Conductive Cooling of SDD and SSD Front-End Chips for ALICE

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(For the ALICE colaboration)

Abstract

We present analysis, technology developments and test results of the heat drain system of the SDD and SSD front-end electronics for the ALICE Inner Tracker System (ITS). Application of super thermoconductive carbon fibre thin plates provides a practical solution for the development of miniature motherboards for the FEE chips situated inside the sensitive ITS volume. Unidirectional carbon fibre motherboards of 160 -300 micron thickness ensure the mounting of the FEE chips and an efficient heat sink to the cooling arteries. Thermal conductivity up to 1.3 times better than copper is achieved while preserving a negligible multiple scattering contribution by the material (less than 0.15 percent of X/Xo).

I. Introduction

The state-of-the art Front-end electronics (FEE) for the coordinate-sensitive Si detectors of the ALICE Inner Tracking System(ITS)[1] at the LHC is situated inside the sensitive region. Therefore the heat drain of about 7kW of power is to be done under the stringent requirement of minimisation of any materials placed in this area containing 6 layers of coordinate-sensitive detectors. A maximum of 0.3% of X/Xo per layer is allowed for all services including detectors, mechanics support, cables, cooling and electronics units. Analysis of various possible cooling schemes was performed earlier as a starting point of the general ITS services design [2],[3]. Solution of the local heat drain problem from the FEE to the cooling ducts was named as the key point in the thermal performance of the whole ALICE ITS. The application of super thermoconductive carbon fibre plastics was proposed in order to get the most efficient integration of the extremely lightweight FEE motherboards and local heat sink units. The implementation of these ideas in a single unit called "the heat bridge" required the development of a new technology of thin unidirectional carbon fibre plates manufacturing. This technology was successfully developed and is improved further at present. We describe below the results of the development and tests of the heat bridges for SDD and SSD front-end hybrid electronics.

II. Carbon fibre motherboards

Novel carbon fibre compound motherboards of efficient thermal conductivity (heat bridges) were proposed for the ITS FEE chips after the analysis of the existing materials, see Table1.

Table 1: Parameters of different materials for thermoconductive motherboards

Material	Young's modulus, E,[GPa]	Thermal Conductivity, [W/mK]	Rad. Length Xo,[cm]
Copper	125	380	1.43
AlN		150	9
CF comp.	450	300-500	18

The application of super thermoconductive fibre Thornell KX1100 for the manufacturing of very thin mechanically stable plates with good thermal properties used both for the FEE support and for efficient heat drain to the cooling arteries was found to be the optimal solution to the problem. The conductivity along the fibre is about 1100W/mK, while the mechanical strength is ensured at the level of steel (E=450GPa). Carbon fibers (CF) have a diameter of about 80 microns and are packed in unidirectional flat sheets (prepregs) impregnated with some compound material (about 35% for the last one). The thermal expansion coefficient of the carbon fibre based compounds is very low (close to zero), resulting in mechanically stable devices. Other properties of CF compounds measured in the present application are: density $\rho = 2.2\ g/cm^3$, electric conductivity 5 Ohm/m, thermal conductivity$\lambda = 500W/mK$ along the fibre,$\lambda = 40W/mK$ perpendicular to the fibre.

The technological problems of making flat thin carbon fibre composite plates (150-330 microns thickness, dimensions up to $10 \cdot 10cm^2$) were studied and successfully overcome[4], providing various options for the manufacturing of heat drain devices in line with the technical requirements of the Alice experiment. The programme included the design and optimization of the unidirectional fibre plates, ANSYS simulations and test analysis and the optimisation of the technology for the baking of plates with the surface quality and flatness, suitable for further chip mounting and bonding of microcables.

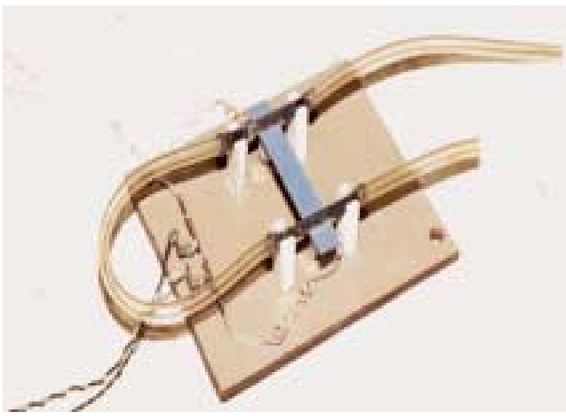

Figure 1: Foto of the SSD heat bridge prepared for studying the temperature distribution along the bridge. Thickness 320 microns, length 70mm. Thermal conductivity 300W/mK. The heat bridge is mounted with two triangular carbon fiber cooling arteries. The heater (representing dummy chips) is glued below the bridge.

Various types of surface coatings were also developed and tested: pure carbon fibre surfaces and insulating Al_20_3 ceramic coatings.

The bridges are used as hybrid motherboards for the FEE and ensure mounting of the chips, bonding the microcables, fixation of the assembled modules to the cooling artery. Miniature heat transfer clips for two types of bridges are also foreseen. Each bridge is formed by unidirectional layers of super thermoconductive carbon fibre. The minimum number of CF layers that could be applied is 2, resulting in a minimum thickness of 150 μm for the board.

The flat carbon unidirectional fibre plates were manufactured ranging in thickness from 150 to 330μm microns in order to get data on the new material conductivity and other parameters.

A summary of the different configurations of heat bridges produced is presented in Table . Different numbers of CF layers were used in the manufacturing of these test samples. Also some different orientations of the carbon fibres were tested along with various tubes and tube-to-bridge contacts.

The experimental setup used for the multichannel temperature map cooling studies is described in [4].

In Fig. 1 the CF heat bridge (coated with Al_20_3) connected to two triangular shape cooling tubes, in preparation for heat drain studies, is shown. The front-end electronics was simulated by minuature dummy chips producing up to 2W of power. Five uniformly spaced temperatures sensors along the 70mm heat bridges were used in case a single-end cooling. We used only one half of the carbon fibre bridge in our data sampling in the case of one central tube or two cooling tubes spaced by 45mm due to the symmetry. Tests were compared with a copper bridge of the same geometry (Length =70mm, width =10.5mm).

Table 2: Types of different heat bridges and cooling arteries used in the 1st studies (see Fig.2).

Heat Bridge	Material Thickness,mm	CF layers: Longitudinal(L)+Perpendicular(P)	Comments
1	Copper, 0.47		one sided cooling, soldered contact
2	CF, 0.56	4L-3P	one sided cooling
3	CF, 0.32	2L-4P	central tube location,rectangular
4	CF, 0,32	2L-4P	central tube location, circular
5	CF, 0.32	2L-4P	central tube location
6	CF, 0.32	4L-3P	2 side circular tubes
7	CF, 0.56	4L-3P	2 side triangular tubes
8	CF, 0.56	4L-3P	2 side triangular tubes
9	CF, 0.37	4L	2 side triangular tubes

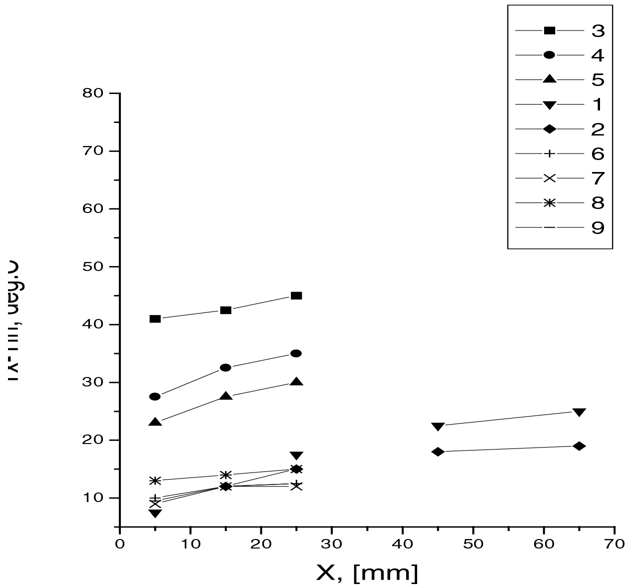

Figure 2: Temperature distributions along the tested heat bridges obtained under 2 W heat load (except samples No.1 and 2 tested under 1W load). Copper bridge No.1 (see Table 2) has an ideal (soldered) contact with the cooling tube fixed to one side end of the bridge.

A summary of temperature distributions measured along the length of the different heat bridges is shown in Fig.2. One can see that the performance of the carbon fibre bridges is better than that of the copper bridge (e.g. dataset (No.9) Fig.2 for a completely unidirectional orientation of fibres in the heat bridge).

1. The mean value of thermoconductivity for samples No. 2,6,7,8,9 was measured to be about 300-310 W/mK (i.e. about 0.78-0.8 of the value for Cu (λ=380W/mK).

2. The mean value of thermoconductivity for the samples No. 3,4,5 (v-shaped, variable cross- section) is about 470-505 W/mK (i.e. about 1.2-1.3 of the Cu).

3. The value of contact temperature resistance for carbon fibre bridges connected to the cooling artery could be about 4.4-5.8 deg.C for 1 W heating power.

4. Maximum temperature gradients of 0.6-0.7 deg.C could be obtained along 70 mm carbon fibre bridge with two cooling channels.

These data on the properties of different CF compounds were used for the ANSYS simulations of the temperature maps and for the further SDD and SSD cooling scheme and technology optimization.

III. Surface quality tests

The carbon fibre heat bridge surface quality tests were done for three batches of CF plates consisting of 12,19 and 19 samples. Plates of about 170 microns thickness had the dimensions of 72mm*6.5mm and were designed as SSD heat bridges. Measurements of carbon fibre heat bridges surface quality was done for 3 test batches. The roughness of the surface was measured and found to be better than 10 microns for pure carbon fibre composite bridges. This parameter was found to be satisfactory and enabled to approve this technology for application in minuature motherboards manufacturing for ALICE SDD and SSD FEE chips.

IV. ANSYS simulations

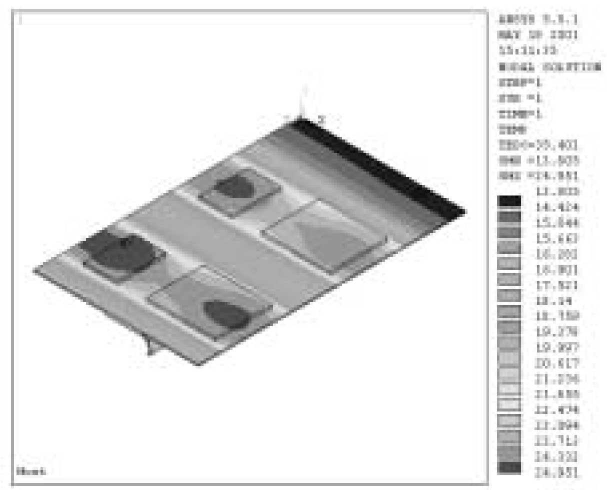

Figure 3: ANSYS simulations of the carbon fibre SDD heat bridge temperature map for the undirectional fibre orientation. Position of the thermoconductive clip is optimised

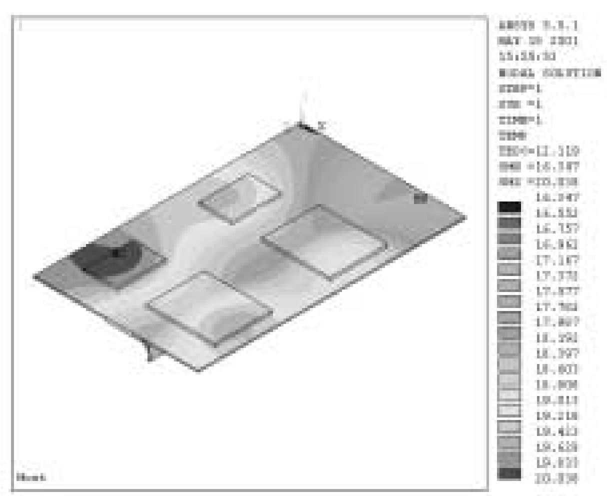

Figure 4: ANSYS simulations of the carbon fibre SDD heat bridge temperature map for the uniform conductivity 180W/(mK)

Some examples of simulations are represented in Figures 3 and 4 (only one half of the hybrid is shown due to the heat dissipation symmetry). The geometry of the SDD heat bridge used was in line with the requirements to place FFE 4 Pascal and 4 Ambra SDD chips to serve one half of SDD (see Figure5). Electronics chips were placed in groups of 4 + 4 chips on one side of the heat bridge. The total power load for one bridge was assumed to be 1.775 W, the heat release is proportional to the chip's area (8 chips 8x8 mm and 8 chips 5x5 mm were used). The following conductivity values were used in calculations for carbon fibre composite:

for the panel in longitudinal direction- 300 W/(mK), in transversal direction- 0.7 W/(m K);

for the clip in longitudinal direction - 150 W/(mK), in transverse direction - 40.0 W/(m K).

(Longitudinal here means the direction of heat drain to the cooling artery, i.e. perpendicular to the cooling tube).

Cooling by water and by neutral ozon-safe freon coming at 13.0^oC as a coolant liquid were studied. The cooling artery is a tube diameter 2mm made of stainless steel. The influence of natural convection was neglected. The nominal value of the heat transfer coefficient from liquid to the tube wall was assumed to be equal 3000 $W/(m^2 \cdot K)$. Calculations were done using ANSYS code. Results of these calculations are presented in Figures 3 and4. Tests of the unidirectional fibre heat bridge (Fig. 3) show that an operational temperature at the surface of the FEE chip at the level of 25^oC is obtained. This value is close to the requirements for the SDD FEE.

A further decrease of the operational temperature down to 20^oC can be obtained by adding additional conductivity to the transverse direction, see Fig.4.

The following conclusions can be drawn from ANSYS simulations:

1. The maximum temperature drop between the coolant and chips of 3-4 layer ITS is about 12^oC using the optimal position of the cooling tube and using the unidirectional fibre orientation.

2. The value of the heat transfer coefficient from coolant to the tube's wall is an essential factor for the temperature level (this factor depends on the liquid flow regime).

3. A noticeable decrease of temperature gradients for the SDD heat bridge is possible in using composites with higher transversal heat conductivity.

V. SDDheat bridges

A side view of the heat bridge for the drift detector front-end electronics (Ambra and Pascal chips) is shown in Figure 5. It consists of 2 main elements : (i) the cooling panel (ii) the heat conducting clip on the panel.

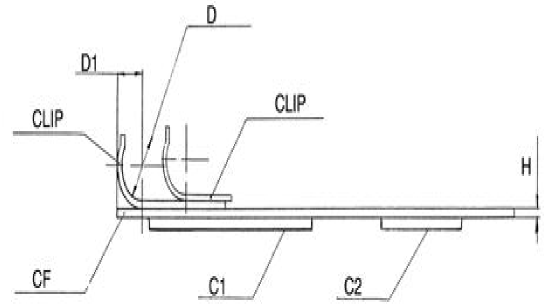

Figure 5: SDD CF motherboard with chips, Side view: CF -carbon fibre motherboard; C1,C2 - FEE SDD chips (Ambra and Pascal); D1=2mm,D=1,9mm;H=240microns. Length of the CF SDD board =65mm, width=20mm

The cooling panel is a flat plate 20x65 mm, 0.18 mm thick. It is made of heat-conducting C.F. THORNEL and of 1 additional layer of ordinary carbon fiber. The panel's area is large enough to place the chips of the primary electronics. The measured value of the heat conductivity in the direction of the fibre is λ=400 W/mK. The panel's clip is also made of THORNEL. The orientation of the layers is -+ 45^o. The heat conductivity is λ= 150 W/mK. The panel's clip plays the following role in this structure :

(i) fixation of the heat bridge on the cooling artery;

(ii) it is an element of the heat transfer from the cooling panel to the cooling artery;

(iii) it is an element of stiffness for the heat bridge .

Test were performed for the SDD carbon fiber composite hybrid with dummy electronics with a heat load of 2 W, temperature gradients reached 8 degrees (this corresponds to approximately 22 degree operational temperature at the surface of the chip when using a cooling liquid at 14 ^{o}C.).

VI. SSD heat bridges

There should be 6 chips of the front-end electronics per one SSD detector side with an area of 6*8mm^2 and 300 micron thickness. The new SSD HAL25 chips are expected to produce about 0.3 W power per SSD hybrid.

The pecularity of the double sided silicon-strip detectors (ALICE SSD) is in the orientation of the coordinate-sensitive elements (strips) almost parallel the ITS axis . Therefore the readout electronics is situated perpendicular to the latter. The problem of the heat drain from this electronics was suggested to be solved by conductive cooling using the available highly thermoconductive materials draining heat to the longitudinal cooling arteries.

The most recent option for the heat bridge has dimensions (73x6.5x0.16mm^3). It has a unidirectional orientation of 2 layers of THORNELL providing efficient heat transfer supported by an additional thin (20μm) carbon fiber layer with a transverse orientation.

The prototype SSD heat bridges were sucsessfully tested for mounting of chips and microcable bonding technology (see Fig.6).

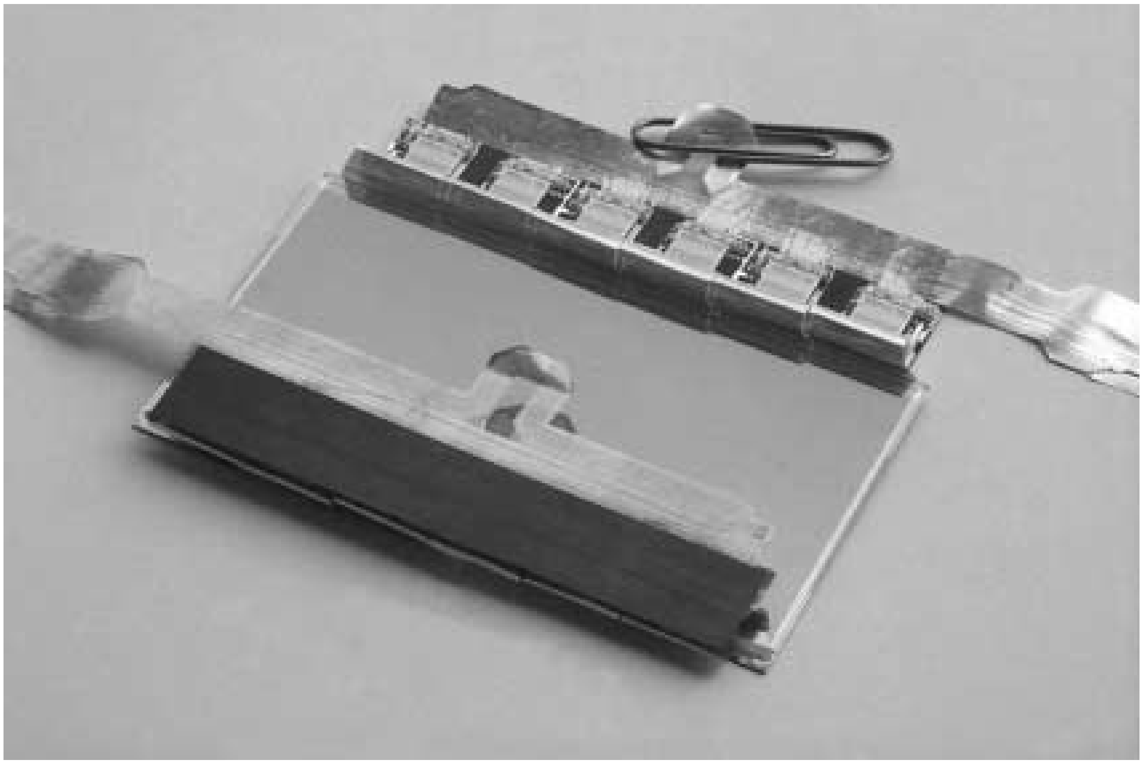

Figure 6: Foto of the SDD detector for ALICE ITS equipped with real CF hybrids with chips and microcables mounted

VII. Conclusions

A novel technology for the design and manufacturing of carbon fibre composite materials with required thermal and mechanical characteristics is developed and tested for application as miniature motherborads for microelectronics.

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