Optimization of the longitudinal segmentation of a SPACAL for the LHCb PicoCal

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Abstract
Longitudinal segmentation of a Spaghetti Calorimeter (SPACAL) W/GAGG module was tested using a GEANT4 Monte Carlo simulation framework. In the case of scintillating fibres that do not present any radiation damage, timing resolution was found to be optimal when the front section is 35 mm and back section 115 mm long. After a radiation dose of 1 MGy, the optimal values of timing and energy resolution were found when the front and back sections were equally long. The results were confirmed for both electron and photon beams.

Keywords
High energy physics (HEP); Particle detectors; Calorimetry; Spaghetti calorimeter (SPACAL)

1 Introduction

The LHCb experiment focuses on the heavy flavor physics, and as such requires precise measurements of particle energy, position and timing. In the case of electrons, positrons and photons, these measurements are provided by the Electromagnetic Calorimeter (ECAL). Current LHCb ECAL is a wall of dimension 7.76×6.30 m^2, located 12.6 m downstream from the interaction point. It consists of differently sized Shashlik modules separated into three regions, per granularity requirements. Shashliks are sampling calorimeters, they have lead acting as the absorber, and their assembly delivers energy resolution with a 10% sampling and 1% constant term [**1**],

$$\frac{\sigma(E)}{E} \approx \frac{10\%}{\sqrt{E}} \oplus 1\%. \tag{1}$$

Shashlik modules can withstand radiation doses up to 40 kGy, because the Wave Length Shifting (WLS) fibres within them lose transparency at higher radiation levels. By the end of Run 5, a central region of the ECAL covering around 176 modules will receive a dose higher than 40 kGy. Not only will those modules become unusable, but many will stop working much before the run ends, which poses a problem. Additionally, Run 4 marks the start of the High Luminosity (HL) phase of the LHC, which requires increase in granularity and introduction of fast timing resolution to cope with the increased pile-up. At the end of Run 6, total radiation dose delivered will be 1 MGy. Taking all previously stated into account, the solution is to introduce a new type of module in the innermost region, more robust to radiation damage, while keeping the current energy resolution. These modules would have to be capable of providing higher granularity and fast timing, with a precision of $O(10)$ ps. [**2**]

1.1 Spaghetti Calorimeter (SPACAL)

High radiation tolerance requirements of Upgrade II are met by the Spaghetti Calorimeter (SPACAL) technology. A SPACAL is a sampling calorimeter, with longitudinal fibres acting both as scintillators

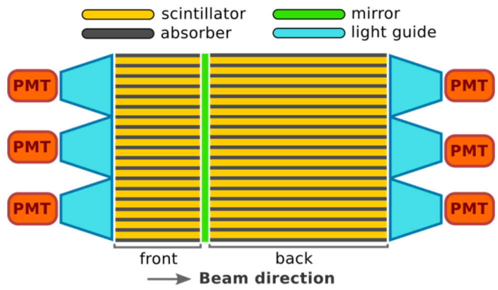


Figure 1: Schematic side view of a SPACAL module configuration. Figure taken from [**1**].

and light-transporting media. A schematic of a SPACAL module is given in Figure 1. In the innermost region, where radiation doses are higher than 200 kGy, a SPACAL module with tungsten (W) as the absorber and garnet GAGG crystal fibres in the active layer proved to be the most promising. Around it, in the region where radiation doses vary between 40 kGy and 200 kGy, studies have shown that lead-polystyrene SPACAL modules are sufficient. Therefore, 32 Shashlik modules closest to the beam pipe will be replaced by W/GAGG, and 144 by Pb/PS SPACAL modules, while upgrading the rest of the Shashliks and rearranging ECAL into a rhombic shape [**2**].

Due to the expected high occupancy, SPACAL modules will be longitudinally segmented into a front and a back section. Such segmentation will help improve time resolution, since complementary information will arrive from both the front and the back. Additionally, it will improve clustering and provide more information for event reconstruction and particle identification, for example in the case of photons and high-energy neutral pions. Having separate front and back sections is expected to dampen the effects of the radiation damage, specifically on the constant term of energy resolution. [**2**]

The current prototypes were segmented around the particle shower maximum. More precisely, the front section was made to be 40 mm long, which is about 7 radiation lengths, or the position of average shower maximum at 20 GeV. The back section of the tested prototype was 100 mm. [**3**] However, it has not yet been checked whether this is indeed the optimal front-to-back separation that will lead to the best time resolution. Therefore, the goal of this work will be to first test different separations of a module with undamaged fibres and find the one that minimizes timing resolution. Then, it will be checked whether the optimum changes once the fibres are damaged, and whether the results stay the same in the case of electrons and photons. It should be noted that, in all the following sections, the study is done on a single W/GAGG SPACAL module.

1.2 Single module simulation

The whole study presented in this report is done through the simulation of a single SPACAL module, which was developed using the GEANT4 Monte Carlo framework. [**4**, **5**] The simulation uses a configuration file to fully describe module geometry. In this file, among other, it is possible to change the lengths of front and back sections, as well as the transparency of the fibres. One can then shoot the primary particles, electrons or photons, and obtain full energy deposition. Full ray-tracing is done for Cherenkov photons only, as these simulations can be very time-consuming. Scinitillation photons are undergoing parameterized propagation on the basis of energy deposition map using probability density functions. It should be noted that this is not real ray-tracing, but that it is validated against the standard one. The scintillation photons are then added to the output, the signal is formed, and the user is able to obtain information on energy and timing resolution. This simulation framework has been validated by comparing its results to the ones obtained from test beams. [**5**] The lengths of the front and back sections were changed such that the total length of the module is fixed to 150 mm.

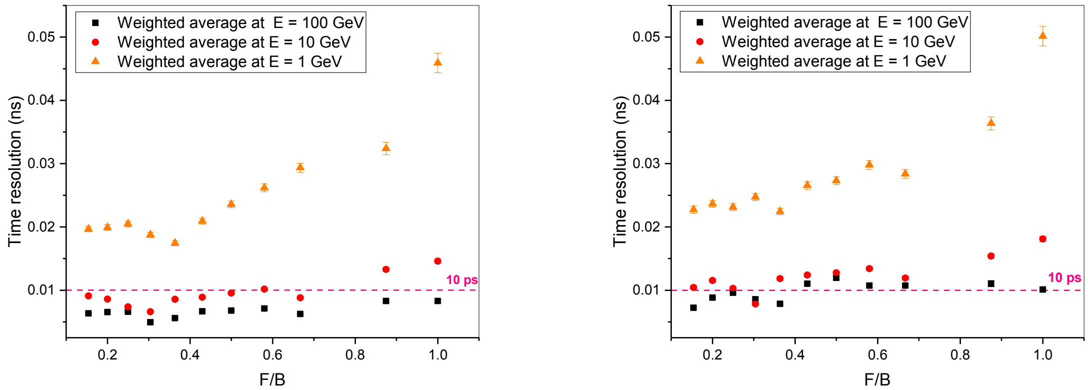


Figure 2: Time resolution weighted average as a function of front-to-back separation ratio in the case of electron (left) and photon (right) beam. The pink line highlights the time resolution of 10 ps.

2 Time resolution study

In this part, radiation effects are completely neglected, i.e. it is assumed that the fibres' absorption length is much longer than the module and thus the radiation damage is negligible. In the rest of the work, this case will be referred to as undamaged fibres.

The simulations were performed on a single W/GAGG SPACAL module at $3^\circ + 3^\circ$ incidence angle of the incoming particles, first shooting electrons and repeating the steps for photons. The results were obtained at multiple different energies: 1 GeV, 5 GeV, 10 GeV, 20 GeV, 35 GeV, 50 GeV and 100 GeV. The goal was to find a front-to-back ratio F/B that minimizes time resolution.

Figure 2 shows dependence of the weighted average of time resolution on front-to-back separation ratio in the case of electrons, on the left, and photons, on the right. It should be noted that the weighted average is obtained by combining the two timestamps, from the front and the back, using as weights time resolutions of the individual sections. The individual time resolutions in the front and the back section are given in Appendix A. A minimum can be observed in both cases when the front is 35 mm and the back 115 mm long. The existence of this minimum is expected. Indeed, when the front section is too short, there will not be enough energy deposited in it which will negatively impact timing resolution. As we increase its length, timing improves since more energy is deposited. However, when the front becomes significantly longer than the back, the module behaves similarly as the unsegmented one, resulting in worse timing resolution. It can also be noticed that the time resolution is slightly better in the case of electrons, which is expected since the photon shower is known to fluctuate more.

3 Radiation damage study

After determining the separation ratio F/B that optimizes time resolution before any damage was done to scintillation fibres, it remains to check whether this result changes after the fibres are exposed to radiation doses up to 1 MGy. Radiation will also affect the constant term of the energy resolution. One of the requirements of the Upgrade II is that the energy resolution of ECAL does not change significantly compared to the current one, so the constant term should not surpass 2%. With the latter in mind, this part will focus on the impact of radiation on both the constant term of the energy resolution, as well as timing.

In the simulation, one can artificially damage the fibres by changing their transparency, that is, changing the bulk absorption length of the material. This is done in the base configuration file, through a rescale factor R which corresponds to the ratio of bulk attenuation length and length of the module.

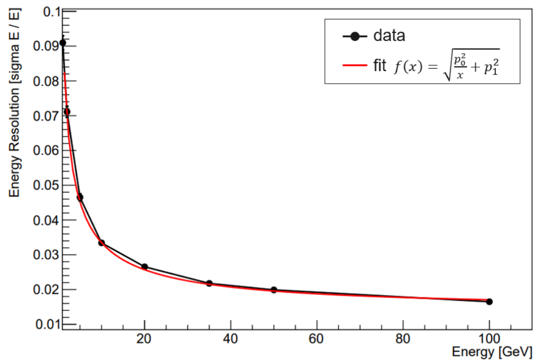


Figure 3: Example of energy resolution $\frac{\sigma(E)}{E}$ as a function of energy, along with the appropriate fit (red).

Defined like this, value $R = 4$ was fixed to represent undamaged fibres, the ideal case where attenuation length is much longer than the module thus making bulk attenuation negligible. This is the value that was used during the study described in Section 2. Furthermore, it was experimentally determined that the value of rescale factor that corresponds to attenuation length in a newly produced module is $R = 0.8$. It was important to use these information to adequately choose values of R at which simulation should be ran. At a radiation dose of 1 MGy, it is expected that the effective attenuation length decreases by 63% [**6**]. Therefore, by plotting effective attenuation length as a function of rescale factor and interpolating it, it was deduced that a 1 MGy dose corresponds to a rescale factor 0.3. Hence, the chosen values for R were: 0.15, 0.3, 0.5, 0.6, 0.75, 1 and 2.5.

Each time a new rescale factor was fixed, the simulation was ran for different separation ratios F/B: 35/115, 45/105, 55/95, 75/75 and 90/60. Naively, one would assume that in the case of radiation damage it is best to have front and back sections equally long, so that one does not end up significantly more damaged than the other, which justifies that one of the examined separations is F/B $= 75/75$. Second direct choice was the one found optimal in the undamaged case, F/B $= 35/115$, and a couple of points were chosen in between. Only one point was chosen where the front section was longer than the back, because timing was considerably worse in this case for the undamaged fibres, so it was not expected to find an optimum on this side. For each F/B value, results were obtained at 1 GeV, 5 GeV, 10 GeV, 20 GeV, 35 GeV, 50 GeV and 100 GeV, same as in Section 2.

3.1 Constant term of the energy resolution

As stated in the introduction, one can express energy resolution in the form

$$\frac{\sigma(E)}{E} = \sqrt{\frac{p_0^2}{E} + p_1^2} \tag{2}$$

where p_0 and p_1 correspond to the sampling and constant term respectively. Based on this, one can plot $\frac{\sigma(E)}{E}$ as a function of energy and fit it with the function of the same form as (2) to extract the constant term. An example of such fit is given on Figure 3. This procedure was repeated for each value of rescale factor and front-to-back ratio, as well as for both particle types.

Figure 4 shows the constant term of energy resolution as a function of rescale factor for electrons (left) and photons (right), at different front-to-back separation ratios. It is not easy to directly extract information from these plots so it was decided to focus on the constant term at 1 MGy, as this is the expected dose at the end of Run 6. However, one can confirm that the abrupt increase in the constant term indeed happens around $R = 0.3$, and that up until then it remains under 2%, as required. The

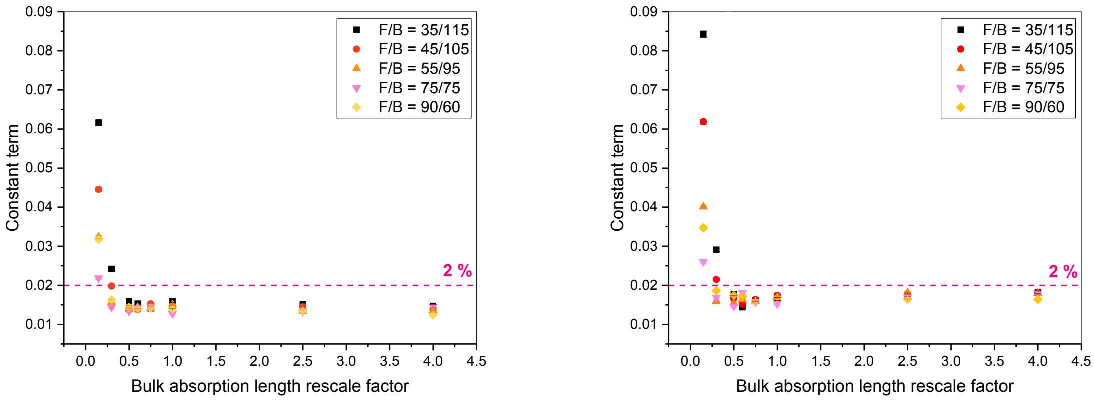


Figure 4: Constant term of energy resolution as a function of the bulk absorption length rescale factor in the case of electron (left) and photon (right) beam. Pink lines indicates upper limit posed by Upgrade II.

constant term is consistently slightly larger in the case of photons, but stays within the imposed upper limit.

Figure 5 shows the constant term of the energy resolution at radiation dose of 1 MGy as a function of front-to-back separation ratio, for both electron and photons. In the case of electrons, the minimal constant term is observed when front and back sections are equally long. This result is expected, considering that damage starts being an important factor once attenuation length becomes comparable to the length of the module. This means that if one section is much longer than the other, it will end up being much more damaged, which is not optimal. A different minimum is observed for photons, but this might be a fluctuation and it requires a further study. However, a conclusion that can be made is that radiation degrades performance of the ECAL more for photons compared to electrons. This result is justified by the fact that a photon shower starts one radiation length further than an electron one and fluctuates more.

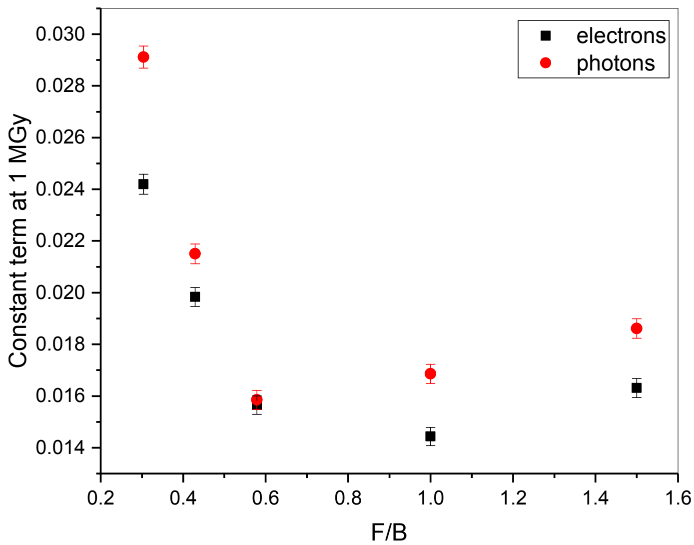


Figure 5: Constant term of the energy resolution at 1 MGy as a function of front-to-back separation ratio, in the case of electron (black) and photon (red) beam.

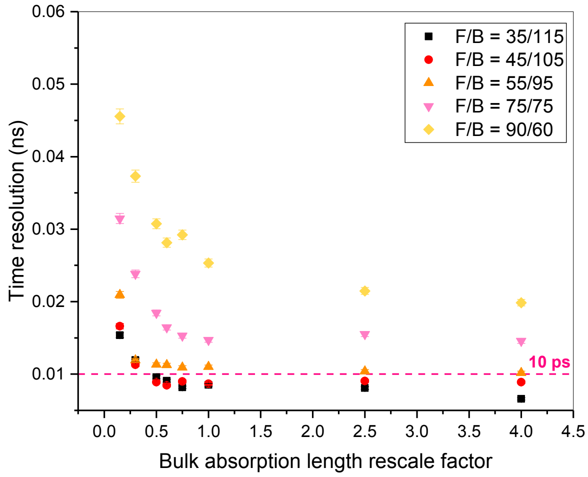
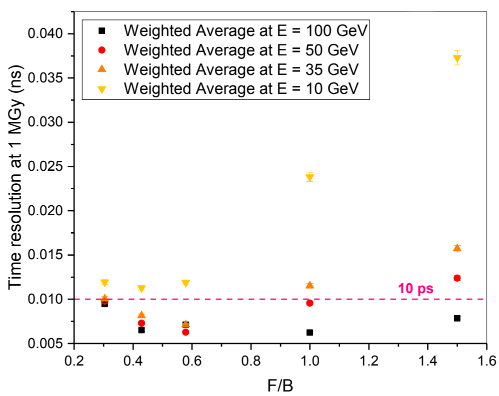


Figure 6: Weighted average of time resolution at $E = 10$ GeV as a function of the bulk absorption length rescale factor in the case of electron beam. The pink line highlights the time resolution of 10 ps.

3.2 Time resolution

Figure 6 shows time resolution as a function of rescale factor at $E = 10$ GeV for different separations, in the case of an electron beam. This plot is given as an example, however, the conclusion that can be made is that the shorter first part is still preferred for better timing resolution, but what is interesting is that as we damage the fibres, the optimal configuration changes. To better show this, time resolution at 1 MGy dose, thus at $R = 0.3$, was extracted for each front-to-back ratio and plotted.

Figure 7 shows time resolution at 1 MGy as a function of separation ratio, at different energies and for both electrons and photons. It can be concluded that, while the best timing resolution is achieved when front and back sections are equally long, other configurations such as 45/105 and 55/95 also give satisfactory resolution at higher energies.



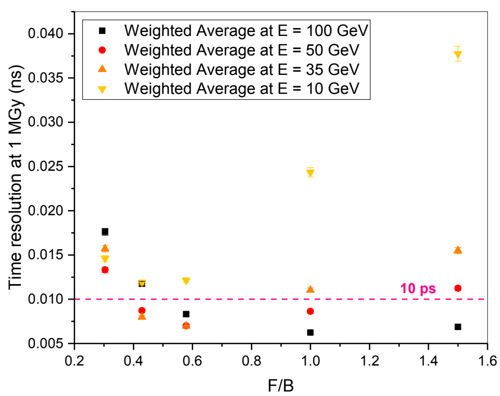


Figure 7: Weighted average of time resolution at 1 MGy as a function of front-to-back separation ratio at different beam energies, for electron (left) and photon (right) beam.

4 Conclusion

This work provided an optimization study of the longitudinal segmentation of a single SPACAL module through a GEANT4 Monte Carlo simulation.

In the first part, undamaged fibres were investigated, and it was found that the best time resolution is achieved when the front section is 35 mm and back section 115 mm long. Apart from the fact that having a shorter first part helps achieve better timing resolution, it is also preferential for the overlapping cluster separation, for instance in the case of high energy π_0 decay.

Higher radiation doses during Run 4, 5 and 6 were the main motivation for introducing SPACAL technology into the inner layers of ECAL. Consequently, the second part involved study on radiation damage. At a radiation dose of 1 MGy, expected at the end of Run 6, the best energy and timing resolution are achieved when the front and back sections are equally long. However, these resolutions still remain satisfactory even if the front section is somewhat shorter, between 45 mm and 55 mm. More importantly, at all previously mentioned lengths, the constant term of energy resolution stays below 2% and time resolution below 10 ps, which is required for the Upgrade II. Additionally, as ECAL is used for measuring energy and position of electrons, positrons and photons, it was important to check that the previous conclusions hold for both electrons and photons. Additionally, it was found that radiation degrades the performance of the ECAL slightly more in the case of a photon beam. The next step for improving this part of the study will be to increase the number of front-to-back ratios at which the simulation is ran. By including more points it will be possible to claim with higher certainty that the minimum for both electrons and photons should be expected at F/B $= 75/75$.

More generally, the study could be improved by including into the simulation the fact that radiation damage is not constant throughout the module. This would involve introducing an attenuation length that changes along the z-coordinate, which is closer to the realistic case.

Taking into account previous conclusions, a SPACAL module that will be used for Upgrade II will most likely have 50 mm long front and 100 mm long back section. While this ratio might partially be chosen as a matter of convenience, it is also a balance between the optima found before and after 1 MGy dose and this study showed that it gives satisfactory performance in both cases.

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I would like to thank my supervisors, Marco and Loris, for teaching me so much over the 8 weeks I spent at CERN, including installing GEANT4, a lot of interesting physics that happens inside a SPACAL module, and that connecting a lot of cables is not that scary. I would also like to thank the rest of the LHCb ECAL group, I really had a great time being a part of it. I hope to see you all again at CERN.

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Appendix

A Time resolution study

In the following are given additional plots made during the time resolution study.

A.1 Front and back section separate timing

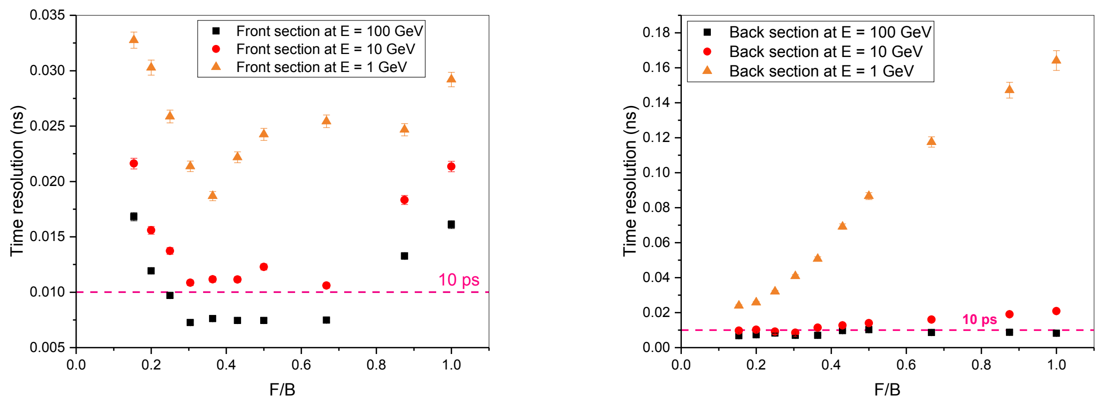

Figure A.1: Time resolution as a function of front-to-back separation ratio in the front (left) and the back (right) section in the case of an electron beam. The pink line highlights the time resolution of 10 ps.

B Radiation tolerance study

In the following are given additional plots made during the radiation tolerance study.

B.1 The sampling term

The following plots confirm that the sampling term indeed does not change and stays below the limit of 10% until a radiation dose of 1 MGy is reached.

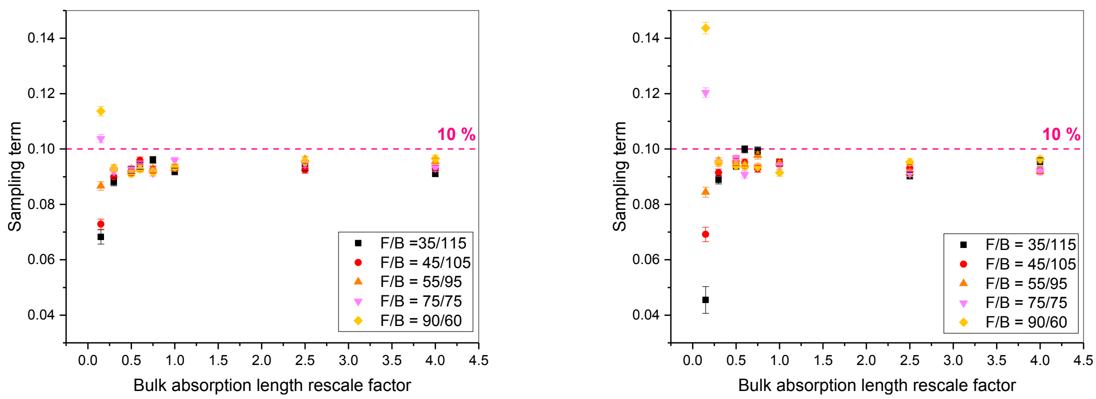

Figure B.1: Sampling term of the energy resolution as a function of the rescale factor, at different front-to-back separation ratios, in the case of electron (left) and photon (right) beam. Pink line indicates a limit posed by the Upgrade II, which is 10%.

B.2 Energy resolution at a radiation dose higher that 1 MGy

Figure B.2 shows energy resolution as a function of energy when the rescale factor is $R = 0.15$, so at a radiation dose higher than 1 MGy. It can be noticed that the fit used previously is not appropriate anymore. Consequently, in this case, the constant term was approximated to be the value of $\frac{\sigma(E)}{E}$ at 100 GeV. This could be a reason why in some cases data points at this value of R vary unexpectedly more from the rest.

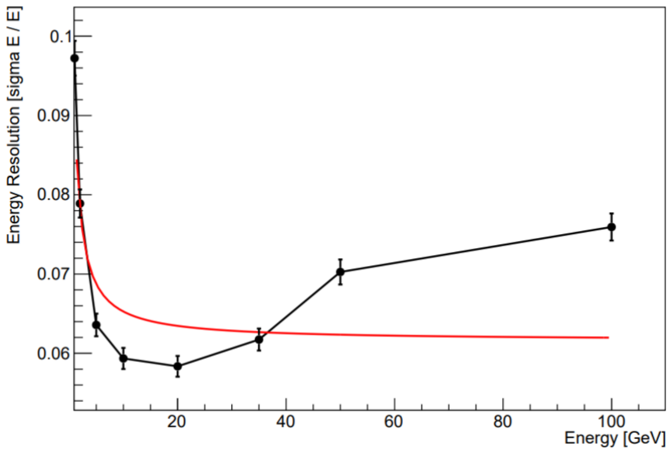

Figure B.2: Example of energy resolution $\frac{\sigma(E)}{E}$ as a function of energy at $R = 0.15$, along with a fit of the form $f(x) = \sqrt{\frac{p_0^2}{x} + p_1^2}$ in red.

B.3 Bulk absorption rescale factor at 2% constant term

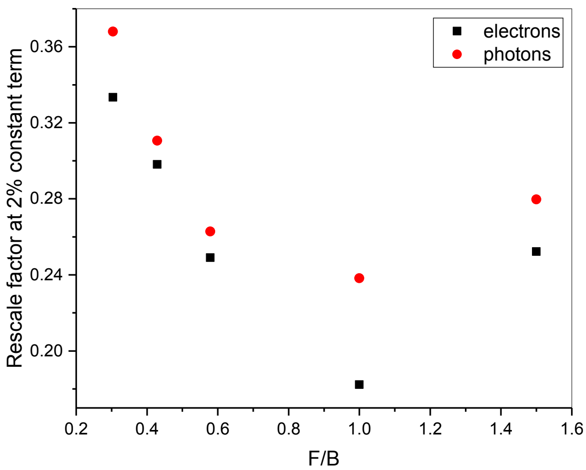

Figure B.3: Bulk absorption rescale factor at 2% energy resolution constant term as a function of front-to-back separation ratio for both electrons (black) and photons (red).

Let the limiting rescale factor be the rescale factor at which the limiting value of constant term 2% is reached. Then this limiting rescale factor corresponds to the radiation dose after which a SPACAL module does not fulfill Upgrade II requirements anymore. One could then search for the optimal longitudinal separation as one that minimizes the limiting rescale factor. Such plot is shown on Figure B.3. The plot concisely summarizes the conclusions made in Section 3.1, specifically that the optimal front-to-back ratio once the fibres are damaged by radiation is $F/B = 75/75$, as well as that photon radiation degrades the performance of the module more. The data points on the plot were found by inverting and interpolating dependence of the constant term on the rescale factor, and a lot of them ended up being somewhere between the points corresponding to $R = 0.15$ and $R = 0.3$. However, taking into account the previously discussed problems with determining constant term when $R = 0.15$, this plot cannot be considered reliable and was thus left out of the main part of the report.

B.4 Time resolution - electrons

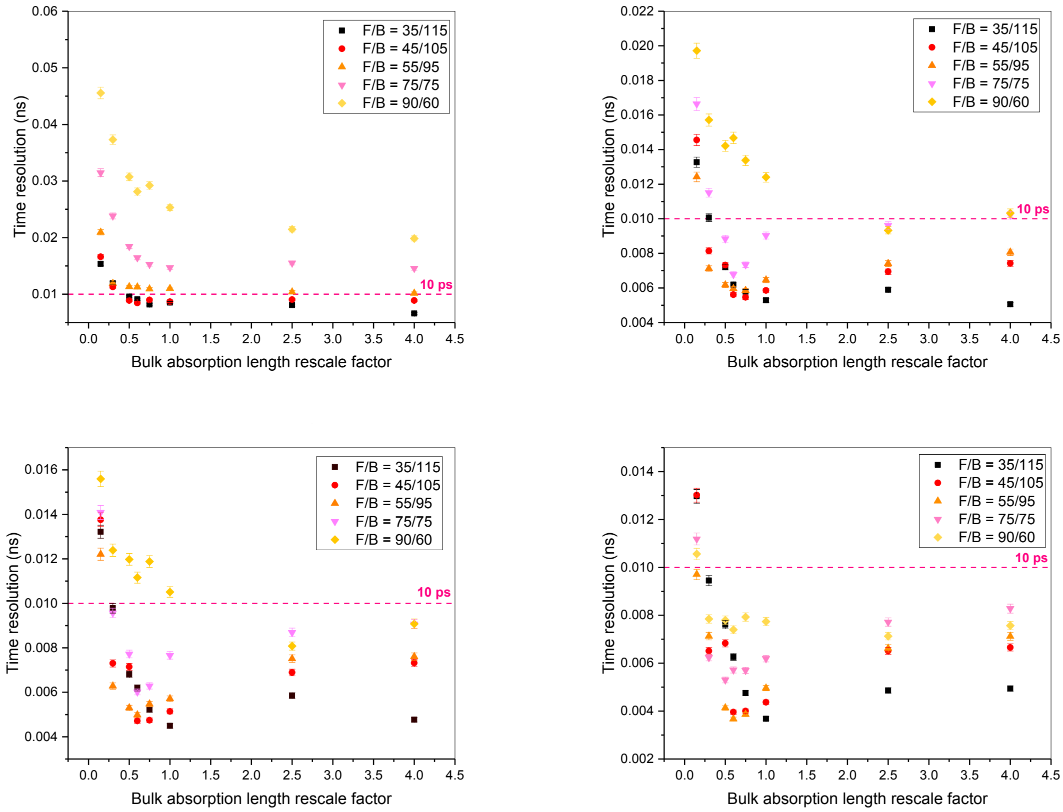

Figure B.4: Weighted average of time resolution as a function of the bulk absorption length rescale factor at $E = 10$ GeV (upper left), $E = 35$ GeV (upper right), $E = 50$ GeV (lower left) and $E = 100$ GeV. The pink line highlights the time resolution of 10 ps.

B.5 Time resolution - photons

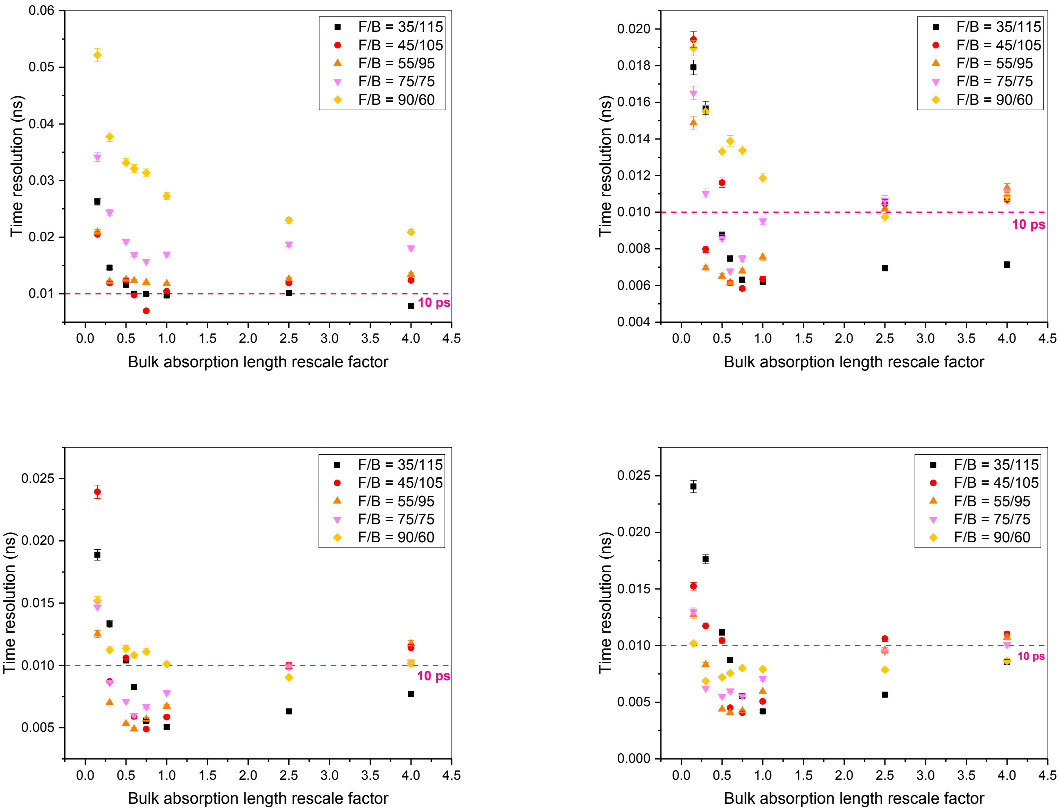

Figure B.5: Weighted average of time resolution as a function of the bulk absorption length rescale factor at $E = 10$ GeV (upper left), $E = 35$ GeV (upper right), $E = 50$ GeV (lower left) and $E = 100$ GeV. The pink line highlights the time resolution of 10 ps.