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Measurement of scintillating fibres for the LHCb experiment

Lab Course E5a

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1 Introduction

Tracking detectors are one of the most critical players in experiments in particle physics. They record the tracks of charged particles, from which conclusions can be drawn about their properties, such as momentum. One possibility to realise such a tracking detector is offered by scintillators, which in the LHCb experiment are realised as 2.5 m long and 250 µm thick fibres. When a charged particle passes through the scintillator, energy is deposited, and the material is excited. During the excitation, this energy is rereleased as photons, which can be detected with silicon photomultipliers.

This lab course aims to investigate the properties of scintillating fibres in more detail and to adapt an existing simulation to reality by comparing measurement and simulation data.

2 The LHCb experiment

The Large Hadron Collider, the world's largest particle accelerator, is home to numerous experiments that study high-energy physics using proton-proton collisions. One of the four largest experiments is the LHCb[1] experiment, which is dedicated to the search for CP violation. In doing so, this experiment tests the Standard Model to look for evidence of physics beyond it. The reason for this search is mainly to explain physical mysteries, such as the observed asymmetry of matter and antimatter in the universe. The structure of the LHCb detector is shown schematically in Figure 1.

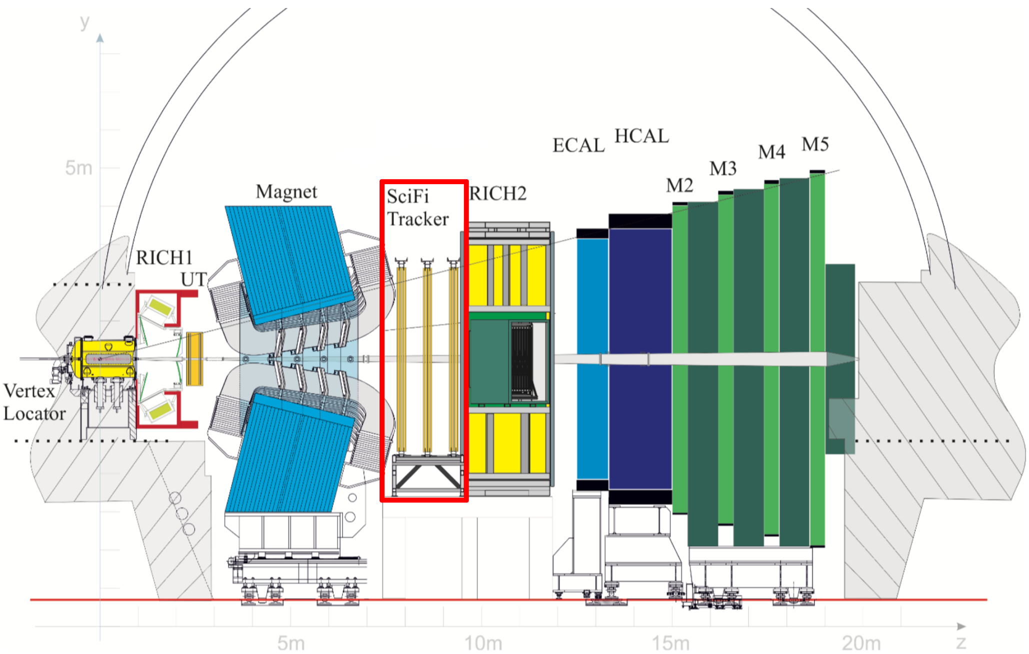


Abbildung 1: Schematic overview of the LHCb detector in Run 3 [1]. The SciFi Tracker is highlighted in red.

It is crucial for the experiment to identify the different particles that are being produced in the

[1]**L**arge **H**adron **C**ollider **b**eauty

central collision. Various subdetectors are used for this task. Cherenkov detectors (RICH[2]) calculate the velocity of a particle, which in combination with the momentum information from the tracking detectors can be used to determine its mass. The ECAL and HCAL calorimeters and the M2-M5 muon chambers are used to determine the energy and type of particles.

Track detection in the LHCb experiment is done with the help of three separate tracking detectors. The vertex locator is positioned closest to the collision point to find the primary vertices of the particle decays. There are also two track detectors, one in front and one behind the magnet. These record the bending of the particle paths in the magnetic field and can thus determine the momentum of charged particles. The tracking detector relevant for this experiment is the scintillating fibre tracker (SciFi tracker) behind the magnet, which is the only one of the three track detectors that consist of scintillating fibres which are read out with silicon photomultipliers (SiPMs).

3 Scintillating Fibre Tracker

The SciFi Tracker is a new detector element integrated into the LHCb detector during a detector upgrade in 2019/2020. It replaces an old track-finding system consisting of drift tubes and silicon strips. Compared to other types of tracking detectors, scintillating fibres offer several advantages. Firstly, they have a high resolution, and secondly, the fibres scatter the penetrating particles less than other methods. In addition, they are inexpensive to manufacture and can thus cover a large area [2].

An important property is the resolution which is said to be better than 100 µm.

Explain how a resolution of less than 100 µm *with* 250 µm *wide fibres can be archieved. Hint: Variance of uniform distribution*

3.1 Simulation

To be able to assess the performance of this subdetector even before it is constructed, various Monte Carlo simulations can be used. One of the simulations, which is used in this lab course, simulates a single fibre. The data from the single fibre simulation is used to make statements about the entire subdetector with another simulation. Thus, it is of great importance that the physical processes in the single-fibre simulation are implemented as close to reality as possible to obtain meaningful results.

The single fibre simulation is implemented in Geant4 and simulates single photons on their way through the fibre. The various interaction mechanisms, such as Rayleigh scattering, attenuation in the materials and reflections at the interfaces, are considered.

For the simulation data, 50 fibres were excited and simulated at 24 points each. The results of the individual simulations are stored in the various text files, which have ascending job numbers. The excitation points are located at a distance of 2400 mm to 100 mm from the fibre end, with a

[2] **R**ing **I**maging **Ch**erenkov Detectors

distance of 100 mm from each other. For an overview, the job numbers are shown in figure 2 sorted by their excitation point.

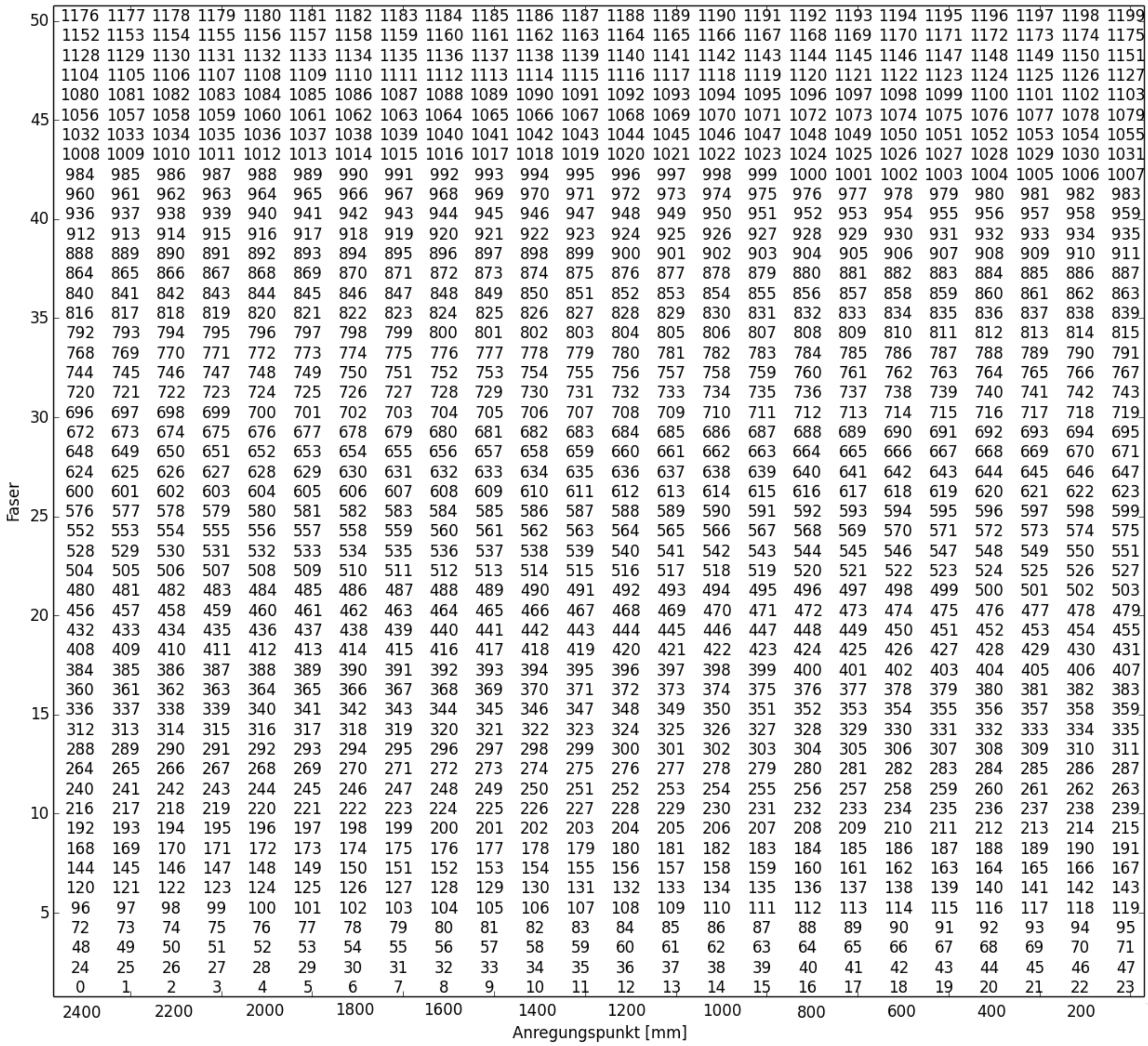


Abbildung 2: Explaination of the numbering scheme of the simulation jobs.

A detector volume is placed at the end of the fibre, which registers all photons hitting it and stores their parameters. The coordinate system is set so that the centre axis of the fibre runs along the x-axis. The stored parameters are:

- y_exit, z_exit: y- und z-coordinates where the photon left the end of the fibre (in Millimeter)
- x_start, y_start, z_start: coordinates, where the photon was created (Millimeter)
- px_start, py_start, pz_start: Components of the momentum direction along the individual

axes at the creation of the photon. It holds $p_x^2 + p_y^2 + p_z^2 = 1$

- reflCoCl, reflClCl: number of reflections at the core-cladding or cladding-cladding interface
- wl: wavelength of the photon (in Nanometer)
- gpsPosX: x-coordinate where the primary particle for the excitation of the fibre was created (in Millimeter)
- length_core, length_clad: distance travelled in the core or cladding (in Millimeter)
- rayleighScatterings: number of Rayleigh scatterings the photon experienced

3.2 Experimental Setup

To use the fibres in the detector, they must be processed into so-called fibre mats. To do this, the fibres are arranged in a hexagonal structure, as shown in figure 3. Epoxy glue is applied between the layers to hold the fibres together.

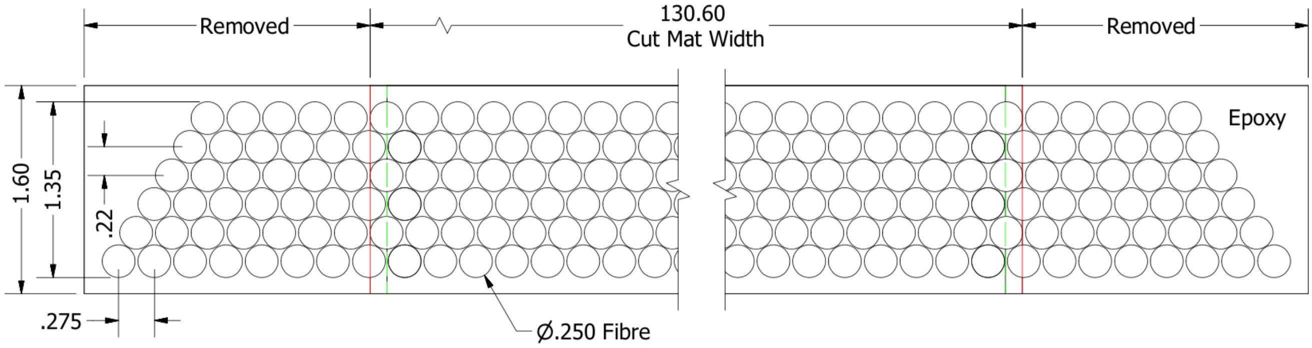


Abbildung 3: Schematic cross-section of a fibre mat with six layers of fibres arranged in a hexagonal pattern. The mat is cut along the red lines. [3]

The SciFi Tracker consists of three stations T1-T3, each consisting of four layers of mats arranged one behind the other. These are positioned in a x-u-v-x pattern. Fibres in x-layers run vertically and are tilted sideways by $\pm 5°$ in the u- and v-layers. The layout of the SciFi Tracker is shown in figure 4. Each layer has 40 mats side by side and two on top of each other. The readout electronics are placed at the outer ends of the mats, and mirrors are mounted at the inner ends of the mats to reflect photons to the SiPMs and thus increase the light yield.

3.3 Scintillating Fibres

3.4 Structure of Scintillating Fibres

The fibres used have a 220 µm thick polystyrene core, an organic scintillator, which acts as the active detector medium. Around this core are two sheaths with outwardly decreasing refractive indices to allow total internal reflection at the interfaces. These each have a thickness of 7.5 µm, resulting in a total thickness of 250 µm. The structure of a fibre is shown in figure 5. Compared to

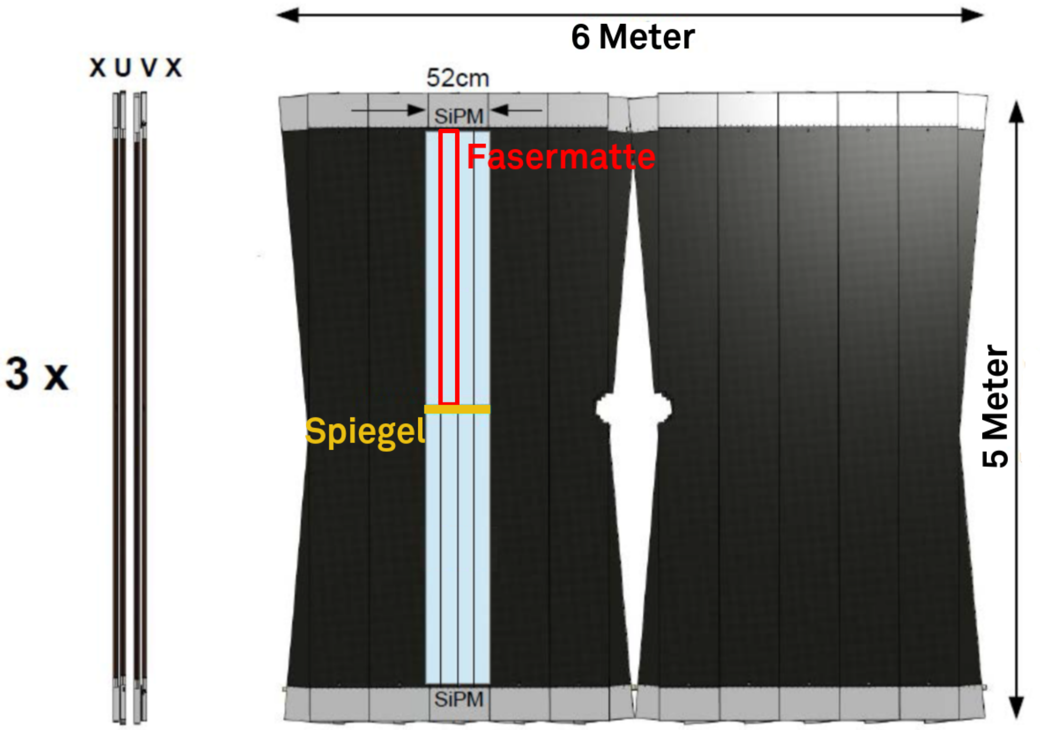


Abbildung 4: Schematic view of the SciFi Tracker. On the left side of the image is a side view of a station consisting of four layers. The right side shows a front view of the SciFi Tracker, with the two halves slightly separated. A single fibre mat is highlighted in red. [3]

inorganic scintillators, where the scintillation mechanism is due to the lattice properties of the crystal, organic scintillators are based on a molecular process. The disadvantage of such scintillators is that they show signs of ageing during prolonged irradiation, which changes the structure and the light yield.

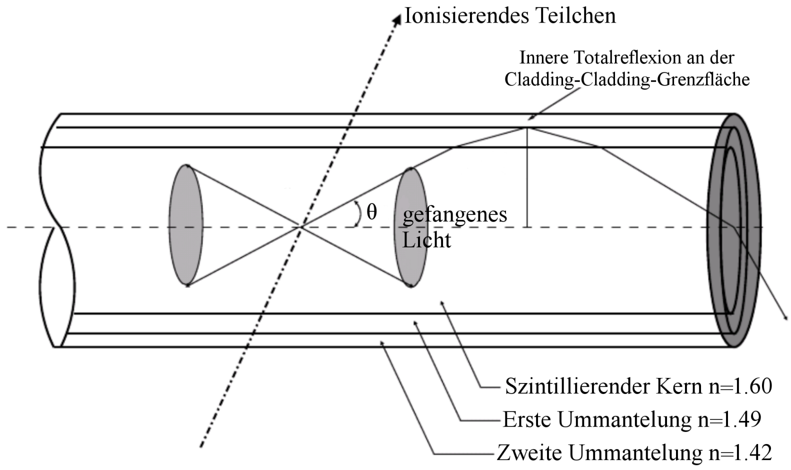


Abbildung 5: Schematic structure of a scintillating fibre of type SCSF-78MJ from the company Kuraray [1].

3.4.1 Scintillation mechanism

When an ionising particle passes through the fibre, the valence electrons of the polystyrene are excited. These electrons (called π-electrons) are no longer bound to a single atom in benzene rings but are delocalised, which means they can move freely throughout the molecule. The energy diagram of these π-electrons is shown in Figure 6. The π-electrons are shifted to a higher energy level upon excitation. Excitations into higher vibrational modes quickly transition to the S_{10} state without radiation. The energy difference of the different energy levels is typically of the order of a few eV. The vibrational states have a spacing of approx. 0.2 eV from each other. A UV photon is finally emitted when S_{10} relaxes to the ground state S_{00}.

Unfortunately, a scintillator made of pure polystyrene also offers some disadvantages. For example, the quantum yield of 3 % is meagre. It describes the number of excited S_{10} states that radiatively transition to the ground state. This low quantum yield is caused by the long average decay time of 308 ns and competing non-radiative transitions, which have a faster decay time. The dye p-terphenyl is added to the polystyrene, which relaxes in a few nanoseconds to increase this quantum yield. Energy is transferred to this dye in the sub-nanosecond range utilizing a non-radiative dipole-dipole interaction called Förster transfer. [2]

Photons emitted from the p-terphenyl have an attenuation length of approx. 1 m, which is not sufficient for the detector with 2.5 m long fibres. A minimum attenuation length of 3 m was specified to ensure that enough photons reach the readout electronics. One method to increase the attenuation length is to use a wavelength shifter. This method is chosen so that the absorption spectrum corresponds as closely as possible to the emission spectrum of p-terphenyl. The wavelength shifter

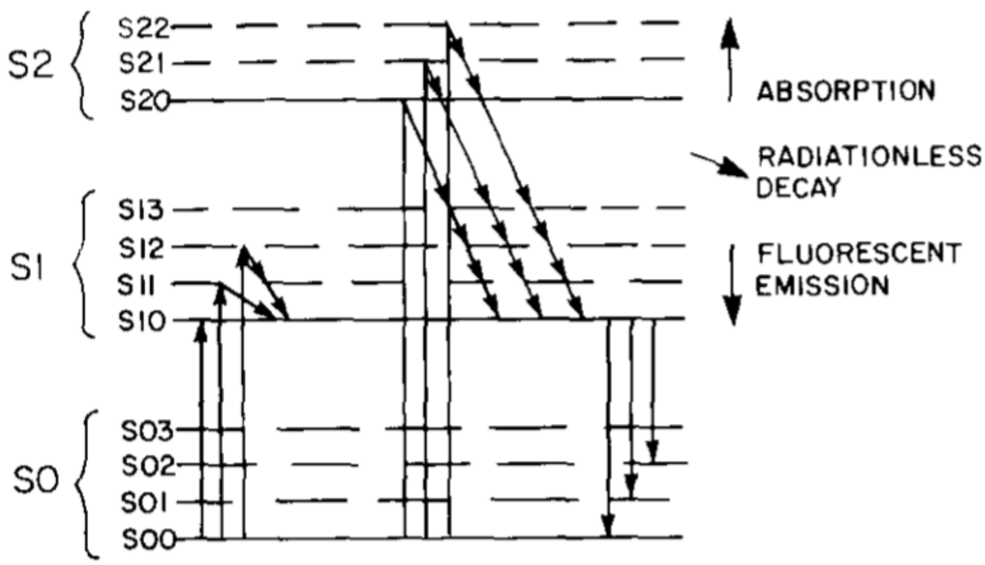


Abbildung 6: Schematic representation of the singlet energy levels of a typical organic scintillator. The dashed lines are vibrational modes. The energy levels are labelled with two quantum numbers S_{ij}, where i denotes the energy level of the electron and j denotes the different vibrational modes [2].

absorbs and emits photons at higher wavelengths, where the fibres have a greater attenuation length. TPB[3] is used as the wavelength shifter in the fibres used here. The absorption and emission spectra of the materials used are shown in Figure 7.

3.4.2 Photon transport

Photons are transported along the fibre by total internal reflection.

Based on the information in chapter 3.4, calculate the maximum angle relative to the fibre axis that meridional photons (photons crossing the centre axis of the fibre) may have to be guided to the end of the fibre by total internal reflection.

Reflections at the interface of the outer cladding and the ambient air can be neglected since the adhesive in which the fibres are later located does not allow total reflection at this interface anyway.

This quantity is also called capture efficiency and plays a role later.

For the later evaluation, it is also essential to derive an expression for the path length L and the number of reflections N of a photon depending on their distance to the fibre end x, as well as its angle θ to the fibre central axis. This is non-trivial for the case where the photon under consideration penetrates the cladding. However, this is relatively easy to calculate analytically for photons moving exclusively in the core.

[3]tetraphenyl-butadiene

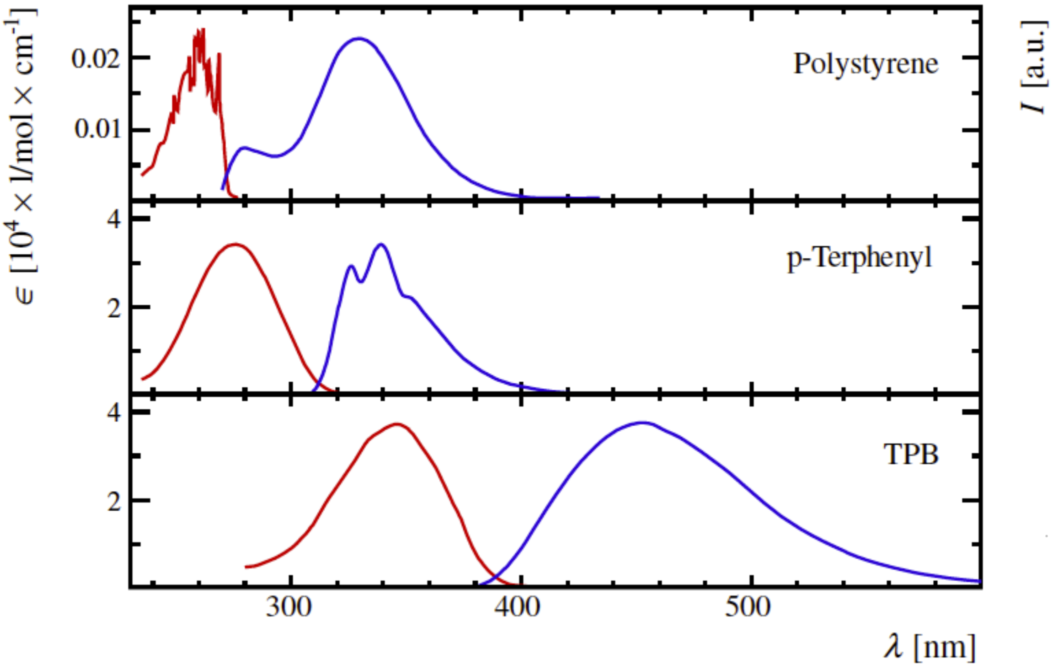


Abbildung 7: Absorption and emission spectra of polystyrene and the added dyes p-terphenyl and TPB. [1].

The following applies

$$L = \frac{x}{\cos\theta} \quad \text{und} \quad N = \frac{x\tan\theta}{2\sqrt{r_{\text{Kern}}^2 - r_{\text{min}}^2}}\,, \tag{1}$$

with the radius of the core material r_{core} and the smallest distance of the photon path to the centre axis of the fibre r_{min}, as shown in figure 8. It can be seen that the total length is not affected by this, but the number of reflections increases.

The reader consider for the special case $(r_{min} = 0)$ *how these equations come about.*

However, one problem with these equations is that r_{min} cannot be measured. Therefore, it is necessary to find an average value for r_{min} from the simulation.

At high values of r_{min}, the photons move increasingly helix-like through the fibre, which allows them to remain in the fibre at angles above the previously calculated critical angle. The reason for this is easily seen when r_{min} is almost equal to the radius of the core material: no matter which angle θ is chosen, the angle to the interface θ_{refl} (under which total reflection happens) is then always 0°. From simple geometric considerations, it can be deduced that the angle to the interface is valid:

$$\theta_{refl} = \arcsin\left(\sqrt{1 - \frac{r_{\text{min}}^2}{r_{\text{Kern}}^2}}\sin(\theta)\right)\,. \tag{2}$$

Even for photons with a high r_{min}, θ cannot become arbitrarily large since the photons must still leave the fibre at the end. Total reflection can also occur here.

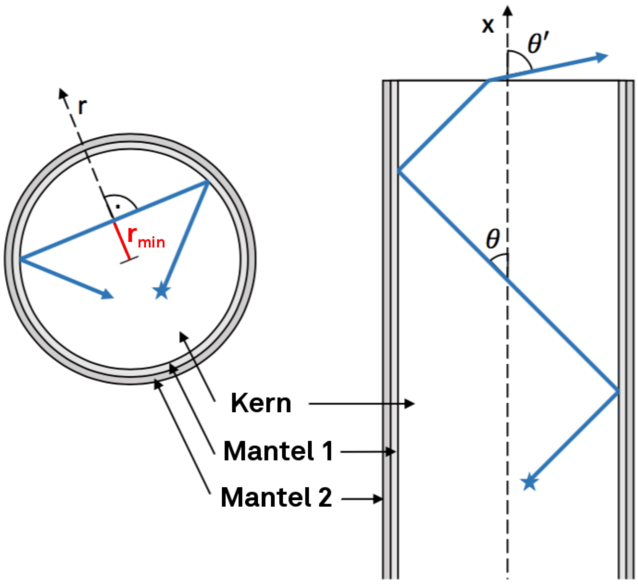


Abbildung 8: Movement of a non-meridional photon through the fibre. On the left side, a cross-section through the fibre is shown. The smallest distance of the photon path to the fibre axis is denoted by r_{min}. On the right side, a side view of the same photon path is shown. The angle θ is defined as the angle to the central axis of the fibre. [4]

When light is guided along the fibre, individual photons can be lost. For example, if the photons perform Rayleigh scattering on the fibre material, they may no longer have the correct angle for total internal reflection. Furthermore, absorption can occur through various mechanisms. For example, molecular vibrations can be excited, and the self-absorption of the wavelength shifter cannot be neglected, especially for small wavelengths. The resulting absorption coefficient a is plotted in Figure 9 for different wavelengths. The attenuation of photons after a path length L in the fibre is generally described by

$$I(x) = I_0 e^{-\frac{L}{\Lambda}}\,, \tag{3}$$

where Λ describes the attenuation length, which is on average 3.5 m for the fibres used in the detector. The attenuation length is the inverse of the attenuation coefficient a.

On the way to the fibre end, two loss mechanisms play a main role [5]. One of these loss mechanisms is the absorption and scattering by the fibre material itself (A_{core}), and the other is the loss that can occur during a reflection at the interfaces between the materials (A_{refl}). These two loss mechanisms have different angular dependencies, making separating them in the analysis possible. The total intensity can thus be written as

$$I(x,\theta) = I_0 A_{\text{core}}(x,\theta) A_{\text{refl}}(x,\theta)\,. \tag{4}$$

Losses through the fibre material depend exponentially on the distance L travelled by the photon and are characterised by the attenuation length Λ.

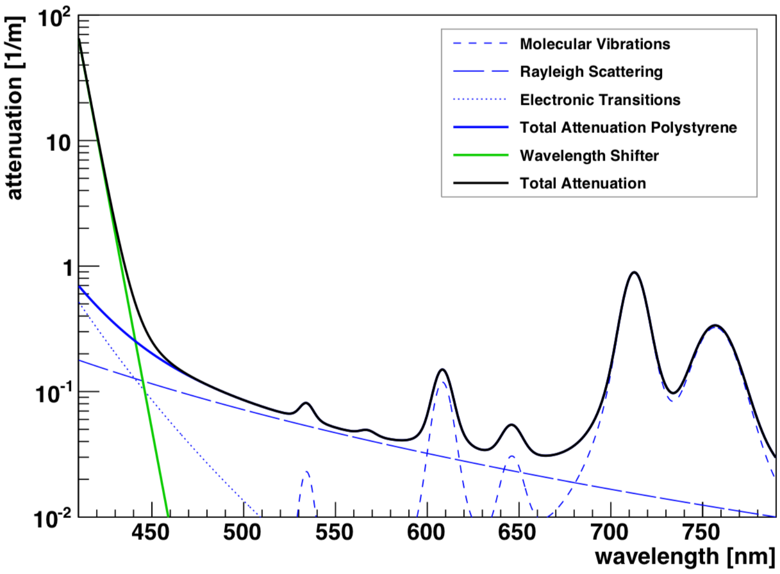


Abbildung 9: Wavelength dependence of the attenuation coefficient of the scintillating fibres used here and the individual components. This coefficient only refers to attenuation when passing through the fibre material. Any reflection losses are not taken into account. [4]

The losses in the core material can be described by

$$A_{\text{core}}(x,\theta) = \exp\left(-\frac{L(x,\theta)}{\mathit{\Lambda}}\right) . \tag{5}$$

The reflection coefficient ϵ describes the probability of a photon being lost in a single reflection at the core-cladding interface. The total number of reflections $N(x,\theta)$ depends on the exact shape of the photon path in the fibre.

For reflection losses $\epsilon \ll 1$, the losses due to reflection can be written as

$$A_{\text{refl}}(x,\theta) = (1-\epsilon)^{N(x,\theta)} = \exp\left(N(x,\theta)\ln(1-\epsilon)\right) \approx \exp\left(-N(x,\theta)\epsilon\right) , \tag{6}$$

which results in the total intensity:

$$I(x,\theta) = I_0 \exp\left(-\frac{L(x,\theta)}{\mathit{\Lambda}} - N(x,\theta)\epsilon\right) . \tag{7}$$

This approximation is valid since the reflection losses are in the order of 1×10^{-5}. When the relations in equation 1 are inserted here, the result is

$$I(x,\theta) = I_0 \exp\left(-x\left(\frac{1}{\mathit{\Lambda}\cos\theta} + \frac{\epsilon\tan\theta}{2\sqrt{r_{\text{Kern}}^2 - r_{\text{min}}^2}}\right)\right) . \tag{8}$$

Finally, an effective attenuation a_{eff} can be defined:

$$a_{\text{eff}} = \frac{a_0}{\cos\theta} + \frac{\epsilon\tan\theta}{2\sqrt{r_{\text{Kern}}^2 - r_{\text{min}}^2}} . \tag{9}$$

As can be seen from equation 8, the reflection losses disappear completely at an angle of 0°. Thus, the attenuation length of the fibre can be investigated separately without the influence of reflection losses.

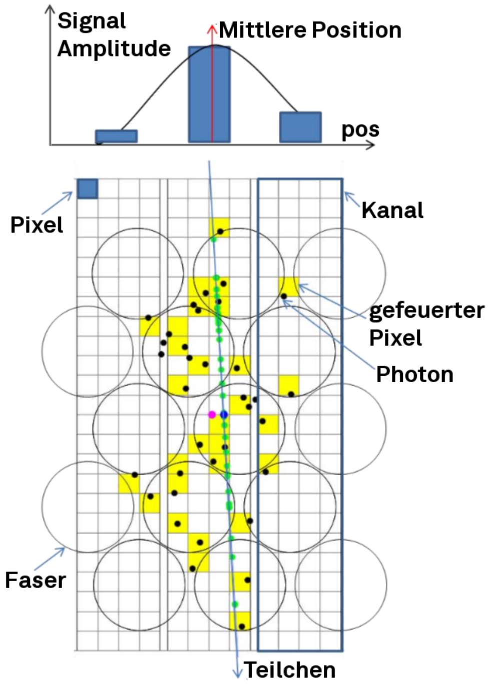
3.5 Silicon Photomultiplier Readout

To measure the photons produced by the fibres, silicon photomultipliers (SiPMs) are attached to the ends of the fibre mats. These consist of a series of avalanche photodiodes operated in Geiger mode. They are divided into $57.7 \times 62.5\,\mu\text{m}$ sized pixels, each representing a reverse biased pn junction. When a photon hits a pixel, an electron-hole pair is created, separated and accelerated due to the high voltage applied. The electrons gain enough energy during the acceleration to trigger more electrons, resulting in an avalanche of charge. These charge avalanches of about 10^6 electrons are registered as a current pulse. After a short recovery time of 25 ns, the charge avalanche is dissipated, and the pixel can fire again. Since several photons hitting the same pixel trigger the same signal as a single photon, the pixel size must be minimised. On the other hand, small pixels are more susceptible to crosstalk, i.e. triggering a charge avalanche in a neighbouring pixel.

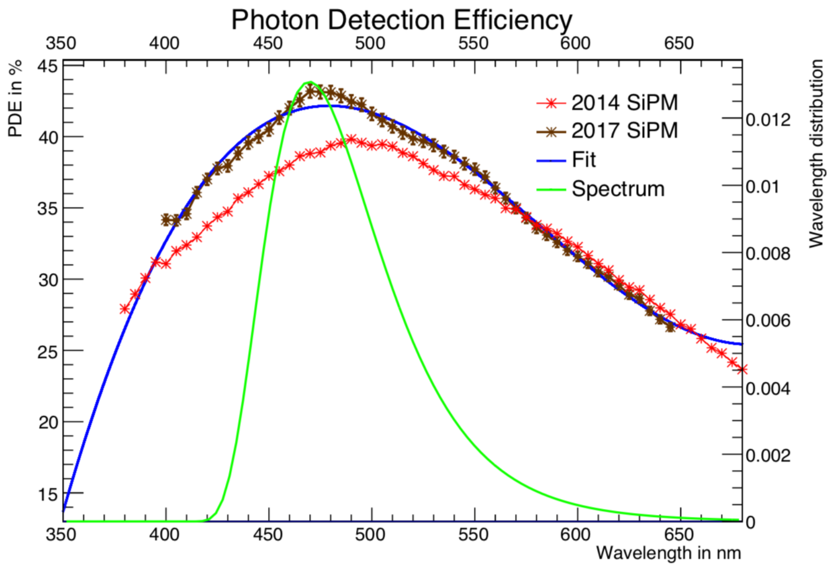
Figure 10a shows an example of the calculation of the mean position of a single particle. An ionising particle traverses the fibre on the path shown in green and excites the fibres in the process. The photons are drawn in black, causing the pixels (yellow) in the three channels to be drawn into the fire. The number of fired pixels is added per channel, and the average position is calculated from the signal strengths. As can be seen in this example, not all photons are detected. There are some pixels with more than one hit and photons that hit in the free area between the channels.

The most crucial property of SiPMs is their photodetection efficiency (PDE). This wavelength-dependent parameter describes the ratio of detected to actual incident photons. The wavelength dependence is shown in figure 10b and is approximate 43 % at maximum. Another essential characteristic is the dark current rate. This is strongly temperature dependent, so the SiPMs are cooled to a temperature of -40 °C.

It should be noted that the SiPMs cannot measure the wavelength of the incident photons. They are also mounted in such a way that they measure all the light emerging from the end of the fibre at the same time. SiPM readout thus measures effective attenuation over all wavelengths. To precisely investigate the dependence of the attenuation on the wavelength and the angle, angle-dependent measurements are therefore necessary with a spectrometer that can resolve different wavelengths.



(a) Example of signal generation of the SiPMs from a simulation. [1]



(b) Photodetection efficiency at different wavelengths. In brown, the measured efficiencies for the 2017 models, which will be used by the SciFi Tracker in the future, are shown. In green, the emission spectrum of polystyrene is shown. [6]

Abbildung 10

4 Experimental Setup

A computer-controlled measuring device is available for the measurement. This, together with the spectrometer and the xy table, is controlled by a central program. The spectrometer can reach saturation, which is the case at approx. 65.000 counts. The room light also provides a slight excitation of the fiber, whereby a signal is measured despite the LEDs being switched off. A dark current measurement before each data collection makes it possible to filter out this constant background excitation by subtracting it. To do this, the count rates without LED excitation are subtracted from those with LEDs switched on. Even if no light enters the spectrometer, a constant dark current signal of approx. 600 counts is measured, which must be subtracted from the actual counts.

The fibre excitation is done with an LED box that can be moved along the fibre with a xy-table. However, the y-axis is not used.

A specially developed device can move the spectrometer along a horizontal and vertical angle. However, this is not possible completely symmetrically around the end of the fibre, as the device itself would collide with the fibre. Therefore, it can only scan the angular intervals [-20°,90°] horizontally and [-6°,90°] vertically.

4.1 Commissioning of the setup

1. Switch on the power supply (in 3 places).
    - x-axis motor
    - angular motors and the x-axis fan
    - LEDs
2. Then boot the PC
3. Start programme
    - Open the terminal.
    - if you get lost: just type cd (**c**hange **d**irectory), this will bring you back to the home directory
    - `cd repos/XYTable/build/`
    - `./bin/xyTableMain` (starts the programme)
    - follow the instructions of the programme
    - the data will be saved in the folder `data/Spectrometer/`
4. check if everything is working with the system check function.
    - This function moves the motors of the x-axis, the horizontal angle and the vertical angle. (Visual check. Since the motors have been detected in a previous step, they should move). Check if there is any stalling of the motor.
    - It is also tested to see if the LED is working.
    - Finally, a graphical user interface is called up with which test spectrometer measurements can be made.
5. now everything should be ready for use
6. The execution of a ReferenceRun is recommended before each new series of measurements.

If you are asked to update, decline. An update of the PC and/or operating system would be fatal for the experiment.

5 Tasks

5.1 Spectrometer Measurement

A spectrometer measurement is to be carried out with the room light switched on and the room light switched off. Any small angle should be used for the measurement. This measurement can be made with a graphical user interface (GUI). This is located in `repos/SpectrometerClass/Spectrometer_gui/build` and can be started with the command

`./bin/SpectrometerGUI`. The maximum current of 20 mA should be used. The integration time should be set to 10000μs in **all** measurements and the number of averages to 5. The "`single`" option can be used to display the light spectrum in the GUI. To start the measurement, select "`Dark + Light`" and enter a group-specific storage location. The measurement starts with a click on "`Measure`".
The intensity (counts) should be plotted against the wavelength, in each case for room light switched on and room light switched off. The plot should be repeated, with the dark counts subtracted from the intensity. In the following, the adjusted, "cleaned" intensity is always denoted as the intensity.

5.2 Radial Symmetry

In this measurement, the radial symmetry of the light intensity is to be verified. To do this, the light intensity is to be recorded for different angles with a fixed excitation position. The horizontal angles should cover a range from $-18°$ to $30°$ and the vertical angle a range from $-6°$ to $35°$. The intensity should be displayed in a two-dimensional histogram.

5.3 Simulation

1. First of all, unphysical simulation errors must be corrected. To do this, the distance between the exit point and the center of the fiber must be determined. What value must this not exceed? Then all photons that have caused Rayleigh scattering should be removed. The simulated data set should be divided into core and cladding photons.

2. The angle θ of the photon to the x-axis (fiber) is not a parameter of the simulated photons. How can this be determined from the direction of momentum? The momentum is standardized.

3. The maximum angle at which total internal reflection can still occur is to be determined for the core and cladding photons (Mathematically, not using a script, but using your own calculations).

4. θ is to be histogrammed for core and cladding photons (in a plot) and the theoretical maximum angles are to be marked. Where does the supposed linear increase come from? Why are there photons with a higher angle than the maximum angle?

5. The minimum distance of the photons to the fiber center should be determined (distance of two lines). Now a two-dimensional histogram of θ and the minimum distance is to be created, in each case for core and cladding photons. How does the distribution come about? Why are no photons detected above a certain angle?

6. The intensity is to be determined for different angles in relation to the excitation location. Use a fit to determine the attenuation length.

5.4 Intensity Measurement

The x-dependent intensity is to be determined for 10 different angles ($0°$ to $40°$). To do this, 20 excitation locations should be selected. Use the recorded data to determine the attenuation length and compare it with the simulation.

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