

Scintillating Fiber Trackers: recent developments and applications

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Physics and Detectors for Physics Applications

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Outline

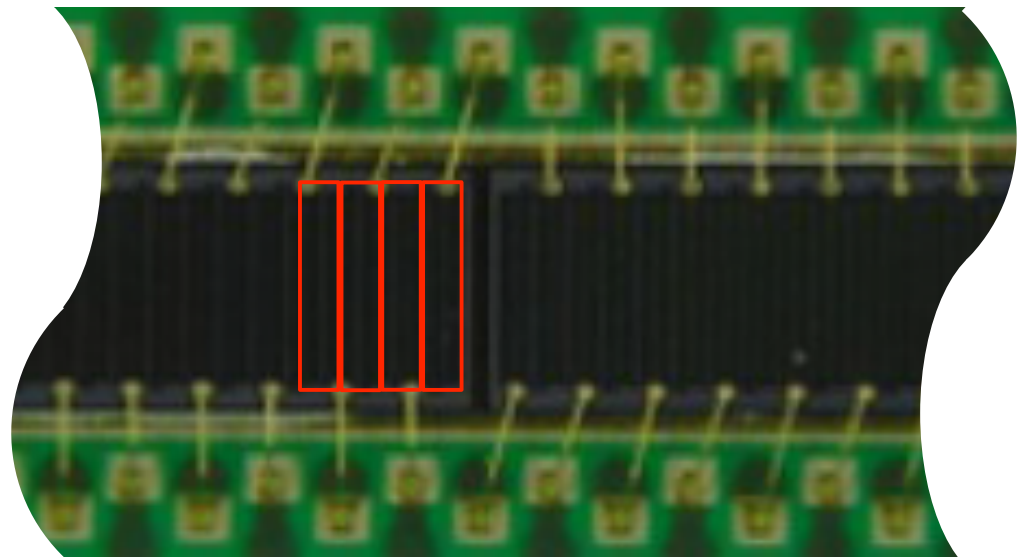
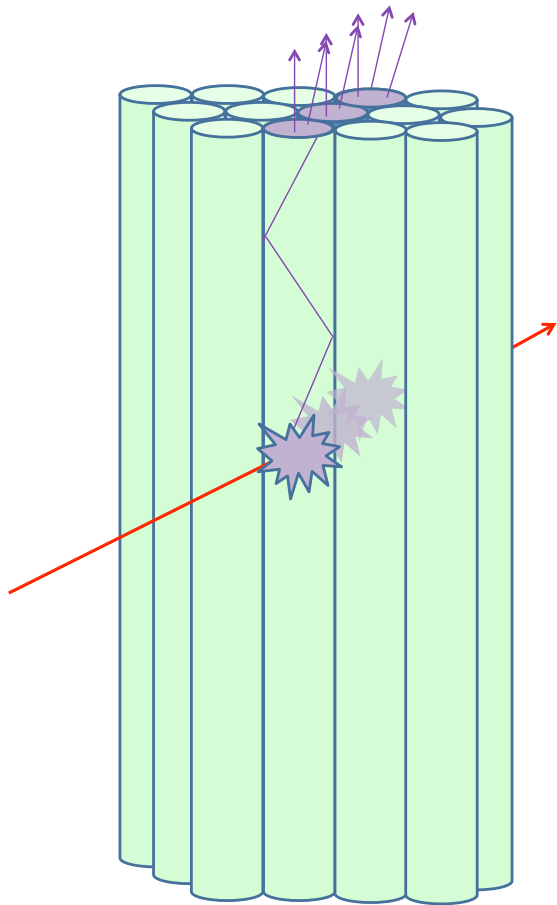
1. Principles of the scintillating fiber tracker
2. Past and present projects: a short review
3. Recent developments:
 - construction of large detectors (several square meters)
 - radiation hardness
4. Prospects for future applications

Disclaimer: this presentation is strongly biased by my own involvement in the LHCb SciFi tracker project...

...and has some overlap with the presentation by R.Ekelhof at yesterday's "Tracker and applications" parallel session

Basic design for Scintillating Fiber Tracker

- Scintillating fiber tracker principle:
 - cover the detection area with thin scintillating fibers
 - read them out with multi-channel photo-detectors → SiPMs



Scintillating Fibers

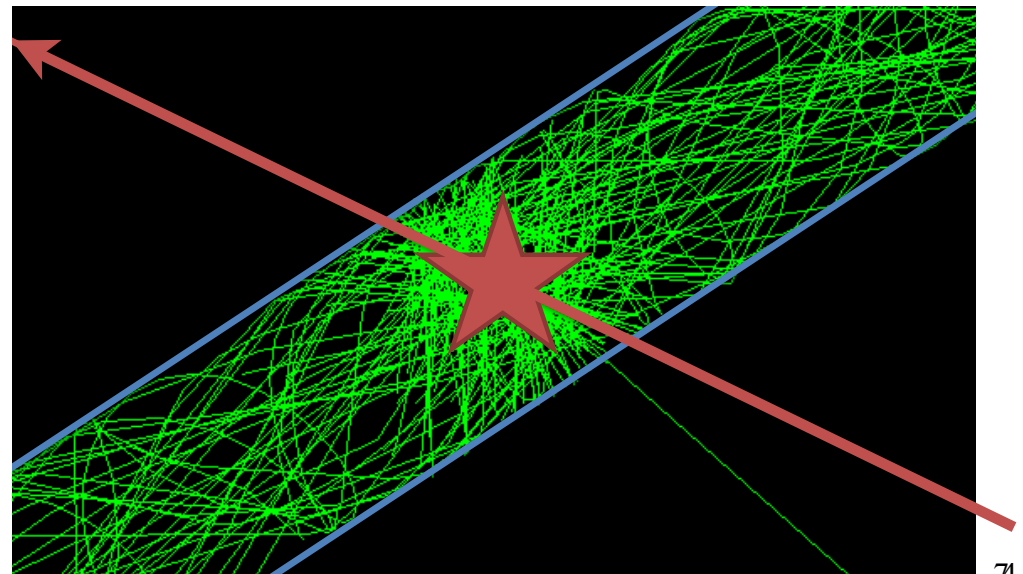
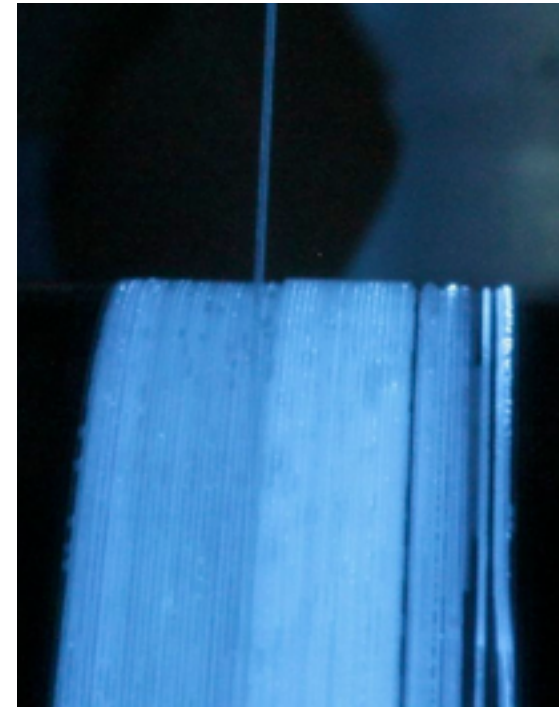
- The scintillating fibers have two roles:

1. act as scintillator

- ~ 2.8 ns scintillation decay time
- light yield: ~ 1600 photons/mm/MIP $\times 5.35\%$ capture
 \Rightarrow 10's of photons
- scintillating dye is expected to be radiation hard

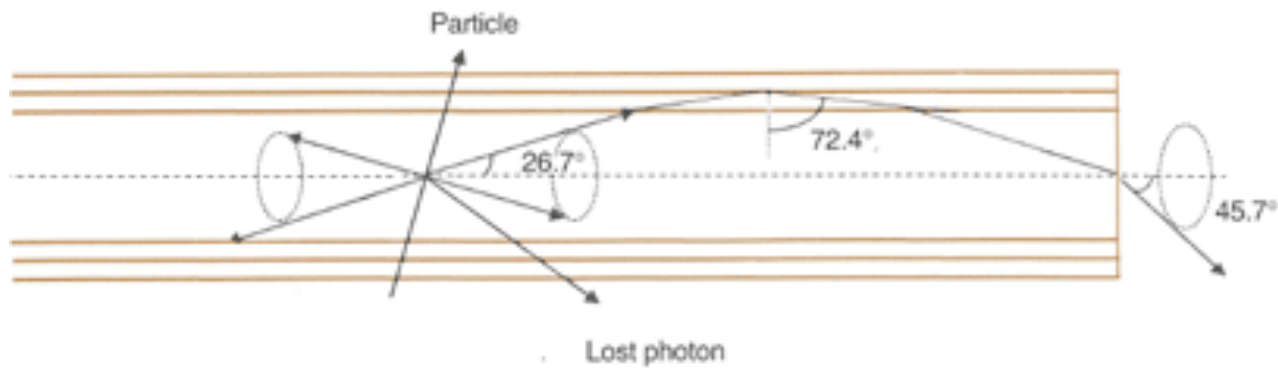
2. transport the light to the SiPM

- 5.9 ns/m propagation time
- attenuation length is an issue
(radiation hardness)



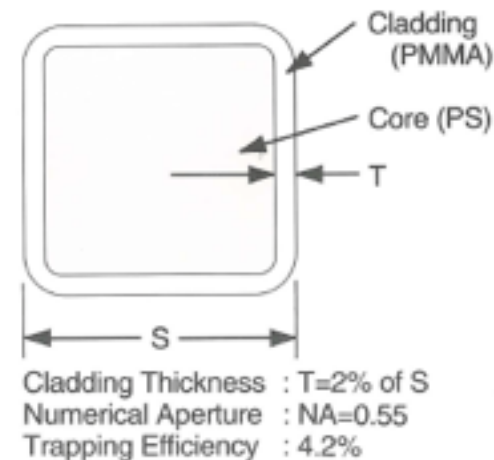
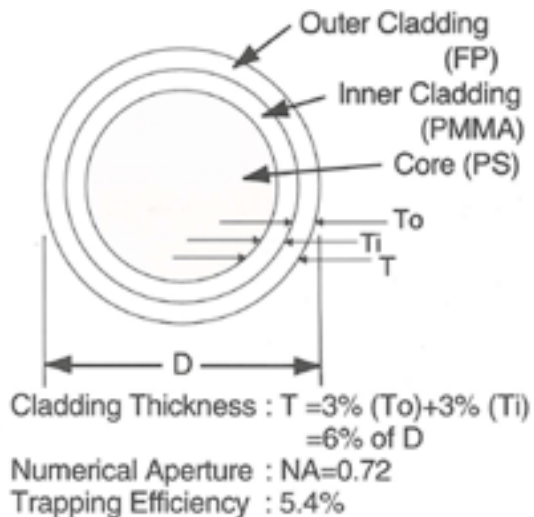
Types of fibers

- Scintillating fibers come in various types:
 - cladding (single, double) to increase trapping fraction
 - layers have decreasing refraction indices (from inside out)



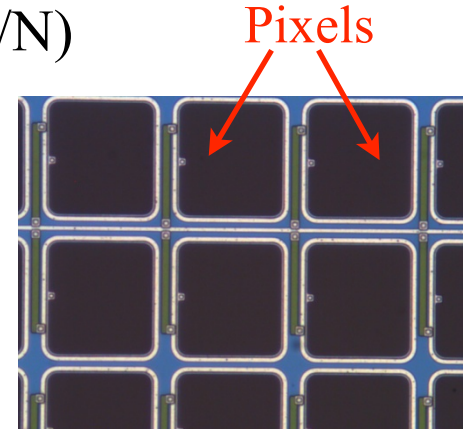
Drawings from Kuraray

- shape (cylindrical or square)

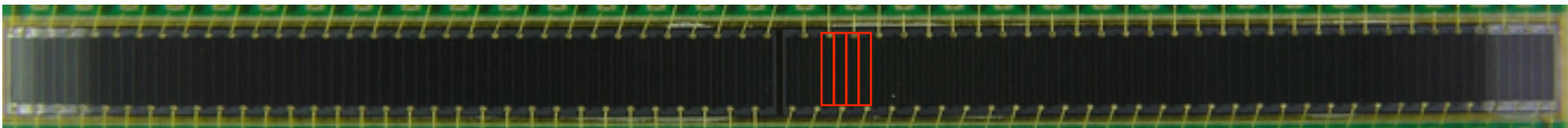


Multi-channel SiPM

- SiPMs are arrays of Avalanche Photo-Diodes (APD)
 - operate in Geiger mode
 - high gain ($\sim 10^6$) \Rightarrow high signal-over-noise ratio (S/N)
 - fast signal pulse (few ns)
 - fast recovery time
 - each channel is made of multiple APDs (pixels)
 - each pixel fires independently of the others
 - sum is \sim proportional to number of photons (up to saturation effects)
 - groups of channels make a multi-channel SiPMs

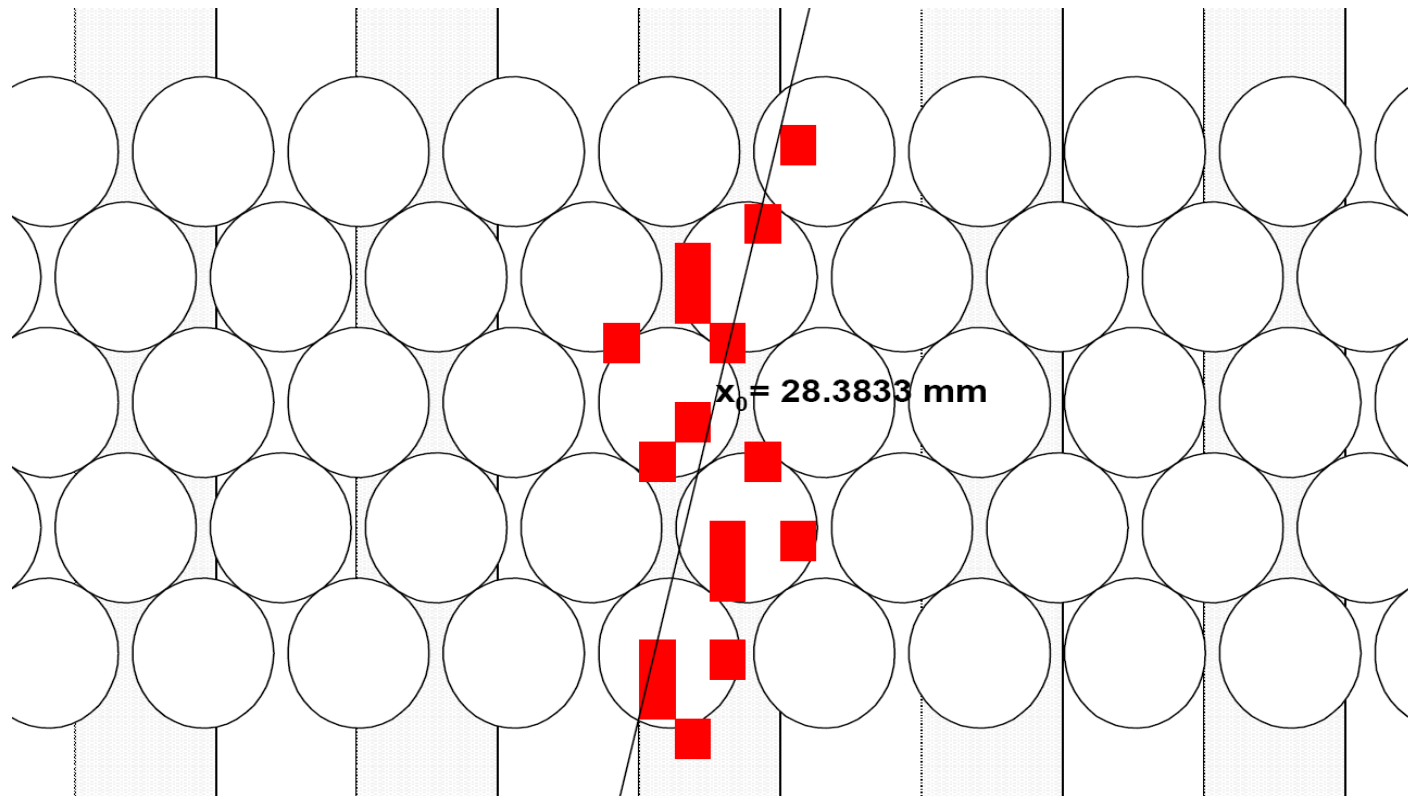


128-channel SiPM (Hamamatsu)



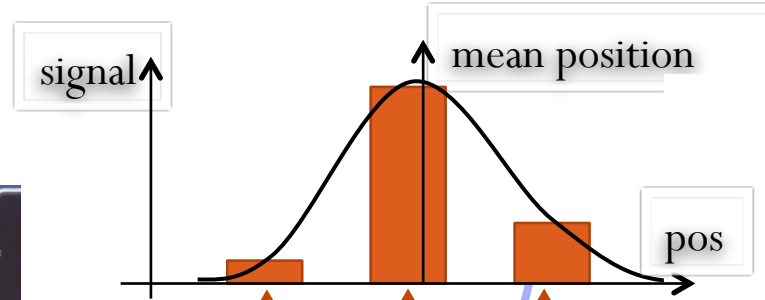
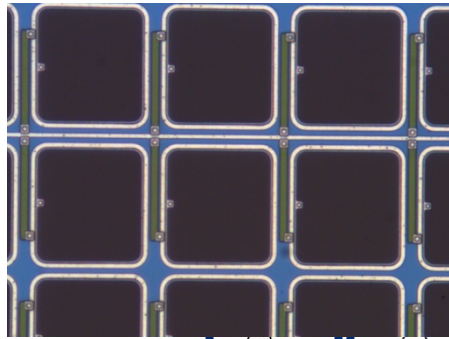
- SiPMs are sensitivity to radiation damage!

Signal cluster detection

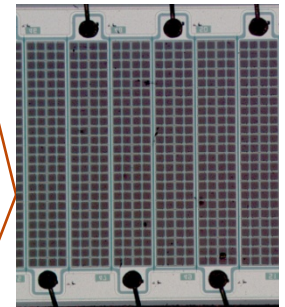
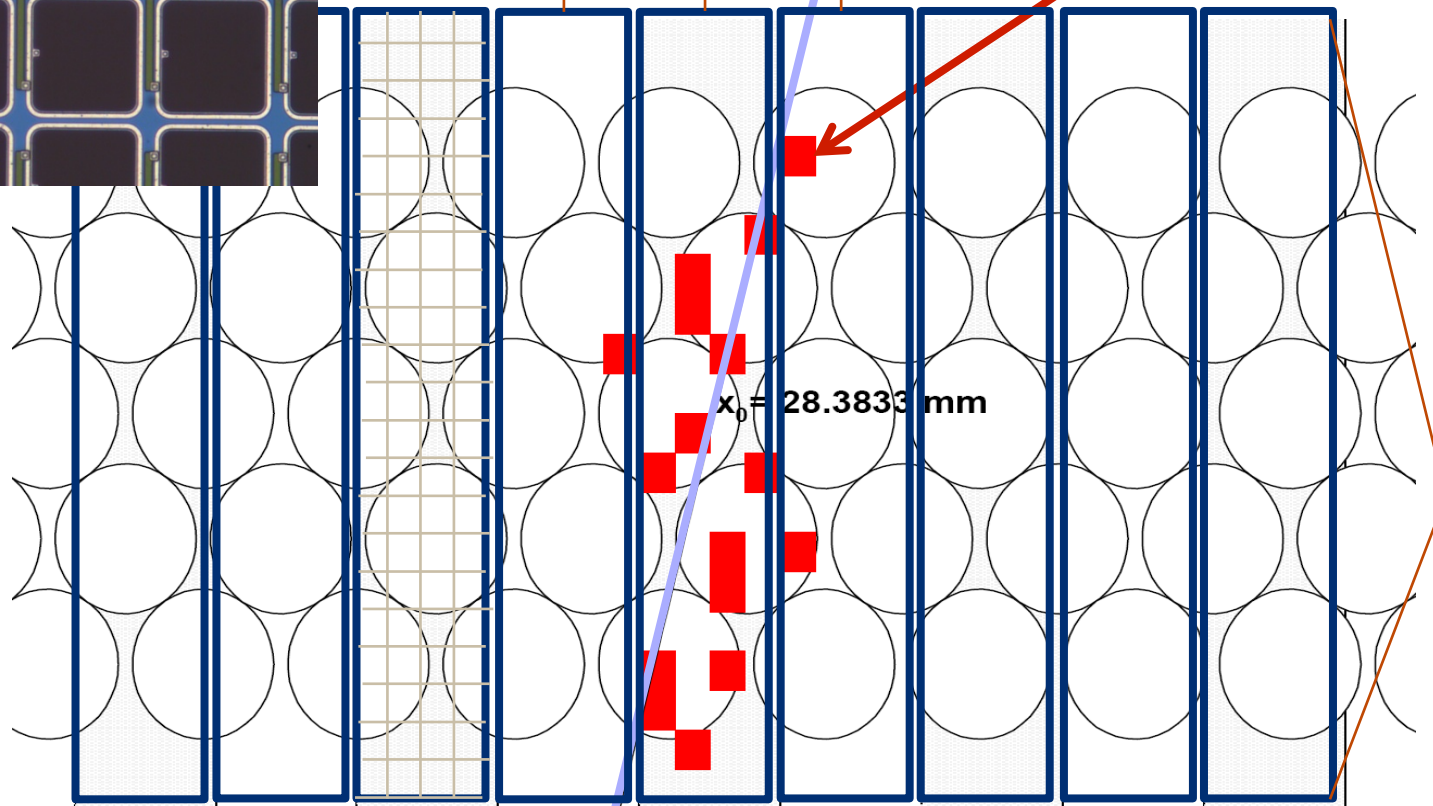


Signal cluster detection

Pixel structure on
on SiPM channel



Photons can create avalanche
in a pixel (red squares)



Channel structure
on SiPM chip

Particle creates
photons in fibers

Not a new concept...

Some Considerations on Luminescent Fiber Chambers and Intensifier Screens

L. REIFFEL AND N. S. KAPANY

Physics Division, Armour Research Foundation, Chicago 16, Illinois

(Received April 21, 1960; and in final form, June 1, 1960)

Factors affecting the performance of filamentary scintillators are considered. Experimental data on light attenuation for both plastic scintillator filaments and thin-wall glass tubing liquid scintillators are presented. A theoretical interpretation which satisfactorily accounts for the performance of luminescent filaments in terms of bulk properties and surface reflection losses is given and permits quantitative evaluation of surface losses for various materials. While plastic scintillator fibers are mechanically convenient, it is suggested that liquid-filled fibers will prove more consistent and stable in their properties. Comments on the utility of arrays of fibers as particle track imaging devices and as image intensifier screens are included.

I. INTRODUCTION

WELL-KNOWN problems associated with particle track detection and measurement in high energy physics have led to a number of recent technical innovations, among which one of the most interesting is the

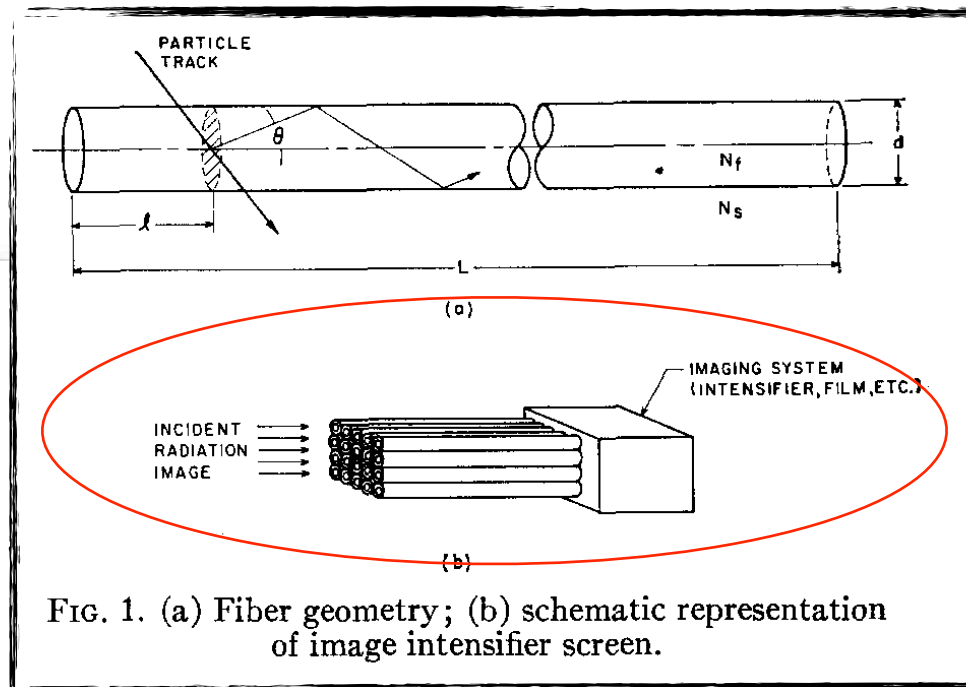
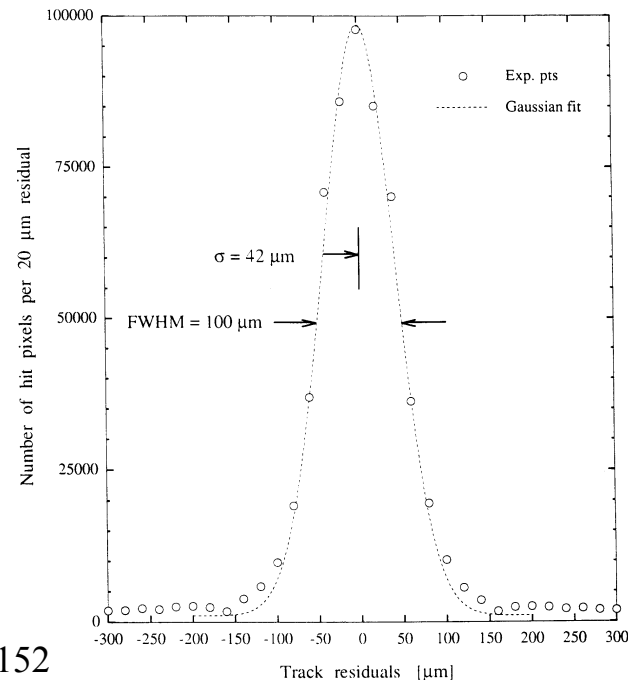
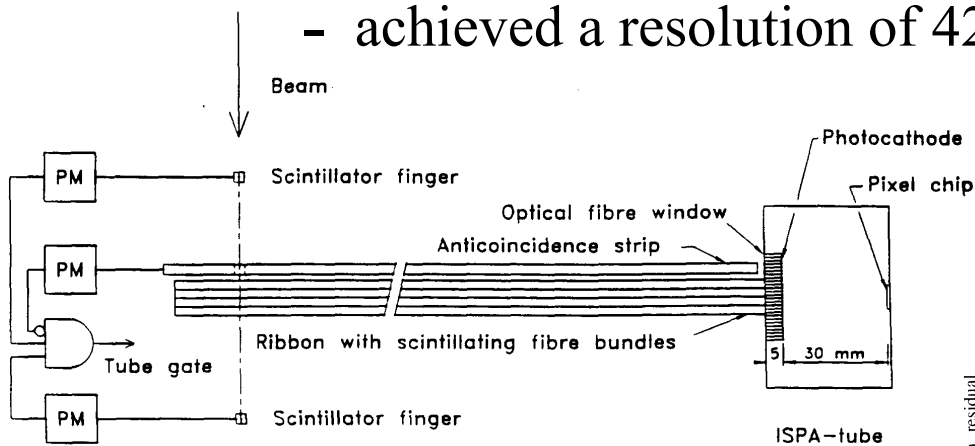


FIG. 1. (a) Fiber geometry; (b) schematic representation of image intensifier screen.

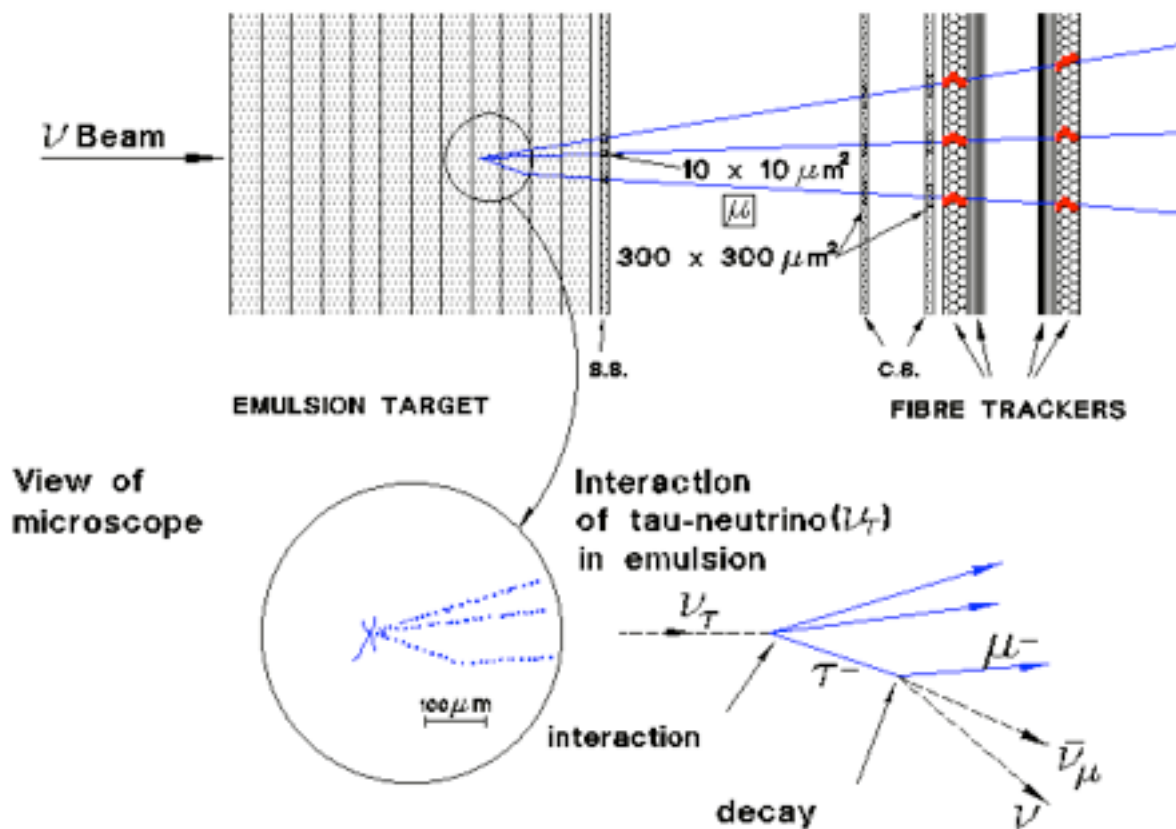
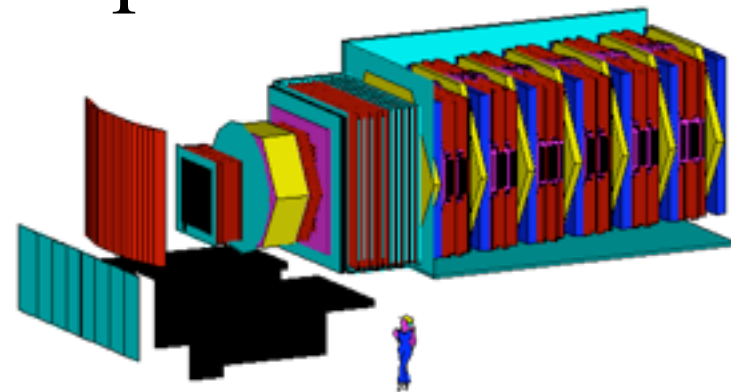
Selection of past and present SciFi trackers

- UA4: hodoscope of scintillation counters (~1984)
- ISPA (imaging silicon pixel array) experiment (~1994)
 - bundles of $60\mu\text{m}$ scintillating fiber target
 - achieved a resolution of $42\mu\text{m}$



Tracking in the CHORUS experiment

- Search for $\nu_\mu - \nu_\tau$ oscillations at CERN SPS (1994–1997)
- High resolution detection of τ leptons
⇒ emulsion detector
⇒ fiber tracker to find interaction points

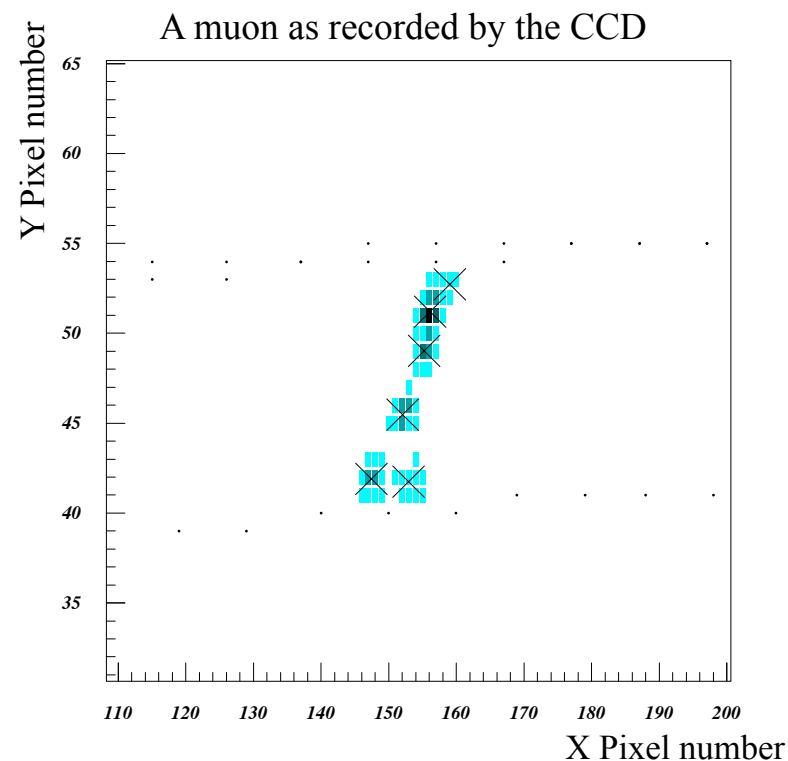
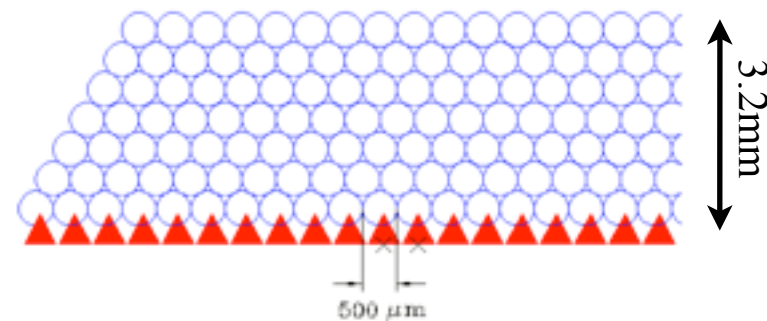


CHORUS fiber tracker

- Fiber tracker constraints and properties

- low occupancy; low rate
- 500 μm diameter fibers, arranged in 7 layers of length 2.3m
- 4 image intensifiers
- photo-detection with CCD
 - CCD: 228 \times 500 pixels of size 16 \times 23 μm^2
 - 4 pixels per fiber after demagnification

- Achieved a resolution of 350 μm



NIM A 344 (1994) 143
NIM A 367 (1995) 367

CHORUS: tracker R&D

NIM A 300 (1991) 53
NIM A 311 (1992) 31

- R&D for a vertex tracker to detect τ leptons
- 20 μm capillary fibers filled with liquid scintillator
- 2 \times 2 \times 150 cm^3 detector
- Achieved $\sim 15\mu\text{m}$ resolution with 5 GeV/c hadrons

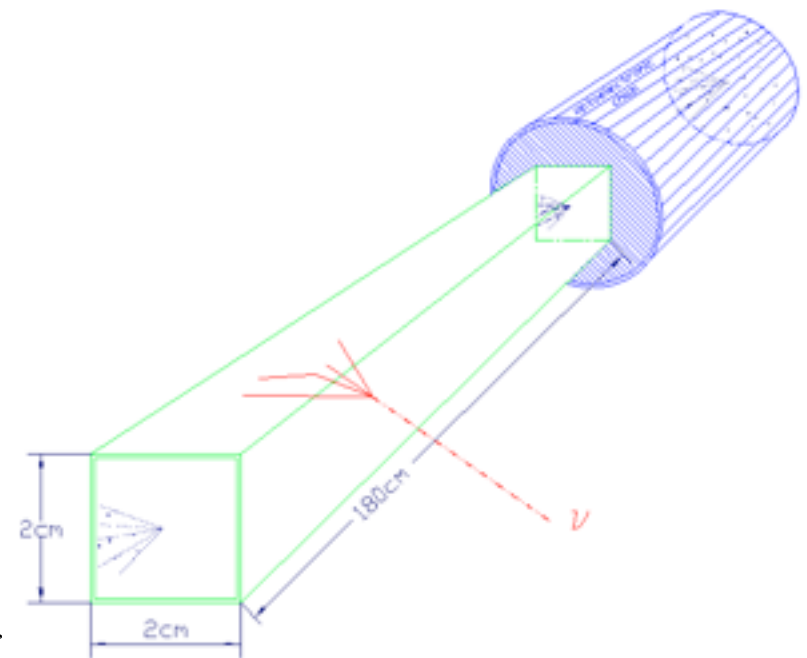
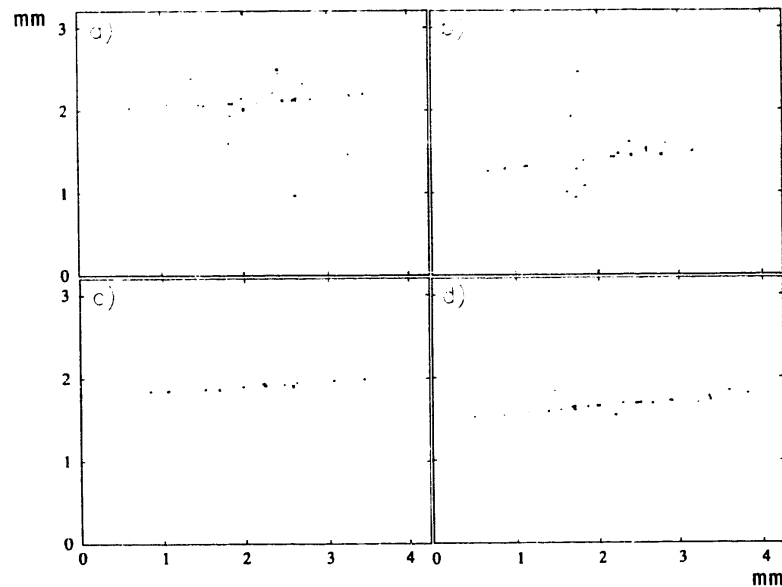
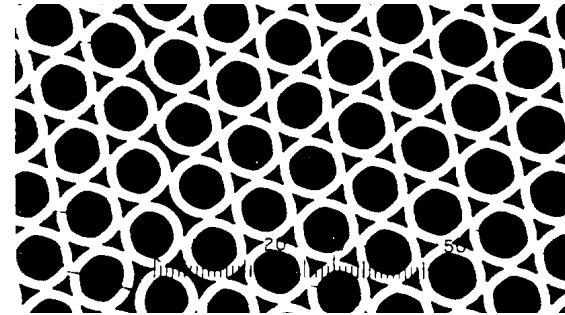
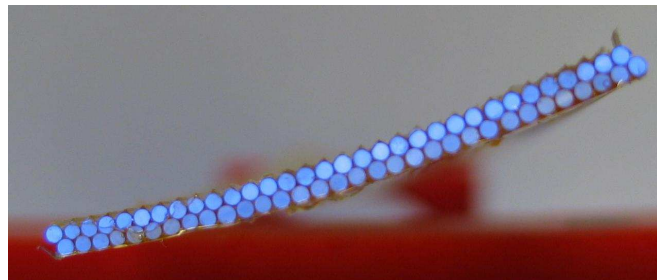


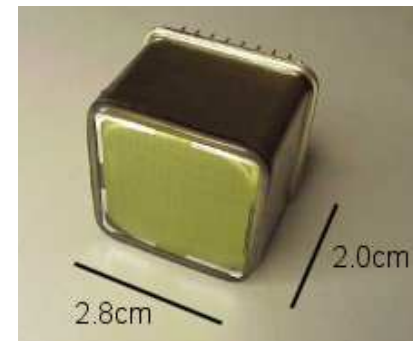
Fig. 4. Tracks produced by a 5 GeV/c hadron travelling at 12° with respect to the bundle axis: (a) using scintillating plastic fibres, no EMA; (b) using glass capillaries filled with PMP-doped IBP, no EMA; (c) using glass capillaries filled with PMP-doped IBP, with EMA; (d) using glass capillaries filled with PMP-doped MN, with EMA.

Selection of past and present SciFi trackers

- D0 scintillating fiber tracker
 - 4 cylindrical layers (80k fibers)
 - readout with Visible Light Photon Counter, operated at 6-8K
- COMPASS: fibre hodoscope
- HERMES recoil detector (HERA)
 - scintillating fiber tracker
 - readout with MAPMT



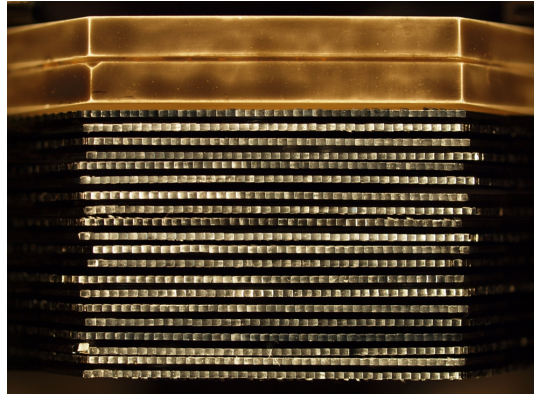
HERMES



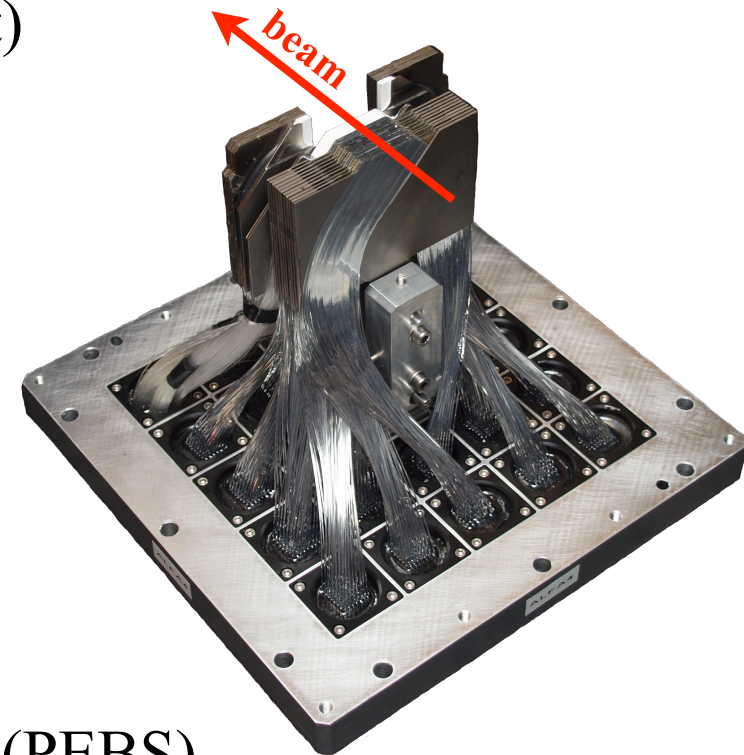
Selection of past and present SciFi trackers

- ATLAS ALFA (luminosity measurement)

- square fibers



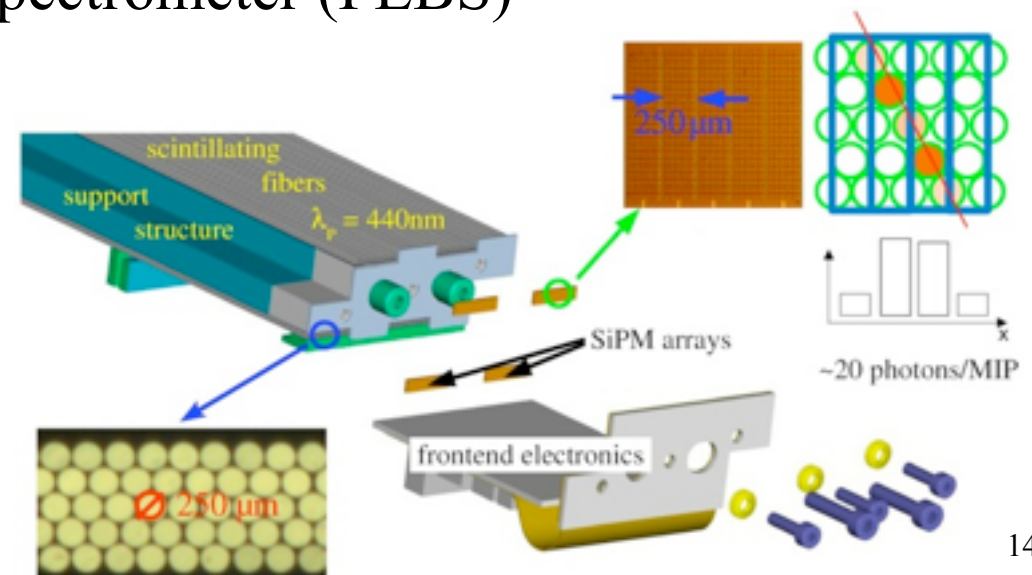
- readout with MAPMTs



- Positron Electron Balloon Spectrometer (PEBS)

- 250 μ m diameter fibers

- readout with SiPMs



Recent developments

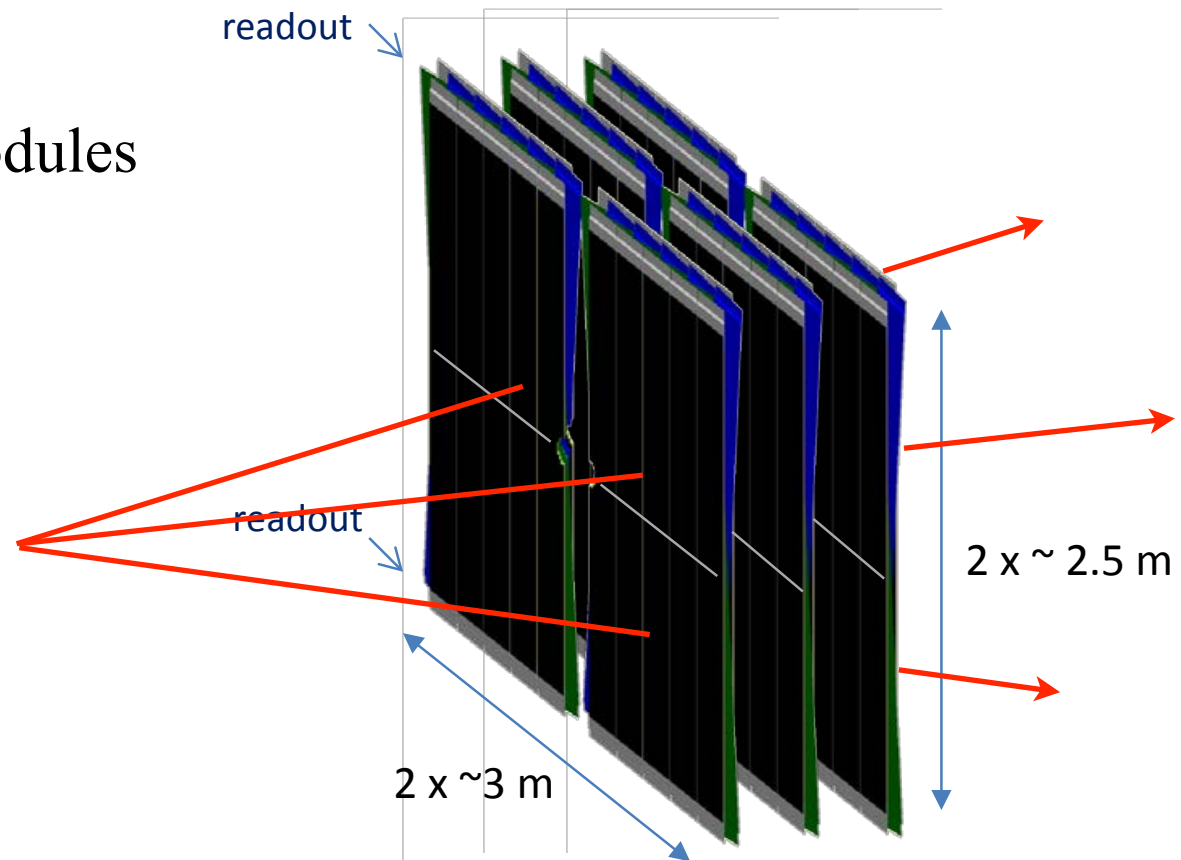
- Two selected topics:
 - A. constraints and requirements for detectors of large dimensions
 - B. radiation hardness of fibers and SiPMs

Large dimension fiber detectors

- Take the LHCb scintillating fiber tracker project as example

- Build large detector modules

- $(2 \times) 2.5 \times 0.52 \text{ m}^2$
- 13cm-wide fiber mats



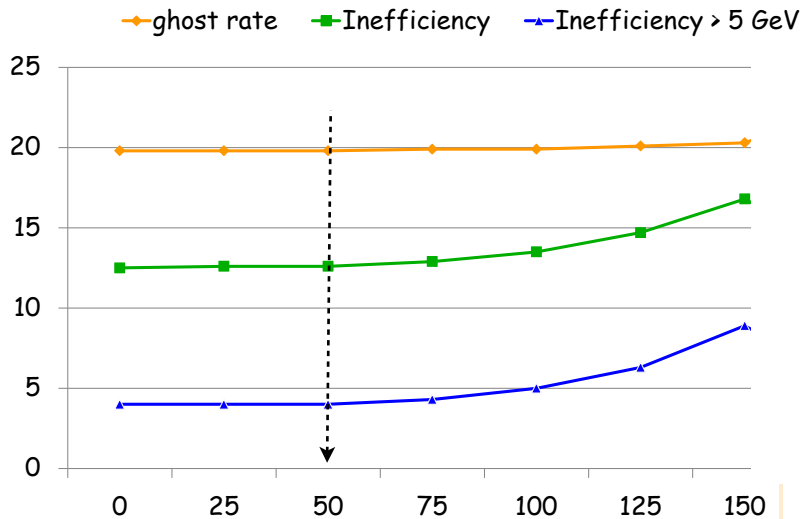
- Questions:

- how can the resolution be kept $< 100 \mu\text{m}$ over the whole surface of the detector?
- how can the S/N be kept high, even for hits at 2.5m from the photodetector?

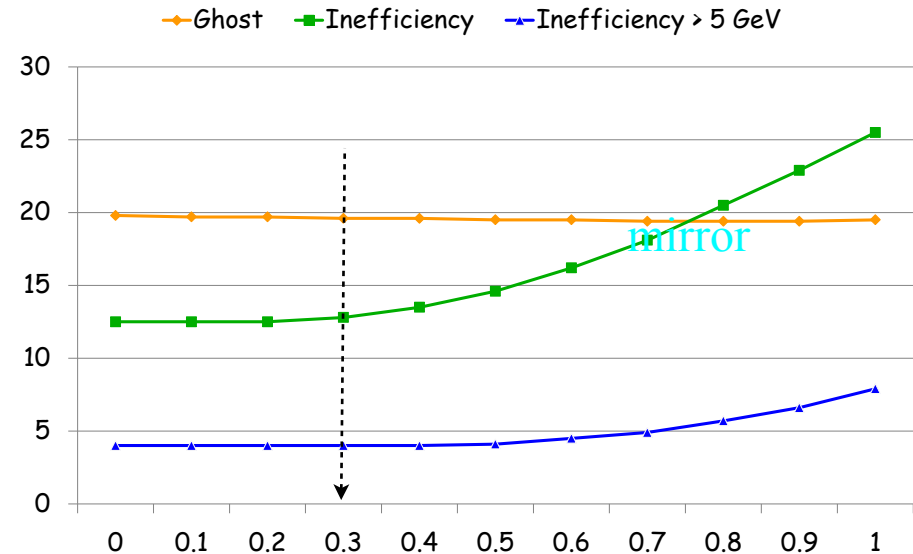
Mechanical tolerances

- Determine the tracking performance from simulation
 - inefficiencies for all and $>5\text{GeV}$ particles
 - ghost rate (also strongly influenced by occupancy)

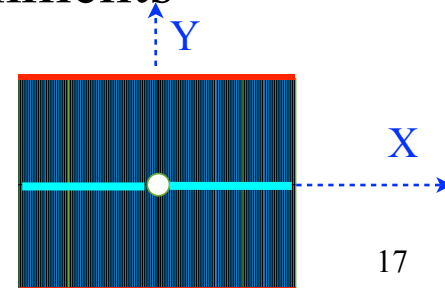
Misalignment in X



Misalignment in Z



- Performance degradation is seen for random misalignments
 - $50\mu\text{m}$ in X (perp. to fibers and particle trajectory)
 - $300\mu\text{m}$ in Z (perp to fibers and \sim parallel to trajectory)



Building large modules (R&D ongoing)

- Wind fibers on a large wheel (circum. $>2.5\text{m}$)
- Two methods currently under consideration to align the fibers
 - wheel with precision-threaded grooves
 - well established technique
 - fiber mats contain only fibers and glue
 - requires cleaning of the wheel
 - use coverlay™ patterned kapton sheets
 - use cheaper unthreaded wheel
 - the kapton sheet remains attached to the fiber mat
 - preserves precise alignment in following production steps
 - adds a little amount of material

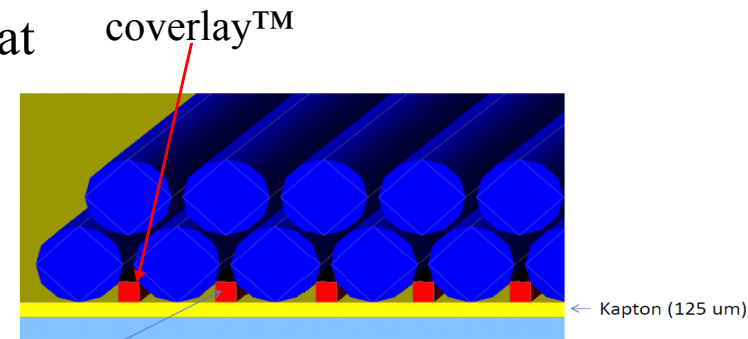
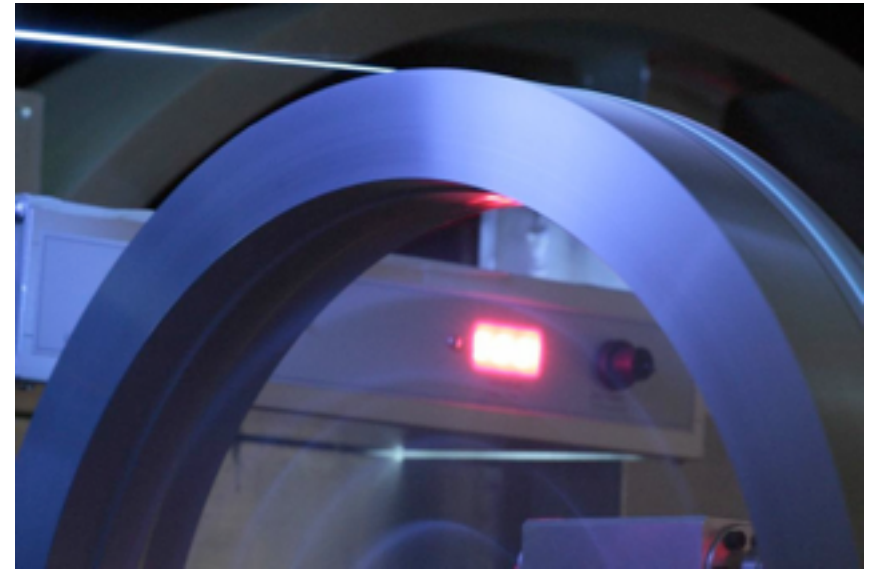
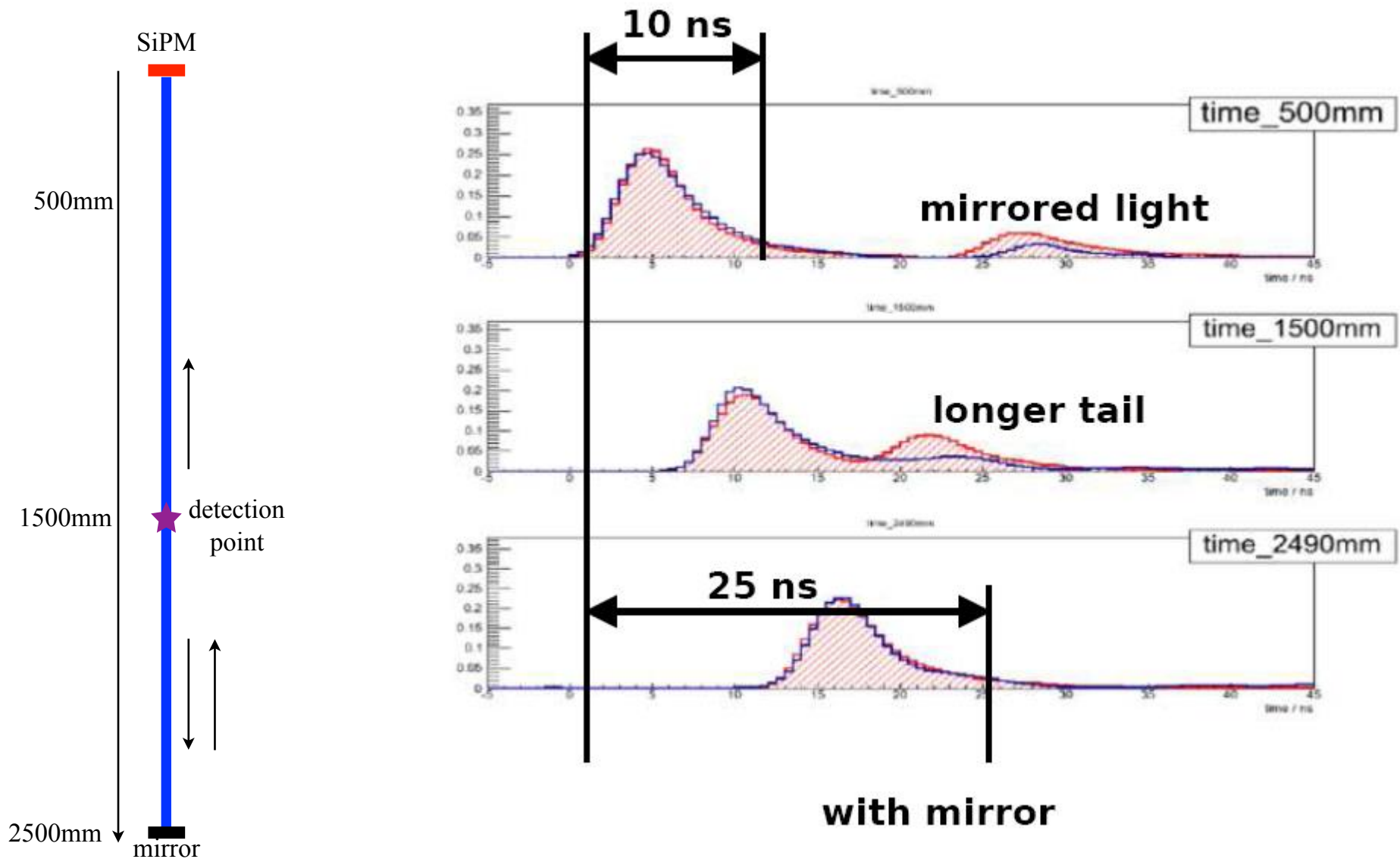


Photo-imagable coverlay (epoxy-like, DuPont)
Can be patterned with 10 um precision.

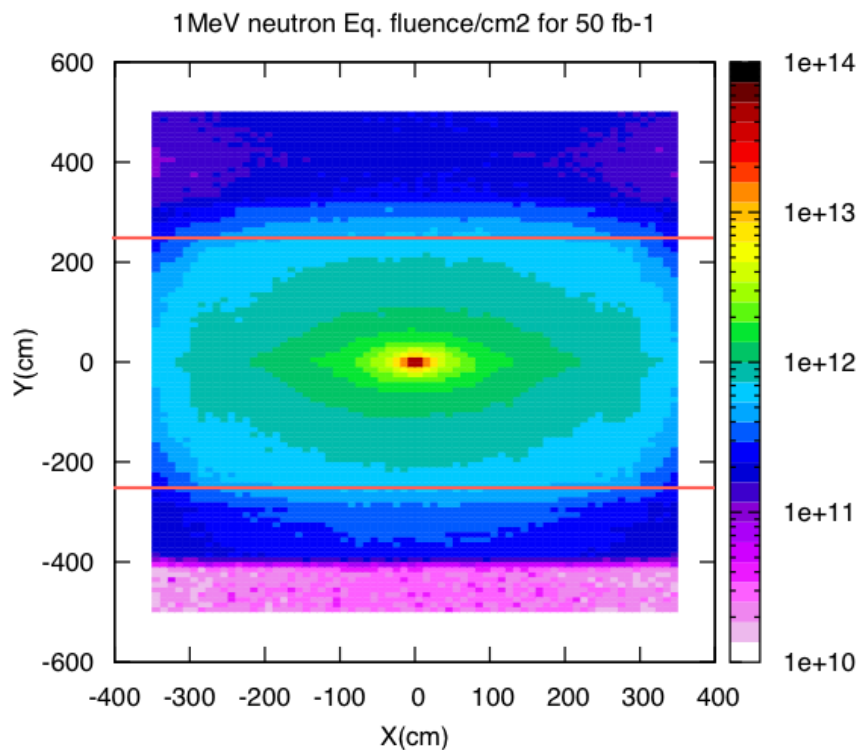
Pulse shape from long fibers



⇒ Use of a mirror is essential to recover signal from far end of the fibers
Achieved ~87% reflectivity with (simple) aluminized mylar foil!

Radiation hardness

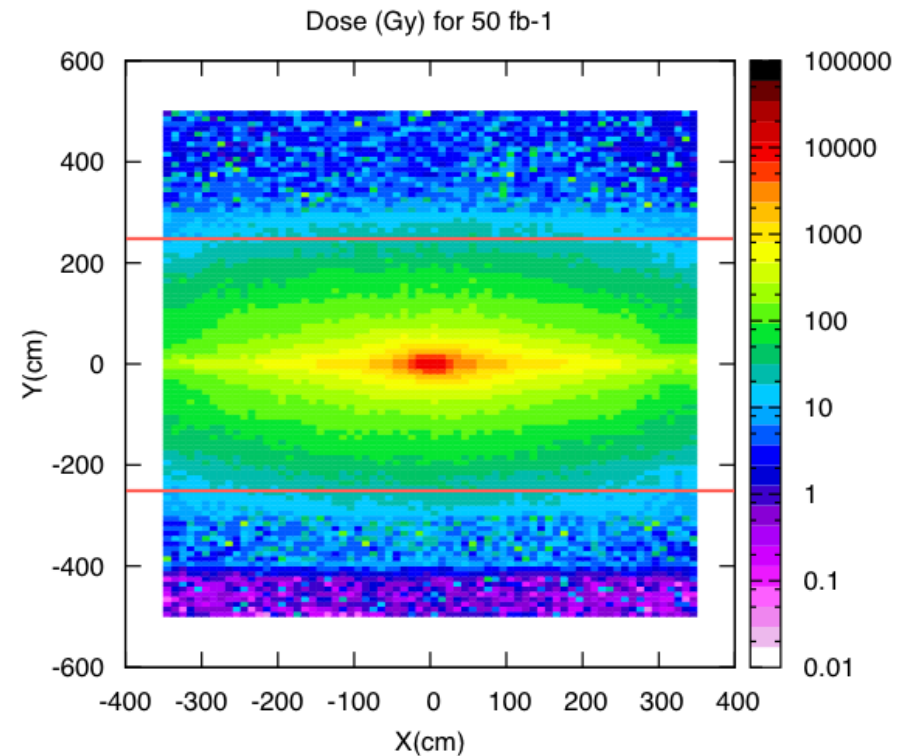
- In the LHC environment, radiation hardness is an issue
 - SiPMs are known to be sensitive to radiation damage
 - scintillating fiber ageing is also a potential problem



Neutrons

$\sim 10^{12}$ n/cm² (at $y=\pm 2.5$ m)

Factor ~ 2 reduction with shielding



Charged particles

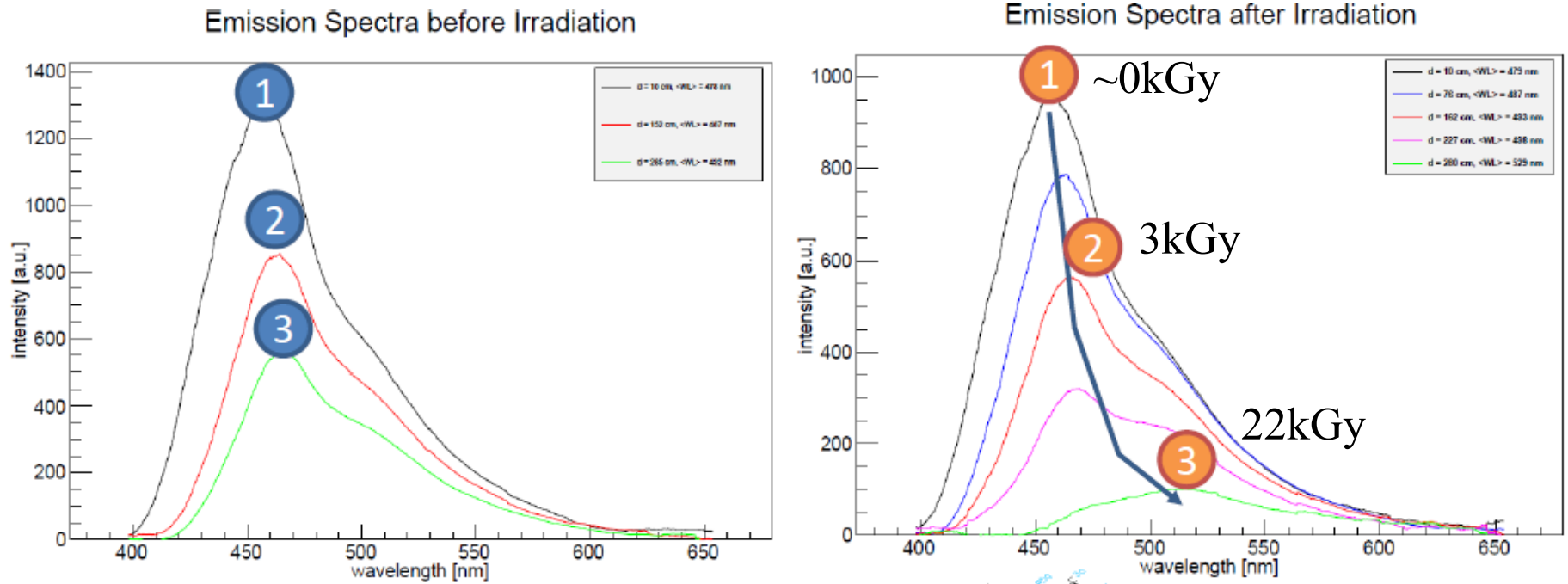
~ 35 kGy in hottest spots

Scintillating fiber radiation hardness

- Several radiation hardness studies are reported in the literature
 - difficult to draw a global and consistent picture
- Fibers have been tested again up to 60 kGy within the LHCb SciFi R&D
 - on double-cladding scintillating fibers (KURARAY SCSF-78, $\varnothing 250\mu\text{m}$)
- Tested effects:
 - a. photon spectrum after propagation through the fiber
 - b. attenuation length
 - c. scintillation process \Rightarrow not affected

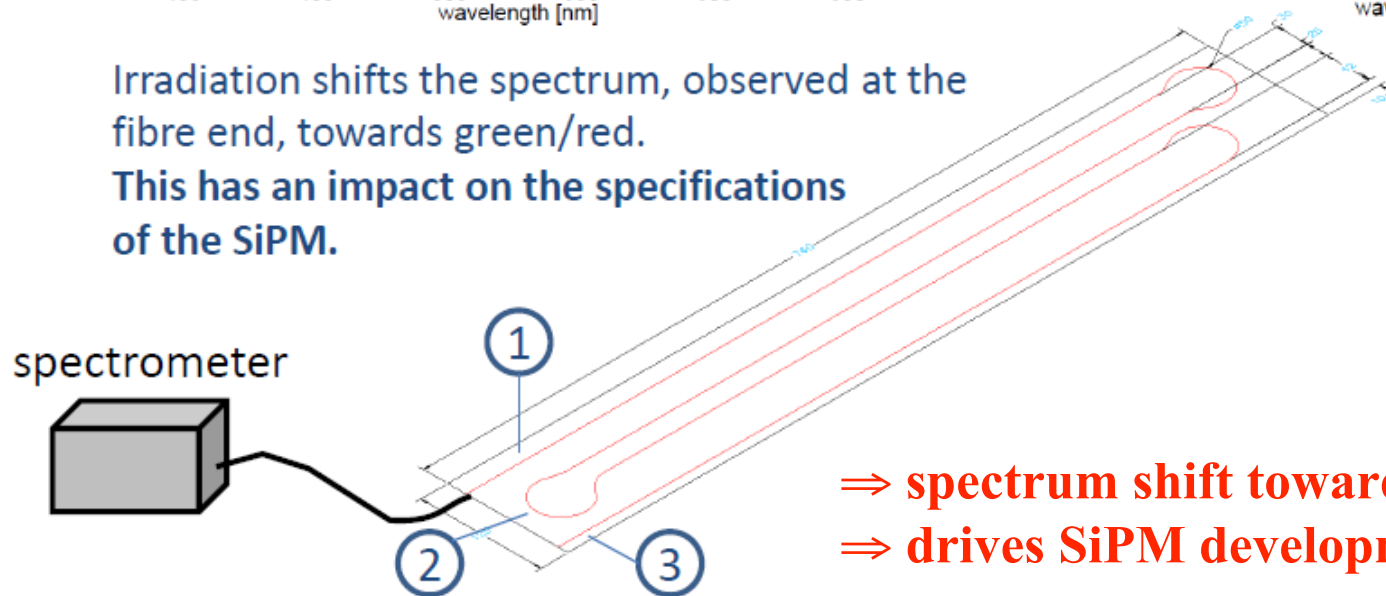


Fiber photon spectrum after irradiation



Irradiation shifts the spectrum, observed at the fibre end, towards green/red.

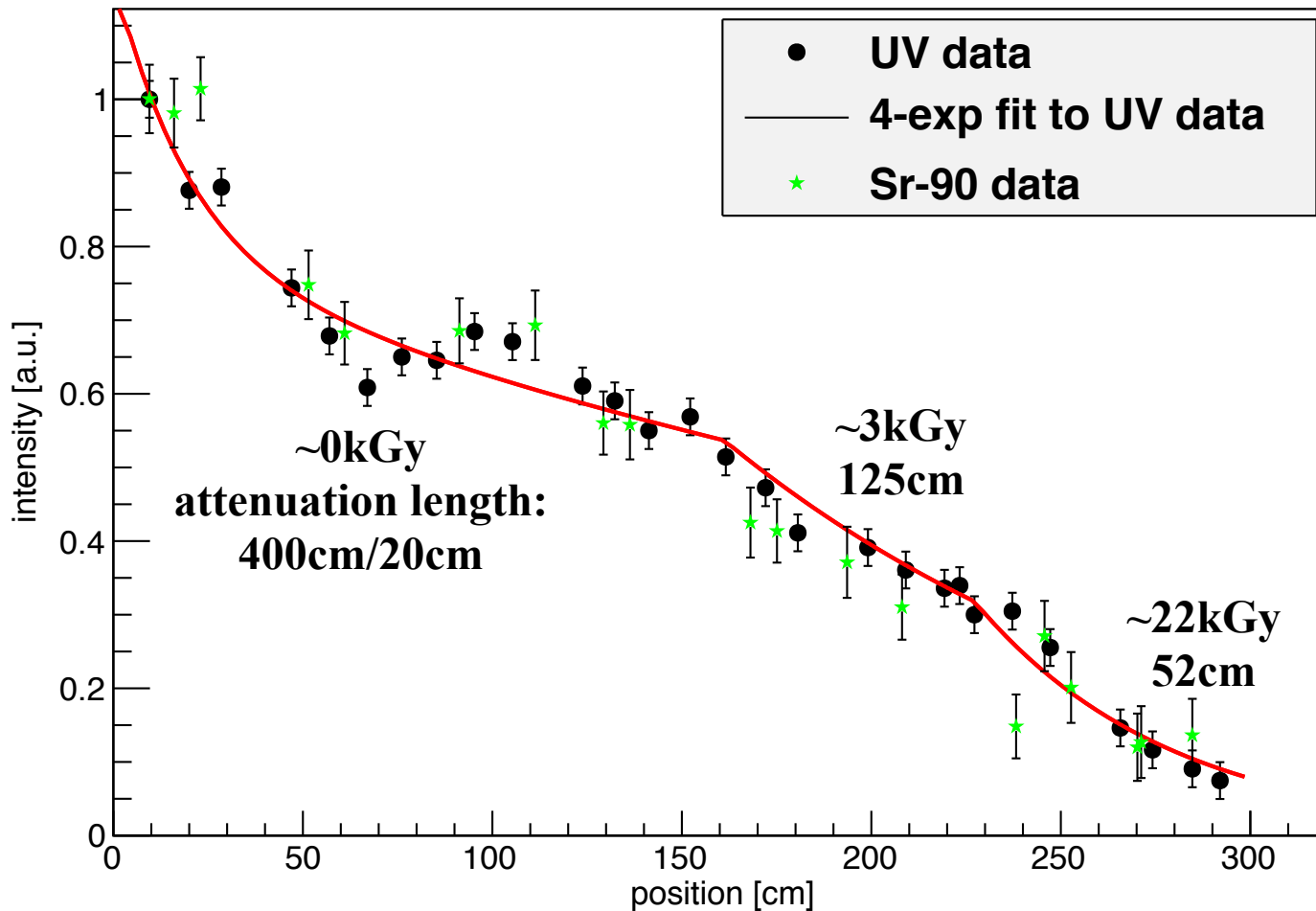
This has an impact on the specifications of the SiPM.



⇒ spectrum shift toward the green wavelength
 ⇒ drives SiPM development

Attenuation length of irradiated fibers

- Irradiated fibers with 24GeV/c protons (at CERN PS)



⇒ attenuation length is an issue for large irradiated detectors
⇒ also justifies the use of mirrors at the un-instrumented end

SiPM radiation hardness

- SiPMs are known to be sensitive to radiation damage
 - at the level of $\sim 10^{11}$ n_{equiv}/cm²
 - LHCb environment requires hardness up to $\sim 10^{12}$ n_{equiv}/cm²
- How can we then operate the SiPM at the LHC?
- The solution comes from three main axes:

1. shielding
⇒ delay the damage
2. cooling
⇒ reduce the primary (thermal) noise
3. SiPM technological improvements
⇒ e.g. addition of trenches between pixels to reduce cross talk

- Count noise as the rate of fake reconstructed clusters

SiPM noise studies

- The thermal noise is the primary source of noise
- The **noise cluster rate** f_C depends on
 - the primary noise frequency f_p (thermal noise)
 - temperature T (f_p is reduced by a factor 2 every 10°C)
 - neutron dose (f_p increases linearly with the dose)
 - pixel-to-pixel cross talk probability p_{x-talk}
 - after pulse probability p_{after}
 - integration and shaping time Δt (depends on electronics)
 - clustering algorithm A , which depends on selection thresholds

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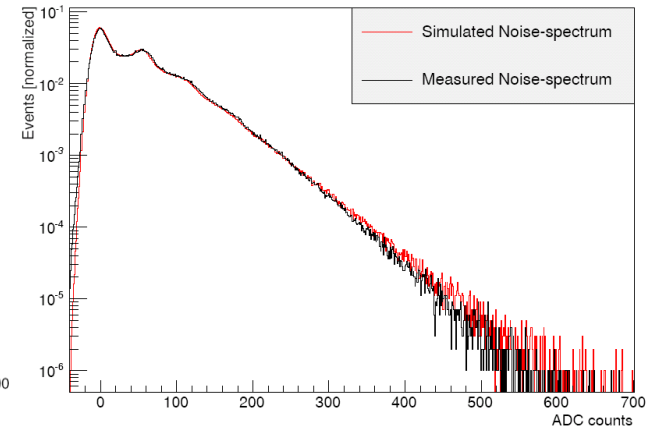
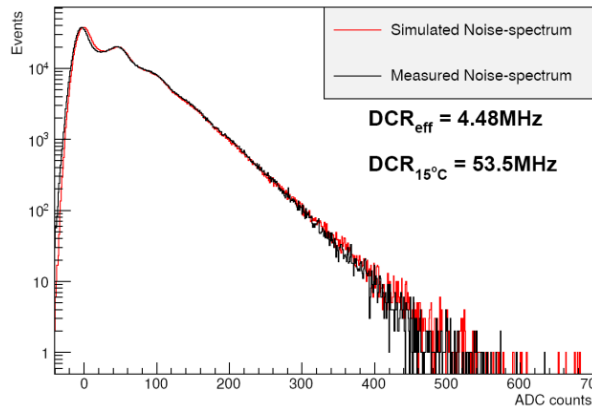
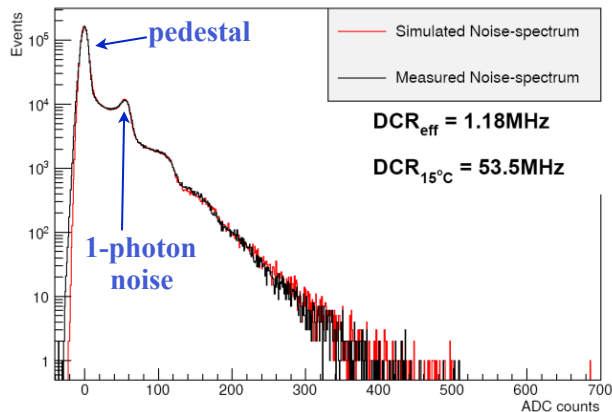
depend on SiPM technology

$$f_C = f \left(f_P(\Delta V, T, Dose), A(th_{seed}, th_{neigh.}, th_{sum}), p_{x-talk}(\Delta V), p_{after}(\Delta V), \int^{\Delta t} \right)$$

- This model can be tuned on measured data to make predictions for other conditions

Example: dark noise spectrum simulation

- Irradiation 8fb^{-1}
- $T = -40^\circ\text{C}$ $\xrightarrow{\text{change T only}}$ ➤ $T = -20^\circ\text{C}$ $\xrightarrow{\text{change dose and T only}}$ ➤ $T = -44^\circ\text{C}$
- Irradiation 8fb^{-1}
- Irradiation 50fb^{-1}
- Slow shaping
- Slow shaping
- Slow shaping



red: simulation

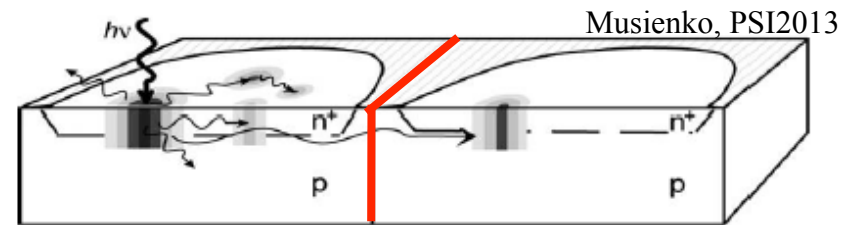
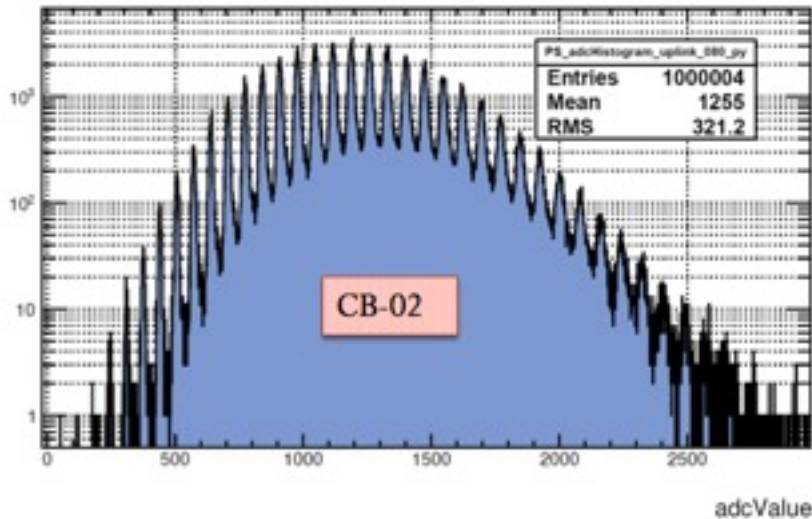
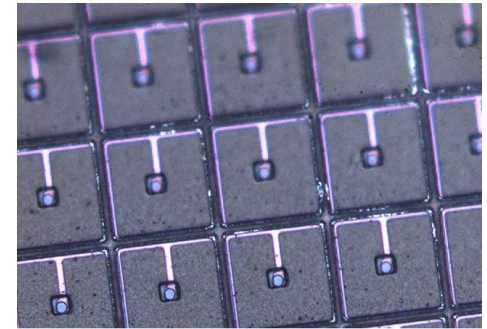
black: measured

Excellent predictive power \Rightarrow can be used to extrapolate to other conditions

In the case of LHCb, find that operating at -40°C is necessary

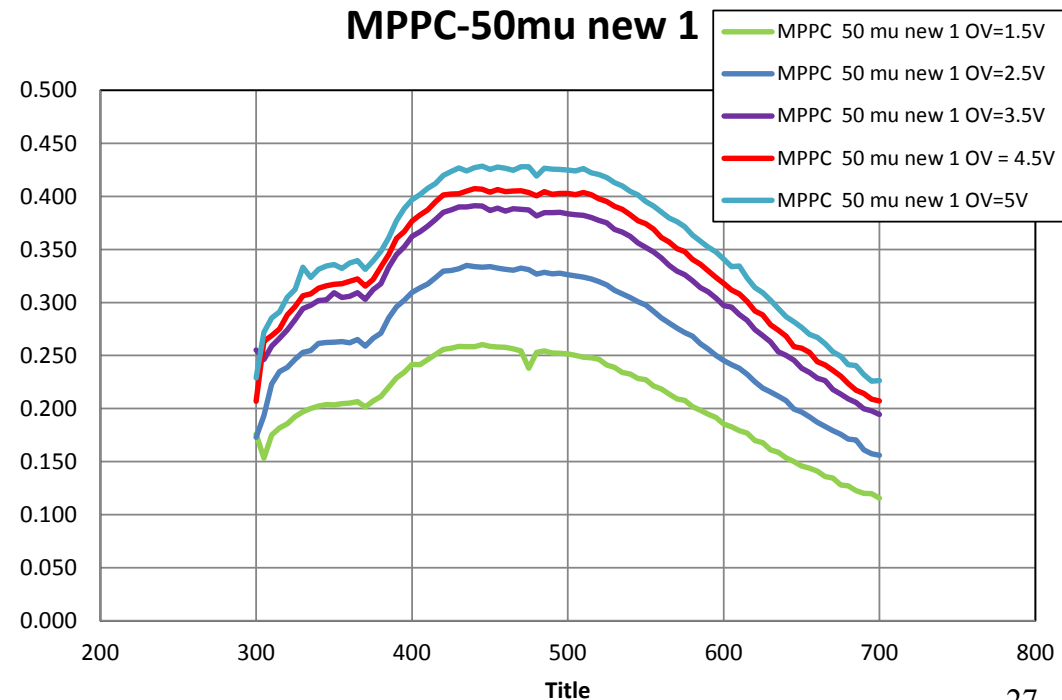
SiPM technological improvements

- Recent improvements on the detector layout:
 - increased geometrical factor
⇒ increased photon detection efficiency (PDE)
 - introduction of trenches between pixels
⇒ reduced optical x-talk



SiPM with trenches [from Hamamatsu, 2013]
 ⇒ high S/N
 ⇒ ~40 individual photon peaks!
 ⇒ high uniformity of the detector
 ⇒ ~flat spectral response over 430–520nm

MPPC-50mu new 1



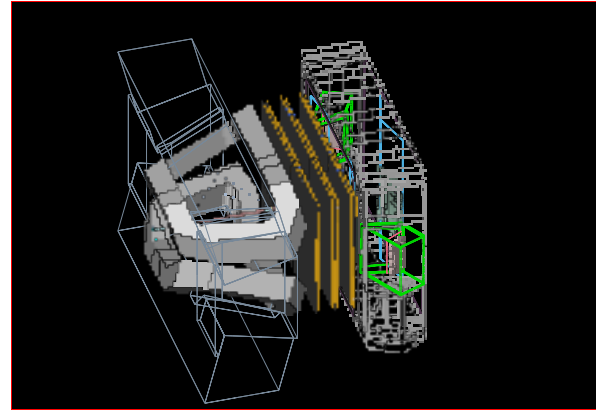
Summary of SciFi technology

- Scintillating fiber trackers using SiPM photodetectors are an interesting alternative to other technologies
 - resolution as good as Silicon strip detectors
 - fast detectors
 - big progress for operation in radiation environments
 - flexible geometry: various detector shapes are possible (plane, cylindrical, oblique cuts, etc...)
 - no high voltage (below 100V), no gas
 - cost mostly driven by length of the detector
 - for Silicon strip detectors, the cost goes as the instrumented surface
- But many aspects still at the stage of R&D ...

Prospects for future applications

- LHC experiment upgrades

- ATLAS ALFA
- LHCb tracker



- Linear Collider experiment (?)

- large surfaces too expensive for Silicon

- Balloon and satellite(?) experiments



- Medical applications

- portability and robustness of the hardware is an asset

Conclusion

- Scintillating fiber detectors have been around for some time
- In the past decade, developments in photodetectors allowed to build larger and more dense fiber tracker
- More recently, the SiPM technology has been improved for radiation hardness, noise reduction, and PDE
- Further improvements can be expected in the near future
- As a result, the scintillating fiber technology is likely to play an important role in future experiments!