Development of a new class of scintillating plastic fibres

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Outline

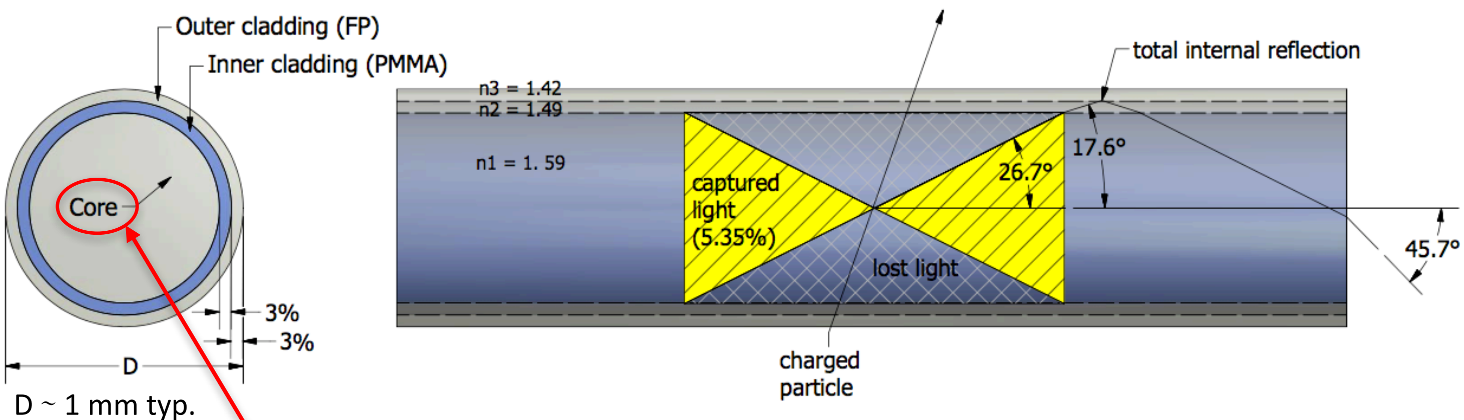
- Scintillating plastic fibres
- The LHCb Scintillating Fibre Tracker
- New fibre development – NOL fibres
- NOL prototype fibre performance
- Summary and outlook

Plastic scintillating fibres

Plastic (organic) scintillators are aromatic molecules (hydrocarbon compounds)

Properties: 10000 photons per MeV, low Z, low density (1 g/cm^3), fast (ns decay times), inexpensive, medium radiation hard

Scintillating fibre:



Active material:
- Solvent (e.g. Polystyrene)
- Activator (e.g. p-Terphenyl) 1-2%
- Wavelength shifter (WLS) < 0.1%

Applications in particle physics: tracking (fibre tracker), calorimetry, active targets (trigger, vertexing) – in combination with modern photodetectors (e.g. SiPMs)

LHCb detector upgrade

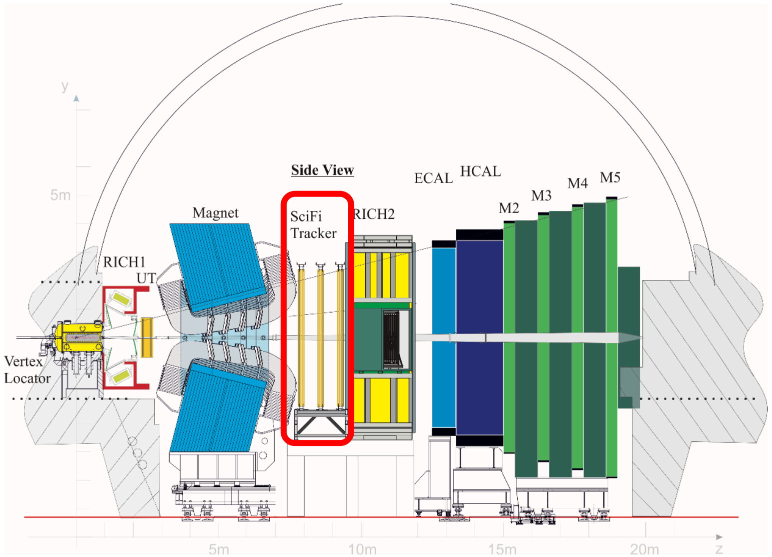
LHCb detector upgrade during LHC LS2 (2019-2020)

Main changes:

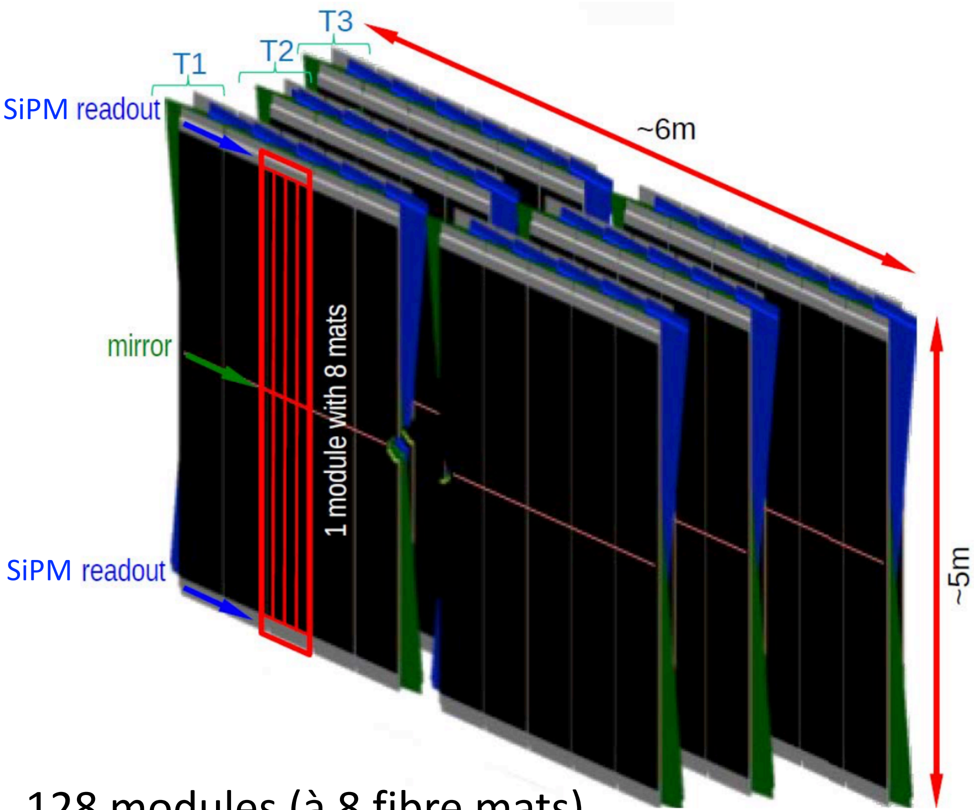
- Luminosity $L_{inst} = 2x10^{33}\ cm^{-2}s^{-1}$ (5x the current) → Goal 50 fb^{-1}
- Full software trigger (40 MHz)
- 40 MHz electronics read-out

New tracking system:

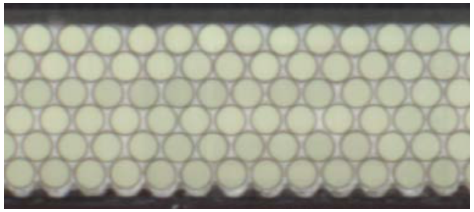
- New Velo, Si-pixels
- New Upstream Tracker (UT), Si-strips
- New Scintillating Fibre (SciFi) Tracker



LHCb SciFi tracker



128 modules (à 8 fibre mats)

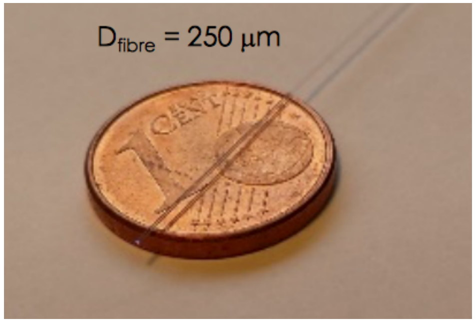


6 fibre layers per mat

- → 340 m^2 total area
- → 3 stations with 4 layers (XUVX)
- → 11,000 km of scintillating fibre
  (Kuraray SCSF-78, ⌀ = 250 µm)
- → 4096 custom-made SiPMs
- → 524k readout channels

Requirements:

- Hit efficiency ~ 99%
- Spatial resolution < 100 µm
- X/X0 ≤ 1% per detection layer
- 35 kGy close to the beam pipe

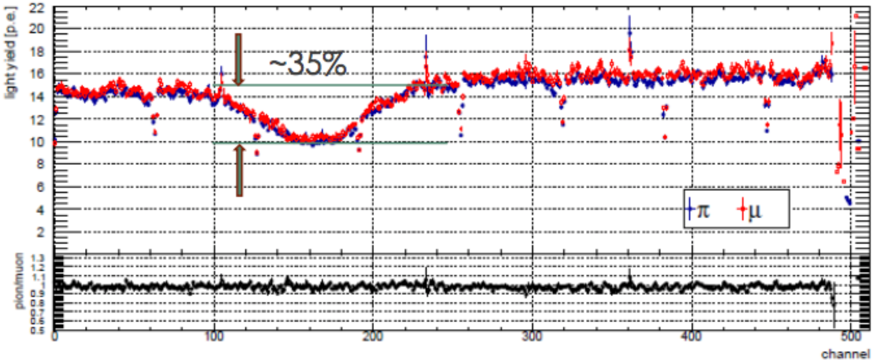


Motivation for fibre R&D

Challenges for scintillation detectors in current and future HEP experiments

- High radiation → radiation tolerant detectors
- High rate → fast detectors

Scan across one fibre mat (@ 2 cm from mirror) after irradiation with the expected dose profile



Finally about 35% light yield drop.
10 p.e. is the limit for optimum efficiency.

e.g. LHCb SciFi tracker

- 35 kGy ionizing dose on fibres in the central region after 50 fb^{-1}
  → loss of fibre transparency
  → less signal → lower efficiency
- 40 MHz readout
- Other upgrades during LS3, LS4 ???

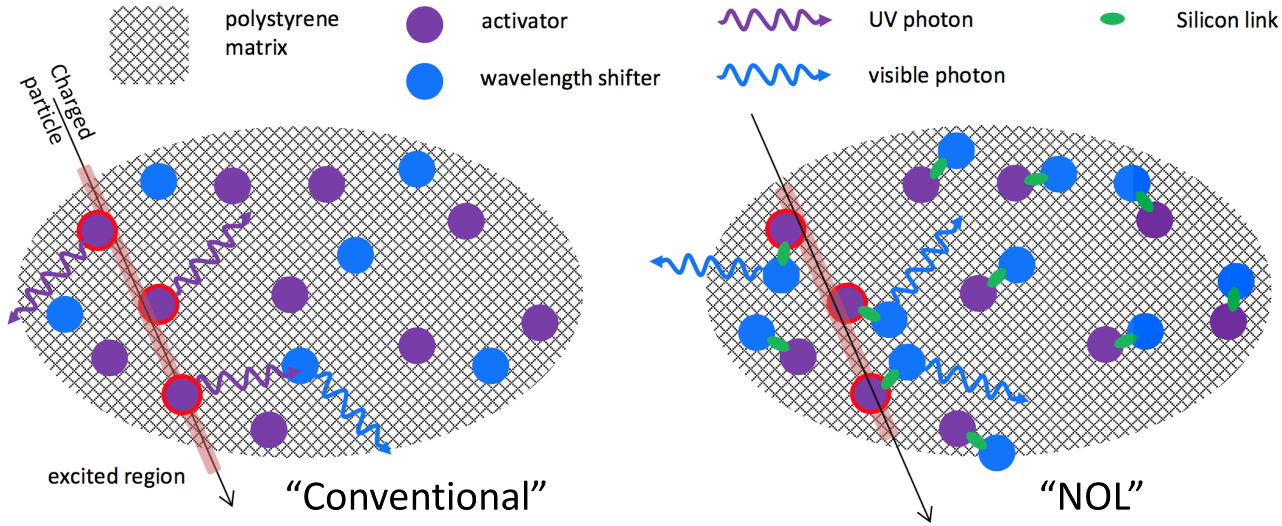
Can we improve the initial fibre performance (mainly the light output) to start with a better fibre in the beginning?

- Energy loss dE/dx is given
- Fibre construction, i.e. cladding, no suitable material with $n < 1.42$
- Activation and wavelength conversion → NOL idea

The NOL idea

S.A. Ponomarenko et al., Nature Sci. Rep. 4 (2014) 6549

NOL: Nanostructured Organo-silicon Luminophores

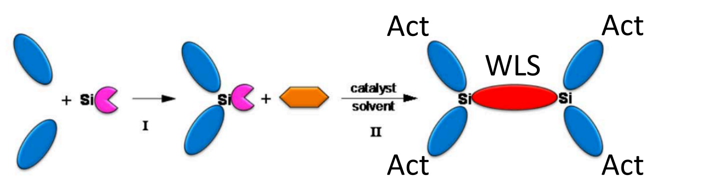


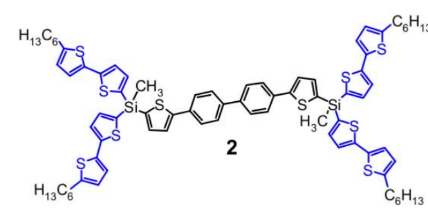
Activator and WLS are chemically coupled using silicon links

→ Non radiative energy transfer (Förster mechanism)

→ Faster and more efficient

→ Higher light yield





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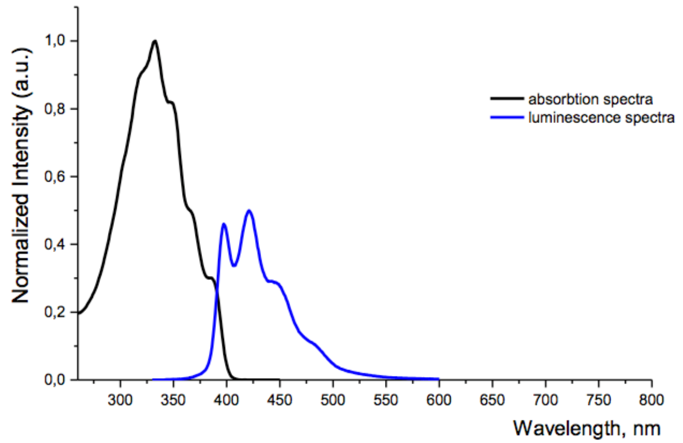
NOL fibres

Applying the NOL idea to fibres puts some constraints on the content of material components

- **Activator content ~ 1-2%**: efficient energy transfer from solvent to activator and high light yield (Förster energy transfer)
- **WLS content < 1000 ppm:** avoid large self absorption (incomplete Stokes shift) and short attenuation length, should be fast and efficient (high QE)
- **Emission in the blue to green wavelength region** to match photodetector's PDE
- NOLs typically have an activator to wavelength ratio of 4/1 or 6/1 → **non-NOL activator has to be added and NOL serves as efficient and fast spectral shifter**

Components and contents need to be carefully selected and adjusted! The used materials must be of high purity!

NOL 11

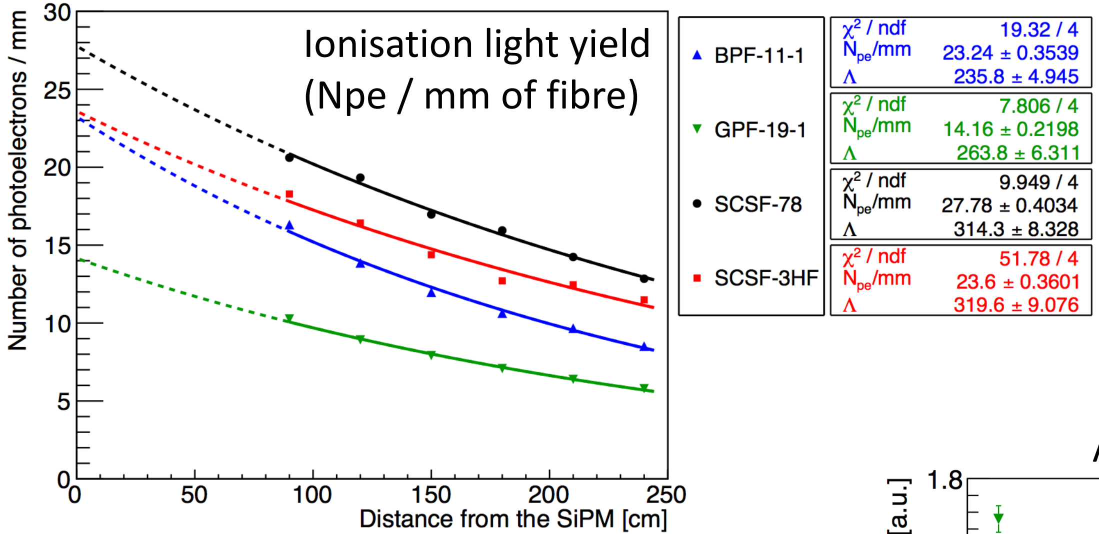


NOL fibre R&D among 3 institutes/companies

- Kuraray CO., Japan
- CERN, Switzerland
- ISPM, Russian Academy of Sciences, Russia

NOL prototype fibre performance

O. Borshchev et al., 2017 JINST 12 P05013



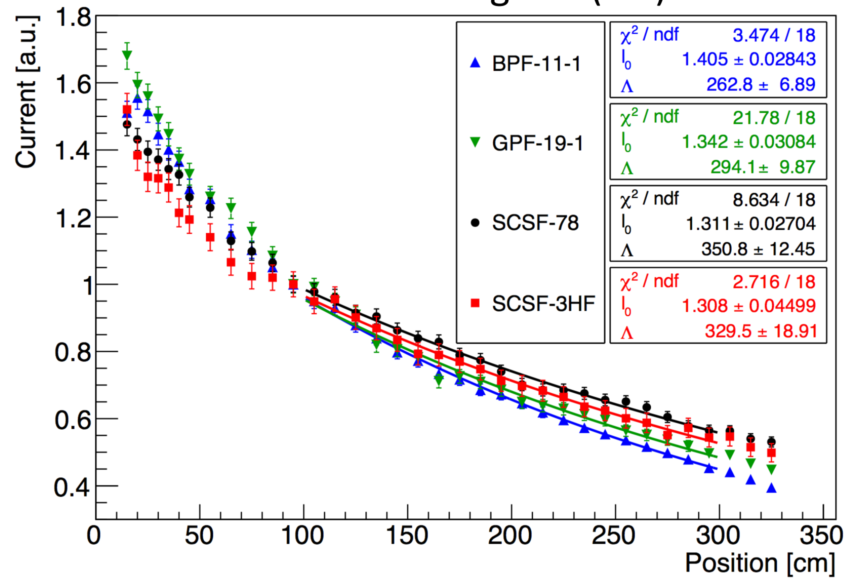
Best blue NOL prototype fibre

Best green NOL prototype fibre

Best blue standard fibre

Best green standard fibre

Attenuation length Λ (cm)

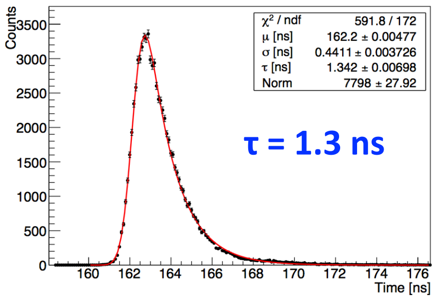


- After 8 iterations NOL fibres clearly improved but still a bit behind in terms of light yield and attenuation length
- 250 cm < Λ(NOL) < 300 cm
  Λ(standard) > 300 cm
- **Self absorption, i.e. choice of materials, contents and purity are key issues**

NOL prototype fibre performance

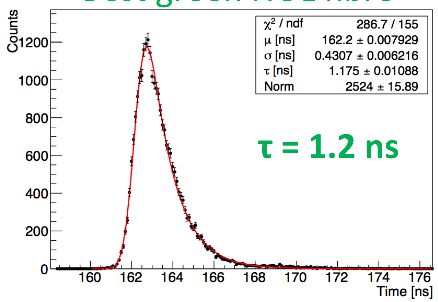
O. Borshchev et al., 2017 JINST 12 P05013

Best blue NOL fibre



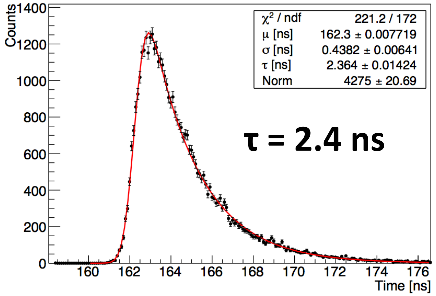
(a) BPF-11-1

Best green NOL fibre



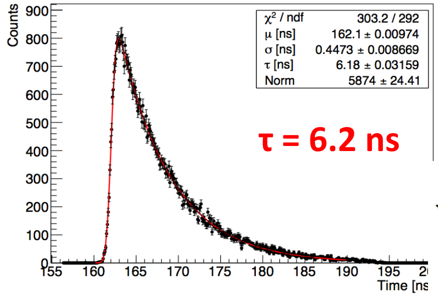
(b) GPF-19-1

Best blue standard fibre



(c) SCSF-78

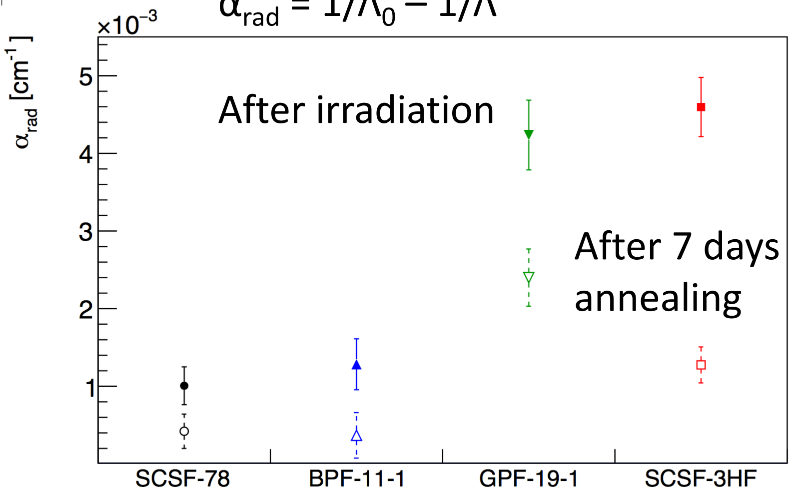
Best green standard fibre



(d) SCSF-3HF

Decay time: NOL fibres are almost a factor 2 (6) faster than the best blue (green) standard fibres, which makes them already very interesting for time critical applications!

Add. attenuation coefficient
$\alpha_{rad} = 1/\Lambda_0 - 1/\Lambda'$



Radiation hardness (tested with X-rays to a dose of 1 kGy):

- Damage is as expected on a level comparable to reference fibres, green fibres more effected
- Hadron irradiations are planned at CERN PS

Summary and outlook

- Current and future HEP experiments impose big challenges on scintillation based detectors, e.g. LHCb SciFi tracker composed of 11000 km of scintillating fibre.
- One way to increase the lifetime of such detectors in high rate and harsh radiation environments is to improve their intrinsic performance (high light yield, short decay time).
- The NOL fibre development is based on the coupling of activator and wavelength shifter using silicon links (→ fast and efficient).
- NOL fibres still have deficits in attenuation length and light yield. Both blue and green NOL fibres show very short decay time constants in the order of 1 ns (new record).
- We have ideas to further improve the performance (optimisation of luminophore concentrations, materials and production process). Goal is at least 20% higher light yield than standard fibres.

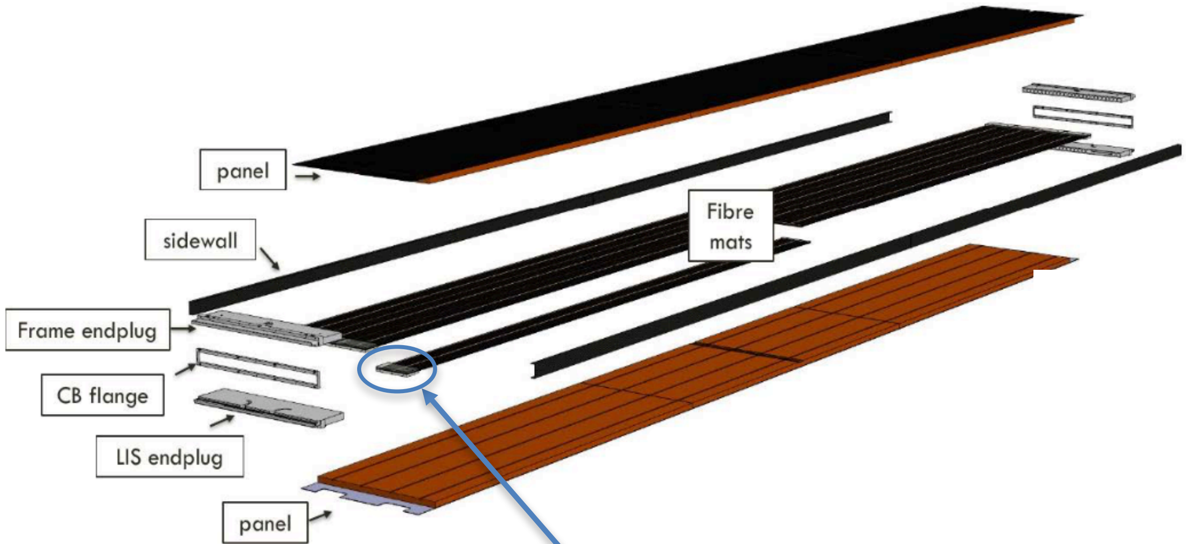
Back-up slides

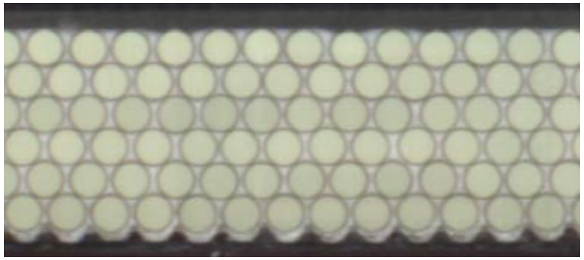
LHCb SciFi tracker

128 modules in total

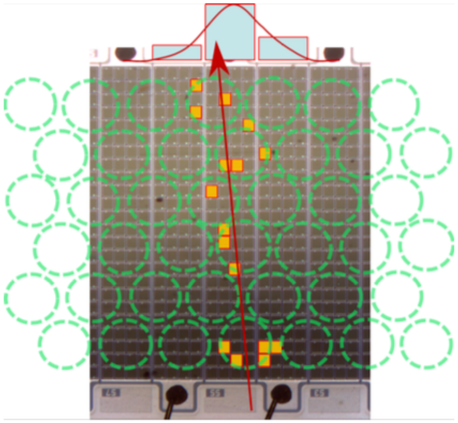
1 module (5 x 0.5 m^2)

- 8 fibre mats
- 2 x 16 SiPMs
- 2 x 32 PACIFIC ASICs





6 fibre layers per mat

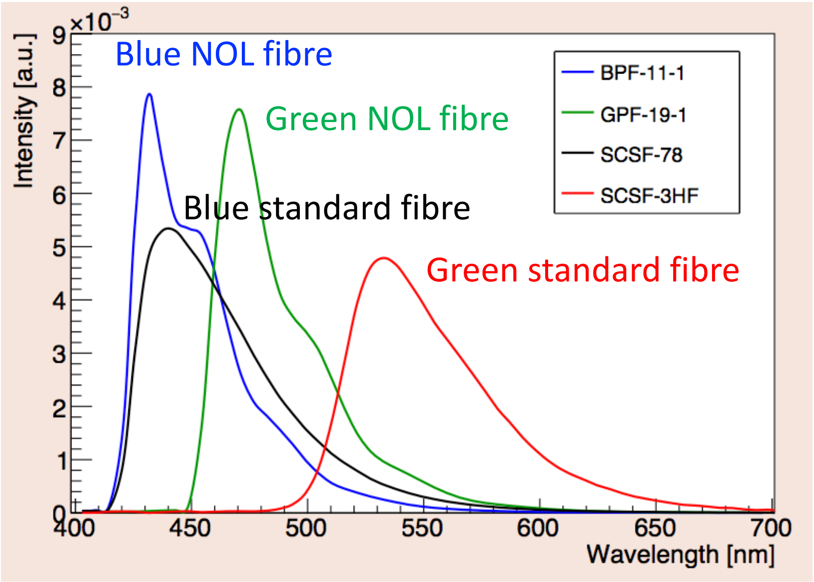


16-20 photo-electrons per 6-layer mat

NOL prototype fibre performance

O. Borshchev et al., 2017 JINST 12 P05013

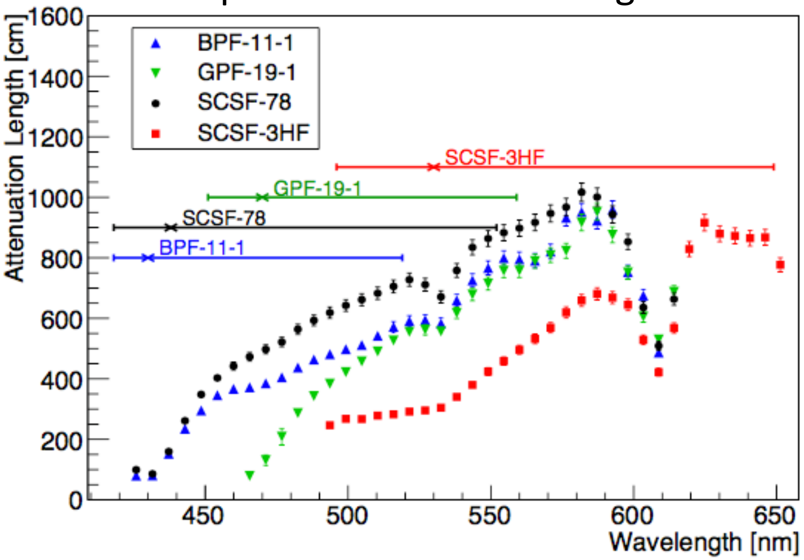
Emission spectra (@ 15 cm from excitation point)



Peak wavelengths:

- Blue NOL: 430 nm
- Green NOL: 470 nm
- Blue standard: 440 nm
- Green standard: 530 nm

Spectral attenuation length

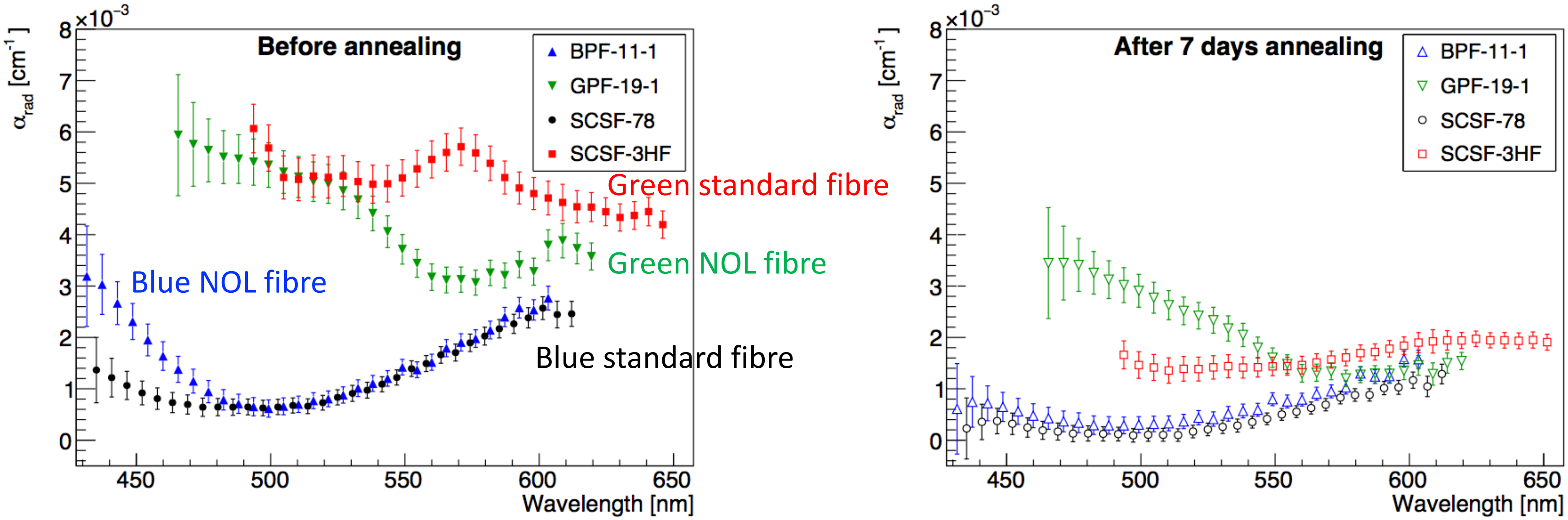


- Longer wavelengths are less attenuated
- Minima: excitation of PS vibration levels

NOL prototype fibre performance

O. Borshchev et al., 2017 JINST 12 P05013

Additional attenuation coefficient after X-ray irradiations (1 kGy dose)



Resistance to X-rays depends on chosen dyes.