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*LHCb SciFi project*

# A set-up to measure the optical attenuation length of scintillating fibres

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## Abstract

The optical attenuation length of a scintillating fibre characterizes the quality of light transport through the fibre. It relates directly to the quantity of detectable light at the readout end of the fibre. An optical bench has been constructed, which allows excitation of the fibre at various distances from the photodetector. Depending on the choice of the photodetector – Si-PIN photodiode or grating spectrometer – the attenuation length is measured as weighted average over the sensitivity of the photodetector or as a spectral distribution. A few examples illustrate its operation and performance. The set-up serves for fibre optimisation in the R&D phase and is expected to be used for systematic checks during the series production phase of the LHCb SciFi tracker project.

## 1. Introduction

Scintillating plastic fibres are considered as active detector elements in the SciFi tracker project. While the scintillating fibre technology is well established and its performance demonstrated [Ref. D0, Ref. Aachen], the particular conditions of the upgraded LHCb detector at the Large Hadron Collider pose stringent requirements on a variety of aspects.

The SciFi tracker will consist of 12 detector planes of  $4.8 \times 6 \text{ m}^2$  size, placed orthogonal to the LHC beam axis. A plane will be made of 6 layers of  $250 \mu\text{m}$  thick fibres, hexagonally packed into mats. In a plane, the fibres are oriented vertically or with an angle of  $\pm 5$  degrees relative to the vertical direction (stereo planes). For technical reasons, the planes will be subdivided in smaller identical units. For what concerns the fibres, the base unit is conceived to be 2.4 m long and 13 cm wide. The full detector will consist of 1152 base units, which leads to a total fibre length of about 10'000 km. One end of the fibre will be read out by SiPM photodetectors. The non-read end is mirrored in order to maximise the quantity of detectable light.

To transport scintillation light over a distance of 2.4 m or, in case of reflected light, over a distance of up to 4.8 m, the attenuation of the light inside the fibre must be as low as possible. Assuming an exponential model of light attenuation, the parameter  $\Lambda$ , called the optical attenuation length, is defined by

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

$I$  and  $I_0$  are the light intensities measured at distance 0 and  $x$  from the excitation point. Generally, the attenuation length is dependent on the wavelength  $\lambda$ .

Light propagates inside a fibre primarily via total internal reflection at the core - cladding interface. Light loss during transport in a fibre has multiple origins:

- Absorption in the fibre core, which is normally consisting of polystyrene. One of the dominating causes is Rayleigh scattering from density modulations. Others are chemical impurities or radiation induced traps which absorb photons in the fibre.
- Losses at the core – cladding interface, e.g. due to non-perfect fusion of the two constituents.
- Reabsorption of photons by the wavelength shifting molecules, in case the absorption and emission spectra of the dye partially overlap.
- Light losses at the cladding/air interface. Over small distances, light can be transported via total internal reflection at the outer cladding / air interface. Imperfect surface quality (roughness) and impurities (dust, grease) lead to losses.

Light travelling on non-meridional trajectories, which are essentially spiralling along the fibre, requires a higher number of reflections and passes more material per linear length. Its attenuation is hence stronger than for meridional rays.

Most of the above mentioned effects are wavelength dependent. Generally, attenuation tends to increase towards shorter wavelengths. This has two main consequences:

- The spectral composition of the detected light changes with the distance it travelled through the fibre. This effect becomes enhanced if the fibre exhibits strong attenuation, e.g. because it was exposed to high levels of ionising radiation.
- A non-uniform spectral sensitivity of the photodetector, i.e.  $S(\lambda) \neq \text{const.}$ , has an impact on the measured attenuation length. The determined 'effective' attenuation length is an average weighted with  $S(\lambda)$ . The use of a (calibrated) spectrometer allows for the determination of the wavelength-resolved attenuation length.

## 2. Set-up to measure the effective optical attenuation length

A set-up has been conceived and built which allows measuring the optical attenuation length in a fast manner. Simple operation and a speedy result were main requirements as the set-up will be used during series production when large numbers of samples need to be characterised.

The set-up shown in Figure 1 consists of an optical bench of 3.5 m length. The fibre under test is held and gently tensioned via magnetic soft rubber fixtures. The two ends are cut with a guillotine-like fibre cutter.

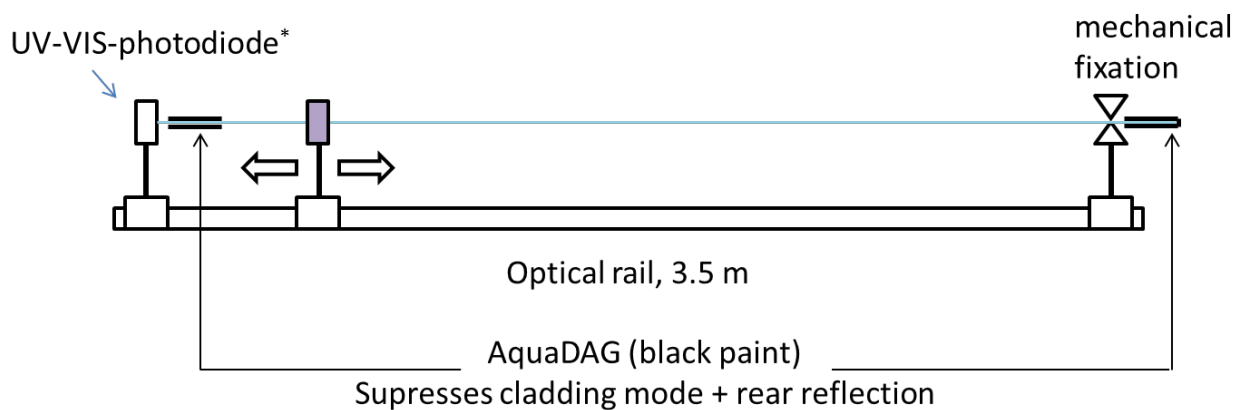


Figure 1: Schematic of the set-up for the measurement. The shown configuration (fibre readout by a photodiode) leads to the measurement of the effective attenuation length.

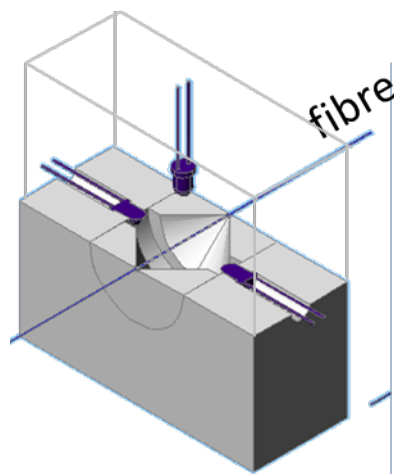


Figure 2: Schematic of the cavity to excite the fibre. The upper (symmetric) half of the body is not shown for clarity. The length of the cavity is 18.75 mm.

As shown in Figure 2, the fibre is excited with an arrangement of 4 UV-LEDs (Bivar, 390 nm), mounted in a cavity made of white Polyoxymethylen (POM) with two small holes through which the fibre passes. The chosen wavelength allows exciting the wavelength shifting dye of the fibre, such that the fibre responds with its genuine emission spectrum. The strength of the excitation light is monitored by a Si-PIN photodiode included in the cavity. The symmetric cavity arrangement has shown to very robust against variations in the fibre placement. The cavity is mounted on a carriage which can manually be moved on the optical rail. The position is read on a ruler with a precision of better than  $\pm 5$  mm.

One fibre end is coupled (without optical grease) to a Si-PIN photodiode of type Newport 818-UV. The other end is blackened with a thin painted non-transparent layer of Aquadag<sup>1</sup>. The outer surface of the fibre is also painted over a few cm before the photodiode with Aquadag in order to suppress light travelling in the cladding.

The 818-UV photodiode is continuously read with a Keithley Picoammeter, connected to a PC running a Labview application. Typical photocurrents are in the 100 – 1000 nA range. The background due to stray light in the room and other sources is below 1 nA. A handheld trigger enables the transfer of a data point to the software, which fills a plot and performs various fits. A more detailed analysis is performed offline using a Root script.

The sensitivity characteristic of the photodiode is shown in Figure 3. It is provided by the supplier Newport and has an uncertainty of 2%.

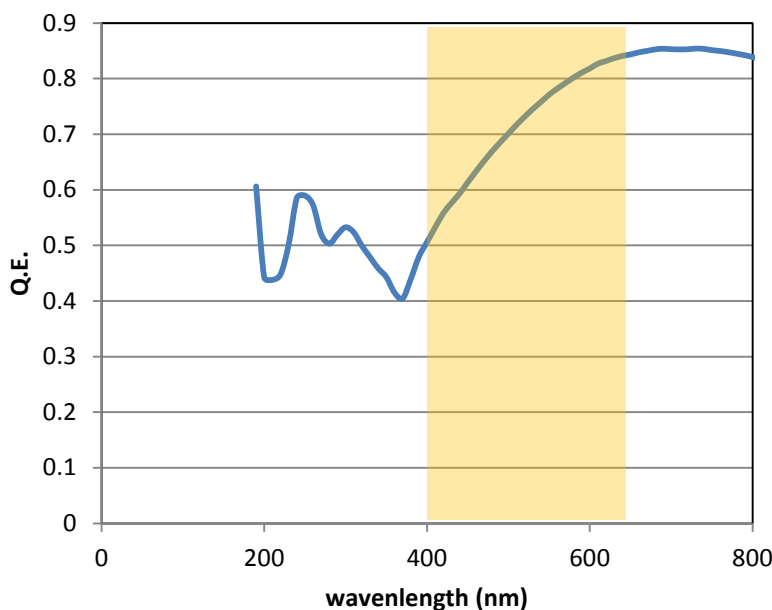


Figure 3: Quantum efficiency of the Si-PIN photodiode Newport 818-UV. The shaded range marks the emission spectrum of the Kuraray SCSF-78 fibre. The peak emission (for short fibres) is at about 450 nm.

<sup>1</sup> Water Based Graphite Coating / Additive is an aqueous-based colloidal dispersion of ultra-fine graphite. Henkel Cooperation.

## Analysis

The effects described in the introduction usually lead to two distinct exponential terms in the attenuation plots.

1. A relatively steep term (short attenuation length) which is attributed to losses of cladding light and non-meridional rays;
2. A more flat term (long attenuation length) describes the losses of light which propagates in a regular manner in the core.

For direct comparison with attenuation length measurements performed at the fibre producer, we perform a single exponential fit to the data range from 100 to 300 cm. This range avoids interference with the steep term which has typical attenuation lengths of 20 – 30 cm, i.e. it is already sufficiently attenuated at 100 cm to be ignored.

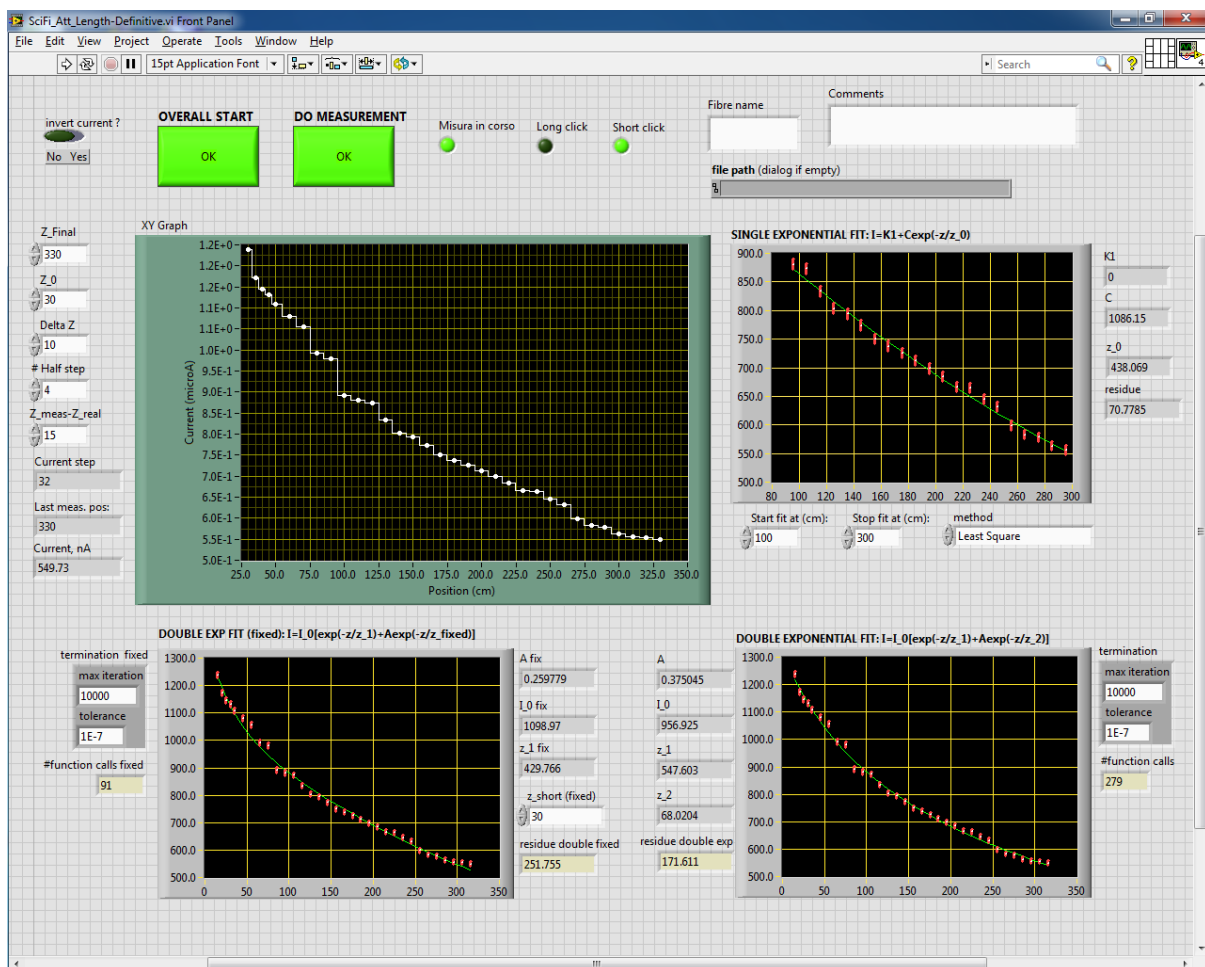


Figure 4: Screen shot of the Labview programme with a display of the measured data (upper left) and set of online fits.

As shown in Figure 4, the Labview programme visualises the data during the measurement and performs a set of online fits: single exponential between 100 and 300 cm, double exponential with and without frozen parameters. This allows for a rapid judgment of the correctness of the measurement and gives a first idea of the quality of the fibre. The errors of the data points are estimated from the fluctuation of the photocurrent and also account for the uncertainty of the position measurement (<0.5 cm). The final results are based on offline fits, performed under ROOT

(Minit package). The result of such a fit is shown in Figure 5. The values of the attenuation lengths obtained from single exponential fits – online or by ROOT offline - agree within about 1%.

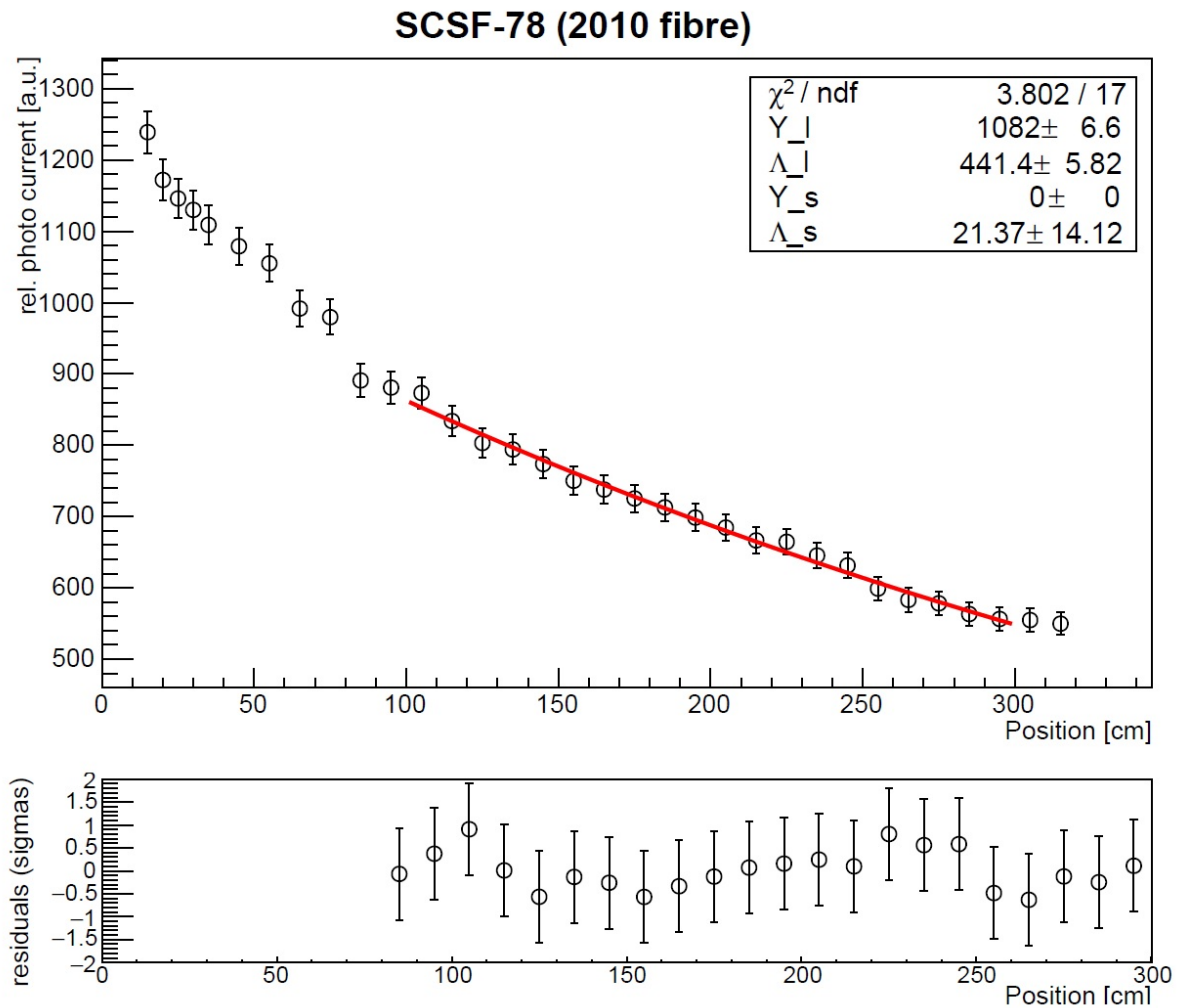


Figure 5: Root fit to the same data shown in the online display (Figure 4). The lower plot shows the residuals (data – fit).

## Discussion

The above described set-up and analysis lead to reproducible results. Repeating a measurement of the same fibre sample several times gives results well within  $\pm 5\%$ .

A couple of points have been found to be essential for reliable measurements:

- The measurements should be performed after having switched on the LEDs for about 15 minutes such that the temperature of the set-up is stabilized.
- Before starting a measurement, the intensity of the LEDs is set to produce a signal on the reference PIN-diode of 40 nA.
- Clean cuts of the two fibre ends have proven to be essential.

Samples taken from the same fibre spool may exhibit differences in the attenuation length of 10-15%. This is believed to reflect the variation of the fibre properties on a spool rather than an instability of the set-up. Visual inspection of fibres close to the excitation point shows that the light

losses along a fibre are by far not fully uniform. The observer finds localised bright spots, randomly distributed along the fibre, where larger quantities of light seem to escape from the fibre.

### Attenuation length measurements provided by Kuraray

When comparing the results obtained with the above set-up with measurements provided by the company Kuraray, our attenuation length appears to be typically 10 – 15% longer. The set-ups are based on the same principle however there are two differences:

- Kuraray uses an Hg arc discharge lamp to excite the fibre. The lamp has several spectral lines of which the ones at 365 and 405 nm are matching the absorption spectrum of the wavelength shifter.
- Kuraray uses a Photomultiplier Tube Hamamatsu R980 with a bialkali photocathode. The quantum efficiency peaks at about 400-450 nm and falls off continuously to the threshold at about 650 nm.

A simple model which takes into account the emission spectrum of the fibre, shows that our measurement, based on the PIN photodiode, gives more weight to the longer wavelength than the PMT data, which in turn emphasises the shorter wavelength. The model predicts a 10% effect in the attenuation length, similar to what is observed.

### 3. Set-up to measure the spectral distribution of the optical attenuation length

The spectral distribution of the optical attenuation length is obtained from measurements of the emission spectrum of the fibre at two different excitation points from the wavelength resolving photodetector.

$$I(x_1, \lambda) = I_0 e^{-\frac{x_1}{\Lambda(\lambda)}}, \quad I(x_2, \lambda) = I_0 e^{-\frac{x_2}{\Lambda(\lambda)}} \quad \rightarrow \quad \Lambda(\lambda) = -\frac{x_2 - x_1}{\ln \frac{I(x_2, \lambda)}{I(x_1, \lambda)}}$$

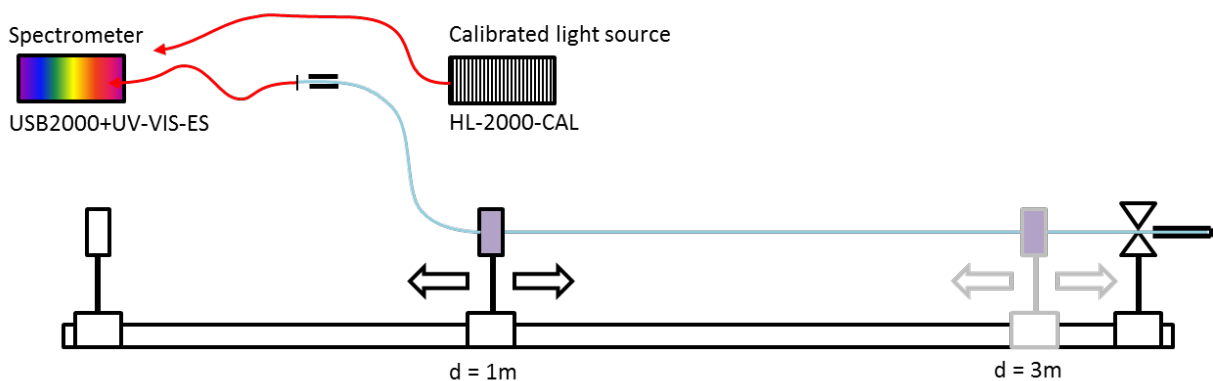


Figure 6: Set-up for the measurement of the spectral distribution of the optical attenuation length.

The method is based on the assumption that the light attenuation follows a single exponential law. The excitation points are therefore chosen such that the short attenuation length can be ignored ( $x_1 = 1 \text{ m}, x_2 > x_1$ ).

The set-up shown in Figure 1 is also used for the measurement of the spectral distribution of the attenuation length, however the photodiode is replaced by an Ocean Optics spectrometer of type USB2000+UV-VIS-ES as shown in Figure 6. The spectrometer covers the range from 200 to 850 nm. The wavelength dependence of its sensitivity has been equalised by means of a calibrated tungsten halogen light source of type HL-2000-CAL. The calibration guarantees that the measured intensity distributions have the correct shape. The measurement of the attenuation length depends however only on the ratio of the intensities at a given wavelength and is therefore independent of the calibration.

The scintillating fibre is fed into the spectrometer by coupling it to large aperture quartz fibre of 1 mm diameter. For the same reason as discussed above, possible attenuation effects of the quartz fibre cancel in the ratio and are expected to have no impact on the measured attenuation length of the scintillating fibre.

## Analysis

Figure 7 shows a set of 7 intensity distributions (different distances to the excitation point) measured at the end of a SCSF-78 fibre, prior to any exposure to ionising radiation. The total light intensity (surface under the curves) drops with the distance and the spectra show the typical shift toward longer wavelength.

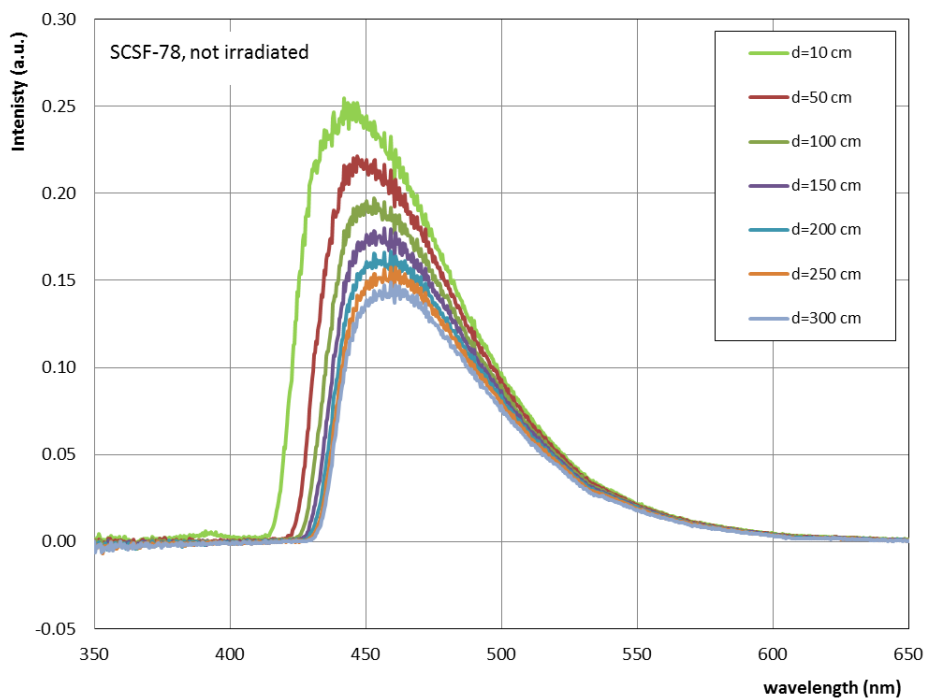


Figure 7: Intensity distributions of a non-irradiated SCSF-78 fibre for excitations between 10 and 300 cm. The spectra show the typical shift towards longer wavelength described in the introduction.

Figure 8 shows the spectral distribution of the attenuation length  $\Lambda(\lambda)$  of the SCSF-78 fibre extracted from the intensity measurements at  $d = 100$  and  $300$  cm. The attenuation length rises from values below  $100$  cm in the blue wavelength region ( $<450$  nm) to values above  $10$  m in the green and red part of the spectrum. The enhanced absorption at  $\lambda \sim 535$  and  $605$  nm is a well-known feature, attributed to the excitation of molecular vibration levels of polystyrene.

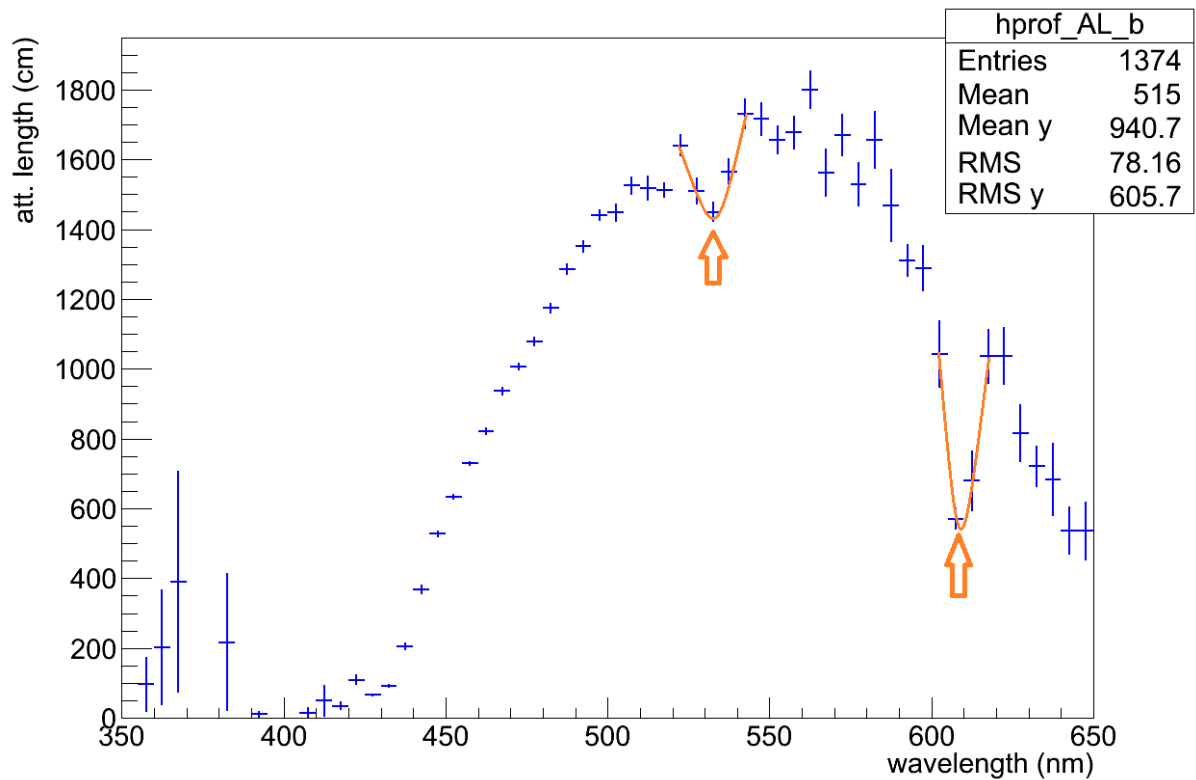


Figure 8: Example of a spectral distribution of the attenuation length, extracted from measurements of the non-irradiated SCSF-78 fibre at 1 and 3 metres. Every data point corresponds to a wavelength bin of 5 nm width.

## Acknowledgement

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