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Characterization of scintillators for the Future Circular Collider as a function of their dimensions

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Abstract. The calorimeters to operate in experiments at the hadronic Future Circular Collider - FCC-hh - will be one of the key pieces for the complete exploration collisions between hadrons. This is because the increase in energy in proton collisions will require detectors that can work in environments of severe radiation, with high energy rates, presenting a high resolution and low granularity. In this context, the choice of the hadronic calorimeter of the FCC detector - hh, the Hadronic Barrel (HB) and the extended barrel (HEB), will be inspired by the ATLAS Tile Calorimeter calorimeter (TileCal). The HB will have 10 layers, with scintillating tiles that will be separated through a reflective material (e.g. Tyvek) and read by wavelength displacement fibers (WLS) of 1 mm in diameter connected to silicon photomultipliers (SiPMs). Our study focuses on the comparison of the luminous signal intensity in the tile of the first layer of the HB and the tile in the last layer of HB, taking into account the dimensions of the tile. A study of the optimization of the signal uniformity with a light-absorbing black strip deposited on the tile was made, and results were compared with similar experiments performed at CERN. The procedure was performed in the Tilemeter, an ATLAS experiment.

KEYWORDS: Future Circular Collider, tile, Calorimeter, signal uniformity

1 Introduction

1.1 Particle detectors

The development of particle physics is directly associated with the use of particle detectors, whose operation is based on the transfer of part of the energy emitted to the mass of the detector [1], and the detection of these particles occurs through the loss of energy of particles when they pass through a certain material [2], thus enabling the detection of the most diverse particles. The detection occurs by the interaction of the particles with the detector, interaction associated with the collision of the particle with the atoms of the medium, resulting in the loss of energy of the particle. However, not all particles can be detected directly, some are detected indirectly through particles that arise from their interactions. [3].

Particle detectors can be divided into two large groups: detectors that function through ionization processes and detectors that function through excitation processes. Ionization detectors can also be divided into gas and emulsion detectors, in which the detection process is based on the trail of the electron-ion pair, which when subjected to an electric field, the charges can be collected. Electrons are collected in the anode, and ions in the cathode of a chamber, where the signal reading is performed by specialized electronics with the amplification of this signal. In semiconductor detectors (silicon, germanium and others), the working principle is based on particle interactions creating a trail of electron-hole pairs[4].

In scintillation detectors (such as the TileCal in the ATLAS experiment), the principle of operation is directly associated with the energy "lost" by the particles that affect the scintillator, causing an excitation of the scintillator particles and, consequently, the emission of light in the visible and ultraviolet (UV) ranges. These detectors can be of various types, but our study is based on organic scintillators with a solid plastic solvent.

1.2 Plastic Scintillators

Plastic scintillators are currently one of the most economically viable options, and their light yield is associated with the interactions of the particle with the scintillator molecules. According to [5]:

> In a scintillating solution, usually composed of a solvent substance plus one or two substances capable of emitting light when dissipating energy, the charged particles and the secondary electrons release energy interacting mainly with the molecules of the solvent, most of them in the scintillating solution, increasing the thermal energy of those who have undergone interaction. Part of the released energy will also be consumed in the creation of ion pairs, free radicals and molecular fragments, making the luminous efficiency of the scintillating solution dependent on the way these products recombine. The concentration of these products will depend on the specific ionization of the radiation, being higher around the trajectory of the particle, mainly in its initial point of interaction, causing a reduction of the luminous efficiency every time this great quantity of ions and excited molecules react among themselves, instead of reacting with the molecules of the scintillators, a phenomenon denominated as extinction by ionization.

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According to [1], plastic scintillators have the advantage of offering an extremely fast signal associated with a decay constant, τ, of 2 to 3 ns and a high output signal. As the scintillators absorb the energy coming from the particle and re-emit this energy in the form of visible light and ultraviolet radiation, with an approximation, we can say that the temporal evolution of the re-emission process can be described as a simple exponential decay, as seen in Figure 1 and given by

$$N = N_0 e^{-\frac{t}{\tau}} \tag{1}$$

where N is the number of emitted photons at time t, N_0 is the total number of emitted photons and τ is the decay constant.

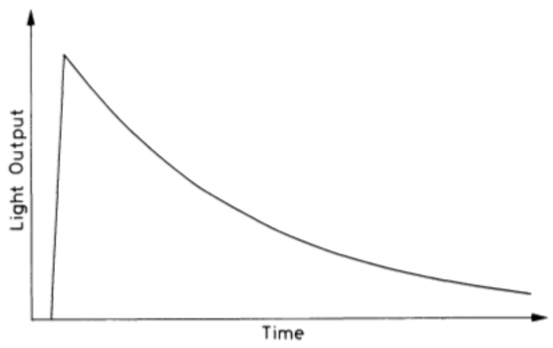

Figure 1. Simple exponential decay of fluorescent radiation

2 The Future Circular Collider and the hadronic barrel

The calorimeters of the hadronic Future Circular Collider - FCC-hh experiments will be one of the key pieces for the full exploration of collisions between hadróns at this accelerator, because the increase of energy in proton collisions, will require detectors that can work at high dose rates. This will require calorimeters with a high resolution, fine granularity, calorimetric systems with adequate capacity to measure time, while the environment of severe radiation limits the choice of available technologies, in this context the use of calorimeters in which its effectiveness is already known, becomes one of the most favorable options [6].

According to the Future Circular Collider (FCC) Conceptual Design Report (CDR)[6], the layout of the calorimeter of the FCC-hh reference detector has been established based on the items below:

- Use of technologies that support the high-radiation environment;
- Under these restrictions, the best possible conventional calorimetry to ensure the best possible energy measurement;
- High transactional and longitudinal spatial resolution, to optimize the combination with techniques for particle detection and use of 3D images for sophisticated algorithms of ID rejection and particle accumulation
- Use of technologies that can achieve time resolution < 100 ps.

In Figure 2, it is possible to see a scheme of the FCC - hh detector, with the Electromagnetic Barrel (BE) calorimeter represented in the figure with the structure in blue and the Hadronic Barrel (HB) calorimeter represented by the structure in green. Our study focuses on the calorimeter of the HB, where the scintillating tiles that are part of our project will be.

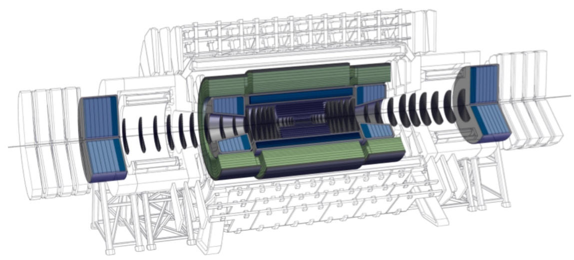

Figure 2. FCC Reference Calorimeter - hh [6]

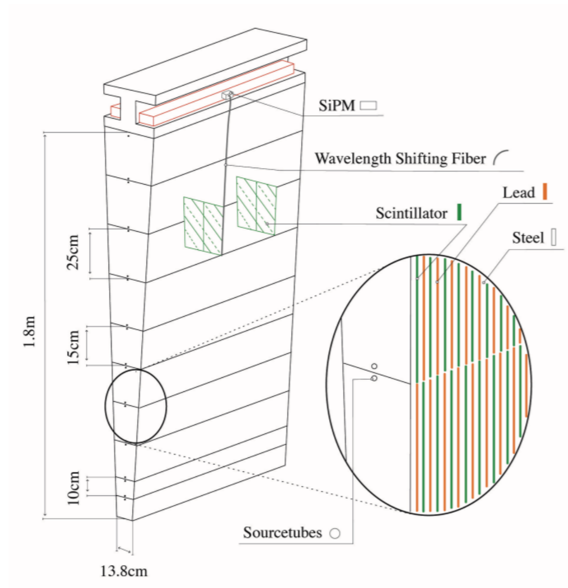

Figure 3. The hadronic calorimeter based on scintillating tiles is proposed for the central barrel (HB) of the FCC-hh reference detector [6]

2.1 The hadronic barrel (HB) and the scintillating tiles

The hadronic calorimeters of the FCC - hh reference detector, the barrel (HB) and the extended barrel (HEB), will be based on scintillating tiles (organic scintillator with a solid plastic solvent), taking as inspiration for the calorimeter design the ATLAS Tile Calorimeter (TileCal), inside an absorbent structure composed of steel and lead, as shown in Figure 3. The central barrel and two extended barrels are divided into 128 modules. Each module will have 10 layers in the central barrel and 8 layers in the extended, longitudinal barrel. Each module will consist of 2 shimmering tiles per longitudinal layer, which will be separated by means of a reflective material (such as tyvek) and read by wavelength shifting fibers (WLS) of 1 mm in diameter connected to silicon photomultipliers (SiPMs) [6].

3 Experimental procedure to determine the influence of the tile geometry and the uniformity of the luminous signal

3.1 Tilemeter

The Tilemeter is an ATLAS experiment dedicated to the characterization of scintillator tiles. As shown in Figure 4, we have a scintillating tile and fiber assembly, in which we place the fiber at one end of the tile and involve the set in tyvek. A ^{90}Sr collimated source is then placed to move under the tile (generally we adopt the movement in one of the axes while the other axis remains fixed). The electrons emitted by the source, when they reach the tile, cause the electrons of the tile to suffer excitation, leaving their equilibrium position. When they return to the initial position (ground state), photons are emitted in the tile (that scintillates - hence the name scintillator). These photons propagate through the tile either directly, or by total reflection in the scintillator or even, by successive reflections in the tyvek. When they reach the fiber, these photons are "captured" by the fiber and sent to the photomultiplier (PM).

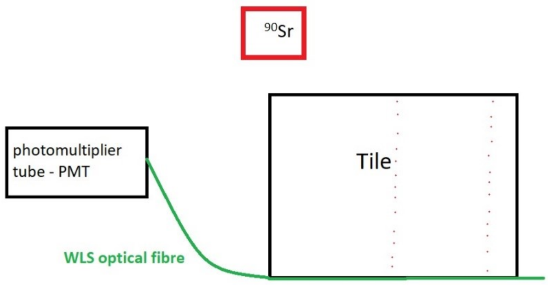

Figure 4. The Tileometer and its operation

3.2 The procedure Followed

Experiments of the FCC - hh scale, which involve high-energy physics, require the use of large detectors. A good performance of these detectors depends on signal uniformity, resolution, granulity and efficiency. Several factors interfere with the uniformity of the signal, such as the size of the scintillating plate. For this reason it is important to measure the uniformity of the signal gain over the entire surface area of the scintillator [7]. In this work, we used the method of measuring the uniformity and the gain of the signal in different regions of the tile, near the edges and in the center of the tile. Allowing the comparison between the measurements performed and other similar experiments performed in CERN.

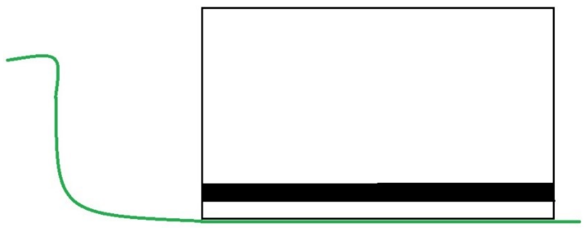

Figure 5. Positioning of the black ribbon on the tile

In our studies, we used two tiles. Tile #1, which we will consider as a rectangle measuring 6.8 cm × 9.6 cm (the tile is in reality a trapeze), and this tile was always measured with a dark tape of 5 mm deposited on one of the faces of the tile. Tile #2, on the other hand, will also be considered as a rectangle with dimensions of 10.3 cm x 24.5 cm (it is also a trapezoid) and, in this tile, we made measurements with the tile without dark tape, with a dark tape of 5 mm width on one side, as shown in Figure 5, and finally, with dark tape (5 mm) around the entire tile.

For the same position, we usually repeat the measurements 3 times. For each of the measurements, we analyzed the signal noise, and to plot the graph, we averaged the noise and subtracted that value from the intensity of each of the signals. After that, we averaged the signal, using this value for the graphical representations.

It should be noted that the measurements presented in the graphs are based on the fibre being read out by a photomultiplier tube (PMT).

The results of the measurements can be seen in the following graphs:

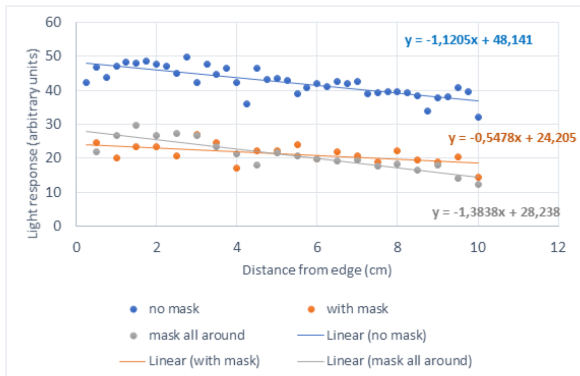

Figure 6. Tile Center (tile #2)

In figure 6 it is possible to see that the tile without the presence of black tape presents a higher signal intensity when compared to the measurement made with the black tape deposited on one of the faces, or with the measurement in which the tape was placed over the entire tile. But the uniformity of the signal is better achieved in the case in which the tape is deposited on one of the faces of the tile.

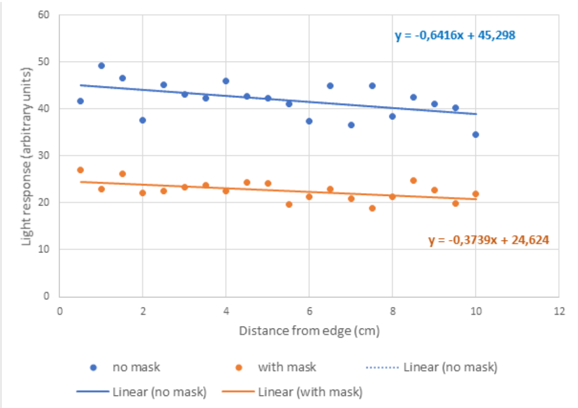

Figure 7. Near the edge (tile #2)

Regarding the positioning of the ^{90}Sr source on the tile, at the center of the tile or closer to the edges, it is possible to identify a difference between the sign of the scintillation point when measured in the center of the tile with the sign of the scintillation point measured near the end of the tile, regardless if it is in tile #2 (Figure 6 and Figure 7) or tile #1 (Figure 8 and Figure 9). This change is caused by the greater distance from the scintillation point in the tile to the optical fiber, because the distance from the edge of the tile where the optical fiber is located to the opposite end, when measured in the center of the tile and in the ends, is different, because the tile is actually a trapeze.

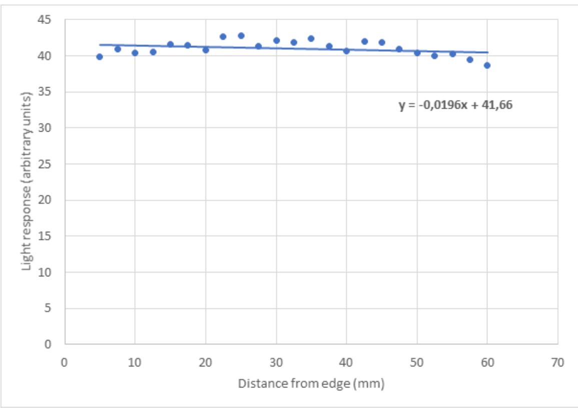

Figure 8. Center (Tile #1, with mask

When comparing Figures 8 and 9 with Figures 6 and 7, it can be seen that the signal is more uniform in tile #1 (smaller) than in tile #2 (larger), and the difference in size in the tiles is responsible for this difference in signal uniformity. It is expected that the same occurs in the tiles that will be used in the FCC HB.

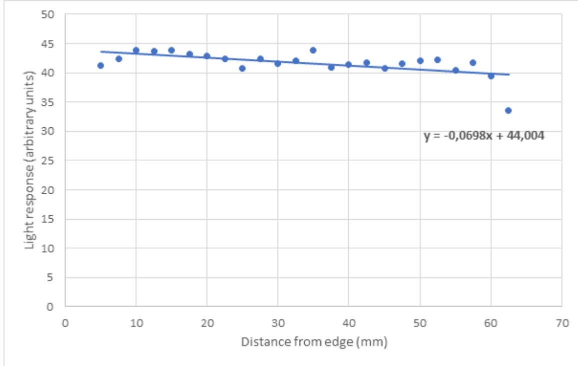

Figure 9. Near the edge (tile #1), with mask

After these measurements, the PMT was removed and a SiPM was used instead. Thus, new measurements in tile #1 were performed in various positions of the tile, sweeping the tile from one end to the other.

Figure 10 shows these results, as well as the near uniformity of the signal as a function of this position in the tile.

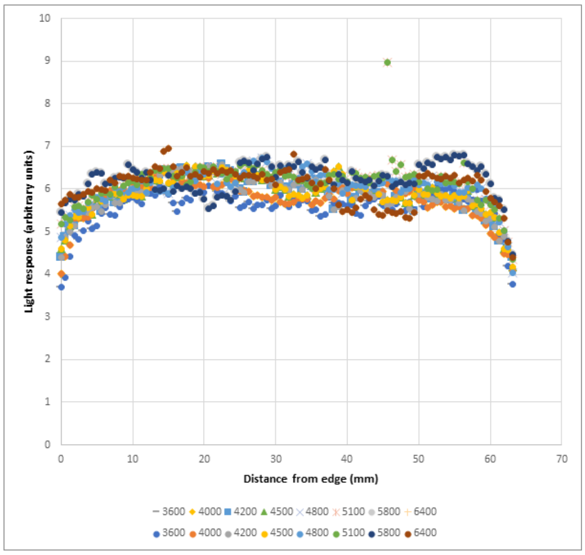

Figure 10. Tile #1 - SiPM

Parallel to the measurements made at LIP, a research group of CERN has produced similar measurements in the same conditions (making use of SiPM, WLS fibers and tyvek). The results found in this experiment also prove the uniformity of the signal, with little loss of signal intensity, as shown in figure 11.

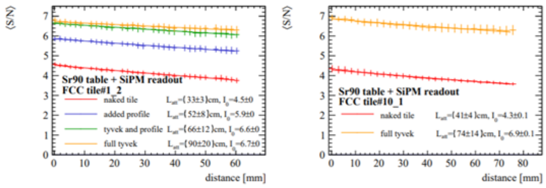

Figure 11. Tile #1 and Tile #10 studied by the CERN team in a similar setup as ours, with SiPM readout [6].

4 Results and Conclusions

From the analysis of the results so far tabulated, to a reduction of the luminous signal intensity, when compared to tile #1 with tile #2 under the same conditions. Another item to be taken into consideration is that the black tape presents a greater uniformity of the signal, but in contrast, it seems to be evidenced that in tile #2 (the largest) this uniformity occurs through a considerable loss of signal. When measuring the SiPM in tile #1 (which contains the black ribbon on one of the faces), it was possible to notice even more clearly this uniformity of the signal, and the results are closer to those already seen in CERN's research group. Some points still deserve further analysis:

- in tile #2, what is it that, when placing the tape around the entire tile (tape with 5 mm) the result of uniformity was worse than with tape on only one of the faces?
- What is the ideal relationship between uniformity and signal, taking into account the tape width and tile dimensions?
- On average, Tyvek has a reflection of 90% and magnesium oxide a reflection of about 98%. Why not cover the tile with magnesium oxide and envelop the set with tyvek? And would the use of Teflon not be feasible?
- Are the fibers (green) and the current scintillator the best light signal response scheme? What if we used orange fibers and a scintillator that produced light in the green range?

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