LHCb SciFi

Upgrading LHCb with a Scintillating Fibre Tracker

15th Vienna Conference on Instrumentation
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Lukas Gruber
CERN, Switzerland

On behalf of the LHCb SciFi Tracker Group

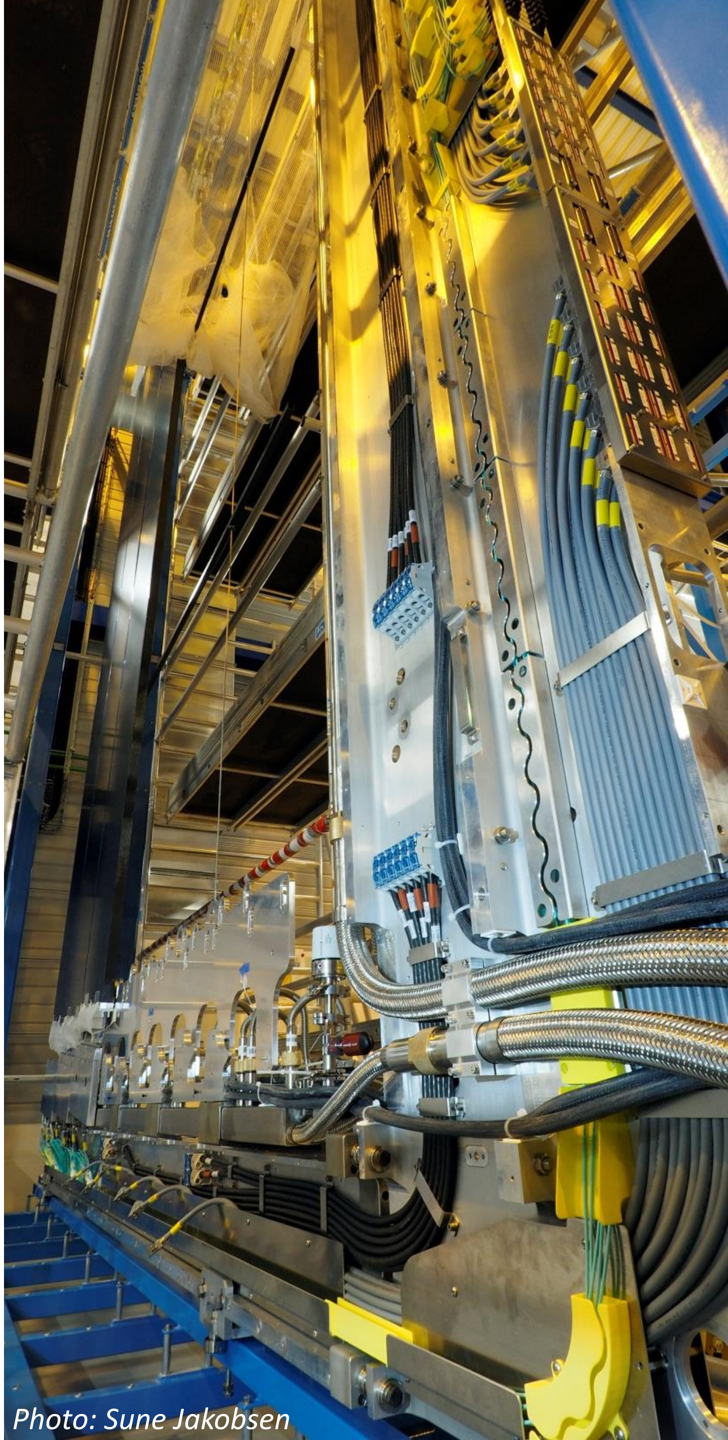


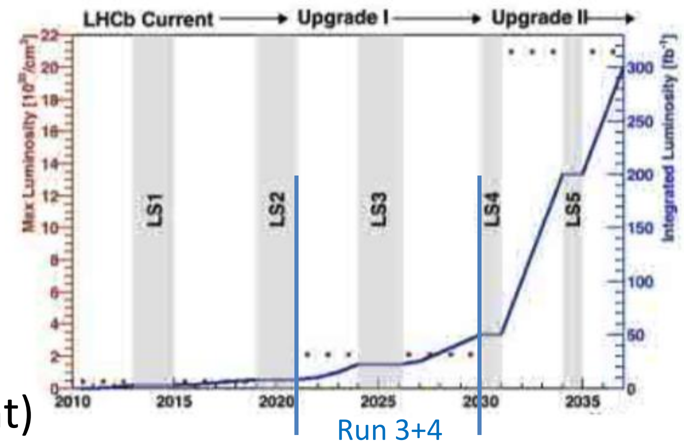
Photo: Sune Jakobsen

Outline

- LHCb experiment upgrade during LHC LS2
- The LHCb Scintillating Fibre (SciFi) Tracker
- Detector components production and performance
- Fibre R&D for future upgrades
- Summary

LHCb detector upgrade

- LHCb is optimized for heavy flavour physics. It has a forward geometry and features very precise vertexing and tracking.
- **LHCb detector upgrade during LHC LS2 (2019-2020)**



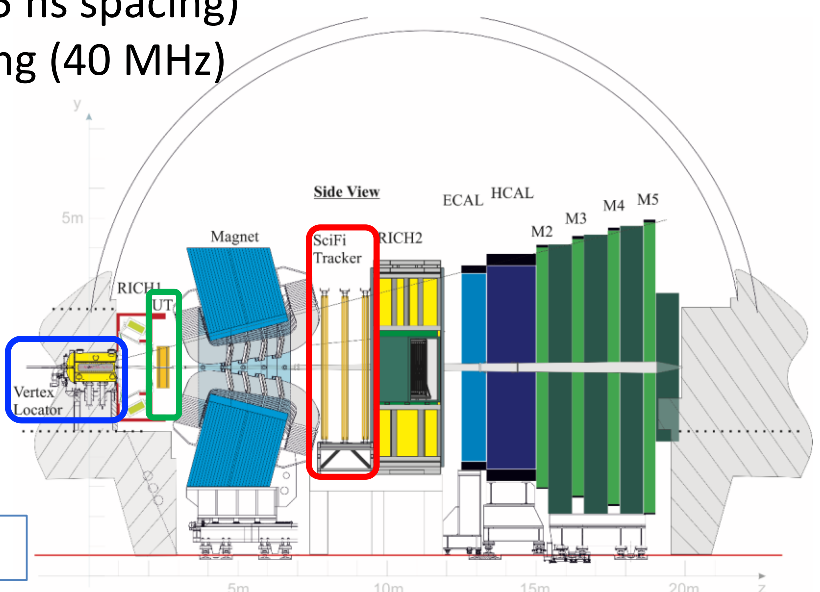
LHCb-PUB-2018-009

Main changes:

- Inst. Luminosity $L_{inst} = 2\times10^{33}\ cm^{-2}s^{-1}$ (5× the current)
  - Goal increase statistics (50 fb^{-1} over 10 years)
- 40 MHz trigger-less read-out electronics (25 ns spacing)
- Full software trigger for every bunch crossing (40 MHz)
  - Event selection at the CPU farm

New tracking system:

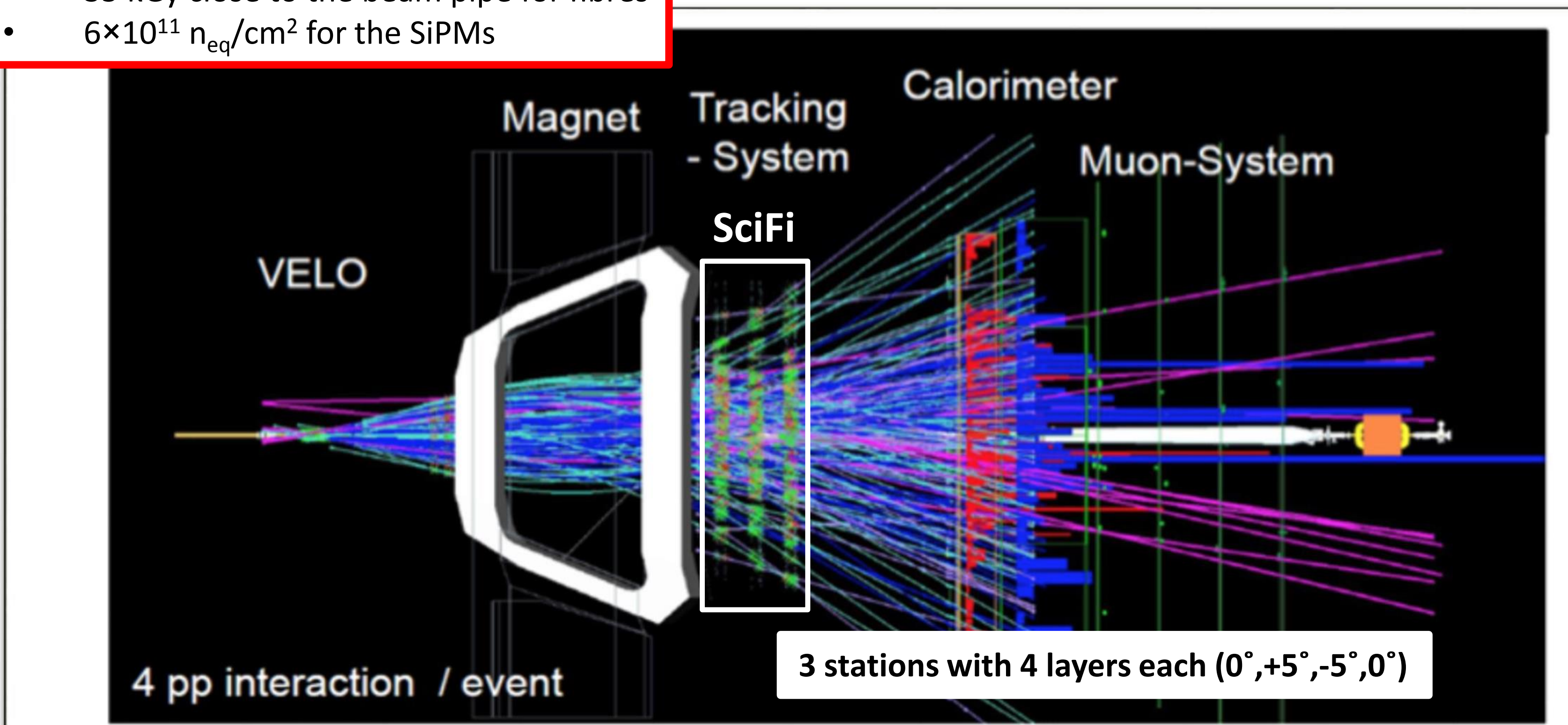
- New VELO, Si-pixels
- New Upstream Tracker (UT), Si-strips
- New Scintillating Fibre (SciFi) Tracker



More info on LHCb VELO Upgrade: Talk by P. Collins, VCI 2019

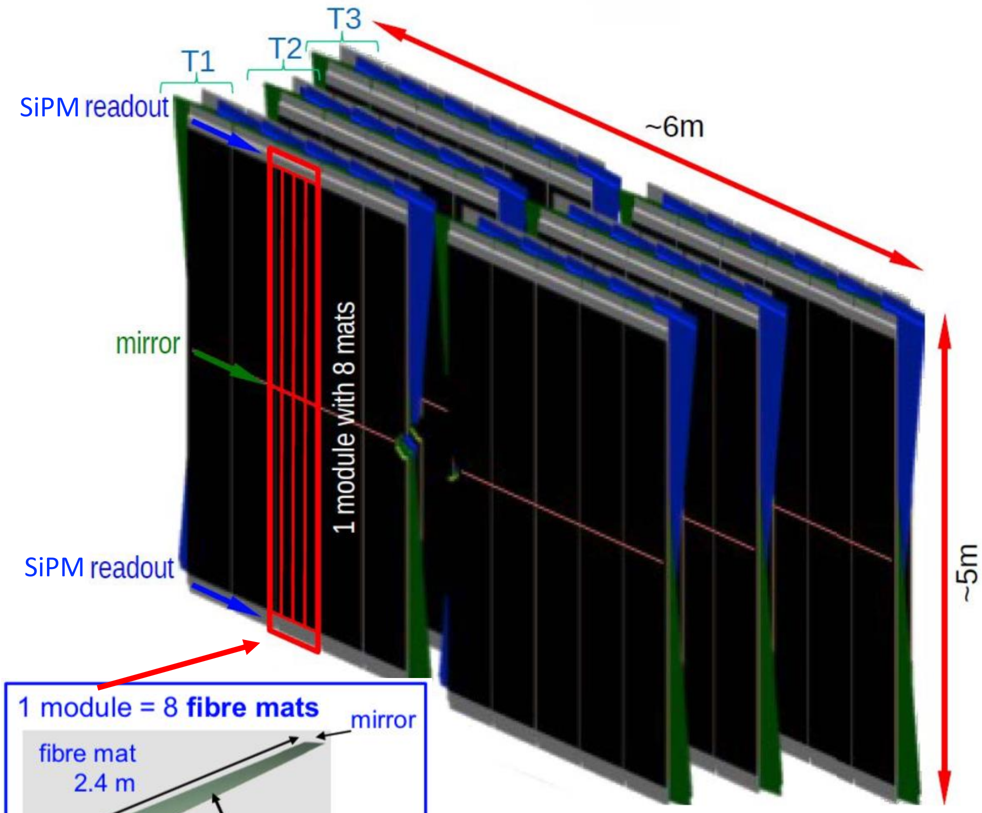
The LHCb SciFi tracker

Requirements:
- $X/X0 \leq 1\%$ per detection layer
- Hit efficiency ~ 99%
- $\sigma_x < 100$ µm (in the bending plane)
- 40 MHz readout (25 ns)
- 35 kGy close to the beam pipe for fibres
- 6×10^{11} n_{eq}/cm^2 for the SiPMs

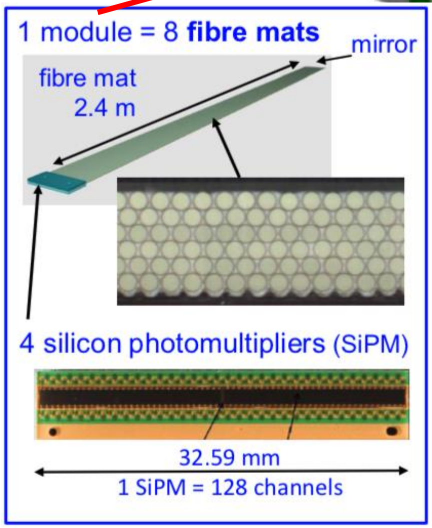


A single event from the LHCb Event Display

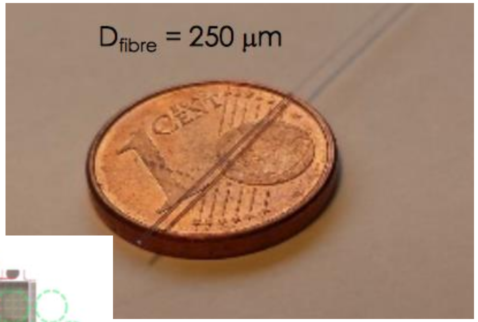
The LHCb SciFi tracker layout

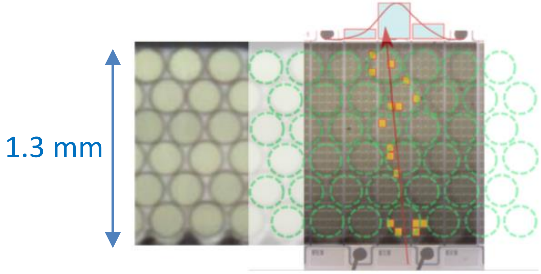


- 3 stations with 4 layers (X-U-V-X)
- 340 m^2 total area
- **10,500 km of scintillating fibre** **(Kuraray SCSF-78MJ, ⌀ = 250 µm)**
- **~ 4.5 million fibres of 2.4 m length**
- 128 fibre modules (à 8 mats)
- 4096 custom-made SiPM arrays
- 524k readout channels



16-20 p.e. for 6-layer mat
(for particles near the mirror)



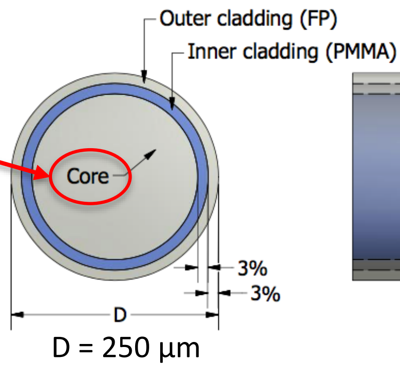


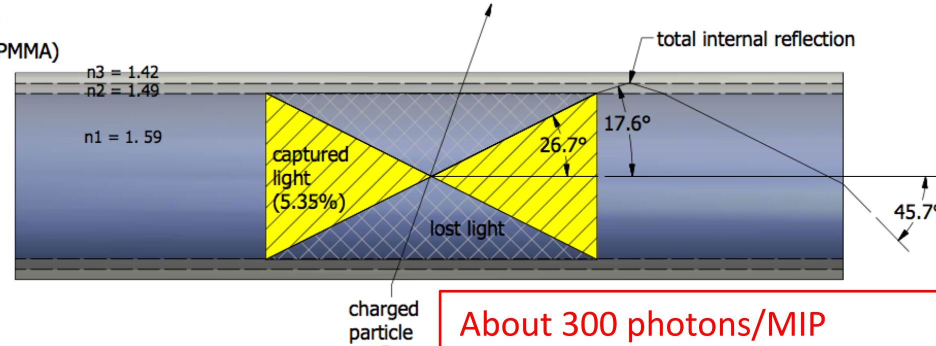
Fibre mat with SiPM

Scintillating fibres

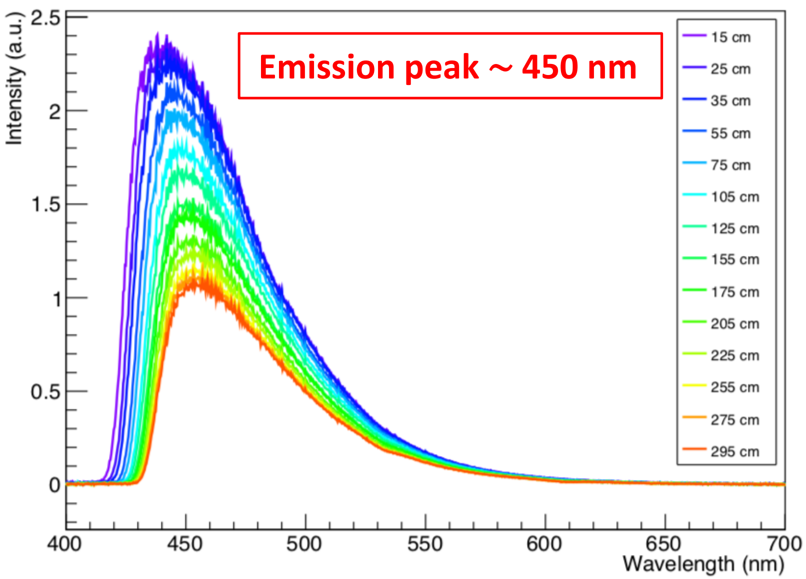
Double cladded round fibres (Kuraray SCSF-78MJ) are used for LHCb SciFi:

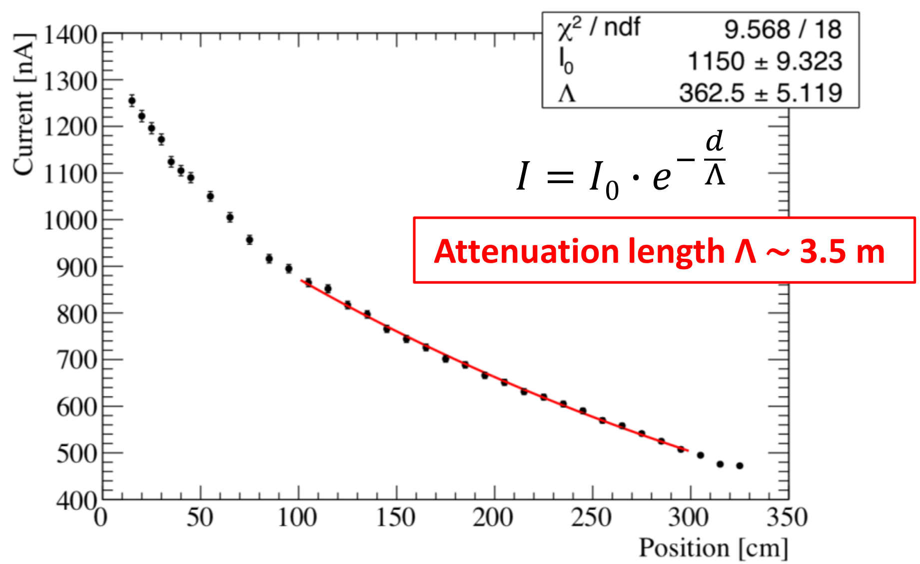
Solvent (Polystyrene)
+ activator (PTP)
+ WLS (TPB)



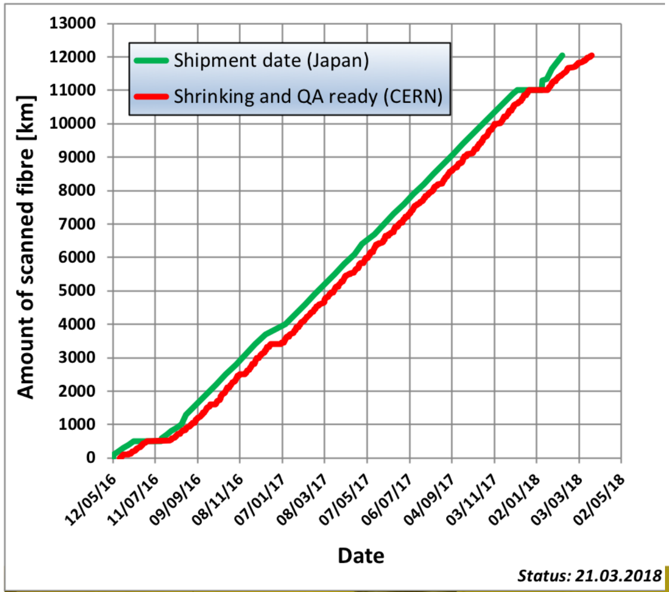


About 300 photons/MIP
3-4 p.e. detected (trapping fraction, attenuation, PDE) @ 240 cm



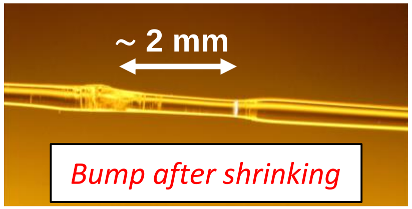


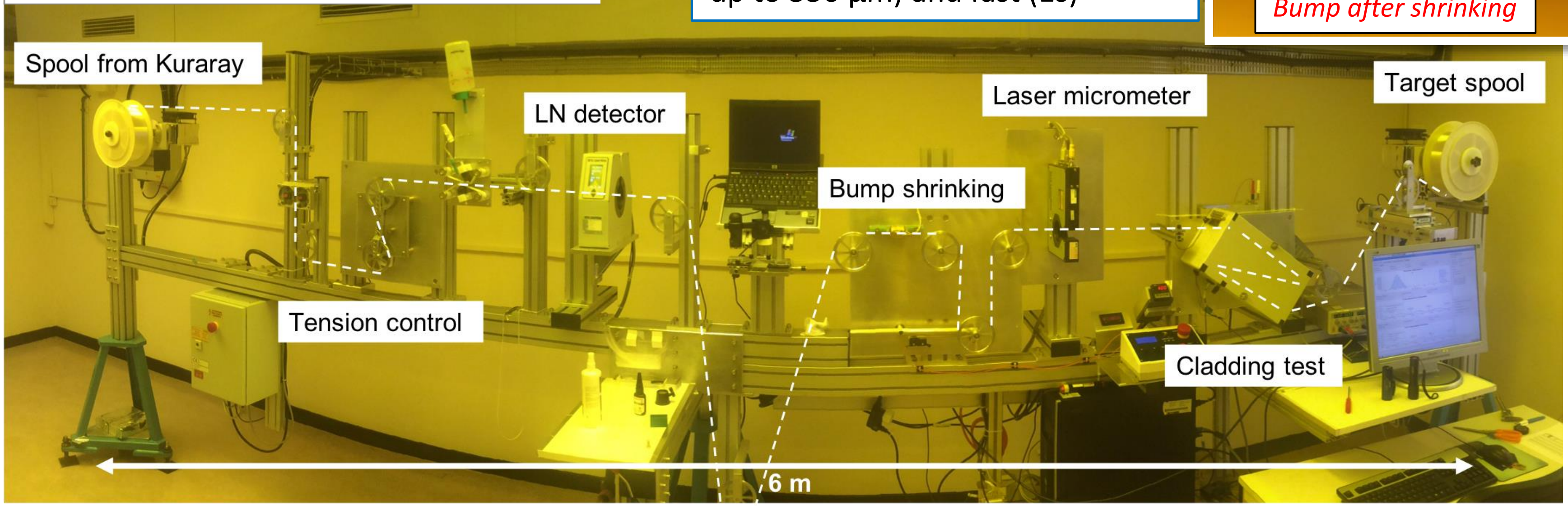
Fibre quality assurance



- **12,000 km of fibre (incl. pre-production & spare), 950 spools**
- **QA procedure:**
  - ✓ Attenuation length and ionization light yield (for every spool)
  - ✓ Radiation hardness (X-rays), decay time, bending radius (for a fraction of spools)
  - ✓ Scanning for diameter anomalies (bumps)
  - ✓ Removal of big bumps ($\Delta D > 100\ \mu m$)
  - ✓ Verification of cladding integrity

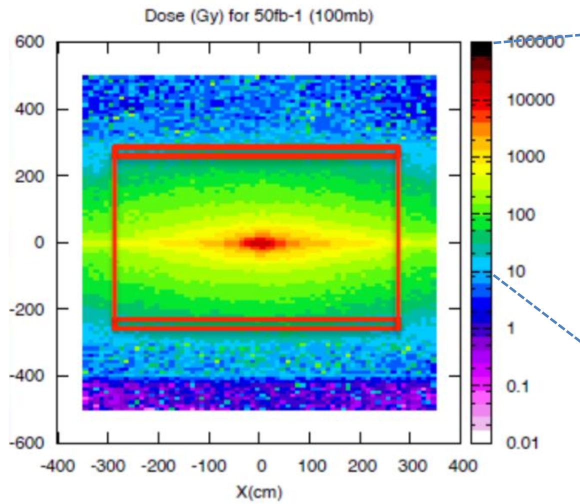
Bump shrinking procedure is automatic, reliable (> 90% success up to 550 µm) and fast (1s)

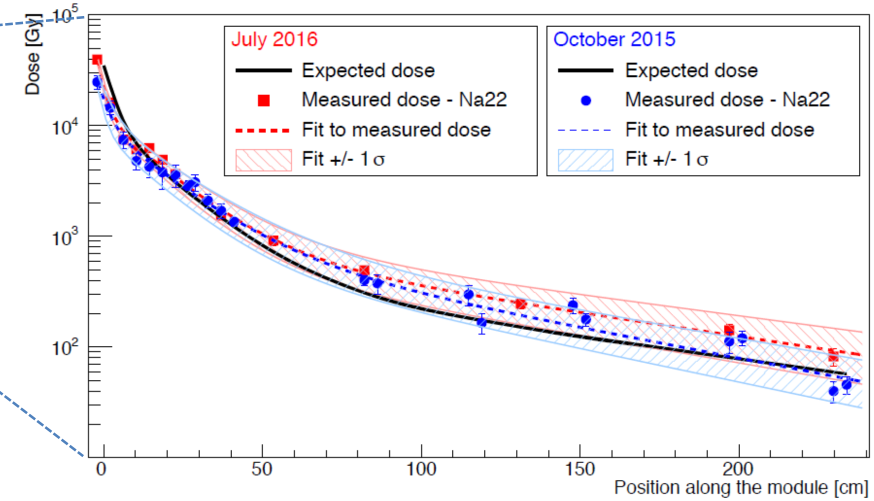




Fibre radiation damage

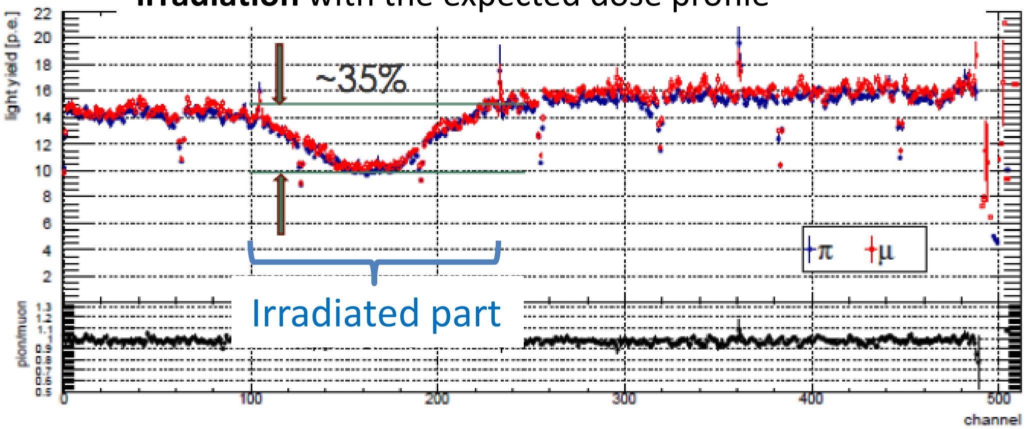
Ionization dose: 35 kGy in hottest region





FLUKA, LHCb Tracker TDR, CERN/LHCC 2014-001

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

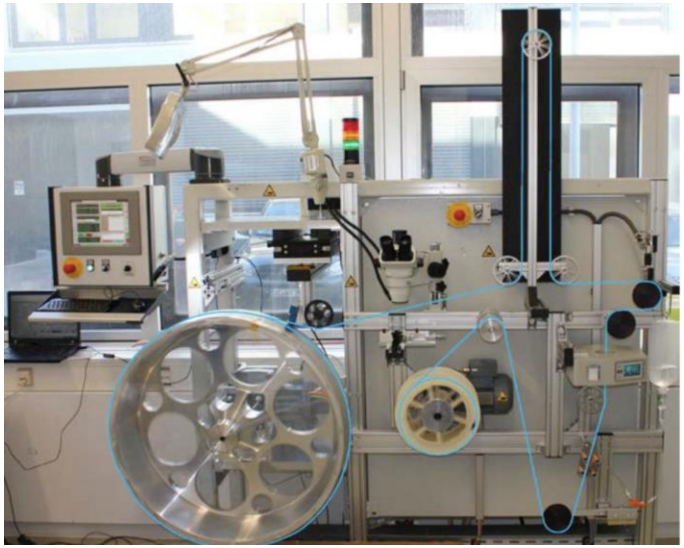


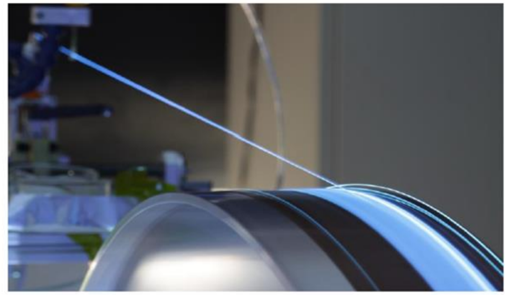
Expected dose profile is very non-uniform. Two mirrored SciFi mats were irradiated at the PS Irrad facility.

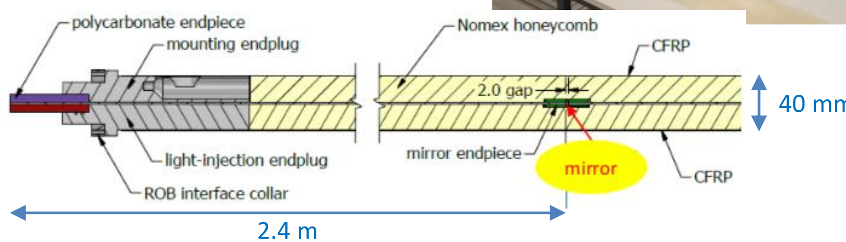
We found about 35% signal drop.
10 p.e. expected at end of lifetime is already the minimum for optimum hit efficiency!

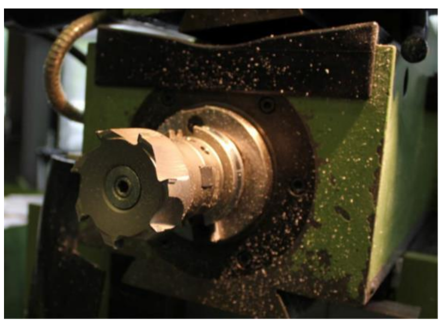
Fibre mat & module production

Custom winding machine (Ø = 80 cm wheel with fine thread) – 1500 mats produced at 4 sites (incl. spares)

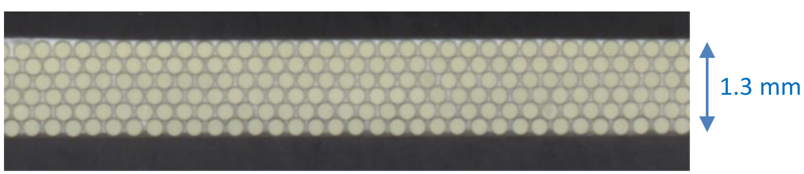


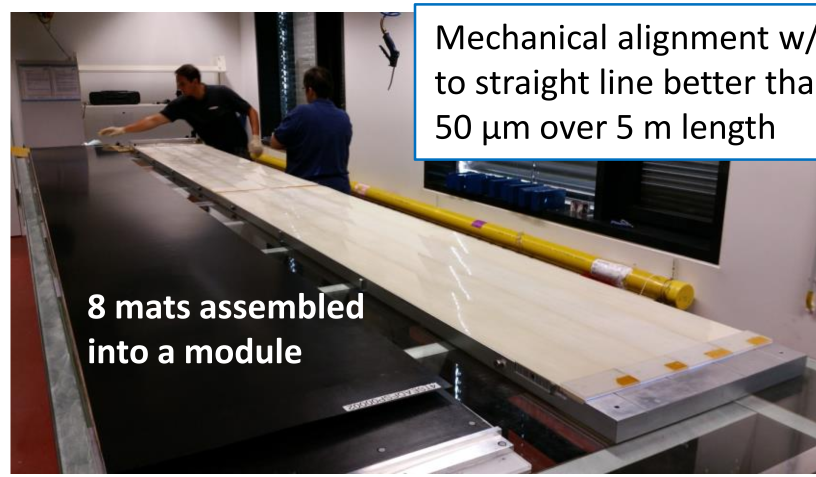






Diamond milling of optical surfaces

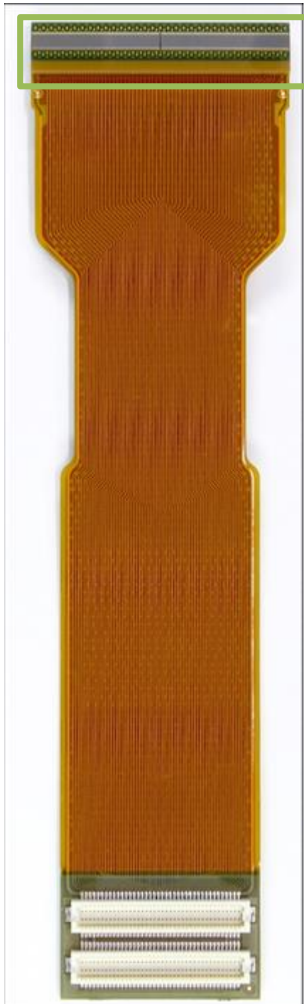




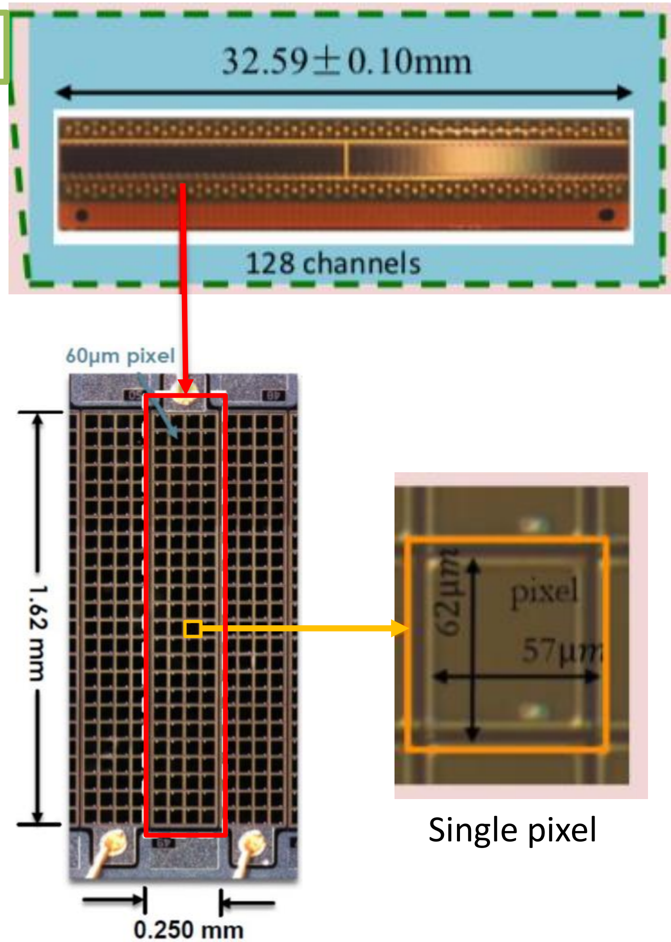
Mechanical alignment w/r to straight line better than 50 µm over 5 m length

Silicon Photomultipliers

(Hamamatsu MPPC S13552 – H2017)

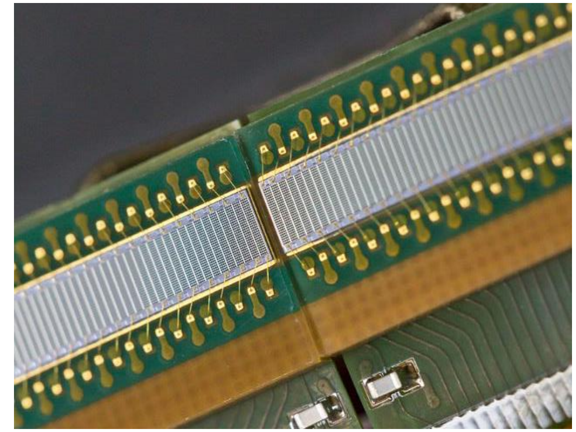


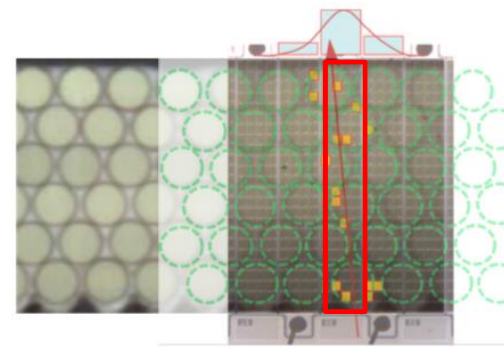
SiPM array +
Kapton flex-PCB



Single pixel

1 channel = 104 pixels



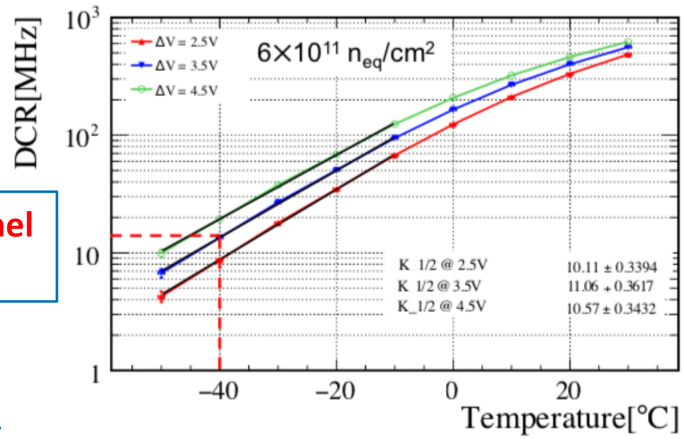


Fibre mat with SiPM

- SiPMs are glued on 3D printed Titanium bar
- Connection to FE-electronics via Flex-PCB
- 524k SiPM channels in total
- 4096 SiPM arrays

SiPM characteristics

DCR per SiPM channel (not irradiated): 0.04 MHz
DCR per channel for an irradiated SiPM:



Challenges:

- Increase in dark count rate (DCR) due to neutron irradiation
- Irradiation of fibre leads to reduced light output seen by SiPMs (10-12 p.e.)

This requires:

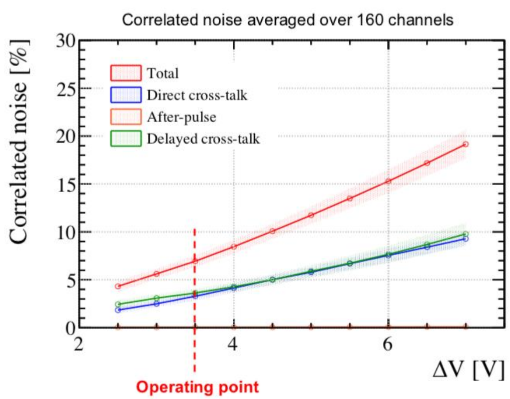
- **Cooling to -40℃** (at end of lifetime)
- **SiPMs optimised for:**
    - High PDE (large pixels)
    - Low after-pulse and cross-talk
    - Thin entrance window (105 µm epoxy)

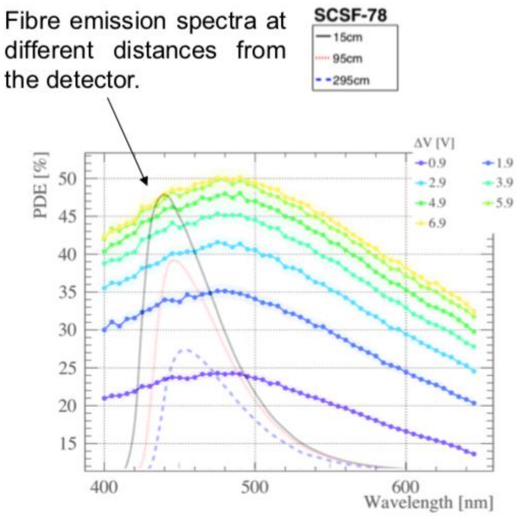
DCR ~ 14 MHz/channel (35 MHz/mm²)

DCR reduced by factor 2 every 10K
→ gain a factor 2^6 = 64 by going from +20 to -40℃

SiPM performance:

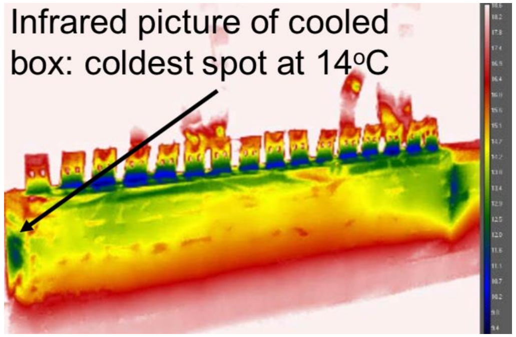
- Peak PDE = 45% (at ΔV = 3.5 V)
- After-pulse < 0.1%
- Direct cross-talk ~ 3.5%
- Delayed cross-talk ~ 3.5%
- Total correlated noise = 7% (at ΔV = 3.5 V)

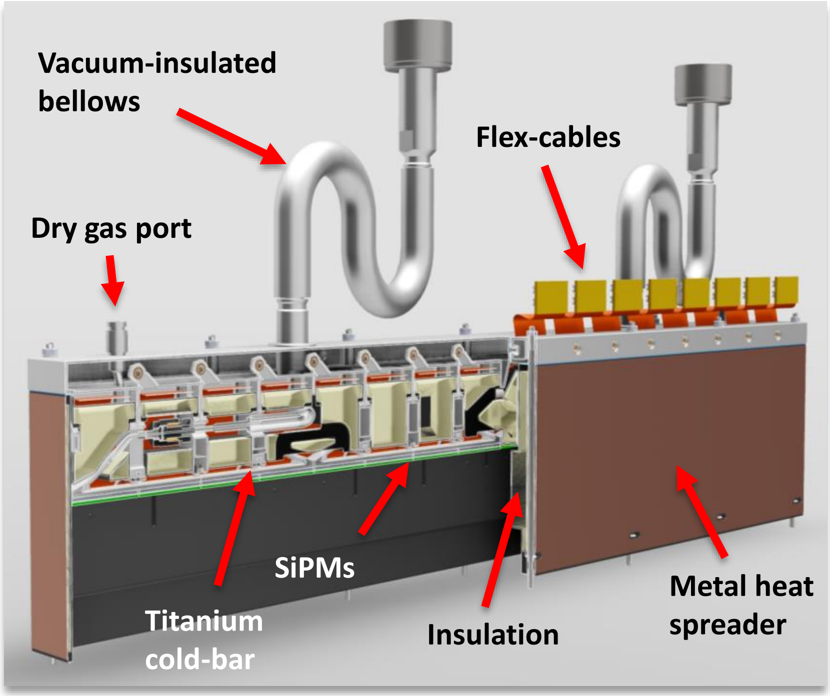


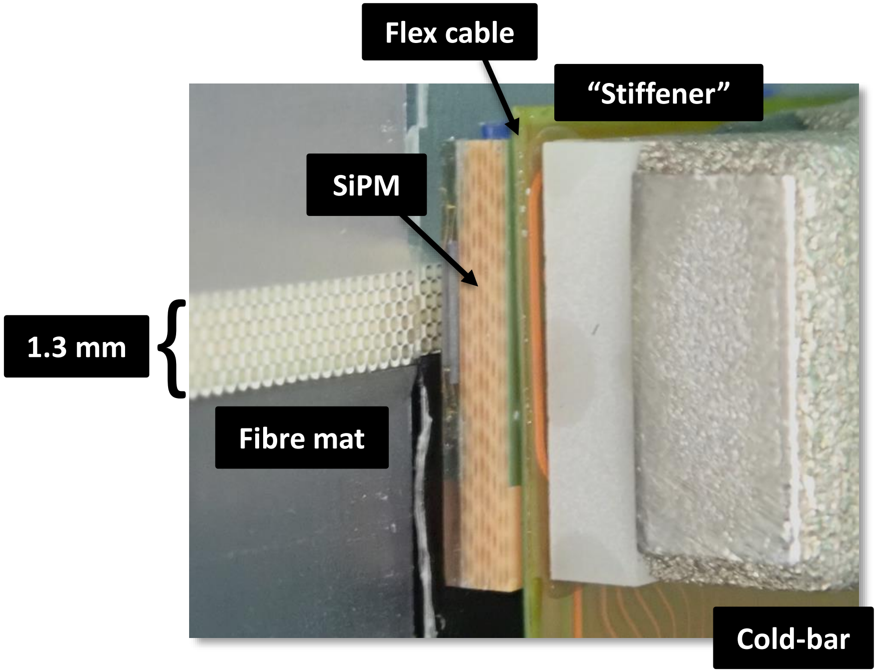


SiPM cooling

- Cold-box houses 16 **SiPM arrays cooled down to -40°C**
- **Cooling liquid:** monophase 3M Novec 649 (Fluoroketone C6K)
- **Challenges:**
  - thermal insulation
  - humidity management
  - 100 m long transfer lines
- **Total mass flow 7.5 kg/s, total heat load ~ 10 kW**
- Near detector cooling lines are **vacuum insulated**
- Humidity management inside the box with **dry air flushing** (dew point -70 °C)







Readout electronics

Challenges:

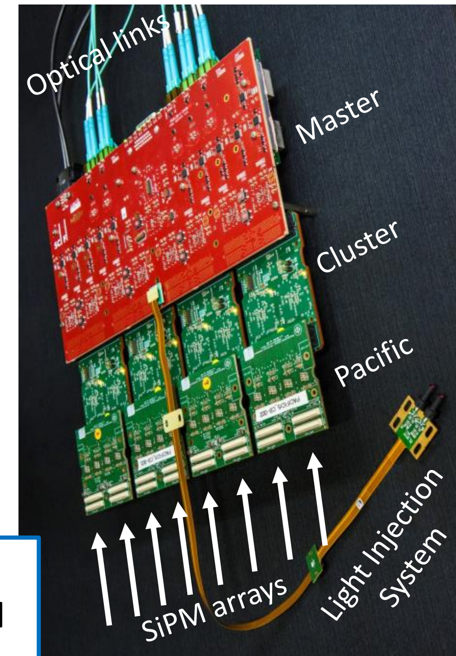
- 524k SiPM channels to be read-out at 40 MHz
- High DCR and noise cluster rate due to radiation damage
- SiPM signals with long tails

This requires:

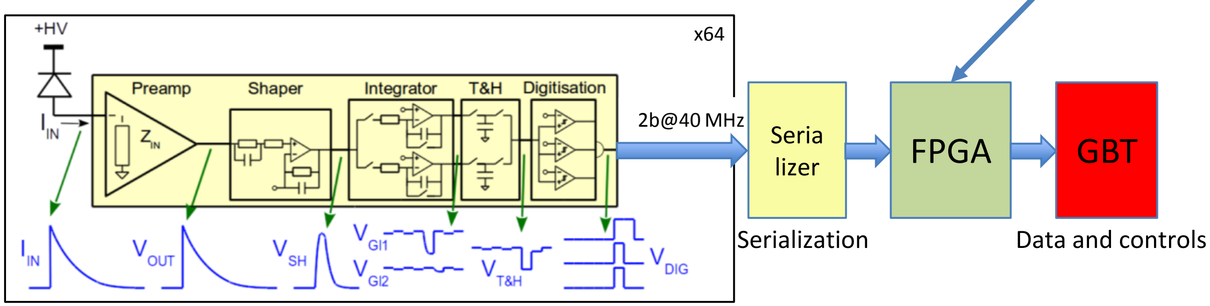
- Low power consumption electronics
- Minimised spillover and dead time (fast shaping and integration)
- Efficient noise rejection, signal digitisation and data processing

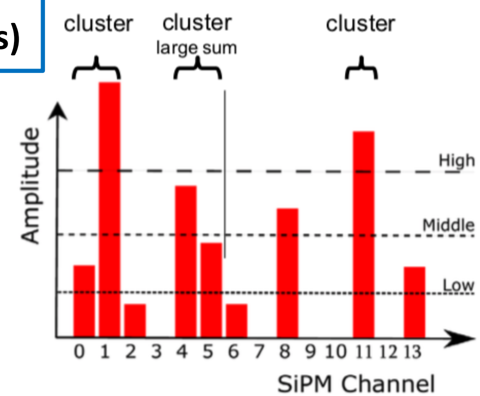
PACIFIC ASIC (for signal digitisation):

- CMOS 130 nm technology
- 64-channel current mode input, 10 mW per channel
- Fast shaping to reduce spillover (10 ns)
- Double gated integrators to avoid dead time (25 ns)
- 2-bit digitization per channel (3 comparators)
  - 000,001,011,111 → 00,01,10,11



Clustering:
~ 14 MHz/channel
< 3 MHz per SiPM array (128 channels)

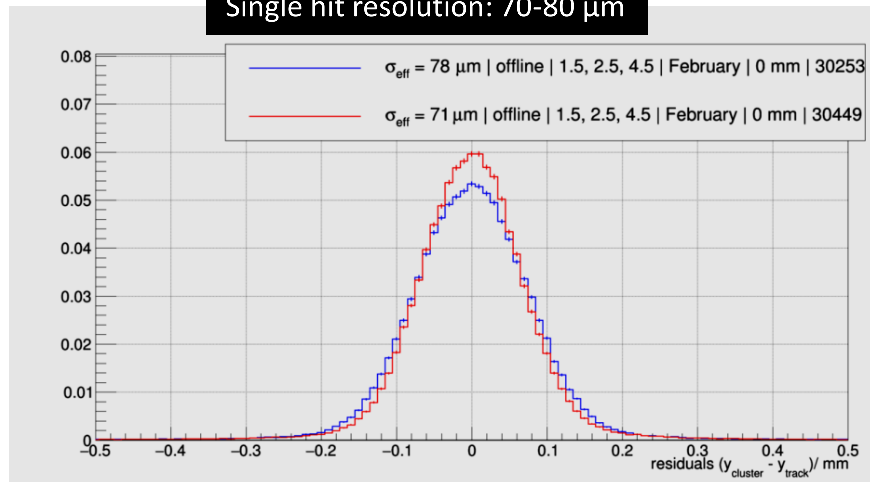




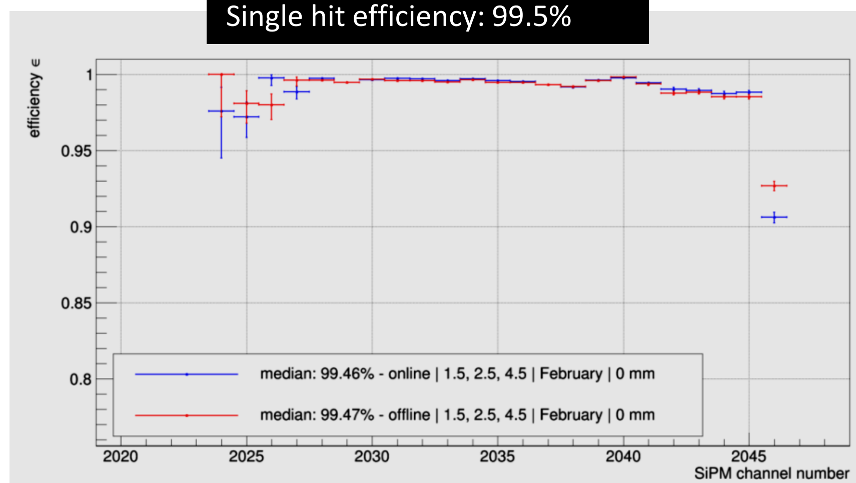
Detector module performance

- **Two fibre modules with final read-out electronics tested at CERN SPS in July 2018**
- **Results are in agreement with our requirements!**

Single hit resolution: 70-80 µm



Single hit efficiency: 99.5%



Spillover to next bunch crossing: 2%

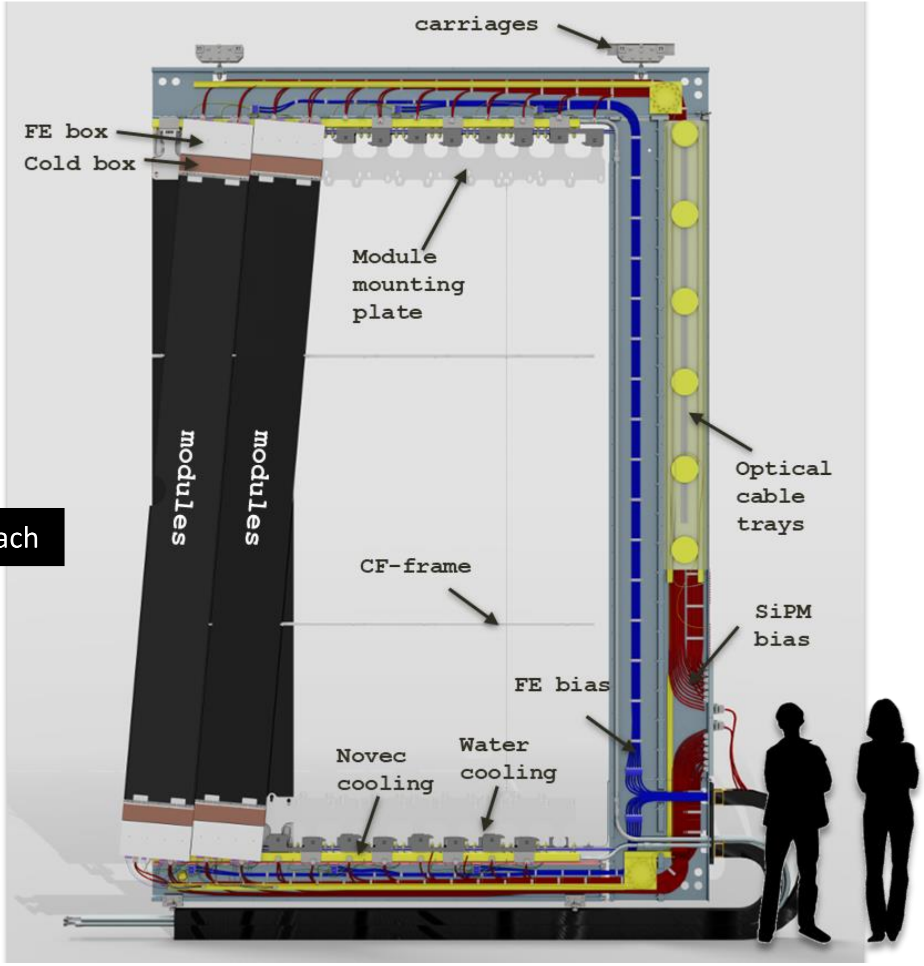
Mechanics and services

C-shaped frames (C-Frames) carry the fibre modules and FE-boxes and all services to and from them:

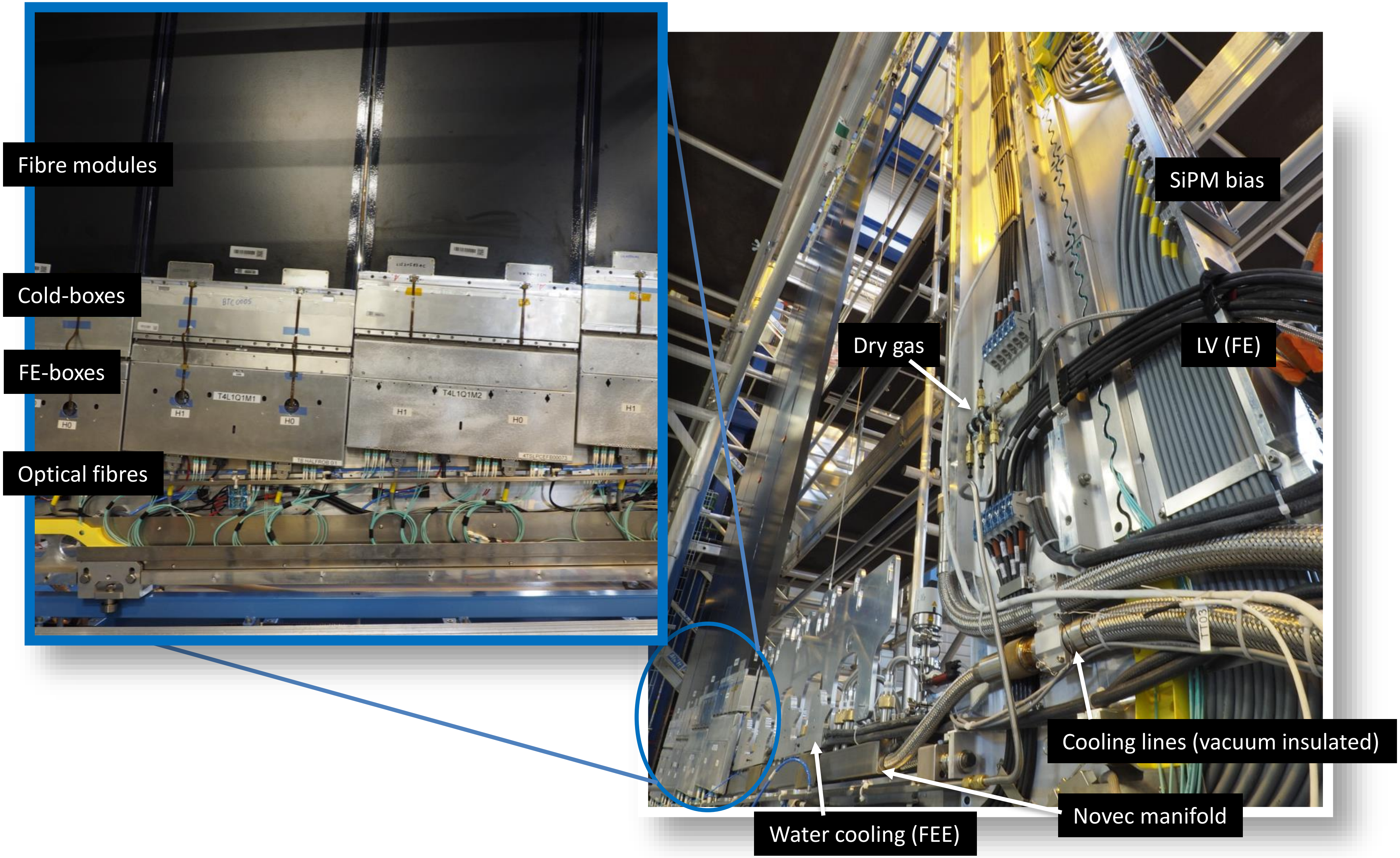
- Optical fibres
- Low voltage (FEE)
- SiPM bias voltage
- Water cooling (for electronics)
- SiPM cooling (Novec)
- Vacuum lines
- Dry gas

12 C-Frames in total with 2 layers each

Very complex integration



Pictures of prototype C-Frame

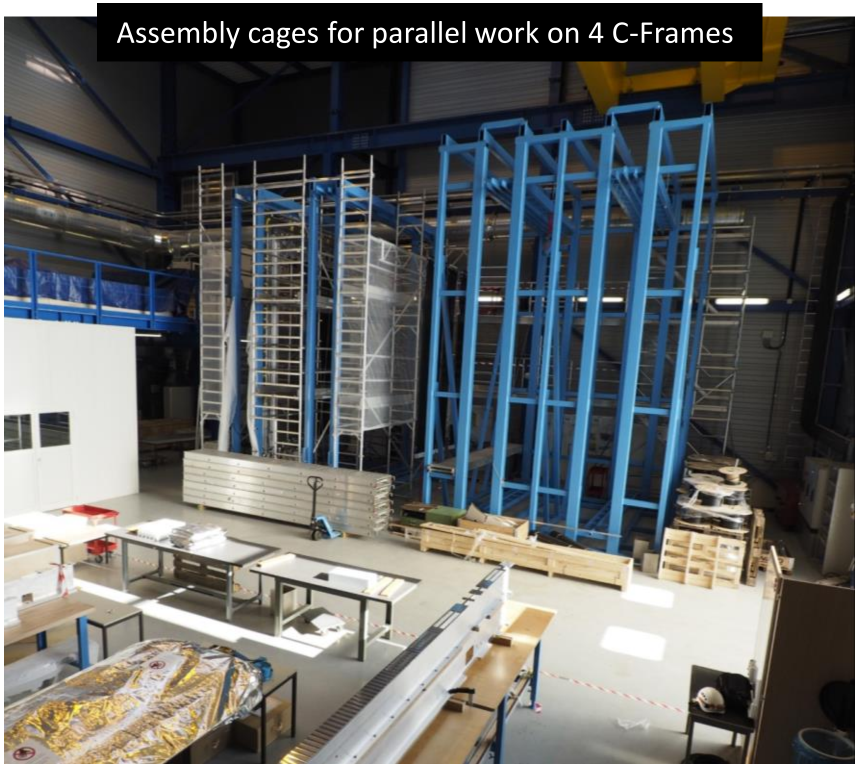


Summary of project status

- Production of fibre mats and modules, SiPMs, ASICs finished
- Production and testing of cold-boxes and FE-boxes ongoing
- Production and testing of services components and C-Frame mechanics ongoing
- First serial C-Frame assembly starting in March

Schedule is VERY tight but project is on track for detector installation starting end 2019!

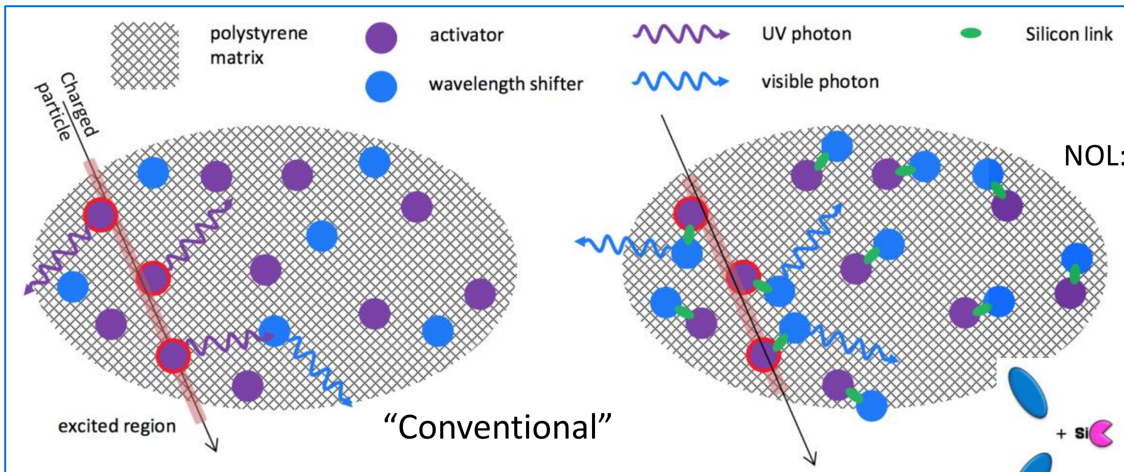
Assembly cages for parallel work on 4 C-Frames



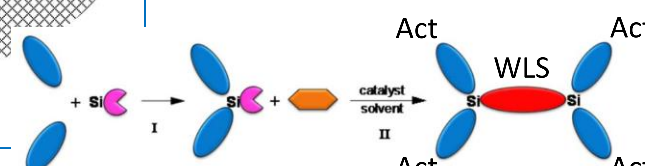
Future upgrades - the NOL idea

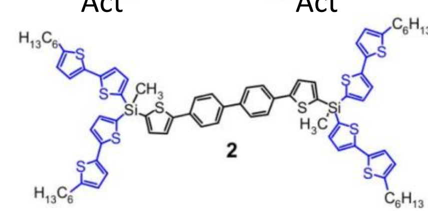
Fibres are suffering from radiation damage.
LHCb is looking for new techniques for future upgrades.
Can we improve the fibre performance to start with a ‘better’ fibre in the beginning?

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



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

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

NOL fibres

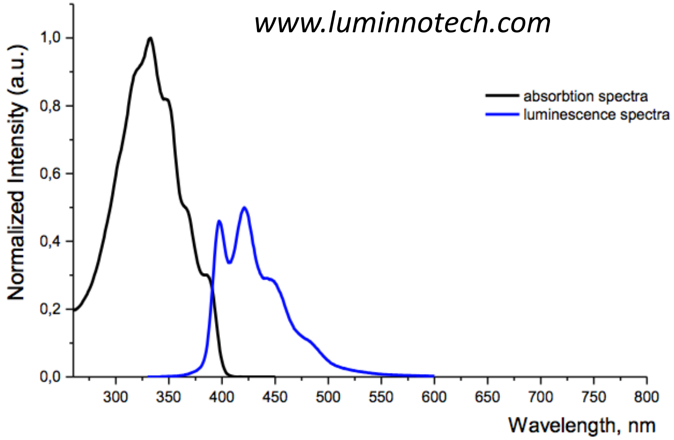
Applying the NOL idea to fibres puts some constraints on the content of material components

- **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

www.luminnotech.com

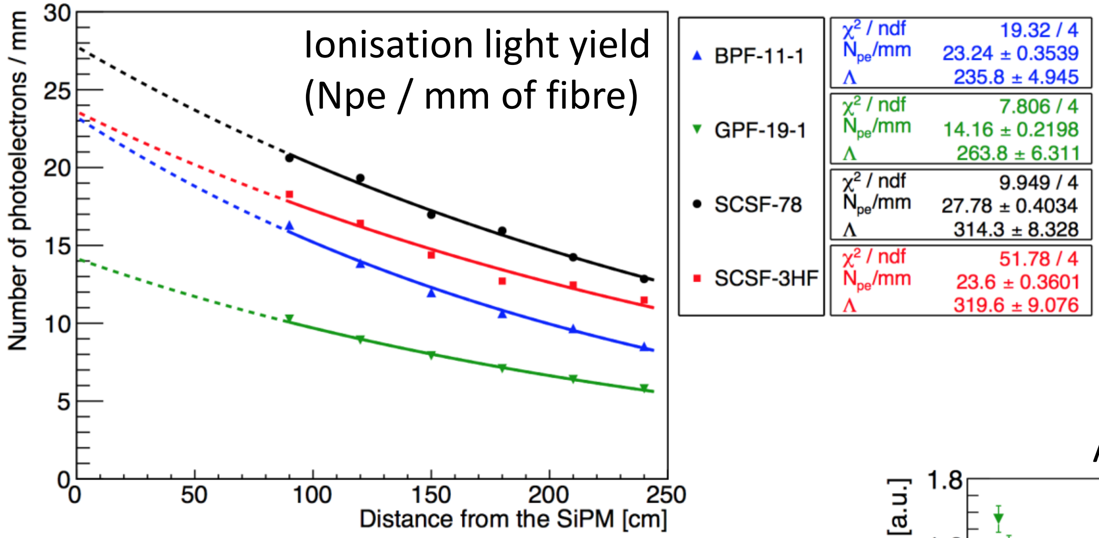


NOL fibre R&D among 3 institutes/companies

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

NOL prototype fibre performance

O. Borshchev et al., 2017 JINST 12 P05013



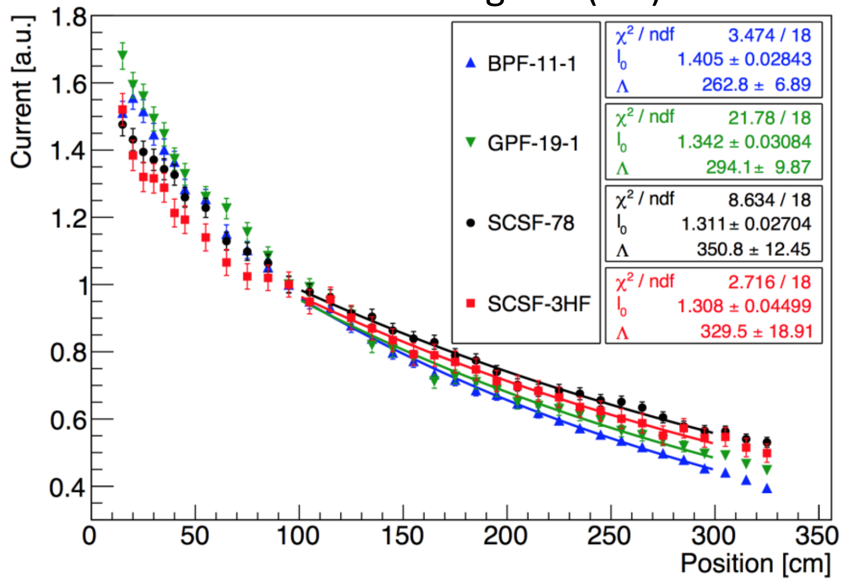
Best blue NOL prototype fibre

Best green NOL prototype fibre

Best blue standard fibre

Best green standard fibre

Attenuation length Λ (cm)



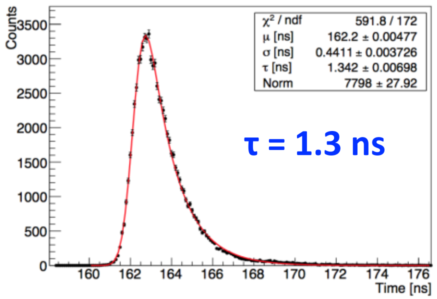
- After 8 iterations NOL fibres clearly improved but still a bit behind in terms of light yield and attenuation length

- Λ(NOL) ~ 300 cm
- Λ(standard) ~ 350 cm
- **Self absorption, i.e. choice of materials, contents and purity are key issues**

NOL prototype fibre performance

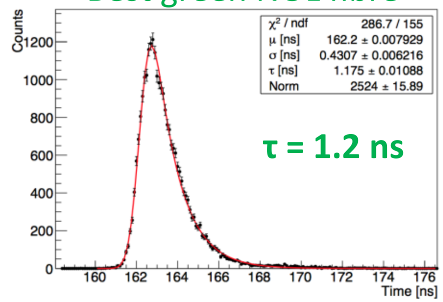
O. Borshchev et al., 2017 JINST 12 P05013

Best blue NOL fibre



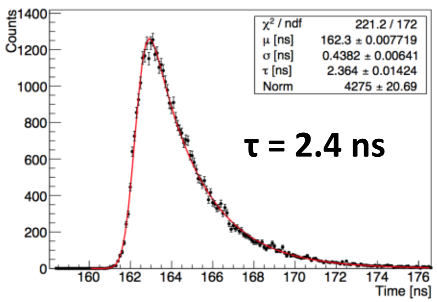
(a) BPF-11-1

Best green NOL fibre



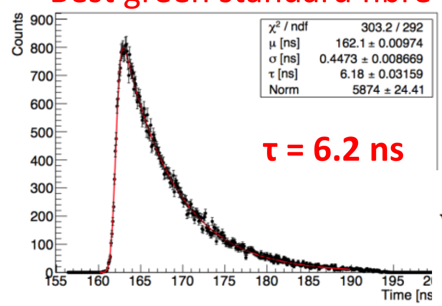
(b) GPF-19-1

Best blue standard fibre



(c) SCSF-78

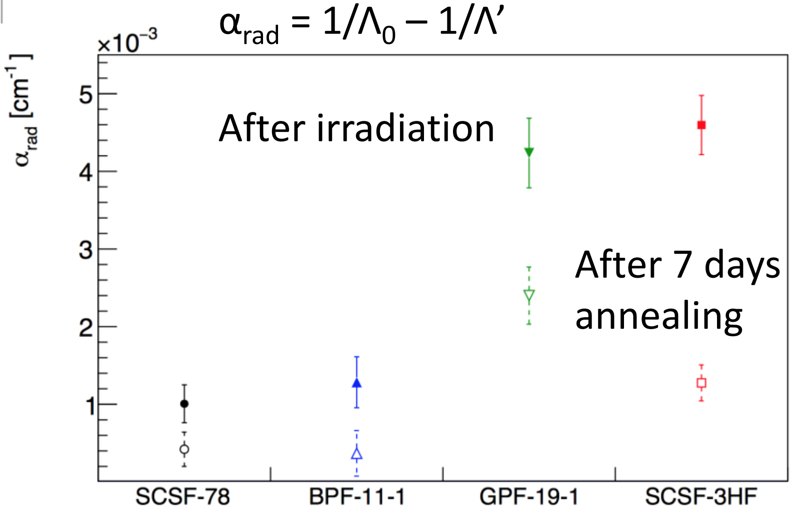
Best green standard fibre



(d) SCSF-3HF

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

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



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

- Damage is as expected on a level comparable to reference fibres
- Hadron irradiations to be done

Summary

- The LHCb SciFi tracker will be the largest scintillating fibre tracker ever built, using 10,500 km of fibre. It will start operation in 2021.
- The detector has to cope with major challenges, amongst others the radiation level as one of the main problems. The chosen design is expected to cope with the LHC conditions until end of Run 4 and 50 fb^{-1} integrated luminosity.
- The construction of the detector is in an advanced state. Installation of the first 6 detector frames will start end 2019. The construction of all 12 C-Frames should be finalised by spring 2020.
- To improve the intrinsic fibre performance a fibre R&D project has been launched. NOL fibres are based on the coupling of activator and wavelength shifter using silicon links.
- The 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.

LHCb SciFi is looking forward to 2021 …

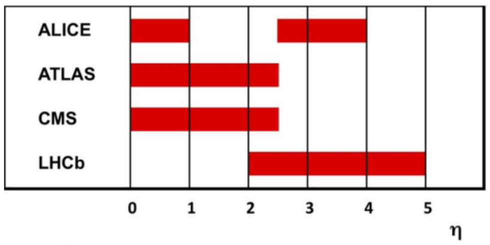
… to see (a little) light at the end of the fibre.

Back-up slides

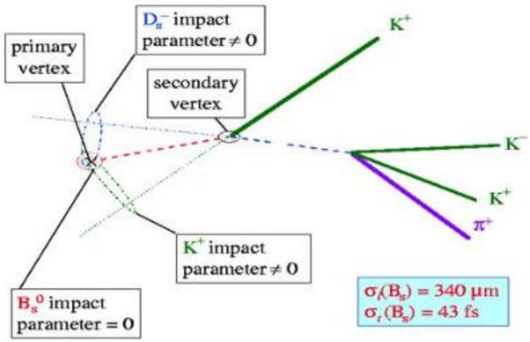
The LHCb experiment

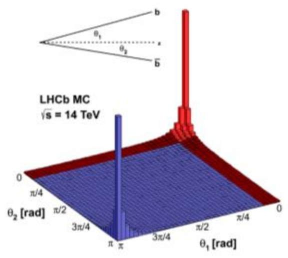
Material from: A. Schopper, EIROforum school 2017, lhcb.web.cern.ch and M. Moll, ESI 2011

- LHCb has forward geometry (like fixed target experiments) and is therefore not a typical collider experiment.
- LHCb is optimized for heavy flavour physics: measurements of rare phenomena in the beauty and charm region (in particular CP violation) and search for physics beyond the standard model phenomena

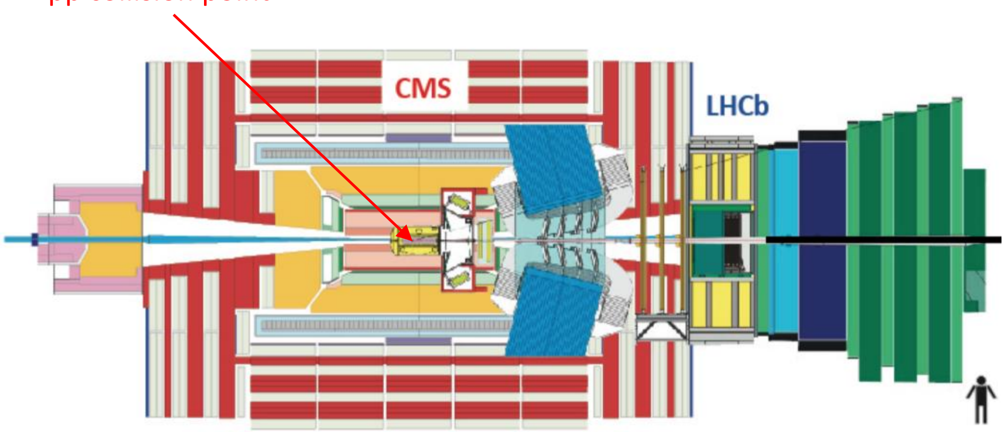


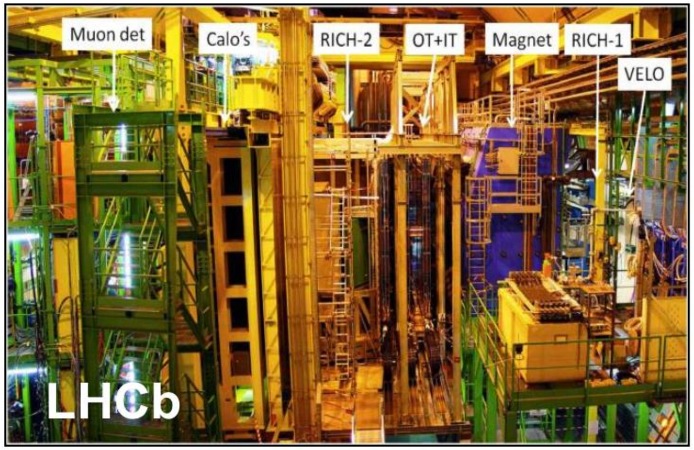
- B-mesons are produced in the forward region
  → forward geometry
- B-mesons decay quickly (after ~ 1 cm)
  → precise vertexing and tracking + powerful PID



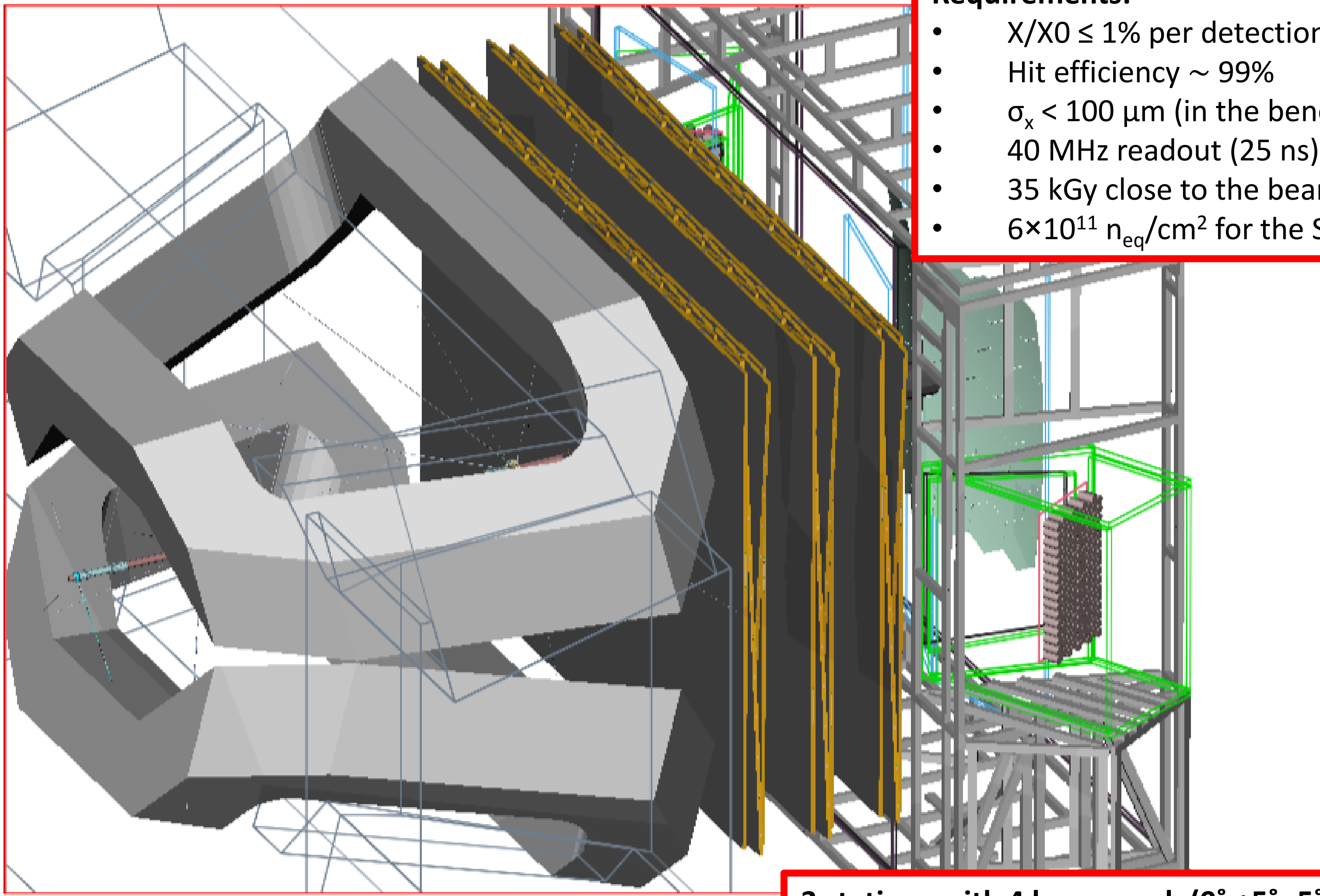


pp collision point





The LHCb SciFi tracker

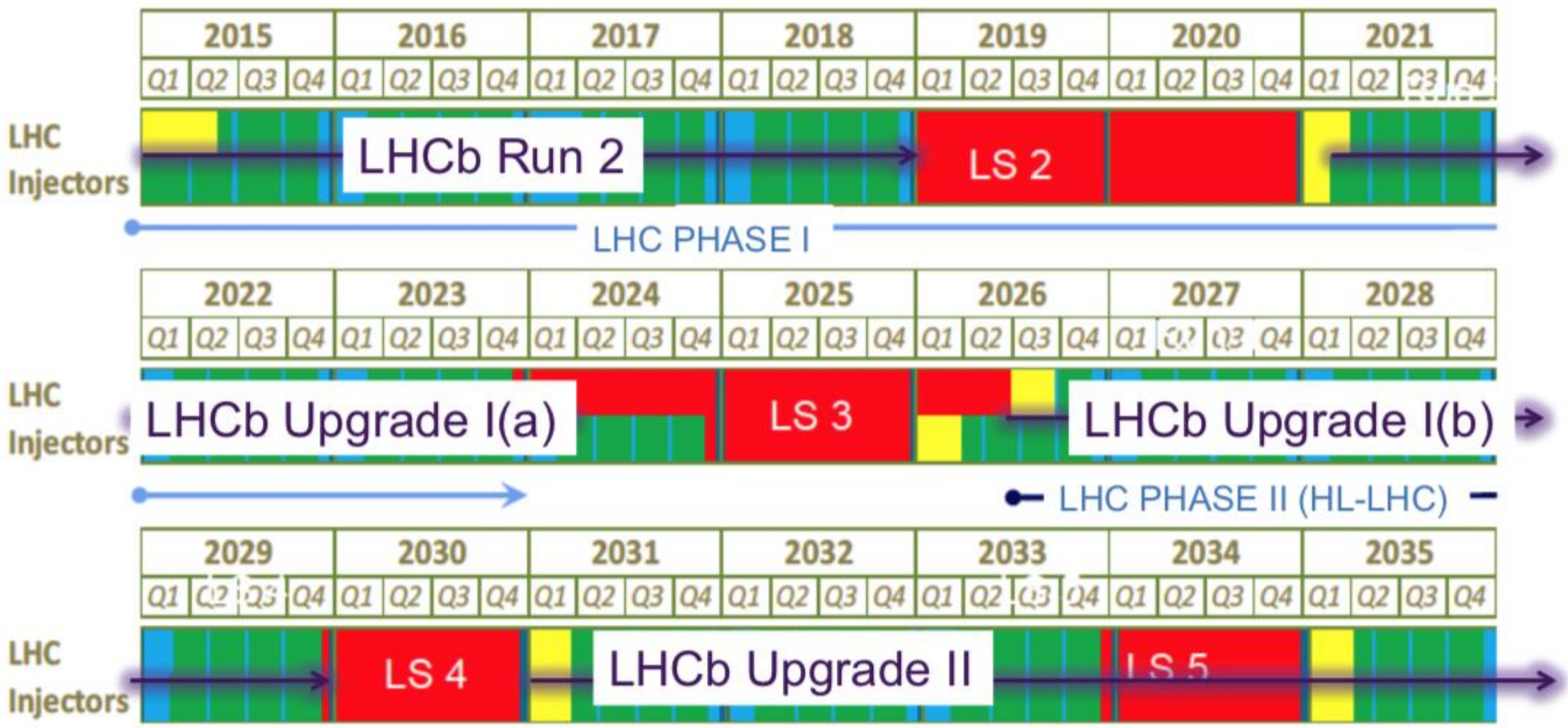


Requirements:

- $X/X0 \leq 1\%$ per detection layer
- Hit efficiency ~ 99%
- $\sigma_x < 100\ \mu m$ (in the bending plane)
- 40 MHz readout (25 ns)
- 35 kGy close to the beam pipe for fibres
- $6\times10^{11}\ n_{eq}/cm^2$ for the SiPMs

3 stations with 4 layers each (0˚,+5˚,-5˚,0˚)

LHCb future upgrades



- LHCb phase II upgrade:
    - SciFi tracker + inner Si-based tracker in LS3 ? + middle Si-based tracker in LS4 ?
    - SciFi tracker with improved fibres ?
    - ???

See: C. Joram, TTFU Elba, May 2017

Basics of scintillating fibres

- Scintillating fibres consist of a core (e.g. Polystyrene, n = 1.59) and one or more thin cladding layers with lower refractive indices.
- Light transport relies primarily on total internal reflection at the interface between core and cladding structure.

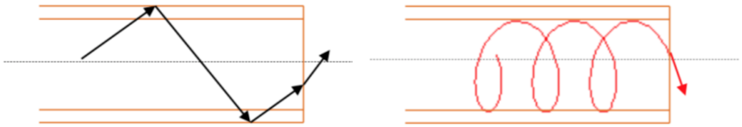
Critical angle: $\theta_{\text{crit}} = \arcsin(n_{\text{clad}}/n_{\text{core}})$

Trapping fraction: $\frac{d\Omega}{4\pi} = \frac{1}{2}\int_0^{90-\theta_{\text{crit}}} sin\theta d\theta$

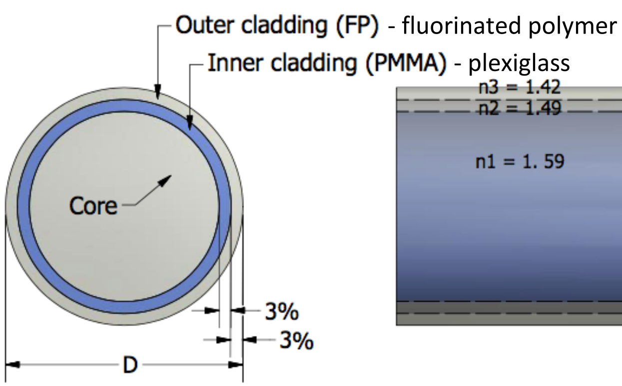
$\varepsilon_{trap} \geq 3.1\%$ for single cladding

$\varepsilon_{trap} \geq 5.3\%$ for double cladding

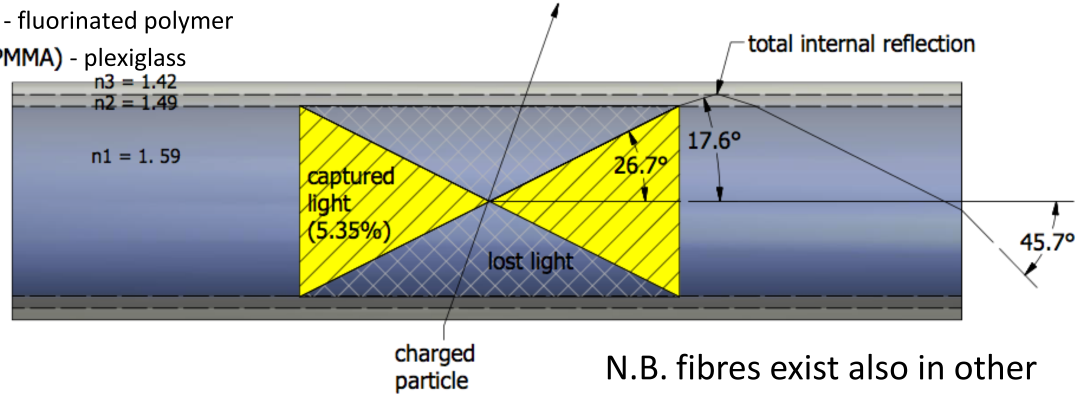
Due to "cladding rays" and helical paths



Double cladded fibres (invented in 1990, CERN RD7 and Kuraray) are still state-of-the-art:

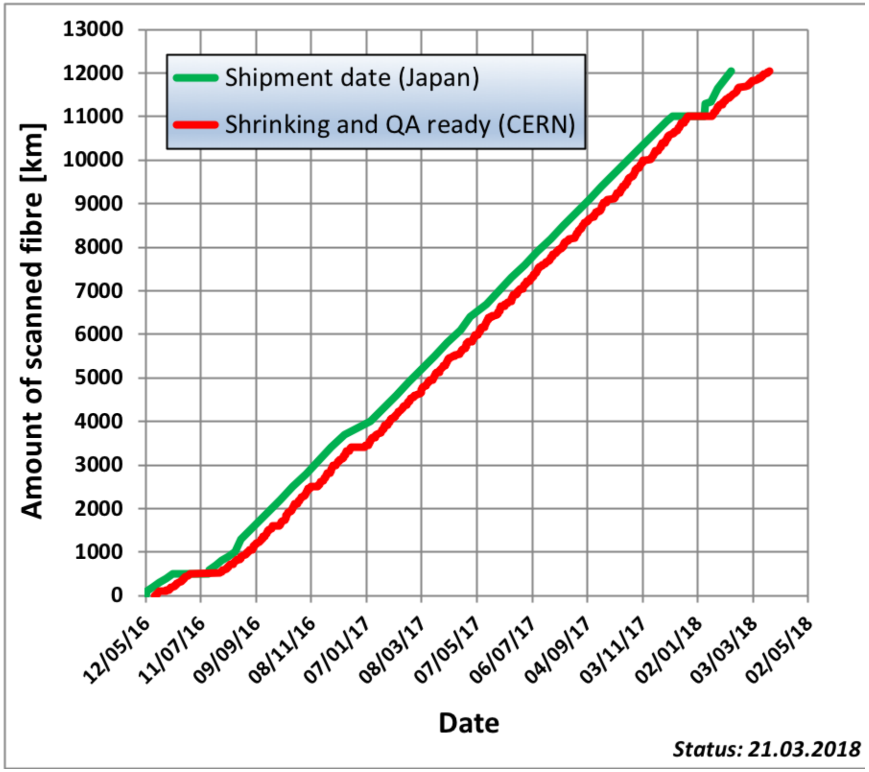


D ≤ 1 mm typ.

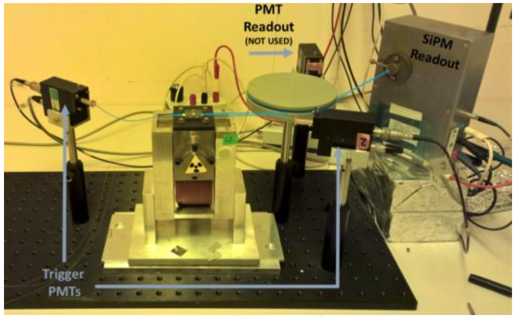


N.B. fibres exist also in other geometries, e.g. square or hexagonal

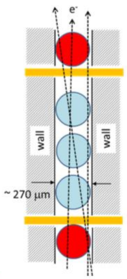
Fibre quality assurance



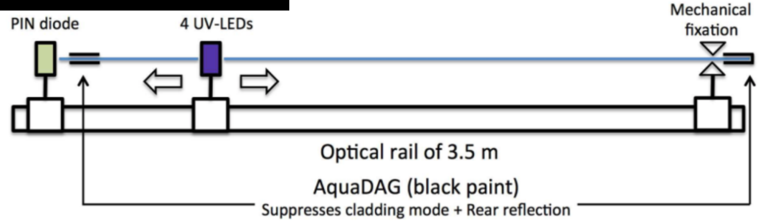
- **12,000 km of fibre, 950 spools (incl. spare)**
- Every mm of fibre is scanned for diameter anomalies (bumps), which would destroy pattern
- Big bumps (ΔD > 100 μm) are removed
- Every spool is characterized in terms of attenuation length and ionization light yield
- A fraction of spools is characterized in terms of radiation hardness (X-rays), decay time, bending radius



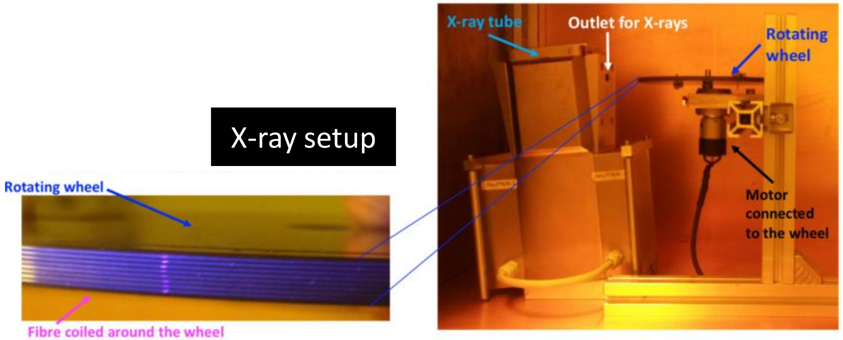
Light yield setup



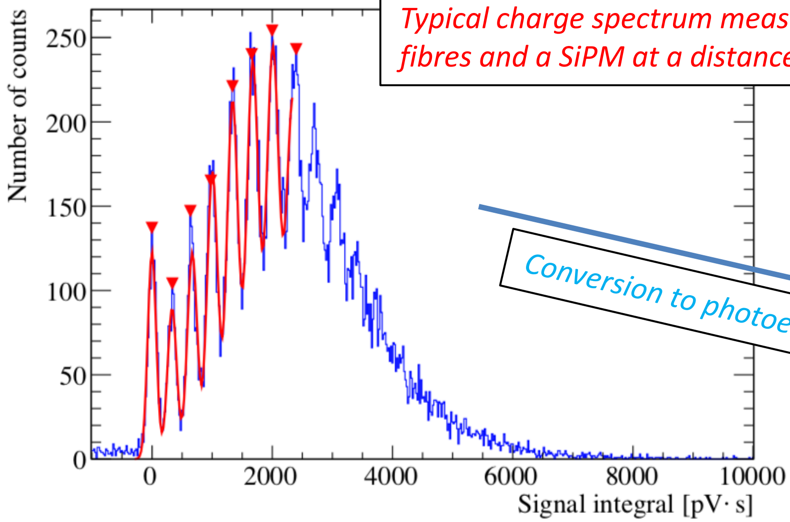
Attenuation length setup



X-ray setup

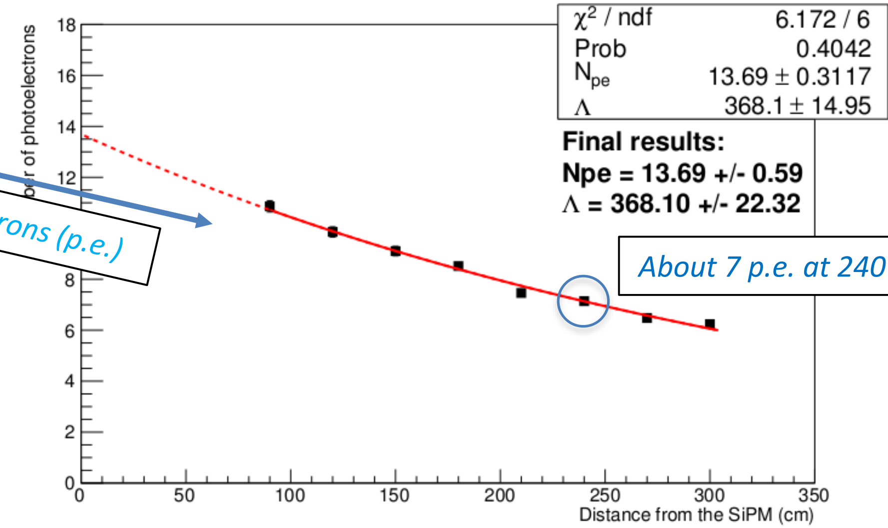


Light yield measurement

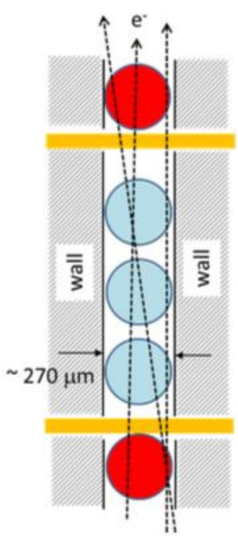


Typical charge spectrum measured with 3 SCSF-78 fibres and a SiPM at a distance of 240 cm.

Conversion to photoelectrons (p.e.)



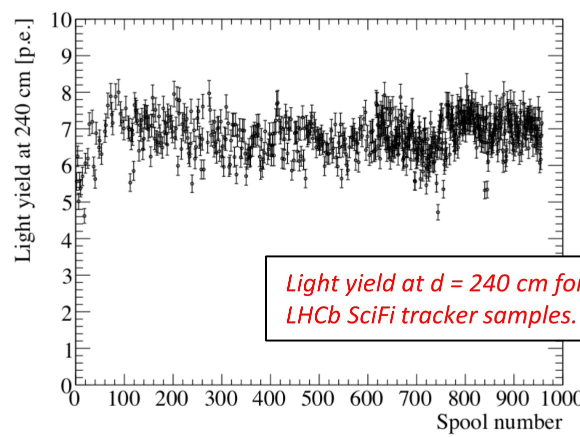
About 7 p.e. at 240 cm



Trigger fibre

3 Test fibres

Trigger fibre



Light yield at d = 240 cm for all tested LHCb SciFi tracker samples.

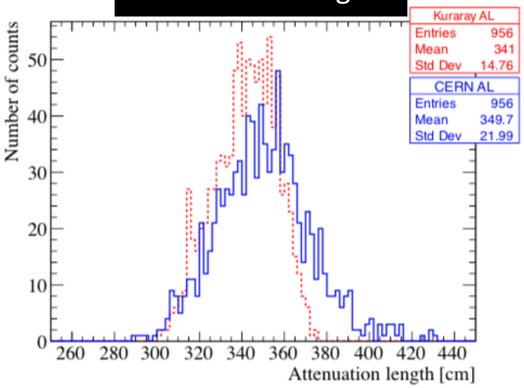
The SciFi tracker fibres are required to have a light yield larger than 4 p.e. at d = 240 cm (using the illustrated setup).

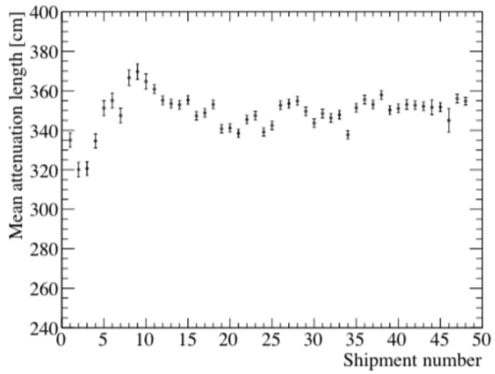
*A.B.R. Cavalcante et al 2018 JINST **13** P10025*

Fibre quality

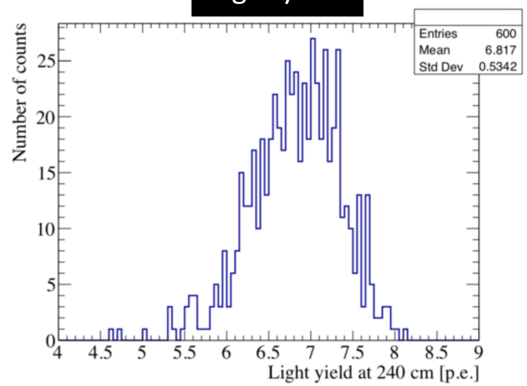
A.B.R. Cavalcante et al 2018 JINST 13 P10025

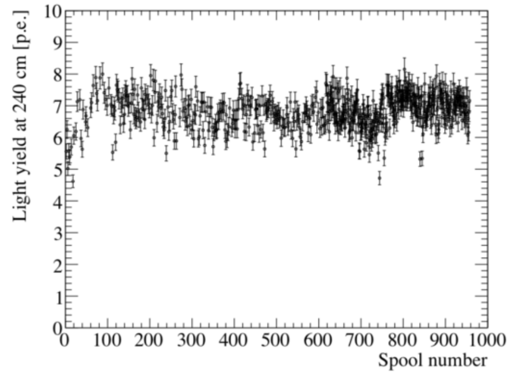
Attenuation length



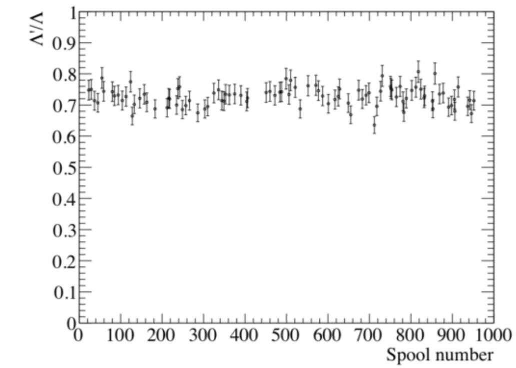


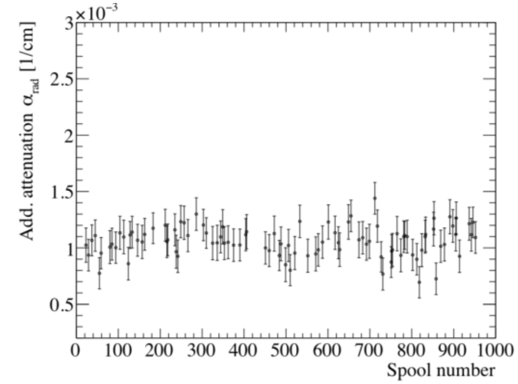
Light yield



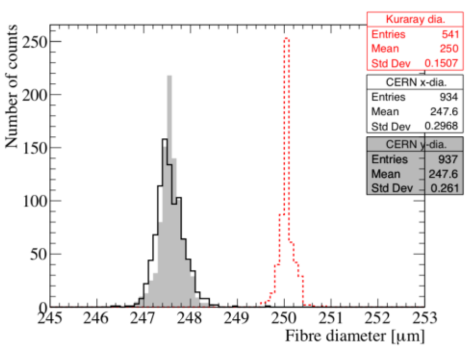


X-ray irradiation

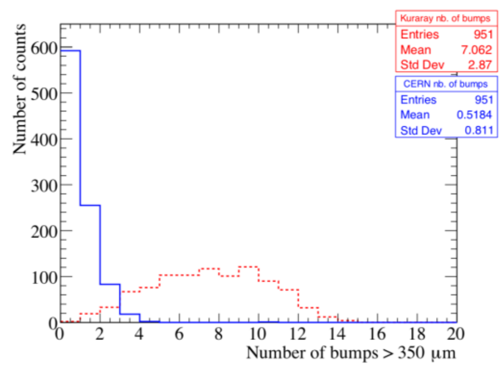




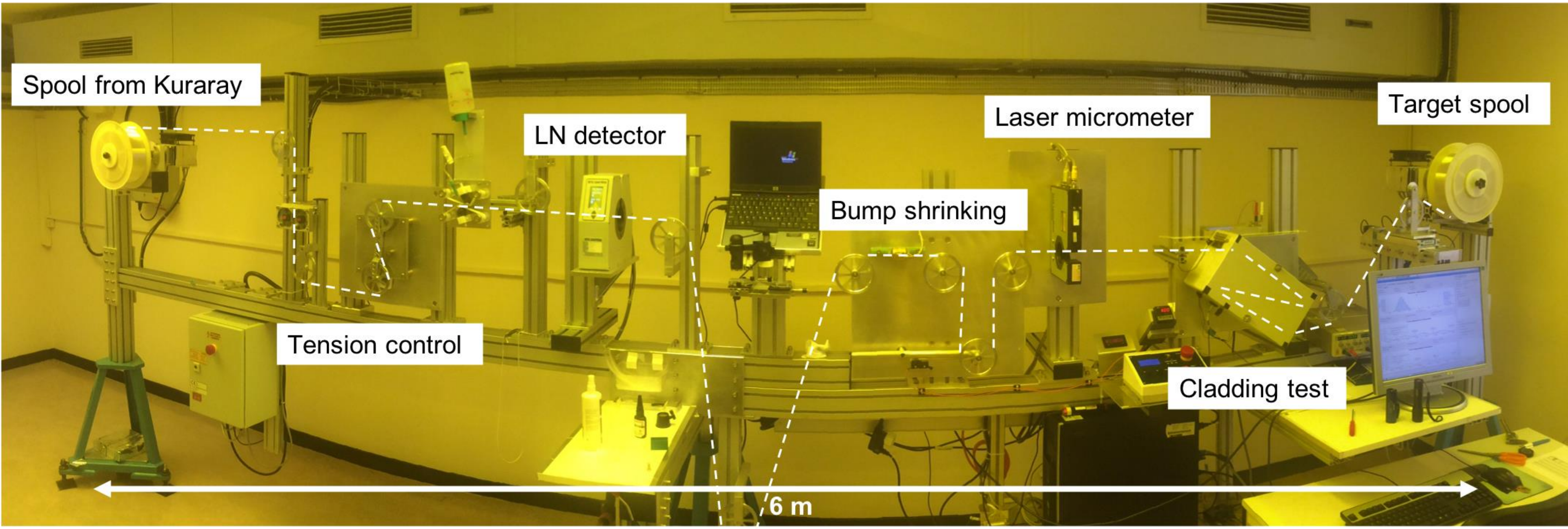
Diameter



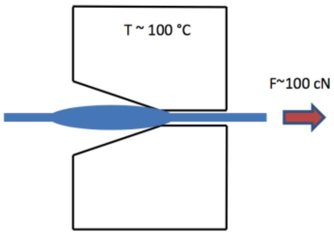
Bumps

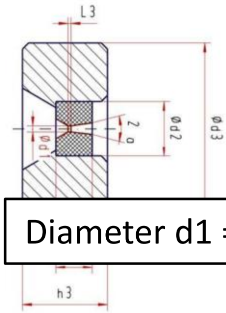


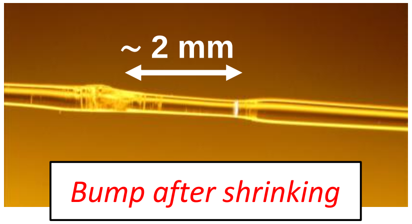
Fibre scanner



- The scanner was used to measure and refine 12,000 km of scintillating fibre for the SciFi tracker.
- The machine is fully automated and reliable and allows to measure the fibre diameter with a resolution of about 1 µm with a rate of 2.4 kHz.
- It also verifies the integrity of the cladding and features a fibre bump removal method.







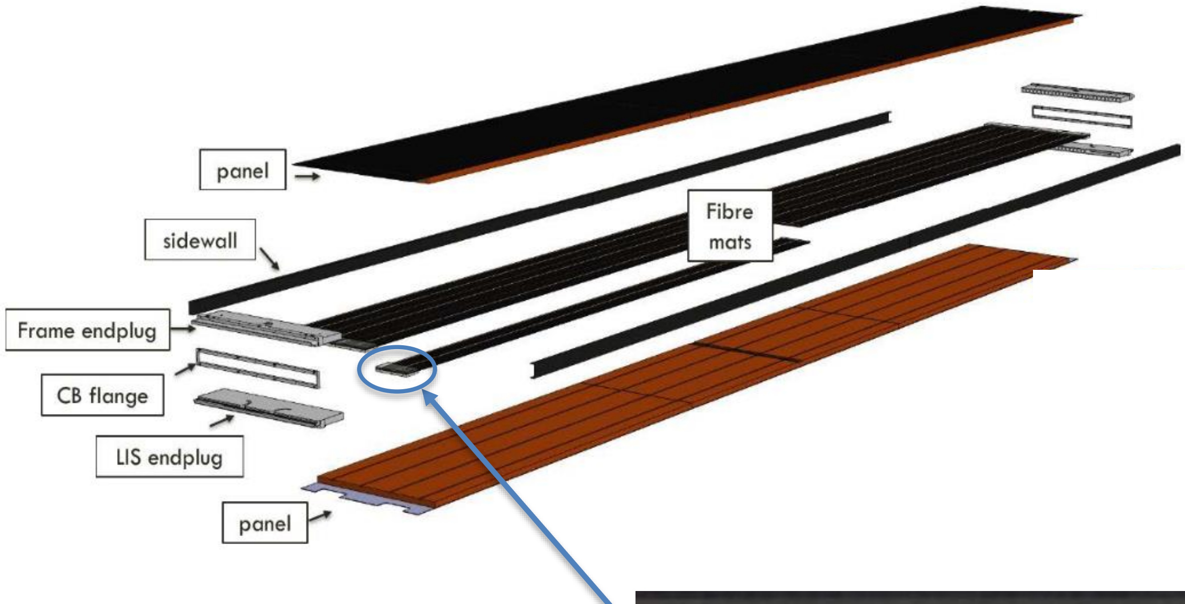
Procedure is automatic, reliable (> 90% success up to 550 µm) and fast (1s)

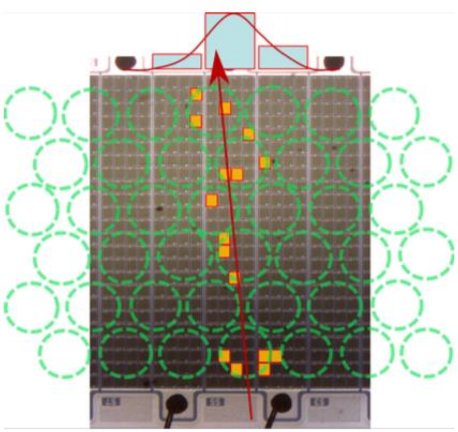
SciFi fibre modules

128 modules in total

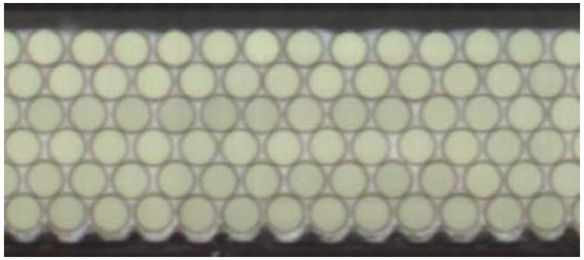
1 module (5 x 0.5 m^2)

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





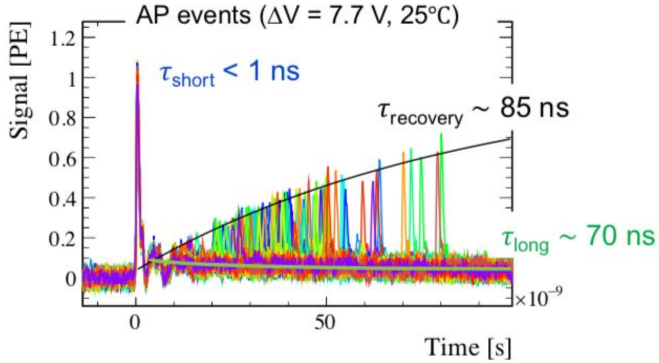
16-20 photo-electrons per 6-layer mat

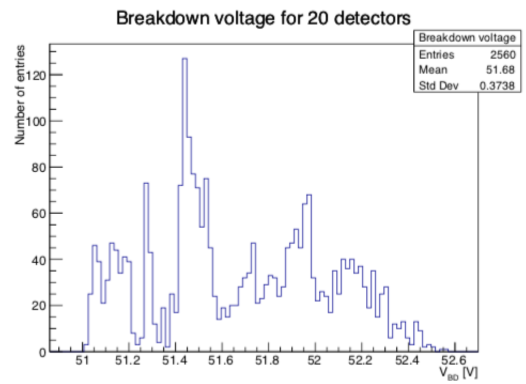


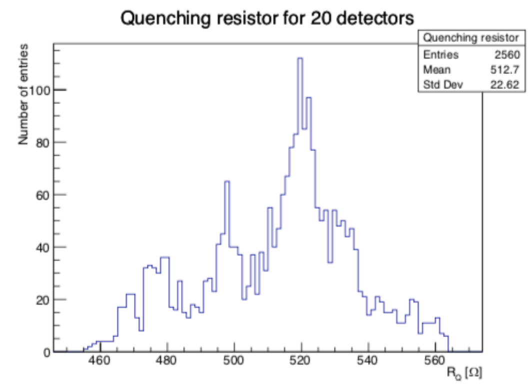
6 fibre layers per mat

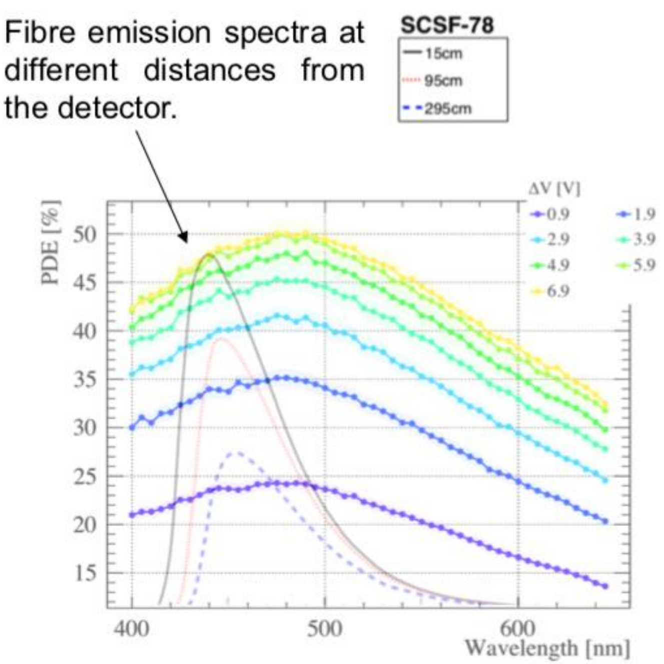
SiPM characteristics

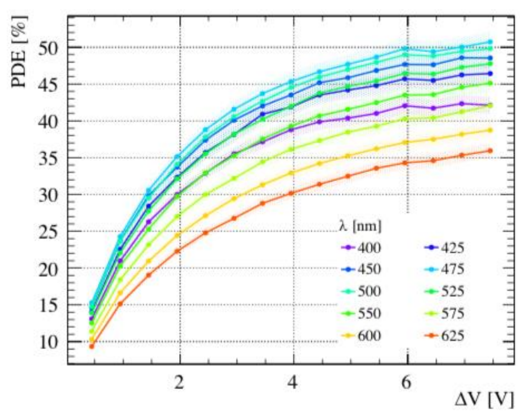
A. Kuonen, PhD thesis, EPFL 2018,
O. Girard, PhD thesis, EPFL 2018

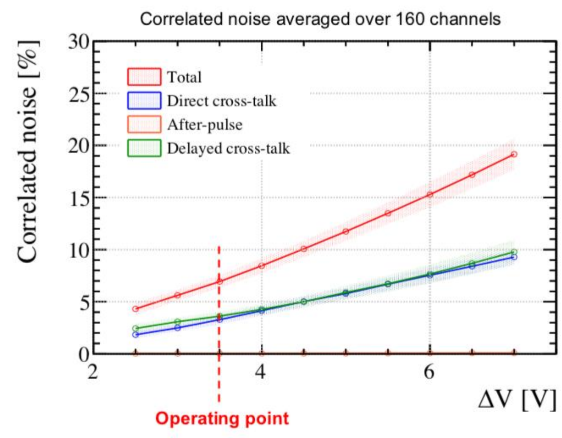












SiPM annealing

A. Kuonen, PhD thesis, EPFL 2018,
O. Girard, PhD thesis, EPFL 2018

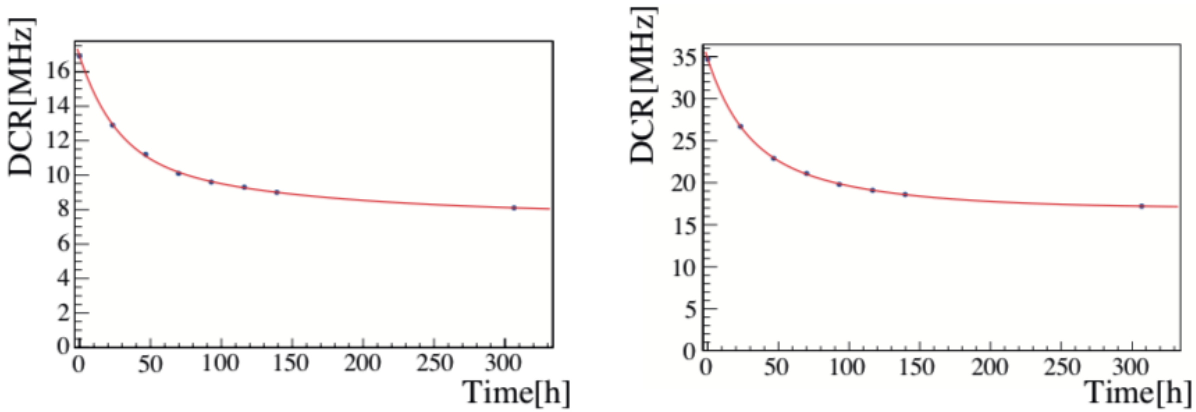


Figure 6.29: DCR as a function of time during the annealing process at 35°C for a H2015 detector irradiated to $6{\cdot}10^{11}\,n_{eq}/cm^2$ (left) and $12{\cdot}10^{11}\,n_{eq}/cm^2$ (right) and measured at -40°C.

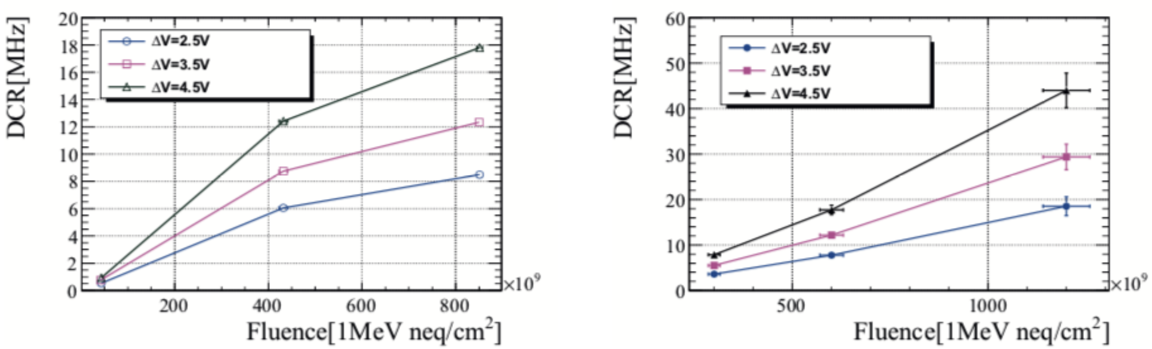


Figure 6.30: DCR for proton (left) and neutron (right) measured as a function of the fluence. Proton and neutron irradiation can be compared with a hardness factor of ~3. All measurements are performed at a temperature of -40°C.

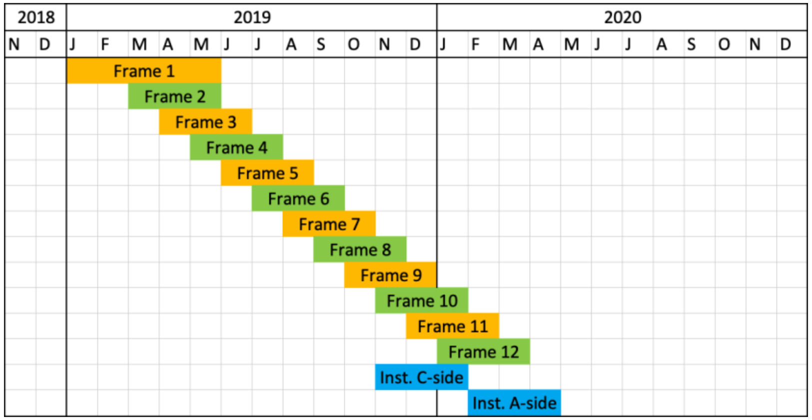
Summary of project status

	R&D	proto	pre-series	series	status
Fibres				100%	☑
Mats				100%	☑
Modules				100%	☑
SiPMs				100%	☑
Flex cables				80%	☑
Cold box				30%	☑
PACIFIC				100%	☑
FEE				10%	☑
C-frames					☑
Services					☑
Controls					☑

Color code: in-time / late but w/o impact on project / delays w/ impact on project

Schedule is VERY tight but project is on track!

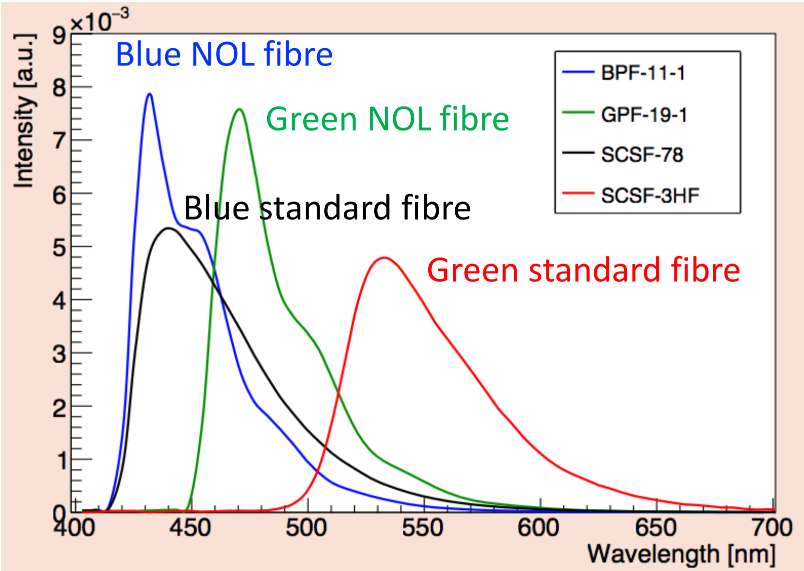
C-Cages for parallel work on 4 C-Frames



NOL prototype fibre performance

O. Borshchev et al., 2017 JINST 12 P05013

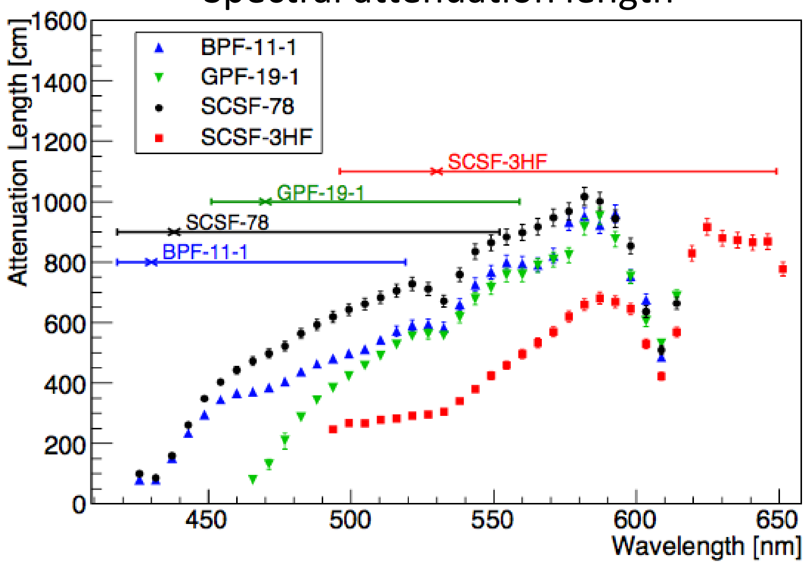
Emission spectra (@ 15 cm from excitation point)



Peak wavelengths:

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

Spectral attenuation length

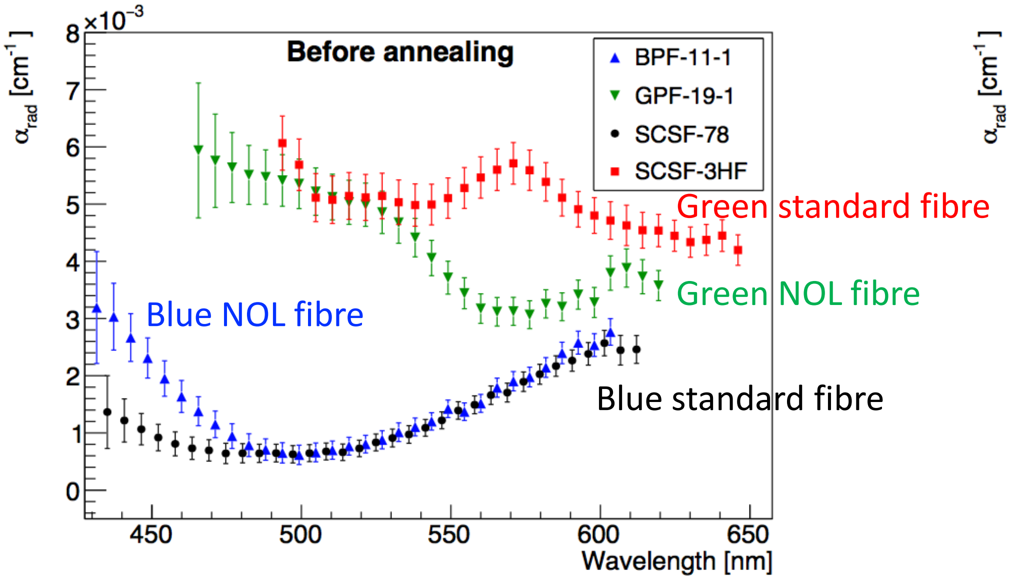


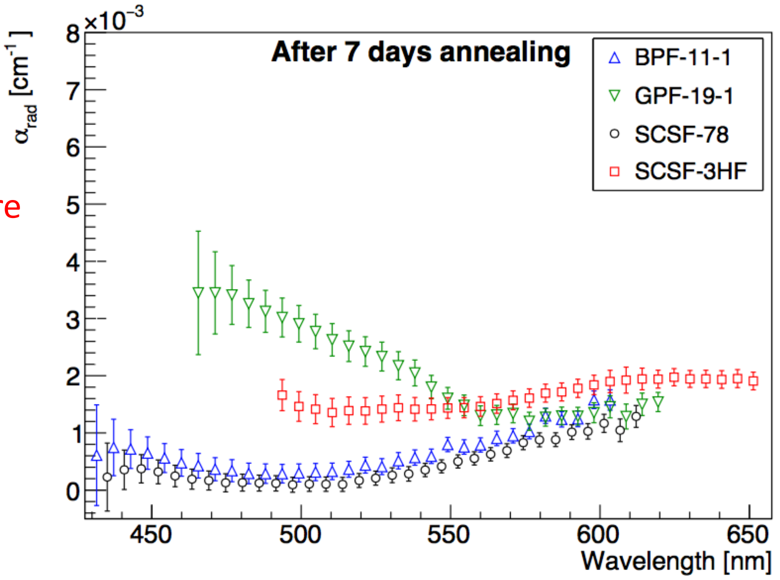
- Longer wavelengths are less attenuated
- Minima: excitation of PS vibration levels

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.