Milestone Report

Design of cooling systems for tungsten / carbon fibre and for hadron calorimeter structures

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MILESTONE REPORT

DESIGN OF COOLING SYSTEMS FOR TUNGSTEN / CARBON FIBRE AND FOR HADRON CALORIMETER STRUCTURES

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Abstract:

The front-end electronics for both, highly granular silicon-based electromagnetic and scintillator-based hadronic calorimeters require a highly integrated and efficient cooling. Thermal properties of tungsten and carbon fibre based absorber elements drive the cooling concepts of electromagnetic calorimeters. The feasibility of a cooling system has been successfully demonstrated for low power calorimeter readout electronics. Thermal modelling and measurements performed on demonstrators constructed within the EUDET project (www.eudet.org) and distributed between two participating labs, meet the thermal requirements. For the scintillator-based hadronic calorimeter, a cooling system has been designed for use in beam test experiments using the mechanical infrastructure constructed within the EUDET project.

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Executive summary

Innovative electromagnetic and hadronic calorimeters such as those designed for ILD at the International Liner Collider (ILC), require the development and the demonstration of the feasibility of a specific cooling system for low power calorimeter readout electronics. A good understanding of the features of the structures to dissipate the thermal power generated by electronics (77M channels and 4,6 kW for a silicon tungsten calorimeter (SiW ECAL)) is necessary in order to properly specify the corresponding requirements for the heat exchangers, the cooling network, the cooling plant and the large leak less water system. In this report thermal studies are presented that lead to the specifications of a cooling system for these large-scale calorimeters.

Thermal properties of tungsten and carbon fibre based absorber elements drive the cooling concepts of highly granular silicon-based electromagnetic calorimeters. The cooling of the front-end electronics for a hadron calorimeter prototype is equally important. For the mechanical infrastructure for scintillator-based hadron calorimeters, constructed within the EUDET project, a cooling system prototype has been designed for use in test beam experiments of readout elements. This will provide important insights into the thermal coupling of electronics to the cooling systems and the local pressure and water flow conditions.

The design of a water-cooling system for absorber structures of highly granular calorimeters has been fully developed and documented as expected. The next step to come up corresponding to the Deliverable 14.8 will be the construction and test of a real size large leak less water-cooling loop to confront thermal simulations of the performances of this thermal modelling of large carbon fibre structures with measurements.

1.   INTRODUCTION

The development of a cooling system for low power calorimeter readout electronics is based on a design close to that of the ILD calorimeters at the ILC, see Figure 1:

    - A silicon tungsten electromagnetic calorimeter featuring Carbon Fibre Reinforced Polymer (CFRP)/Tungsten structures and silicon detectors, called briefly SiW ECAL[1];

    - An analogue hadronic calorimeter featuring stainless steel absorber stack structures and scintillator tiles read out by silicon photomultipliers called briefly AHCAL.

Each detector structure to be thermalized is composed of 1 barrel and 2 end caps.
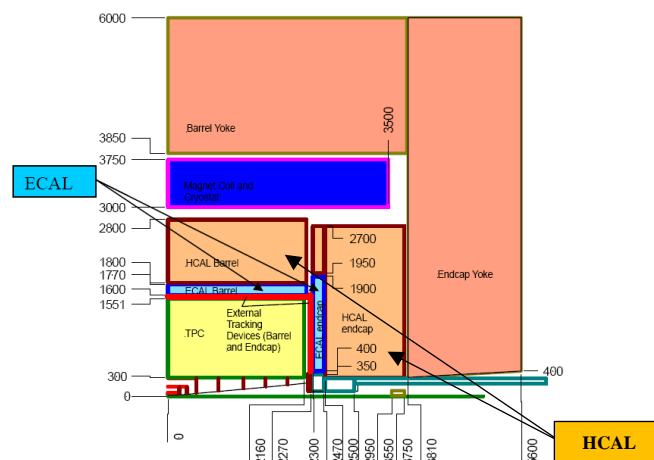

Figure 1: Cross section through one quarter of the ILD Detector with Electromagnetic and Hadronic calorimeters.

Maximum compactness for the structure of high-granularity calorimeters becomes possible by the development of microelectronics embedded in the detector volume. This approach faces however one particular technical challenge: the design of the cooling system for sensors in a confined environment. It is the purpose of the CALICE collaboration [2] to study and develop such high-granularity calorimeter prototypes.

The detector efficiency is strongly affected by the values and fluctuations of the temperature of electronics components located either in tungsten and carbon fibre structures for electromagnetic calorimeters or in a steel absorber stack for hadronic calorimeters. However, to cool down homogeneously the detector, several constraints exist, leading to an important impact, not only on size and geometry, but also on the technology to adopt. Among these constraints are the heat power to dissipate, the wide surfaces available for exchange, the gradient accepted in detector elements (20°C for a SiW ECAL slab for an operating range between $20°C < T < 40°C$ maximum), to maintain the detector temperature close to the ambient temperature, the precision of cooling regulation (tolerance +/- 2.5°C), the hydraulic network and the number of circuits, the 'hostile' environment (high radiation levels, magnetism…), the mechanical constraints due to electronic design (geometry of DIF card which is part of the last ASU of the slab), the available space.

The cooling system is required to operate at temperatures between 20°C and 40 °C. In order to meet these requirements, a leak less water-cooling system has been chosen. In case of leaks in the cooling circuit, external air ($P_{ATMOSPHERIC}$) enters into the circuit preventing thus the cooling water to spill out of the cooling system. Therefore, the detector electronics will not be exposed to water spray. In summary, the general characteristics of leak less cooling system for both ECAL and HCAL calorimeters will be the cooling of the front–end to remove the power, low water speed, a low temperature gradient and a very limited risk of water leakage.

2. ECAL: SPECIFICATION OF LOCAL COOLING SYSTEM

2.1. COOLING SYSTEM FOR LARGE CARBON FIBRE STRUCTURES

The left part of Figure 2, shows a schematic 3D view of a SiW ECAL barrel module as designed for the ILD Detector. The alveolar structure has a trapezoidal shape, with 5 columns of alveoli. It has the following sampling at normal incidence: 22.8 radiation lengths (X_0) are distributed over 20 layers of $0.6X_0$ (2.1 mm) thick tungsten absorber plates, followed by 9 layers of 1.2 X_0 (4.2 mm) thick plates, leading to an overall thickness of 186.5 mm. The alveolar structure is fabricated by moulding of pre-impregnated carbon fibre and epoxy onto tungsten sheets, leaving free spaces between two layers to insert 15 detection units, called detector slabs.

In the current baseline of the ILD detector the SiW ECAL barrel is made of 8 staves, each stave of 5 identical modules. To this adds two end caps comprising in total 12 modules that are somewhat larger than the barrel modules. The ILD Detector will hence need ultimately a cooling network for at least 40+24=64 modules. With 5 alveoli columns per barrel module (and 3 per end cap module), each containing 15 alveoli, 4080 slabs are to be cooled down for the SiW-ECAL.

One detector slab has a width of about 180 mm, a length of up to about 1760 mm and a height of less than 10 mm. It consists of two active readout layers mounted on each side of an H-shaped support structure. This support structure includes also the tungsten absorber.

An exploded view of a readout layer on one side of a slab and the support structure is shown in the right part of Figure 2. As relevant for this report the layer comprises the readout ASICs SKIROC [3]

and the DetectorInterFace (DIF) card. Both are the main heat sources of the detector. An important element of the cooling system is a long copper sheet, see e.g Sec. 2.4.
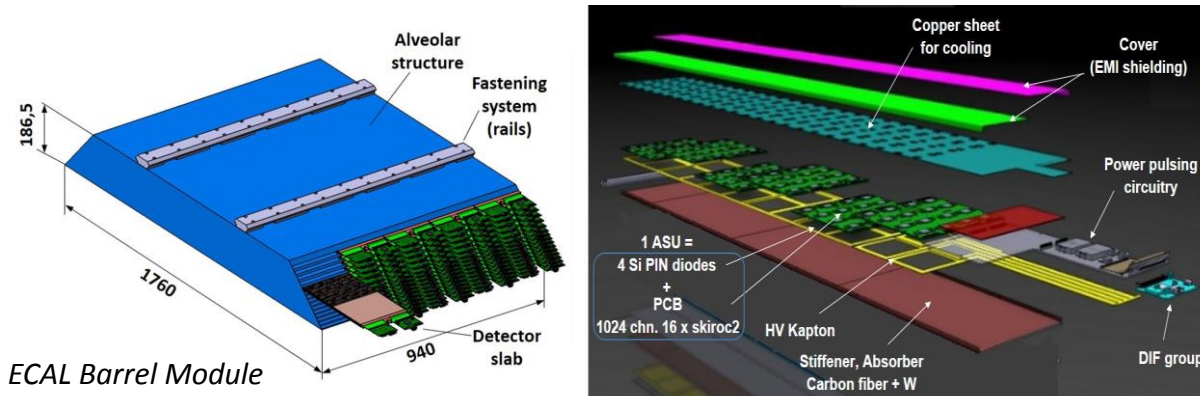

Figure 2: (Left) Schematic view of an ECAL barrel alveolar module with one detector slab extracted. (Right) Exploded view of half a long slab with 6 ASU – (An assembly line for long slabs with 8 connected ASU is AIDA-2020 deliverable D14.3)

In order to achieve a good heat transfer between the electronics and the cooling circuit, the following has to be taken into account. First, a solid conduction between electronics and cooling plate is preferred over natural convection, which is not directly available here due to the alveoli type structure. Secondly, the length of the cooling screen should be as long as possible, to increase the available exchange surface.

2.2. PRELIMINARY THERMAL CONSIDERATIONS

This current baseline design of ILD SiW ECAL [4] with highly integrated layers designed for minimal thickness and cooling capacity gives the global value of thermal power to be dissipated. The system includes 40 identical barrel modules and 24 end cap modules resulting in 8160 layers to be connected to heat exchangers All slabs together contain ~75k Active Sensor Unit (ASU) supporting 300k Wafer and PCB carrying 1,2M SKIROC ASICs. The SKIROC ASIC dissipates 25 µW/channel for a total of 77M channels. Note at this point that the SKIROC ASICs can be power pulsed with a duty cycle of 1%. The power pulsing is essential for the power management of a full detector.

Taking into account power pulsing the total heat dissipated by 256 ASICs and two DIF cards amounts to ~1W per slab, leading to around 4.6 kW for the whole SiW ECAL. This heat must not be released to the surrounding air nor being conducted to the detector itself, where the temperature has to be kept in the vicinity of 25°C to 30°C. Hence, one water circuit per column of each module has been foreseen to remove the heat from the front end electronics.

2.3. THERMAL ANALYSIS OF SLABS AND MODULES

The thermal analysis of heat conduction of one complete slab and one module takes into account the influence of the heat dissipation of the DIF on the current design of cooling system. The heat dissipation of the DIF is mainly provoked by a FPGA mounted onto it. The dissipated power by the FPGA has been varied between 300 mW and 2 W in order to provide optimised proposals for

the cooling system, especially for the contact areas. The numerical simulations allow for demonstrating the feasibility of a light, fast connected and performing system, even in difficult conditions of conductivity. The copper drain is adapted to the DIF card to be in contact with FPGA. With the nominal FPGA power of 300mW, the power to be dissipated per slab in the barrel is 1 W. The performances of the local cooling system have been simulated for both barrel and end-cap configuration covering the power range of the FPGA and meet thermal requirements.
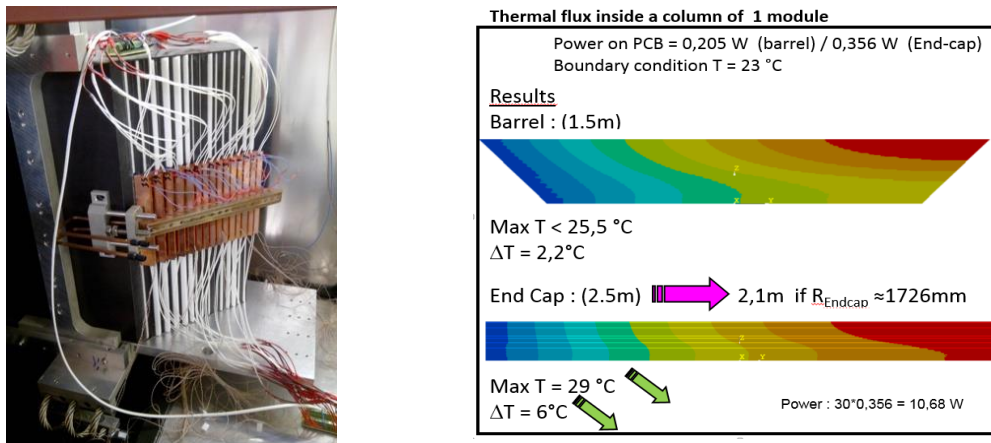

Figure 3 (Left): EUDET module equipped for thermal tests with 15 dummy slabs directly connected to the heat exchanger (Right) Thermal analysis of module: the passive cooling is satisfactory with maximum variation of Temperature of 2,2°C for Barrel modules and 6°C for the longest End-Cap modules.

It is of primary importance to make the simulations closest to the reality. Thermal tests have been performed to validate that the thermal gradient assumed in the simulations agrees with the one in 'real' slabs and modules. For these thermal tests the so-called *EUDET Module* was used. This technological prototype for a SiW ECAL module (funded in part by the EUDET project) corresponds in size to an ILD SiW ECAL barrel module except for the number of columns (3/5); it is integrating the real components with tungsten and pre-impregnated carbon fibre. The central column of the EUDET Module is equipped with 15 slabs, which mimic the final slabs. Further tests have been performed to determine the limit of power pulsing for such a cooling system. Thermal power values applied on slabs from 15 W to 30 W show the limit of heat load that can be produced by evolution of electronics consumption. These cooling tests validate a correlation with simulations (transfer coefficients, contacts, conductivities, design of copper foils, geometries), and check the thermal dissipation behavior of the system. Comprehensive studies on heat dissipation for SiW-ECAL modules have been performed.

2.4. CU SHIELDING & THERMAL DRAIN

The power dissipation is distributed along a detector slab concentrate at the location the readout ASICS. The goal is to transfer the residual heat as uniformly as possible from the ASU chain (~1500 mm length, 180 mm wide) up to a cold block located at one slab end. The challenge is the thermal drain thickness, which should be close to the thickness obtained by simulations (0.5 mm). The second aspect is to optimize the thermal contact between the copper and each ASIC, even if the ASIC and its bonded wires are protected inside the PCB by an isolating resin. One proposed solution is to use a thermal conductive agent.

Considering the power dissipation of the DIF board, a fastening assembly to the copper drain has been developed. To improve the heat transfer along the copper drain, in particular the local contact

between ASICs and the copper shield, several thermal conductive agents have been tested with specialized companies. The most appropriate solution for now is conductive grease.

2.5. DESIGN OF LOCAL HEAT EXCHANGERS

The cooling system for the EUDET Module is foreseen to be most representative for the final heat dissipation management of the whole detector.
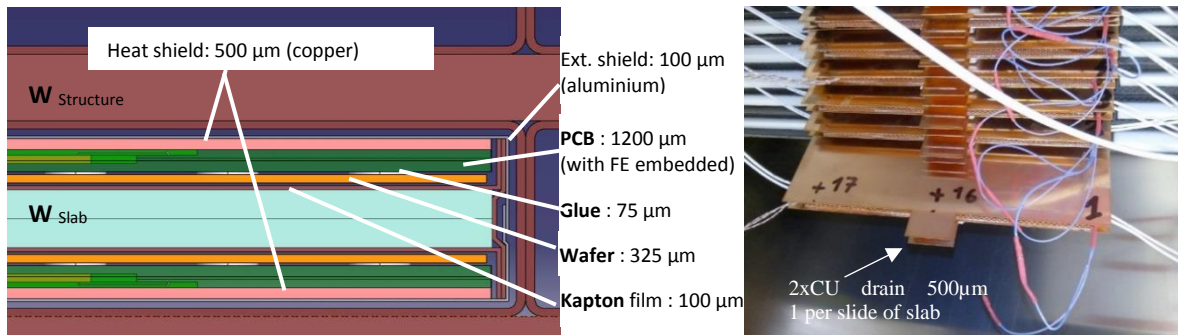

Figure 4: Design of connection of heat exchangers - (Left) Schematic view of a slab with 2 copper drains (Right) Copper drain extremities for one column as tested on EUDET module.

Figure 4 illustrates the current design of the general local cooling system developed for tests, including terminations going to each slab. The cooling technology is active, using fluid circulation. This solution allows fulfilling heat dissipation and mechanical requirements. This solution allows fluid circulation through a network of contact areas / connector fixed on each of 2 x 500µm thick layers of copper of one slab. Free space has been found under the fastening system of the EUDET Module to let a passage for pipes and cables under rails, toward the exterior of the detector. Cold copper blocks, brazed on pipes, inserted between the 2 copper sheets of the slab in the free space between the 2 DIF cards assure the connection of pipes to each slab. There is one cooling water exchanger in front of each column.

The tested prototype of the heat exchanger fits the dimensions of the EUDET Module. The design and construction of the heat exchanger presents a number of engineering challenges. Water is circulating in the whole copper bloc which offers the maximum surface for heat exchange with a minimum thermal resistance with each copper drain. A particular innovative effort is proposed to reduce the dead area whereby the whole column of 15 slabs (30 layers) is connected to the cooling network (see Figure 5). This technology solution supports greatly the reduction of passive materials and dead zones as well as the compactness of this instrument.

Figure 5: (Left) Design of connection of heat exchangers with one copper drain extremity (Middle) heat exchanger for 15x2 connections (Right) location of cooling system on one SiW-ECAL barrel module.

3.   AHCAL: SPECIFICATION OF LOCAL COOLING SYSTEM

The space constraints are less stringent for the AHCAL than for the SiW ECAL and the channel and power density is lower. Moreover the steel absorber structure provides good thermal conduction. Taking into account the power pulsed electronics no dedicated cooling device (as e.g. a copper drain) is needed inside the AHCAL detector volume.

The cooling system for the steel absorber stack constructed within the EUDET project will provide an important infrastructure for realistic beam tests of readout elements as well as insights into the thermal behaviour and the local pressure and water flow conditions for a cooling system that is scalable to the hadronic calorimeter of a collider detector.

3.1.   COOLING SYSTEM FOR HCAL STRUCTURES

The design of a sector of the AHCAL barrel as foreseen for ILD is shown in Figure 6 (left). It consists of 1.9cm thick steel plates, interleaved with 48 active layers of 6.5mm thickness (including two 0.5mm thick layers of steel cassette), 2160 mm length and up to 1080 mm width. The active layers are constructed from HCAL Base Units (HBUs), arranged in 2 to 3 slabs of 6 HBUs length. A typical HBU has a size of 36×36 cm^2, is equipped with 144 scintillator tiles, each read out by a Silicon Photomultiplier (SiPM), and 4 readout ASICs [5]. At the layer edges smaller HBUs are foreseen to accommodate the varying layer width. Each active layer is served by one set of interface boards: the Detector InterFace (DIF) for data acquisition, the POWER board to provide the necessary voltages, and the CALIB board to steer the LED calibration system. These interface boards need active cooling. The power consumption of the SiPMs and of the readout ASICs in the active layers, which is reduced by power pulsing, is only 40 µW per channel (15 µW for the SiPM and 25 µW for the electronics), which is small enough to be removed through the steel absorber structure (see Figure 7).
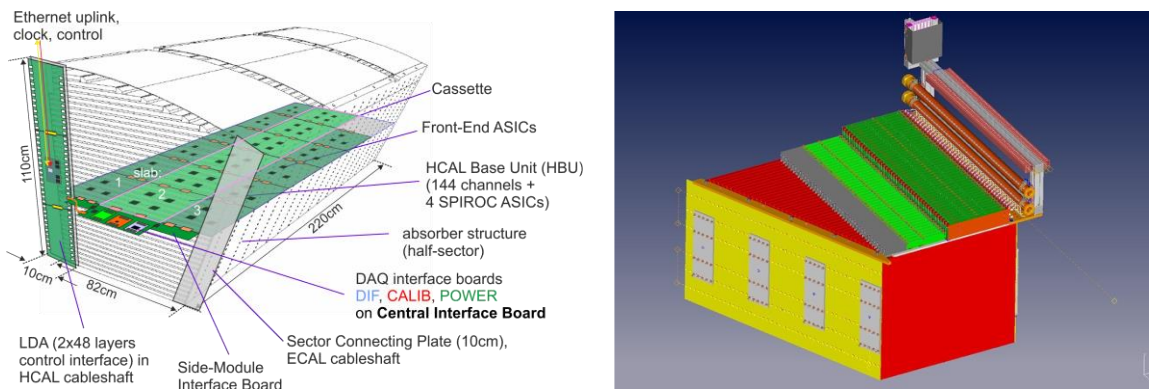

Figure 6: (Left) Sketch of one sector of the AHCAL barrel as planned for ILD sector (1/16 in phi, 1/2 in z direction of the complete barrel). (Right) Design of the fully equipped AHCAL stack for beam tests.

Within the EUDET project, a steel absorber structure has been built that corresponds in size to an AHCAL barrel sector except for the length, which is only 2 instead of 6 HBUs. This structure is used for beam tests of the AHCAL prototype. It is planned to fully equip this stack with active layers within the next 2-3 years (Figure 6 right), and then test the prototype in hadron beams. For these beam tests, a cooling system for the interface boards is necessary to test the readout elements in realistic conditions, close to the conditions in a collider detector. The design of the cooling system is similar to the local cooling system for the ILD AHCAL and will provide important insights into the thermal coupling of electronics to the cooling systems and the local pressure and water flow conditions. These

findings are relevant for any highly granular low-power scintillator-SiPM hadron calorimeter in a collider detector.
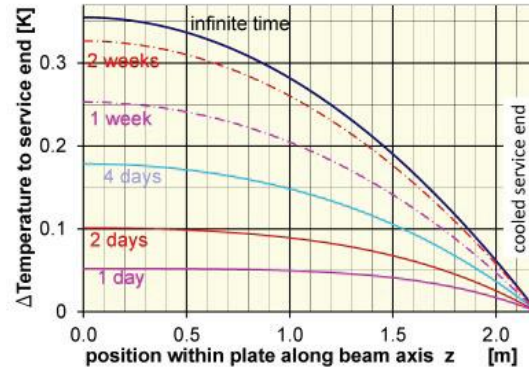

Figure 7: Simulation of the temperature development within one half of the ILD AHCAL barrel. [6]

3.2. MODIFICATIONS OF THE EXISTING ABSORBER STACK

Figure 8: partly equipped EUDET steel absorber stack, with copper cooling elements for the front end electronics visible on top of the setup.

The EUDET steel absorber stack has been partly equipped with active layers of several different sizes and used in beam tests in 2014 and 2015. For this purpose, a first version of a cooling system has been designed and implemented (see Figure 8). This system has been successfully operated in several beam tests and showed sufficient cooling for layers of up to 2×2 HBUs, operated without power pulsing. The active layers were equipped with the previous generation of the interface boards, which differ in geometry and power consumption from the current generation. Therefore, the local cooling elements, which consisted of copper plates with cooling pipes attached via small copper blocks, need to be re-designed. In addition, the necessary cooling power and flow rates are not representative of a full AHCAL barrel sector because only 15 active layers were equipped.

As a first step towards equipping the complete EUDET steel stack with active layers of 2×2 HBUs, the stack itself has to be slightly modified in order to fit the current steel cassettes (which have a symmetric design to fit left and right side slabs while the final AHCAL barrel cassettes will have a dedicated design). These modifications have been implemented in the mechanical design (Figure 6 right). The re-design of the local cooling elements will be realised next.

3.3. DESIGN OF LOCAL THERMAL COUPLING

The geometry of the local cooling element and the necessary cooling power depends on the geometry of the interface boards, on the duty cycle of the detector and to a smaller extent also on the number of HBUs per layer. The size and location of the power dissipation of the current interface boards has been measured with 1×6 HBUs connected without power pulsing. The results have been used to estimate the numbers for the beam test and the ILC case. For the beam test case the scenario without power pulsing, which leads to the highest power consumption, is shown, while for the ILC case realistic power pulsing with ~1% duty cycle is assumed. As Figure 9 shows, the total numbers for the two cases are very similar, with some differences in the locations. In order to ease the design and production of the cooling plates, the heights of the components with the highest power consumption will be adjusted by small copper spacers that are attached to the components with thermally conductive glue (see Figure 10 left). These spacers will then make the thermal contact with the local cooling plates that are connected to the water-cooling system (Figure 10 right).
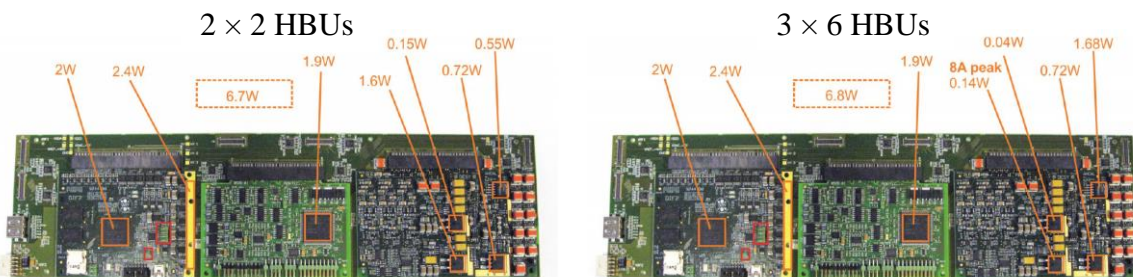

Figure 9: size and location of the power dissipation on the AHCAL interface boards. The number in the box is the power consumption of the readout ASICs embedded in the active layer. Left: for the testbeam case of a layer of 2 x 2 HBUs without power pulsing. Right: for the ILC case of a layer of 3 x 6 HBUs with power pulsing with ILC duty cycle.
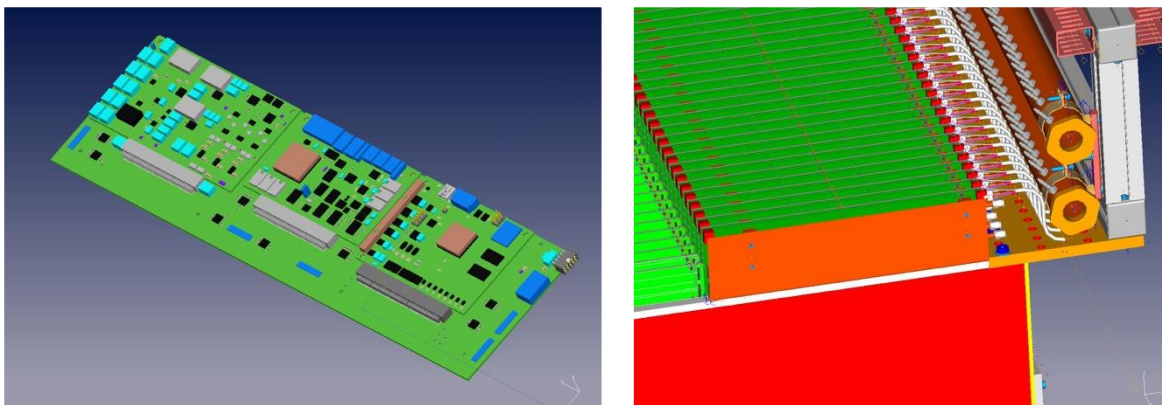

Figure 10: (Left) mechanical design of new AHCAL interface boards with copper spacers on the local hot spots. (Right) detail of local AHCAL cooling elements.

4. CONCLUSION

This note concludes, to a large extent, the design phase of a highly integrated and efficient cooling for calorimeters and constitutes therefore a milestone within the WP14 AIDA2020 program. Reliable estimation of cooling needs can be obtained by the flexible thermal model of tungsten / carbon

fibre and for hadron calorimeters. The report highlights the technological challenge to construct such compact and highly efficient cooling systems. This concerns in particular the integration of the heat exchanger onto the slabs front end. All elements of the cooling system represent technology reaching beyond nowadays state-of-the art.

The design allows for the validation of important engineering issues like heat dissipation of the front end electronics embedded into the calorimeter layers, mainly by passive cooling. In Parallel to this study, the construction of the large leak-less cooling loop will be implemented, corresponding to the Deliverable 14.8 [month 36].

Again, the progress in this context will benefit from the collaboration between CALICE and other calorimeter collaborations (ATLAS HGTD, CMS HGCAL).

In conclusion the integrated sub-atmospheric water-cooling system will constitute a significant step towards the realization of a SiW electromagnetic calorimeter and a scintillator based hadronic calorimeter for an ILC detector.

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ANNEX: GLOSSARY

Acronym	Definition
ASU	Active Sensor Unit: A thin PCB that carries 16 ASIC on one side and four silicon wafers the on the other side.
DIF	Detector InterFace Board between the SMB and the DAQ
HBU	HCAL Base Unit: a PCB that carries 4 readout ASICs on one side and 144 scintillator tiles with SiPMs on the other side
SiPM	Silicon Photomultiplier: single photon sensitive silicon detector built from an array of avalanche photodiode pixels
Slab	A cassette featuring one (short) or several (long) ASU connected to the SMB and the DIF, a HV Kapton housed in a carbon fibre cradle.