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Plastic in particle physics – aging of WLS Optical fibers using the Fibrometer testbench of LOMaC

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Abstract. The ATLAS barrel hadronic sampling calorimeter, uses scintillating plastic tiles as the sensitive medium and wavelength shifting (WLS) plastic optical fibres to guide the collected light to photodetectors. The same type of detection principle is one of the options for hadron calorimetry at future coliders. Regarding this type of detection systems and during the internship at LOMaC the following was studied: the natural aging of WLS fibres during 20 years. For the optical fibres, light yield follows the trend of the used reference fibers for the measurements taken during a period of 20 years. The optical fibres attenuation length decreases during this period of time. The ratio of light intensity at different points of the fibre over time remained constant.

Keywords: LHC, Tile Calorimeter, Optical fibres, Aging

1 Introduction

For this paper we have performed a 20 year old follow-up study [1] on the natural aging of a set of wavelength shifting fibers identical to ones in the ATLAS [2] Tile Calorimeter (TileCal). The fibers were collected during different stages of the mass production procedure towards the optical instrumentation of this detector.

1.1 The scintillating tiles hadronic calorimeter of ATLAS/LHC

The TileCal is the barrel hadronic calorimeter of the ATLAS experiment at the CERN Large Hadron Collider (LHC). A hadronic calorimeter is a detector that measures the energy of hadrons. In fact these type of detectors are usually designed to stop most of the particles coming from a collision, with the exception of muons, and force them to deposit all their energy before leaving the hadronic calorimeter volume. Their structure is usually built out of alternating layers of a passive or "absorbing" high-density material and an active material, these being, respectively, low-carbon steel and plastic scintillator (scintillating tiles) in the case of the TileCal – Figure 1.2 [3]. The optical part of the detection system of the TileCal starts at the scintillator tiles. These absorb the energy of the particles being excited and emit light onto two optical wavelength-shifting fibers (WLS Fibers) placed at two opposite edges of each scintillating tile, which shift the blue light they receive into green light. These WLS fibers, along with others from different adjacent tiles are collected in a bunch guiding light into a single photomultiplier tube (PMT), which converts the light signal into a measurable electric signal proportional to the deposited energy.

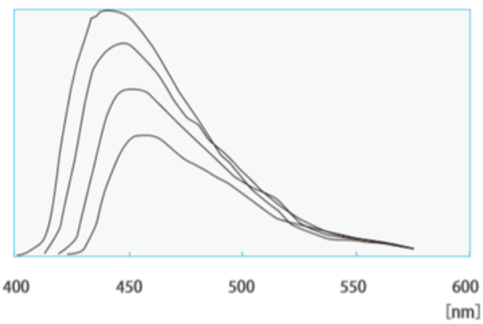

Figure 1. Emission peak in the blue region (400 - 485 nm) for a typical scintillator

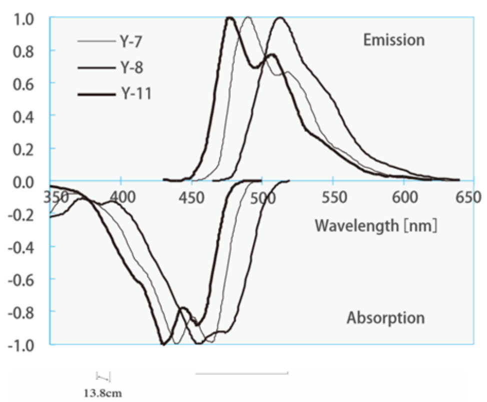

Figure 2. The absorption peak for the Y-11 WLS Optical Fibres and corresponding emission peak around the green wavelength (500-565 nm) [4].

1.2 Scintillation and Fluorescence processes

Scintillation is a process by which ionizing particles while interacting with a material produce radiation in the ultraviolet wavelength, that is absorbed by scintillating dopants in this material, which emit photons of a longer wavelength, that is of lower energy. In a fluorescence process, such as the wavelength shifting process, the material absorbs photons of a given energy, then emitting photons of longer wavelength. The absorption and emission happening at the scintillator tiles is a scintillation process. In Figure 1.2 the emission spectrum for the scintillation process occurring in the scintillating tiles can be depicted. In the TileCal the scintillating tiles photons are emitted in the blue region of the visible light spectrum. Fluorescence takes place in the wavelength shifting fibres. In Figure 1.2 are shown the absorption and emission spectra from the WLS optical fibers used in TileCal. Blue light coming from the tiles is absorbed, followed by emission of photons of a wavelength corresponding to the green region of the visible light spectrum.

1.3 The Future Circular Collider (FCC)

In future experiments as is the case of the FCC [5], one of the options for the hadronic calorimeter is to use the same type of design as the one used for the scintillating tiles barrel hadronic calorimeter of ATLAS – Figure 1.3. The design of the detector has to be updated in order to face-up to the experimental conditions at the future experiment. In Figure 1.3 the current option for the hadronic calorimeter for the Future Circular Collider is sketched, where the expected main differences relative to TileCal are:

- The calorimeter would be composed of alternating layers of lead and steel as passive materials, instead of only steel, and use an improved version of the plastic scintillator chosen for TileCal as the active material;
- The scintillating tiles and the photodetectors used would be smaller,in order to improve the granularity of the detector and increase the spatial and energy resolution, resulting now in a single WLS fibre/scintillator tile and a photodetector/ WLS fiber;
- Instead of the Photomultiplier Tube (PMT) the option would be to use e.g. Silicon Photomultipliers (SiPM).

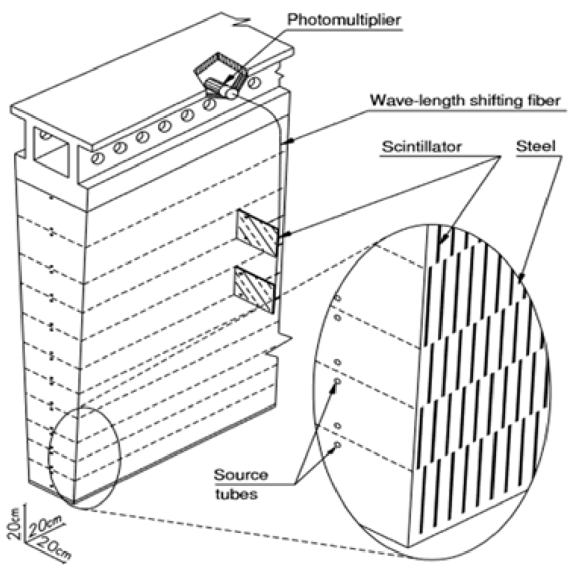

Figure 3. ATLAS/LHC scintillating tiles hadronic calorimeter concept.

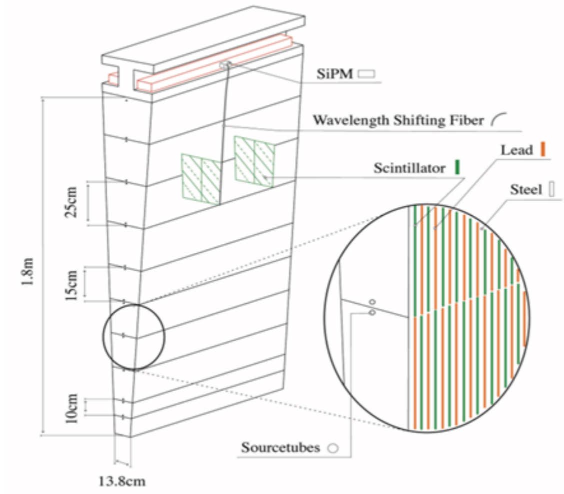

Figure 4. FCC hadronic calorimeter concept.

1.4 Motivation

The ATLAS detector has to be operational for the full duration of the LHC experiment that for now is expected to be a total of at least 35 years (up to 2040). Also, a very long period of operation for any future hadronic calorimeter is expected. Fibres and scintillator tiles composing the optical system are not replaceable for this whole time. Thus, it is of extreme relevance to know the expected degradation of these materials. In this paper we focused on the wavelength shifting fibres. The degradation on optical fibers degradation can be separated in three types:

- Natural Aging
- Radiation Damage
- Mechanical Damage

The measurements reported in this paper refer to the evaluation on the expectations on optical fibers degradation resulting from natural aging using the LOMaC optical fiber test bench.

1.5 Fibrometer Layout

The parameters characterising the optical fibres are measured by a dedicated experimental device called the Fibrometer – LOMaC optical fiber test bench. The Fibrometer concept for optical fibers characterization is very close to the readout optics concept used at the TileCal and so it is from this perspective an adequate setup to be used for this type of studies. The Light Source, composed by a UV-LED attached to a small plastic scintillator (exciting it), produces blue light which excites a single WLS fibre at a chosen point. The plastic scintillator used is from the same material of the ones used for the tiles at TileCal. The excited fibres will then emit green light which will travel through the fibre, into the PMT, which measures the amount of remaining light by converting the light signal into a measurable electric signal – Figure 1.5. The Light Source, powered by a DC power supply and moved

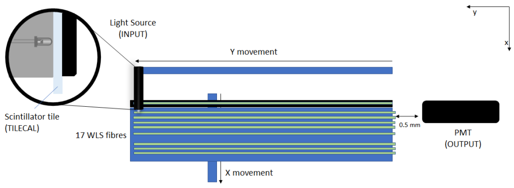

Figure 5. Fibrometer concept.

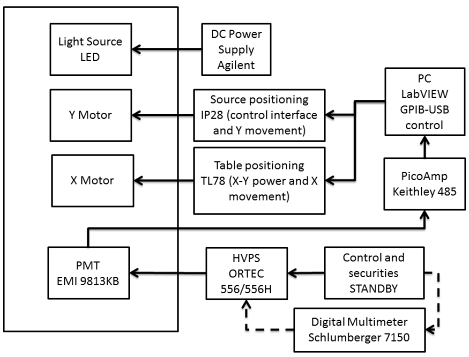

Figure 6. Fibrometer block diagram.

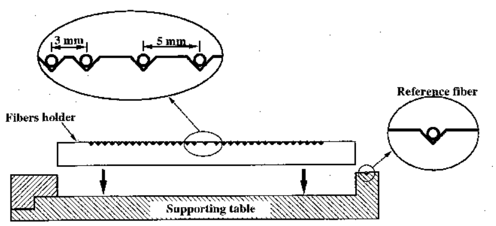

Figure 7. Optical Fibre table positions at the Fibrometer.

by a motor along the fibres' length parallel to the y-axis, is aligned with a 3mm slit collimator placed in front of the PMT window. The motion along the x-axis is done by a different motor moving the table holding the fibres. The PMT is powered by two different high-voltage power supplies, as a procedure to achieve a higher stability during consecutive measurements, and the resulting electric pulse is measured using a picoammeter by a 400 ms integration for increased precision. The user interface of the control and aquisition systems is done using LabView and communication with the hardware is done through GPIB protocol. A block diagram showing the different elements of the Fibrometer is present in Figure 1.5.

The Fibrometer for a series of measurements uses two reference optical fibres: the fixed reference and the fibre holder reference (fibre 9). The fixed reference fibre is never removed out of the system and is at a separate place from the other fibres in the table. The other fibers are positioned over fiber holder plates with 130 mm width. There are two different plates, A and B, each with its individual reference fiber. The fibre holders we use are able to hold 17 optical fibres with lengths up to 250 cm. Fibres are distanced by 6 mm from each other but by 8 mm, for the corresponding adjacent optical fibers, from fibre 9 – Figure 1.5. Reference fibre 9 is only moved out from the system when the optical fibres being tested are changed, but it is never removed from the corresponding fibres holder plate. The reference optical fibers can be used for normalisation – in the standard procedure all fibers are normalized to the fixed fiber response – and for monitoring the response of the system over time – the fibre 9 normalized response should be constant over time.

1.6 Wavelength shifting optical fibre response

The optical fibre response corresponds to the combination of the processes of light production and change of light intensity as it travels through the optical fibre core. The fibre is excited at a chosen point and then measured at the end of the fibre facing the photodetector (PMT). This gives the amount of remaining light after it travelled the distance from the point chosen to the photodetector. The distance to the end of the fibre is then changed and a new measurement is done. Assuming the initial amount of light produced after excitation is constant, not taking into account small changes along the WLS fibre, and as the voltage across the UV LED is constant, the variation of light intensity measured at the photodetector with the distance to the end of the photodetector can be translated in a model using a simple equation. Despite other approximations also seeming reasonable, a sum of two exponential functions was shown to be the most accurate way to describe the light response going through the WLS fibre:

$$I_i\,[x] \;=\; I_o^i \cdot e^{-\frac{x}{Lat_i}} \qquad (1)$$

$$I\,[x] \;=\; \sum_{i=0}^{n=1} I_i\,[x] \qquad (2)$$

resulting also in a model where all parameters have a clear and individualized physical meaning.

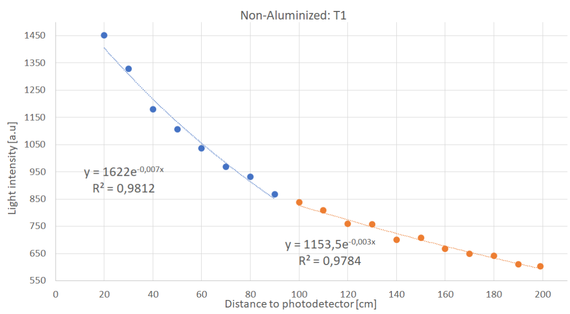

Figure 8. Response of a WLS optical fiber measured with the Fibrometer. The experimental data is fitted using two separated exponential functions for two intervals of x.

There are two relevant parameters for each one of the exponential terms: I0, representing the initial amount of light produced at the excitation point and the attenuation length, L_{at}, which represents the distance light has to travel through the fibre for that component to be reduced to about 36.8% of its initial value. For historical reasons, due to the fact that only the region further away to the photodetector is used in the readout of the scintillating tiles instead of the sum of two exponential functions, the composition of two exponential functions is used to describe the optical fiber response:

$$I_0\,[x] \;=\; I_o^0 \cdot e^{-\frac{x}{L_{at}^0}} \qquad 20\,cm \;<\; x \;<90\,cm \qquad (3)$$

$$I_1\,[x] \;=\; I_o^1 \cdot e^{-\frac{x}{L_{at}^1}} \qquad 100\,cm < \; x \;<200\,cm \qquad (4)$$

In Figure 8 the application of this procedure is presented where the two above mentioned intervals in x have a different exponential fit applied for a 200 cm long fiber. For different fiber lengths fit intervals are adjusted accordingly.

1.6.1 Fibre aluminization

In the TileCal, an aluminium mirror coating is added to the end of the fibres away from the PMT which increases light collection [6]. The achieved reflectivity with the system used at LOMaC are in the range of 70%-85%. Figure 9 compares the signal of a non-aluminized fibre with that

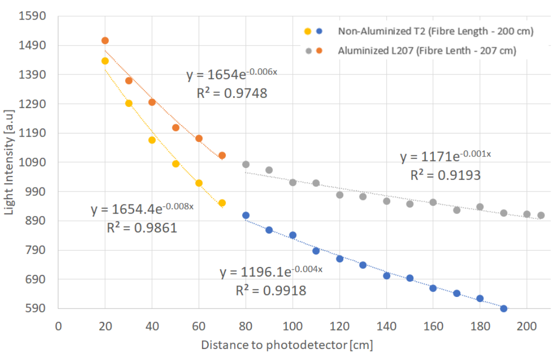

Figure 9. Aluminized vs non-aluminized response.

of an aluminized fibre but 7 cm longer. The comparison of the parameters describing the two signal responses Figure 10 leads to the conclusion that aluminizing a WLS fibre leads to a considerable increase in the attenuation length of the fibres and decrease in the non-uniformity of the signal particularly in the region closer to the mirror.

	L_{attS} [cm]	L_{attL} [cm]	I_{0S} [a.u]	I_{0L} [a.u]
Non-Aluminized T2 (200 cm)	125	250	1654	1196
Aluminized L207 (207 cm)	167	1000	1654	1171

Figure 10. Aluminized vs non-aluminized parameters comparison.

This ultimately results in an increase of the signal measured by the PMT and a dependence of this increase with the distance from the aluminum mirror.

2 Experimental results

2.1 WLS fibers ageing

2.1.1 Reference fibers

When we point our Light Source to a region of the optical fiber, at its tip we get a light intensity that is transformed into an electric current by the PMT of the order of nanoAmperes. As this current is very small it is as well very susceptible to environmental changes such as temperature, humidity and even how long the system has been running, amongst others. To take these factors into account we have two reference fibers, one that is permanently attached to the back of the fibrometer and another that goes at the center of each fibre holder plate. We name them fixed reference fibre and fibre 9. We used the intensity of the fixed reference, when the source is at 30 cm from the PMT, [$I(30)$], to normalize the intensities of the other fibers. In this way we reduce significantly the uncertainty in our results. To illustrate, during 2019 the intensity $I(30)$ had a RMS of 14.4% for fibre 9 and 13.0% for the fixed reference. When we use the fixed reference to normalize the reference 9 the RMS of the intensity drops to 2.4%, because, by doing this, we are taking into account the dispersion due to external factors measured during the same time period by an independent probe that is also made of a material with identical characteristics in composition and optics and is in fact an identical 200 cm WLS optical fiber.

In order to study the natural aging of the optical fibres being tested it is needed to first check on the evolution along time of the reference fibers. In particular on Figure 12 there are several changes that at first glance are not comprehensible. However we have some clues on why some of the changes are present.

For each year we plot the average measured intensity on each reference fiber at 30cm from the PMT to get Figure 11. Until 2011 we can observe a regular decay in the intensity read by both fibers but from there onward we can

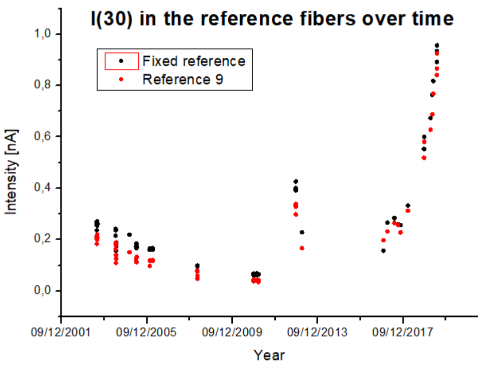

Figure 11. Reference optical fibers response along time: The absolute response of the fibre 9 and the fixed reference.

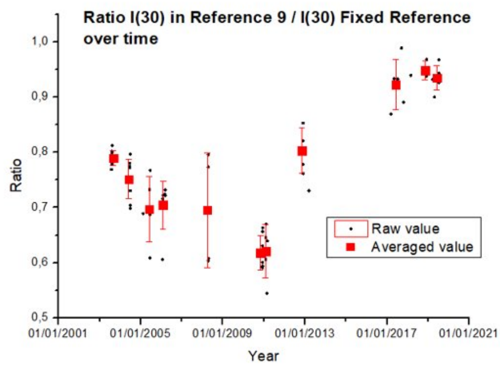

Figure 12. Reference optical fibers response along time: The normalized response of fibre 9 with the fixed reference.

see an increase in the intensity. This can be explained by changes on the setup and the environment, the fibrometer was dismantled and mounted again to move it from its former location to FCUL. The source that illuminated the fibres was changed from a ^{90}Sr radioactive source to an UV LED; this was probably already the case in 2011 which could possibly explain the observed sudden jump. For the last data points from 2017 to the present data something more can be added where a change in several aspects of the light source towards its optimization were made:

- Variation of the DC power of the Light Source;
- Distance of the Light Source to the optical fibers;
- Adjustment of the Light Source support, size of spot, uniformity, used LED;
- Distance of the PMT to the table.

that may explain the huge variations in the most recent years however a deeper review of the logbooks and data must be done.

From Figure 11 we can see as well that both fibers follow the same behaviour, this means that this abnormalities are not due to the fibers but to external factors. Because of this we were expecting for the ratio between both reference fibers to be constant (within some tolerance). This is not what we see in Figure 12, where we can still see changes of the order of 40%. We see a similar pattern in Figure 11: a decrease until 2011 and then a big increase. The factors that can explain this behaviour require a wide review of all the recorded data and could come from the assembly itself: any issues related to the ageing of the photodetector, the Light Source, mechanical details or even problems related to the re-assembly of the Fibrometer in a new location.

2.1.2 Non-Aluminized Fibers

We have studied two different types of fibers: the aluminized ones and the non-aluminized ones. For the non-aluminized we had 4 different production batches to study: T1,T2, T3 and T4, fibers of 200 cm. And for the aluminized ones we have fibres of different lengths: 114 cm, 118 cm, 137 cm, 142 cm, 159 cm, 193 cm and 207 cm. We will present the results for T4 but the conclusions are more or less the same for the other types of fibers.

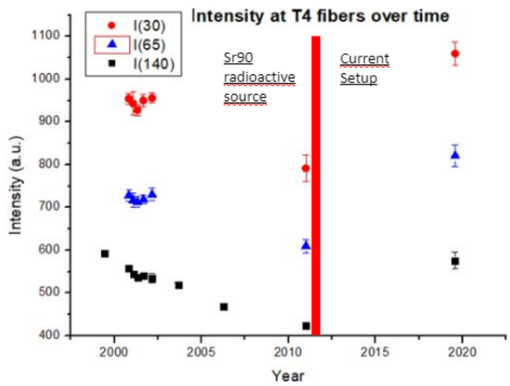

Figure 13. Light intensity at different distances from the PMT over time.

In Figure 13 the normalized intensity over time is plotted and we can see the decrease in the intensity over time until 2011, but in 2019 we see a sudden increase. Each series of data corresponds to a different distance from the PMT, the closer to it, the higher the intensity. This evolution mimics closely the behaviour seen above for the reference fiber which is what we should expect. We can conclude clearly that the intensity has too large a dependency on external factors to be used directly to evaluate any changes related with time.

There are promising alternatives for quantifying the natural aging like using quantities that do not depend on signal intensities but on relative intensities within each single tested optical fiber. We represent in Figure 2.1.2 the attenuation length (*Lat*) over time. The *Lat* gives us an idea of the shape of the curve of the intensity along the fiber. Considering the big dispersion in the value of 2011 we can see an overall decrease in the *Lat*. This is what we could expect over time, the efficiency on the transmission of light to decrease i.e. the optical fiber to be less transparent, due to some possible degradation of the inner structure of the polymer or the scintillating dyes. In a simpler and direct look a problem could be understood when

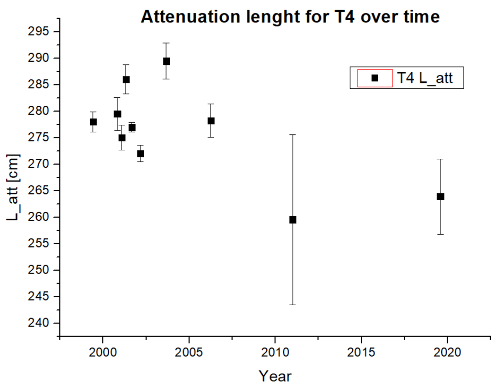

Figure 14. Attenuation length and intensity ratio for T4 non-aluminized WLS optical fibers over time.

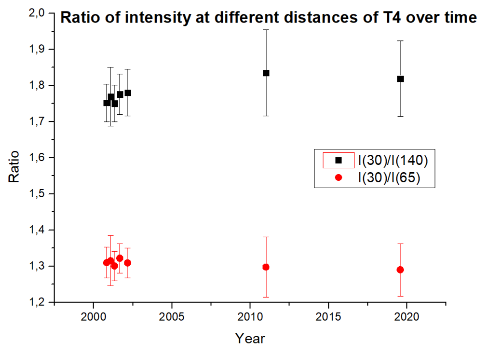

Figure 15. Attenuation length and intensity ratio for T4 non-aluminized WLS optical fibers over time.

we consider the ratio between the different intensities in Figure 2.1.2. In this simpler look we could expect that the results would follow a similar trend to the Latt, because we compare the relative intensity between two points of the fiber. In fact we notice in one case a slight increase and in the other case a slight decrease. Is the attenuation length more sensible to overall changes in the intensity? In fact in its calculation it uses several points that are included in an exponential fit. The remaining question is what should we expect from a variation in 15 cm on the attenuation length? Making a simple calculation the expected signal in 100 cm for an attenuation length of 280 cm is 0.699 while for an attenuation length of 260 cm is 0.680 and the ratio 1.028. Within the error bars, recent and past results for the intensity ratios are compatible with each other. However they are also compatible with an increase of 2.8% that would correspond to the change in the attenuation length measured from Figure 2.1.2. In the end we believe that further measurements in the future might help understanding better the current and past results.

3 Conclusion

Even though we presented the results of the more representative fiber, T4, since we observed the same trends in the other aluminized and non-aluminized fibers, it should be added that there were cases for which we have obtained different time responses. So it is difficult to present a final and general conclusion. It would have been important to have more data from previous years, specially between 2011 and 2019, however the system was inactive during a long period of time, was reallocated and many other changes such as the ones described along the paper occurred that could have impact on the measurements. We finish with the suggestion that a new set of measurements should be done in the future with a frequency of about six months or every year to better understand what happened after the system changed and be used for a validation of the present results.

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References

[1] J. Silva et al., Nuclear Instruments and Methods in Physics Research Section A **580**, 318 (2007)

[2] ATLAS Collaboration, Journal of Instrumentation **3** (2008)

[3] J. Abdallah et al., Journal of Instrumentation (2013)

[4] Kuraray Co., *Scintillating fibers catalogue*

[5] FCC Collaboration, European Physical Journal: Special Topics (2019)

[6] J.G. Saraiva et al, IEEE Transactions on Nuclear Science **51** (2004)