9 September 2024
fabiana.liviette.gamboa.chacon@cern.ch

Study of exit angle distribution for scintillating fibres for the LHCb SciFi tracker Upgrade II

Fabiana Gamboa Chacón
CERN, CH-1211 Geneva, Switzerland
Supervisor: Gianluca Zunica

Keywords: LHCb experiment, Scintillating Fibre (SciFi) Tracker, exit angle, LHC

Summary

This project presents the analysis of the light exit angle distribution in scintillating fibres used in the SciFi tracker of the LHCb experiment at CERN. The study focused on comparing the SCSF-78 fibres, currently used in the SciFi tracker, with two possible alternatives for future upgrades, the BCF-12XL and BCF-20XL fibres. The exit angle distributions were measured for different excitation distances using a UV-LED and their performance was analysed comparing the peak emission angles and width of the distributions. The results showed that the BCF-12XL and BCF-20XL fibres exhibit narrower exit angle distributions compared to the SCSF-78 fibre, which is advantageous for efficient light collection by silicon photomultipliers (SiPM) in the detector.

Contents

1 Introduction

In the Large Hadron Collider (LHC) protons are collided to probe the fundamental forces of nature. During these collisions, the constituent particles of protons (quarks and gluons, collectively known as partons) undergo a process called hadronization. Governed by the principles of quantum chromodynamics (QCD), quarks and gluons carry a property known as color charge. Due to a phenomenon known as confinement, these color-charged particles cannot exist freely in nature. Instead, they rapidly recombine to form color-neutral particles known as hadrons [1].

Unlike other experiments at the LHC, which are of the 4π type (covering the entire solid angle around the collision point), LHCb is a forward spectrometer, which means that it is optimized to study particles produced at a small angle to the collision beam, where heavy quark hadrons are mainly produced.

To achieve its scientific goals, LHCb is composed of several sub-detectors that work together to track, identify and measure the properties of particles produced in collisions. One of the sub-detectors is the SciFi Traker. The Scintillating Fibre tracker (SciFi) is placed downstream of the magnet. It consists of scintillating fibres read by multi-channel silicon photomultiplier arrays. The entire tracker is composed of twelve sensing layers grouped into three stations (T1, T2, T3). Each detector plane is divided into five or six modules, which are mounted on C-frames that carry, in addition to the modules, the readout electronics and the rest of the detector infrastructure [2][3] (see Figure 1):

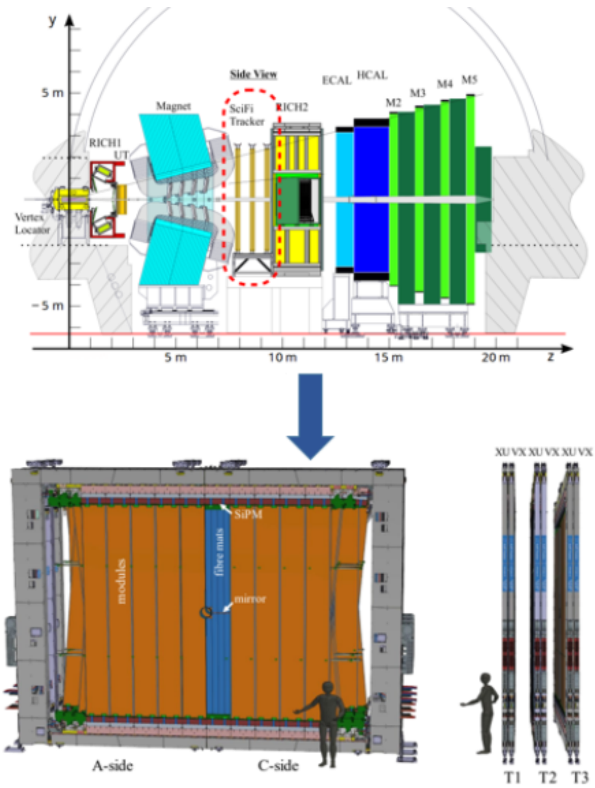

Figure 1: Top: schematic sideview of the LHCb detector. Bottom: front and side views of the 3D model of the SciFi Tracker detector.

In the SciFi tracker, double-cladded plastic scintillating fibres produce light through a multi-step process. When an ionising particle crosses the fibre, it excites a molecule of the polymer core, which is made of more than 98% of polystyrene (PS). The activator is added to couple to the PS via exchange of a virtual photon and the de-excitation process happens via non-radiative dipole-dipole coupling, called Förster Resonance Energy Transfer (FRET). However, the photon that is released can only travel a few µm in the plastic, being in the UV spectral range. Thus, a second scintillator acting as wavelength shifter is added. As a result, the UV photons are absorbed and then re-emitted in the visible spectral range, this is done because photons in the blue/green wavelength have a longer attenuation distance[2].

The LHCb upgrade has been designed to run at a nominal instantaneous luminosity of L = 2 $\times 10^{33}$ cm^{-2} s^{-1} and to collect events at the LHC crossing rate of 40 MHz. An all-software trigger reconstructs all events in real time at 30 MHz visible interaction rate [4]. LHCb Upgrade Ib is scheduled during the Long Shutdown 3 (LS3) in 2026-2028, and Upgrade II, when the SciFi tracker will be upgraded, during LS4 in 2032-2034 [2].

This project describes the measurement process and results for the exit angle distribution of the actual fibre used in the SciFi Traker SCSF-78 and possible fibres for the next SciFi Traker upgrade BCF-12XL and BCF-20XL.

2 Exit angle distribution of Scintillating Fibres

2.1 Scintillating Fibres

The diameter of the scintillating fibres currently used in SciFi Traker (SCSF-78), which includes the two claddings, is 250 μm. As scintillating light is emitted isotropically inside the fibre, the inner cladding (IC) and outer cladding (OC) are used to improve the photon trapping efficiency. The light yield of the fibre is 8000 photons per MeV of deposited energy (as well as in all the fibres used for this project); this is equivalent to an average of 300 photons for a minimum ionising particle that passes through a 250 μm thick fibre. The scintillating fibre captures 5.35% of the produced light via total internal reflection [4]. The activator material for this fibre is p-Terphenyl (PTP) (12% by weight) and the second scintillator which acts as a wavelengthe shifter is tetraphenyl-butadiene (TPB) (0.1% by weight).

For this project, the exit angle distribution of two new scintillating fibres was analyzed (BCF-12XL and BCF-20XL) and compared with the actual fibre. The diameter of these new fibres, which include only one cladding, is 500 μm and consist of a polystyrene-based core and a PMMA (polymethylmethacrylate, C5H8O2) cladding. The trapping efficiency ranges from 3.4% for events occurring at the fiber axis to approximately 7% for events near the core-cladding interface, according to the manufacturer [6]. The specifications of the fibres used for this project are listed in Table 1 [5][6]. In the case of the two BCF fibres, they don't have an nOC since they are single cladding fibres.

Fibre	Emission Color	Diameter,μm	ncore	nIC	nOC
SCSF-78	blue	250	1.59	1.49	1.42
BCF-12XL	blue	500	1.60	1.49	-
BCF-20XL	green	500	1.60	1.49	-

Table 1: Table of fibre properties and characteristics (ncore, nIC and nOC are the refraction indexes of the core, inner and outer cladding, respectively).

2.2 Measurement setup

A single BCF-12XL and BCF-20XL scintillating fibre with a diameter of 500µm is excited with a UV-LED at 17 distances (called pins) from the fibre end. The distances are 22.7 cm, 47.5 cm, 72 cm, 96.5 cm, 121 cm, 145.5 cm, 170 cm, 194.5 cm, 219 cm, 243.5 cm, 268 cm, 292.5 cm, 317 cm, 341.5 cm, 366 cm, 390.5 cm and 415 cm as shown in Figure 2 and the light is detected with the camera from -70° to 70°. The SCSF-78 fibre was measured at the first 10 distances.

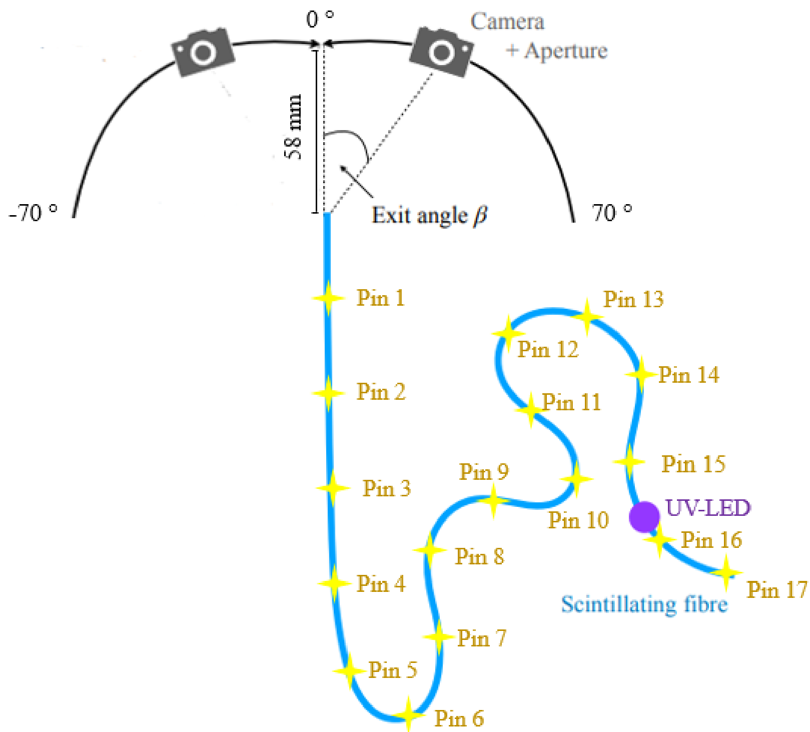

Figure 2: Schematic setup (not to scale) of the exit angle measurement of a scintillating fibre.

The camera was mounted d = 58mm from the fibre end on a rotating stage providing a coverage from β = -70° to β= 70° with a step of 2°. The end of the fibre is surrounded by a plastic support that allows to maintain a correct alignment of the fibre, in addition, this support is placed in a holder, which is level with the camera as shown in Figure 3. The whole setup is covered with a light tight black cloth to shield it from external light.

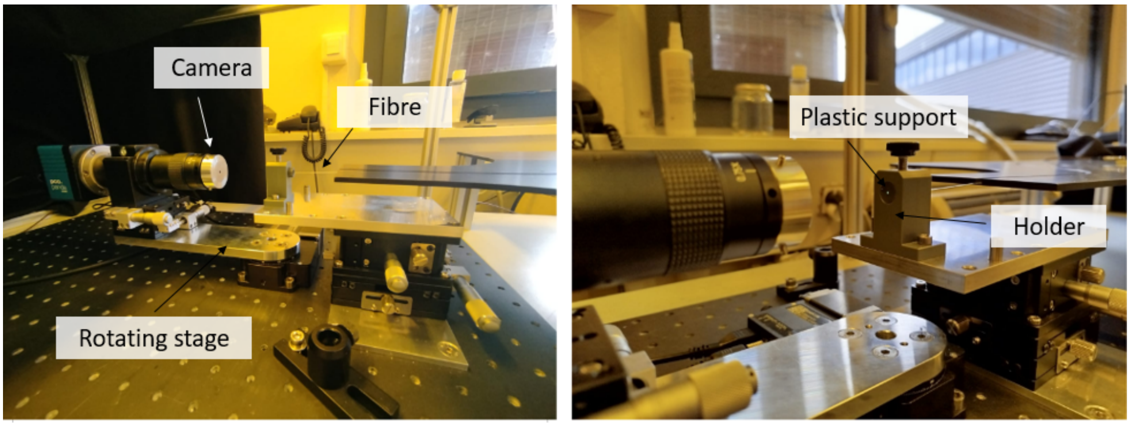

Figure 3: Picture of the setup of the exit angle measurement of a scintillating fibre.

2.3 Exit angle results

Figure 4 shows the simulated fibre exit angle distribution for the SCSF-78 fibre. The majority of detected photons exits the fibre from the core without refraction at inner cladding IC (blue) or with refraction at the IC (green). A small contribution is given by photons exiting the fibre from the IC with refraction at the core (pink). Photons that refract or exit the fibre via the outer cladding OC have no representative contribution to the total distribution as they are heavily suppressed [2].

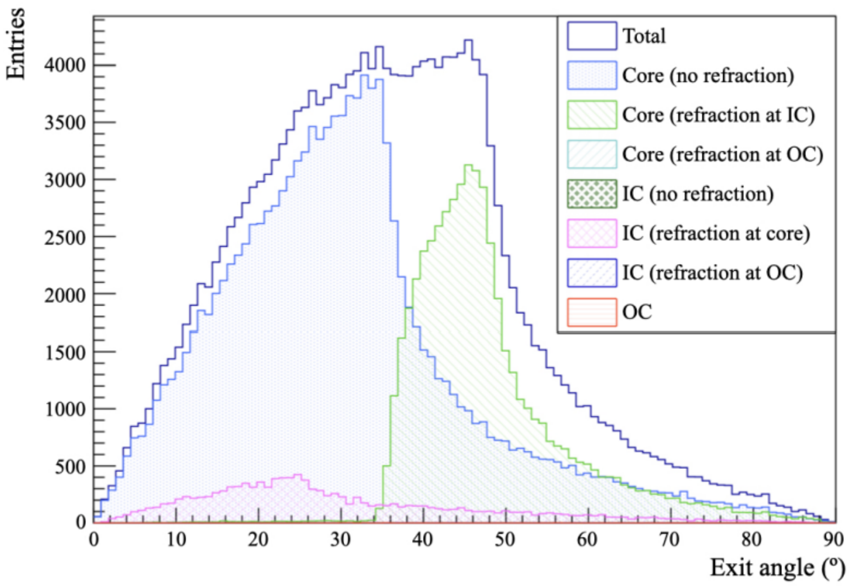

Figure 4: Simulated fibre exit angle distribution in air.

Looking at Figure 5, we see the SCFS-78 fibre exit angle distribution for positive and negative angles. For this fibre, the distributions peak is around 30°. It is possible to observe a considerable difference in peak position of approximately 10° and a narrower distribution with a lighter tail for higher pins (longer distances from the end of the fiber). In addition, the contribution from the core photons with refraction at the inner cladding (green curve in

Figure 5) is strongly suppressed when the distance of the UV-LED from the end of the fibre is increased.

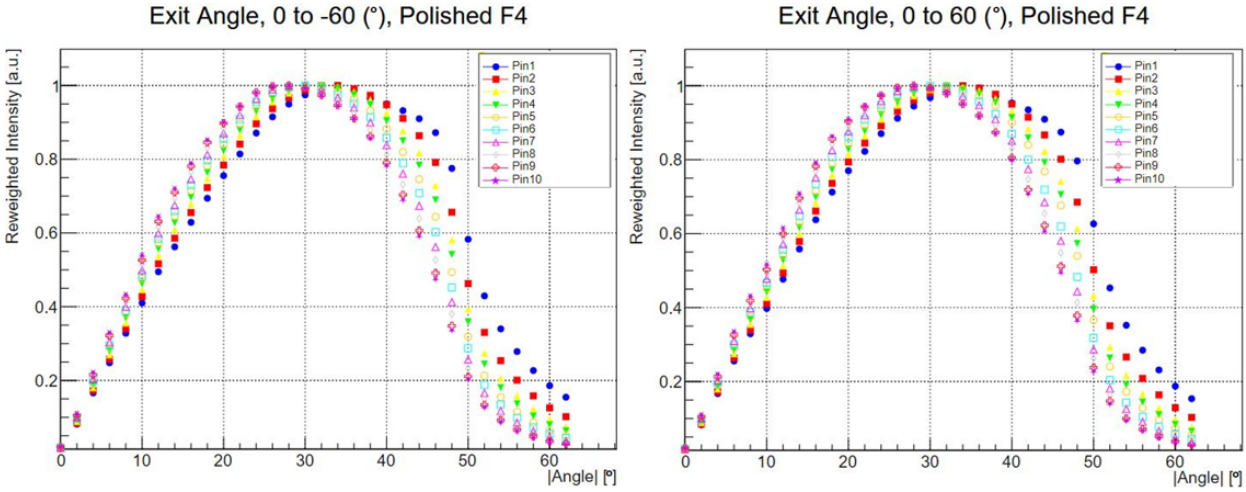

Figure 5: Measured exit angle distributions for the SCSF-78 fibre for negative (left) and positive (right) angles.

Figure 6 shows the distributions of the BCF20XL fibre for positive and negative angles. For this fibre, the distributions peak is around 25°, which is at a lower angle than the peak of the fibre that is currently being used in SciFi tracker. Similarly to what observed for the SCFS-78 fibre, the distributions peak is at a slightly higher angle for the most distant pins. For negative angles, the peak of the distributions is slightly shifted towards higher values, most likely due to a small misalignment of the fibre inside its plastic support or camera's miscalibration. This distributions show that the contribution from the core photons with refraction at the inner cladding is strongly suppressed for all pins and a lighter tail for positive angles. Looking at Figure 6 it is clearly visible that BCF20XL fibre has a narrower distribution than SCFS-78.

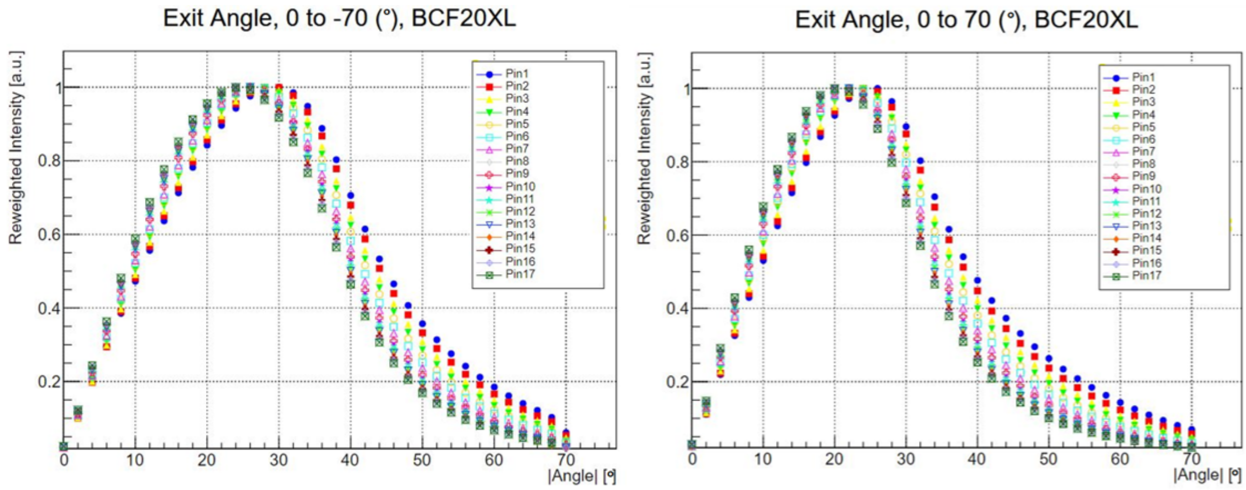

Figure 6: Measured exit angle distributions for the BCF20XL fibre for negative (left) and positive (right) angles.

Figure 7 shows the distributions of the BCF12XL fibre for positive and negative angles. The behavior of the exit angle distribution for this fibre is very similar to BCF20XL fibre. The peaks are also quite shifted between positive and negative angles (almost 10°) due to the same reasons mentioned before.

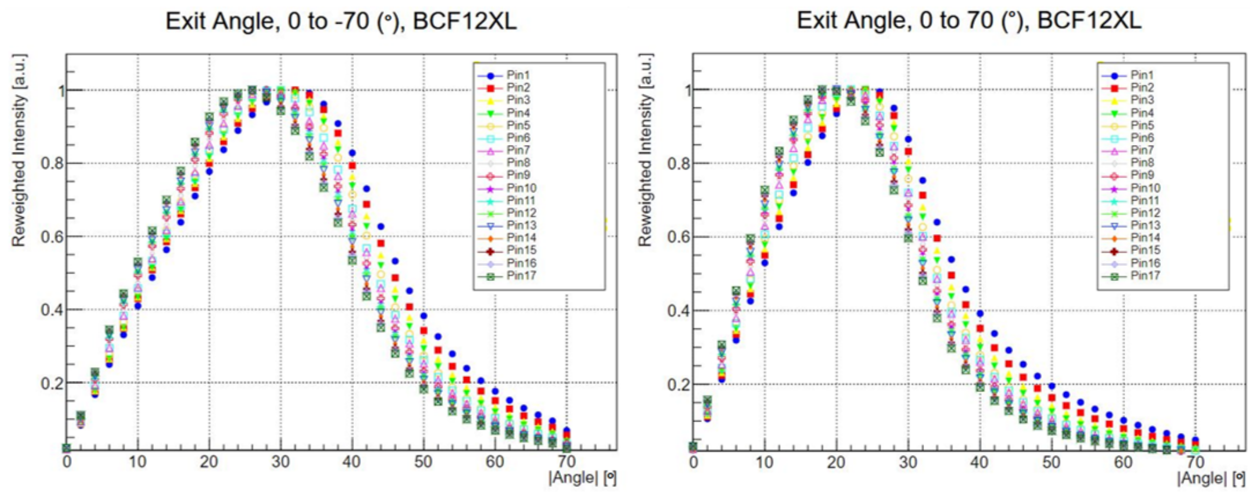

Figure 7: Measured exit angle distributions for the BCF12XL fibre for negative (left) and positive (right) angles.

Figure 8 shows the comparison between the three fibres for Pin 1 and Pin 10. As said before, the exit angle distributions of BCF12XL and BCF20XL are clearly narrower than the distribution of SCFS-78 fibre, which is beneficial taking in account that the light exiting from the fibres is collected by SiPMs (Silicon pixel detectors) positioned at the end of the fibres, so the more focused the light is the more likely it is to be detected by one of the pixels. This figure shows as well the slight difference between the BCF20XL and BCF12XL distributions, with the latter having a lighter tail at both pins.

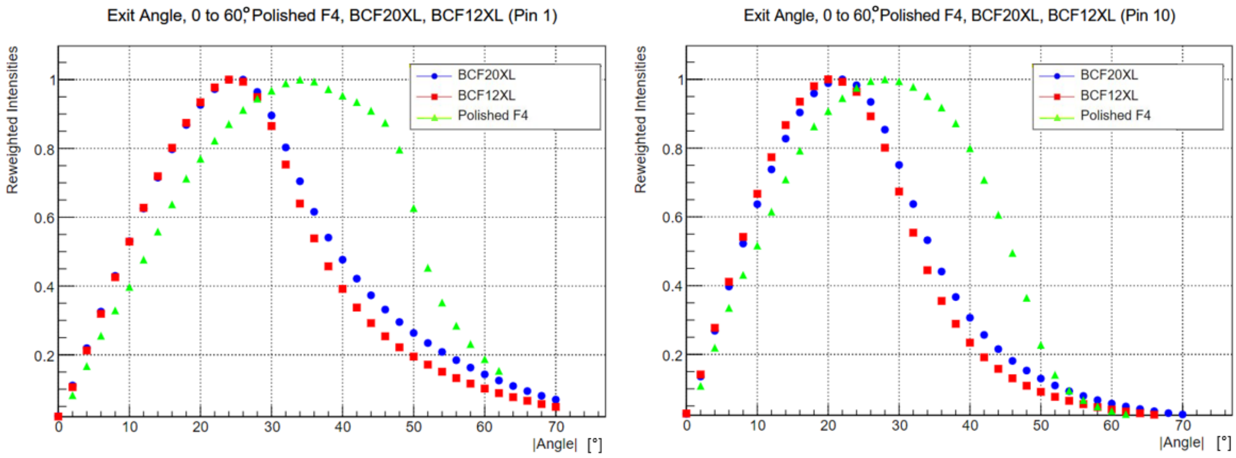

Figure 8: Comparison of the exit angle distributions at Pin1 (left) and Pin10 (right) for SCFS-78, BCF12XL and BCF20XL fibres.

3 Conclusion

BCF12XL and BCF20XL fibres have a narrower exit angle distribution than the SCSF-78 fibre currently used in the SciFi Tracker of the LHCb experiment. The behavior of BCF12XL is slightly narrower than BCF20XL. In addition, it was observed that the peak output angle distribution is lower in BCF12XL and BCF20XL fibres. This is beneficial, as photons exiting the fibre at a smaller angle are more likely to be detected by the silicon pixel detectors (SiPMs) located at the end of the fibres, making the use of these fibres in the next LHCb upgrade feasible.

References

[1] G. Dissertori J. Butterworth and G. Salam. Hard processes in proton-proton collisions at the large hadron collider. Annual Review of Nuclear and Particle Science, 62, 2012

[2] C. Trippl. Development of microlens-enhanced sipms for a radiation-hard scintillating fibre tracker at lhcb. "École Polytechnique Fédérale de Lausanne", 2023

[3] LHCb collaboration. Lhcb tracker upgrade technical design report. "CERN", 2014

[4] LHCb collaboration. The lhcb upgrade i. "CERN", 2023

[5] Kuraray. Plastic scintillating fibers. 2024. http://kuraraypsf.jp/psf/sf.html

[6] Luxium Solutions. Plastic scintillating and wavelength-shifting fibers. 2024.