CERN Summer Student Program
Report

Feasibility study of a PEEK Light Guide for the LHCb ECAL upgrade II

Submitted by

Jose Fernando Martinez Rosales
National Autonomous University of Honduras (UNAH)
Faculty of Engineering

Supervisor

Augusto Sciuccati

Department of Experimental Physics
European Organization for Nuclear Research (CERN)
Geneva, Switzerland

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Abstract

This study presents a feasibility analysis for the lead module Light Guide in the electromagnetic calorimeter (ECAL) upgrade II of of the LHCb (Large Hadron Collider beauty)experiment using Polyether Ether Ketone (PEEK) as a candidate material. Finite Element Analysis (FEA) simulations were conducted to understand the mechanical behavior of the Light Guide design under operational conditions. Additionally, PEEK test samples were fabricated using 3D printing and subjected to an annealing process to enhance their mechanical properties. The samples are pending to undergo mechanical testing (tensile, compression, and flexural tests) and thermal testing to determine key characteristics such as tensile strength, modulus of elasticity, thermal stability and radiation resistance tests.

The combined results from FEA and 3D printing/annealing study evidence the feasibility of using PEEK for light guide in the ECAL upgrade II, offering possible advantages in terms of Radiation and thermal performance. The study concludes with recommendations for the implementation of PEEK in the future ECAL upgrade II and outlines the next steps for production of the Light Guide.

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1 Motivation

The Light Guide design plays a critical role in accurately directing light to the photomultipliers (PMTs), which are essential for precise particle detection and measurement. However, the existing materials and manufacturing processes may not fully meet the demands of the high-radiation, high-stress environment in which the ECAL is expected to operate after the long shutdown three.

The objectives of this study are to help...

1. **...determining the feasibility of the current light guide design and**
   - Need to analyse and understand the behaviour of the light guide under stress
   - Get a glance of the production capabilities
2. **...understanding the material (PEEK)**
   - Practical test produce pieces with the available equipment
   - Ensure durability and reliability
   - Proposing the need for a post treatment

2 Introduction

The LHCb (Large Hadron Collider beauty) experiment is dedicated to the study of heavy flavor physics at the Large Hadron Collider (LHC). Its principal objective involves the search for indirect manifestations of new physics through the observation of CP violation and rare decays in beauty and charm hadrons. The LHCb detector is subdivided in many subdetectors, one of them is the electromagnetic calorimeter (ECAL), in general the calorimeter system is designed to stop particles as they pass through the detector, but the ECAL is responsible for measuring the energy of lighter particles, such as electrons and photons also providing position measurements of the particles produced.

2.1 The ECAL Upgrade II

In the LHCb upgrade II the ECAL system will be redesigned changing the current Shashlik modules to SpaCal modules in the inner regions of the ECAL, thus allowing to cope with maximum instantaneous luminosity. The new arrangement main objective is the mitigation of degradation due to radiation damage and at the same time enhancing the physics performance for the upgrade requirements like improved granularity and a time response of 10 ps, meaning new modules will use dense and radiation hardened materials [1].

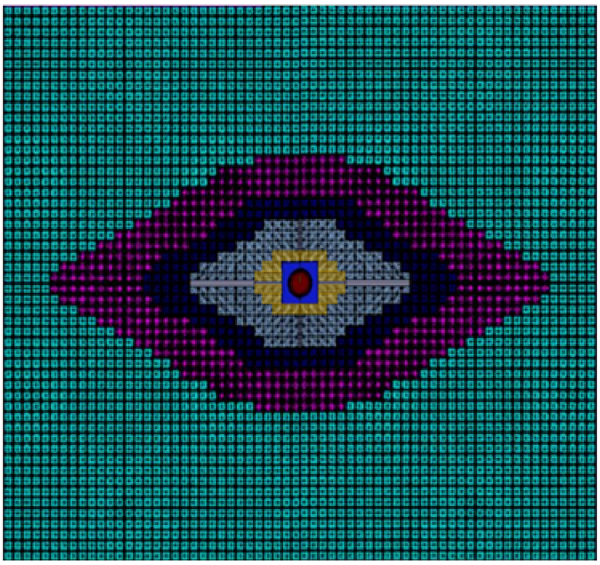
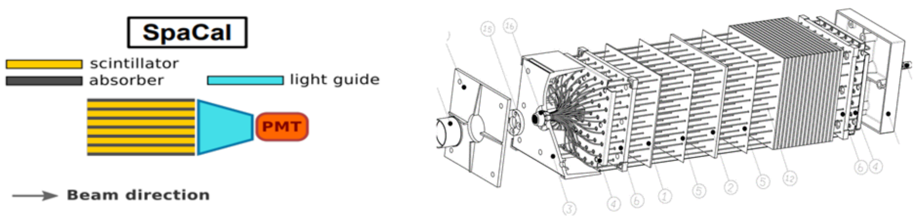


Figure 2.1: Representation of the ECAL for the Upgrade II, the gray and yellow parts are the new Tungsten and lead SPACAL modules respectively, the rest are Shashlik modules.

The upgrade II is going to change the existing ECAL layout by replacing the Shashlik-type modules with a new technology, the SpaCal Modules, These modules are based on a sampling calorimeter in which scintillating fibres are inserted into a dense absorber. The scintillating fibres convert the deposited energy into light and transport it to the photodetectors, avoiding wavelength-shifters which entail a reduction in light collection efficiency. This technology will be utilized in the tungsten absorbers for the inner most modules, and for the outer layer lead will be utilized. Both modules are equipped with scintillating plastic fibers and single sided readout for the long shutdown 3 (LS3) and double sided readout for LS4 [2]. Both modules have at the end of the absorber blocks a light guide with photomultiplier holder, see Figure 2.2a and 2.2b. The rest of the ECAL will remain with shashlik modules as shown in Figure 2.1.

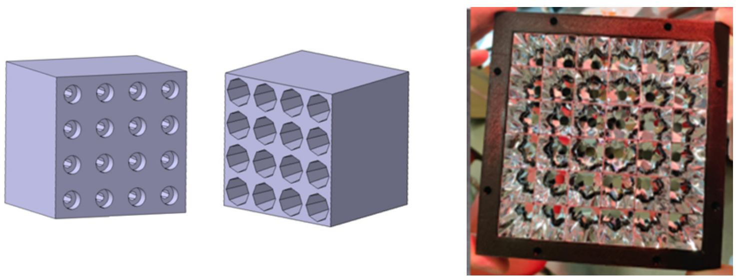


(a) (b)

Figure 2.2: Module representation; (a) SPACAL module for LS3, (b) Shashlik module

2.2 Light Guide design for lead modules.

The light guide directs light emanating from the scintillator fibres towards the Photomultipliers (PMTs), for a more accurate measurement and ensuring an optimal data acquisition. There are different Light Guide variations ;circle to circle, octagon to square or octagon to octagon etc. Every configuration has inside a laser cut reflective foil that ensures there is a minimal loss of light. For this report the focus will be on the octagon to octagon proposal, see Figure 2.3a and 2.3b.



(a) (b)

Figure 2.3: Light Guide; (a) Light Guide 3D model, (b) Reflective foil

3 Feasability study

For this study, two areas are going to be of utmost importance, the manufacturing/post treatment and the material itself. Thus, the following aspects are crucial:

Identify difficulties in design and manufacturing

• By understanding what can affect the Light Guide design proposal so it can be also applied to other Light Guide designs in consideration.

Scalability of the manufacturing process

• Having an idea how the manufacturing of these parts is going to be done and if the current method is ideal.

Analyse the material feasibility

• If the material proposed (PEEK) is adequate for the Light Guide

• Assess the mechanical stability of the materials under operational conditions.

• Give an idea of the behaviour of PEEK and what can be done to improve its manufacturing.

3.1 PEEK and its properties

PolyEther Ether Ketone (PEEK) is a semi-crystalline thermoplastic polymer belonging to the Poly Aryl Ether Ketone (PAEK) class. This is a recent and relatively expensive material which has good heat resistance (up to 250 °C) and very good fire retardance (UL94 V-0), as well as low smoke, toxic and corrosive fume emission without resort to the use of additives [3]. PEEK can be easy to machine, has excellent mechanical properties, is radiation hard [4] and can be 3D printed, see Figure 3.1.

As noted the versatility and flexibility of PEEK allow its processing through several methods such as extrusion, injection molding, and compression molding followed by machining and 3D printing. This last one allowing an easier manufacturing of more complex shapes and forms, it increases design flexibility and it reduces waste of material.

Considering that the additive manufacturing of high-performance thermoplastics is quite challenging due to the requirement of high thermal processing conditions and complex process-structure-property relationships [5].

To understand more the mechanical properties, some reference like molded PEEK's most important properties can be used:

- Young's Modulus $E = 3.4$ GPa
- Ultimate tensile strength $\sigma_{UTS} = 116$ MPa
- Compression strength $\sigma_C = 13...46$ MPa
- Elongation at break $\varepsilon = 15\,\%$

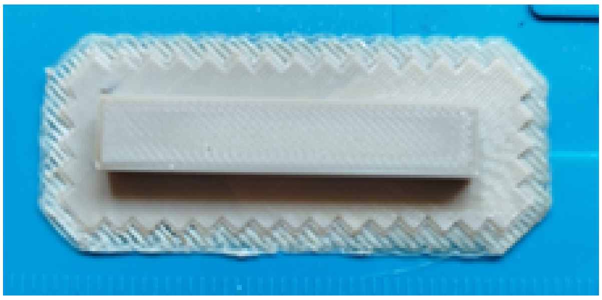
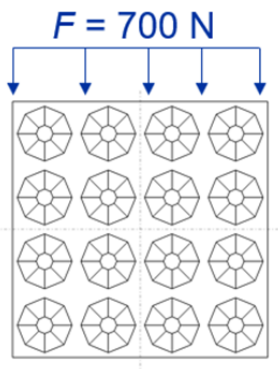


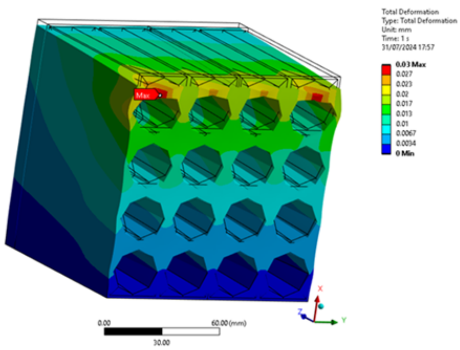
Figure 3.1: PEEK sample printed at point 8 workshop

3.2 Finite Elements Analysis

The Finite Element Analysis was done through ANSYS, based on a convergence study to understand the deformation of the Light Guide when put under a compression force. The force applied on all the top surface of the Light guide is approximately 700 N as shown in Figure 3.2a. The results of the simulation are shown on Figure 3.2b, as seen in the graph, the deformation of the element is minimal, with a neglectable order of magnitud.



(a)



(b)

Figure 3.2: Light Guide Finite Element Analysis; (a) Force representation acting over the Light Guide, (b) Convergence study result

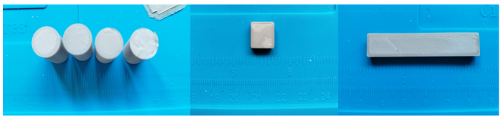
3.3 3D printing PEEK

For the 3D printing of PEEK a set of different geometries of polymer samples for compression tests ISO 604 and ASTM D695 were printed, using a CreatBot PEEK-300 (see Figure 3.3a) and natural PEEK filament which was dried for 3 days at 65 °C. This temperature is the maximum the 3D printer allows.

The test samples were 3D printed with Creatbot PEEK-300 as seen in figure 3.3b, the cilinders (left) are ASTMD695 and the parallelepipeds (middle and right) are the ISO604.

They were printed used different parameters as this is one of the most influential parts of 3D printing, the ones shown on Table 3.1 are considered to influence, roughness and elastic modulus [5].

(a)



(b)

Figure 3.3: 3D printer and samples; (a) 3D printer used, (b) Result of Printed Samples, ASTMD695 (left) ISO 604 (middle and right)

Table 3.1: Parameters used in 3D printing

Parameters	Value
Nozzle Temperature [°C]	415-420
Chamber Temperature [°C]	90
Bed Temperature [°C]	130
Infill density [%]	100
Printing speed [mm/s]	15-50
Raft [layers]	3
Specimen orientation	Flat

4 Annealing

Post treatments can conveniently and effectively improve the mechanical properties of 3D-printed polymeric structures. Annealing or thermal annealing is a process in which the sample is incubated at a high temperature close to the melting point for a certain period as seen in. It is one of the most widely used post-processing techniques [6].

For example, annealing at 200 °C results in approximately 30 % enhancement of tensile strength in 3D-printed PEEK, mainly because of the increase in crystallinity [7]. But annealing can also enhance the compression end flexural strengths.

The annealing setup was performed with a specific configuration for the time and temperature as shown in Figure 4.1, the process it self was done in an oven as seen in Figure 4.2a.

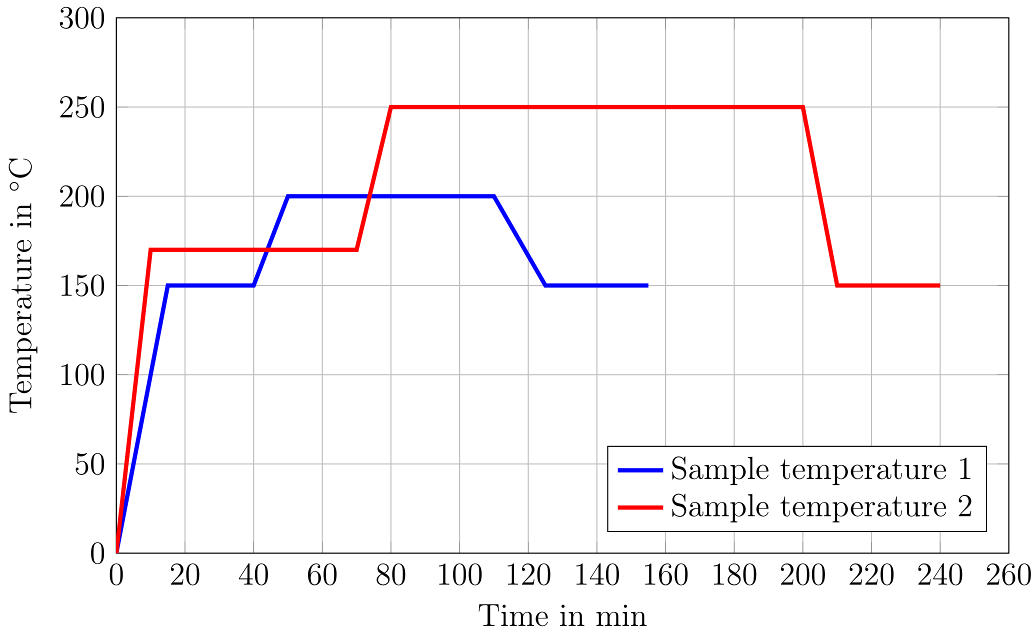


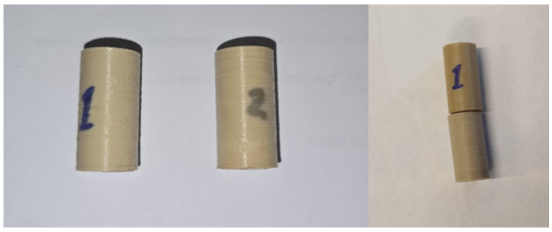
Figure 4.1: Annealing temperature time profile

4.1 Annealing results

The Annealing results are as shown in Figure 4.2b. A variation can be noticed from the annealed samples to the unannealed samples. The layers visible in the 3D printing are less noticeable after the treatment. Also the layers of the annealed samples with different temperatures and time look different, as seen with sample 1 and 2, shown in Figure 4.2b.

More testing needs to be conducted to verify and demonstrate the enhancement capacity of annealing PEEK.

(a)



(b)

Figure 4.2: Annealing process; (a) Oven used in the Annealing post treatment, (b) Annealing result comparison between annealed samples to the left and annealed and unannealed samples to the right

5 Conclusion

The results obtained regarding the 3D printing and Annealing of PEEK will provide a guideline for the CERN ECAL group (PicoCal) for the future production/manufacturing of the Light Guide , but it may also need further testing with the finish module and the LG under stress fully 3D printed with PEEK and annealed to really understand the behavior of the material and geometry in a real-world scenario.

Several considerations emerged during the experimentation with PEEK and annealing:

Current production limitations:

- At present, the in-house production of the ight Guide at CERN is not feasible due to unreliabilities with the PEEK 3D printer. The quality of some samples was not optimal, requiring multiple adjustments and tries, displaying the difficulties of mass production with the available equipment.

- Given these constraints, there is a strong case for considering external contractors for the printing and annealing of PEEK components, unless CERN acquires additional and more reliable 3D printing equipment.

- The production process time demands also present a challenge, particularly with 100 % infill PEEK parts. For example, a single Light Guide could take over 40 hours to print at a printer speed of 15 mm/s, assuming only one printer is used.

Annealing as a critical process:

- Annealing all printed PEEK parts is crucial as it significantly enhances their mechanical properties. Also, this process can be efficiently performed with the equipment currently available. It can be done in less than 4 hours.

Manufacturing Process:

- Despite the challenges, 3D printing remains the most viable manufacturing process for the current Light Guide design. The complex geometry of the Light Guide makes machining or molding methods impossible. Additionally, the high cost of producing molds for less than 200 pieces, this including both the tungsten and lead Light Guides, further support the 3D printing option.

Literature

[1] Picatoste, E. *Scintillating sampling ECAL technology for the LHCb ECAL Upgrade II. Journal of Instrumentation, 19(04), C04016.* 2024. URL: https://iopscience.iop.org/article/10.1088/1748-0221/19/04/C04016/meta (visited on 08/10/2024).

[2] LHCb collaboration. *LHCb Particle Identification Enhancement Technical Design Report*. 2024. URL: https://cds.cern.ch/record/2837018/files/BORDELIUS_CERN-report.pdf (visited on 07/29/2024).

[3] General Infrastructure Services Department. *The Use of Plastic* and other Non-Metallic Materials at CERN with respect to Fire Safety and Radiation Resistance, SAFETY INSTRUCTION 41. REV*. 2005. URL: https://edms.cern.ch/document/335806/1.02 (visited on 08/12/2024).

[4] M. Tavlet, A. Fontaine and H. Schônbacher. *COMPILATION OF RADIATION DAMAGE TEST DATA*. 1998. URL: https://inis.iaea.org/collection/NCLCollectionStore/_Public/30/002/30002738.pdf (visited on 08/05/2024).

[5] Greco, A., De Luca, A., Sepe, R., & Gerbino, S. *Investigation on tensile properties of FFF PEEK: Effects of printing parameters and post-processing treatment.Procedia Structural Integrity,53, 178-184.* 2024. URL: https://doi.org/10.1016/j.prostr.2024.01.022 (visited on 08/01/2024).

[6] Chen, W., Zhang, X., Tan, D., Xu, P., Yang, B., Shi, K., ... & Xue, L. *Improvement in mechanical properties of 3D-printed PEEK structure by nonsolvent vapor annealing. Macromolecular Rapid Communications, 43(7), 2100874.* 2022. URL: https://doi.org/10.1002/marc.202100874 (visited on 08/14/2024).

[7] Challa, B. & Gummadi, Sudeep K. & Elhattab, Karim. & Ahlstrom, J. & Sikder, P. *In-house processing of 3D printable polyetheretherketone (PEEK) filaments and the effect of fused deposition modeling parameters on 3D-printed PEEK structures*. 2022. URL: https://doi.org/10.1007/s00170-022-09360-4 (visited on 07/10/2024).