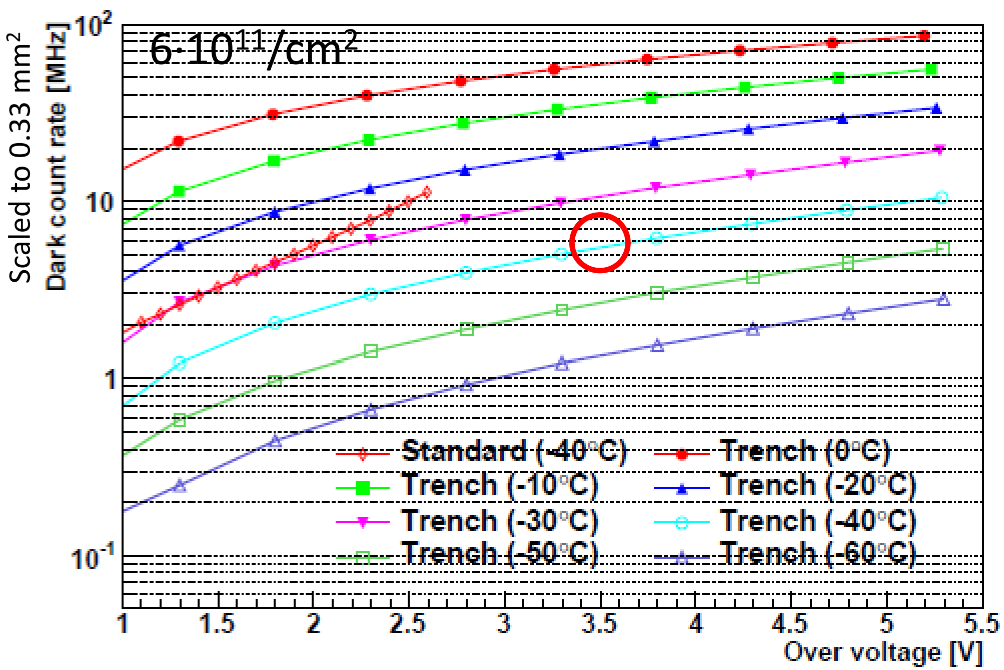


# Survive the radiation




## Neutrons:

- The SiPMs are exposed to $1.2 \cdot 10^{12}$ $n_{1Mev.eq.}$ /cm² (50 $fb^{-1}$)
- A detailed FLUKA simulation showed that shielding (Polyethylene with 5% Boron) can halve this fluence → tests so far done for $6 \cdot 10^{11}$/cm² .
- The SiPMs need to be cooled. Our default working point is -40°C. Noise reduced by factor ~64.

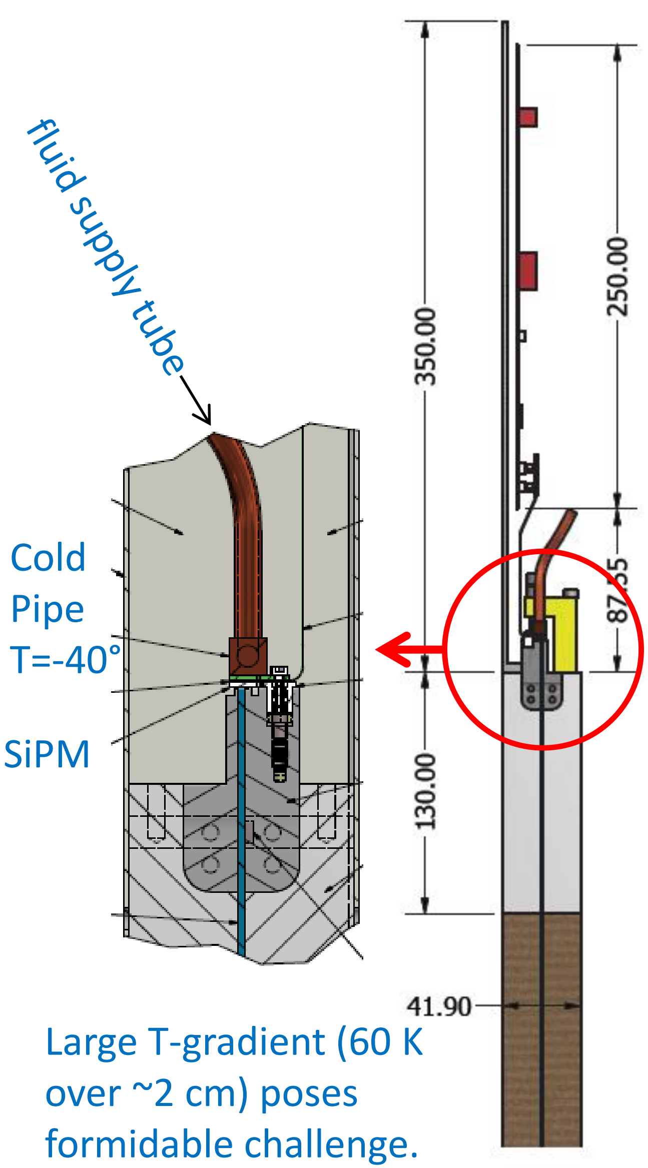


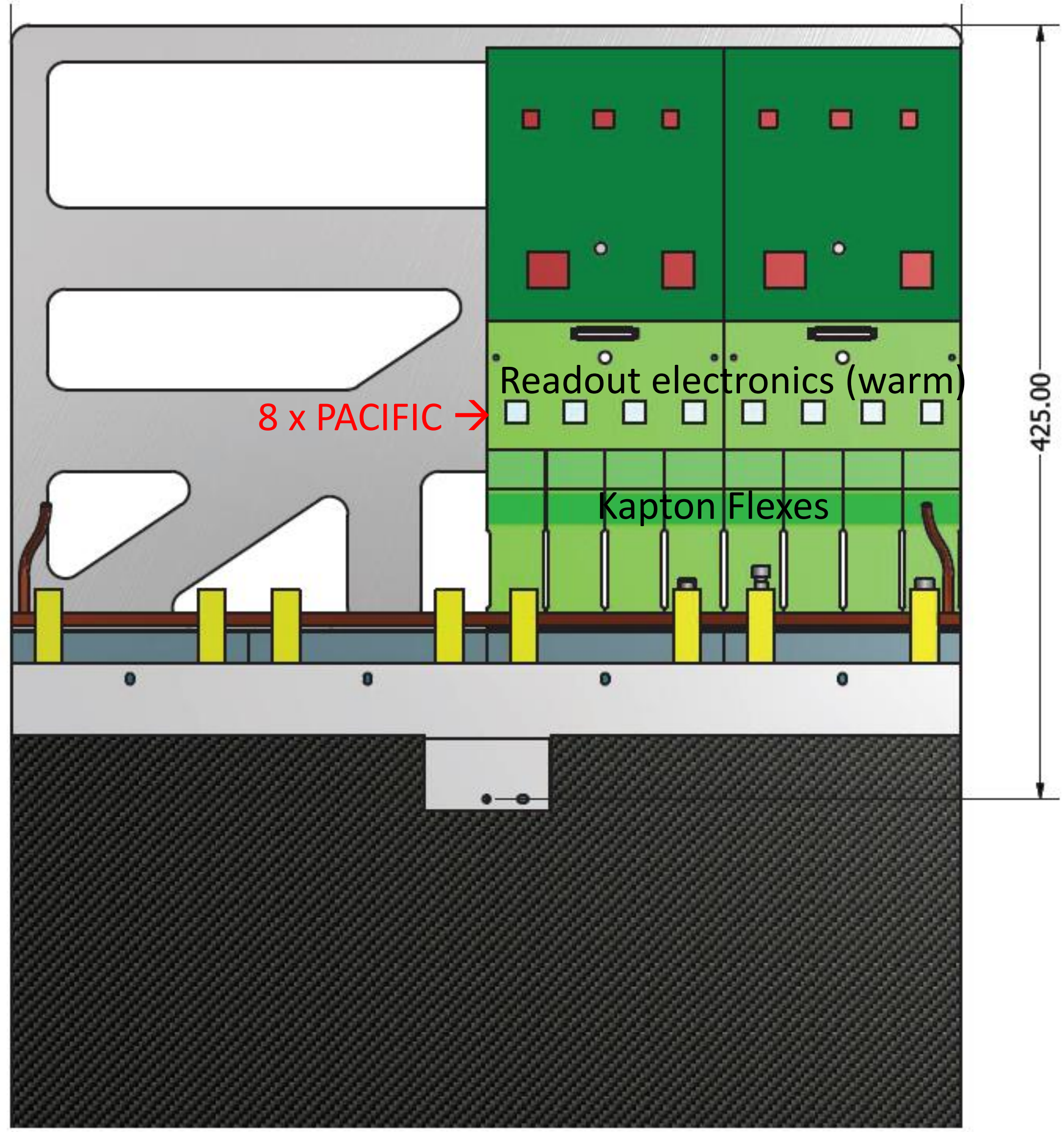

- Dark counts are primary noise source.
- Keep pixel-to-pixel cross-talk low → avoid double-noise hits (which can seed noise clusters)

(The expected neutron fluencies don't appear to be a problem for the fibres (to be better verified!)).

Hamamatsu 2013 technology (singe channel devices)

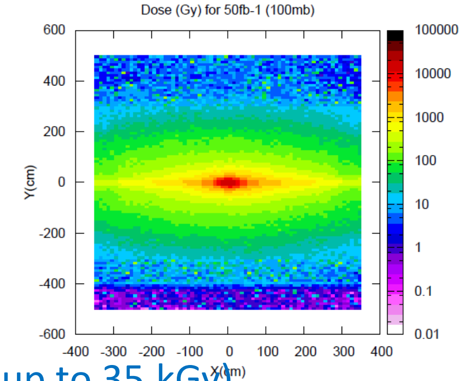
# SiPM cooling in Readout Box



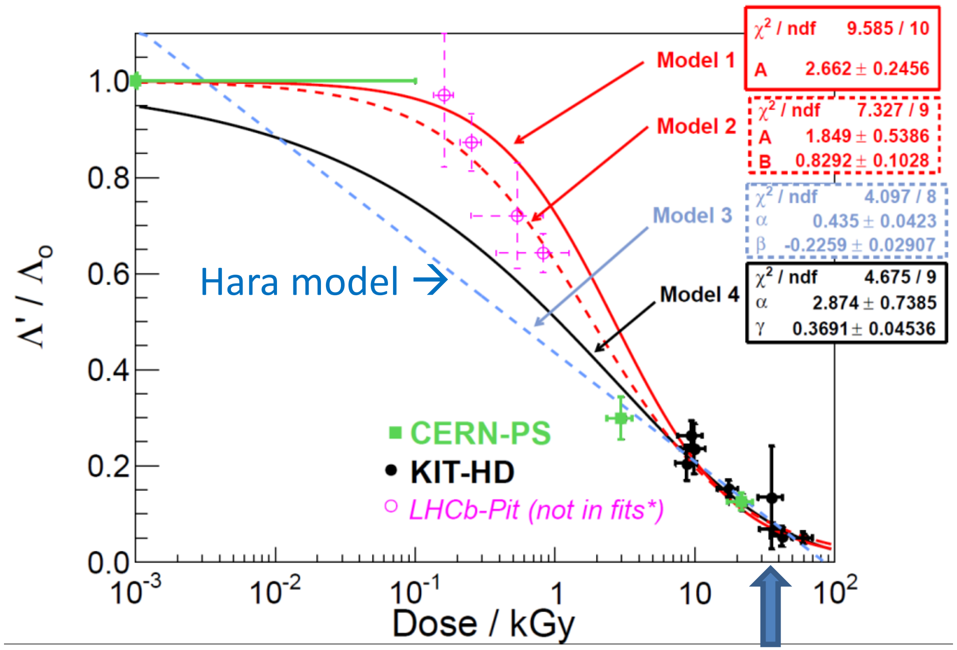

Large T-gradient (60 K over ~2 cm) poses formidable challenge.

# Survive the radiation




## Ionizing dose:

- The fibres get significantly damaged in the central part of the detector (up to 35 kGy).




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

There is no generally accepted model → **Need more low dose data**.

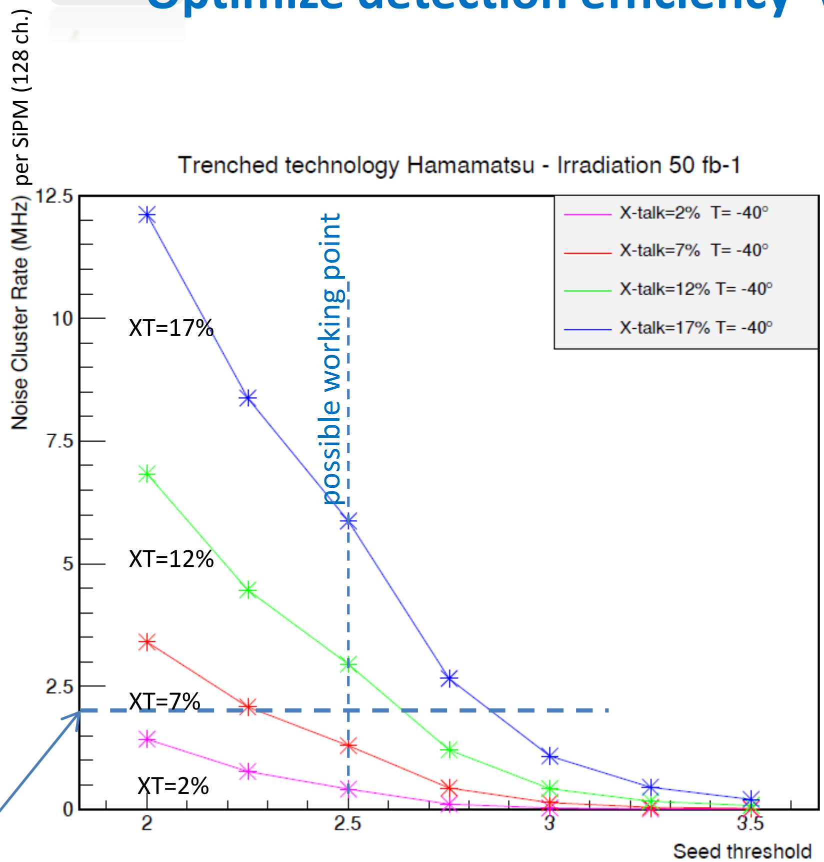
## Survive the radiation

### Fibre annealing?

- Can we hope for some annealing effects ? Controversially discussed in literature. But also non-agreeing observations in Heidelberg (yes) and at CERN (no).
- 6 fibre layers in the central part will provide safety margin.
- Ultima ratio: be prepared to replace some central detector modules after n $fb^{-1}$.

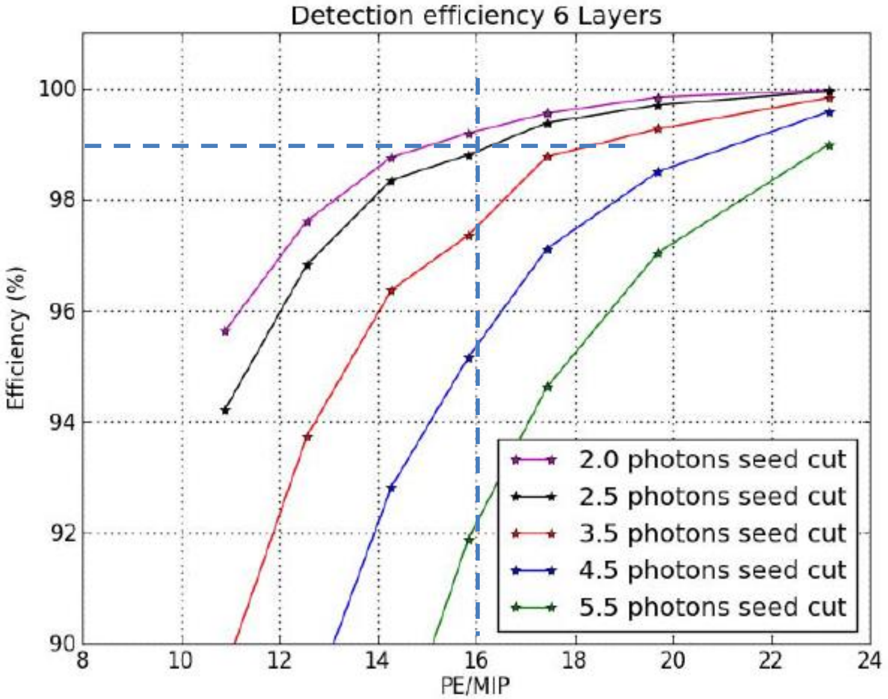
# Optimize detection efficiency vs ghost rate

~ ghost hits




considered acceptable

Seed = charge (in p.e.) of a SiPM channel to launch a cluster search




Total cluster charge (in p.e.) for a MIP hit.

**Need X-talk <10%**

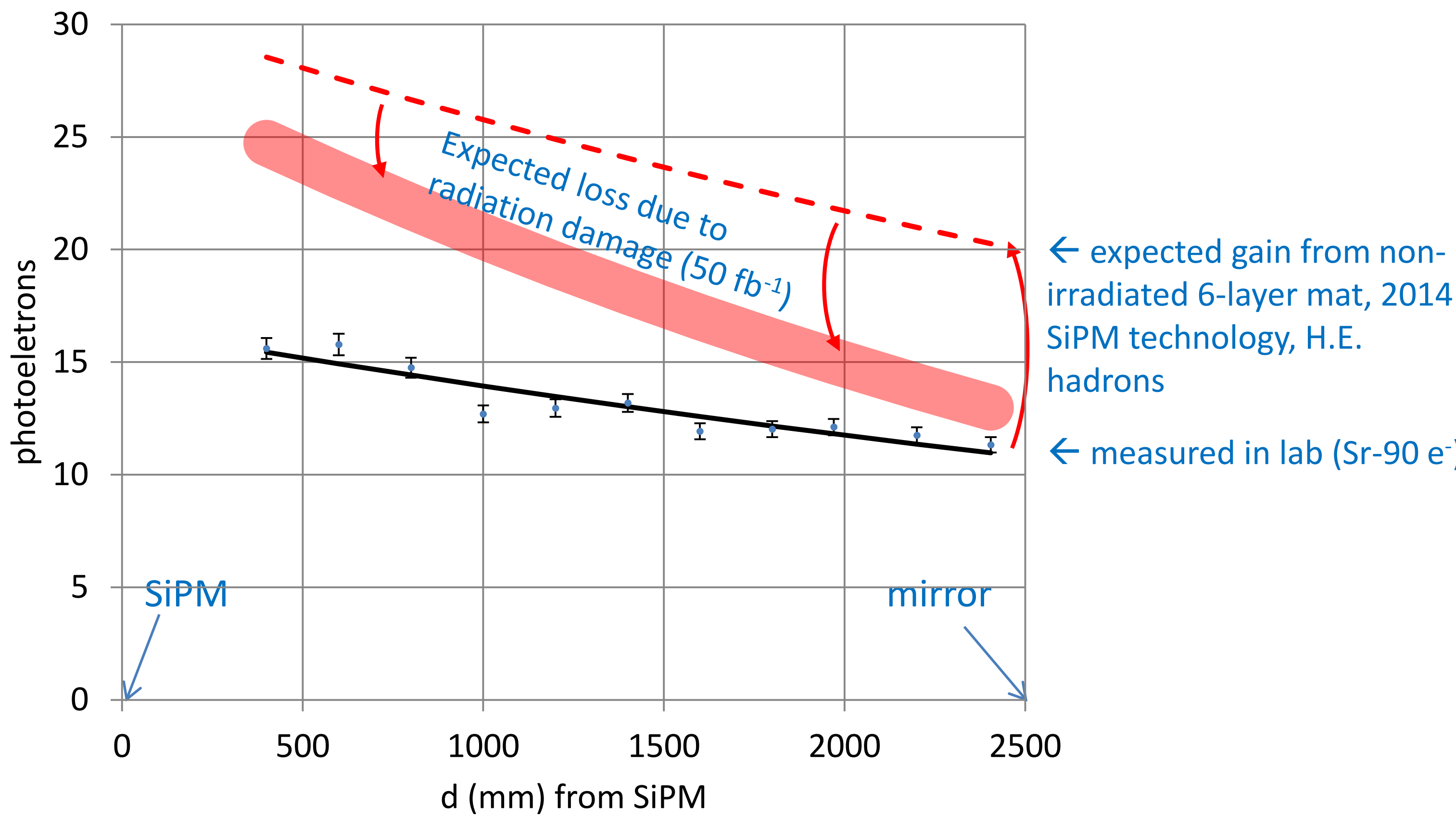
**Need 16 p.e to guarantee 99% detection efficiency (in single module).**
**12 p.e. give 96%**

# Where do we stand ?

- **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. Aim to test them in SPS beam in autumn.
- **SiPMs** — 64-ch. SiPM arrays from Hamamatsu and KETEK successfully tested. First 128-ch. arrays from KETEK look promising. Expect new arrays from Hamamatsu soon. **Increased PDE and(!) reduced XT.**
- **RO electronics** — Single channel of PACIFIC being tested. 8-channel version submitted a few days ago. Full scale prototype ASIC in 2015.
- **Design** — Efforts for overall detector design, Readout Box, mechanics getting in full swing. Lots of challenges like beam pipe hole, cooling (insulation, condensation).
- **Production** — Starting to think of tooling, logistics and QA. Mass production of fibre mats and modules will require sustained efforts and tight quality control.

## 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).



# Summary and Outlook

- Scintillating fibre technology in combination with SiPM arrays allow building **large-area and low-mass tracking detectors with good spatial resolution**.

- As in every light based detector, lots of effort is spent in **producing enough photons** and **loosing only few** of them.

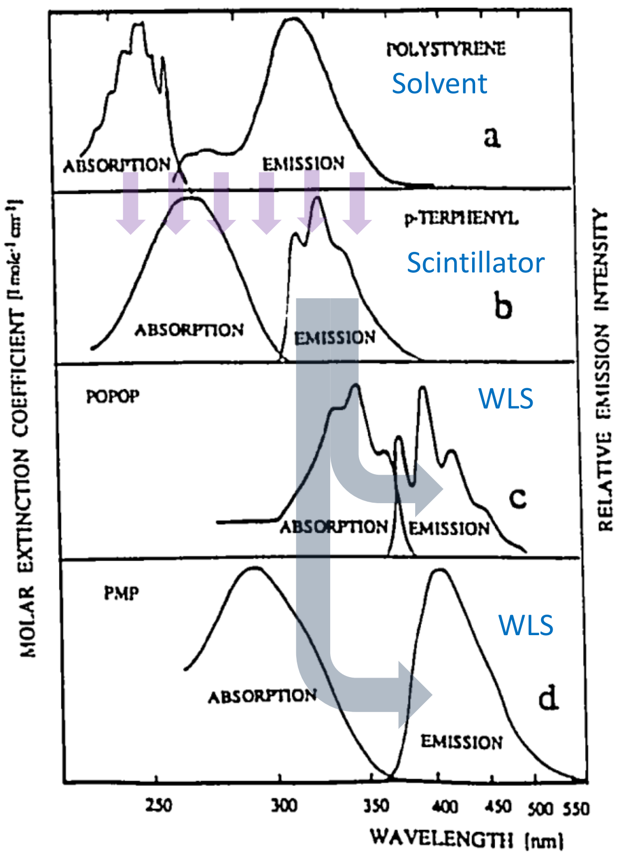
- **Radiation is the main enemy**, both for the fibres (ionizing radiation) and the SiPMs (NIEL = neutrons). The radiation environment of LHCb is already pretty challenging.

- There was relatively little activity in scintillating fibres during the last two decades. Compared to e.g. silicon, the **fibre technology hasn't evolved very much** in terms of e.g. light yield, radiation hardness, attenuation length, … . NOL technology could have a large impact.

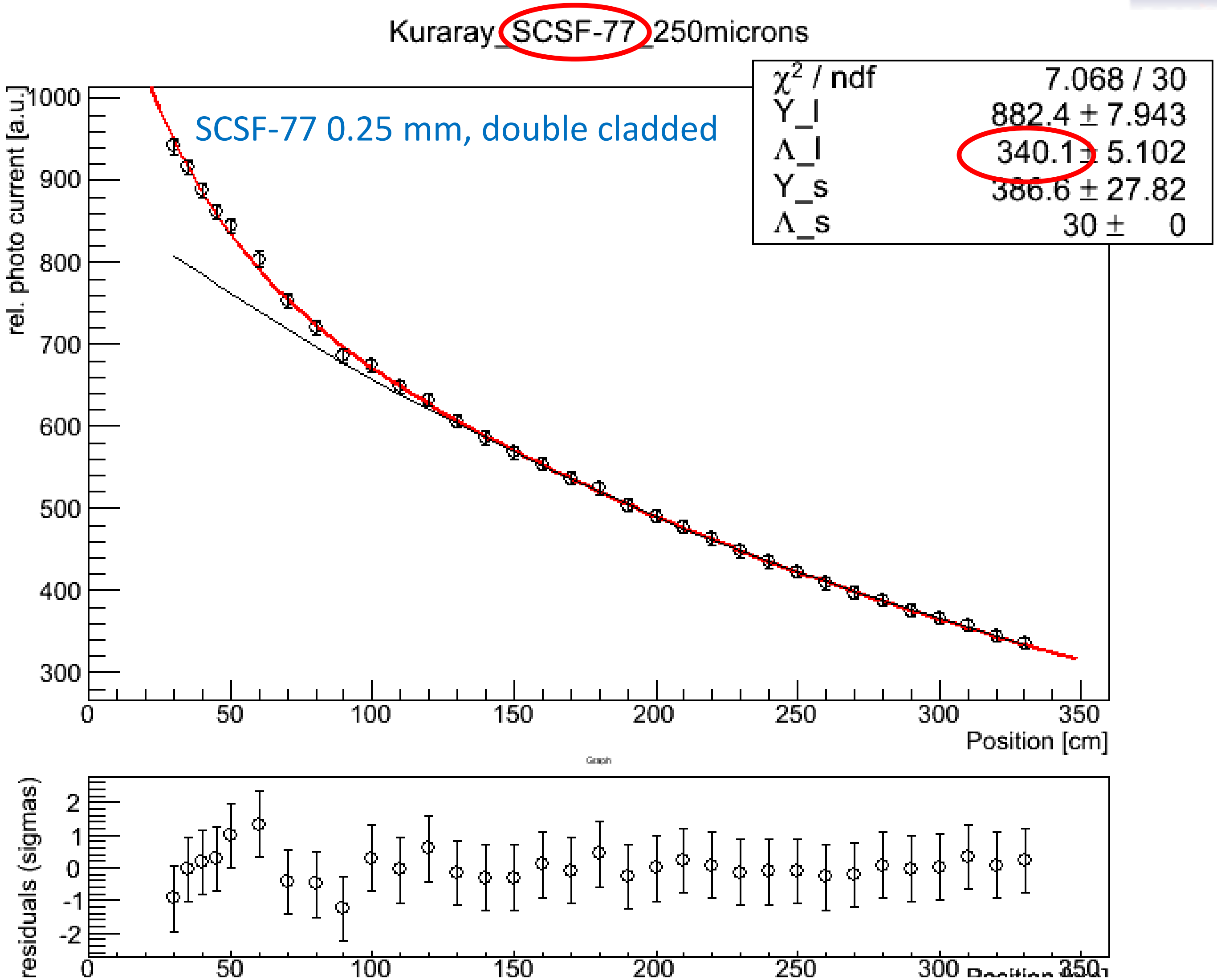
- Building a precise large-area fibre trackers is a **labour intensive endeavour** with lots of in-house production. Industrial partners producing high quality fibre mats would be welcome.

Back-up slides

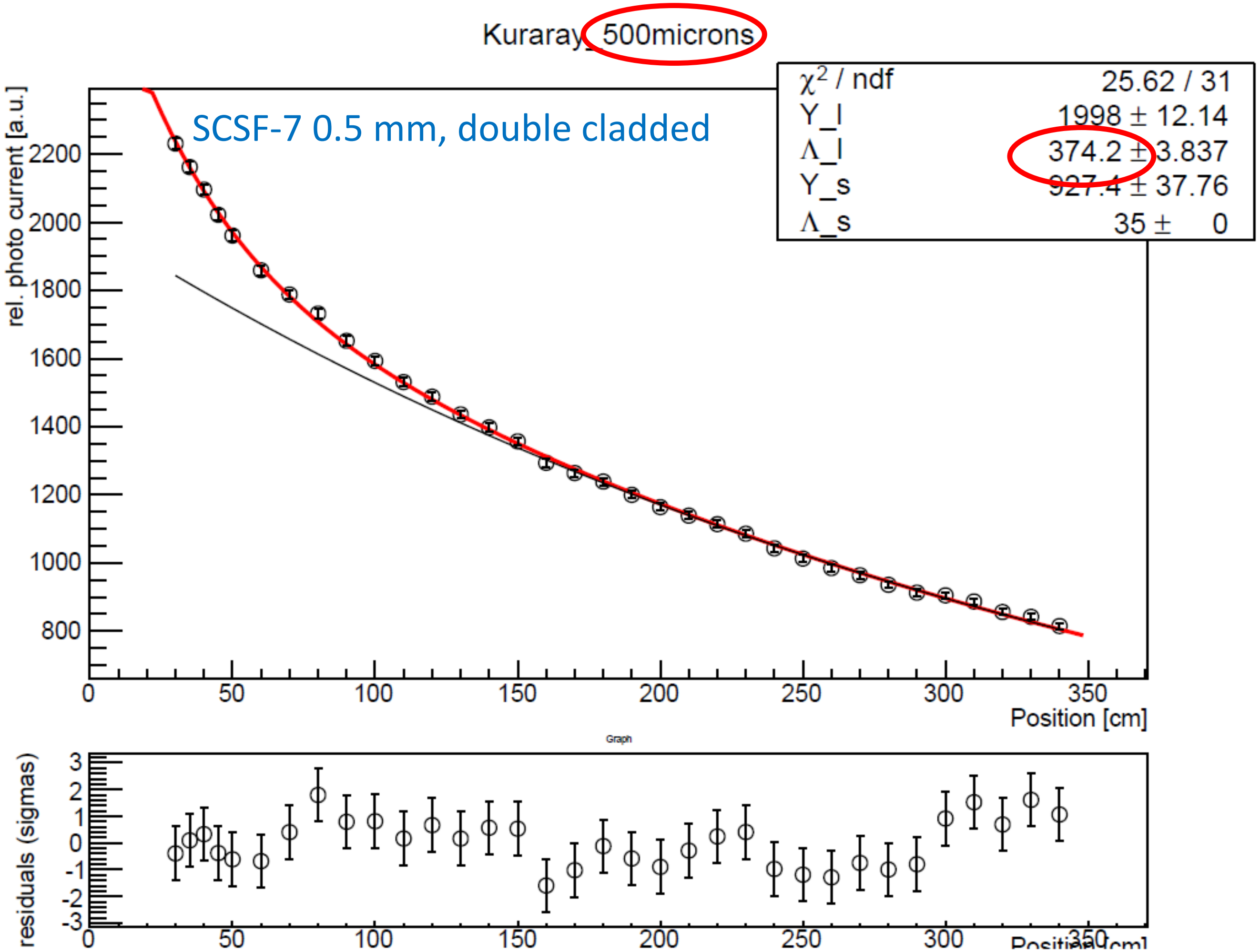
H. Leutz, NIM A364 (1995) 422



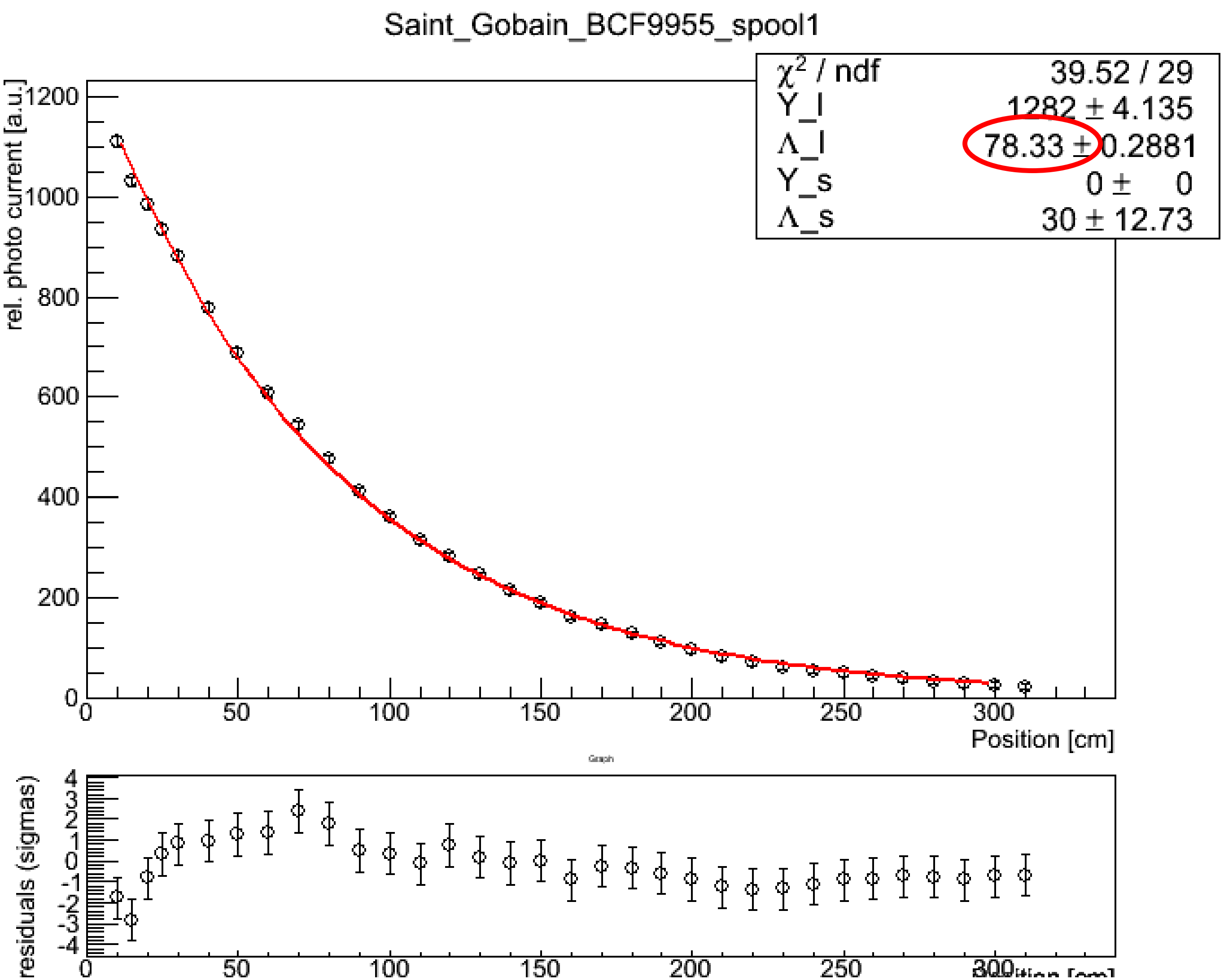
## Concentration of 2nd fluor halved



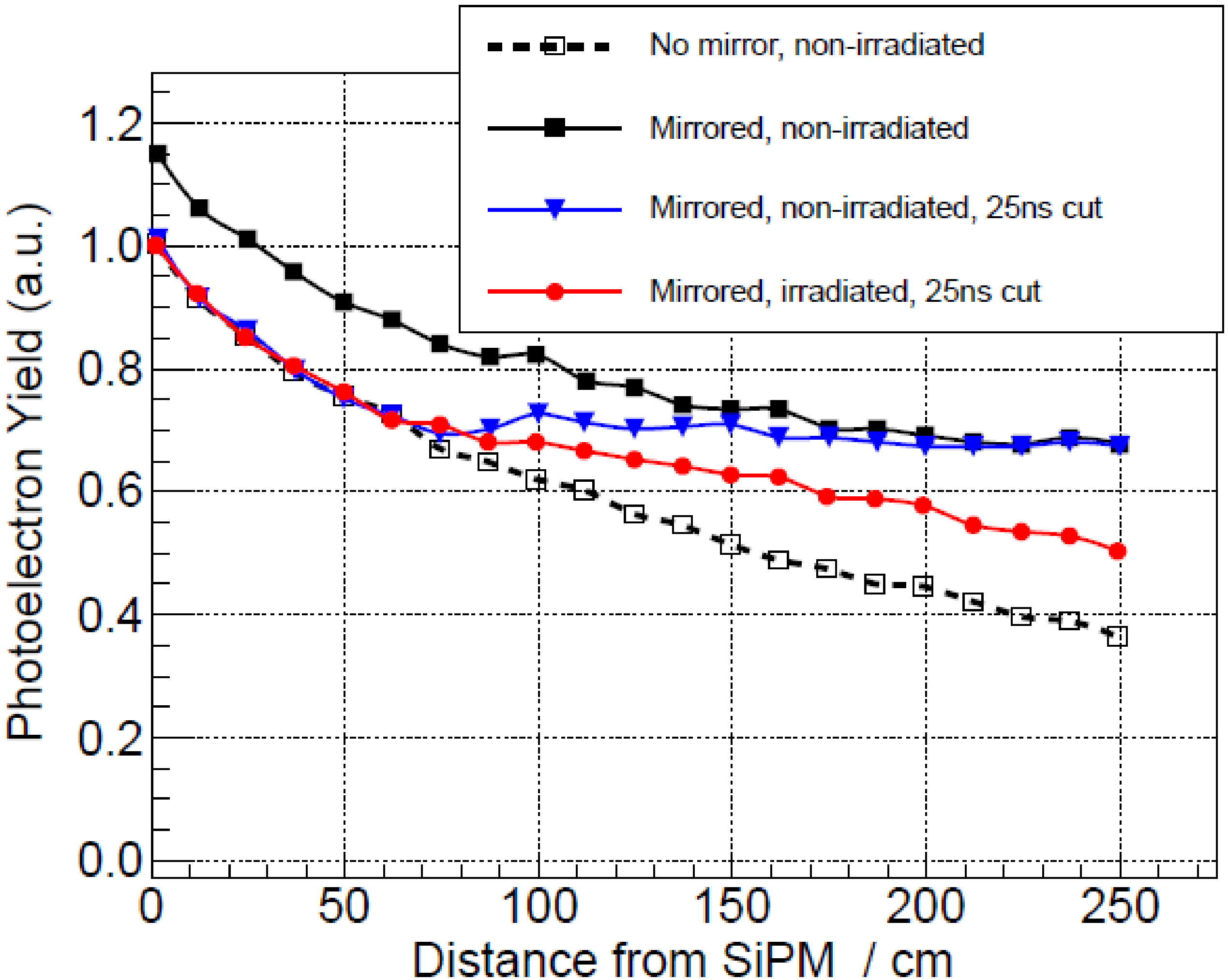
# Diameter double; 250 → 500 μm



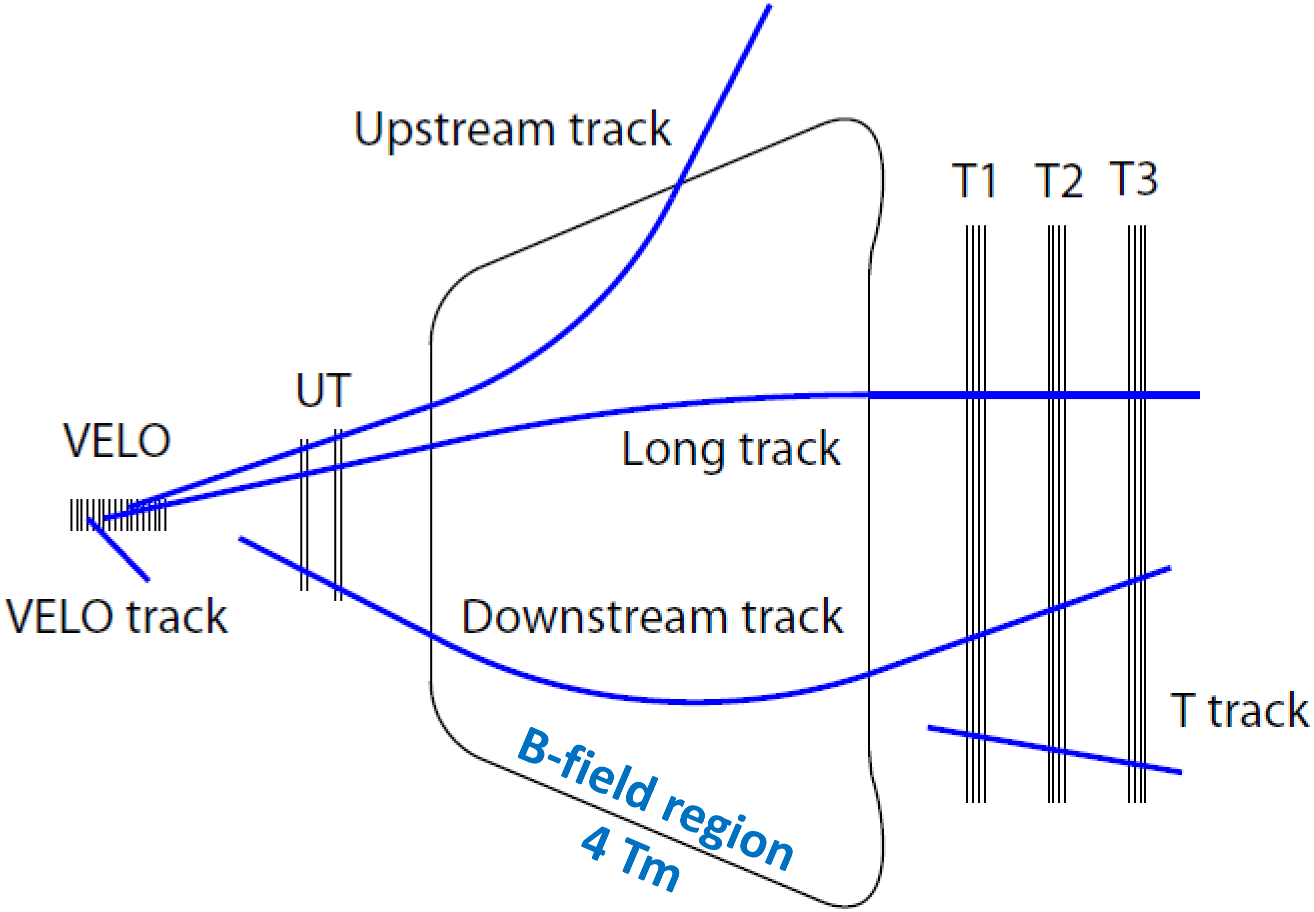
# Special test fibre with singe fluor formulation



## Current M.C. model of the relative photoelectron yield



# LHCb track types



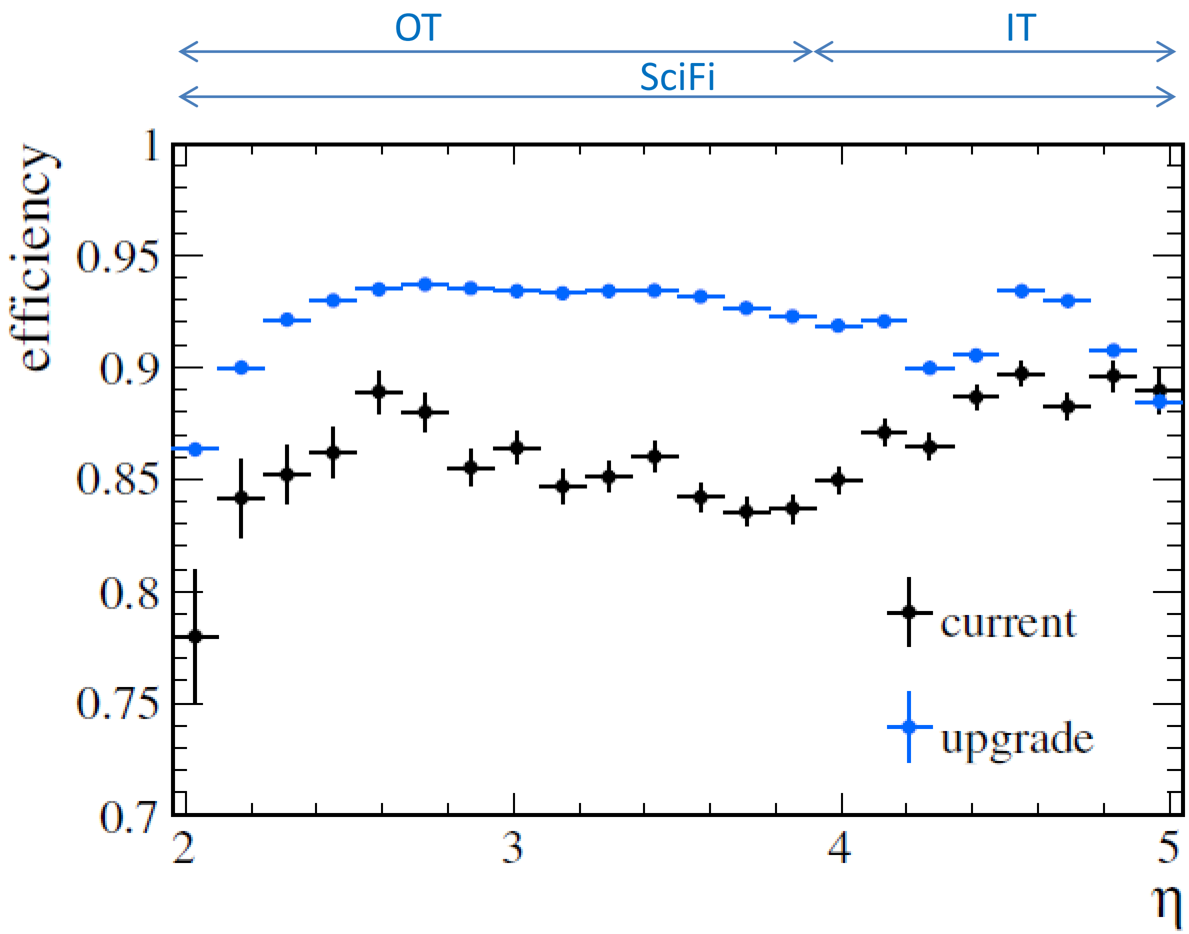



Figure 4.5: ~~Ghost rate and~~ efficiency of the Forward pattern recognition algorithm on samples of simulated $B_s \to \phi\phi$ events in upgrade running conditions at $\nu = 7.6$, for the upgrade and the current detector. For the efficiency a cut of the track momentum of $p > 5$ GeV/$c$ is applied.