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2015 JINST 10 C08005

(http://iopscience.iop.org/1748-0221/10/08/C08005)

PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *May 18, 2015*
ACCEPTED: *June 22, 2015*
PUBLISHED: *August 6, 2015*

SECOND INTERNATIONAL SUMMER SCHOOL ON
INTELLIGENT SIGNAL PROCESSING FOR FRONTIER RESEARCH AND INDUSTRY
UNIVERSITY PARIS-DIDEROT CAMPUS, PARIS, FRANCE
14–25 JULY 2014

Scintillating Fibre Tracking at High Luminosity Colliders

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ABSTRACT: The combination of small diameter scintillating plastic fibres with arrays of SiPM photodetectors has led to a new class of SciFi trackers usable at high luminosity collider experiments. After a short review of the main principles and history of the scintillating fibre technology, we describe the challenges and developments of the large area Scintillating Fibre Tracker currently under development for the upgraded LHCb experiment.

KEYWORDS: Particle tracking detectors (Solid-state detectors); Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Photon detectors for UV, visible and IR photons (solid-state)

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doi:10.1088/1748-0221/10/08/C08005

Contents

1 Introduction

Plastic scintillating fibres (PSF or SciFi) as the active element in tracking detectors have been used for more than 30 years. A comprehensive review of the principles, technologies and some major implementations up to the mid-1990s can be found in [1]. The SciFi technology allows building intrinsically fast, low mass detectors with a high degree of geometrical adaptability. Scintillating plastic fibres are also found in applications as active target arrangements as well as the active media in electromagnetic and hadron calorimeters. However, these are beyond the scope of this article and are not discussed any further.

It is in particular the impressive evolution of the photodetection technology, currently culminating in the so-called Silicon Photomultiplier (SiPM), which revived the interest in the SciFi technology and has opened up new fields of applications. The intrinsic properties of the SiPM, in particular the combination of high sensitivity, high gain and fast pulse shape, implemented in a solid-state sensor of sub-mm^2 size, allow for designing large-scale high-resolution SciFi detectors read out at the bunch crossing rate of a modern hadron collider such as the LHC.

On the other hand, the most advanced photodetection technology only mitigates some of the intrinsic limitations of the SciFi technology. The achievable spatial resolution is correlated with the fibre diameter and thus with the light yield, unless one conceives staggered multi-layer fibre arrangements which come at a cost in terms of the number of readout channel and material budget. A further limitation is the moderate radiation hardness of plastic scintillators which currently prevents their use in very harsh radiation environments.

LHCb is developing a large planar SciFi tracker which will, from LHC Run 3 onwards (2019), replace the currently installed Outer Tracker (based on gas straw tubes) and Inner Tracker (silicon microstrips) by a single detector technology [2]. The SciFi detector is based on fibres of 250 μm diameter read out by arrays of SiPM photodetectors. The total active detector surface is 360 m^2.

This article, which originates from a lecture given at the INFIERI detector school in summer 2014, is organised as follows. It starts off with a short review of the scintillating fibre technology including the degradation of the fibres under ionising radiation. This is followed by a recap of the principles and performance of SiPM photodetectors. For the SiPM as well, the degradation due to radiation damage is a critical issue. The general design principles of SciFi tracking detectors are discussed in section 4, followed by a short historical overview of a selection of SciFi trackers. The last two sections are devoted to the design and technological choices of the LHCb SciFi tracker and the current R&D status.

2 Plastic scintillating fibres

Scintillating fibres in a tracking detector have two functions: (1) they convert the ionisation deposited by charged particles to optical photons and (2) they transport the optical signal to the readout devices which, in order to minimise the material budget, are often located outside the active volume.

A plastic scintillating fibre consists of a core, typically made of polystyrene (refractive index $n = 1.59$), and one or more thin cladding layers, made from polymers with lower refractive index, e.g. PMMA ($n = 1.49$) or a special fluorinated polymer ($n = 1.42$). The thickness of each cladding layer is typically 3% of the total diameter.

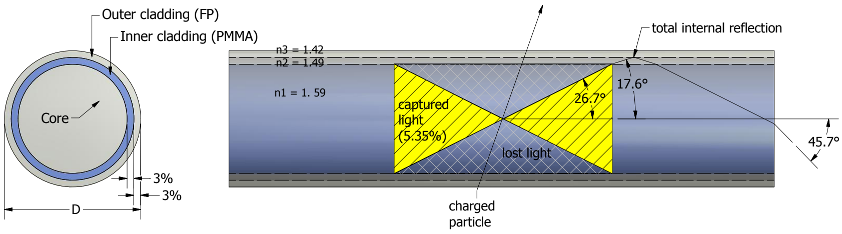
Signal generation in a plastic scintillating fibre is a multi-step process. Ionisation energy deposited in the core of the fibre leads to excitation of molecular levels (specifically of the so-called π electrons) in the benzene rings of the polymer chain. The relaxation time and scintillation light yield of polystyrene are however poor. An organic fluorescent dye with matched excitation energy levels is added to the polystyrene base ($\sim$1% by weight) to improve the efficiency of the scintillation mechanism. Energy is transferred quite rapidly (sub-ns) from the base to this ‘activator’ dye by means of a non-radiative dipole-dipole transmission, known as the Förster resonant energy transfer, where the excited energy state of the dye will subsequently relax by emission of a photon. The activator dye is chosen to have a high quantum efficiency ($> 95\%$), a particular emission wavelength spectra, and fast decay time (less than a few ns). Often, a second wavelength shifting dye is admixed ($\sim$0.05% by weight) which absorbs the photons from the activator (blue or UV) and re-emits them (isotropically) at longer wavelengths (blue-green). In this wavelength range, the probability of re-absorption by the dyes is reduced and the photons profit from a generally better transparency of the polystyrene.

Light transport in the fibre relies primarily on total internal reflection at the interface between the fibre core and the cladding structure. Meridional rays, i.e. those crossing the fibre axis, are reflected if their angle of incidence relative to the surface normal exceeds the critical angle $\theta_{\mathrm{crit}} =$

arcsin$(n_{\text{clad}}/n_{\text{core}})$. The corresponding solid angle element

$$\frac{d\Omega}{4\pi} = \frac{1}{2}\int_{0}^{90-\theta_{\text{crit}}} sin\theta d\theta, \tag{2.1}$$

also called trapping fraction, describes the fraction of isotropically emitted photons which will be transported towards one end of the fibre. For round fibres with a single cladding ($n_{\text{core}} = 1.59, n_{\text{clad}} = 1.49$), this fraction is 3.1 %. With a second fluorinated cladding ($n_{clad,fluor} = 1.42$), the fraction is increased to 5.3%. In practice, the trapping fraction is slightly larger, as rays with helical paths and light reflected at the cladding-air interface contribute, however these are attenuated quickly along the length of the fibre due to the increased number of reflections and longer pathlength.



(a) end view

(b) side view

Figure 1. Schematic: light trapping and propagation in a scintillating fibre.

A simple approximation of the intensity of light at a given distance is an exponential, $I(z) = I_0 \cdot e^{-z/\Lambda_{\text{att}}}$. The attenuation length, Λ_{att}, has various wavelength dependent contributions, $\Lambda_1(\lambda)$, $\Lambda_2(\lambda)$, etc., which can be attributed to different phenomena such as Rayleigh scattering, self absorption by the dyes and radiation induced defects. Essentially all effects show increased attenuation for short wavelength (blue, UV). Consequently, the emission spectrum of a fibre will first lose its short component and shift towards longer green and red wavelengths. Particularly for long fibres, this aspect must be considered when selecting the optimum photosensor. Typical values for the attenuation length are of the order Λ_{att} =3–5 m, averaged over the sensitivity window of a typical photosensor (400–600 nm, more details are in section 3)

To illustrate, we consider an example which resembles the LHCb SciFi. Manufacturers quote intrinsic light yields of the order 7000–10000 photons per MeV. A minimum ionising particle ($dE/dx = 2$ MeV/cm) generates in a ø250 μm fibre ($d_{\text{core}} = 220\,\mu$m) approximately 260 scintillation photons. Assuming a trapping fraction of 5.3% and an attenuation length of 3 m, only about 7 photons will arrive at the photosensor in 2 m distance. Assuming the photosensor to be a PMT with an average photon detection efficiency of e.g. 20 % and some Fresnel reflection losses at the interface between fibre and PMT the average detected signal becomes about 1 photoelectron (PE). Figure 2 shows an experimental verification using a Kuraray[1] SCSF-78MJ fibre of 250 μm diameter. Taking into account the statistical (Poissonian) fluctuations of these numbers, one has to conclude that a single fibre is unable to guarantee 100% hit efficiency, as $\epsilon_{\text{hit}} = 1 - P(0, 1.0) = 1 - e^{-1.0} = 63\%$.

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[1] Kuraray Trading CO LTD, Tokyo, Japan.

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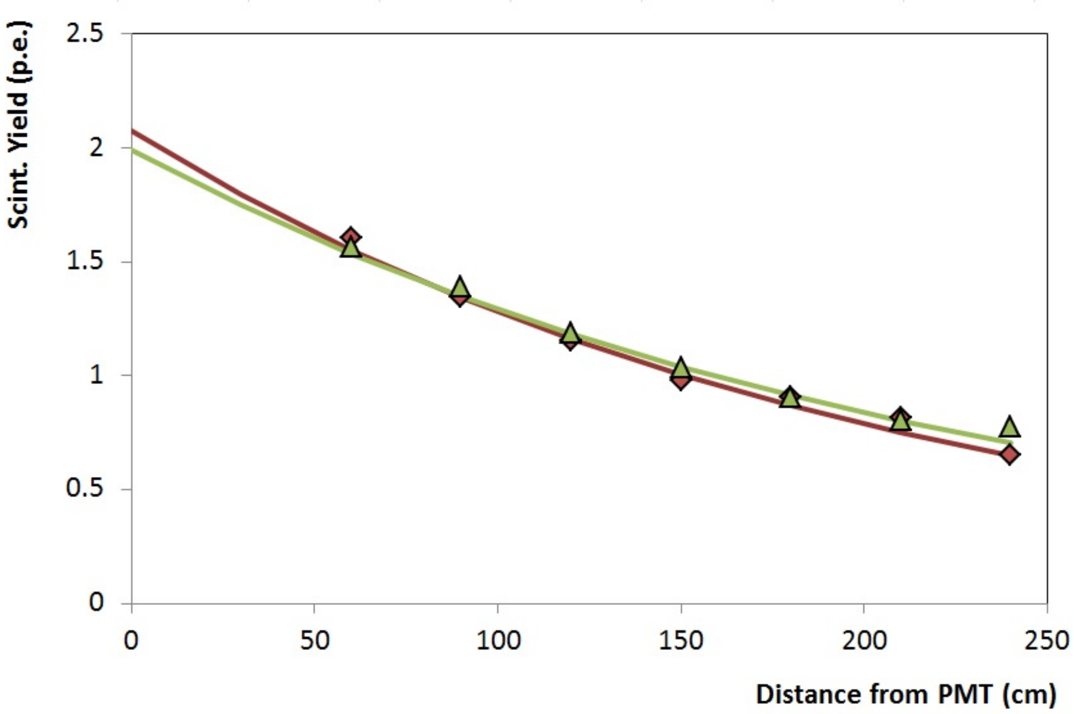

Figure 2. Light yields measured with a PMT (bialkali photocathode) from two non-mirrored Kuraray SCSF-78MJ fibres of 250 μm diameter. The fibres are excited by electrons from an energy filtered Sr-90 source ($E = 1 \pm 0.1$ MeV). The fibres are from two different batches produced within about 6 months.

2.1 Radiation tolerance of the fibre

Plastic scintillators which are exposed to substantial doses of ionising radiation show a decrease in light yield which is attributed to two major causes: (1) degraded transmission properties of the base plastic and (2) a degradation of the scintillating fluors. The second cause can usually be avoided by the choice of robust fluors that are added to the base scintillator material [3]. A large amount of research has been done since the 1980s to find robust organic scintillators which can be dissolved in plastic and still retain good optical qualities [1, 4]. Typically one or two stable compounds with large Stoke's shifts and good quantum efficiency are chosen. The degraded optical transmission of the base plastic, typically polystyrene (PS), is a result of the creation of additional scattering and absorption centres produced during irradiation. These light loss centres are macromolecule radicals produced in the polymer under ionizing radiation [5]. The increased attenuation of the light is stronger in the blue wavelengths with less effect in the green. To reduce the impact of this effect, the radiation hardness of scintillating fibres can be improved by choosing additional scintillating dyes with large Stoke's shifts. It has also been observed that there is a radiation dose rate effect on the creation of certain types of attenuation centres which are dependent on the availability of oxygen within the fibre for production [4, 5]. Additionally, different types of attenuation centres have also been observed to decay over time, with time constants depending on the radical type and, for certain other types, the abundance of oxygen within the polystyrene matrix that can aid in annealing. As such, the total effect on the loss of light transmission depends on the particular environment within which the fibre is located, as well as the ionization rate to which the fibres are exposed.

3 Silicon photomultipliers (SiPM)

The SiPM is a silicon based photodetector, which is fast, compact and single photon sensitive. A good overview of the most important characteristics is given in ref. [6]. A SiPM consists of many pixels which are themselves microscopic avalanche photon detectors (APDs), with typical sizes from 20×20 to $60 \times 60\,\mu\mathrm{m}^2$, connected in parallel as a macroscopic (mm^2 area) channel. Each pixel is operated in Geiger-Müller mode such that a single photon absorbed in the pixel will trigger a complete discharge (avalanche) with the release of the full charge. The discharge stops as the current is drawn via a quench resistor and the cell then recharges. The total signal of a SiPM is the sum of the charge of all triggered pixels. The charge produced in a single pixel corresponds to the gain $G = Q/e$. The gain depends on the surface of the pixel, the thickness of the amplification region which determines the capacity and the operation voltage above the avalanche limit (ΔV): $G = C \cdot \Delta V / e$. Different technologies will provide gains for $50 \times 50\,\mu\mathrm{m}^2$ pixels from 10^6 to 10^7. Impurities and thermal generation of free charges are responsible for a permanent rate of avalanches that are not induced by photons. This results in a Dark Count Rate (DCR) which is typically of the order of several 100 kHz/mm^2. For SciFi applications, detection of single photons is required. With a detection threshold set to 0.5 PE, a dark noise signal is *a priori* indistinguishable from a photon induced signal.

Other noise sources are the after-pulses which are due to temporarily trapped charges near the avalanche region. The after-pulses occur delayed after the primary avalanche, i.e. at a time when the pixel is usually still recovering. Their amplitude depends therefore on the delay and is generally smaller than a single PE pulse. A very significant effect for SciFi applications is the optical cross talk (x-talk). During the avalanche in a pixel, a large number of IR photons are produced. Silicon is is largely transparent to IR and allows these photons to reach neighbouring pixels and trigger there secondary avalanches. X-talk produces signals at the same time as the primary avalanche.

Over the past decade, the SiPM manufacturers have made significant progress in reducing the DCR by material and design optimisations. The best devices show now at room temperature $f_{\mathrm{DCR}} = 100\,\mathrm{kHz/mm}^2$ (see section 7.3). However, like other silicon devices, SiPM are sensitive to the so-called Non Ionising Energy Loss (NIEL) of hadrons which leads to damage of the silicon lattice and as a consequence a large increase of the DCR and the associated leakage current. The DCR increases linearly with the particle fluence (usually expressed in the number of 1 MeV neutron equivalent particles per cm^2) and rapidly reaches levels where the initial DCR is insignificant. In a SciFi tracker, where single photon sensitivity must be maintained, the DCR can only be managed by reducing the operational temperature which reduces the DCR by a factor of 2 typically for every 10 K.

4 General considerations: tracking with scintillating fibres

The primary functions of a tracking detector are (1) to determine the track parameters (position and angle) with the required position and (2) to achieve the first function with high efficiency. Ignoring factors like particle momentum and upstream material, this translates to the requirements of high single hit resolution and large hit efficiency.

The hit efficiency is directly linked to the signal amplitude (in a SciFi tracker, this is usually measured in p.e.) and the minimum threshold (in p.e.) at which the photodetector can be operated. A track is usually reconstructed from a combination of true and false hits measured in the various detector layers. This can lead to so-called ghost tracks which are tracks not matched to a charged particle in the event. In a SciFi tracker, the ghost rate is related to the noise hit or noise cluster rate, which depends again (but not only) on the threshold applied to the photodetector.

Strictly speaking, the requirements for high spatial resolution, which tends toward a small fibre diameter, and high hit efficiency, which tends toward a large fibre diameter, are contradicting each other. In first approximation, the spatial resolution of fibre is given by its diameter divided by $\sqrt{12}$, while the number of photons scales linearly with its diameter. This dilemma may be resolved or at least mitigated by clever geometrical arrangements of the fibres. Staggered multi-layer arrangements increase the signal amplitude without impacting on the achievable resolution. Such arrangements can be implemented without inflating the number of readout channels, if the channel geometry of the photodetector can be adapted to the multi-layer structure.

The signal amplitude for a given fibre diameter can be increased by choosing fibres with high intrinsic scintillation yield and long attenuation length. We will describe in section 7.2 a promising innovative approach to increase scintillation yield which is however currently still in a validation and demonstration phase.

Augmenting the trapping fraction of a fibre by applying low-refractive index cladding materials could be another way to improve performance. However, the double cladding structure (CERN RD7 and Kuraray, 1990) with a fluorinated polymer of $n = 1.42$ is still the current state of the art.

Given the relatively low light levels, the efficient detection of the scintillation light calls generally for single photon sensitive detectors with high gain ($\mathcal{O}(10^6)$). The signal amplitude scales directly with the photon detection efficiency of the photosensor. The invention and evolution of the SiPM photosensor in the past two decades is clearly boosting the use of SciFi technology and opens new applications.

In a harsh radiation environment, such as that observed at a high luminosity hadron collider, the design, operation and the achievable performance of a SciFi tracker is largely driven by radiation related effects. The ionising dose may lead to a degradation of the fibre transparency and hence reduce the amplitude of the detectable signal. The detector design needs to accommodate these losses, e.g. in form of extra fibre layers. In addition, the performance of the photodetector itself may suffer from radiation induced effects, leading to increased noise levels and therefore impacting on the minimum applicable threshold. Shielding, low temperature operation and very fast readout electronics are able to mitigate these effects.

Scintillating fibres allow building light weight tracking detectors which require a minimum of mechanical support. The mechanical flexibility of fibres leads to a large choice of geometrical arrangements and readout schemes to best match the specific requirements of the tracking detector. Figure 3 shows several examples.

The traditional technology of building multi-layer fibre mats is based on the winding of fibres on a wheel which carries a fine-pitch thread. This method can give positioning precision in the $\mathcal{O}(50\,\mu\text{m})$ range, but lacks the precision and repeatability of a silicon device produced by wafer-

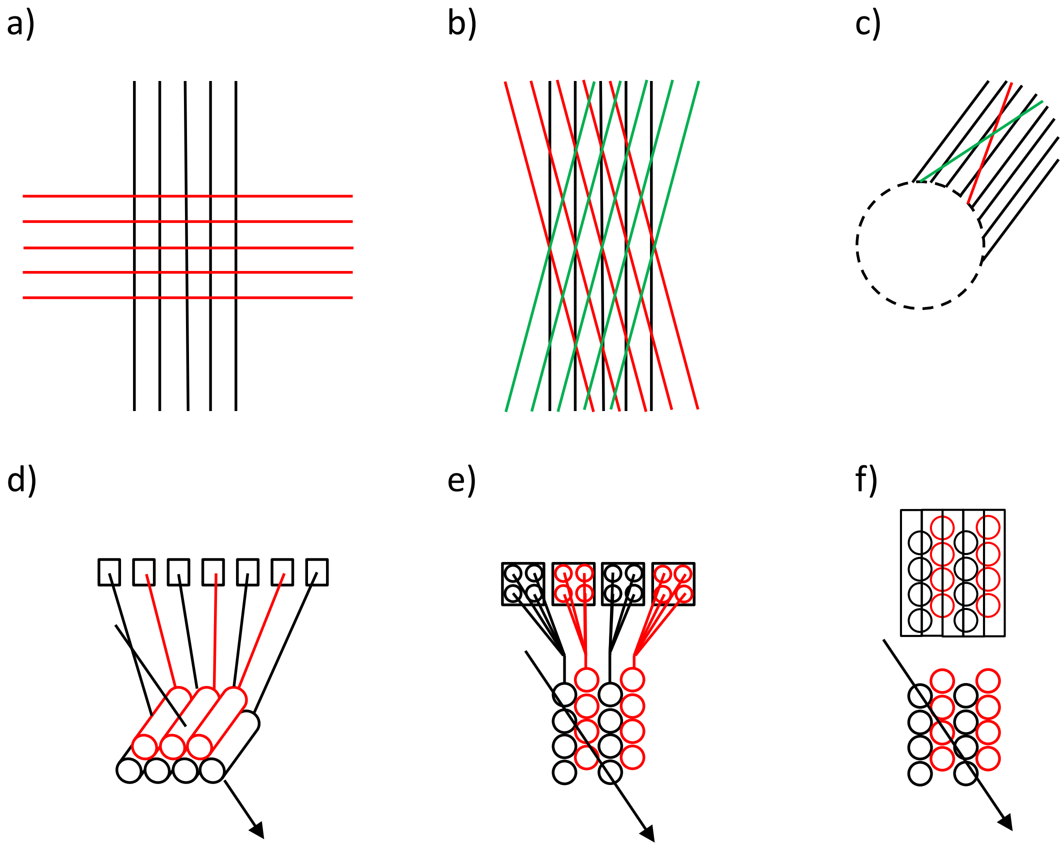

Figure 3. Sketches *(a)–(c)* show a selection of planar and cylindrical arrangements of scintillating fibres, including stereo layers. Colours are used for clarity and do not correspond to different fibre types. The LHCb SciFi tracker described below is based on a planar stereo layer arrangement as shown in b). Connection schemes to the photodetectors are shown in the bottom row *(d)–(f)*. The rectangular boxes represent photodetectors or individual channels of multichannel devices. Scheme f) is similar to the one implemented in the LHCb SciFi tracker.

level microfabrication including photo-lithographic patterning. The construction of a large-scale fibre tracker is generally a labour-intense endeavour of which only a small part can be outsourced to industry. One may speculate whether the currently rapidly evolving 3D printing techniques may allow for more effective methods to produce high precision fibre mats or other geometrical arrangements. We are not aware of any specific R&D being performed in this direction.

5 A bit of history

The Swiss physicist Jean-Daniel Colladon (1802–1893) was the first to discover in 1841 that a light ray can be guided and bent in a jet of water employing total internal reflection at the interface between the water jet and the surrounding air. More than a century later G.T. Reynolds and P.E. Condon [7] describe in 1957 a scintillating filament, apparently unclad, and its potentially fast timing and good space resolution which makes it suitable for particle tracking.

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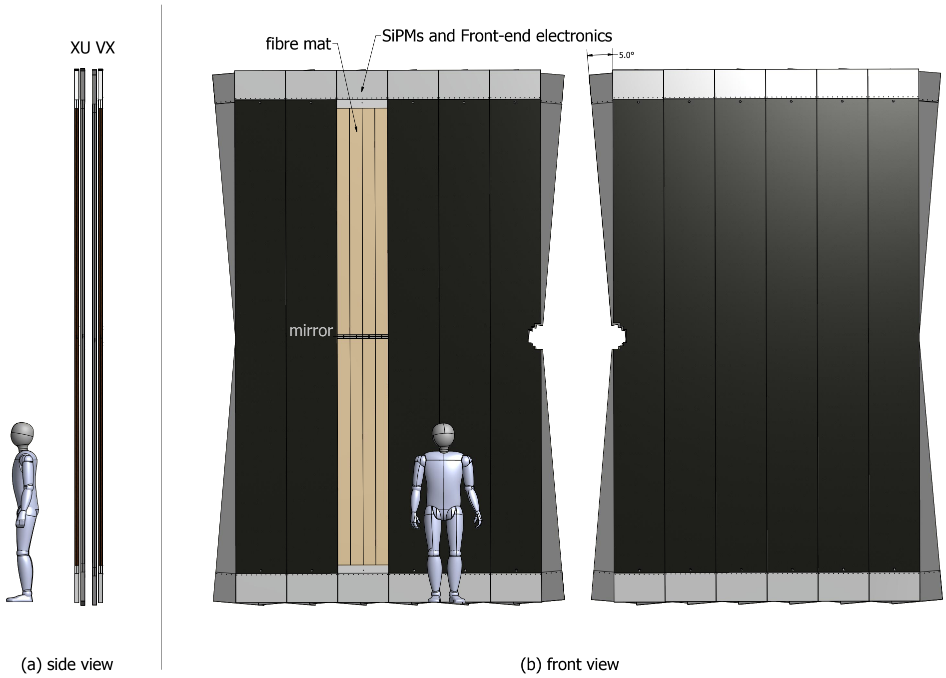
The SciFi technology was for the first time applied at major scale in the CERN UA2 detector upgrade which took place from 1985–87. A cylindrical arrangement of some 60’000 fibres in 24 layers were used for tracking and pre-shower measurement. It’s worth mentioning that the development of the production technology and the fibre production itself was performed by the French nuclear research institute CEA-Saclay. The 2.1 m long fibres had 1 mm diameter and were single-clad [8]. The 24 layers were grouped as triplets consisting of axial and stereo layers, which allowed to derive also the axial coordinate of tracks. The fibre ends were fed into 32 collector plates, which were viewed from the other side by complex 3-stage image intensified CCDs [9]. A readout cycle lasted about 10 ms. The opposite non-read end of every fibre was polished and mirrored by a sputtered aluminium film ($R \approx 0.5$). The UA2 SciFi tracker achieved a photoelectron yield of 2.8 for MIPs traversing a single fibre at 1.1 m distance from the photosensor, leading to a single hit efficiency of $> 90\%$. A single hit spatial resolution of 0.35 mm was obtained. The resolution of a track was found to be better than 0.2 mm.

The CERN CHORUS experiment [10] adopted parts of the UA2 technology, in particular the readout concept. They read a total of 1 million 2.2 m long fibres of 0.5 mm diameter with 58 image intensified CCDs. They introduced multi-layer fibre ribbons in which the layers were staggered by half the fibre diameter and a winding machine to produce these ribbons. To suppress inter-fibre cross-talk, which for small diameter fibres occurs due to the penetration of primary (UV) photons into the neighbouring fibres, the fibres were painted with an extramural absorber (EMA) which acted at the same time as diffuse reflector and glue.

The Central Fibre Tracker (CFT) of the Fermilab D0 experiment marks another milestone [11]. Its 80,000 double-clad fibres of 835 μm diameter are arranged on 8 concentric support cylinders ($20\,\mathrm{cm} \leq R \leq 52\,\mathrm{cm}$, $166\,\mathrm{cm} \leq L \leq 252\,\mathrm{cm}$). Every cylinder carries two doublet layers, an axial one and a stereo one. Doublet layers consist of two fibre layers with about a half-diameter staggering. The scintillation light is coupled into clear light guide fibres and brought to the readout devices, so-called Visible Light Photon Counters (VLPC). These are essentially highly doped silicon avalanche photodiodes with unprecedented characteristics: quantum efficiency around 75% and a gain of about 40,000, which makes them capable of detecting and even counting single photoelectrons. The small gap between the impurity band and the conductance band requires to operate the VLPC at cryogenic temperature ($T = 9\,K$) The D0 collaboration reported photoelectron yields of about 10 per fibre, a hit efficiency of 99.5% and a doublet hit resolution of $100\,\mu m$. The readout electronics of the CFT was fast such that it could be included in the L1 trigger (every 132 ns).

6 The LHCb SciFi Tracker

The LHCb SciFi Tracker is part of a major upgrade campaign of the LHCb detector to allow operation during the LHC Run 3, which begins in 2019, at a levelled luminosity of $2 \times 10^{33}\,\mathrm{cm}^{-2}s^{-1}$ and at a readout rate of 40 MHz (bunch crossings every 25 ns). The SciFi tracker is designed to replace the current Outer Tracker (based on gas drift tubes) and the Inner Tracker (silicon microstrips). It consists of three tracking stations with four independent planes each (X-U-V-X, stereo angle $\pm 5^\circ$) and extends over 6 m in width and 4.8 m in height, as seen in figure 4. Blue emitting scintillating plastic fibres of type SCSF-78MJ from Kuraray with $250\,mu$m diameter are arranged in a staggered close-packed geometry to 6-layer fibre mats. The mats are 2.4 m long with a mirror applied at the non-readout end. The scintillation light exiting at the opposite end is detected by linear arrays of SiPM detectors (64 channels of$0.25 \times 1.6\,\mathrm{mm}^2$ size). The height of a SiPM channel (1.6 mm) extends over all 6 layers of the fibre mat. The pitch (0.25 mm) allows resolving the clusters of hit fibres of typically 2 or 3 channels width. The geometrical layout and the fibre-photodetector coupling scheme correspond to the ones shown in figure 3 b) and f). The signals are processed with a fully customised three-threshold electronics which can improve the spatial resolution beyond the digital resolution $D_{\mathrm{fibre}}/\sqrt{12} = 72\,\mu\mathrm{m}$. A discussion of how to read and process the signals from nearly 600,000 SiPM channels at a rate of 40 MHz is unfortunately beyond the scope of this article.



(a) side view

(b) front view

Figure 4. Layout of one of three stations for the LHCb SciFi Tracker.

While the chosen technology — staggered fibre mats with SiPM array readout — has been previously demonstrated in the PerdAIX balloon experiment [12], the LHCb requirements and the LHC environment push it to the limits in several respects.

The scintillation light has to travel up to 2.4 m, the reflected light even up to 4.8 m, before it can be detected by the SiPM. This requires $250\,\mu\mathrm{m}$ fibres of particularly long attenuation length (> 3 m) which is a challenge for the fibre producers. With a propagation delay of 6 ns/m there may be spill-over effects into the next bunch crossing.

The ionising dose in the inner region close to the LHCb beampipe is expected to reach 35 kGy, falling off rapidly ($\approx 1/r^2$) away from the beam pipe to values of about 50 Gy close to the SiPMs. This means, however, that radiation damage affects mainly the region where most signal events originate and the light which must travel the furthest to the SiPM.

The SiPMs, located more than 2.4 m above and below the beampipe, will be exposed only to small ionizing doses, but they suffer from a neutron fluence of up to $6 \cdot 10^{11}\ \mathrm{cm}^{-2}$ (1 MeV neutron equivalent) during the foreseen lifetime of the detector. Proportional to the neutron fluence, the leakage current (or, equivalently, the dark noise rate) of the SiPMs rises to values which *de facto* makes them unusable. *Normal* operation can be restored by cooling the SiPMs, which suppresses the noise rate by a factor of about $2^{\Delta T/10}$. The SiPMs in the LHCb SciFi Tracker are foreseen to operate at -40°C to manage the increased leakage current.

There is unfortunately no equivalent remedy which would neutralise the radiation damage to the scintillating fibres. The detector design foresees sufficiently thick scintillating fibre layers, such that the signal after radiation damage still guarantees the high hit efficiency required for tracking.

The SciFi tracker design is expected to yield, at the end of its lifetime (35 kGy, $6 \cdot 10^{11}\,\mathrm{neq/cm^2}$), between 12 and 16 PE, depending on the position. This will allow for a hit detection efficiency above 98% and a spatial resolution around 60 μm.

As described below, a novel scintillation material, the so-called NOL, promises higher initial light yields and should be not more affected by radiation damage than standard material. If validated, this material is a candidate for the innermost detector region. If it turns out that all precautions are insufficient to guarantee appropriate performance over the full lifetime, the detector is designed such that the most damaged inner most modules can be replaced.

7 LHCb SciFi R&D: challenges and strategies

In the following we concentrate on a number of challenges which are critical for the performance of the LHCb SciFi detector and outline the taken strategies to cope with them.

7.1 Degradation of the scintillating fibres in ionising radiation

Previous irradiation studies have typically focussed on other fibres such as 3HF [13], Bicron-12 [5] and Kuraray SCSF-81 fibres. The fibre foreseen to be used in the LHCb Scintillating Fibre Tracker is the Kuraray SCSF-78MJ fibre. This newer fibre has a longer attenuation length than previous fibres and uses two different dyes[2] that result in a fast scintillation time with good light yield. Unfortunately, it has received limited study in literature, and under circumstances different from the LHCb upgrade environment, with reported results that are inconsistent or contradictory. The particular fibre type, the bonding of fibres with glue into ribbons, the dose profile along the fibres and the dose rate profile results in a complex system where the absolute magnitude of the radiation damage becomes difficult to judge purely from results in literature. As such, a campaign of measurements to cover to the total expected dose received in LHCb was undertaken.

Irradiation of SCSF-78MJ

The maximum expected dose after 10 years deposited in the scintillating fibres in the LHCb upgrade ranges from 35 kGy near the beam pipe decreasing rapidly ($\approx 1/r^2$) down to 50 Gy 2.5 m away. Achieving this dose profile with similar dose rates over this length of fibre was not possible in a lab setup due to beam and time constraints, and, as such, an attempt was made to achieve comparable results in multiple separate measurements. To achieve the higher doses greater then 1 kGy, fibres were irradiated in proton beams where the dose rate was considerably higher than expected in the LHCb upgrade environment. To achieve doses lower than 1 kGy, the fibres were irradiated using

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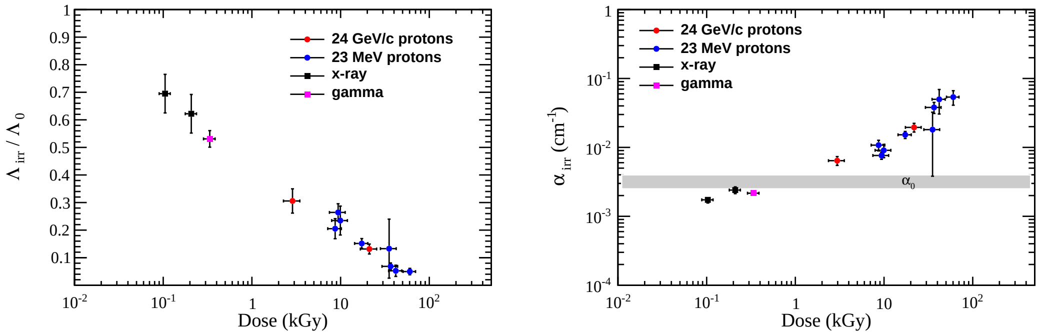
[2] Assumed to be p-Terphenyl (PT) and Tetraphenyl Butadiene (TPB) based on spectra and decay times.

x-ray or gamma sources with lower dose rates. In the proton and x-ray irradiations, several fibres were grouped and epoxied onto plastic holders to simulate the similar environment of the tracking detector. Sections of the fibre were then irradiated step-wise to a dose profile similar to the LHCb upgrade. A summary of the measurements and doses achieved is shown in table 1.

Table 1. Irradiations of scintillating fibres conducted for the LHCb SciFi upgrade detector at different facilities.

Beam Type	Facility	Doses (kGy)	Dose rate (kGy/h)
24 GeV/c protons	CERN PS	3, 22	1.7, 0.4
24 MeV protons	KIT	9–60	$1.8 \cdot 10^3$
F^{18}(e^+ to 511 keV γ)	CERN/AAA	0.5	$\sim 2 \cdot 10^{-2}$
35 kV x-ray	Uni. HD	0.1, 0.2	$3.5 \cdot 10^{-3}$

Measurements were made of the attenuation length before and after irradiation using a UV LED source to stimulate the fibres. The CERN PS measurement also used a Sr-90 beta source to measure the light yield and attenuation length. In all measurements, the light output was measured with a calibrated PIN diode, as well as with a photospectrometer to examine the wavelength dependent transmission damage.



(a) combined data for Λ_{irr}

(b) combined data for α_{irr}

Figure 5. The combined attenuation length data as measured with a PIN diode are shown with statistical errors versus the total integrated ionisation dose from four different fibre irradiation studies.

In general, the results agree with previous measurements of other fibre types over a similar range of doses [13]. A rather rapid onset of damage to the transparency is seen at lower doses, seen on the left in figure 5. If the increased loss of light is attributed to additional scattering or absorption within the fibre due irradiation, the new attenuation length can be described as $\Lambda_{\mathrm{irr}} = \frac{1}{\alpha_0+\alpha_{\mathrm{irr}}}$. A plot of the reduced attenuation length, $\Lambda_{\mathrm{irr}}/\Lambda_0$, as well as the attenuation coefficient, α_{irr}, as a function of integrated ionizing dose for the irradiations conducted for the LHCb upgrade are seen in figure 5. Given the rapidly decreasing profile of the ionizing dose along the fibre, and the results seen in the LHCb SciFi Tracker irradiation measurements, including spectral measurements, the total expected loss of signal from the highly irradiated region around the beam-pipe will be close to 40%.

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7.2 Nanostructured Organo Luminophore Fibres

Recently, a Russian group has developed a novel type of plastic scintillator, in which so-called Nanostructured Organosilicon Luminophores (NOL) are admixed to the polystyrene (PS) matrix [14]. Unlike traditional plastic scintillators, where the activator and wavelength shifting dyes are independently and randomly distributed in the PS matrix, the NOL approach couples activator and wavelength shifters via bridges of Silicon nanoparticles to dendritic antenna structures. The close geometric correlation of activator and wavelength shifting complexes is expected to reduce losses of UV photons and to increase the overall efficiency of the conversion process by profiting from non-radiative energy transfer (Förster transfer). This was demonstrated by comparing the light yield of disk-shaped scintillator samples (diam. 25 mm × 0.2 mm), exposed to 5.49 MeV α-particles with that of standard scintillators (UPS89 from Amcrys-H, Ukraine) of the same geometry. The authors of ref. [14] report, for different NOL formulations, up to 49% higher light yield and at the same time reduced decay time constants. Measurements still need to be performed with minimum ionising particles, the tolerance of the material to ionising dose needs to be established and the results need to be confirmed by other groups. If NOL material is found to maintain its appealing properties in fibre form, NOL fibres would be an attractive option for the LHCb SciFi tracker, particularly for the inner region where the signal degradation due to ionising dose is most expressed.

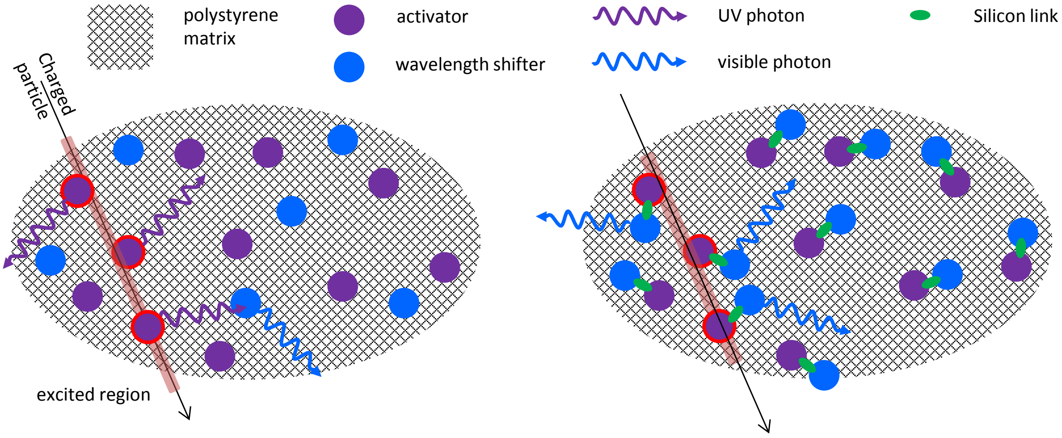

Figure 6. Simplified principle of light yield increase in NOL fibres. Left: conventional plastic scintillator. Right: NOL scintillator.

7.3 SiPM optimisation

SiPMs and, in particular, arrays of SiPMs fulfil most of the requirements of a high resolution scintillating fibre tracker. Two SiPM manufacturers, Hamamatsu [3] and KETEK ,[4] are developing dedicated devices for the LHCb SciFi Tracker. As shown in figure 7, these arepairs of 64 channel monolithic linear arrays with a 0.25 × 1.6 mm^2 channel size. For yield and reliability reasons, the array package consists of two dies (of 64 channels each) with a small gap in between. In the

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[3] Hamamatsu Photonics K.K., 325-6, Sunayama-cho, Naka-ku, Hamamatsu City, Shizuoka Pref., 430-8587, Japan.

[4] KETEK GmbH, Hofer Str. 3, 81737 München, Germany.

following we briefly touch on the most important parameters which need to be optimised or a good compromise found.

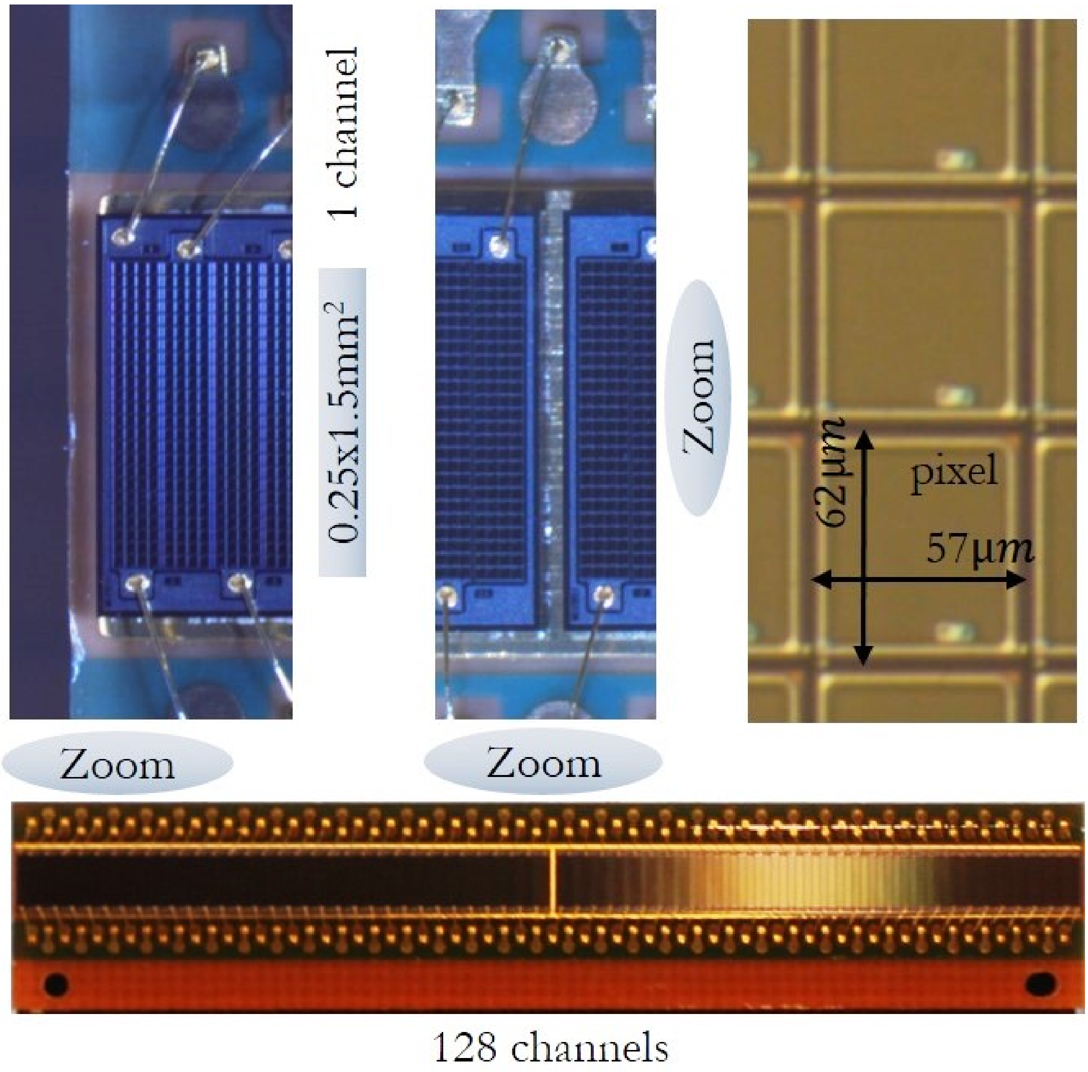

Figure 7. Hamamatsu multichannel array with 128 channels in one package. It consists of two dies glued and bonded on a carrier PCB. A thin epoxy layer protects the silicon surface and the bonding wires mechanically. Non-active zones are present due to manufacturing tolerances at the edges and in the middle. The detector technology is based on trenched pixels with transparent thin metal film resistors.

- **Photodetection Efficiency (PDE)**. The PDE of a SiPM should be maximised for the emission wavelength region of the scintillating fibre. The PDE can be split into three factors: the geometrical efficiency or fill factor, $\varepsilon_{\text{geom}}$, the quantum efficiency (which is close to one for blue light), QE, and the avalanche trigger probability, ε_{AT}, which depends on the voltage above breakdown, ΔV. Optimisation of these parameters has led to a peak PDE (at 420 nm wavelength) around 45% for a pixel size of ($50\,\mu$m$\times 60\,\mu$m) and $\Delta V = 3.5$ V.

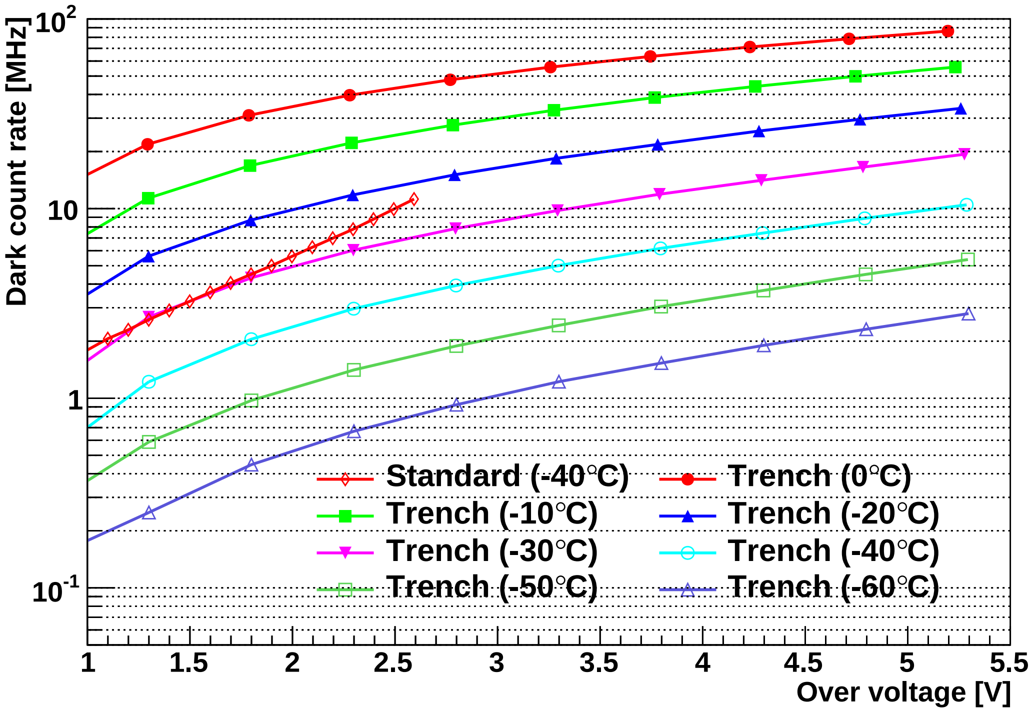

Figure 8. DCR as a function of temperature and over-voltage ΔV for irradiated Hamamatsu detectors, with and without trenches. The DCR corresponds to a channel of $0.375\,\mathrm{mm}^2$ surface. The fluence was 3×10^{11} MeV neq/cm^2. The detector profited from an annealing of one week at +40°C.

- **Dark Count Rate (DCR)**. Higher ΔV will result in higher gain and PDE, but also in higher x-talk and significantly larger DCR. Larger pixels, which are preferable for optimised PDE, lead again to a higher x-talk probability due to the larger gain and also increased DCR. The best balance between PDE, x-talk and DCR must be found for the specific application.

- **Cross talk**. In the most recent SiPM devices, trenches filled with opaque material were implemented around the pixels, reducing cross talk probability by more than a factor 10 below 3% for a gain of $3 \cdot 10^6$.

- **Geometrical optimisation**. The spatial resolution in a staggered multi-layer fibre mat is in first approximation given by the fibre pitch divided by $\sqrt{12}$. Reducing the SiPM channel width below the fibre diameter would not lead to an improved spatial resolution and be expensive taking into account the additional associated readout electronics. The SciFi tracker represents essentially 150 m of fibre end surface which must be covered with active silicon channels with the minimum number of gaps. The inactive edges of the SiPM array package and the gap in between the dies must be minimised. The active Silicon surface must be protected from the fibre ends. This is ensured by a thin epoxy or glass window, which also covers the bond wires. As the light is emitted from the fibres in form of cones, the window thickness must be minimised ($< 100\,\mu$m) in order to limit its contribution to optical cross talk.

- **Radiation effects and noise**. The SiPM in the LHCb SciFi tracker will be exposed to an accumulated fluence of about $6 \cdot 10^{11}$ MeV neq/cm^2 (after shielding). This leads, at room temperature and for $\Delta V = 3.5$ V, to DCR values in excess of 1 GHz per channel. Various irradiation campaigns with neutrons at the TRIGA reactors in Ljubljana (Slovenia) and Mainz (Germany) gave no evidence of a reduction of the charge gain nor of a degradation of the transparency of the 100 μm thick epoxy entrance window.

Single photon detection with SiPMs in such a radiation environment is however still possible due the following circumstances. The small detector channel area limits the DCR, as it is proportional to the sensor area. The typical channel dimension of $0.25\,\text{mm} \times 1.6\,\text{mm}^2$ such that the area is only 0.4 mm^2. Fast signal shaping and short integration time will also reduce the random overlap of noise signals. The typical shaping and integration time in LHC detectors is only 25 ns. In addition, cooling of the SiPM will allow the DCR generated due to radiation damage to be reduced by a factor of two for every 10 K reduction for the Hamamatsu SiPMs and a factor of two for every 15-18 K for the different detector variations from KETEK. As mentioned above, LHCb will operate its SiPMs at -40°C. A further reduction of the DCR is achieved by annealing periods of typically 1 week duration at +40°C.

Appropriate online clustering of the channel information ensures a separation of signal clusters from noise generated clusters. The signal from a particle traversing a fibre mat is typically concentrated in one channel with a large amplitude or distributed over two or more channels having smaller amplitudes. The dark noise can be assumed to be non-correlated between detector channels and therefore a high threshold can be set for single channel clusters and a sum-over-channels threshold for multi channel clusters. The so-called noise cluster rate is therefore two orders of magnitude lower than the DCR. Figure 8 shows the dependence of the DCR on temperature and over-voltage ΔV. Compared to the standard technology, the beneficial effect of adding trenches is clearly visible. In the highest occupancy region in the centre of the detector an average noise cluster rate of up to 5MHz per SiPM array at the end lifetime of the experiment is expected. This noise cluster rate is significantly lower for the outer regions of the detector where higher signal and lower noise is expected. In comparison to the signal cluster rate of up to 100 MHz the noise cluster rate is reasonably small.

8 Summary and Outlook

The readout of scintillating plastic fibres by state-of-the-art SiPM photodetectors allows for conceiving precise and fast tracking detectors operated in high luminosity environments. The geometrical adaptability, the low material budget and, last but not least, cost are additional positive factors. On the other hand, plastic fibres show significant degradation when exposed to ionising radiation. Similarly, the SiPM technology suffers from a steep increase of the DCR, linearly scaling with the NIEL. The LHCb SciFi tracker design copes with these challenges by a staggered six-layer fibre mat concept and optimised SiPM arrays, operated at -40°C. Fast readout and online signal clustering and thresholds further mitigate the DCR problem.

While the performance and radiation hardness of the SiPM technology has seen a continuous evolution over the past decade, driven by demanding applications in high energy physics, but also in medicine and other industrial domains, innovation in scintillating plastic fibres has essentially ended

25 years ago with the introduction of the double-cladding technique. The NOL technology promises higher light yields and may extend the application range to even higher doses. The cumbersome and very labour intense production of fibre detectors may also be seen as a bottleneck. While silicon and more recent gaseous tracking detectors have been produced by highly precise and automated microfabrication technologies, including photo-lithographic patterning, there is no obvious alternative to the traditional drawing, winding, casting and machining of fibres. One can speculate whether the evolution of the 3D-printing technique will pave new roads. Ideas being developed for consumer markets are promising and inspiring [15].

Acknowledgments

We would like to thank our colleagues from the LHCb SciFi team for their cooperation which has led to the detector design and results presented in sections 6 and 7. The fruitful and efficient collaboration with the SiPM development teams of Hamamatsu and KETEK is highly appreciated. We would also like to thank the team at Kuraray and the team around S. Ponomarenko (RUS) for their continuous efforts in optimising the performance and quality of scintillating fibres.

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