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THE M-MODULE

Initial thermal measurements at room temperature

W. O. Miller
HYTEC INC, Los Alamos

T. Dubbs, W. A. Rowe, H. F.-W. Sadrozinski, A. Seiden, A. Webster, R. Wichmann
SCIPP, UC Santa Cruz, Santa Cruz CA 95064

Abstract

We report the first measurements on a thermal prototype of a novel concept to construct silicon modules. In order to safely cool both detector and frontend electronics, we sandwich a heat spreader made from highly conducting Pyrolytic Graphite between two single-sided silicon detectors. We measure the temperature profile as a function of heating rate and find that the temperature increase of the silicon detectors is below 3^{o}C for realistic power levels.

CONSTRUCTION OF THE M-MODULE PROTOTYPE

The principle of the M-module is shown diagramatically in Fig.1: two single-sided silicon detectors of 300 μm thickness sandwich a so-called "heat speader" of high thermal conductivity which conducts the heat generated both by the frontend electronics and and through self-heating of the radiation damaged silicon detectors to the side, where the "EAR" connects to the cooling channel.

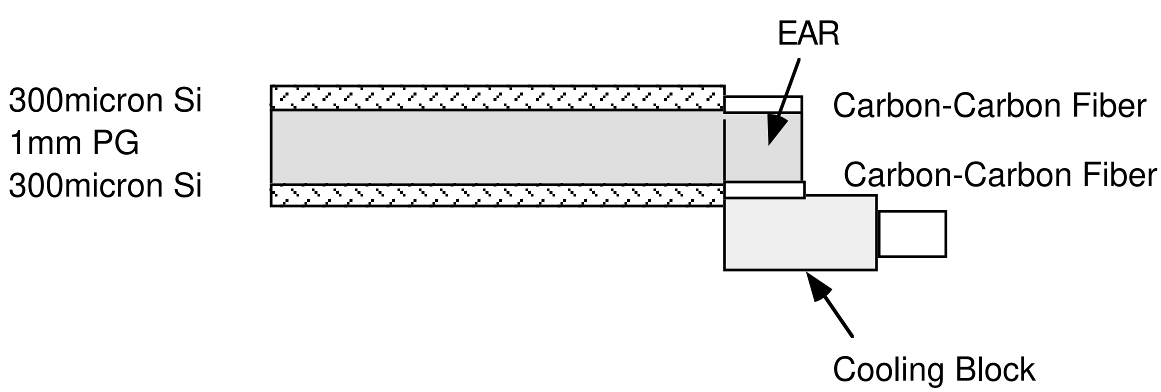

Fig. 1 Schematic of the M-Module

The heat spreader is made of Pyrolytic Graphite which has a thermal conductivity of 1300 W/cm/^{o}K, and radiation length of 22cm. In order to minimize it's contribution to the material budget, we reduced the effective thickness with cut-outs as shown in Fig. 2 to close to 0.3% of a radiation length, comparable to the contribution of one silicon detector of 300 microns. The asymmetric shape is choosen to have maximum heat conduction underneath the frontend electronics chips, which will be located to the right of the broken line in Fig. 2.

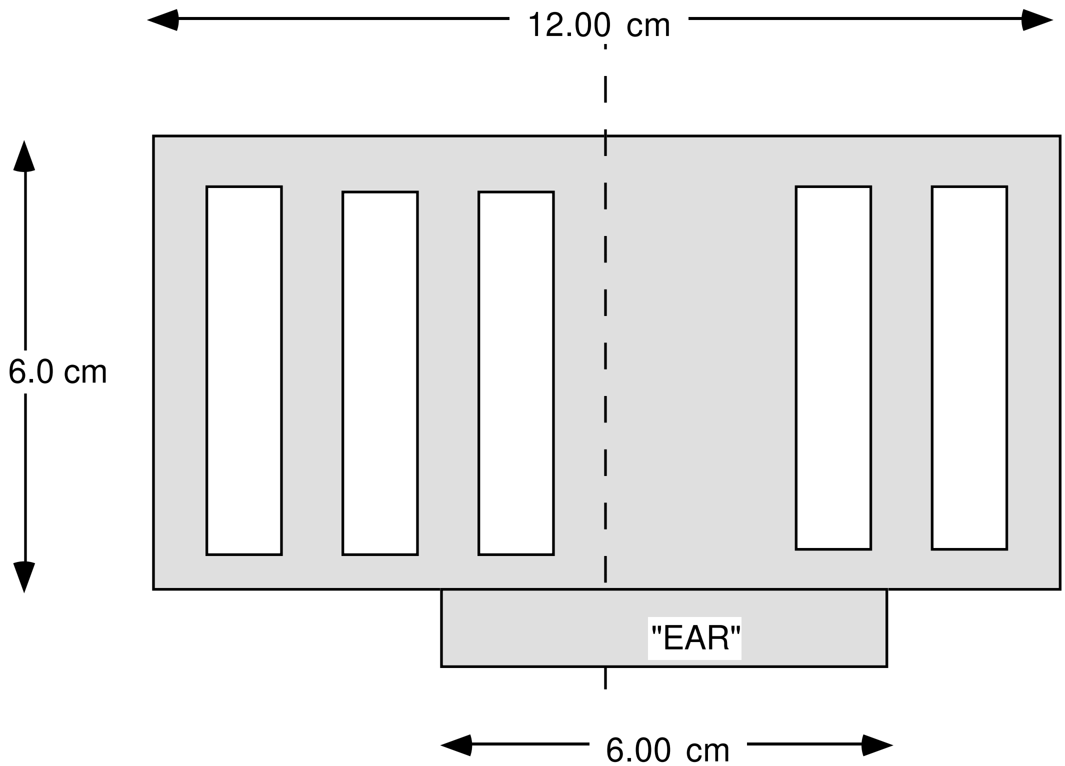

Fig.2 Heat Spreader made of Pyrolytic Graphite (PG).
The cut-outs reduce the mass by 28%

Fig. 3 shows the thermal prototype including the location of the RTD's used to measure the temperature profile. The frontend electronics contributes a constant amount of heat to the module and is simulated by a Kapton based Heater Tape [1] located across the module as in the widely tested r-ϕ modules [2-5]. The solid part of the PG heat spreader matches this location (Fig.2). Cooling was provided by tap water flowing through the cooling block. In the first part of the tests, the cooling block was made of stainless steel.

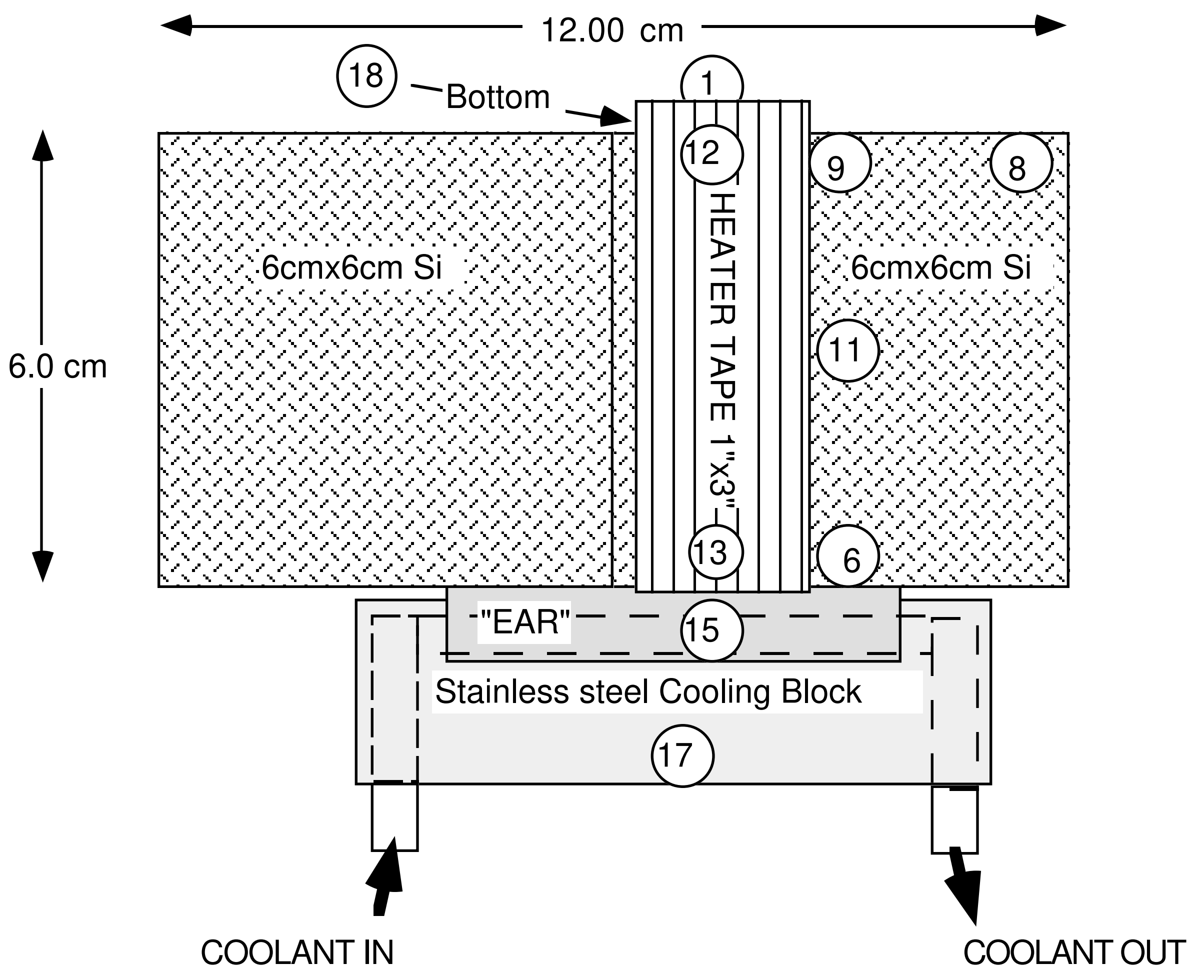

Fig. 3 Lay-out of the Thermal Prototype of the M-Module. The circled numbers indicate the location of RTD's to determine the temperature profile.

The use of a stainless steel block with relative large thermal resistance has the disadvantage to change the temperature of the module relative to the cooling water as a function of the heat input into the module. This is shown in Fig. 4 where the temperature of the EAR and the cooling block at two cooling water temperatures are shown as a function of the heater tape power. On the other hand, it allows us to determine the heat input from the ambient air of 30^{o}C into the silicon wafers, using the data from two runs with the cooling water at different temperatures, 17^{o}C and 29^{o}C.

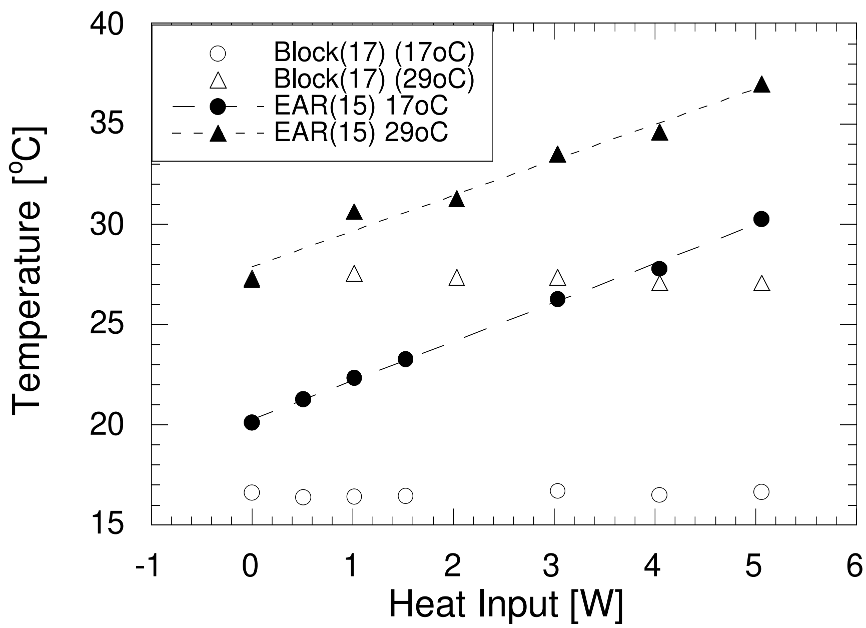

Fig. 4 Temperature of the Ear and the cooling block at the two temperatures of the cooling water, 17and 29^{o}C, at 30^{o}C ambient temperature

Assuming that the convective heat input from ambient is proportional to the temperature difference between ambient and the silicon, we can determine the thermal resistance of the stainless steel block R and the effective convection coefficient of the silicon h_{conv} from the data in Fig. 4 with the following equation:

$$T_{EAR} = T_{Block} + Q*R + R*h_{conv}*(T_{EAR}+\Delta T-T_{amb}),$$

where the average silicon temperature was approximated to be ΔT above T_{EAR}, with $\Delta T = 1^{o}C$ from the following data. and the ambient temperature was measured to be constant at $T_{amb} = 30^{o}C$.

The data in Fig. 4 results in R=2.56 [$^{o}K/W$] and the effective convection coefficient of the silicon $h_{conv}=10$ [$W/m^2/^{o}K$], averaged over the temperature distributions on the module. This value is close to the one measured by T. Kondo etal in a thermal study of the "classic r-ϕ module" [6].

We can now interpret the data and find the heat exchanged through convection for the two cooling scenario's as a function of heater tape power. At a cooling water temperature of $17^{o}C$, and a power input of 3W through the heater tape, a power of 0.5W is picked up from ambient through convection. At the same heat input of 3W, but a cooling water temperature of $29^{o}C$, the silicon gave 0.5 W to ambient, as shown in Table 1 (positive numbers are heat put into the silicon, negative are heat supplied by the silicon). It should be noted that a power of 0.5W corresponds to about 1μA/channel at 300V bias, about half the anticipated self heating load after 10years of operation of ATLAS at the LHC. Adjusting the relative temperatures of ambient and cooling fluid allows to tune the amount of convective heat supplied by the ambient air.

TABLE 1. Heat Power Input from Ambient (in Watt)
as a function of Cooling Water Temperature and Heater Tape Power

Cooling Water	Heater Power		
Temp [^{o}C]	0 W	3 W	5 W
17	1.3	0.5	0
29	0.3	-0.5	-1.2

In the following, we will refer all temperatures to the temperature of the EAR to eliminate the temperature step in the stainless steel block.

TEMPERATURE PROFILE

We have measured the temperature at several location on the modules as indicated in Fig. 3. Based on tests with the RTD's we estimate the error to be 0.2^{o}C. During the measurements we observed that after change of the heater tape power, thermal equilibrium was reached extremely fast, due to the high conductivity of the heat spreader. On the other hand, we could not prevent our measurements to be influenced by air movement, which might have introduced temperature changes of less than 0.5^{o}C. A better controlled environment -cooling box- is being targeted.

Far Corner (RTD #8)

The temperature in location #8, which is in the corner of the module away from the cooling block, indicates how well the silicon detector is cooled, once it is self-heating and how efficient the heat from the frontend electronics is conducted to the cooling ear, without heating up the detectors themselves. Fig. 5 shows the temperature of RTD#8 for two cooling water temperatues. Because the heat exchanged with the ambient air depends on the coolant temperature, the various data points correspond to very different "self heating terms", as shown in Table 1. As expected, the module is slightly warmer relative to the EAR when the cooling liquid is cooler, because more heat is picked up from ambient. At 3W input into the heater tape and a heat pick-up of 0.5W from ambient, point #8 is 1.0^{o}C above the temperature of the EAR, which agrees well with the results of the FE analysis.

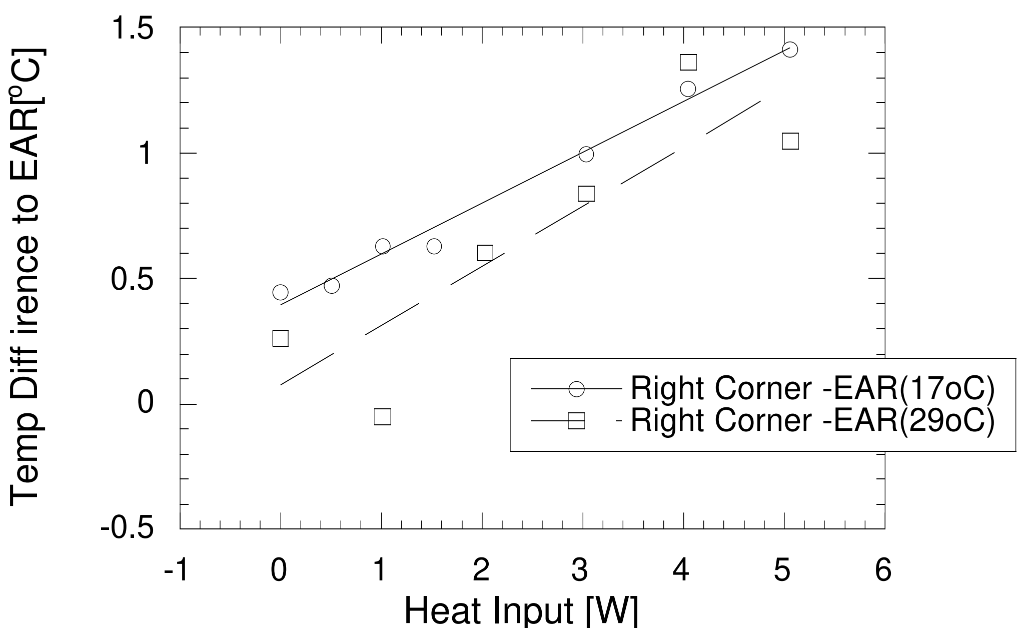

Fig. 5 Temperature of RTD #8 relative to the EAR.

Edge of PG opposite Cooling #1

Located on the PG heat spreader at the edge of the module in-between the ends of the Kapton heater tape, RTD#1 shows how well heat from the electronics chips is conducted away from far away edege of the silicon detectors (Fig. 6). Again heat exchange with the ambient influences the data. At the point of zero heat exchange, at a heater input of 5W at 17^{o}C coolant temperature, point #1 is 1.6^{o}C above the EAR.

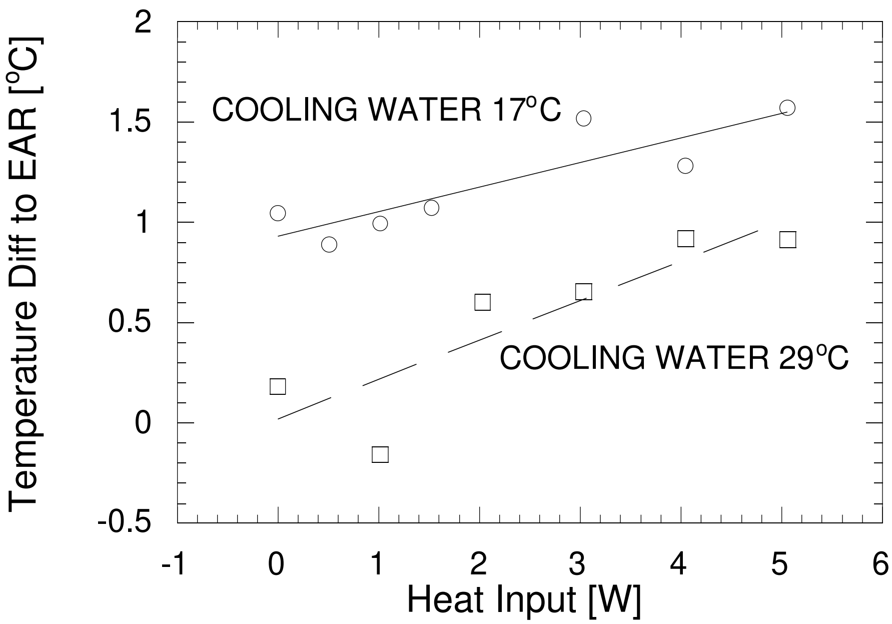

Fig. 6 Temperature of RTD #1, between the heater tapes on the edge of PG opposite to the EAR.

Close to FEE #9

RTD #9 is on top of the silicon, close to the far edge and to the FEE. Its temperature depends much on the efficient cooling of the electronics and indicates how much heat from the electronics is flowing into the silicon detectors. Fig. 7 shows the temperature of RTD #9 relative to the EAR. No strong dependence on the temperature of the coolant and the heat exchange with the ambient air is observed. We include a data point taken with only the bottom Kapton heater delivering 3W of heating power at a coolant temperature of 29^{o}C: no large change is observed. The temperature at this point is about 1.6^{o}C for zero exchange with ambient and 5W heater tape power.

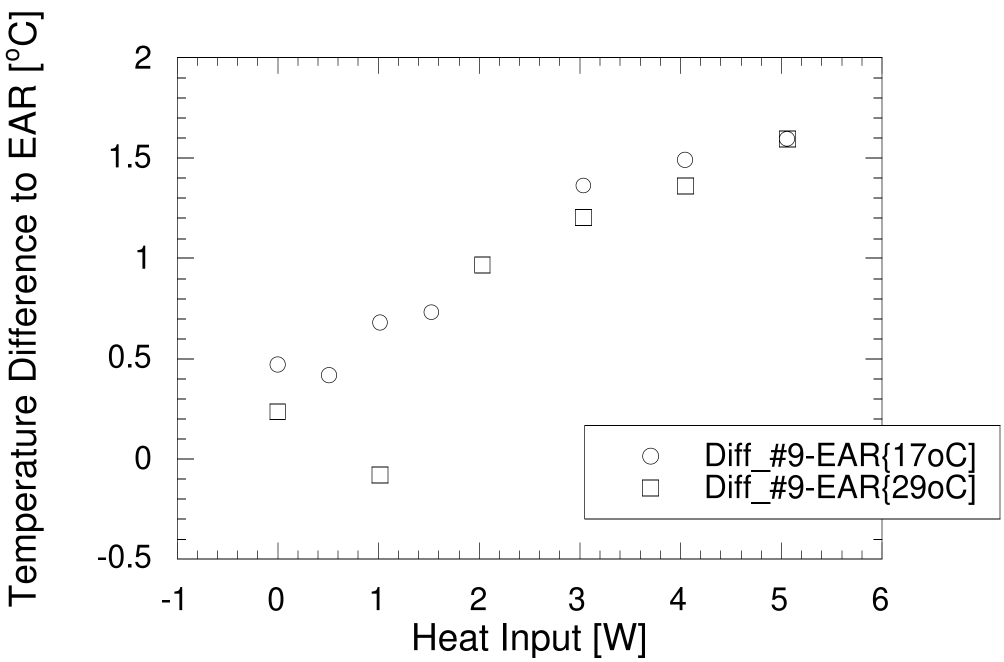

Fig. 7 Temperature difference relative to EAR of RTD #9, close to the heater tape on top of the silicon.

Electronics Top #12 and Bottom #18

Fig 8 shows the temperature on the outer face of the Kapton tape (#12 on the top and #18 on the bottom). For both coolant temperatures, the temperature reaches a maximum of close to 3^{o}C above the EAR. It is interesting to note that the bottom is about 0.5degrees cooler than the top at large input loads. We are investigating if this is due to convection or the extreme anisotropy of the heat conductivity of the PG material: the heat conductivity is about a factor 30 better along the PG than normal to it, i.e. in the direction from top to bottom. The cooling channel is connected to the underside of the EAR.

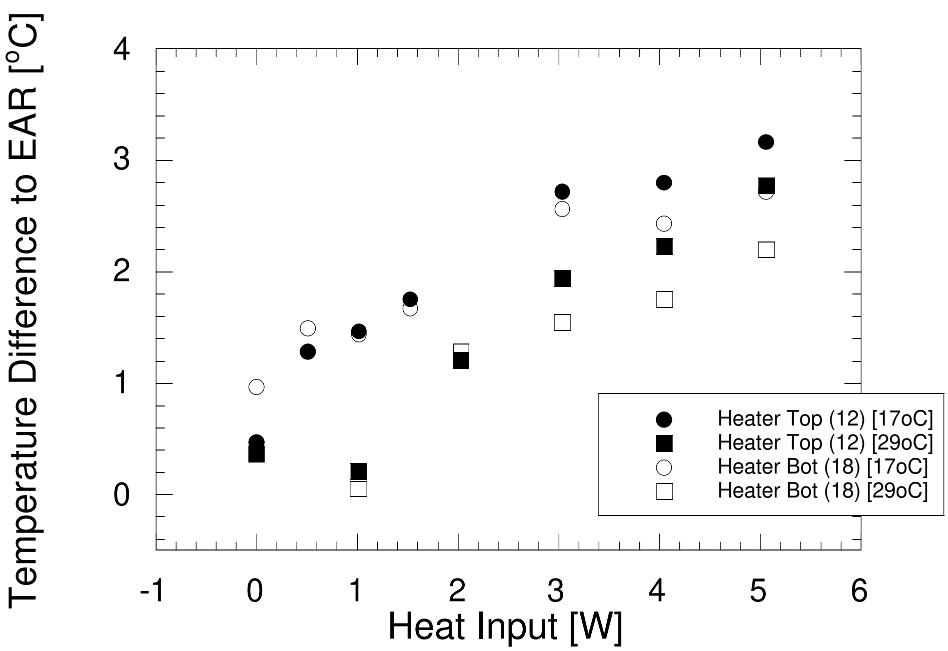

Fig.8 Temperature of the RTD #12 (top) and #18 (bottom), at the outer surface of the Kapton heater tape.

CONCLUSION

The M-module allows safe and predictable heat removal both from Fee generated power and from self heating of the detector. The largest temperatures encountered on the thermal prototype are about 3^{o}C on the Kapton at 3W heater power and 0.5 W due to convection. The largest temperature measured on the silicon is 1.5^{o}C, both relative to the temperature on the EAR.

We will continue the measurement in an environmental chamber to control and adjust heating from the ambient. We will also exchange the stainless steel cooling block with one made of copper to improve the coupling between the module and the coolant.