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The Hadron Calorimeter Design and Construction

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ABSTRACT

The design of the LHCb Hadron Calorimeter is being described in this note. An internal structure consisting of thin iron plates interspaced with scintillating tiles have been chosen.

The HCAL consists of two symmetric movable parts getting in touch in operation position without non-instrumented zones. The lateral dimensions of the HCAL active area is of X=8.4 m in width, Y=6.8 m in height, and is distanced from the interaction point at Z=13.33 m. Both halfs are assembled from stacked up modules. Each half of about 245 tonn is located on the separate platform.

Attention is paid to the strength analysis of the module as a basic assembling unit. Different phases are being discussed: the iron plates glueing, the submodule and module construction, the scintillating tiles and fibers preparation for insertion, the pre-installation test and calibration. The documentation incorporates a set of tools needed for detector assembly.

In the summary the construction rate is estimated.

1 Introduction

The purpose of the hadron calorimeter (HCAL) in the LHCb experiment [1, 2] is to provide data for the zero-level hadron trigger. It has to fulfil the acceptance requirements of LHCb and havs an active area front surface of $8.4 \times 6.8\,\mathrm{m}^2$. The total weight of the detector is around 500 tonns.

The HCAL is being designed as two symmetrical parts that join together in the operation position. Both parts reside on a separate platform and can be moved out for maintenance access.

The inner structure of HCAL is the same as has been tested in the LHCb HCAL Prototype design [3, 4] and consists of thin iron plates interspaced with scintillating tiles arranged in parallel to the beam axis. The light is collected by wave-length shifting fibers running to the back of the calorimeter, where photo-multipliers are located.

This design is based on several years of R&D study of HCAL Prototypes [3] that includes both mechanical design and optics assembly experience.

2 The overview of the HCAL

A view of half of the HCAL detector is shown in Fig. 1.

It consists of 26 stacked up modules. In the middle there are two shorter modules that allow to pass the accelerator beam pipe. The halfs are placed on separate movable platforms. The inner surfaces being in touch during operation are flat and have been designed to exclude any non-instrumented zone. This mean that the innermost master plate in each module has half-width and the periodic structure (see later) is being continued in the opposite half of the HCAL.

Modules have dimensions of $420 \times 165 \times 26\,\mathrm{cm}^3$ and a weight of ~ 9.5 tonn. Those are designed as the largest construction elements being assembled, tested and mounted separately. The instrumented depth of the detector is 122 cm that corresponds to average thickness of $5.6\,\lambda_I$ interaction length.

The following sections describe the HCAL design in descending order: the module as a base unit, then sub modules as a constructive elements for modules and then a master-spacer plates.

3 The module design and strength analysis

A module is shown in Fig. 2. It consists of eight submodule units that are joint together with 20 mm thick iron beams, welded from the front and rear sides. At the rear side a 4.2 m long back-holder is attached to house the fiber bundles, the PMT's and the cables. The back-holder is made of an I-shape steel beam with several welded reinforcing ribs. Submodules are joint to the back-holder over studs and nuts. At the same time the back-bolder transmits the weight of the rear part of the HCAL to the supporting platform. Hense, the load of the detector is concentrated on the front surface and back-holders. The

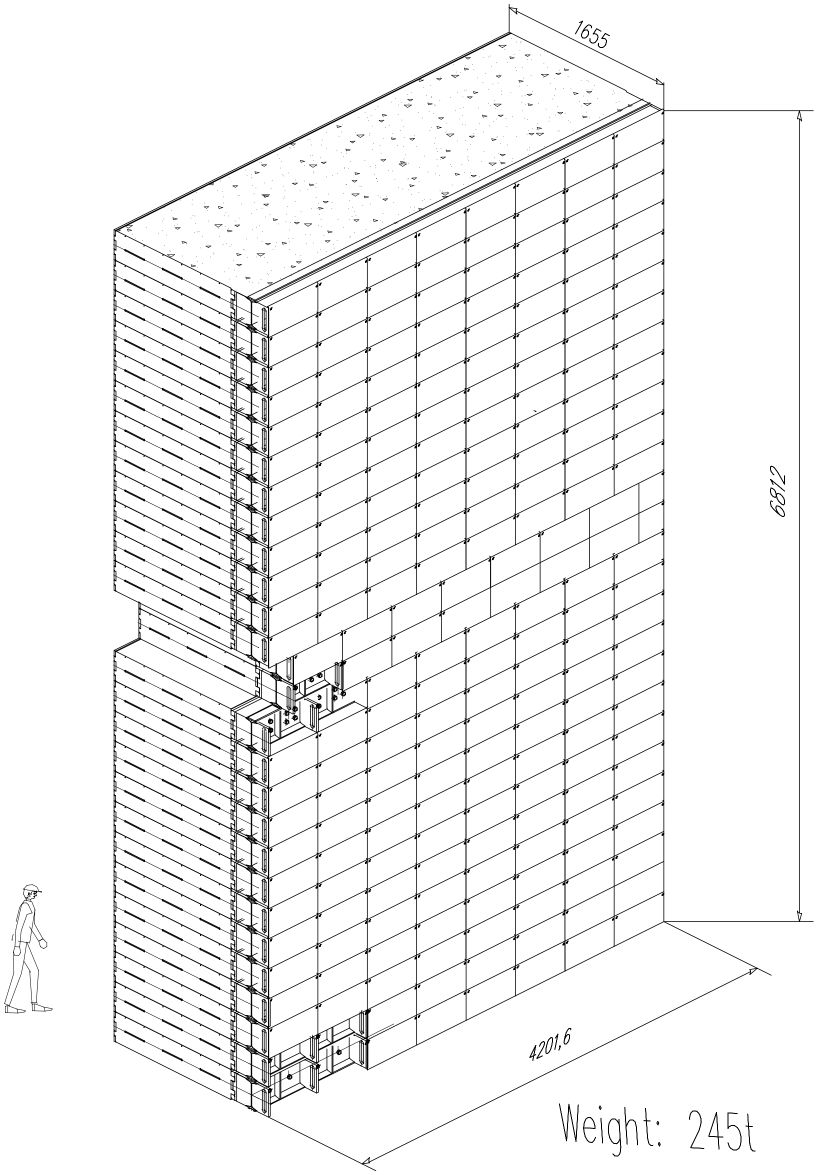

Figure 1: The view of one half of the hadron calorimeter. There are 26 horizontal modules stacked up. Two central modules are shorter to allow the accelerator beam-pipe to pass.

module assembly procedure is to be performed on the special assembling tool to ensure the tolerance requirements of better than 0.6 mm in the vertical diection. The width of the module in the horizontal direction is somewhat less critical and can be within two millimeters.

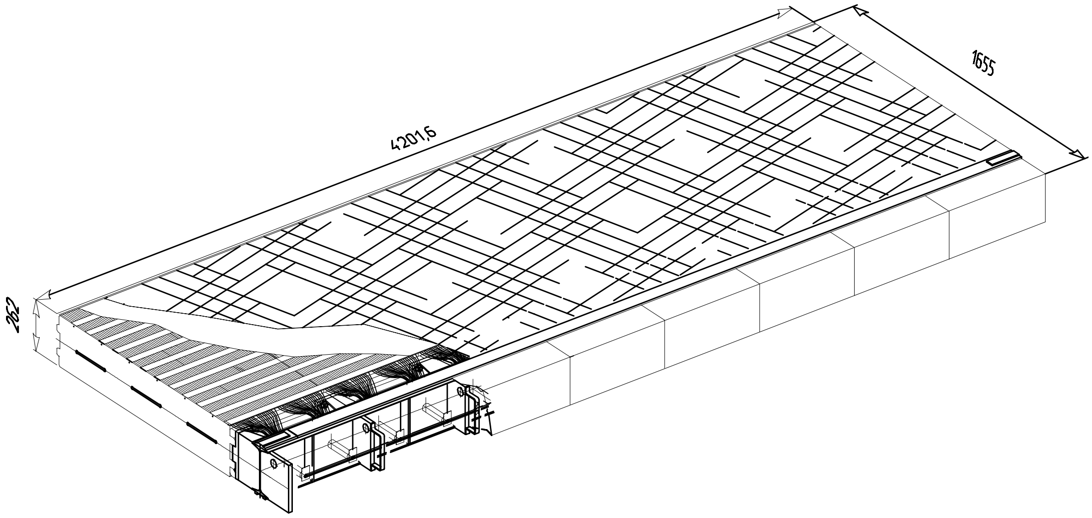

Figure 2: The module internal structure. Eight submodule units are joint on the back with I-shape holder. The whole module is covered with light protecting black paper shown as hatched surface.

Each module being assembled has to pass the quality control with measurement of the relevant reference points to be within mentioned tolerances. A simple pre-installation procedure has to be made at this stage. For that the constructed module is been laid on top of the preceding one to adjust the joining inserts fixing the relative positioning. Small steel peaces can be adjusted to take up the horizontal clearance if any. This procedure allows slightly release strict tolerance requirements for the module construction.

The contact surface between two modules is well defined. At the front face it is the 20 mm thick bar welded to each submodule, and on the rear side – the flat steel strap welded on flange I-beam and milled during back-holder construction. This mean that the weight of the module is being distributed to front and back. No contact is foreseen between master plates. The clearance of 0.6 mm left for contacting surfaces allow them to be nonparallel within this value to be taken up during final assembly.

The strength analysis has been done for the model of described mechanical structure using ANSYS program. The internal stresses and displacement have been calculated for the bottom module in HCAL as being in the ultimate environment. Fig. 3 show the model being analysed, coordinate axes direction and the location of nodes with fixed displacement. The weight of upper modules has been simulated as two 150 tonn load distributed over both front and rear contact surfaces.

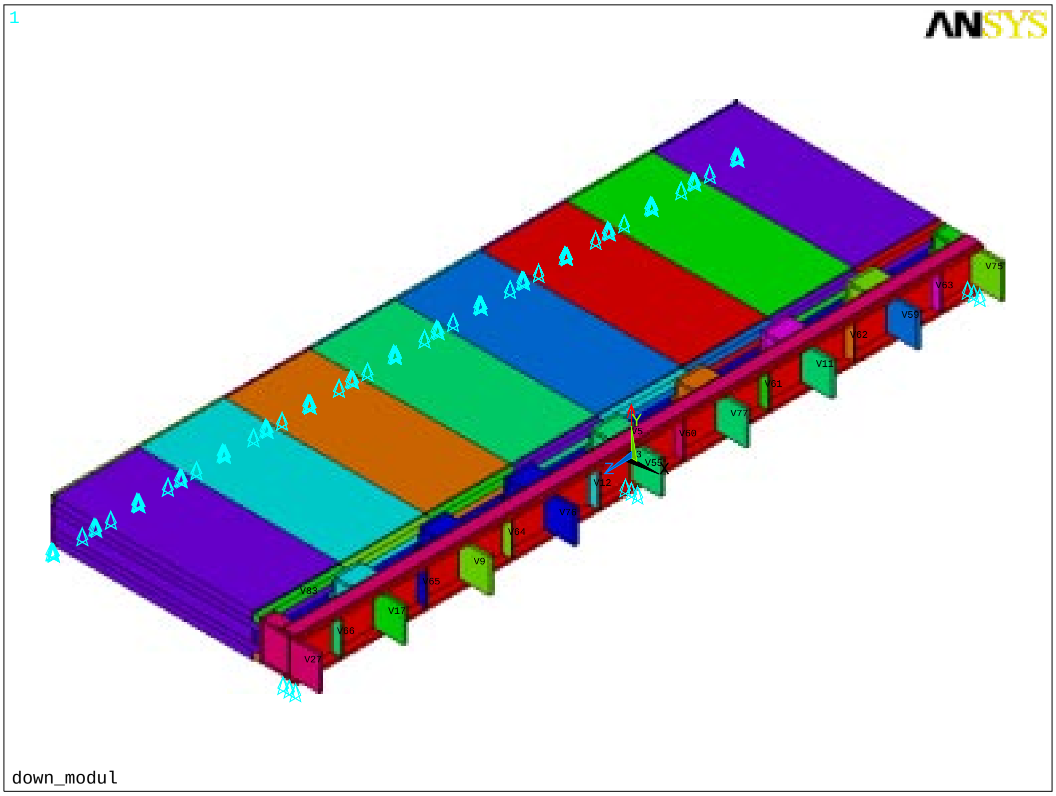

Figure 3: The ANSYS model of the bottom module. Triangles on the bottom are pointing out fixed nodes. X-axis directed along submodules, Y-axis – vertically and Z-axis – along I-beam of back-holder.

The expected elastic deformation in Y-axis (vertical) is shown in Fig. 4. The largest values does not exceed 55 micron and as was expected, are concentrated on the I-beam between ribs.

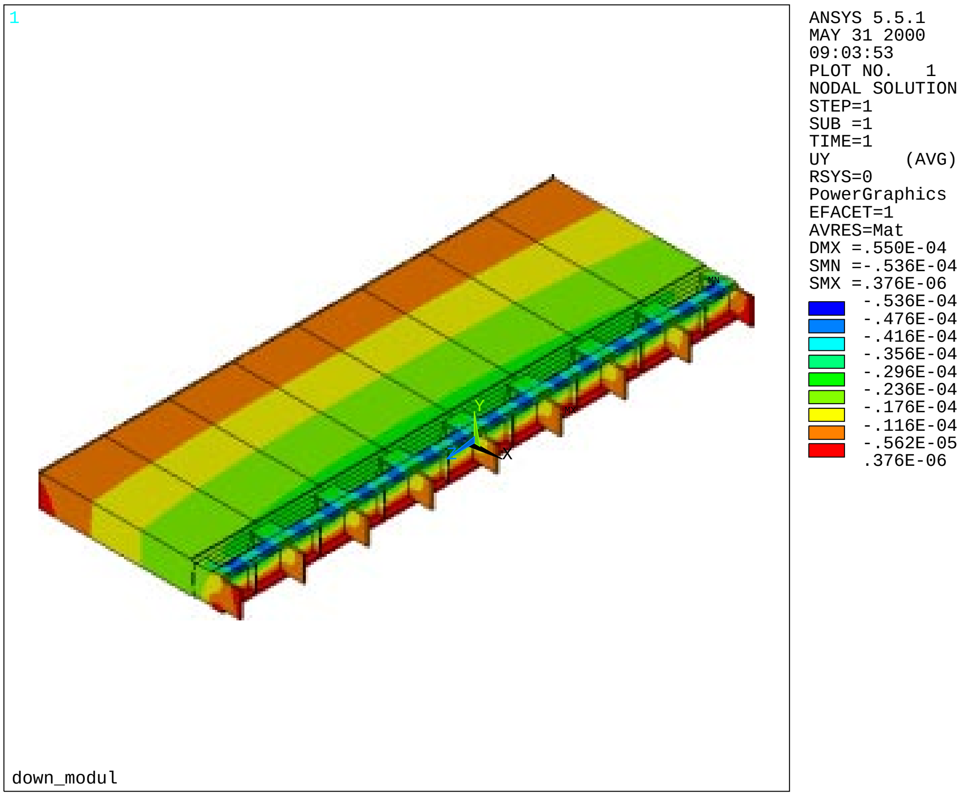

Figure 4: The ANSYS solution of deformation in Y-direction for the bottom module that has been loaded with 150 tonn on both front and rear sides. The maximal displacement is less than 55 micron.

The results of strength study are shown in Fig. 5. The largest stress of ~ 9 kg/mm^2 is located in the front bar of the module as having smaller contact surface (not seen in the figure). The I-beam tension is restricted within 5.6kg/mm^2 that is safe enough.

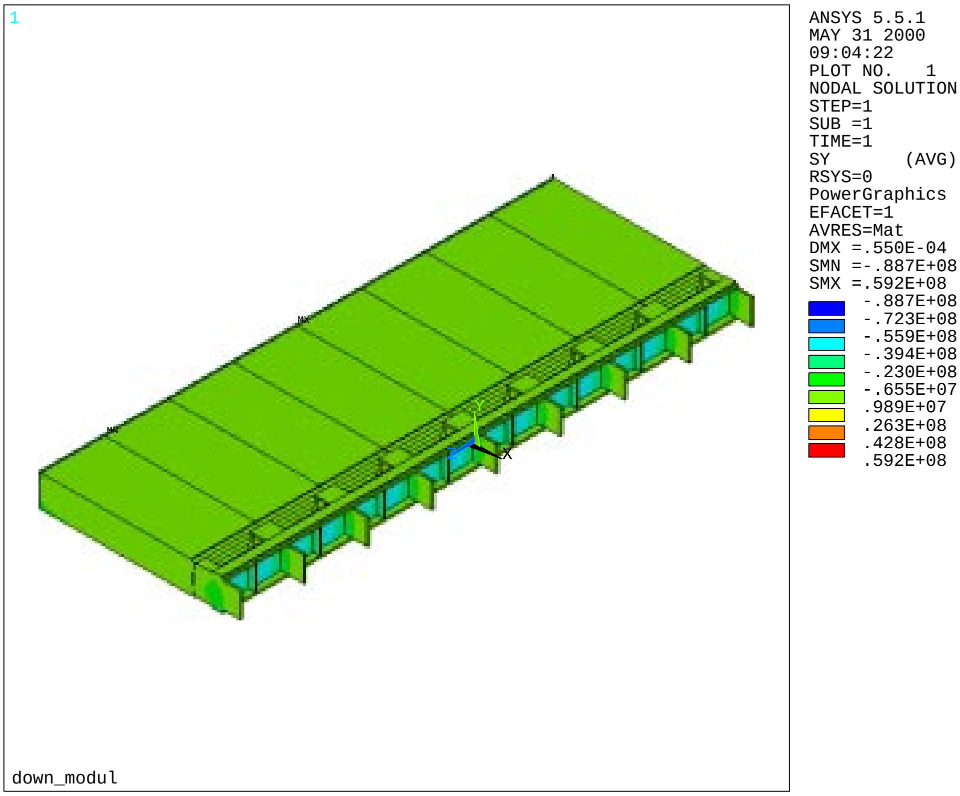

Figure 5: The ANSYS solution for internal stress along vertical Y-axis. The tension range in the back-holder is within 5.6 kg/mm^2

Another strength study has been done for the module located in the vertical position, rest on two legs. This situation is used during optics assembly. The maximal stress around support points does not exceed 4.4kg/mm^2 in the vertical direction. The displacement is within 30 micron as shown in Fig. 6.

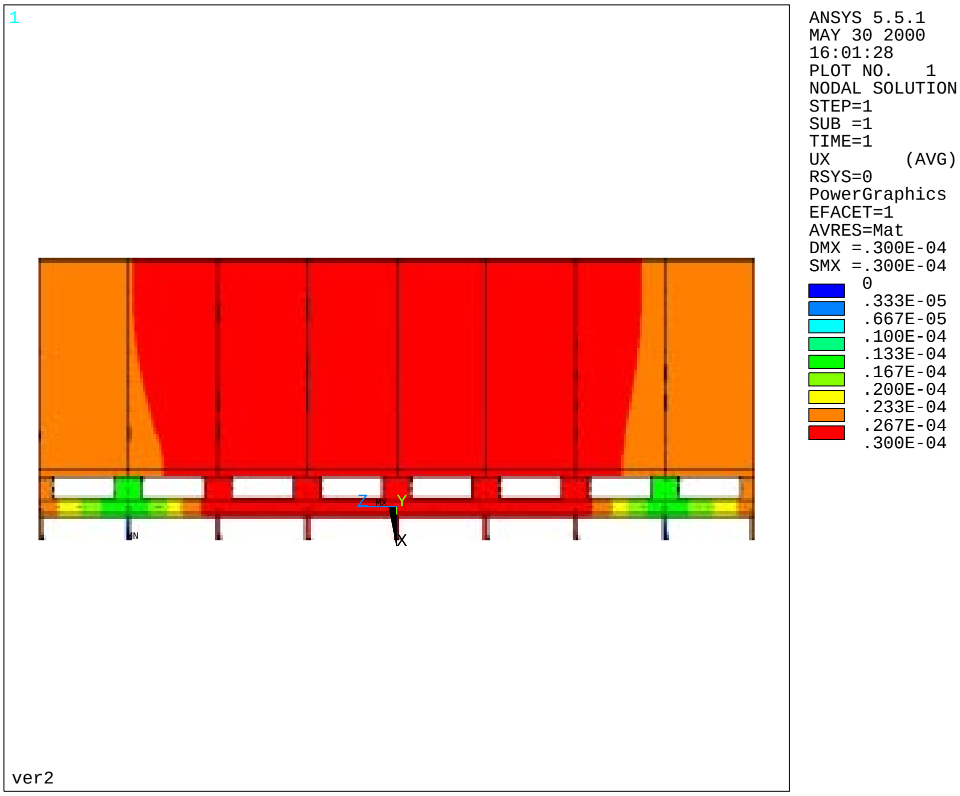

Figure 6: The ANSYS solution of the vertical displacement for two-point legs. The deformation range in X-direction (along the gravity vector) is found to be within 30 micron.

This result ensures that two supporting leg would be enough to hold module in the vertical position.

4 The submodule design

The submodule internal structure shown in Fig. 7. Several identical 6 mm thick master plates are glued together with 4 mm thick spacers. For both masters and spacers a low carbon laminate steel of type "Steel-3" (or Fe-360) is to be used. The acceptable thickness tolerance throughout whole surface should be within ±0.05 mm. The epoxy glue of type Araldite AW 106 with Hardener HV 953 U is to be used, mixed in equal volume proportion. It has 10-12 hours hardening time under ambient temperature and corresponds well to 2-3 hours of the submodule glueing cycle.

Each submodule has a periodic structure. The period consist of two master plate with five types of spacers. Only six types of iron plate pieces are needed for HCAL passive radiator construction. The free space left between spacers is used for scintillating tile insertion after module being constructed.

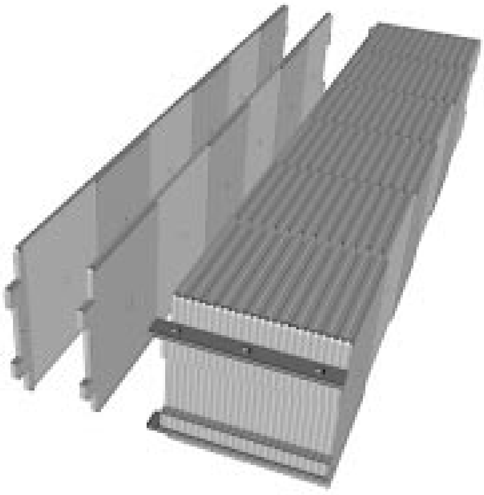

Figure 7: The view of HCAL inner structure. Two master plates shown detached have several spacers glued. The gaps between spacers are used for scintillating tile insertion during optics assembly.

The spacer height is 2.25 mm less than for master plate at each side to hide fiber running between masters. Spacer layout for one period is shown in Fig. 8. There are four different types of spacers, two attached to the calorimeter front side and two at the end. Those follow the ledges on the master plate. The fifth spacer is designed to be used in four places to minimize the different pieces types.

During the assembly the spacers are fixed on the master surface with a lock washer incerted in the central hole and with a 4 mm diameter steel pin on the side.

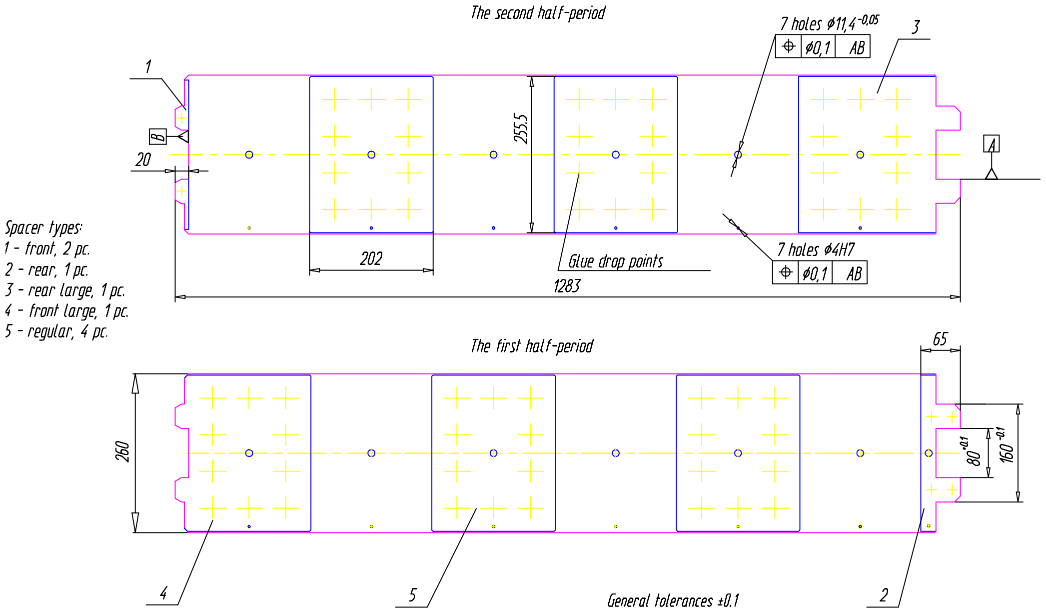

Figure 8: The spacer layout for the period of two master plates. The crosses on spacers mark places for glue application.

The submodule glueing have to be divided in the following steps:

- prepare masters and spacers, visual quality check;
- surface clean, degreasing in the bubbling bath with washing solvent and drying with hot air;
- apply glue on masters and spacers;
- stack up 52 masters with spacers in assembly tool;
- leave for the night in the stressed state for hardening;
- next day the two pairs of connecting straps are being welded on each corner of the submodule;
- rust-proof coating in dipping-bath;
- check gaps and store for further module assembly.

The production rate and manpower needed for the mentioned items have been monitored during HCAL Prototype assembly and are well checked currently in mass production of ATLAS TileCal submodules. Despite of very like structure the tools for LHCb HCAL assembly have to be designed and constructed again. This results from lower dimension and less restrictive tolerance requirements.

Fig. 9 show the schematic view of submodule assembly tool.

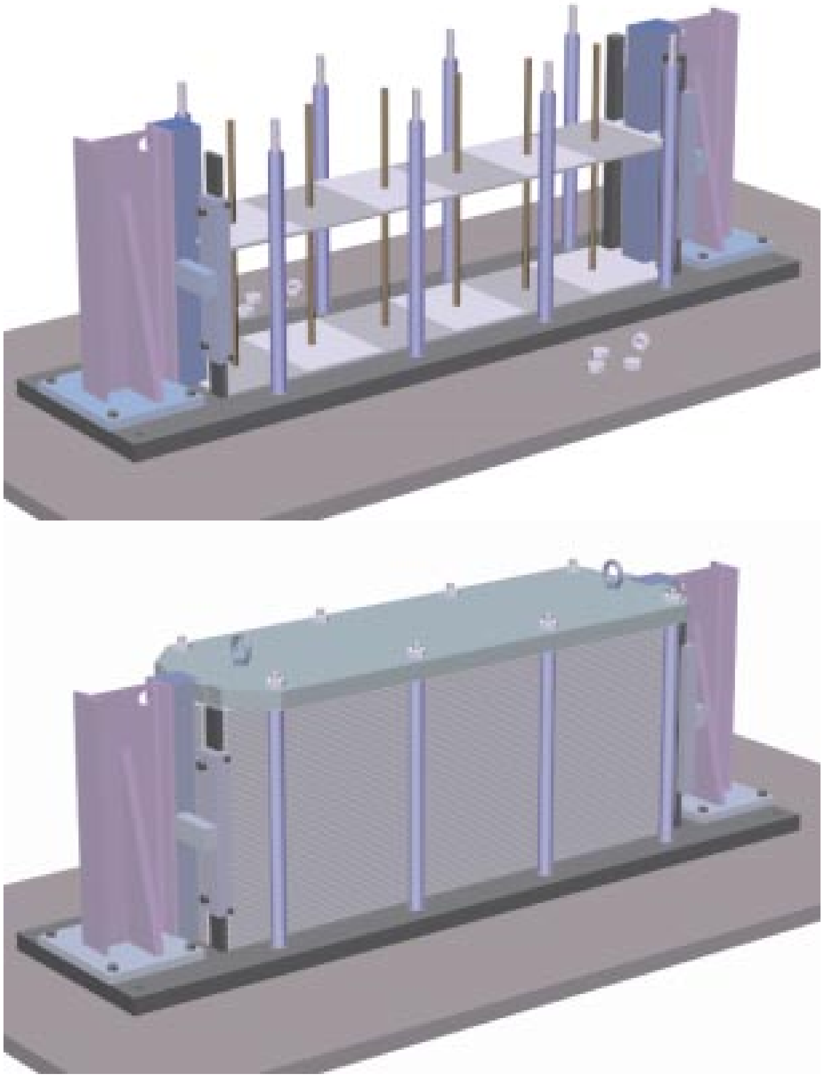

Figure 9: The submodule assembly tool. Up – master plate insertion. Down - all plates stressed for hardening.

The top figure show the stacking up in progress. The master plate with spacers is being sinking on to preceding half period. In the bottom figure whole submodule unit has already been stressed by cover plate and rest for hardening.

The constructed submodule with reference dimensions is shown in Fig. 10. The width is $\Delta X = 525.2\,\mathrm{mm}$, height - $\Delta Y = 262.0\,\mathrm{mm}$ and depth $\Delta Z = 1286\,\mathrm{mm}$. The volume ratio of the iron to scintillator is **Fe:Sc = 5.47:1**. This value coinsides within 5 % with that used in the HCAL Prototype construction.

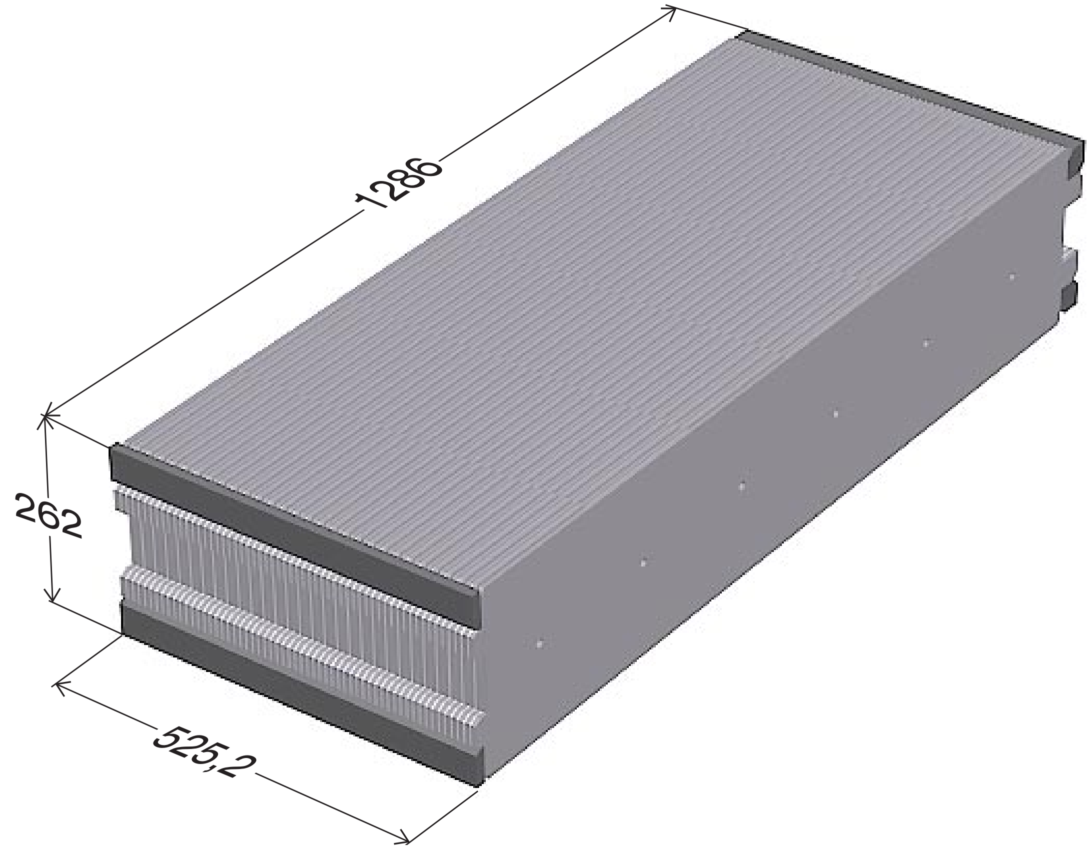

Figure 10: The constructed submodule with a basic dimensions. The depth is 3 mm larger than master plate length due to the welded beams at the rear side, where the back-holder is screwed down.

5 The optics production and assembly

The optics for HCAL includes two components: scintillating tiles and wave-length shifting fibers. The scintillating tiles production has to be done with modern technology of injection in to the mould. The raw components to be used are: the polystyrene PSM-115 as a base with 1.5 % paraterphenyl (PTP) and 0.03 % POPOP as a primary and secondary dopants.

This technic is widely used for a large scale calorimetry detectors and has been tested for HCAL Prototype [3]. Currently several enterprises in Russia and worldwide can fabricate the high quality tiles.

The tile dimension to be used in HCAL is shown in Fig. 11.

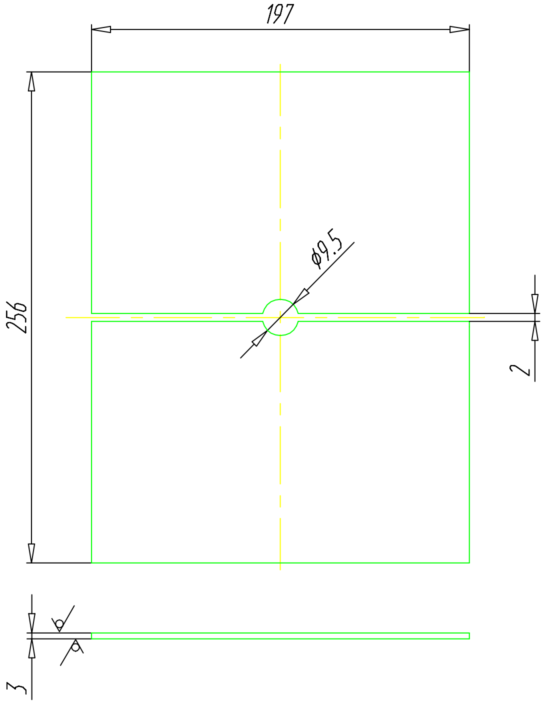

Figure 11: Scintillating tile dimension. Two type has to be produced: whole tile of 256 × 197 mm^2 and two half-tiles (shown in figure) for smaller cell size.

Two type of tiles both 3 mm thick have to be produced with basically the same moulding tool. The larger cell size (26 × 26 cm^2) requires the tile of 256 × 197 mm^2 and for smaller cell of 13 × 13 cm^2 the tile has half height – 127 × 197 mm^2. The 2 mm thick internal partition is foreseen in the moulding tool, that currently is being designed. The most critical issue in mould construction is the internal surface quality. It has to be treated up to the optical class to ensure high internal reflection inside tile without light loss.

Another item to be payed attention to is the mechanical strength of the mold to perform reliably several tenth of thousands injection cycles. The ageing of mold results in worsening of the tile thickness tolerance, that lead to non-uniformity in response.

Being produced tile immediately is to be wrapped in the TYVEK envelope. The TYVEK thickness used in Prototype of 120 ÷ 150 micron is found to be sufficient for reliable light collection. The edges of the wrapped tile are to be remain open for further fiber insertion inside envelope during module optics assembly.

Ordinary office scotch tape is to be used to fix the envelope. Control samples used in Prototype assembly three years ago show that this is a cheep and reliable solution.

The output quality control of each batch is foreseen during the tile production. It has to be performed using testing set-up with PMT anode current measurement in response to β-source irradiation at different points on the tile. This procedure will assure the equal light responce for all tiles during the long term production period within 5 %. The previous experience show that up to 10 % of tiles, usually at the beginning and at the end of the production batch, do not pass this check and have to be thrown out.

A second optical component is the WLS fiber. The detail study of those properties is done elsewhere [5]. Several types of fibers have been studied for their light yield, timing and radiative hardness [6]. The candidates are Pol.Hi.Tech.(S250), Y-11 (MS250) of Kuraray and BCF-92 of Bicron Corp. The multi-cladding fibers of $1 \div 1.5\,\mathrm{mm}$ in diameter are preferable solution. The maximal number of fibers in the single bundle for the largest cell is 54 (52 WLS fibers, 2 LED calibration). Those fit well within $1\,\mathrm{cm}^2$ even for the fibers of 1.5 mm in diameter.

Here we concentrate on fiber preparation. The fiber in large quantity ($sim77$ kilometers) are delivered on ~ 1 m diameter spool. It has to be cut on to 1.6 m long pieces and to be polished at one side for aluminium mirror coating. Up to 50K fibers has to be produced in total. The existing tools allow to perform this job with average rate up to 300 pieces per day (4 day per week) in IHEP. The coated mirror has to be varnish over for protection. Typical reflectivity of 85 % has been obtained recently for the test sample of 170 fibers. The quality control for prepared fibers is foreseen using the measuring set-up. The aim is to check the mirror reflectivity and attenuation length of the fibers after coating. The testing procedure is currently under development. The fiber responce to several blue light emission diodes arranged along fiber length has to be measured with the same PMT. Up to hundred fibers have to be checked during one scan, to allow needed performance of this check. All data are to be processed online by the computer to allow immediate bad fiber separation.

The optics assembly has been elaborated during the HCAL Prototype construction. For that purpose the iron module should be rotated to the vertical position.The design of the corresponding tool is shown in Fig. 12.

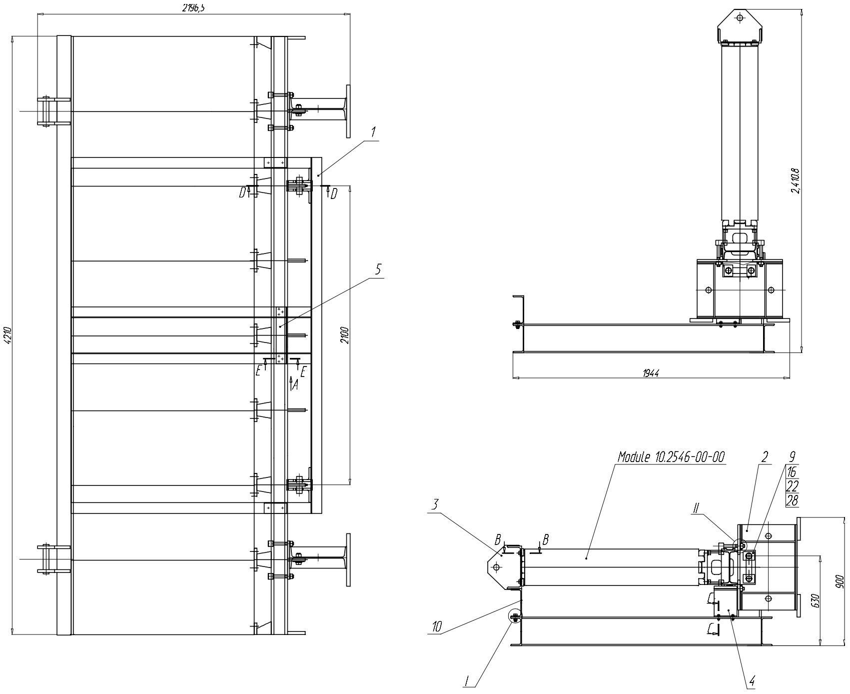

Figure 12: The tool for module rotation in vertical position for optics assembly.

This tool consists of several separate parts: the basic frame, two detachable legs and upper C-shape beam. Legs have to be attached to module in advance for safety reason. The pivot height allows to rotate the module with legs about gudgeon using crane. The procedure is being completed there is no need in the the base frame anymore and the module stay vertically on the legs.

Optics assembly starts with tile insertion in slits between master plates. Then the fibers are fed from top to bottom in TYVEK envelope and joint in the bundle according to cell composition. The fiber ends then are pushed in to the teflon reusable cup to fill up with an epoxy glue (Araldite 2011 have been used for HCAL Prototype). After 10 hours the glue become hard and cups are removed.

Two LED sources are embedded in each module. The ligth is transmitted through equal-length transparent fibers to each PMT in the module to allow timing synchronization and short-term stability monitoring as described in [4]. The existance of two LED with variable pulse despite of the redundancy for the LED calibration system creates new feature for the linearity monitoring of the PMT - FE elecrtonics chain, as described in [7].

The manual cut and polishing of bundles used for the prototype was adequate for that case, but for the mass production a small tool with handy mill machine is being currently under design. It will incorporate both thin cutting fraize and tungsten and/or diamant cutter for fine cleanoff.

At the end of optics assembly tiles and fibers are covered with MAYLAR protective foil and black paper for the light protection.

6 The PMT block and pre-installing test

The assembled module has to be checked for response. The radioactive Cs^{137} source is to be used for that purpose. Six stainless steel pipes are fed through holes in the calorimeter module, being connected together in pipeline with C-shape tubes. The radioactive source is driven by distilled water flow at the speed of about 40 cm/s. This system has been tested with HCAL Prototype. It includes hydraulic part equipped with computer controlled pump and valves, reversing the water flow direction, the lead-wall garage unit and coil sensors, detecting the source movement inside the pipe.

The signal readout is done with PMT's attached to back-holders as shown in Fig. 13. The new shorter 10-stage PMT has been developed recently [7] to fit in the total calorimeter depth limitation. Several PMT options have been studied [8] as a candidates for use in the LHCb calorimeters. The general requirements to PMT's for HCAL are presented in the Table 1.

Table 1: The requirements to the PMT for HCAL.

Item	Parameter
Tube length	not more than 75 mm
Photocathode diameter	more than 15 mm
Gain	5×10^5
Quantum efficiency at 490 nm	more than 12 %
Linearity for 20 mA peak current	better than 2 %
Cathode uniformity within $1\,\mathrm{cm}^2$	better than 5 %
Pulse FWHM	less than 10 ns
Long term stability	better than 2 % per 100 hours
Short term stability for $I_A < 20\mu A$	better than 2 %

A combine type of high voltage divider is foreseen for PMT's: several upper dinodes have individual resistive chain, and the last four dinodes are connected together and supplied by four separate bias voltage sources. A capacitors of the order of 10 nF on the PMT devider at last dinodes will prevent the potential drop after large pulses.

A flat and compact divider is currently under construction using SMD technology. The final PMT choise is expected to be done before the start of the mass production of HCAL modules.

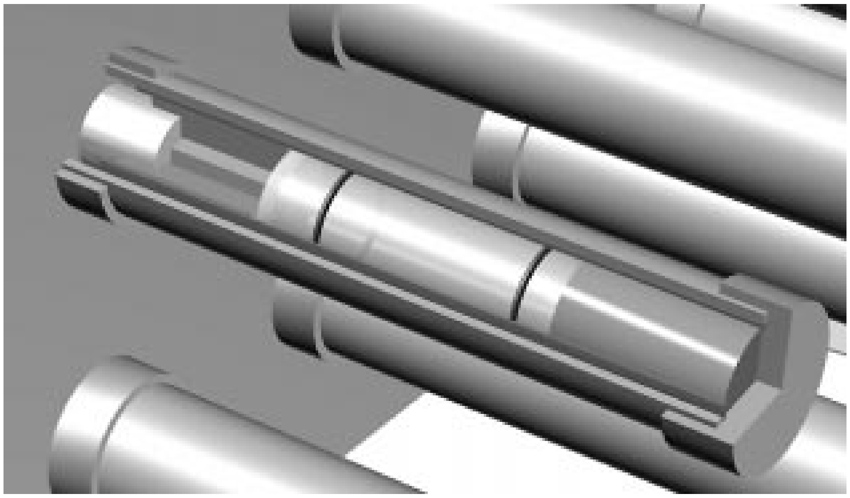

Figure 13: The PMT block attached to module. The square light mixer followed by PMT and HV divider are seen in the cut.

The PMT is connected to polished fiber through square 35 mm long light mixer, both housed inside 3 mm thick steel tube and 50 micron mu-metal foil wound in 6 layers as a stray magnetic field protection.

The pre-installation test aim is to find out broken or weak fibers and replace them at the assembly stage. All system has to be tested with Module-1 currently under construction. Being once calibrated on the X7 test-beam line at SPS, Module-1 will define an absolute energy scale setting with respect to Cs^{137} induced current measurement. This allows to calibrate each assembled module better than 10 % tolerance without putting all of them on the beam.

7 Summary

In summary the construction time-scale has to be considered.

Three phases have to be outlined in further construction of the HCAL detector:

- iron plates preparation and assembly;
- scintillating tiles production, fibers preparation and assembly;
- PMT check, assembled modules test and calibration.

The following Table 2 describes some of the mentioned items in term of production rate that follows from our experience.

Our experience show that production of the iron plates by ordinary milling technology could cause certain delay. Currently more productive punching technique is being considered. The design of the several die is in progress under ISTC grant in Russia. The

Table 2: The construction rate of the HCAL components. An estimate made for working team of 4-5 person.

Item	total units	time required
Master/spacer production, set	23K	
milling		20/day
punching		200/day
submodule mechanics assembly	424	4/week
Module mechanics assembly	53	2/month
Tiles production	70K	200/day
Fiber aluminization	45K	300/day
Module optics assembly	53	2/month
Test and calibration	53	3/month

start for mass production of HCAL modules is scheduled for the fall of year 2001 and will take about 30 month.

References

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