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THE M-MODULE

Thermal measurements at -10^oC

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Abstract

We have extended measurements on a thermal prototype of a novel concept to construct silicon modules from room temperature to a controlled ambient environment between 0 and -10^oC. 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 power and find that the temperature increase of the silicon detectors is below 3^oC 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 spreader” of high thermal conductivity which conducts the heat generated both by the frontend electronics and through self-heating of the radiation damaged silicon detectors to the side, where the “EAR” connects to the cooling channel.

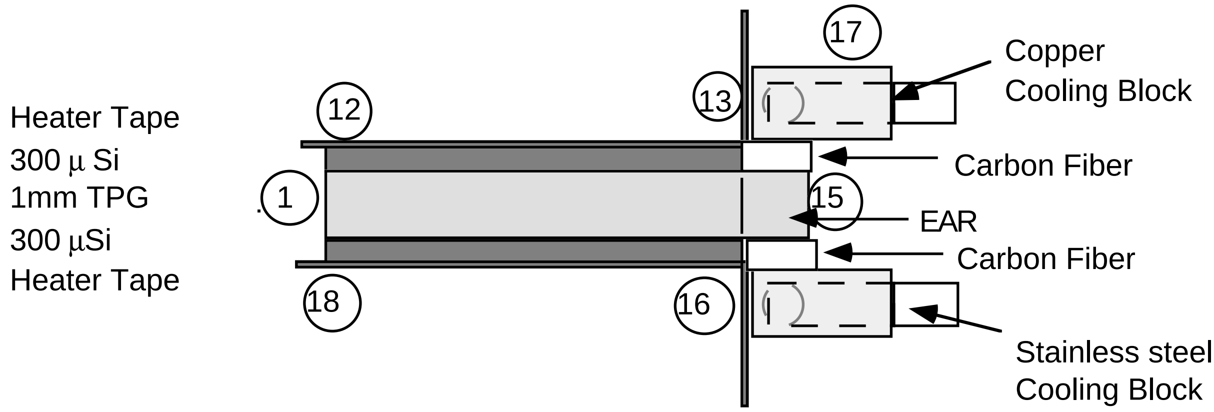

Fig. 1 Schematic of the M-Module

In our previous, room temperature measurements [1], the cooling block which supplies cooling between the liquid coolant and the EAR, was made out of stainless steel, in order to facilitate our understanding of convective heat transfer. In this series of measurements, we added a copper block on top of the EAR and ran the liquid coolant through it. As we will see below, this allowed a reasonable constant temperature of the cooling block throughout the experiment, allmost independent of the heating power.

The heat spreader is a 1mm thick piece of Pyrolytic Graphite made by B.F. Goodrich, which has a thermal conductivity of 1300 W/m-^{o}K, and radiation length of 19cm. In order to minimize it's contribution to the material budget, we reduced the effective thickness with cut-outs as shown in Fig. 2: averaged over the 12cmx6cm active area, and including the EAR, this amounts to 720μm, about 0.37% of a radiation length, comparable to the contribution of one silicon detector of 300 microns. The asymmetric shape is chosen to have maximum heat conduction underneath the frontend electronics chips, which will be located to the right of the broken line in Fig. 2.

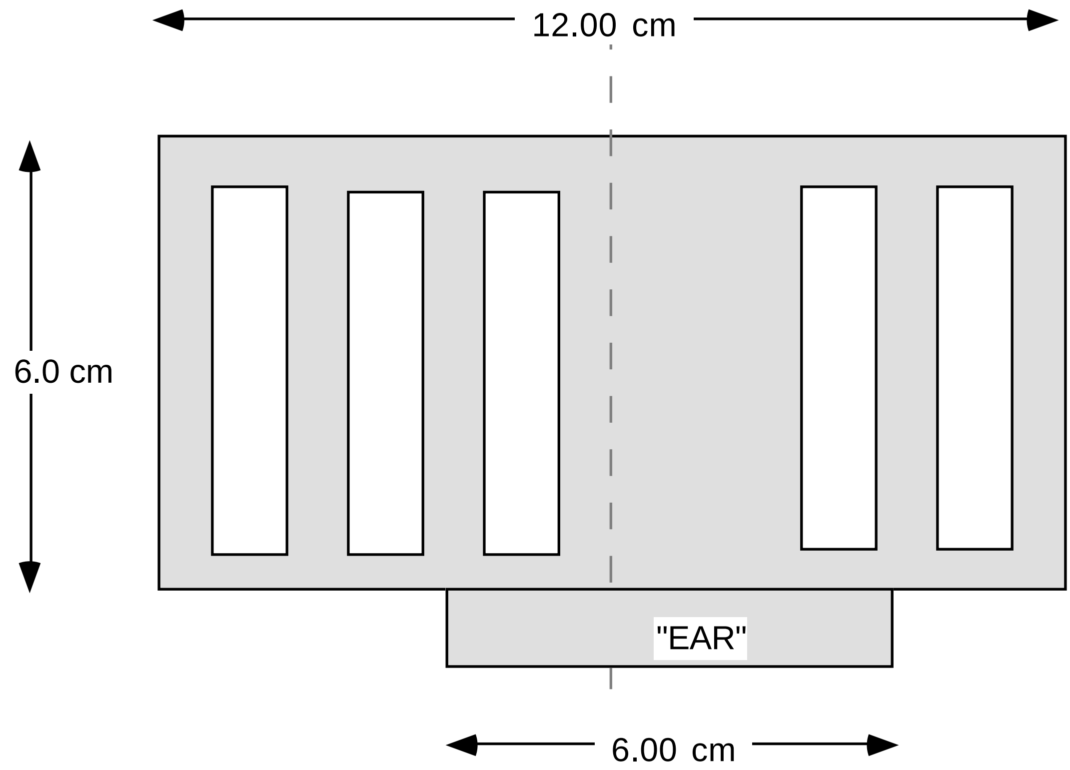

Fig.2 Heat Spreader made of Pyrolytic Graphite (PG).
The cut-outs reduce the mass by 28%

Fig. 3 shows the thermal prototype including the location of the RTD's used to measure the temperature profile. The frontend electronics contributes a predetermined amount of heat to the module and is simulated by a Kapton based Heater Tape located across the module like in the widely tested r-ϕ modules [2,3]. The solid part of the PG heat spreader matches its location (Fig.2). All glue joints were made with 5min Epoxy. In order to prevent the air to be trapped in the cut-outs, we notched the PG pieces to allow the pressure to equalize with the environment.

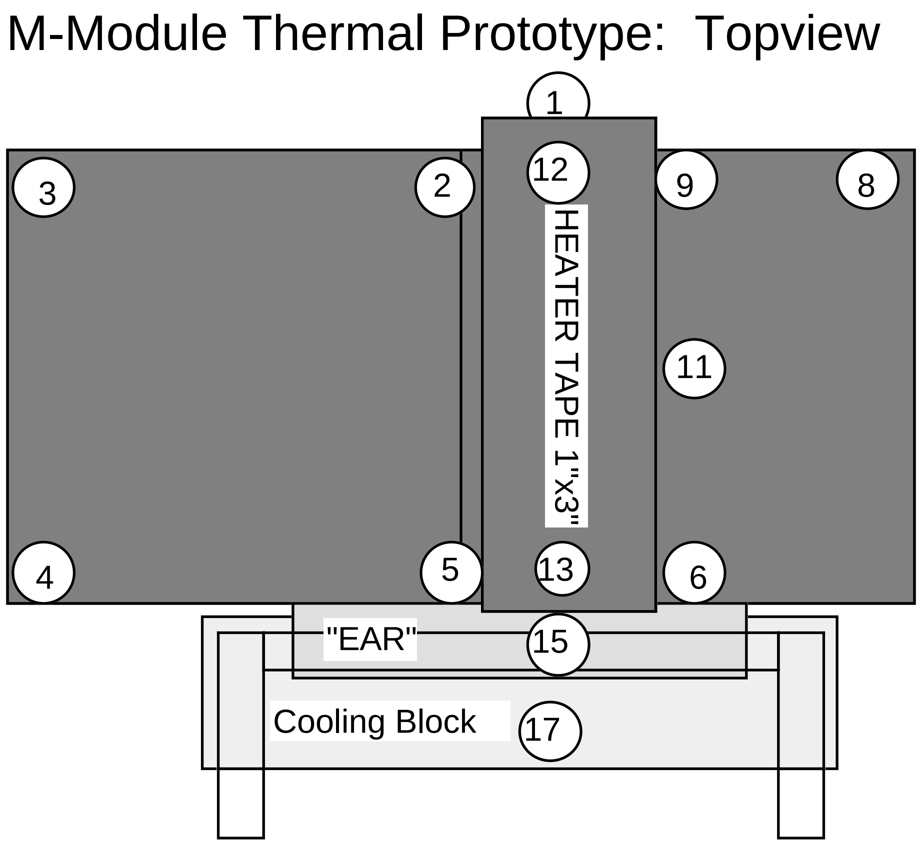

Fig. 3 Lay-out of the Thermal Prototype of the M-Module. The circled numbers indicate the location of RTD’s to determine the temperature profile.

MEASUREMENTS

As indicated in both Fig. 1 and Fig. 3, the surface of the module was covered with 20 RTD to monitor the temperature. In addition, one RTD measured the ambient temperature. We had tested the RTD’s before installation between -20 and $+50^{o}$C, and found them uniform to 0.1 Ω. In order to get immediate feed-back during the measurements, we used a computer controlled scanner (Keithley Model xyz) and read the resistances from an electrometer (Keithley 617) directly into the computer with a LABVIEW program. We found out that we needed a settling time of about 10sec for the resistance readings to stabilize.

The measurements were performed in the cold box of the LBNL ATLAS pixel group. The temperature of both the coolant (water-alcohol) and the ambient gas (N_2) were controlled independently. We performed a reading at room temperature and found the scatter of resistance values of the order 0.1^{o}C, due to the fact that all leads were of the same length and the scanner resistance was finite but uniform. The measurements of the temperature profile were performed at a coolant temperature of -10^{o}C, and ambient gas temperatures of -10, -5, and 0^{o}C, respectively.

EFFICIENCY of COOLING

Fig 4 shows the temperature on the EAR (RTD#15) and the cooling block (RTD#17) as a function of the heater tape power for the three different ambient temperatures. Although the coolant was kept at a constant temperature, we observed a slight rise in cooling block temperature. We will investigate in the future if this effect is caused by a boundary layer in the coolant.

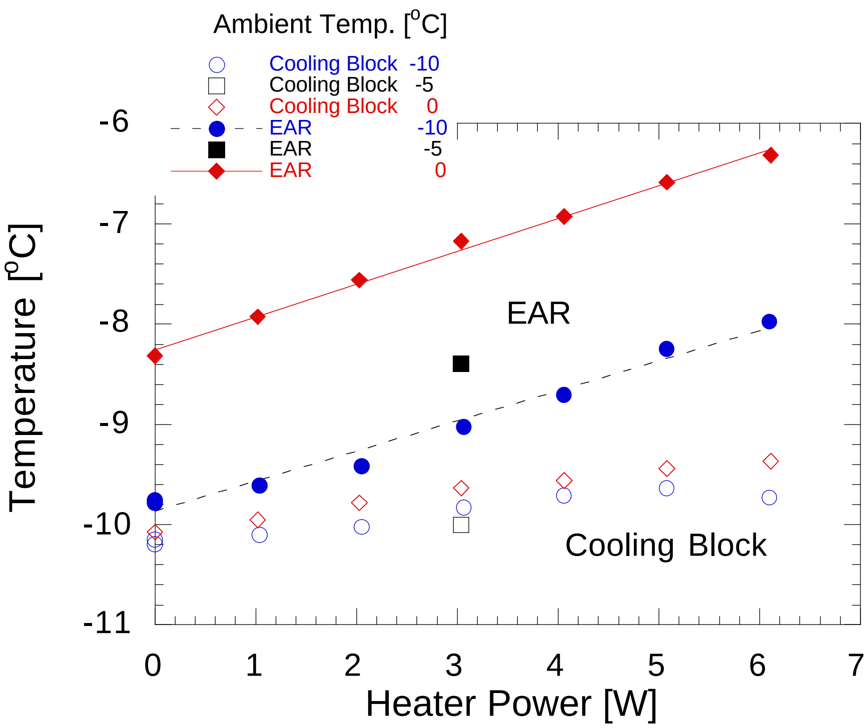

Fig. 4 Temperature of Ear and cooling block as a function of the heater tape power, at the three temperatures of the ambient gas, -10, -5 and 0°C, and coolant at -10°C.

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 between the EAR and the cooling block R and the effective convection coefficient of the silicon h_{conv}. In Fig. 5, we show the temperature difference between the EAR and the cooling block, which can be expressed as a function of the heat Q:

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

where the average silicon temperature was approximated to be ΔT above T_{EAR}, with $\Delta T = 1^oC$ from the following data. and the ambient temperature was measured to be T_{amb} = -10, -5 and 0°C. It should be noted, that during the first two low power settings at -10°C, the ambient was close to -8°C, thus convectively heating the module and causing the lower curve in Fig .5 to deviate from a straight line through zero.

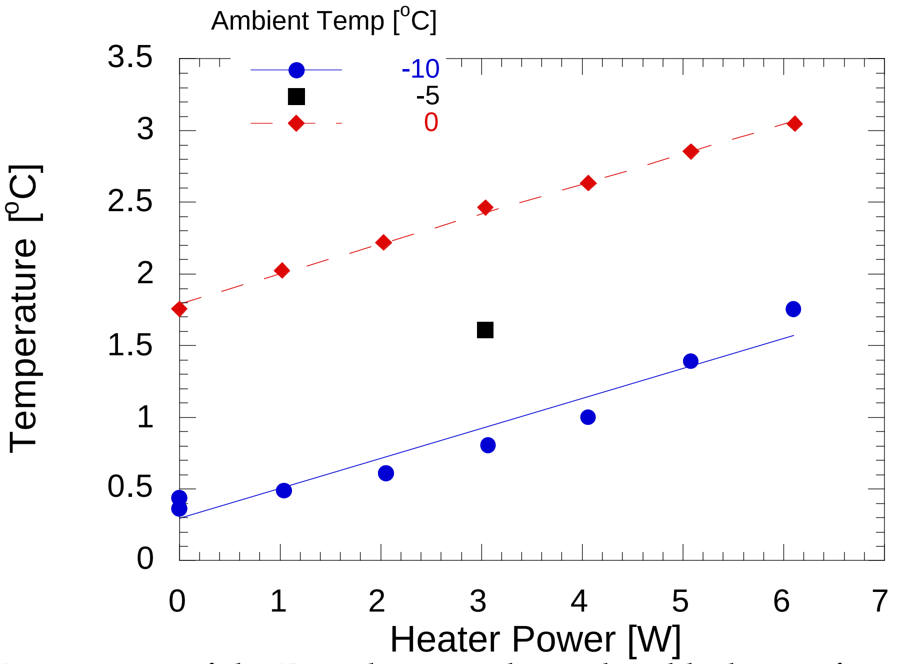

Fig. 5 Temperature of the Ear relative to the cooling block, as a function of the heater tape power, at the three temperatures of the ambient gas, -10, -5 and 0°C, and coolant at -10°C.

The data in Fig. 5 yield R= 0.25 [°K/W] - about a factor 10 smaller than when we used a stainless steel cooling block [1]-, and the effective convection coefficient of the silicon h_{conv} = 10 [W/m^2/°K], averaged over the temperature distributions on the module, which is close to the value measured by T. Kondo *et al* in a thermal study of the “classic r-ϕ module” [4] and our previous measurement [1].

At a power input of 3W through the heater tape, the module picks up 0.3W at -10°C and 0.7W at 0°C ambient through convection. 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 10 years of operation of ATLAS at the LHC.

In the following, we will refer all temperatures to the temperature of the EAR to eliminate the small temperature step between coolant and the EAR.

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 less than 0.2^{o}C. In Fig. 6, we show the temperature at RTD #1, which is on the outside of the PG material in between the heater strips on the edge opposite to the EAR,

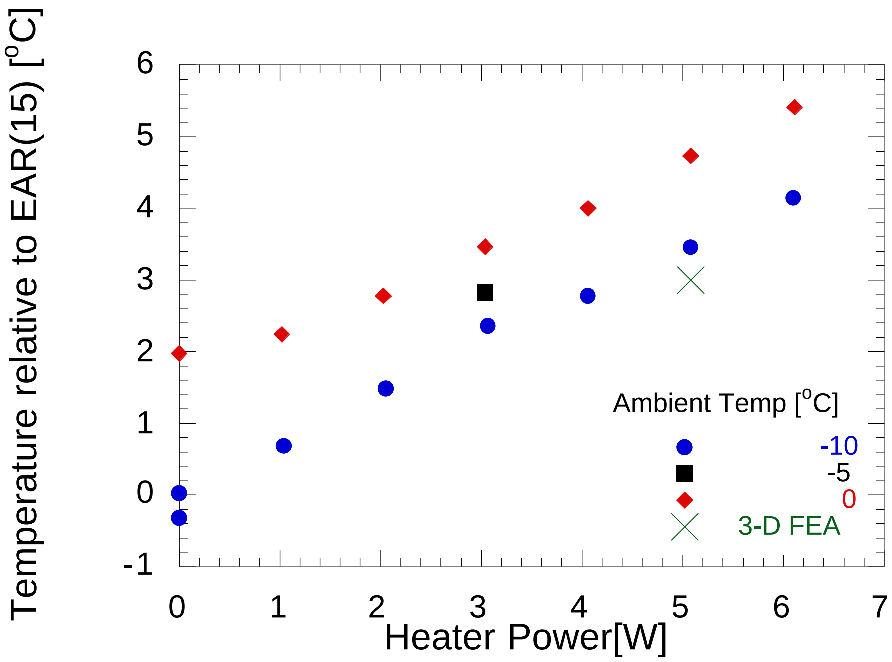

Fig. 6 Temperature of RTD#1, on the edge opposite to the Ear relative to the EAR, as a function of the heater tape power, at the three temperatures of the ambient gas, -10, -5 and 0^{o}C, and coolant at -10^{o}C.

At an ambient temperature of -10^{o}C and heater power input of 3W, the Edge is 2.4 ^{o}C above the EAR. At the higher ambient temperature of 0 ^{o}C, noticeable convective heating is observed at zero heater power. Thus the temperature increase with increasing ambient at 3W power is not linear. For 5W power input, we have added the prediction of a 3-dimensional FEA simulation, which includes the different materials including the PG heat spreader, the silicon wafers, and glues. Its input differs from our experimental set-up in that the electronics is simulated with the ATLAS chip set imounted on a Kapton hybrid, while we are using in the experiment a Kapton heater tape. Thus we would expect differences in the temperature profile in the region of the heater tape. At RTD#1, the data show a temperature of 3.5^{o}C relative to the EAR, while the simulation predicts 3.0^{o}C. Although the agreement is quite good, we will discuss this discrepancy in the following.

In Fig. 7, we show, in pairs of boxes, the temperature on several selected RTD location, together with the prediction of the FEA simulation. The measured data are in the squares on the right, the simulated values on the left. They are for 3W heater power and temperatures of -10^{o}C for both the coolant and the ambient gas.

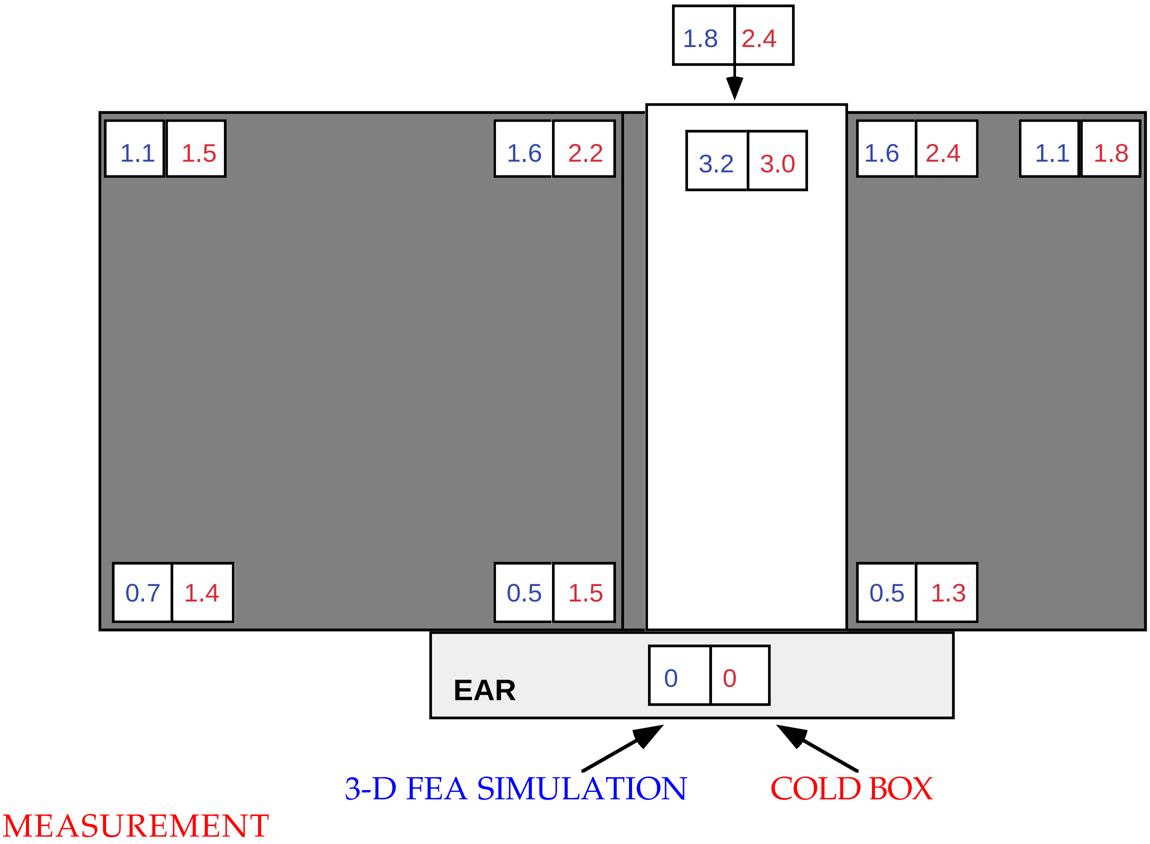

Fig. 7 Temperature profile of the M-Module, with a selection of RTD's indicated in the squares. Measured data are on the right, simulated values on the left. Heater tape power=3W, ambient gas and coolant at -10^{o}C.

It is interesting to notice that all temperatures on the modules are about 0.6^{o}C higher than predicted. We speculate that this is due to our way of construction the module, for example the additional pieces of 0.5mm thick carbon fiber material between EAR and cooling block as indicated in Fig. 1, and we will investigate this further. For the moment, we will simply subtract this "temperature step" from the data. The result for the corrected temperature profile is then shown in Fig. 8. With the temperature step of 0.6^{o}C removed, the data in Fig 8 agree very well with the simulation and show about 2^{o}C variation across the module. As mentioned before, the exact temperature of the electronics depends of the exact design of the hybrid.

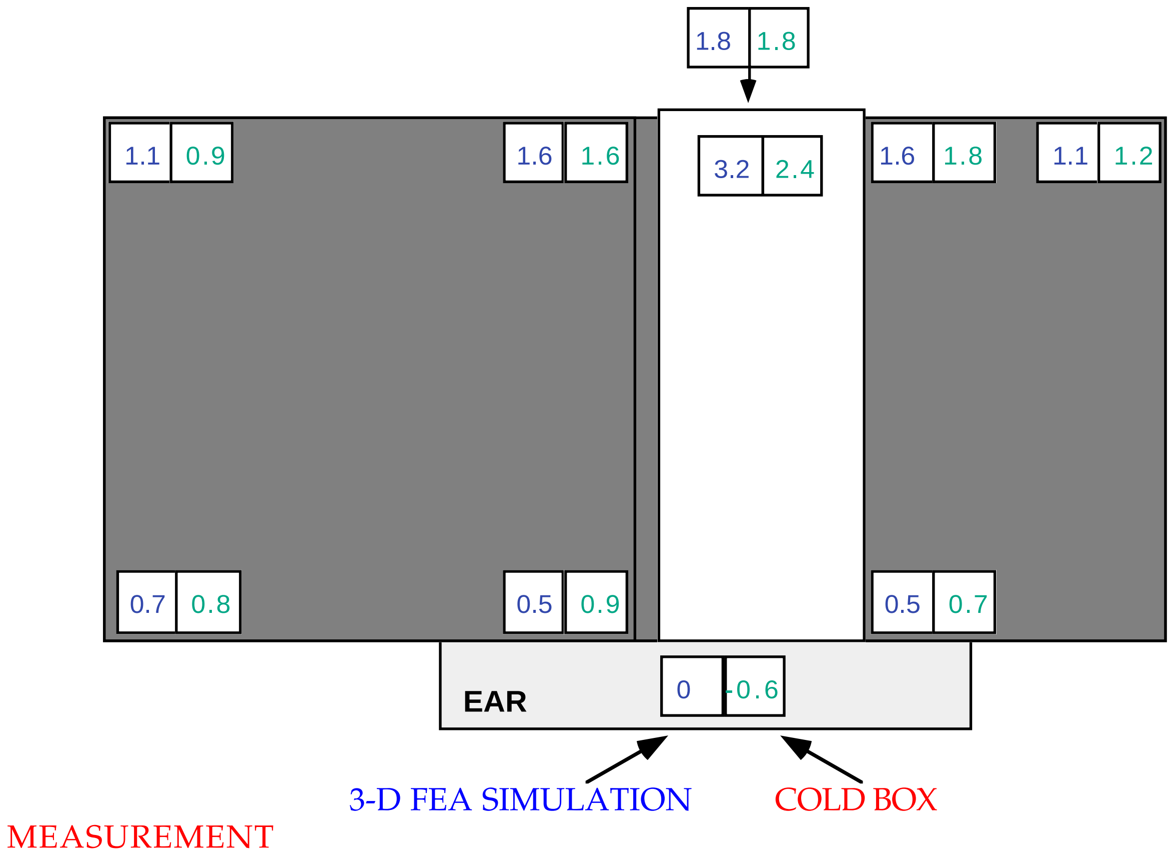

Fig. 8 Temperature profile of the M-Module after subtracting 0.6^{o}C to account for the temperature step in the EAR. Measured data are on the right, simulated values on the left. Heater tape power=3W, ambient gas and coolant at -10^{o}C.

CONCLUSION

The M-module allows safe and predictable removal of heat both from FEE power and from self heating of the detector. The largest temperatures encountered on the thermal prototype are on the Kapton heater and amount to about 3.5^{o}C above the coolant at 3W heater power and 0.5 W due to convection. The largest temperature difference measured across the silicon module is 1.5^{o}C.

Our results show that the temperature distribution across the module can be simulated reliably with 3-dimensional FEA, but we do not understand the temperature step at the EAR. Therefore, we will investigate better thermal coupling between the coolant and the module.

ACKNOWLEDGEMENTS

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