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Design and Manufacture of a Cable Feed-Through Part in Carbon Composite

Mechanical Engineering

Bachelor's thesis

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Abstract.

At CERN, the center of nuclear physics research in Europe, there is the largest and most powerful particle collider in the world, the Large Hadron Collider (LHC). LHC is the last link in a chain of particle accelerators taking the accelerated particles up to 99.9999991 % of lightspeed. The particles are not only accelerated in the LHC, but they are also collided into each other. The particles go round the LHC in two beams going in opposite directions. The beams are then collided in four different collision points around the 27-kilometer circumference. One of these points is located inside the detector called Compact Muon Solenoid (CMS). CMS is a solenoid-based detector, designed to study high energy collisions.

During the next long shutdown of the LHC, the Long Shutdown 3 (LS3), LHC is to be upgraded to increase the number of collisions. The new and more powerful HL-LHC (High Luminosity LHC) means that the CMS is going through upgrades as well. The upgrades include the complete redesign of the inner parts of the tracker, to achieve higher resolution. The inner parts of the tracker are divided into two regions, the barrel region and the end cap region. The outer part of the barrel region is referred to as the TB2S (Tracker Barrel with 2S-modules). It contains two-sided silicon strip tracker modules, designed for particle tracking. The 2S-modules are attached to ladder structures, which form multiple overlapping layers of sensors, efficiently surrounding the collision point. The services, like electricity and cooling are routed to the 2S-modules through the ladder front panel. The front panel needed to be designed from scratch to house all the needed connectors for the services.

The ladder structure is made of carbon-fiber composite c-profiles. Carbon-fiber reinforced composites are the chosen material for the detector’s inner structures, due to its strength, radiation resistance and low density. The front panel was also designed to be made of carbon-fiber composite, so that different thermal expansion coefficients would not impose problems. The production method was chosen as the SMC/BMC ((Bulk Molding Compound/ Sheet Molding Compound). The material is either as a bulk molding compound (BMC) or as sheets (SMC) and it has the fibers and the matrix already combined. The material is inserted into a preheated mold that is then closed with high pressure. Due to high temperature and pressure the material hardens into the shape of the mold.

The aim for this study is to find the correct parameters for the molding process to produce parts of acceptable quality, reliably. The initial values for the parameters are found in existing literature. The parameters were then tuned in between the molding cycles, based on the results of previous tests. Acceptable quality was achieved after thirty-five iterations and confirmed with twenty additional parts. The manufacture of the additional parts was then used to estimate the time needed to produce the full patch of parts.

Key words: CERN, LHC, CMS Phase 2 Upgrade, carbon fiber reinforced composites, compression molding, TB2S front panel

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1 Introduction

1.1 CERN

CERN, the European Organization for Nuclear Research was founded in 1954 and is the leading particle physics laboratory in the world. CERN's main objective is to learn more about the Universe, what is it made of and how does it work. CERN is a collaborative effort between 23 Member States and other nations around the world contributing and participating in its research programs. (CERN, 2023.) It is most known for as the place of discovery of the Higgs boson, as the birthplace of the Large Hadron Collider (LHC) and from the invention of the World Wide Web (Meroli, 2023).

CERN's headliner, standing at the circumference of 27 km, constructed into a tunnel at the mean depth of 100 m underground, is the Large Hadron Collider or the LHC. The design of the LHC started back in the early 1980's, while its predecessor, the Large Electron-Positron, was still being designed and built. In December 1994, the construction of the LHC was approved by the CERN council. LHC is currently the most powerful particle collider in the world, able to accelerate particles up to 99.9999991% of light speed. It is called Large due to its circumference, Hadron since it accelerates hadrons as in protons or ions, and Collider for the opposing accelerated beams are collided within the experiments of the LHC. (CERN, 2021.) There are nine experiments combined from which one is called Compact Muon Solenoid or CMS (CERN, 2023).

The LHC is only the last link in a chain of particle accelerators. A series of smaller particle accelerators slowly bring the particles up to around 99.9998 % of lightspeed before injecting them into the LHC. In addition to just pre accelerating the particles, the smaller machines also prepare the particle beam to arrive at the LHC in bunches, opposed to a continuous beam. This allows, among other things, the beam to be divided into two beams that are then directed into opposing directions around the LHC. (CERN, 2021.)

1.2 CMS

The concept of the Compact Muon Solenoid CMS was first presented in October 1990, in the Aachen LHC workshop. The limited space requiring a compact design, set the need for a strong magnetic field. The only feasible way to create a magnetic field strong enough was a solenoid. A superconducting solenoid of fourteen meters long and about three meters in radius, able to generate a magnetic field of four tesla was determined to guarantee a good enough momentum resolution, for high momentum muons, without unreasonable demands on the chamber space resolution. The detailed technical proposal for the entire detector was published in 1994. (CMS, 1994.)

CMS is designed to track all particles flung out from the interaction point due to the particles of the opposing beams interacting with each other. These interactions include two particles merely grazing each other, straight head on collisions, and everything in between. The interaction point is surrounded by different kinds of silicon sensors. When a particle passes through the silicon sensor, the particle induces a current in the sensor triggering the sensor. The data collected from the CMS consists of which sensors were triggered and at what time. From this data, with the knowledge of how particle tracks bend in the strong magnetic field, all the particle tracks can then be digitally recreated. (CMS, 2000.) Luminosity is the measure used to estimate the probability of a collision in a collider like the LHC. Luminosity is the number of potential collisions divided by the surface area and the specified time. In the current LHC the designed luminosity of protons is $1 \times 10^{34}\ cm^{-2}\ s^{-1}$. (CERN, 2021.) At design luminosity, the LHC has a bunch crossing rate of forty megahertz, which means on average about one billion interactions per second at the interaction point. Comparing this to the measly one hundred interactions per second that can be archived by the online computer farm, running at maximum capacity, it becomes apparent that some major filtration is needed, before any data is allowed to be archived. CMS does this in two steps, first the Level-1 (L1) trigger reduces the rate of forty megahertz to one hundred kilohertz. This data stream is then sent to the High-Level Trigger system, which then further reduces the data, before handing it out to the computer farm for more complete processing. (CMS, 2000.)

The L1 trigger consists of the muon trigger and the calorimeter trigger. As seen in the exploded view of the CMS detector in Figure 1, the outermost layer of the detector, surrounding the solenoid, consists of four layers of muon detectors. In the barrel region these muon detectors are made of multiple layers of drift tubes (DT), cathode strip chambers (CSCs) in the end cap region, and the resistive plate chambers (RPCs) which cover both regions. Moving radially inwards, past the solenoid, the two calorimeters are located. The hadron calorimeter (HCAL) in both the barrel and the end cap regions inside of which is the electromagnetic calorimeter (ECAL) which provides the calorimeter data for the L1 trigger. (CMS, 2006.)

Inside the calorimeters there is the silicon tracker. The silicon tracker consists of the silicon pixel detector closest to the interaction point and the silicon strip tracker, which fills the space between the pixel detector and the ECAL. The silicon strip tracker consists of ten layers of silicon microstrip detectors in the barrel region and nine layers in each end cap, which provide the precision needed to distinguish the tracks of separate particles. The total area of the silicon strip detectors is two hundred square meters and consists of 9.6 million silicon strips. The silicon pixel detector consists of three layers of silicon pixel detectors in the barrel region and two layers in the end caps near the interaction point to further improve the measurements of the impact parameter and the particle tracks. The total area of the silicon pixel detector is about one square meter and contains sixty-six million pixels. The pixel detector and the four inner most silicon strip tracker layers together are considered as the tracker inner barrel (TIB) and the six outer silicon strip tracker layers are considered as the tracker outer barrel (TOB). (CMS, 2006.)

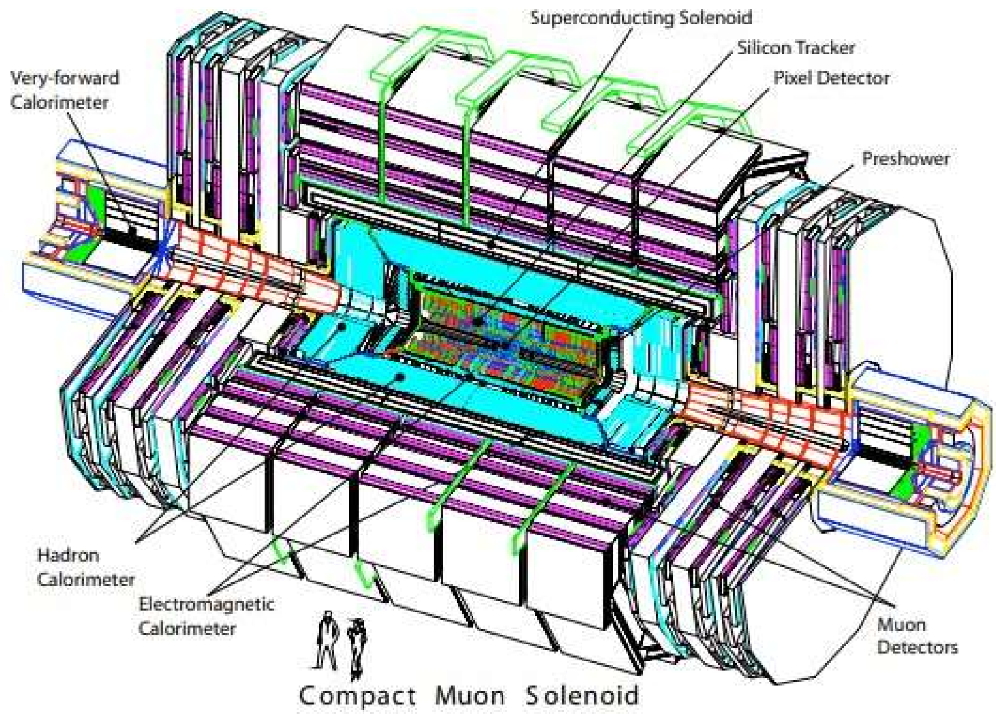

Figure 1 - The CMS structure (CMS, 2006)

1.3 CMS Phase-2 Upgrade

The LHC will be undergoing an extensive upgrade program during the Long Shutdown 3 (LS3), scheduled to begin at the start of 2026 and end early 2029 as described in the HiLumi website (HiLumi, 2022). The upgrade program, referred to as Phase-2, is expected to see the LHC entering the High Luminosity Phase (HL-LHC), increasing its luminosity to at least $5 \times 10^{34}\ cm^{-2}\ s^{-1}$ (Mersi, S., 2016). This means that the number of pile-up events will increase from the current amount of about forty, up to two hundred per collision. Additionally, the radiation levels will get up to an astonishing 1.2 Grad as stated by Orfanelli in his article The Phase 2 Upgrade of the CMS Inner Tracker. (Orfanelli, S., 2020.) Practically, the massive increase of interactions in the new collider will result in the old detector not being able to keep up. The accuracy and speed of the detector will need to be upgraded, to collect all the data from the events produced by the new collider. Additionally, the radiation levels inside the detector will cause the equipment to deteriorate at a much quicker pace so it needs to be swapped with equipment more capable of handling the increased radiation levels.

The old silicon tracker of the CMS will be replaced with a completely new one. The new tracker will comprise of two parts, the Inner Tracker (IT) and the Outer Tracker (OT). The new IT will be a four layered pixel tracker and have approximately two billion pixels the size of 2500 micrometers squared (Orfanelli, S., 2020). Around the IT will be the six layered OT, comprising of p_T modules having two silicon sensors a few millimeters apart from each other. The inner three layers of the OT will have modules, referred to as PS modules, consisting of one pixelated sensor and one microstrip sensor, as opposed to the 2S modules of the three outer layers, consisting of two microstrip sensors. (Chowdhury, S., R., 2020.) In the barrel region the three PS layers are referred to as the Tracker Barrel with PS modules or TBPS and the three 2S layers the Tracker Barrel with 2S modules or TB2S. The 2S modules of the TB2S are attached to both sides of ladder structures alternately, so that the modules on opposite sides overlap each other. This is done for maximizing the coverage of the modules. (CMS, 2017.)

1.4 Objectives, scope, and methods

The objectives of this thesis are to clarify the manufacturing process known as compression molding and its application in creating carbon fiber composite parts. This is done in the form of a literature review utilizing the latest research knowledge in the field. The theory is then applied in practice in a case study. In the study, main goal was to determine the process variables to manufacture a front panel for the TB2S ladder. A batch of four hundred front panels is needed for the upgraded CMS and due to the complex shape, they are to be manufactured in house. To help with the writing of this thesis, ChatGPT language model was utilized in making the search strings better for finding the most relevant articles, as well as helping with the translation of a handwritten text.

2 The Design and Shape of the Part

2.1 Background of the design

The TB2S ladder structure is made of two parallel C-profiles running in the longitudinal direction of the ladder, the open sides facing away from each other. These profiles are connected to each other with shorter, perpendicular profiles of the same kind, forming the “ladder” structure. The ladder is equipped with the 2S-modules as described briefly in chapter 1.4. The auxiliary systems needed for these sensors include electrical powering, cooling, and fiber optics for output, later on referred to as “services.” These services run the length of the side profiles reaching all the modules and gather at the front end of the ladder. These services are then run through the front panel for a couple of reasons. First, running the services through the front panel, which will be left exposed after assembling the ladders to the wheels of the TB2S, means that the connections will be left conveniently reachable. It also means that the whole TB2S ladder with all the modules and services can be fully assembled before installation to the wheel, and that the services can be fully contained within the ladder envelope. (Barinoff, M., 2021.)

The complications with running the services through the front panel come from the adapter for the optical fiber, the MT-MPO adapter (mechanically transferrable multi-fiber push on). Not only is the MT-MPO adapter very bulky, but also quite long. The front end of the ladder has one 2S module coming up to the front panel, taking half of the radial space, leaving minimal room between the front panel and the module. On the other hand, the length of the MT-MPO adapter means that it needs to be fixed into an angle so that the minimum allowed bending radius of the cable can be met. This means it would not be practical to use the same C-profile as elsewhere in the ladder structure, given all the modifications that would be required to be done to it. That is why M. Barinoff designed a completely custom front panel to cater to all functional requirements. (Barinoff, M., 2021.)

2.2 Functional needs

The front panel needs to provide mechanical support to the MT-MPO -adapter, the electrical octopus, the cooling pipe connection sleeves, and the preheater connectors. The space between the front face of the front panel and the component directly in front of it, in the assembled tracker, is about twenty-four millimeters. The maximum allowed height of the front panel, not to collide with the adjacent ladders in the wheel, is twenty-nine millimeters minus installation clearance. Furthermore, the sides of the front panel need to fit on top of the C-profiles on both sides for gluing the structure together. Also using the SMC/BMC method yields its own constraints for the design. (Barinoff, M., 2021.)

2.2.1 MT-MPO

Due to the space constraints in the front of the front panel, an angled MPO connector needs to be used on the outside of the front panel. This angled connector is a standard commercial product and has the angle of 125 degrees between the cord initiation and the plugin axis. To get the cord to run parallel to the face of the front panel, an additional fixing angle of 35 degrees is needed. Height wise, the connector should be as low as possible from the 2S-module behind the panel, but still high enough so that the MPO-connector stays over the connection sleeve of the cooling pipe of the ladder. After the connector was positioned, two triangular supports were added to the top and bottom side and a rectangular window cut for the connector in the design. The top flange of the front panel was then made to go over the top of the connectors structure. (Barinoff, M., 2021.)

2.2.2 Electrical octopus

The electrical octopus goes through the front panel and brings electricity to all the 2S-modules. The front panel is only at the halfway point in total length for this octopus, and threading the connectors of either end of the octopus would need a sizable cutout to be designed to the front panel. Instead of threading the connectors through a closed cutout, a much more practical way of getting the octopus to go through the front panel is to design a U-shaped slot, to which the octopus can then be clamped to. The original idea was to use a cable tie to fasten the octopus to the U-shape. The cable tie was later changed to a flat clamp, screwed to the panel with flanged inserts. These inserts were to be inserted from below the top flange of the front panel for maximum reliability. The top flange was then made to go around the U-shape to keep it continuous. Keeping the flange continuous allows the front panel to retain the mechanical properties of the C-shape. (Barinoff, M., 2021.)

2.2.3 Cooling pipes cutouts

The 2S-modules are cooled by a carbon dioxide cooling circuit, keeping their temperature sufficiently low during operation. The length of the cooling pipes changes drastically during the operation cycle due to thermal contraction, so the cooling pipe sleeves on the ends of the cooling pipe, going through the front panel, need to be able to move freely in their longitudinal direction but still be supported in the radial directions. Additionally, the cooling pipe is installed to the ladder after soldering the two sleeves on the pipes. Therefore, the sleeves need to fit through the front panel during the ladder assembly. That is why the cutout was designed to allow the sleeves to pass through the larger slot and the narrower slot extending further to the sides to secure the pipe sleeve definitively. Lastly a cooling pipe sleeve blocker was designed to lock the sleeve into the narrow pocket, still allowing the longitudinal direction thermal expansion and contraction. (Barinoff, M., 2021.)

2.2.4 Preheater

The proximity of the preheater in the front of the ladder makes the front panel a convenient place to place the preheater services. The preheater and the environmental temperature sensor require two two-pinned Hirose DF3-connectors which do not take up too much space. The top flange still needed to be lowered a bit on the opposite side of the panel to the MT-MPO -adapter. (Barinoff, M., 2021.)

2.2.5 SMC/BMC manufacturing method

Regarding the manufacturing method, few things need to be considered when designing the part. Firstly, the flanges of the front panel cannot be quite in ninety-degree angle to the face of the panel, but instead they must have a small draft, to be able to separate the part from the mold. For this, any seemingly perpendicular surfaces to the face of the panel have instead one-degree draft in the final design. Furthermore, to help with rigidity in the demolding process, a five-millimeter brim was added to the outside perimeter, and the open ends were closed. (Barinoff, M., 2021.)

3 Carbon Fiber Composite

3.1 Material needs

As described in the chapter 1.4 the conditions inside the CMS are extreme. All the materials used especially in the tracker region need to withstand the immense radiation levels present, and yet be as low density as possible as to minimally interfere with the particle tracks of each collision. Still the inside structure needs to be strong enough to carry the weight of all the equipment inside. On top of that all materials need to be non-magnetic, not to interfere with the strong magnetic field created with the superconducting solenoid. So, the material properties needed are as follows:

- Radiation resistance
- Low density, high strength
- Non-magnetic

High energy radiation can cause degradation and weakening of properties in materials exposed to it (Little, E., A., 2013). Outside of CERN, this is specifically an issue in nuclear power plants. One commonly used material in these environments is oxide dispersion strengthened (ODS) ferritic steel. It tends to outperform conventional steels when exposed to high radiation levels (Sagaradze, et al. 2001). Another commonly used material in nuclear reactors is carbon fiber/epoxy composite due to it also being highly resistant to ionizing radiation (Liu et al., 2022). The disadvantages of ODS steel are its high density and magnetic nature.

In order to accurately track the particle tracks inside the CMS, the particles need to be able to travel freely. Any structure on the way of the particles has the potential to impede or distort their tracks, which makes tracking them more difficult and measurements less accurate. That is why the low-density, high strength materials are needed for the structural components of the inner tracker. Generally, aluminum is considered a lightweight material but compared to composites like glass- or carbon fiber/epoxy it is inferior. Comparing these two composites on the other hand, the weight becomes less of a differentiating factor due to their similar manufacturing methods. A study was conducted by Khan, Z., et al. comparing the tensile strength and Young’s modulus of the two materials (Khan, Z., I., et al. 2021). The study found these properties to be remarkably higher in the carbon fiber/epoxy composite, regardless of the fiber-epoxy ratios tested.

Magnetic materials would likely impose many problems inside the magnetic field generated by CMSs solenoid. This rules out non-austenitic steel alloys and iron-based materials. Here aluminum could be considered for it is non-magnetic. Aluminum is actually used in many parts of the detector, but lesser density of carbon fiber composites makes them the more desirable choice for the inner tracker. On top of the qualities listed above the carbon fiber composites offer also good resistance to creep and good thermal stability (Yan, M., 2019).

3.2 Discontinuous Carbon Fiber Composites

There are continuous and discontinuous fiber reinforced composites. Continuous means that all the fibers on individual layers are oriented in the same direction. Discontinuous means that orientation of the fibers is random. Continuous unidirectional fiber reinforced composites are extraordinarily strong in the direction of the fibers, but very brittle in the perpendicular direction. This can be improved by adding another layer of unidirectional fibers oriented perpendicular to the first layer making a sheet of material strong in two directions. Orientation of the fibers is key here, for it limits the complexity of the part and makes the manufacturing process quite difficult. The advantage of discontinuous material is that the complexity of the part is less constrained, while the difficulty of the manufacturing process stays relatively constant. The stress-strain response, of the discontinuous carbon fiber reinforced composite remains predictable overall, and the stiffness is similar to the continuous counterpart. The strength is reduced but still achieving up to 50 percent of that of a continuous material. (Czel, G., 2015)

4 Molding compounds and compression molding

4.1 The process in theory

The two commonly used techniques for forming plastics and fiber reinforced composites are compression molding and injection molding. (Leon, Y., W., 2014.) Other techniques used in forming fiber reinforced composites include autoclaving, winding and pultrusion. Compression molding stands out due to its low-cost, high efficiency, low internal stress, good mechanical stability, and excellent repeatability (Xie, J., et al. 2019). Here the focus is on the compression molding process due to it being the chosen method for the front panels.

The process variables of compression molding are compression temperature, pressure-holding time, compression pressure, cooling rate, and mold opening temperature. Based on tests conducted by Jiuming Xie et al. the parameters can be ranked. In descending order, Compression temperature, pressure-holding time, and compression pressure have significant impact on the mechanical properties of the end product. The cooling rate based on their test data has significantly less of an effect. (Xie, J., et al. 2019.)

Sheet molding compounds (SMC) and bulk molding compounds (BMC) are fiber reinforced composite materials designed for molding. Their main ingredients are the thermosetting resin matrix, reinforcement fibers and inorganic filler. Thermosetting resin refers to an epoxy that can be melted and formed but cannot be melted again. In the case of SMC and BMC the most common types of matrices are unsaturated polyester and vinyl ester, where vinyl ester is more commonly used in applications where technical requirements are high. The advantage of using thermosets over for example thermoplastics are that thermosets do not become brittle in the lower temperatures, as well as they do not soften up in higher temperatures, meaning that they keep their properties and dimensions very well in a wide range of temperatures. (European Alliance for SMC/BMC, 2016.)

Inorganic fillers are used to further improve the physical properties of the compounds, and reduce the need for fibers, reducing the cost. To further improve the material properties and processability, other additives may be used as well for example mold release agents, thickeners, and cure initiators. Typical length of fibers in the BMC are between 6 and 12 millimeters, and for SMC between 25 to 50 millimeters, the fibers most commonly being glass fiber but for example carbon fiber can also be used. (European Alliance for SMC/BMC, 2016.)

Compression molding is a process where the material is formed into the desired shape using pressure and heat. An already weighted amount of material is placed into a mold that is located inside a press. The mold is then heated to a predesignated temperature, generally between 140 and 160 degrees

Celsius. A pressure of around one hundred bar is then applied by the hydraulic rams of the press, which forces the heated and flowing material to fill all the cavities of the mold. The curing agent is activated by the temperature increase and the matrix starts to set. After the cycle is completed and the matrix has solidified, the mold is opened, and the part removed. (European Alliance for SMC/BMC, 2016.)

4.2 The process in practice

The heat press has two parallel beds with evenly spaced-out threaded holes for attaching molds into. The beds are hydraulically moved and pressed together. The pressing cycle is programmed via the machine's interface, and it includes the temperatures of the beds in Celsius, the pressing force in kilograms and the stroke times in seconds. Additional steps can be included if needed. The machine goes though the cycle automatically after it is initiated, given that none of the safety mechanisms are inhibiting it. The machine also has all the necessary safety equipment including for example a light curtain, an emergency switch, and switches on all the doors that stop any operation if a door is opened.

The manufacturing process of a front panel starts with turning on the heat press and attaching the mold to it. The mold itself is divided into four parts as seen in **Virhe. Viitteen lähdettä ei löytynyt.**Starting with the baseplate part of the bottom mold, it is fixed to the bottom bed of the heat press with two screws. The alignment pins with springs are then inserted into their corresponding holes. The top part of the mold is placed on top of the bottom mold, being adequately aligned with the help of the alignment pins. (Barinoff, M., 2021.) After that, the top bed is lowered, and the top part of the mold screwed into it. The top bed and the top part of the mold are then raised gain and the rest of the mold assembled by securing the two sides together and also to the bottom part with screws. Lastly the beds are closed so that the mold will reach the target temperature quicker and more evenly.

While the mold is heating up, the material is prepared. When using BMC, the compound is directly injected into the mold as a paste like substance. In the case of the SMC, the sheets are cut into the shape of the bottom mold cavity. These shapes are then stacked on top of each other until the desired weight is reached. Before the molding process, it is especially important to remember to slather the mold with the release agent, to make the unmolding as convenient as possible, not to damage the piece when opening the mold. After getting the piece out of the mold, the mold needs to be cleaned thoroughly to avoid the piece sticking into the mold.

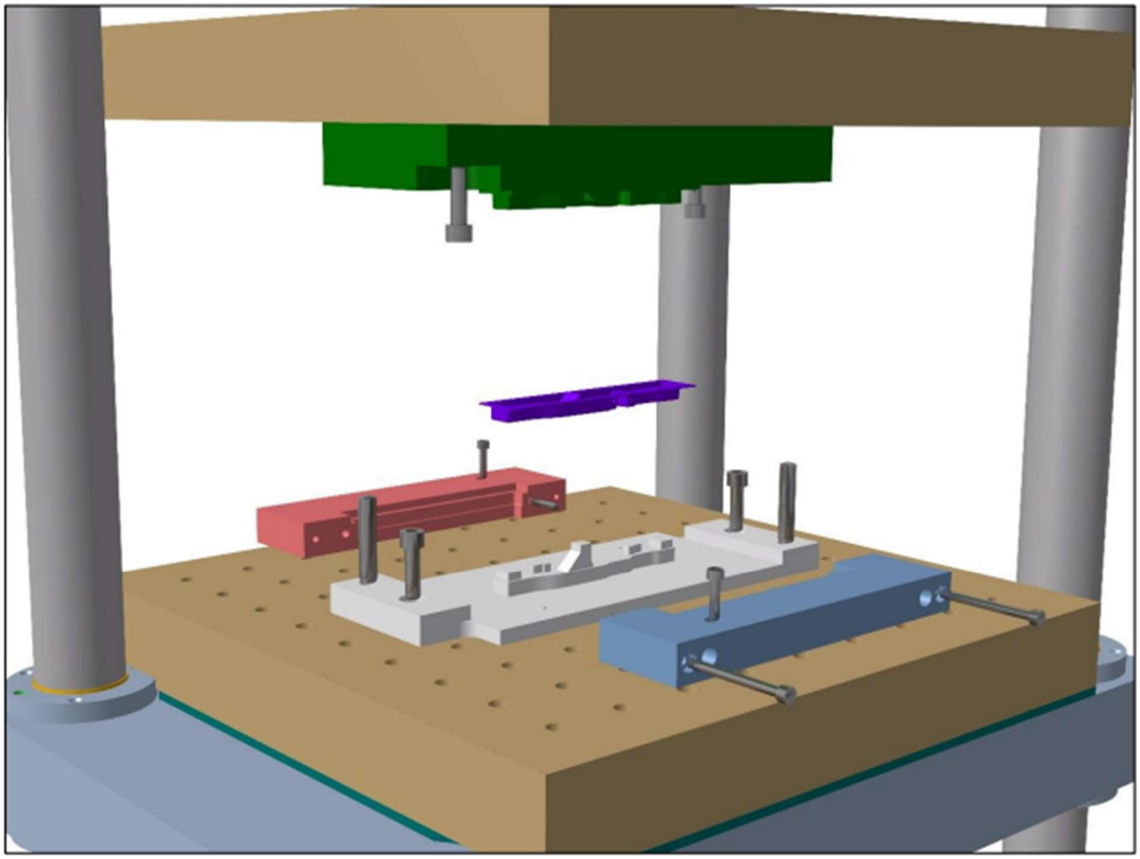

Figure 2 - The mold parts (Barinoff, M., 2021)

5 Testing

The material used for this chapter can be found in Appendix 1. First material tried was the BMC, which is a paste and as that was injected into the mold. The initial tests were made with one press of three thousand kilograms, holding for six hundred seconds in 150 degrees Celsius. Four iterations of tests were made, with the amount of material used varying between 9.9 grams and fifteen grams. In three out of the four tests the mold was not completely filled, and the part was of less than sufficient quality. In the test number four, the material amount was 11.7 grams, which yielded the best results with a fully replicated piece, without any major aesthetic issues. After the initial tests with BMC the material was changed to SMC. From the sheets of SMC, pieces were cut with CNC that could be stacked and placed into the mold. The cut pieces resemble the outlined shape of the front panel with rectangles cut out from the cooling pipe cutouts.

In the following few tests, the cycle parameters were kept as in the first four tests. The blank weight started from 13.7 grams with poor results, climbing up to 15.2 grams, seeing an increase in the quality of the produced parts. Before making the part number ten, an initial heating step was added to the start of the cycle. This preliminary step uses the pressure of one hundred kilograms, which is not enough to close the filled mold. The step lasts for ninety seconds before the actual molding cycle is then conducted with the same three thousand kilograms of pressure for six hundred seconds. The temperature was also lowered to 145 degrees Celsius. This new cycle yielded a near perfect part in the initial test, with 15.8 grams of material and two acceptable parts with 15.9 grams and 16.5 grams of material used.

From part number 13 onward the small rectangular cut out pieces, from the holes in the blank that would become the cooling sleeve holes, were used to fine tune the weight of the blank to the desired range. Test parts numbered 13 and 14 were discarded due to their inadequate quality based on the suspicion of the material having gone bad and not flowing as it is supposed to. In the tests 15 and 16 a blank of sixteen grams was used and the initial holding step was reduced to forty and twenty seconds, respectively. These changes did not yield the desired results and the time was switched back to ninety seconds.

A change in the holding pressure of the actual molding step was tried next. Four tests were made with the pressure used varying between 3000 and 3600 kilograms and it was concluded that the pressure of three thousand kilograms functioned the best. In the tests numbered 21 to 26, different variations of creating the blank were tried. Plyer count of the full-size pieces was varied between five and six, and the extra rectangular piece count was varied between two and seven with the weight of the blank varying between 15.5 grams and 18.1 grams. From these tests it was learned that the plyer counts of six seems to yield the most consistent results with the rectangles bringing the weight of the blank to around seventeen grams. Although some defects were still present around the extremities of the piece.

On the test number 27, the initial holding time of the preliminary step was again reduced, this time to seventy seconds, hoping to get the material flowing to the extremities. However, the problem persisted. At this point it was proposed that the placement of the rectangles could be asymmetrical on the different ends of the blank. This idea came to be from the notion that there seemed to be some consistency to the way the defects formed more on the preheater end than the MT-MPO end of the piece. A test was done with a six-plyer blank with two rectangles on the preheater side and one rectangle on the MT-MPO side, bringing the total weight to 16.9 grams. The resulting part had no visible defects and was deemed ok. This result was then confirmed during the following seven tests. The blanks were made with six plyers and an asymmetric number of rectangles on each end, the preheater side having one additional compared to the other end. The weights varied between 16.8 grams and 17.5 grams yielded the most consistent results. No more major defects were present on the resulting parts, and they were deemed satisfactory. The detailed test information can be seen in table 1.

Table 1

BMC								
#		mass (g)	pressure (kg)	pre heat step (s)	holding time (s)	temperature (C)	fill (1-3)	quality (1-3)
1	-	9.9	3000	0	600	150	1	1
2	-	15	3000	0	600	150	1	1
3	-	11	3000	0	600	150	2	2
4	-	11.7	3000	0	600	150	3	2
SMC								
#	plyers/rectangles	mass (g)	pressure (kg)	pre heat step (s)	holding time (s)	temperature (C)	fill (1-3)	quality (1-3)
5	-	13.7	3000	0	600	150	3	2
6	-	15.2	3000	0	600	150	3	2
10	-	15.8	3000	90	600	145	3	2
11	-	15.9	3000	90	600	145	3	2
12	-	16.5	3000	90	600	145	3	2
13	5/0	15.5	3000	90	600	145	2	1
14	5/6	16.4	3000		600	145	2	1
15	-	16	3000	40	600	145	2	1
16	-	16	3000	20	600	145	2	1
17	-	16	3000	90	600	145	2	2
18	-	16	3600	90	600	145	2	2
19	-	16	3400	90	600	145	2	2
20	-	16	3200	90	600	145	2	2
21	5/5	15.5	3000	90	600	145	2	1
22	6/7	16.9	3000	90	600	145	3	3
23	6/7	18.1	3000	90	600	145	2	2
24	6/0	17.4	3000	90	600	145	2	2
25	5/4	16.6	3000	90	600	145	2	2
26	6/2	16.9	3000	90	600	145	2	2
27	6/4	17.1	3000	70	600	145	2	2
28	6/3	16.9	3000	70	600	145	3	3
29	6/3	16.8	3000	70	600	145	3	1
30	6/3	16.9	3000	70	600	145	3	2
31	7/1	17.3	3000	70	600	145	3	3
32	6/3	17.3	3000	70	600	145	3	3
33	6/3	17	3000	70	600	145	3	3
34	5/10	16.8	3000	70	600	145	2	2
35	6/3	17.5	3000	70	600	145	3	3
36	6/3	18.2	3000	70	600	145	3	3
37	6/3	17.2	3000	70	600	145	3	3
38	6/3	18.3	3000	70	600	145	3	3
39	6/3	17.2	3000	70	600	145	3	3
40	6/3	16.9	3000	70	600	145	3	3
41	6/3	17	3000	70	600	145	3	2
42	6/3	17.1	3000	70	600	145	3	3
43	6/1	17.6	3000	70	600	145	3	3
44	6/1	17.1	3000	70	600	145	3	2
45	6/1	18	3000	70	600	145	3	3
46	6/1	17.7	3000	70	600	145	3	3
47	6/3	16.9	3000	70	600	145	3	3
48	6/1	17.8	3000	70	600	145	3	3
49	6/1	17.2	3000	70	600	145	3	3
50	6/1	17.3	3000	70	600	145	2	2
51	6/3	17.6	3000	70	600	145	3	3
52	6/3	17	3000	70	600	145	3	3
53	6/3	17.1	3000	70	600	145	3	3
54	6/1	17.7	3000	70	600	145	3	3
55	6/1	18.1	3000	70	600	145	3	3
56	6/1	17.9	3000	70	600	145	3	3

The process was now assessed to be sufficient for producing the full series of four hundred front panels. What was left was to estimate the time needed to produce the full series with one machine. The factors that affected that time were the time the cycle takes to create the part and the time it takes to release the part from the mold, clean the mold, reassemble the mold, and apply the release agent. Creating the blanks was not a factor since it could be done during the machine's cycle thus not adding any down time in between the cycles. Parts 36 to 46 were made during about half a working day, by one person working on the entire process. The next ten parts were made by a team of two people which did not significantly affect the time it takes to produce ten parts.

To conclude, the full cycle for acceptable quality parts was found to consist of an initial preheating step and the actual molding step. The initial step applies one hundred kilograms of pressure for seventy seconds, which is not enough to start the curing process. The point of the initial step is to liquify the resin and let it flow all throughout the mold. Afterwards the press squeezes the mold closed with three thousand kilograms of pressure for six hundred seconds. The whole time the beds of the press and the mold are kept at a consistent 145 degrees Celsius. The blanks put into the mold are made with six plyers of SMC/epoxy cut to shape corresponding the bottom molds cavity. The cutting of the shapes leaves rectangular pieces of consistent size, from the cooling pipe sleeve cutouts. These rectangles are used to finetune the weight of the blank aiming between 16.8 grams and 17.5 grams making sure that the preheater end has one more rectangle than the MT-MPO end.

6 Finished Part

The part coming out of the molding process is not finished but requires postprocessing. As described in the chapter 2.2.5, there still remains the brim, and the ends are capped, a freshly molded piece can be seen in the three. The brim on the straight flange needs to be sawed off and the ends sawed to length. The more complicated flange needs to be milled, to get rid of the brim there. All the outside edges as well as the inside edges of the slots need to be cleaned up by hand to get the part into the desired shape. At this step, any defective pieces may also be discarded.

After the part has been cut to its final shape and all the burrs and sharp edges removed, the holes for the electrical octopus clamp can be drilled utilizing a designated jig. The threaded inserts are then pressed into the holes from inside the flanges, making sure that the flange of the insert is pressed flat against the flange of the front panel. Lastly in the finishing step the inserts and the preheater connector clip are glued to their specified locations. After that, the same epoxy glue is used to treat the edges that were cut as well as any exposed fibers, to make sure no dust will get to the inside of the tracker. The finished part with the cooling pipe sleeve blockers can be seen in the Figure 4 - Finished part with inserts, preheater connector clip and cooling pipe sleeve

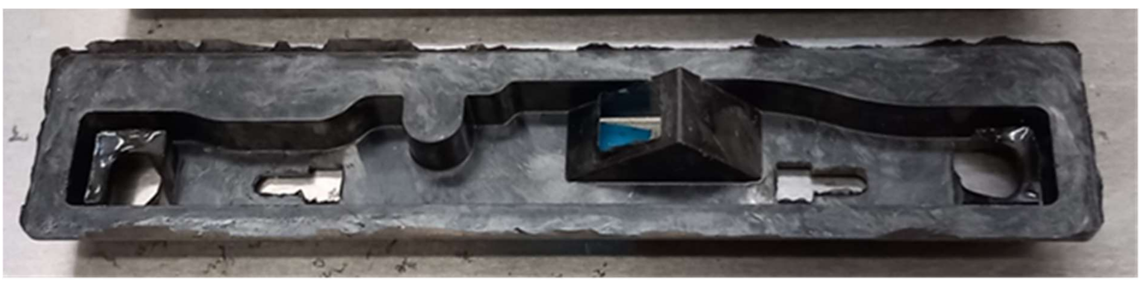

Figure 3 - Part freshly out of the mold.

Figure 4 - Finished part with inserts, preheater connector clip and cooling pipe sleeve blocker.

7 Conclusion

CERNs flagship particle collider, the LHC is to be upgraded during its Long Shutdown 3 into its high luminosity counterpart the HL-LHC. This upgrading sees the luminosity of the LHC increasing at least five times to its current luminosity. Due to the increase in the luminosity, the detectors around the four collision points need some upgrades as well. In one of these detectors called the CMS, it means a complete redesign of the inner parts of the detector, among other things. In the inner parts of the detector, in the barrel region, the new trackers outer regions are referred to as the TB2S or the Tracker Barrel with 2S-modules. The 2S-modules are attached to ladder structures, to ease the installation and the maintenance of the modules. The modules need cooling, power, and bandwidth for data transfer. These “services” are routed to the individual modules inside the ladder structures through the ladder front panel.

Due to complex requirements set by the different connectors of the services, the front panel needed to be designed from scratch. The basis was the same c-profile as in the rest of the ladder structure, but in order to fit the MT-MPO connector, the upper flange needed to be raised in the specified area for the connector. The feed through for the electrical was designed as a u-shape on the upper flange, to make its installation more convenient. The part of the flange where the preheater connectors would attach to was lowered so that the overall height of the front panel would stay within its constraints. The overall shape still has the two flanges similar to the c-profile for the strength they offer. These flanges needed to be angled outwards due to the chosen production method. Lastly some shaping was done to fit the part nicely on the ladder structure.

The chosen manufacturing process was SMC/BMC. In the BMC, the material is a paste like compound with the epoxy matrix and the reinforcement fibers readily mixed with the other necessary components. The paste is directly injected into the mold in a predetermined quantity. The SMC works very similarly but is formed into sheets, which are cut and stacked to form the blank. The blank is then placed inside the mold for the molding process to begin. The mold consists of the upper and the lower parts that when closed leave a cavity in between them of the desired shape and size. The lower part of the mold is further divided into three parts to ease the release of the cured part. To begin the molding process the mold first needs to be attached into the beds of the press and preheated to the desired temperature. The material is then inserted into the mold and the upper and lower parts of the mold squeezed together with the press. The combination of heat and pressure cures the material. The cured part is extracted from the mold after the pressing cycle has ended.

The first material to be assessed was BMC. The pressing cycle consisted of a single press of three thousand kilograms for six hundred seconds in the temperature of 150 degrees Celsius. Several iterations were made with slight variations to the parameters before deciding to change the material for the SMC. The process was then honed for the SMC over several iterations, making small adjustments to pressing cycle parameters and material amounts at a time. Acceptable quality was achieved consistently after 35 iterations. The process was then definitively confirmed with an additional twenty parts produced. From the time used to manufacture these twenty parts an estimate for the full patch manufacturing time was also deducted. The final parameters for the pressing cycle were as follows: initial heating step with one hundred kilograms of pressure for 70 seconds followed by a six hundred-second press under three thousand kilograms of pressure. The temperature of the mold was set to 145 degrees Celsius. The blank part is made of SMC sheets cut to the general shape of the front face of the front panel. The blank is fine-tuned with rectangles cut from the same sheets to achieve a weight somewhere between 16.8 grams and 17.5 grams. The rectangles are placed on the ends of the blank with the preheater side having one more than the opposing end.

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Appendices

Appendix 1 Notes from the molding process, Boyer, F., Viljakainen, A. (2023)

18.01.22 Balcony #11. (14g).
Idem #10.

31.03.22 • LADDER #1
On utilise BMC VE 9,9g 3000kg pdt 600s à 150 °C.
→ la pièce n'est pas complètement remplie.
• LADDER #2.
Mêmes conditions que #1 mais avec 15g.
→ Pièce pas remplie mais sans doute dû à la matière qui est vieille et qui ne flue pas du tout
• LADDER #3.
11g → la pièce est quasi remplie il manque juste de la matière dans les extrémités
LADDER #4 11,7g → la pièce est remplie sauf à une extrémité.

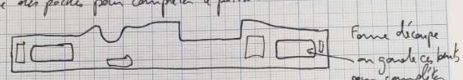
4.04.22 - Ladder #5
13,7g de SMC VE → pièce bien remplie mais quelque manque.

- Ladder #6
15,2g SMC VE 150°C 600s à 3000kg
→ Pièce bien remplie !!

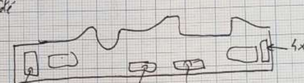
13.04.22 Ladder #10
On teste avec SMC/epoxy 15,8g.
On fait une première compression à 100kg de manière à mettre les deux parties du moule en contact sans pression pdt 90s
Ensuite on applique comme d'habitude 3000kg pdt 600s
la presse est à 145°C.
→ Pièce nickel !! Dès le premier essai.

14.04.22 • Ladder #11
Même paramètre que #10 15,9g. SMC/epoxy
→ Pièce OK
• Ladder #12
Même paramètre que #10 16,5g SMC/epoxy
→ Pièce OK

11.10.22
• Ladder #13
SMC/epoxy 15,5g.
Même paramètre que #10 5 couches de SMC et on utilise les restes de matière des poches pour compléter le poids.

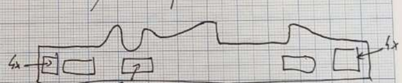


→ Manque résine sur côté
• Ladder #14
16,4g de SMC



→ Manque toujours résine
Le Matériau est peut être trop vieux et la viscosité n'est plus la même. On décide de changer le temps de maintien

→ Ladder #15
16g de résine



Maintien sans pression de 40s (car oubli d'enlever film vert sur un côté) initialement prévu à 50s
→ toujours un manque de matière sur les extrémités

13.10.22 • Ladder #16
16g résine 5 plis SMC Maintien 40s
→ manque aux extrémités

• Ladder #17
Suppression temps de maintien 3000kg
→ Résultat meilleur mais quelque manques aux extrémités

• Ladder #18.
Suppression temps de maintien 3600kg
→ Résultat moins bon et difficulté à démouler

• Ladder #19
Même que #17.
→ Résultat similaire à #17

• Ladder #20
VE. SMC 5 plis.
→ Résultat OK.

19.06.23 • Production Front panel ladder #21.
m = 15,5g SMC/epoxy 5 plis + 5 carrés ▭ le long du profil.
SMC frais.
Cycle presse : "TB2S ladder epoxy smc"
→ pièce remplie mais qques zones sèches sûrement dû à un manque de matière.

20.06.23 • ~~Front~~ Ladder #22
m = 18,9g. 6 plis + 7 rectangle ▭
→ Pièce OK !!
• Ladder #23
m = 18,1g 6 plis + 7 rectangles ▭
→ Pièce remplie mais peut-être trop de matière.
• Ladder #24.
m = 17,4g 6 plis.
→ manque un peu aux extrémités
• Ladder #25
m = 16,6g 5 plis + ~~deux bouts~~ + 4 rectangles
→ Petit manque aux extrémités

21.06.23
• Ladder #26.
m = 16,9g 6 plies + 2 rectangle ▭
→ Part OK but still some lack of fiber and resin at the extremities
• Ladder #27
m = 17,1g 6 plies + 4 rectangle ▭ 2 on each side.
holding step from 90s to 70s.
→ Part OK but still some lack at the same area
We will try to put more material at this extremity.

22.06.23 Ladder # 28
M = 16,9 g 6 plier + 3 rectangle (1 left, 2 right)
→ piece ok, material filled the whole mold (no more gap)
Ladder # 29
M = 16,8 g 6 plier + 3 rectangle (1 Left, 2 right)
trying the same again to see if it was just a fluke
→ piece cracked on the end

Ladder # 30
M = 16,9g 6 plier + 3 rectangle (1 left 2 right)
retry
→ part ok! a bit more overflow than normally, don't know why
Ladder # 31
M = 17,3 6 plier + 1 rectangle (right side)
→ part ok!

26.06.23 Ladder #32
m = 17,3g 6 plies + 3 rectangle (2 on right side)
→ OK
Ladder #33
m = 17 g 6 pliers + 3 rectangles (2 on right side)
→ OK
Ladder #34
M = 16.8 6 plier 10 rectangle (3L, 3M, 4R)
→ OK, mold not fully filled on the ends.
Ladder #35

22.06.23
- Ladder # 36
m : 18,2 g ; 6 pliers + 3 squares (2 right + 1 left)
→ OK (manque matière haut gauche)

- Ladder #37
m : 17,2g 6 pliers + 3 squares (2R + 1L)
→ Part ok!

- Ladder # 38
m : 18,3g 6 plier + 3 squares (2R + 1 L)
→ Part OK (un peu trop de matière)

- Ladder #39
m : 17,2 g 6 pliers + 3 squares (2R + 1L)
Part Ok

- Ladder # 40
m : 16,9 g 6 plies + 3 squares (2R + 1L)
→ Part OK

- Ladder #41
m : 17 g 6 plies + 3 squares (2R + 1L)
→ Not OK encoches à droite

- Ladder # 42
→ m : 17,1 g 6 plies + 1 square (1 right)
→ OK

- Ladder # 43
m : 17,6 g 6 plies + 1 square (1 R)
→ Ok, little delamination on the outside wide round corner

- Ladder # 44
m : 17,1 g 6 plies + 1 square (1 right)
→ part Ok! A gap in both ends

- Ladder # 45
m : 18 g 6 pliers + 1 square (1R)
→ Not OK fissure sur un coté (peut-être au démoulage)
a piece cracked off when taking off the mold, also a crack next to that spot on the side (less aggressive part removal needed)

- Ladder #46
m : 17,7g 6 plies + 1 square (1R)
→ part OK

28.06.23
- Ladder # 47
m : 16,9 g 6 plies + 3 squares (2R + 1L)
→ OK (Bourrage moule Haut)

- Ladder # 48
m : 17,8 g 6 plies + 1 squares (1R)
→ OK

- Ladder # 49
m : 17,2 g 6 pliers + 1 square (1R)
→ OK

- Ladder #50
m : 17,3 g 6 plies + 1 square (1R)
→ Not OK (cassé en bas à droite)

~~- Ladder #51~~
~~m : 17,8 g 6 plies 1 square (1R)~~
~~→~~

- Ladder # 51
m : 17,6 g 6 pliers 3 squares (2R + 1L)
→ Not OK Moule complètement bourré.

→ Demontage partie haute du moule pour débourrage et remontage à chaud impossible.

- Ladder # 52
m : 17 g 6 plies + 3 squares (2R + 1L)
→ Nickel!

- Ladder # 53
m : 17,1 g 6 plies + 3 squares (2R + 1L)
→ OK

- Ladder # 54
m : 17,7 g 6 plies + 1 square (1R)
→ OK

- Ladder # 55
m : 18,1 g 6 plies + 1 square (1R)
→ OK

- Ladder # 56
m : 17,9 g 6 plies + 1 square (1R)
→ OK!