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FINAL REPORT ON THE
SUMMER STUDENT PROGRAM

Development and testing of the element of the cooling system for the readout the electronics of the Silicon Tracking System of BM@N experiment

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Abstract

The cooling system is an essential part of the BM@N Silicon Tracking System. To select the optimal materials and achieve the minimum temperature drop between the readout chips and the cooling liquid, calculations were performed using ANSYS[1], as well as experimental measurements were carried out with various materials and adhesives used for heat bridges.

1. Introduction

Modern fundamental science has advanced in understanding the laws of nature that underlie our world. Recreation in laboratory conditions of processes that took place in the Universe at different stages of its evolution with the help of modern heavy ion accelerators is one of the most hot topics in physics research programs of today.

To conduct such studies in the energy range of the highest baryonic densily the NICA accelerator facility (JINR, Dubna, Russia) is currently under construction. After putting the NICA collider into operation scientists will be able to create in the laboratory a state of matter similar to that in which the Universe stayed shortly after the Big Bang – the Quark-Gluon Plasma (QGP)[2].

Baryonic Matter at Nuclotron (BM@N) experiment is one of the main scientific projects at the Nuclotron Based Ion Collider Facility (NICA, Dubna, Russia) with the main goal to investigate the equation of state of dense matter using high energy heavy ions collisions. The Nuclotron at JINR will provide beams of heavy ions with energies up to 6A GeV for isospin symmetric nuclei, and 4.65A GeV for Au nuclei. In central heavy-ion collisions at these energies nuclear densities of about 4 times nuclear matter density can be reached. These conditions are well suited to investigate the equation-of-state (EOS) of dense nuclear matter which plays a central role for the dynamics of supernovae core collapse and for the stability of neutron star[3].

The detector system's task is to restore tracks and thus momenta of charged particles originating from the interactions of heavy-ion beams with nuclear targets.

Modern electronics has a trend for miniaturization to achieve high power and speed of the readout electronics. Unfortunately, this leads to excessive heat production and as a result to complexity of the cooling system. Thus, thermal conductivity of new materials to be used for heat bridges to be verified during the design of modern microelectronic circuits.

The cooling system has to maintain the thermal conditions for the readout electronics in the optimal range. Excessive heat can increase the amount of noise and eventually the results of measurement will be distorted or the system will cease functioning. To ensure normal operation, it is necessary to cool the box with the readout electronics boards with the help of liquid cooling systems to keep the optimal thermal state of the readout electronics within the permissible limits to ensure the best working conditions of electronics.

In this regard, the final goal of this work is to develop the design of a cooling system for the input electronics of the silicon tracking system of the BM@N setup.

2. Details of the Measurements

Front end board (FEB) of the STS module is mounted on a thermal bridge of type L, which is called hereafter a “fin”, and this fin is attached to the heat sink “the radiator”. The material of this fin greatly affects the cooling efficiency since the FEB electronics consumption is very tight. At the moment, several possible materials are considered from which this fin could be made i.e. aluminum, and various up-to-date composite materials made of thermal conductive carbon fiber. To complete these tests a custom designed test stand was built and several samples were tested, with its help.

2.1 Thermal conductivity

Thermal conductivity of the used materials is of paramount interest for the cooling system components choice.

The thermal conductivity of a material l is defined through the equation (1)

$$Q = \lambda A \frac{\Delta T}{d}, \quad (1)$$

where Q is the heat flow through the sample with a cross section A and a length d resulting in a temperature difference ΔT. The thermal resistance of an object $R = \frac{1}{\lambda A} d$ can be introduced through

$$Q = \frac{\Delta T}{R}. \quad (2)$$

Analogous to electrodynamics a total thermal resistance may be expressed for multiple series-connected materials as

$$R = R_{Al} + R_c + R_c \quad (3)$$

By measuring the heat flow and temperatures of a material, for which the dimensions A and d are well known, the thermal resistance and conductivity can be calculated through $R = \frac{\Delta T}{Q}$ and l= A /d R.

Figure 1 demonstrates in the in-plane direction (x and y) the test setup for the thermal conductivity measurements used in the work. The setup consists of two 0.75mm thick and 50mm wide duralumin plates "Д16T" with a length of 100 mm. They were placed next to each other with a gap of 19,5 mm[4]. Plates was connected to a heater (fig. 2), and the other one to a "LAUDA RA 8" chiller [5] operation at temperature of 10^0C.

On each duralumin plate three temperature sensors were placed for readout to obtain the temperature values at different points along the plates. The Q values were calculated through estimation the slope of the graphs. Thus, Q_1 and Q_2 can be calculated and the mean value estimation

$$Q = \frac{Q_1+Q_2}{2} = \lambda_{Al} A \frac{\frac{dT_1}{dx_1}+\frac{dT_2}{dx_2}}{2} \quad (4)$$

To prevent heat losses from the aluminium plates by convection the setup was fully enclosed in a box covered with isolating foam Airex (C70.75) with a thermal conductivity of 0.033 W / m * K.

However, the heat radiation of the sample caused a loss of power, as was indicated by considerable systematic errors in measurement of heat fluxes Q_1 and Q_2 which we observed in compare of theoretical and experimental results. To minimize the impact this effect, a simple radiation screen, consisting of several layers of aluminum foil, was placed a few millimeters above the sample (Fig. 1).

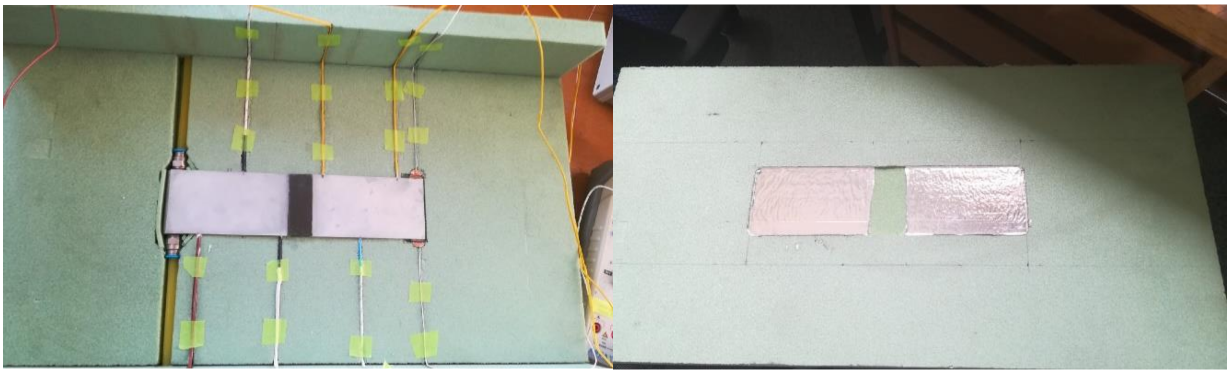


Figure 1. The test setup for the thermal conductivity in the in-plane direction (x and y) (l.h.s.); Al radiation heat deflection foil (r.h.s.)

Figure 2. Heating element used in tests simulating four readout chips

Usage of the modern thermal conductive composite materials for building heat bridges is considered to process a perspective in this field. We produced and tested of few of such.

All carbon fiber samples were 50 mm wide and 20 mm long. They were placed on both aluminum plates with a connection area of 2.5 mm x 50 mm each. The connections of the tested sample to the aluminum plates were carried out using double-sided tape with a thickness of 800 mm.

As described above, the thermal resistance was calculated based on the measurement of the heat flux Q and the temperature drop ΔT, which was calculated using the plot depicted on Fig. 3. The result had to be corrected for the temperature drop over the thermal resistance of the tape used to bond the samples, that is why a correction was estimated with a sample made out of the same aluminum as the aluminum plates of the test stand which the temperature sensors were placed. To verify the reliability of the experimental results, they were contracted to results predicted within the ANSYS software model of a sample under tests (Fig. 4)[1].

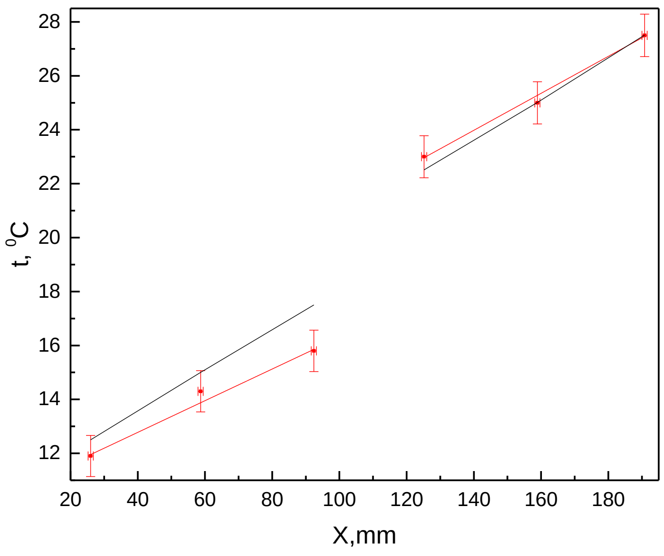


Figure 3. Confrontation of the measured and prediction results for the Al sample used for estimation of systematic errors of the used method

The discrepancy measured and prediction result observed on Fig. 3 could be explained by the fact that the part of the heat flow heats data the isolating material of the test stand. To take this in account the average values of the heat flux through the sample were taken.

By extrapolating T1 (x) and T2 (x) to the edges of the aluminum parts that are in contact with the sample, one can calculate the temperature drop across the sample $\Delta T = T_2(x_2) - T_1(x_1)$.

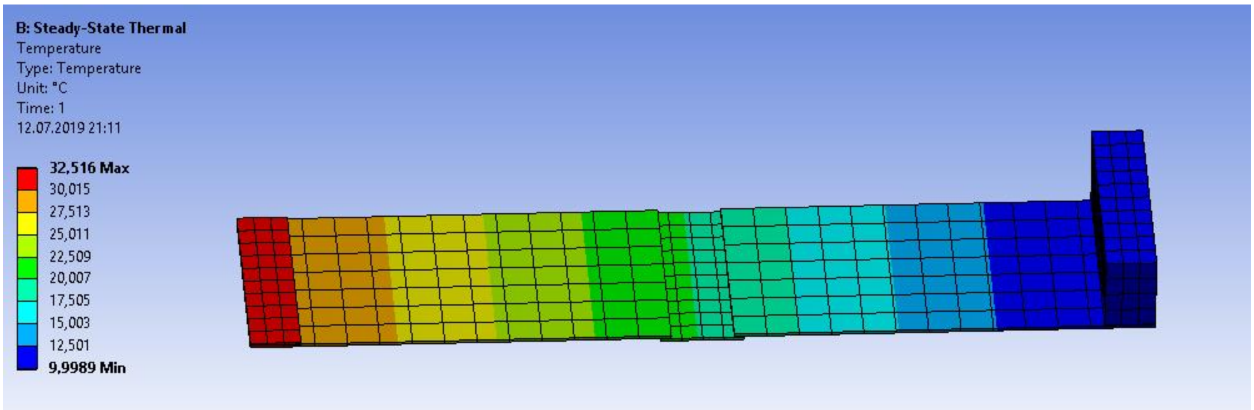


Figure 4. The thermal model of the test setup for the thermal conductivity used for modeling ANSYS of heat conductivity of samples as described in the text

The thermal resistance and thermal conductivity of the double-sided tape were measured at 0.5 and 1 W, resulting in its average value of l 0.071. The data of thermal resistance are summarized in Table 1.

Table 1. Thermal resistance of the tape used for attaching the testing samples

P, W	Rc, K/W
0,5	9,2±1.9
1	9,5±1.95

The concept of measurements is based on measurement of a temperature difference between the “refrigerator” and the “heater”. Due to the high thermal conductivity of Mitsubishi carbon fiber K13D2U[https://www.900gpa.com/en/product/fiber/CF_00D7088B15?u=metric], it has excellent thermal properties in the planar direction which makes it an ideal candidate for heat transfer from silicon sensor modules.

The total thermal resistance of a sample is expressed as

$$R = R_s + 2 * R_c \tag{5}$$

where R is the measured resistance, R_c is the resistance caused by a tape used to attach the sample to the test stand and R_s is the resistance of the 15mm long sample.

The thermal conductivity of carbon fiber was evaluated from the thermal resistance of the sample. Five samples were measured at 1 W heat power. The sample different in number of layers, their carbon fiber threads orientation, appearance of graphene paper in between the layers, type of adhesives used to glue the layers together. The results of measument are summarized in Table 2. Each sample had an orientation of threads at angle of “0^0” or “90^0”, where “0^0” means that measurements go along the fiber and 90, respectively, against.

Measured samples were as follows

1. 3 layers of prepreg "EX-1515 / K13D2U 2K, 120 GSM, 33% RC, carbon non-woven and glue (ED20 + ETAL 45M), 0.75 mm thick.

2. 6 layers of prepreg "EX-1515 / K13D2U 2K, 120 GSM, 33% RC, carbon non-woven and glue (ED20 + ETAL 45M), 1,27 mm thick.
3. 6 layers of prepreg "EX-1515 / K13D2U 2K, 120 GSM, 33% RC, carbon non-woven and glue (ED20 + etal 45M), with FGS - 0.003 graphene paper at the edges, 0.75 mm thick.
4. Prepreg "EX-1515 / K13D2U 2K, 120 GSM, 33% RC, arbon non-woven 8g/m^2, with FGS (0.003) and glue (ED20 + ETAL 45M), diamond powder of two fractions, 0.75 mm thick.
5. From 2 sides of a layer of carbon fiber T300 (dry impregnated resin), at the edges (5mm), 4 layers of K13D24 prepreg, in the center FGS graaphene paper 10 layers + resin

Table 2 .The thermal conductivity various types of carbon fiber

№ simple	l "0^{0}", W/m*K.	l "90^{0}" W/m*K.
1	12±4.7	3,7±0.9
2	17±4,5	8±2
3	64±12,1	22±3.7
4	254±82.9	14±3.4
5	147±28,1	

The theoretical and measured temperature values are presented in Fig. 4. The on average they differ by a factor of 2 in between which can be associated with a large error in l values.

The best result achieved so far was shown y sample No. 4. It has thermal conductivity of 245 W/mK

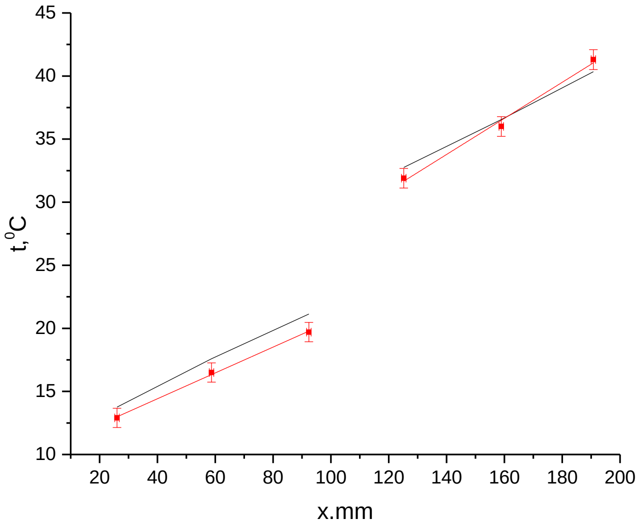


Figure 4. Analysis of the measurements of composite samples in comparison to theoretical prediction calculated within ANSYS

2.2 Measurement of thermal conductivity of a thin layer of the adhesives

The measurement of thermal conductivity in transverse direction of thin materials is based on the same concept as described above. As shown in Figure 5, the two aluminum blocks are 50x20x20 mm in size[5]. The upper aluminum block was glued to the heater, which as connected to the power supply Rohde and Schwarz hmp 4040[6]. The lower one, was connected to the chiller LAUDA MC 250[7].

Figure 5. The test setup for measuring the thermal conductivity in a thin layer of adhesives.

The industry offers a wide variety of electrically conductive adhesives, while the isolating ones are quite few. To fill in this gap and due to the need of having electrically non-conductive adhesive for production of BM@N STS modules we prepared a home-made glue based on epoxy with diamond powder filling.

Measured samples were as follows

1. Diamond power filling with two fractions of diamonds of size of 30-40 mm and 7-10 mm, in -1 to -1 proportion in epoxy.
2. Diamond power filling with two fractions of diamonds of size of 7-10 microns, in -1 to -1 proportion in epoxy.
3. Diamond power filling with two fractions of diamonds of size of 30-40 mm and in -1 to -1 proportion in epoxy.
4. Diamond power filling with two fractions of diamonds of size of 30-40 mm and 7-10 mm, and -1/2 to -50 proportion in epoxy.
5. Diamond power filling with two fractions of diamonds of size of 30-40 mm and 7-10 mm, and in -4 to -1 proportion in epoxy -1 to -1.
6. Diamond power filling with two fractions of diamonds of size of 30-40 mm and 7-10 mm, and in -18 to -1 proportion with epoxy, 60% of diamond and 40% to epoxy.
7. Boron Nitride in commercially available KTK glue, in the ratio 1/10.

Temperature distributions of samples were measured with Fluke Tis40 thermal camera and by thermocouple. An example of result for sample No. 1 is shown in Figure 6. The visual data was processed with the help Origin[8] software to process the final plots (Fig. 7).

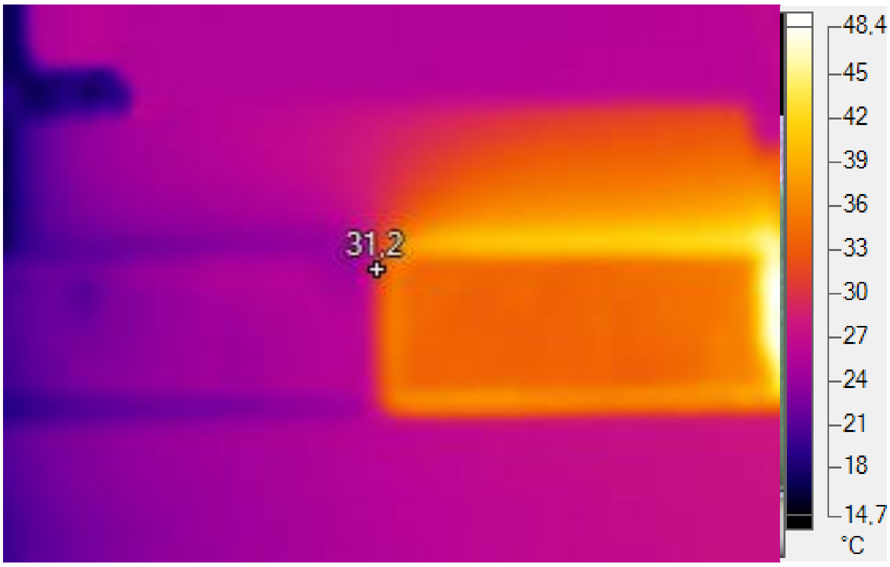


Figure 6. Thermal image of a sample No. 1

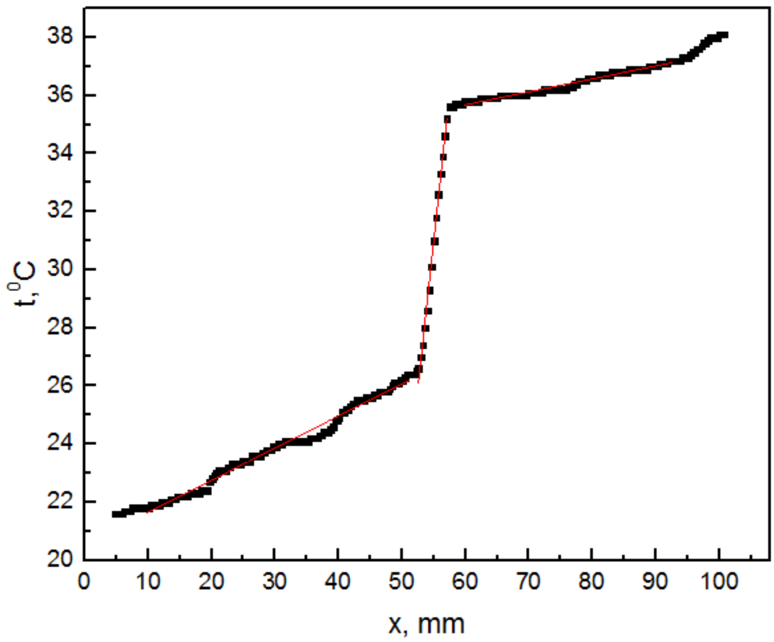


Figure 7. Heat flux meter temperature distribution of a thin layer of glue.

Table 4. Results of the measurements for samples No. 1–4

Образец	1	2	3	4
R, K/W	1,9	2,96	2,94	2,27

To evaluate the thermal conductivity of the adhesive, a thermal resistance was compared on the sample adhesives. A lower value corresponds to a higher coefficient of thermal conductivity. The exact values were not calculated due to the large systematic errors of the results.

As expected the best result was shown by home-made adhesive with the based on 2 fractions of diamond powder filler to the epoxy. The fine fraction filled the volume between the coarse fraction, thereby improving the overall thermal conductivity of the layer.

When measuring thermal resistance 5-8, we changed the experimental procedure, for more accurate results, the thermal mat was changed to the FGS paper, since this is a thinner material with lower thermal resistance, the values of which are presented in Table 5.

Table 5. Thermal resistance of samples No. 5–7

Simple	5(1)	6	7(7)
R, К/Вт	0,28±0,08	0,05±0,01	1,58±0,46

The best performance was shown by sample 6, with a coarse-to-fine diamonds concentration ratio of 18/1, for more accurate results, measurements were carried out at 5 and 10 W, a graph for determining the temperature gradient of a sample with a thickness of 1.38 (Fig. 8).

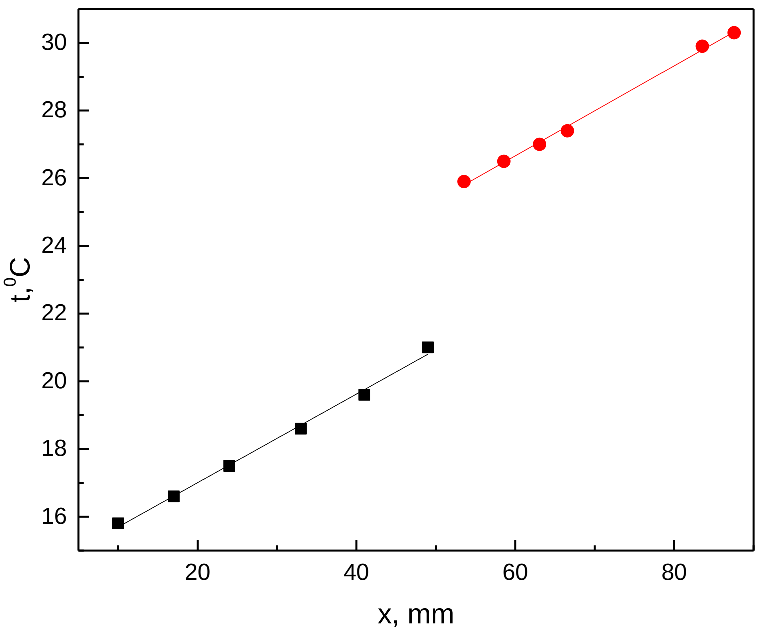


Figure 8. Graph for determining the temperature gradient in sample No. 6.

Figure 9 shows the image 7 the glue of sample 6 with the addition of diamond powder as seen in a microscope.

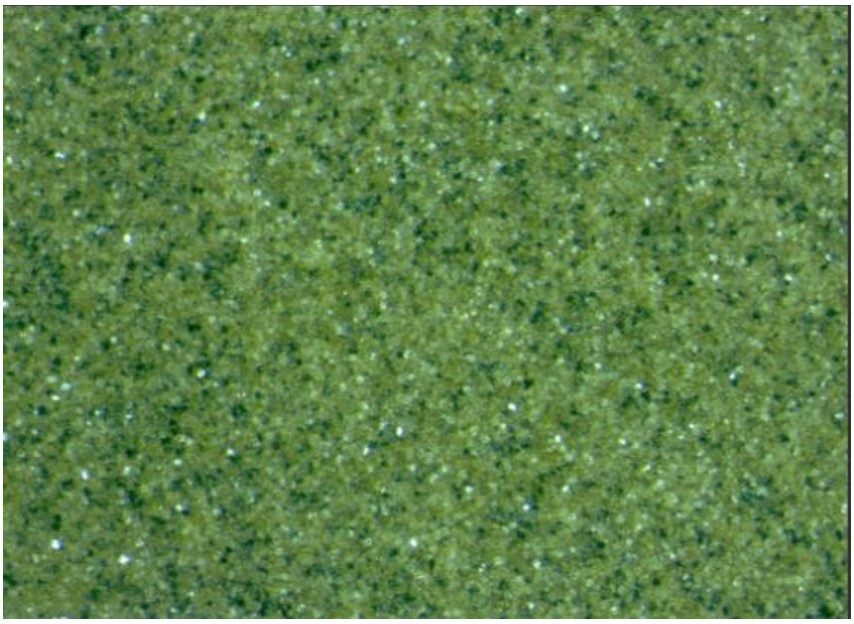
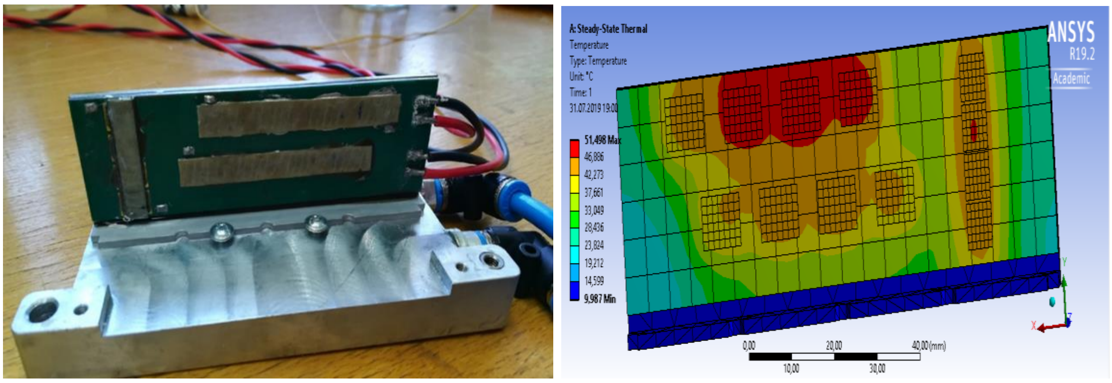


Figure 9. Image of electrically non-conductive home-made adhesive, sample No. 6 with the diamond powder mixture under the microscope

2.3 Temperature gradient measurement on FEB.

Finally, tests were conducted for the assembled FEB prototype followed by thermal model simulation of FEBs equipped with duralumin fin.

The same a heater was used as described in Chapter 2.1 with 9.6 W supplied to the chips, 3.2 W to the LDO with the fin was attached to an aluminum radiator (Fig. 10 (a)), which was connected to the “LAUDA MC 250” chiller. Theoretical simulations were performed within ANSYS (Figure 10 (b)). The predicted and measured temperature distributions are presented in the Table 6.



Figures 10. FEB on a duralumin fin attached to the radiator.

Table 6. Temperature values

	T, degrees (measurements)	T, degrees (predictions)
Chip (upper row)	36±0,1	47,5
Chip (lower row)	40,6±0,1	42,9
LDO	43,3±0,1	42,2
Base of the fin	15,3±0,1	10
Temperature drop on FEB	25,3±0,1	31,5

If the average temperature of the chips was 40^{0}C the temperature of the fin base was 15^{0}C. If the average chip temperature was 35 ° C the fin base temperature was 10 ^{0}C. The temperature different between the chip and the fin base was 25^{0}C.

The temperature was also measured with a thermal imager, followed ANSYS simulations. Results for the FEB of size 90x40 mm, are shown in Figure 11. To normalize the visual data to the data measured in the thermocouple control points.

Results of the ANSYS simulations are shown in Figure 12 with the numerical data presented in Table 7.

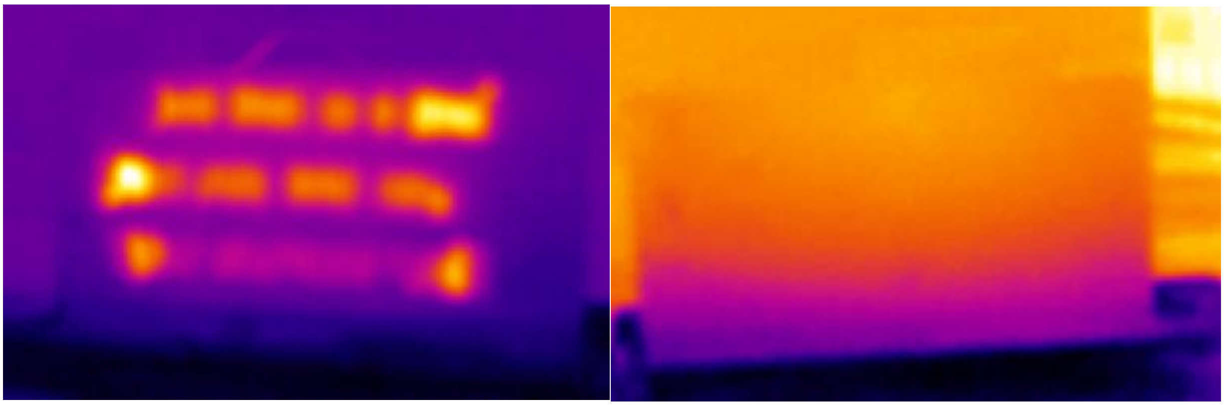


Figure 11. A thermogram of a FEB prototype attached to a radiator (a), back-side view of the aluminum fin (b).

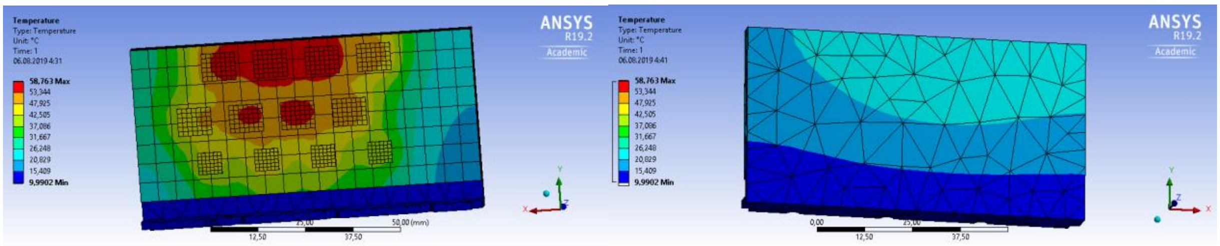


Figure 12. ANSYS model predicted temperature distributions of the front-(a), back-side of FEB (b)

Table 7. Temperature values

	T, degrees, (thermal camera)	T, degrees (ANSYS)
Chip (range 1)	46,1±0,1	55,2
Chip (range 2)	44,3±0,1	48,1
LDO	32,1±0,1	40,3
Base of the fin	12,3±0,1	10
Temperature drop on FEB	33,8±0,1	48,8
Temperature drop on fin	12,5±0,1	16,1

The measurement revealed that if the average temperature of the chips was 48^0C the temperature of the fin base was 16^0C. If an average chip temperature was 45 ° C fin base temperature was 12 ^{0}C. Thus, the typical temperature difference between the chip and the base of the fin is 33^0C on the base attached the radiator and 12^0C along the widest side of the bridge.

Based on the measured data, one can conclude that in order to achieve the operating temperature of the chips attached to the aluminum fin, it is necessary to keep temperature of the radiator at around 0^0C. Further measurements and calculations are needed, however, to confirm these results and to evaluate fluid cooling flow in the radiator.

Conclusions

The cooling system is an essential part of the BM@N Silicon Tracking System. To select the optimal materials and achieve the minimum temperature gradients between the chips and the coolant, calculations were performed using ANSYS, followed by the experimental measurements carried out with various materials of thermal bridges and adhesives. The best coefficient of thermal conductivity was depicted by sample No. 4 made of K13D2U carbon fibers layers glued together epoxy glue with diamond fullings. However, due to economical reasons and by complexity of production the study has to be continued yet before important decision on the final material choice for the BN@N STS cooling bridges can be taken.

Various types of adhesives have also been tested. The best results were shown in sample 6, with 2 different fractions of diamond powder, in a ratio of 1/18. The FEB thermal prototypes were tested on an aluminum heatsink. The temperature difference between the chip and the cooling surface was 25 °C with a fin for a FEB size of 101.5 x 16.1 mm at 33 ° C, and with a FEB of size of 90 x 40 mm, respectively. Based on the measured data, corrections were made to the results of simulations, and general recommendations were made on the use of the adhesives.

Acknowledgments

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