Error Analysis of Attenuation Length Measurements for the LHCb SciFi Quality Assurance Lab

M. Ozkaynak
CERN

Abstract
The setup for measuring the attenuation length of scintillating fibres for aging effects was analysed and tested for potential sources of error. It was found that the current method of taking one measurement is inadequate and there is a need for multiple measurements. The setup was also found to have several limitations such as damaging the fibre during measurements, unstable power supply, being prone to errors due to operator and too small current being used in the LEDs.

1 Introduction

The attenuation length setup and method used in [1], was tested for errors. The setup was tested for systematic errors, any potential operator effects, effects of method of measurement, and repeatability of measurements.

2 Systematic Errors

2.1 Warmup and Fluctuations of Electronic Components

The existing LabVIEW program has been duplicated and modified in order to take one measurement every second for a given amount of time. Initially all equipment was tested for half an hour and this was repeated for 3 hours if a warmup point could not be seen within the half an hour.

2.1.1 Ammeter

Keithley 487 Picoammeter was used in order to measure the current. Only the ammeter was turned on and connected to the photodiode at the start. All lights were switched off, apart from the table lamp when the zero check was done. The current readout on the ammeter disconnected from all other components can be found on Figure 1.

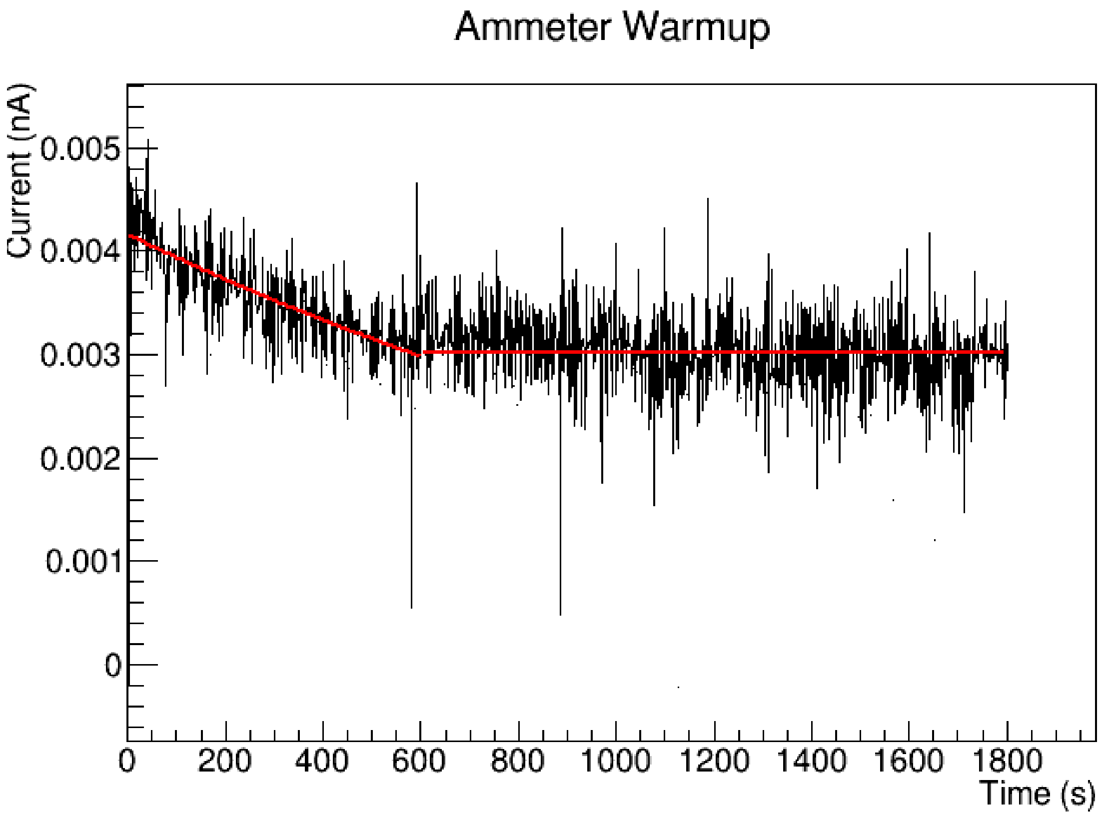


Figure 1: The current readout from the ammeter

The ammeter showed fluctuations of the order 0.005 nA, with a decreasing trend. This decreasing trend stopped at around 10 minutes mark. Until the 10 minutes mark, the rate of decrease was -0.0005565 nA/s which was negligible compared to the measurements, as measurements were in the range of μA.

2.1.2 Power Supply and LED

Having checked the required warmup for the ammeter, the combination of the power supply and LED was checked. For this, half an hour was found to be inadequate and so it was repeated for three hours. However, there still was not a clear point where the power supply and LED combination is stabilised. After having changed the LEDs, there still was a decreasing trend. However, once the Statron 2229.91 power supply was exchanged with a Keithley GPC-3030D power supply unit, the rate of decrease in the current read out from the LED photodiode had decreased by one order of magnitude. The Keithley GPC-3030D power supply unit also does not seem to have as much fluctuations as the previous one. There was, however, a definite drop of 1.1 nA observed at around two minutes and fluctuations were never as large again. This means that, the Keithley power supply unit definitely needs to go through a warmup time unlike the Statron one. Once the warmup time had passed, the rate of decrease was 5.9×10^{-5} nA/s and the largest fluctuation was 0.4 nA that happened over a much larger period of time than needed to affect our measurements. Once the power supply was switched with a new one the warmup measurements were repeated for one hour and can be seen in Figure 2

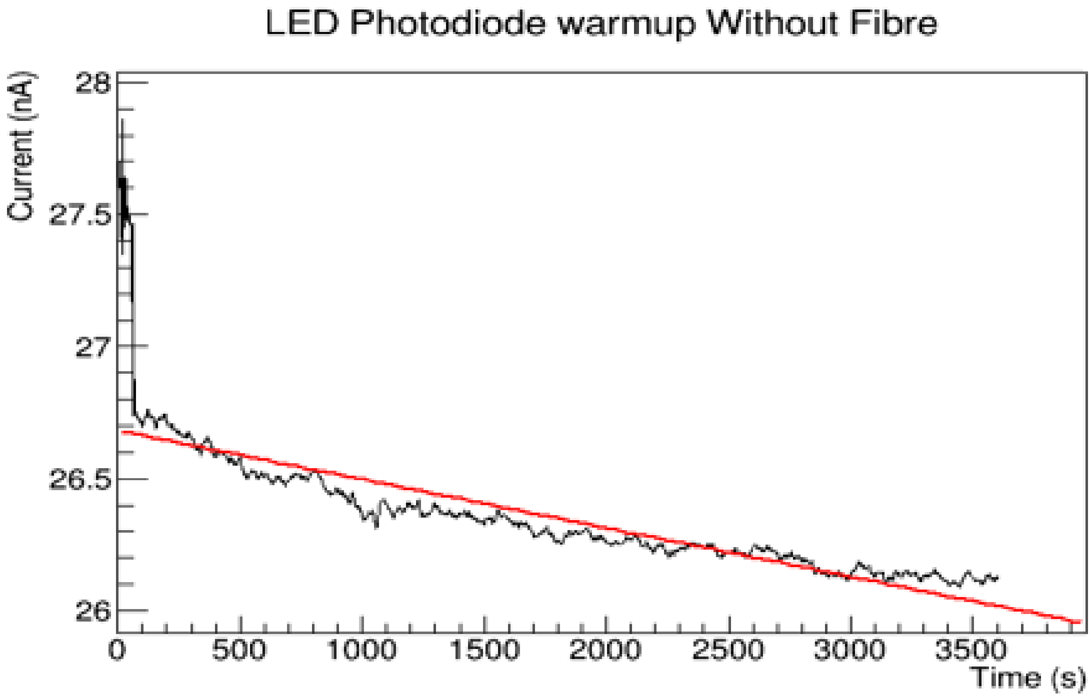


Figure 2: The LED photodiode readout using the Keithley GPC-3030D power supply unit

The stability might be further improved upon by using a power supply that controls the current rather than the voltage.

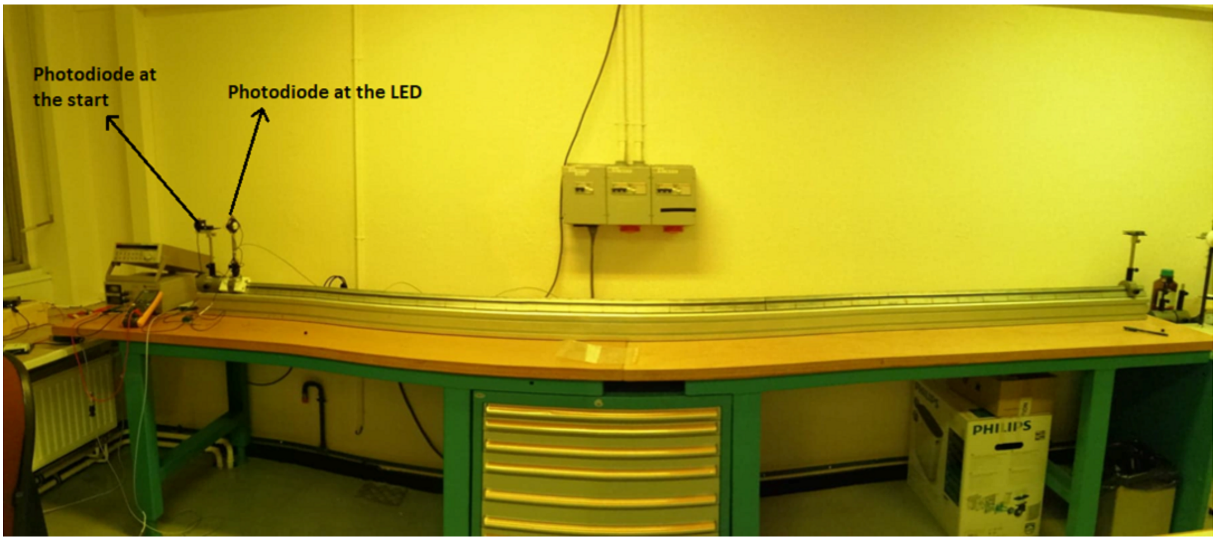


Figure 3: The experimental set up

3 Random Errors

Certain errors affected the mean of our results, some are not reproducible and therefore could not be investigated fully.

3.1 Positioning of the apparatus

The current setup does not ensure that the apparatus will be set at the exact aimed position every time a measurement at a particular distance is taken. Bold marks have been used to pronounce the distances where a measurement should be taken. As the marks are not exact and the large thicknesses introduce variance in the position, there is variance in the current readout through distance variation.

It was decided to measure the distance variance indirectly through the intensity in the photodiode at the start, since the current setup was more suited for measuring the variations in the intensity than the variations in position. The LED was brought to the same point to be measured from the previous one 20 times, and the differences in the intensity was taken as average. Overall the average percentage error on the intensity due to positioning was found to be 0.32%.

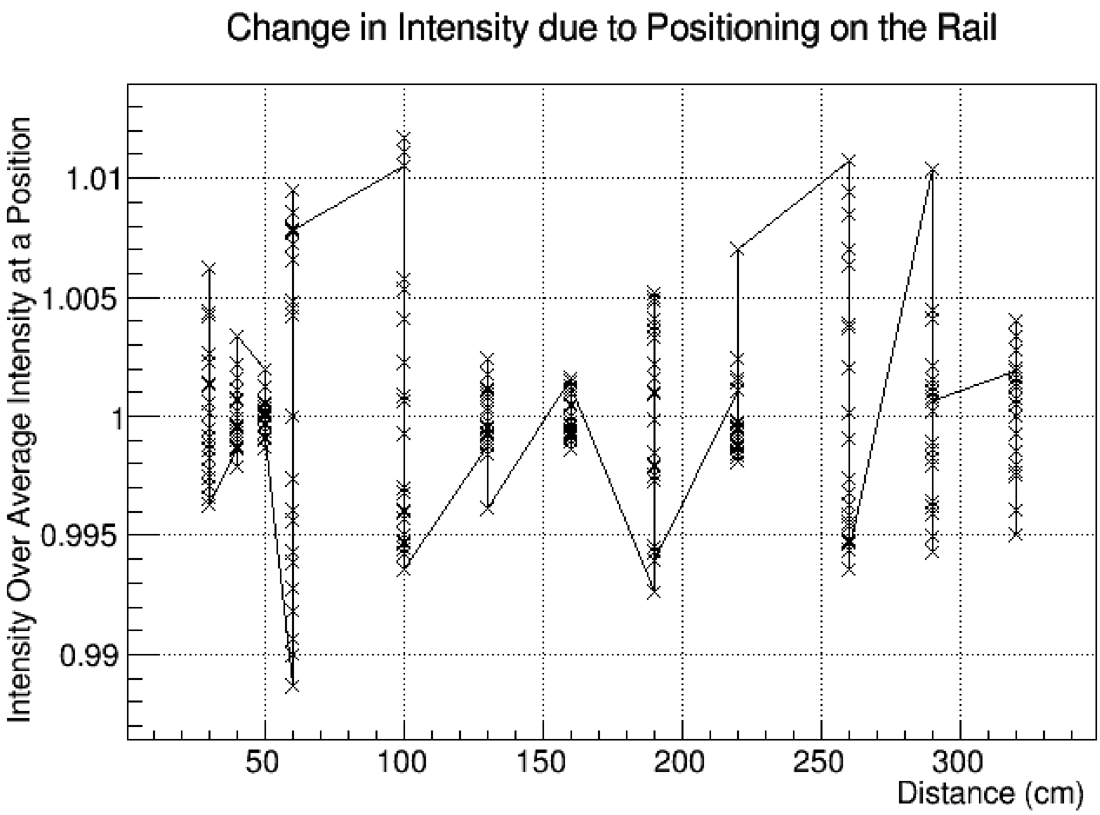


Figure 4: Difference in intensity when bringing the rail to the same position multiple times

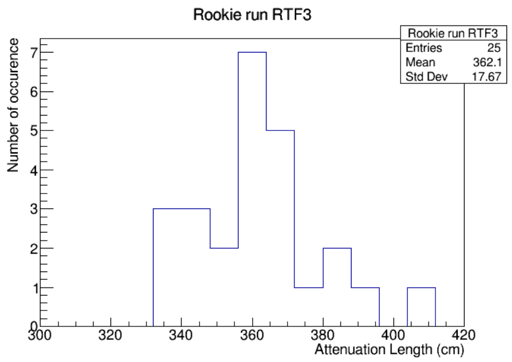
In order to eliminate this error mechanical blocks that will ensure that the rail can be put to the exact same position each time could be introduced. For example a removable clamp that would go in front of the LEDs that extends to the table, and screws or super-glued blocks can be added to the bottom of the rail, that will hold the clamp onto the same position every time.

3.2 Positioning of the fibre

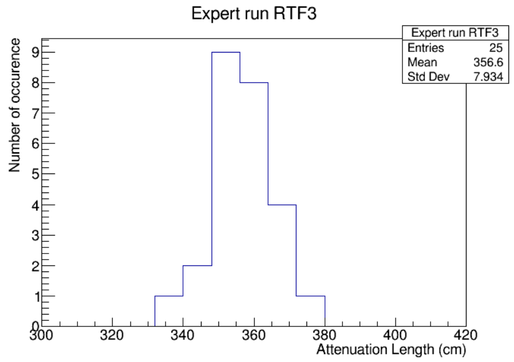
During resets, it is not possible to be able to put the fibre into the exact same state it was in, in the previous measurements. Not only that but also the fibre can also move along the direction of measurement. In a uniform fibre, the effect of this would be small however, if there were damaged positions that show as dips in the graph that were now on the measurement positions due to this shifting effect, the value of the attenuation length measured could also drastically change between different reset measurements. Especially considering that the fibres do not appear to be uniformly damaged by the UV across their length, certain points with more damage can affect results significantly. This shows a need to take more than one reset measurement in order to be able to observe and if necessary exclude any reset measurement that might be affected by such outliers.

3.3 Delay between click and measurement

It was noticed that there is a delay between pressing the clicker and the datalogger logging the data. This introduced the problem that before the previous data has been logged, the operator might have moved the apparatus again. The data taken will in this case correspond to an incorrect position. Given that enough measurements have been taken, it has been shown that even though an unaware operator can reach the same mean, the standard deviation of the attenuation length measurements increases by 2.23 times as much compared to an aware operator. This can be seen in Figure 7, where the rookie refers to moving the apparatus before the data has been logged for sure and the expert refers to waiting for the data to be logged before moving the apparatus.



(a) Not waiting for the delay in the data logger before moving apparatus



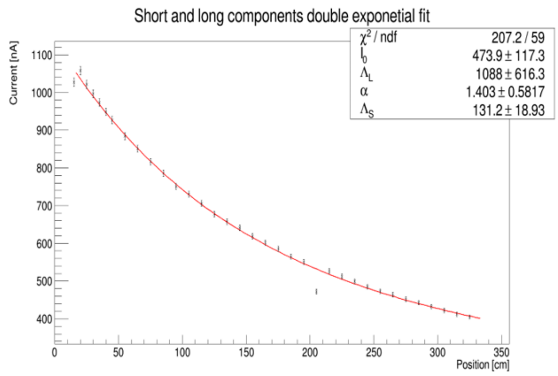
(b) Waiting for the delay in the data logger before moving apparatus

Figure 5: 25 repetitions by the same operator, testing the effect of the delay on the program, using the fibre named RTF3

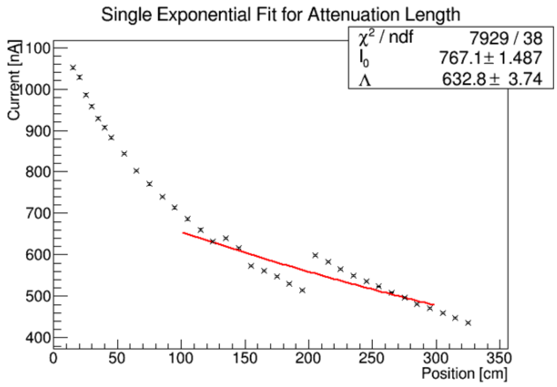
A second beep after the first beep has therefore been introduced to let the operator know that they can move the LEDs. The second beep should end before the apparatus is moved ahead.

3.4 Random off point(s)

In certain measurements, it was observed that one measurement point would be discontinuous with the rest. Deleting this point and retaking the measurement can fix the problem only if the point had arisen due to a positioning error or dust on the fibre, otherwise it is possible that a "random effect" of unknown cause has occurred. The random off point due to this random effect can remain despite taking off the fibre and putting it back on to the setup and disappears after a while. The only way of distinguishing that this discontinuous point arises from a random effect and not UV damage is the 'off point' disappearing and being continuous with the rest of the data points in later measurements. In a certain type of random error deleting some of the previous measurements and retaking them would shift the discontinuity backwards, that is, to the point up to where you decide you want to start to redo the measurements. Interestingly, when going all the way back to the starting position, the current output seems to remain unchanged. It is both unknown why this shifting of discontinuity occurs. Overall it was observed that the random effect that can cause outlier attenuation length measurement on average happens with a probability $\frac{1}{18.33}$. Different types of random effects, affecting the measurements are shown in Figure 6.



(a) Outlier appearing in only one position, was present despite resetting the setup, however mysteriously disappeared after three days



(b) Random shift in the measured intensity values

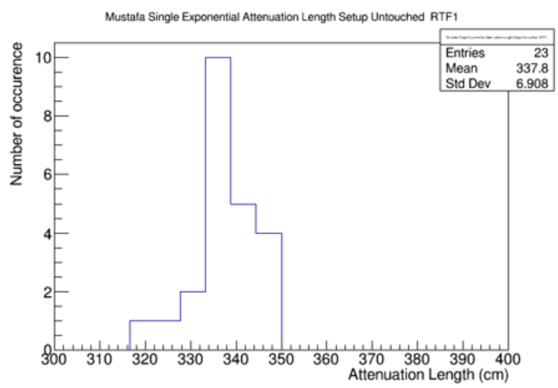
Figure 6: Examples of random errors that occur

4 Measurements

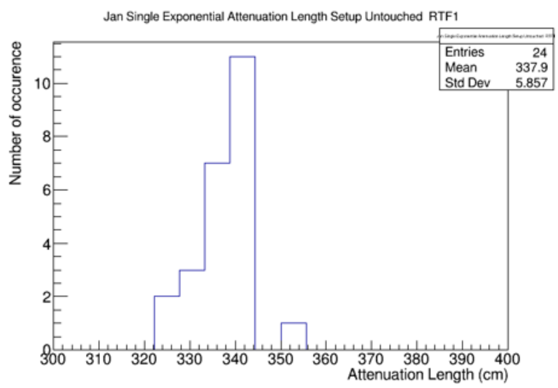
Two types of measurements were done, one from hereon referred as the repeats, where the fibre was left in place as it is between the measurements and the labVIEW program was just run continuously. The other type of measurement, the resets, was done by taking off the fibre from the rail, putting it back into its packaging and then taking it back out in order to put it on to the rail.

4.1 Repeats

Measurements were done without causing any alterations to the setup where possible. However, slight changes in the positioning of the fibre could still happen if the LEDs are moved carelessly. A bump observed at 2 meter mark is especially prone to causing shifts in the fibre positioning. This could then affect the fibres position in front of the photodiode at the start. The main variance was due to the inability to put the LEDs onto the exact same position during repeated measurements. Between repetitions, different operators do not appear to make a difference on the mean attenuation length obtained, however it can be observed that they have slightly different standard deviations, this could be because certain operators are more precise when it comes to placing the LEDs at the same position.



(a) Operator 1

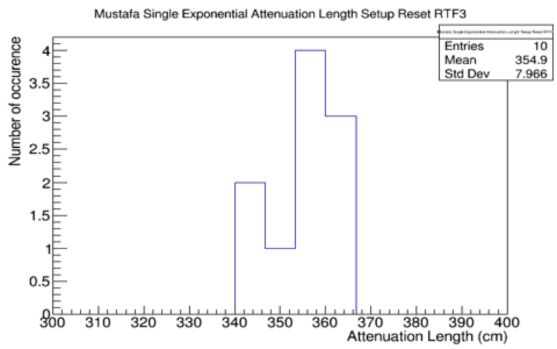


(b) Operator 2

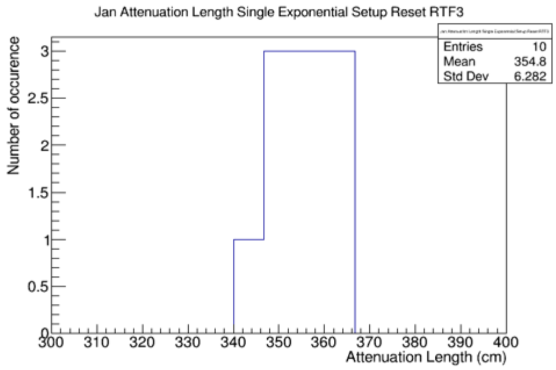
Figure 7: 25 repetitions by two different operators, using the fibre named RTF1

4.2 Resets

It was identified that the resets can have varying effects on the result of the measurements. This might be possible due to not positioning the tip of the fibre at the same point in front of the photodiode, having a different amount of tension in the fibre, or other unknown systematic effects. As it has been shown previously some points are more prone to damage or will demonstrate random effects, these potential variations can result in a shift in the actual measure points on the fibre and therefore affect the attenuation length measured. This makes it a necessity to redo resets more than once in order to get a mean attenuation length from potentially different points in the fibre.



(a) Operator 1



(b) Operator 2

Figure 8: 10 resets by two different operators, using the fibre named RTF3

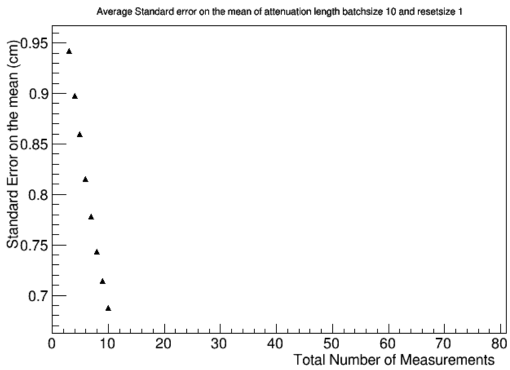
4.3 Standard Error Calculation from Combining Repeats and Resets

Having observed that the repeats and resets all seem to vary and at the moment no sure way of getting rid of these variations, it was decided to use standard error on the mean for the sample of data, in order to find the required number of repetitions and resets to approach the population mean to a certain limit. [3]

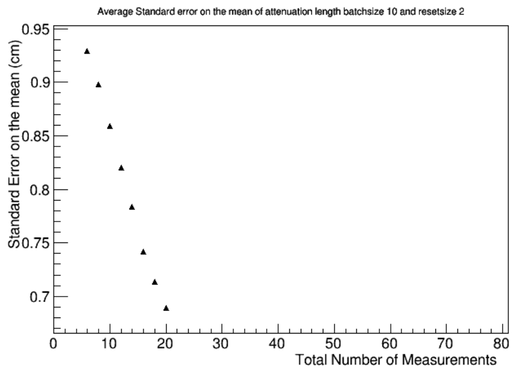
$\sigma_{\bar{x}} = \frac{\sigma}{\sqrt{n}}$

where σ is the standard deviation, n is the number of repeats, and the $\sigma_{\bar{x}}$ is the standard error on the mean. The standard error on the mean is then calculated for each reset and averaged by taking the standard error as a percentage of the mean attenuation length of the repeats. The percentage standard errors were then averaged and multiplied with the mean attenuation length across resets.

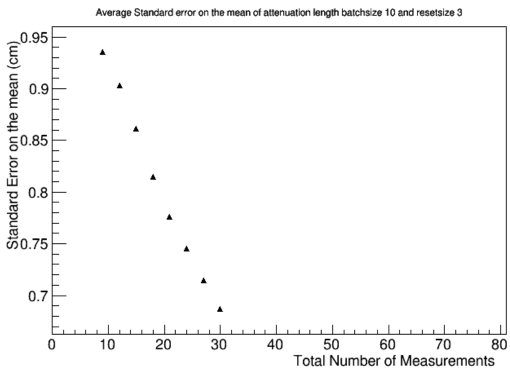
A sample data set with 8 resets and 10 repetitions at each reset was taken. The measurements were each given numbers to identify them, and a random number generator was used in order to pick measurements at random from the sample data. Up to 10 repeats was checked for up to 8 resets. e.g. For 3 resets and 5 repetitions, the random number generator would first pick three numbers that correspond to different reset data sets, then proceed to pick 5 further numbers for each reset set that correspond 5 different repetition measurements in each of the reset set picked. Since this also adds an element of randomness to the standard error calculated this way, this method was repeated for 10000 times and the average of all 10000 runs was taken.



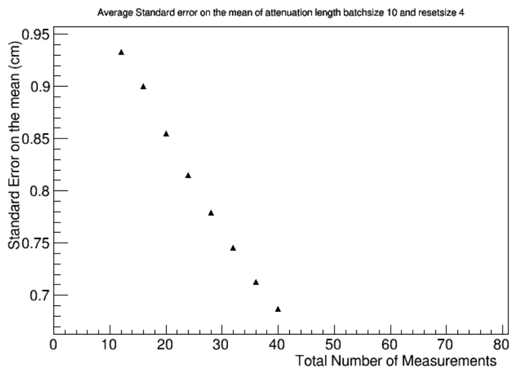
(a) No resets



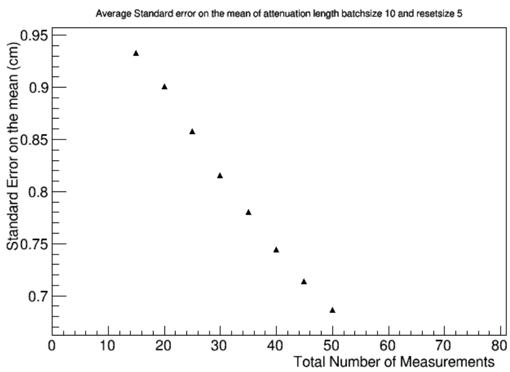
(b) 1 Reset



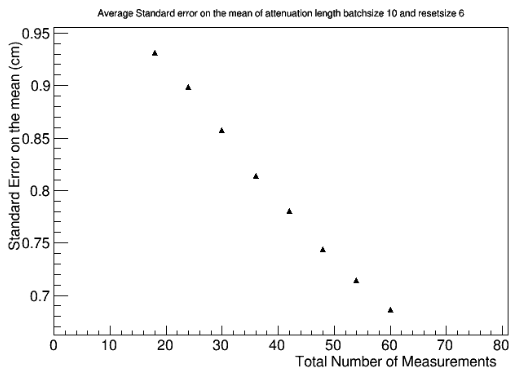
(c) 2 Resets



(d) 3 Resets



(e) 4 Resets



(f) 5 Resets

Figure 9: Standard error simulations of three to ten repetitions for up to five resets

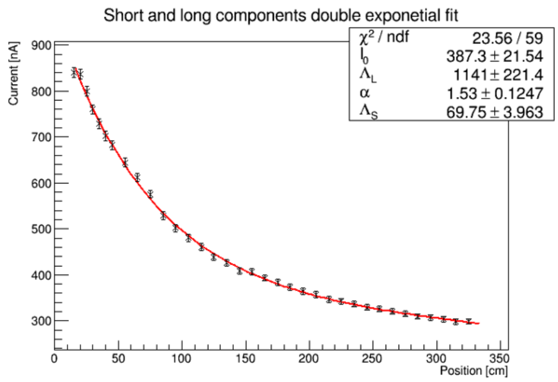
As the average of the standard error obtained from resets is taken, increasing the number of resets do not appear to make a significant contribution to decreasing the standard error. However as previously discussed there is the potential of taking unrepresentative measurements with only one reset as the measurement points could coincide with points on the fibre that are more prone to UV damage, or had anomalies.

3 resets and 5 repetitions at each reset can be used in the future as an optimal method. In order to be able to observe the aging effect of the scintillating fibres which should be 1.4% [1] corresponding to 4.9 cm for a fibre with attenuation length of 350 cm for 1 year. For which the 0.86 cm standard error that can be obtained from 5 repetitions should be low enough to allow the observation of the aging effect. If however results would like to be seen faster, considering that the aging measurements are taken once every 3 months, assuming a linear aging effect, the change should be of the order 1.225 cm every three

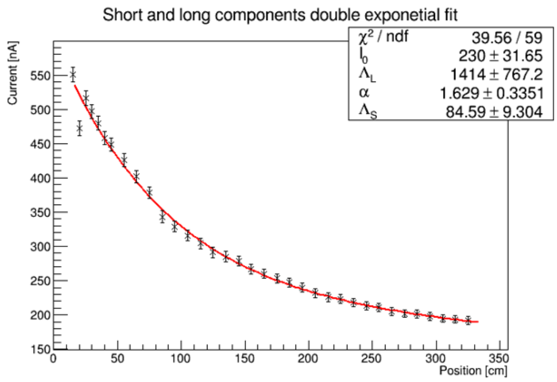
months. This would mean that if the effect of aging is desired to be observed as soon as possible, the precision would also have to be increased. However it should be noted that the standard error on the mean only represents how far away a mean value is from the population mean, not necessarily how much the repeated measurements will vary. Therefore standard deviation is still used as uncertainty in order to give a more representative value for how much the results can vary.

4.4 UV damage

Leaving the fibre in one position and reading out how the photodiode at the start changes overtime with the LED continuously shining on the fibre has led to the result that the fibre is being damaged by the UV LEDs. This phenomenon can be seen in Figure 10 where the LEDs were left on the 25 cm mark over 14 hours.



(a) Before Exposure



(b) After Exposure

Figure 10: Damage after UV exposure to the 20 cm mark overnight.

This damage might have been caused by one of the following ways:

1. The double cladding might be damaged
2. Free radical production [2]
3. Wavelengthshifters in the fibre might be damaged in a different way
4. Transparency might be degrading

In case of 1, any other points measured after the damage point should have also been affected and show a dip, however as it can clearly be seen from Figure 4, that after 25 cm point, there is an increase and the subsequent positions and therefore, the damage seems to be dominant in light production rather than transmission across the fibre. However it is not possible to eliminate if there is any effects on transmission, there are suggested investigations in order to ensure that the damage has no component in light transmission across the fibre. With the free radical production there should be either an increase in another position that corresponds to the dip due to UV damage or an overall increase throughout the rest of the points. The free radical production would explain why the dips disappear after sufficient uniform exposure to UV despite there initially being dips regardless of the uniform exposure. Degradation of transparency could also explain why the damage appears to be localised however would fall short when considering the results of the uniform exposure to UV.

5 Uniform UV exposure

A setup was created with two stationary LEDs at 60nA readout from the PIN photodiodes at the LEDs, the fibre was attached on a rotating disk and moved at constant speed, exposing the fibre uniformly to UV light. This to investigate if long-term uniform exposure to UV light could affect the attenuation length or not. Measurements seemed to indicate that the damage is localised as it can be seen from both Figure 4 and Figure 5. Thus it does not damage the fibre farther in either direction. However, even with a uniform exposure to UV light, certain points on the fibre were observed to be more or less prone to damage compared to the rest of the fibre. As it was possible to miss points of interest due to the limited number of points measured in the original setup, for day 1 measurements were taken every two centimeters and is shown in Figure 11

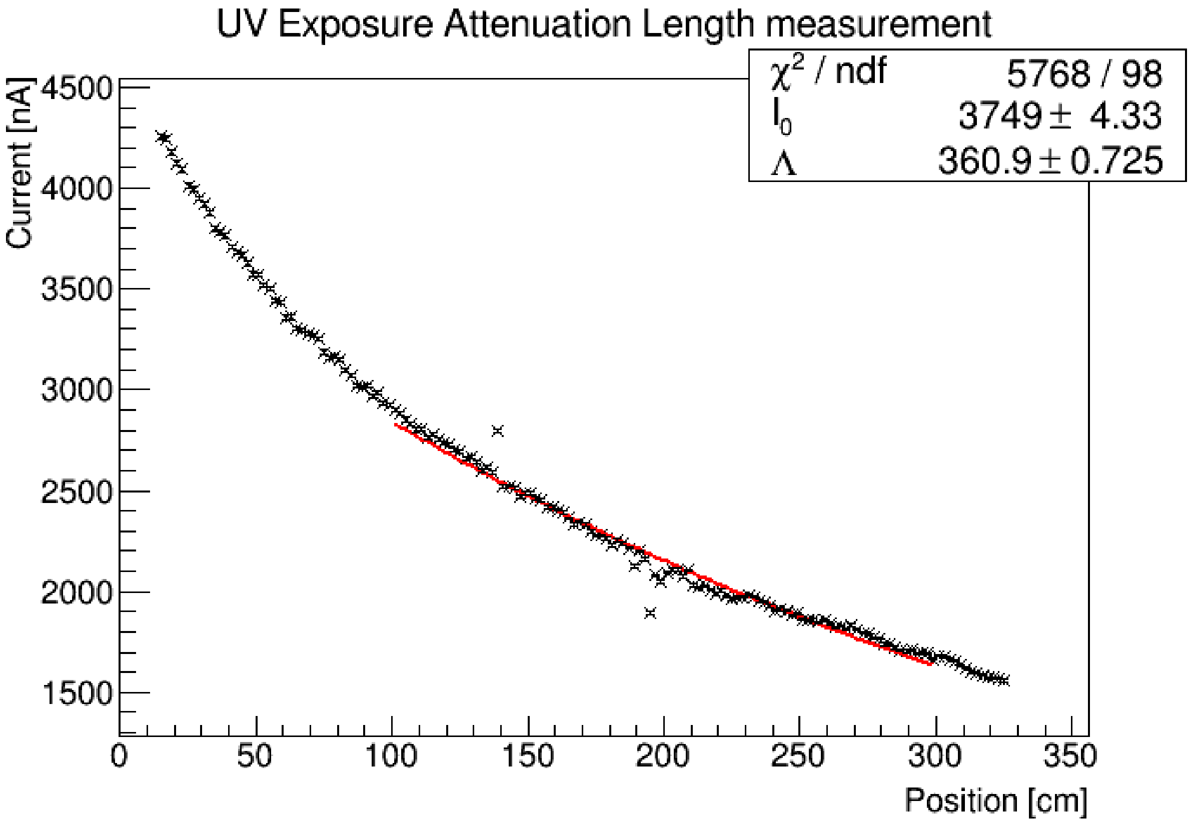


Figure 11: Day 1 measurement, with measurements every two centimeters

The rise in the point that was less prone to damage disappears by day two, and the dips disappear between the second and sixth day. On the sixth day all the irregularities seem to have disappeared, though the attenuation length is seen to have been decreased by 25 cm. This can be seen in Figure 6.

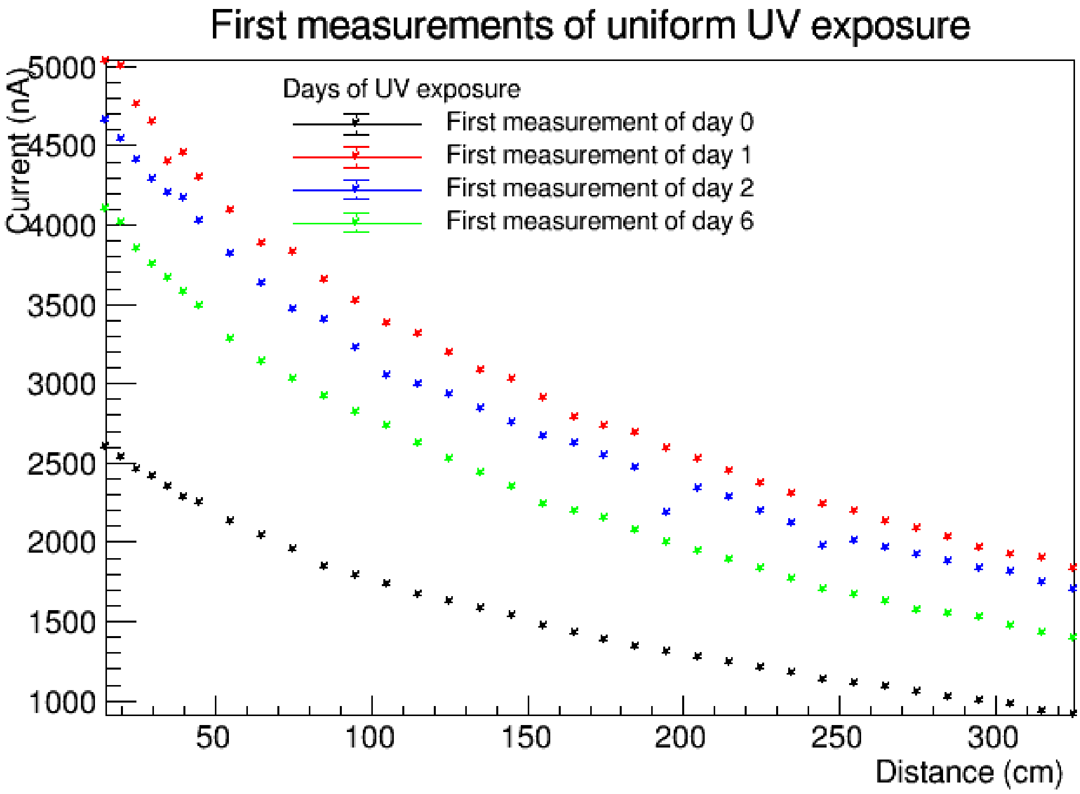


Figure 12: First measurements taken on every day of measurement with uniform UV Exposure

Overall 5 repeat measurements were done for 3 resets on each of the days and the results of the means were found to be: For day 0 mean attenuation length was found to be 347 $\pm$ 2 cm
For day 1 mean attenuation length was found to be 345 $\pm$ 7 cm
For day 2 mean attenuation length was found to be 353 $\pm$ 4 cm
For day 6 mean attenuation length was found to be 322 $\pm$ 4 cm
It should however be noted that the apparent increase in the mean attenuation length for day 2, and the large standard deviation of day 1 compared to rest are both due to there being specific points that were more affected by the UV exposure compared to the rest.

6 Importance of aquadag and cutters

During one of the repeated measurements with resets every ten repeats, the end of the fibre was cut with a guillotine for approximately 40 cm instead of the normal cutter and there was a significant increase in the attenuation length measured compared to before despite the aquadag being applied correctly. This led to further measurements investigating if the type of cut at the end of the fibre, the applied aquadag and the length of the fibre each showed an effect on the measured attenuation length which can be seen in Figure 12.

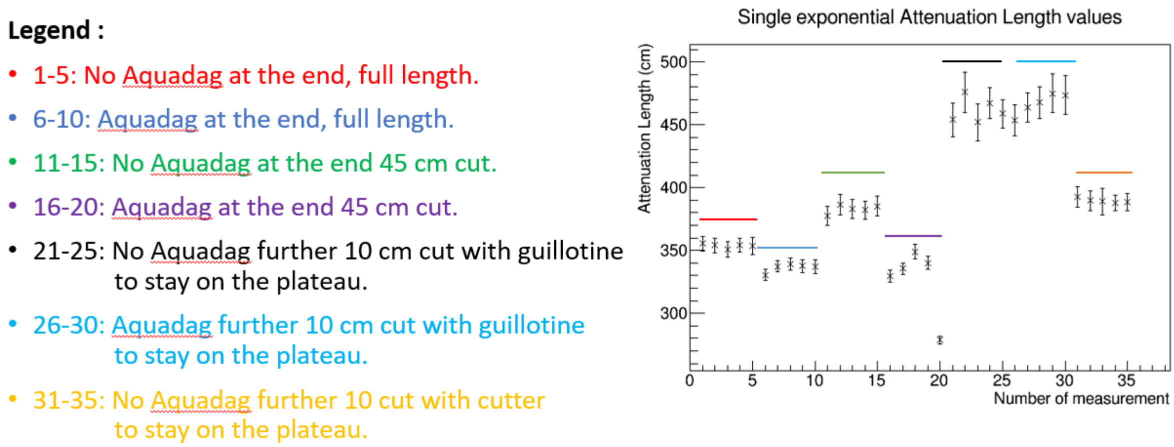


Figure 13: Measurements investigating the effect of aquadag, length of fibre, and the type of cut on the attenuation length.

It has been found that decreasing the length of the fibre increases attenuation length when there is no aquadag applied on the fibre. This most likely stems from effects due to the reflections at the end of the fibre being more significant when there is less distance to travel when is no aquadag to suppress the reflections. In the case of cutting the fibre end with a guillotine, the aquadag appears not to make any effect. Cutting the tip again with a cutter further decreases the attenuation length measurement to pre-guillotine cut levels. The way the cut was made and the aquadag applied, have therefore been shown to be an effective methods of minimising the reflection at the end of the fibre.

7 40 nA vs 60 nA on the LED Photodiode

Previously 40 nA had been used in order to investigate the attenuation length of scintillating fibres. Different voltages from the power supply and the corresponding current through the LED was investigated in order to determine if 40 nA was indeed the optimal choice. The comparison was made with 60 nA as it was a higher current that still did not saturate the fibre. The results can be seen in Figure 14. Mean attenuation Length of 40 nA was found to be 339 $\pm$ 7 cm
Mean Attenuation Length of 60 nA was found to be 348 $\pm$ 2 cm.

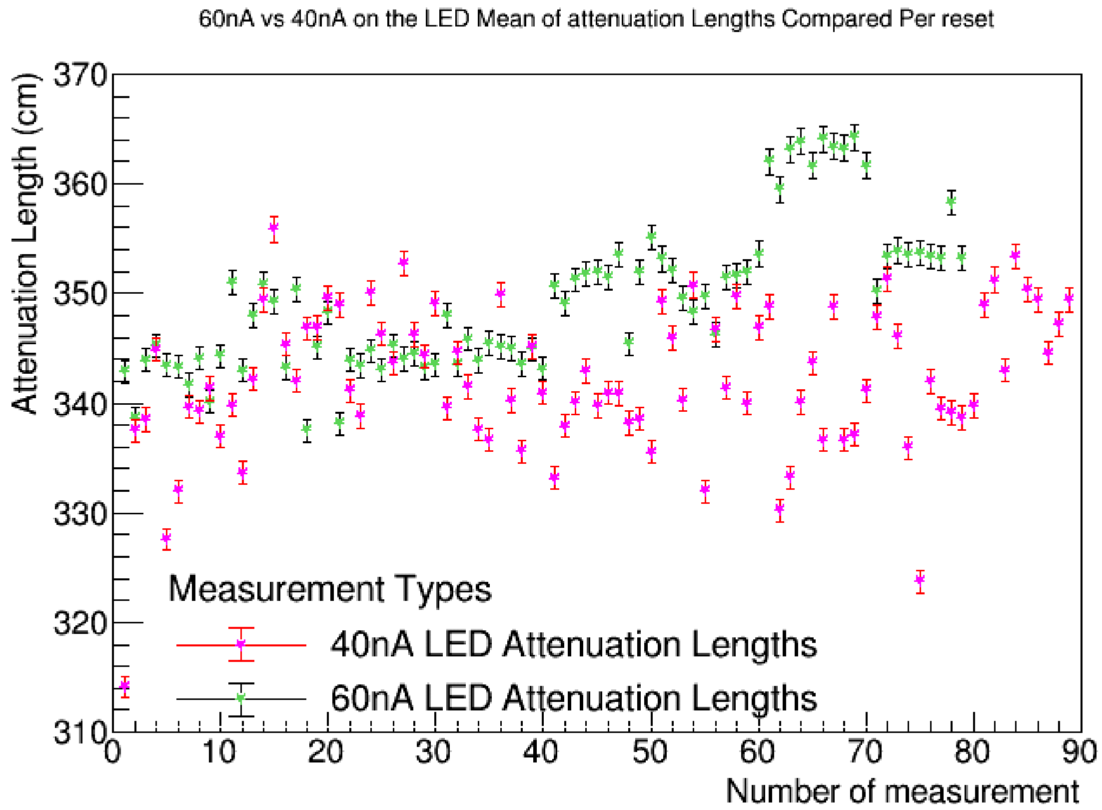


Figure 14: 60 nA measurements compared to the 40 nA measurements

It should be noted that the 60 nA measurements were reset at every 10 repeats whereas 40nA measurements were reset with every 5 repeats. These measurements however were done with the Statron 2229.81 power supply unit before it was switched out with a different one and therefore should be repeated with the Keithley GPC-3030D power supply unit to be used in the future measurements in order to ensure that the trend that 60 nA on the LED has less standard deviation compared to 40 nA is consistent.

8 Results

It was found that the measurement errors due to the electronic equipment were negligible. Though the Keithley GPC-3030D power supply unit showed a definite need for warming up before stabilising. A minimum warm-up period of 15 minutes would ensure that any effects due to the power supply is negligible. The investigation shows that there is a need for multiple measurements in order to be able to investigate the aging effects on the scintillating fibres. Using 3 resets and 5 repetitions of the setup has been suggested, this also allows for any outliers to be identified. The number of repeats can be adjusted if the precision of the measurements is deemed to be too low or too high. A single measurement runs the risk of coming across certain points in the fibre that are more or less prone to aging which could affect the attenuation length measured which assures that there should be more than one measurements of reset and repeat types at least. The uniform UV exposure also shows the limitations of the current setup as it is damaging the fibres further during testing. However if a method of recovering the damage due to UV exposure can be found, it would get rid of the main concern for taking many measurements.

9 Further investigations

Identifying the reason for the damage on the fibre due to UV is paramount in going forward. If it is indeed due to free radical production at particular points, there is the potential of reversing this effect. Passing a small enough current through the fibre or grounding it could replace the lost electrons of the free radicals, however this could also interfere with the measurements for natural aging as it has a component due to oxidation which also produces free radicals [2].
An investigation can be done by taking measurements before and after irradiating the 2-meter spot; which is halfway of the range of the single exponential fitting. The measurement after the irradiation then can be divided into two by fitting the single exponential from 1 meter to 2 meters and comparing it with a single exponential fit from 2 meters to 3 meters. This would help show if the points after the 2-meter spot are affected all together or if it is only the dip at 2-meter spot that causes a change in the attenuation length.

A repeat of the uniform UV exposure should be done with a new fibre in order to investigate if the increase or the dip points can be recreated with a different fibre. It should be noted that even with the resets, points of interests might be "in between" marked positions and therefore it might be a good idea to do measurements every 4/5 cm in order to get a grasp of where points of interest might be.
A measurement with using exact positioning can also be done to see how much of the standard deviation of the mean of repeats is caused by the uncertainty in the distance. Untangling this source of error can also help investigate the random off points that seem to appear.

As the power supply has been switched with a new one, new measurements should be done, investigating the rate of decrease of the current on the photodiode at the start with a fibre through the LED, as the Keithley GPC-3030D power supply unit is more stable compared to the Statron one, it can isolate and help investigate the UV damage on the fibres better. The UV damage measurements should be done starting from the end of the fibre, in case the damage has any effect on the transmission capabilities of the fibre, and the absolute error should be updated with the findings over different positions' UV degradation rates.

Acknowledgements

I would like to thank Jan de Boer, Lukas Gruber, Sune Jakobsen, and Ana Barbara Rodrigues Cavalcante, for their contributions and support during this project.

Bibliography

[1] A.B.R. Cavalcante, B. Dey, L. Gavardi, L. Gruber, C. Joram, R. Kristic, O. Shinjie and V. Zhukov *Refining and testing 12,000 km of scintillating plastic fibre for the LHCb SciFi tracker* 1 2018 JINST 13 P10025

[2] A. Artikov, J. Budagov, I. Chirikov-Zorin, D. Chokheli, M. Lyablin, G. Bellettini, A. Menzione, S. Tokar, N. Giokaris, and A. Manousakis-Katsikakis, *Properties of the Ukraine polystyrene-based plastic scintillator UPS 923A* Nucl. Instrum. Methods Phys.Res., Sect. A 555, 125−131 (2005).

[3] Ifan Hughes and Thomas Hase, *Measurements and Their Uncertainties: A Practical Guide to Modern Error Analysis* Oxford University Press (2010)