Air Cooling of Silicon Strip Test Setup for a Linear Collider Experiment

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Abstract

We have investigated the feasibility of using air to cool silicon microstrip detectors prototype in the frame of the EUDET project and the SiLC R&D Collaboration. General advantages of air cooling in HEP experimental conditions include minimal material in the path of the particles and no potential of coolant spills in the silicon region. A prototype cooling system was developed and will be tested with heat source provided by flat resistive heaters. Heat source can load up to 1 mW/channel and will be studied, making the results applicable to various silicon detector systems. The measurements are compared to cooling system performance predictions. A set of simple equations has been identified and tested which reliably describe the lab setup.

1 Silicon Micro Strip Detector Prototype Setup

The goal of the R&D on Silicon Tracker systems for the International Linear Collider (ILC) experiments is to study various silicon sensors technology, associated FE electronics and system design geometries allowing high level event characterization and consequently minimizing the overall detector material budget.
One of the important questions is the operating condition of the Silicon detectors in various system configurations. This physical coupling provides thermal connection of the silicon sensors and eliminates the need to control cooling environment. Preliminary thermo-mechanical studies [1] show that because of the relatively low power consumption of the FE electronics [2] the main cause of increase in temperature heat will be the environmental

conditions in which the various Silicon tracking components will run. Indeed and furthermore, at ILC because of the relatively low radiation levels, the silicon modules can operate at the ambient enclosure temperature, i.e. up to 30°C and with a temperature gradient of 10°C (i.e.±5°C around 25°C). The goal is to maintain Si tracking component within this temperature conditions by enclosing it in an insulating box and possibly applying air flow cooling inside this box to maintain the desired temperature conditions.

The silicon tracker system prototypes will utilize custom designed front-end electronics fabricated using a 0.13 µm CMOS UMC process. The chain of front-end electronics includes a preamplifier/shaper chip, analog memory plus digitization ADC circuit, and the digital management of the overall system functioning. The preamp/shaper chip will have 128 channels, a shaping time of about 0.5 to 2 µs, dynamic range of 20-25 minimum ionizing particles, signal to noise of 20:1 and a gain of 35 mV/fC.

The total power dissipation of the chip is foreseen to be less than 1 mW/channel, leading to a total heat load of 1.8 W per Si module (made of 1,800 channels) without power cycling. It is intended to have power cycling in the FE chips thus a factor 70 to 100 lower power dissipation.

2 Conceptual Design of Cooling System for the ILC silicon Tracker Prototype

Air cooling is desirable as it eliminates the possibility of coolant spills in the region of the silicon and implies a simpler and lower-mass system, minimizing the material in the particle path.

The cooling system must keep the area of the Si strip detectors and front end electronics at less than 30°C, where CMOS components and Si subtrate become temperature sensitive.

The design goal is to keep the electronics and sensors at condition below 30°C to allow for a safety margin. The cooling system must eliminate temperature fluctuations with time to maintain the required position accuracy of the detector elements. Of course, the flow of cooling air must not itself affect the positioning of the sensors by introducing vibrations; we ensure this by limiting the air flow to the detector and electronics region.

Fig. 1. shows the proposed mechanical structure from Carbon composite material with view of mechanical support for the Silicon strip detector prototype inside.

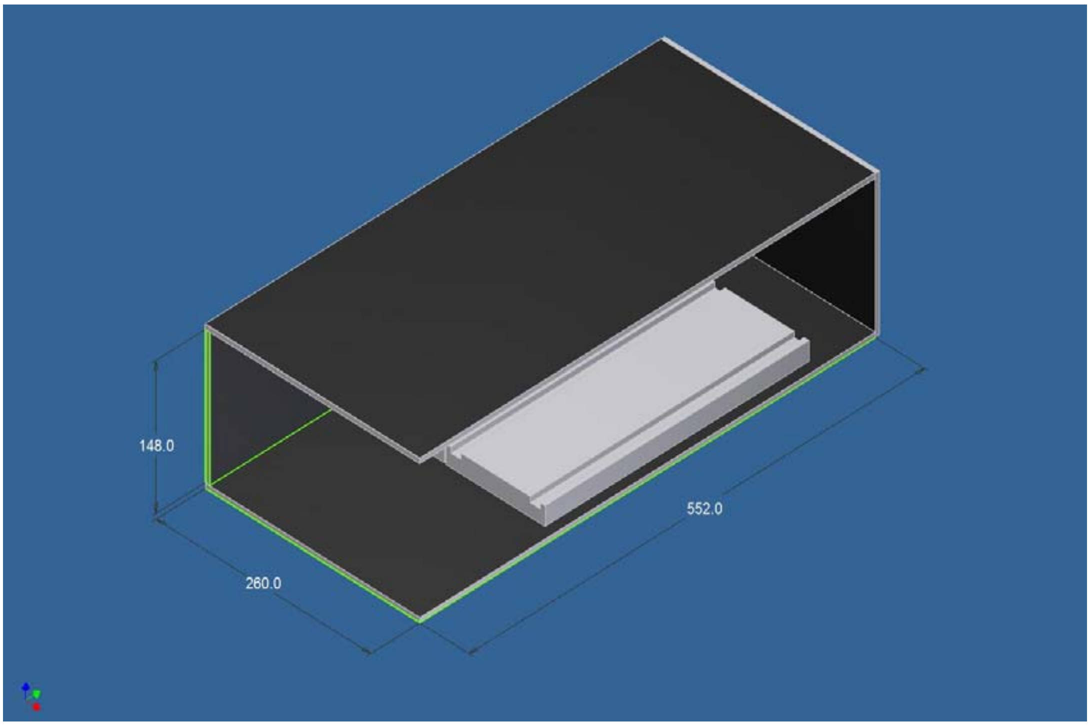

Fig. 1. Design view of the main mechanical construction of the Faraday/cooling box Silicon tracking prototype.

Fig. 2 shows the proposed air flow distribution supplying the plane for the silicon telescope inside a beam test prototype of Silicon tracker.

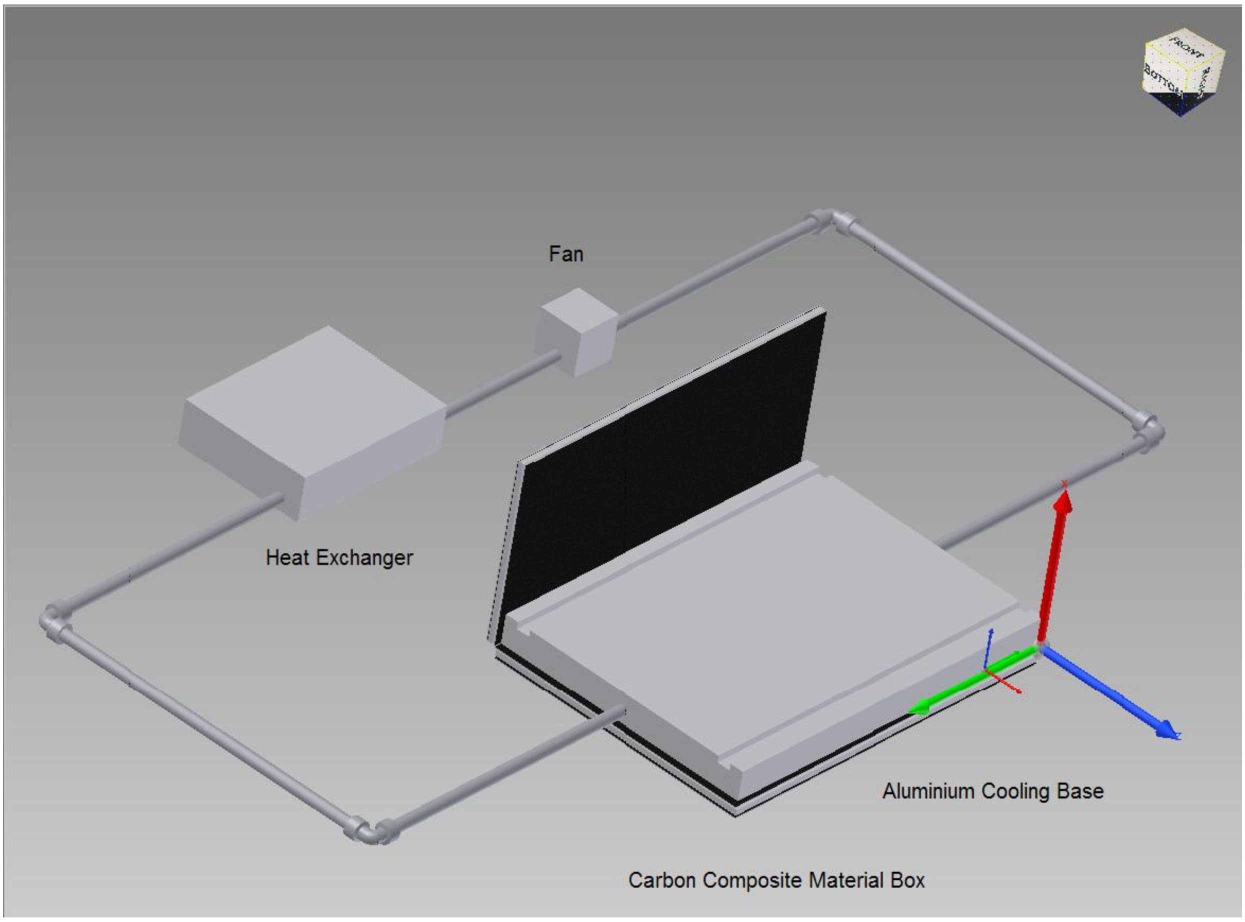

Fig. 2. Design view of the silicon detector support and enclosure showing the entry and exit path of the cooling air and the elements of the cooling system.

The cooling air is driven into the aluminum cooling base of Silicon sensors support by a fan and circulated through a heat exchanger located outside of the system. Dry air circulation is considered over the prototype box in order to avoid condensation problems if needed.

The test beam box prototype id made of modern Carbon Composite Material technology that provides humidity control and thermal isolation of the cooling air inside the base support making it possible to use chilled cooling air.

The Carbon composite material is performed from double side 200 microns Carbon fibers shit envelope with Reticulated Vitreous Carbon Foam (RVC) of 2.5 mm inside. Such mechanical structure provides the necessary mechanical stability, humidity control and thermal isolation of the cooling air inside, making it possible to use chilled cooling air, providing a safety margin for the test prototype cooling needs.

The cooling system design is formulated as ACAD Inventor project for effective study of various problem and mechanical design and construction realization.

The air cooling conceptual design prototype is under preparation in the laboratory with a test box made of Carbon composite material with reticulated vitreous carbon foam.

The thermal flow load of the Si strip detectors and CMOS front end electronics will be provided by flat resistive heaters arranged in the geometry planned for the test beam setup. The heaters were powered to simulate heat loads from 1 to 83 W (1-27 mW/channel).

The dimensions of the lab sensors support were 240 x 320 x 26 mm, representing the geometry of the test beam setup at the time of the laboratory measurements. Three sensors recorded temperature changes at various points along the length of silicon sensors support.

A large aspect ratio width/height was chosen to minimize the hydraulic diameter, directly proportional to the Reynolds number, in an attempt to simulate laminar flow [3].

Five different air velocities proposed for studies ranging from 1.0 to 5.0 m/s.

A flowmeter, capable of measuring 2.5-25 SCFM with precision ± 10% was suggested to measure the air flow rate.

The air velocity was determined with an anemometer, precision ± 10% .

3. Model of Cooling System Performance

Three main quantities performance are studying and characterized as a function of heat load and air velocity:

- The maximum temperature recorded by the sensors when the heater is being heated corresponds to the maximum temperature reached by the chips. This quantity is essential in determining whether it is possible to use air cooling to maintain the temperature of the front-end electronics at less than 30 $^{\circ}$C.
- The heating of the air as it flows through the base support, ΔT_1, is measured as the difference between room temperature and air temperature at the test box base support outlet.
- In addition to illustrating the general behavior of the cooling prototype, ΔT_1 enables the confirmation of flow rate, as will be shown below. If chilled instead of room temperature air is being used, ΔT_1 is important in studying the range of temperatures reached within the test box to avoid condensation on the outside of the detector enclosure. ΔT_2 is the temperature difference between the air and the prototype, namely the difference between the average ΔT_1 and the average temperature change recorded by the six sensors when the resistors are heated.

It also can be calculate the heat transfer coefficient. Both ΔT_1 and ΔT_2 can be compared to the predicted cooling system performance with a set of equations describing the cooling design.

4. Basic Descriptions of Heat Flow Processes

The basic heat transfer equations were used for cooling performance predictions for a system experiencing heat loss by convection [3].

Assuming uniformly distributed heat, the temperature difference between the electronics and the air can be expressed as:

$$\Delta T_2 = Q/A_h \times (l/h), \qquad (1)$$

where Q is the heat load (W), A_h is the heated area in the plenum (* cm^2), and h is the heat transfer coefficient (W/°C cm^2). From laboratory measurements of ΔT_2, one can determine h and compare to predictions of the heat transfer coefficient. The heat transfer coefficient can be calculated as follows:

$$h = JC_pG(C_pM_u/K)^{-2/3} \qquad (2)$$

where J is the Colburn factor, a quantity which can be derived from the Reynold's number (N_R) The Reynold's number represents a measure of the type of flow a system is experiencing, laminar or turbulent. Laminar flow is advantageous as it implies a minimum disturbance to the components being cooled and thus reduces vibration effects. Turbulent flow is desirable as it is more effective in transferring heat from the surface components to the cooling air. The actual transition between laminar and turbulent flow is historically not well understood and poorly defined. In this case, J was calculated for both laminar and turbulent flow and set to a value (0.0038) which could be indicative of either; therefore, J makes no assumption on the type of flow in the system. C_p is the specific heat of air (l J/g °C), G is the mass flow per unit cross sectional area per unit time (g/s cm^2), M_u is the viscosity of air (1.8 X 10^{-4} g/s cm), and K is the thermal conductivity of air (2.6 X 10^{-4} W/cm °C). The heat transfer coefficient can also be expressed as:

$$h = G4.8 \times 10^{-3}. \qquad (3)$$

Knowing G and h, the change in the cooling air temperature can be calculated:

$$\Delta T_1 = Q/(GA_c\ C_p) \qquad (4)$$

where A_c is the cross sectional area of the plenum (* cm^2).

5. Preliminary Results

Figure 4 shows predicted ΔT_1 as a function of power for five different air velocities. For the case of the test setup, in which the maximum heat load on basis is 15.4 W, ΔT_1 ranges from 2.0-5.3°C as the air velocity is increased from 1.0 to 5.0 m/s.

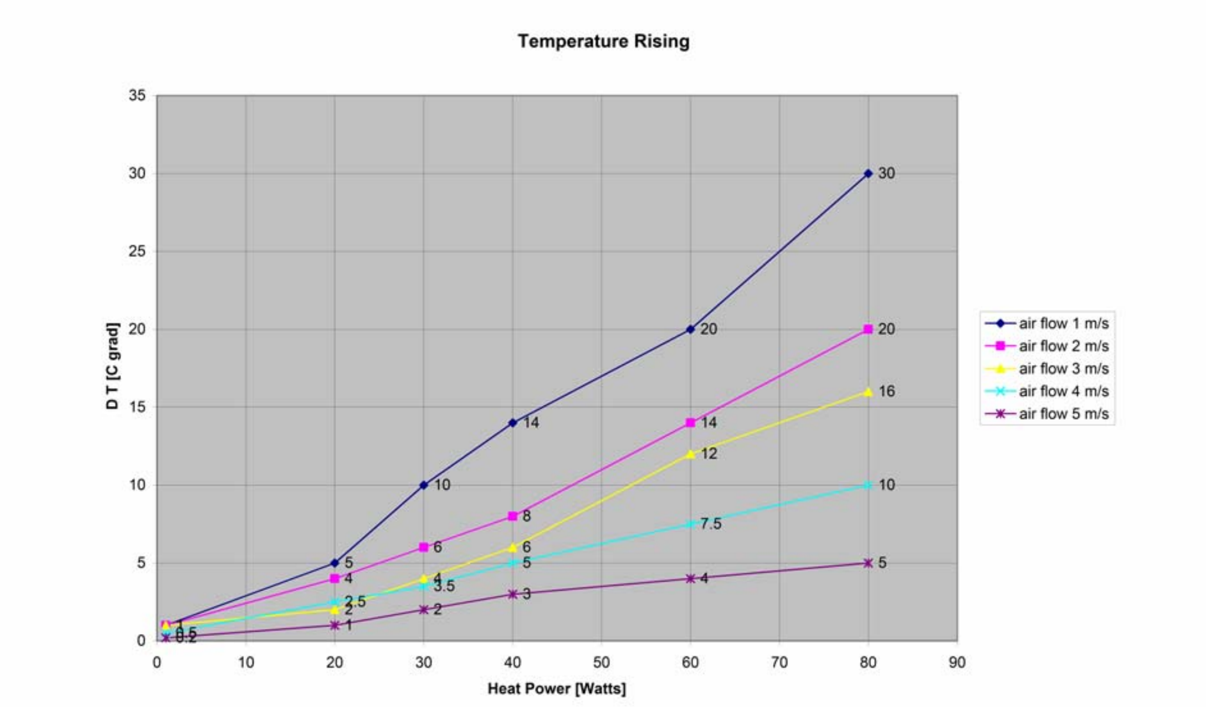

Fig. 4. The heating of the air flowing through the cooling base ΔT_1, as a function of power for various velocities (ν). Both the calculated values of ΔT_1 are shown.

The temperature difference between the cooling air and electronics as a function of power for various air velocities is shown in Fig. 5. At a heat load of 15.4 W, ΔT_2 ranges from 5.2-15.8°C as the air velocity is increased from 1. to 5.0 m/s.

The determination of ΔT_2 enables the comparison between measured and predicted heat transfer coefficients as a function of air velocity, shown in Table 1. The predicted heat transfer coefficient is calculated from Eq. 2.

Table 1. Predicted heat transfer coefficients

Velocity [m/s]	**Predicted *h* [W/$^\circ$C cm^2]**
1.0	0.0030±0.0002
2.0	0.0044±0.0002
3.0	0.0057±0.0003
4.0	0.0071±0.0004
5.0	0.0090±0.0005

Table 1: Predicted heat transfer coefficients

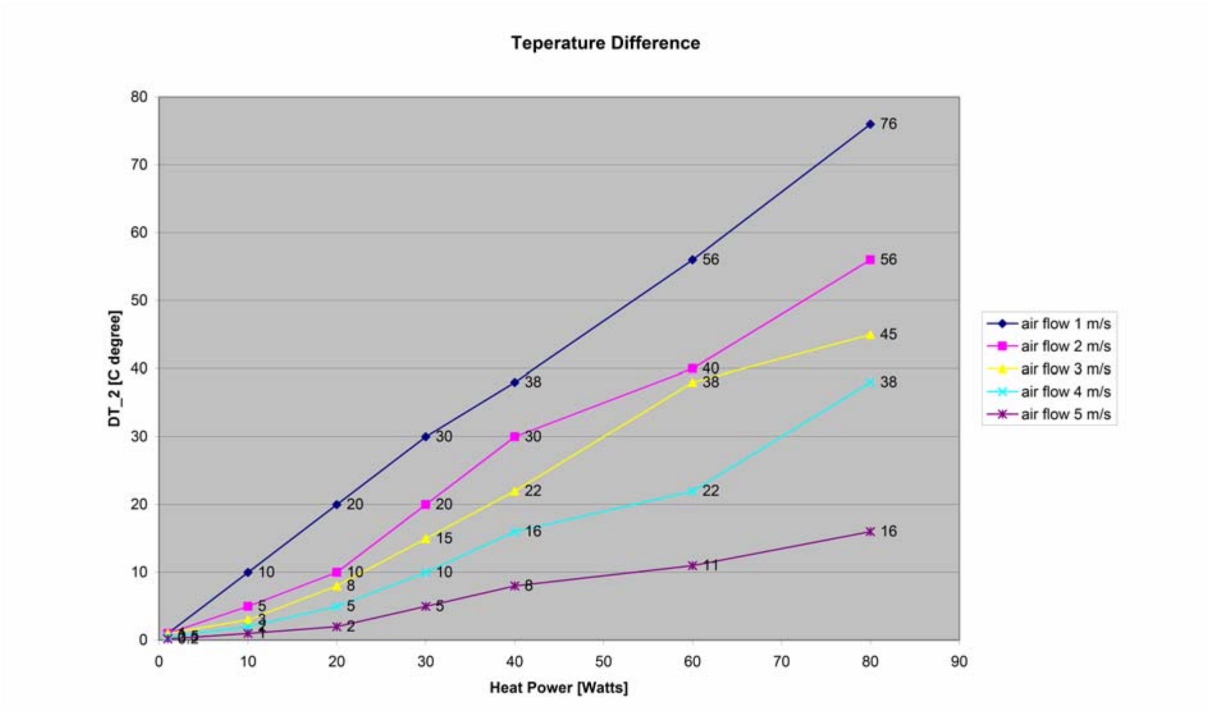

Fig. 5. Temperature difference between the electronics and the air versus power for various velocities (v). The ΔT_2 predictions are included.

The trends displayed by ΔT_1 and ΔT_2 give us confidence in our predictions. As expected, the heating of the air increases as the heat load is increased and the air velocity is decreased. The temperature difference between the cooling air and the electronics behaves accordingly, with ΔT_2 increasing with increasing power and decreasing air velocity. These predictions reliably describe our test setup, enabling the use of these equations to simplify future cooling studies should changes in the front-end electronics specifications occur.

6. Main Technology Elements and Test Box Preparation

The Basic technology processes are used according the development of Federal State Unitary Enterprise Obninsk Research and Production Enterprise "Technologiya", State Research Centre of Russia [4].
The main technological elements where tested for the construction of the test setup box:

- Figure 6 shows the Carbon Fiber material used for building the cooling box; it is based on honeycomb double-sided layers mechanical structural panels and as core material an honeycomb polimide structure.
- Figure 7 shows the constructed elements that made the cooling box, e.g. Carbon rods and Carbon strips.
- Figure 8 shows the low material budget gas tubes from Carbon composite material and polyimide tubes

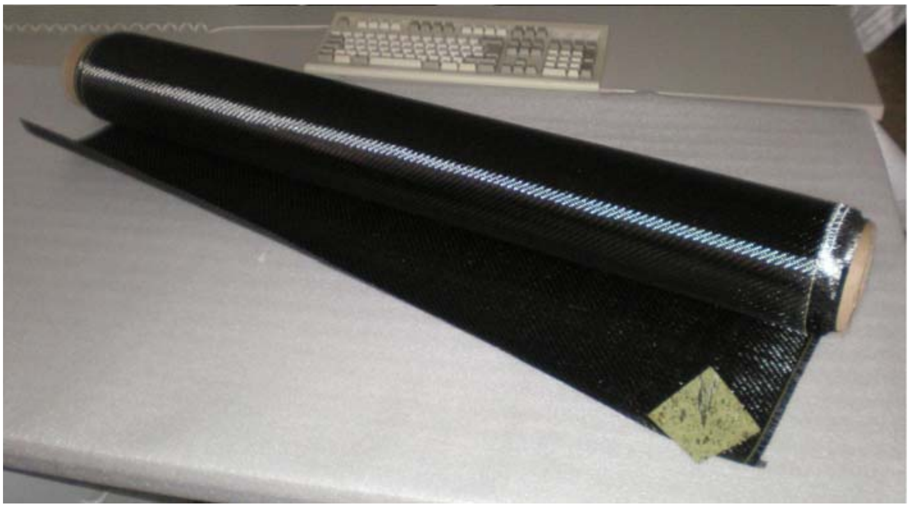

Fig. 6. Double sided honeycomb panel

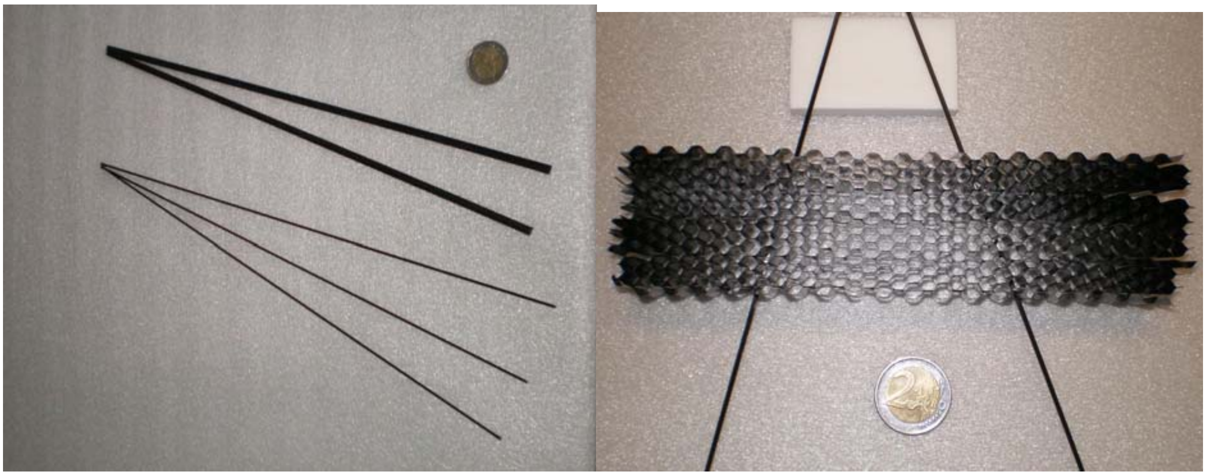

Fig.7 Double side honeycomb Carbon composite material components

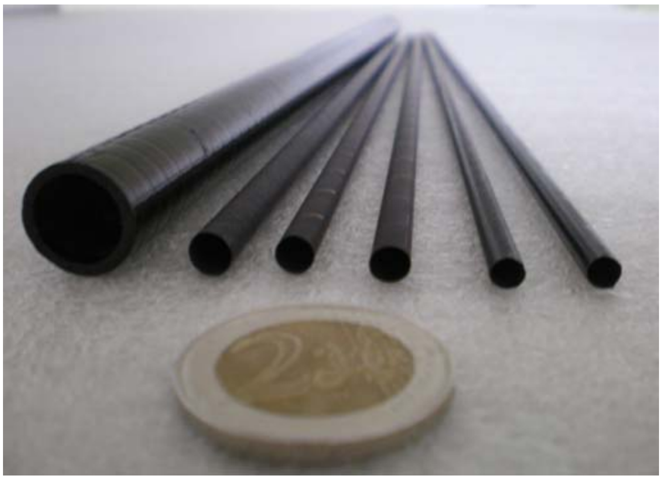

Fig.8. Low material budget gas tubes for the cooling system of SILC sensors test setup

The cooling box prototype was produced, with mechanical support strength (Figure 9):

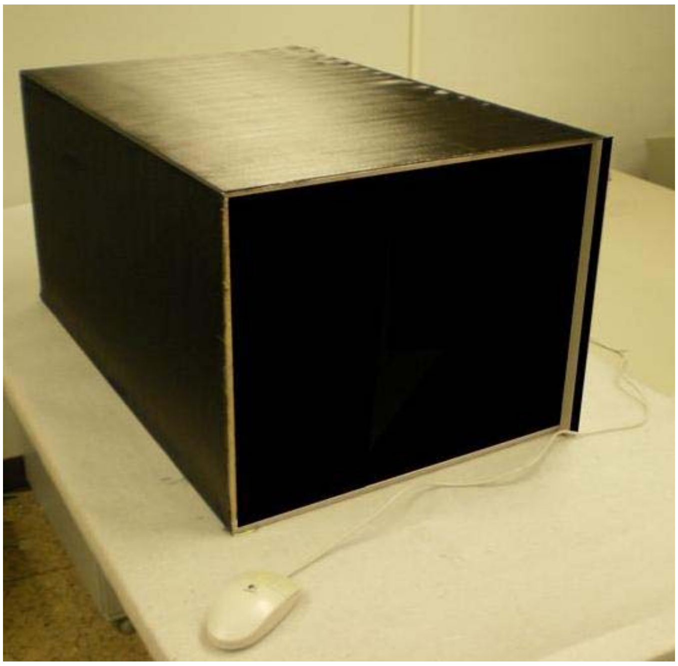

Fig. 9. Cooling Box made of Carbon fiber composite material technology for the

This prototype will be further tests of the mechanical support structure and the cooling system elements. This cooling system will be used in the scheduled test beams at CERN, in 2008 [5]. Another box of larger dimension but following the same scheme will be built for the larger size Silicon prototypes that will be part of the last session of EUDET test beams in 2009.

Acknowledgement

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