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Memorandum

Issues with thermal performance measurements of a prototype of Pixel support structure with Alpine Geometry (ATLAS)

To	*Entity*	*For information*	*Entity*

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History of versions

Version	*Date*	*Pages*	*Changes*
01	2016-01-22		
02	2016-01-25		Corrections from Jessica
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04	2016-02-14		English version
05	2016-02-26		

Description of the last Changes

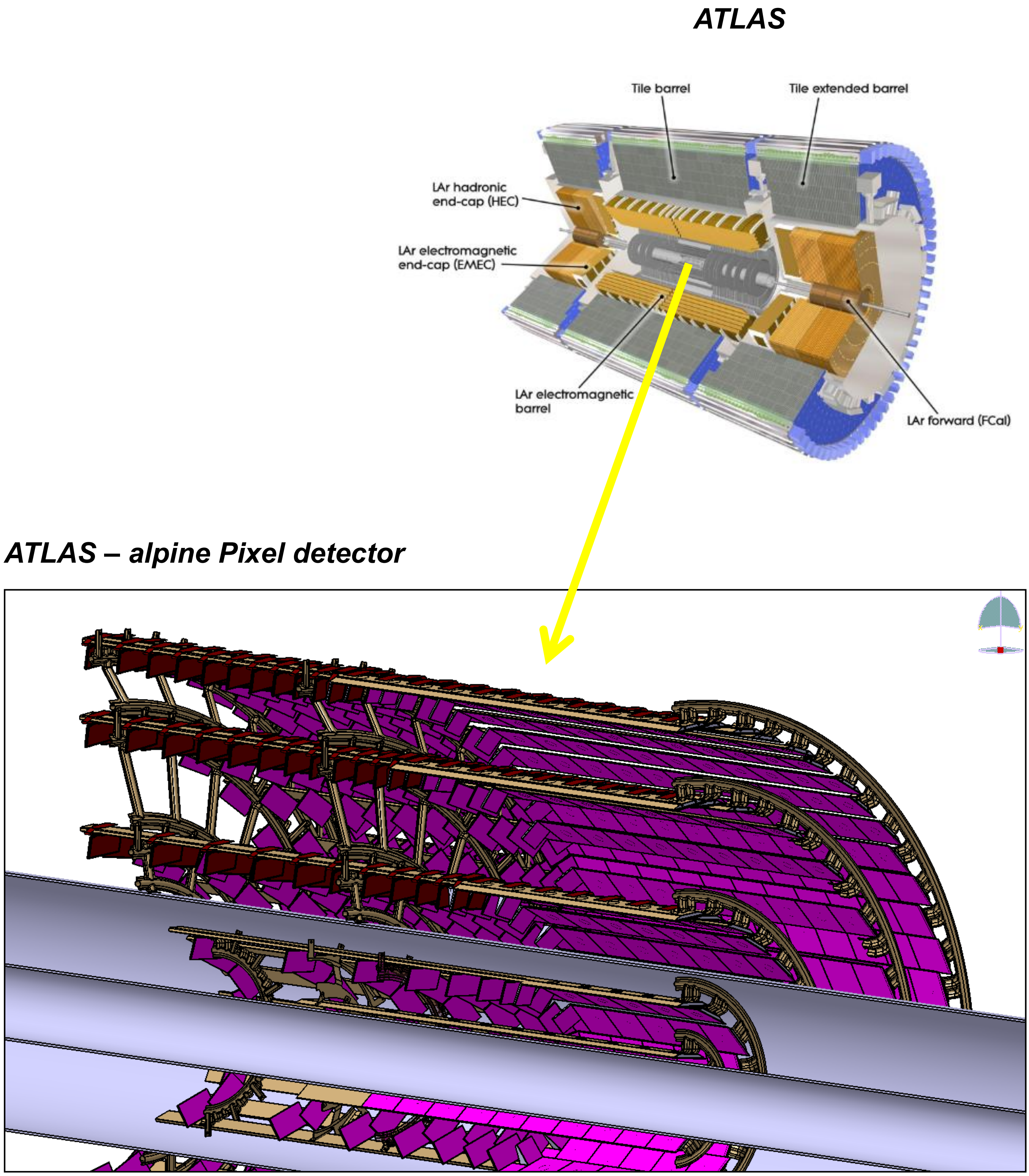
SUMMARY

1. INTRODUCTION

1.1 Aim of the document

This document presents issues with thermal performance measurements done with prototypes of Pixel support structure developed for the ATLAS Pixel detector for the replacement of the Inner Detector for HL-LHC Phase 2 (ITK). It specifically addresses the Alpine layout, which is one layout candidate, but it aims to be a contribution to define the right thermal measurement protocols whatever the design.

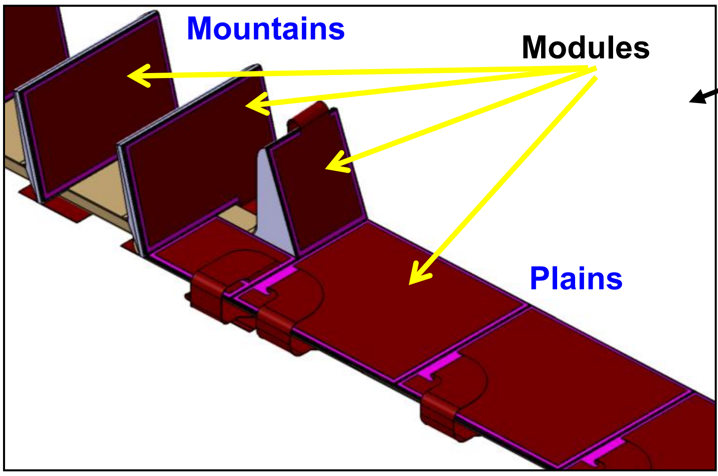
1.2 Experimental context

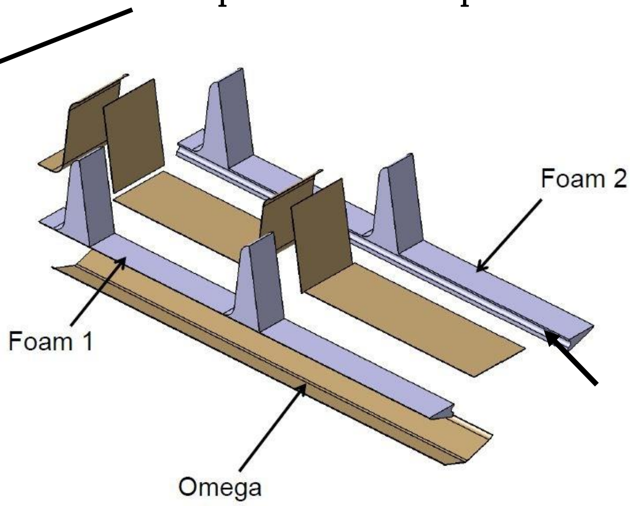


The pixel detector is the tracking device located closest to the LHC beam-pipe. The sensitive modules contain silicon sensors (pixels) connected to read-out chip (Front-end). They are supported by mechanical structures (generally called staves) made of carbon composite shells and carbon foam glued together. Some modules are parallel to the beam-pipe axis (plain modules) and the others (mountain modules) are inclined (~70 degrees)

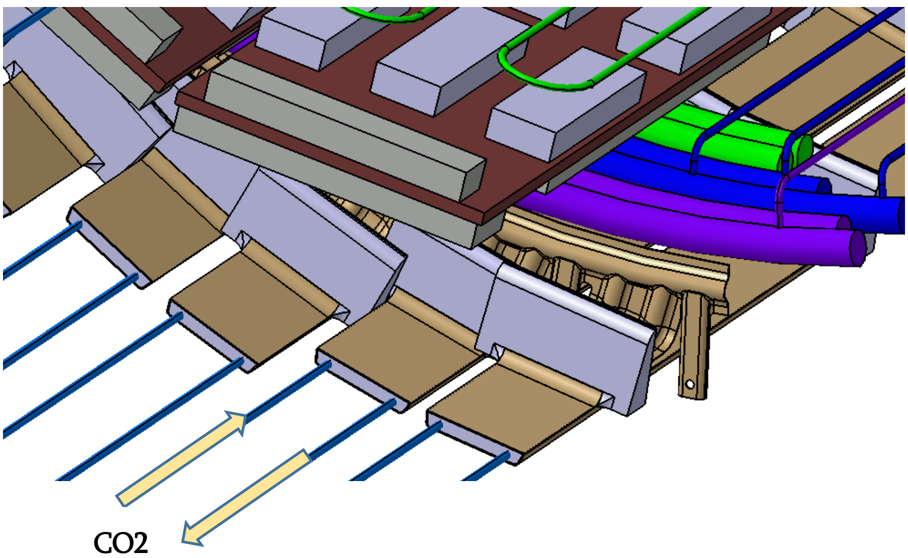
Stave :

Split view of the components :





The module cooling is performed with diphasic CO_2 flowing in titanium tubes (diameter 1.5 to 2 mm) glued onto the foam. Currently, the inlet and outlet of the tube are located on the same end of the stave. The tube is bent at 180° on the other end.



The Pixel detector will be surrounded by a dry gaseous nitrogen environment.

1.3 Thermal performance specifications

The main specifications are:

1. Module temperature always <-20°C
2. Temperature gradient within a single module <1°C

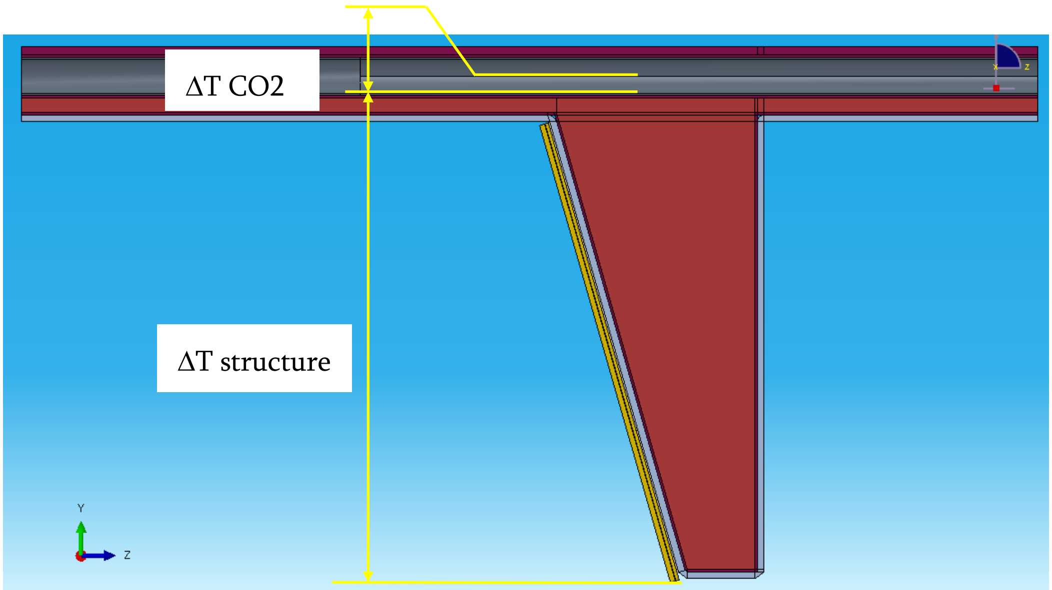
The mountain elements are the most challenging concerning the thermal performances.

The temperature of the diphasic CO_2 is supposed to remain between -30°C and -35°C within the core of the fluid (specification under discussion). The gradient between the fluid and the hottest point on the mountain can be split into two parts:

- Gradient between the fluid and the inner wall of the pipe,
- Gradient between the inner wall of the pipe and the hottest point.

The first component is computed with the Matlab program which includes a thermodynamic model specific to diphasic CO_2. Taking into account the thermal power injected in the evaporation channel, the pressure and the fluid temperature, it estimates the exchange coefficients along the tube depending on the gas/liquid ratio.

Cross-section of a mountain crossing the tube axis



2. EVALUATION OF THERMAL POWER

2.1 General concepts

As a first step, different geometries, materials and assemblies are evaluated in order to fulfil the required specifications. The exchange with the environment, including the one with the gaseous nitrogen is not taken into account.

Finite Element models, taking only into account heat transfer through conduction, are processed to compute the temperature map.

Based on the optimal configurations given by simulations, prototypes were built. Temperatures were measured at certain points to create a thermal map, and compared to the simulations result. The two targets are:

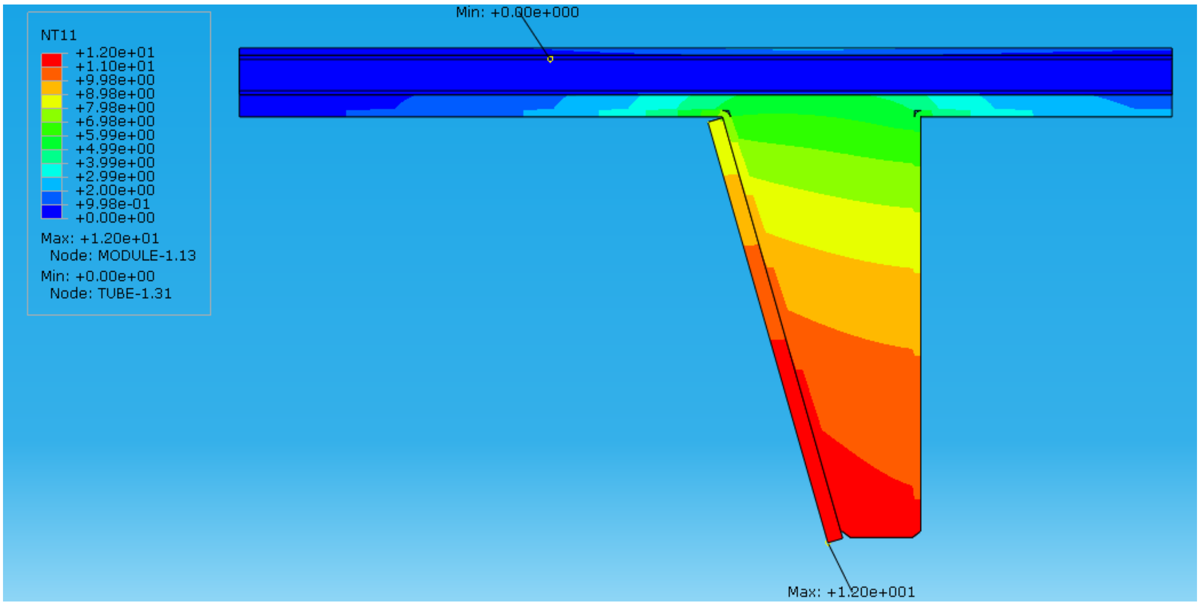
- Compare the different prototypes and so the conceptual choices,
- Compare the prototype with its simulation model.

For this last point, the environment should be as close as possible to the simulation.

2.2 Simulation results

<u>The data given below do not correspond to the optimal configuration that should fulfil the requirements.</u>

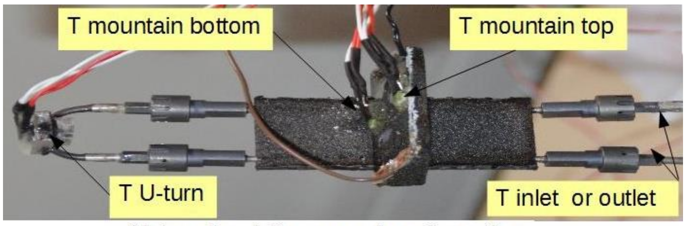
Assuming a nominal heat power of 5.3W, corresponding to 0.7W/cm2 produced by the heater, the simulation gives the following results:



The temperature on the tube is normalised to 0°C to display the gradients.

2.3 Thermal performance measurement from prototypes

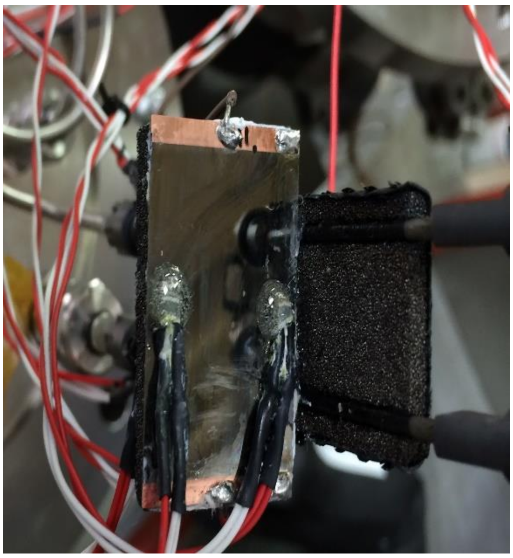
2.3.1 Prototype setup



Alpine stavelette general configuration

The mountain prototypes are cooled down by diphasic CO_2. The flow of the cold fluid and the pressure are monitored. PT100 temperature probes are glued with cyanoacrylate-glue onto the heater (silicon substrate coated

Zoom on glued probes



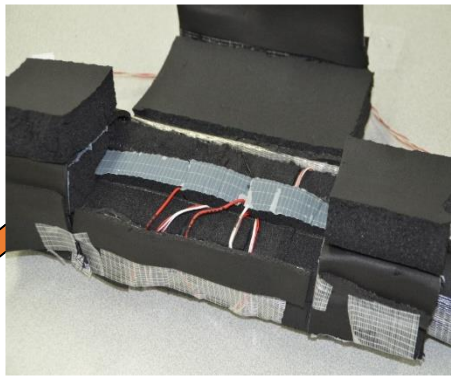
with resistive material that mimics a module). An epoxy-glue blob covers and surrounds the probe. Some probes are also glued onto the CO2 inlet and outlet tubes and the U-Turn. At these points, the measured temperature should be equal to the fluid temperature if the heat exchange is negligible.

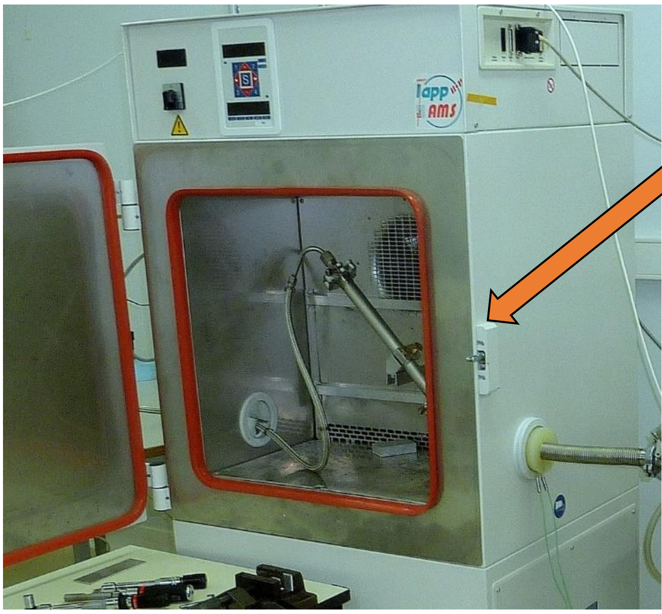
2.3.2 Configuration of test setup

The goal is to build a setup which is as close as possible to the simulation environment.

For the first tests, the thermal isolation from the environment was done with foam. However, the variations of temperature induced by the external environment demonstrated that this thermal shielding was not performant enough. These results were confirmed by doing similar measurements within a climate chamber with controlled temperature.

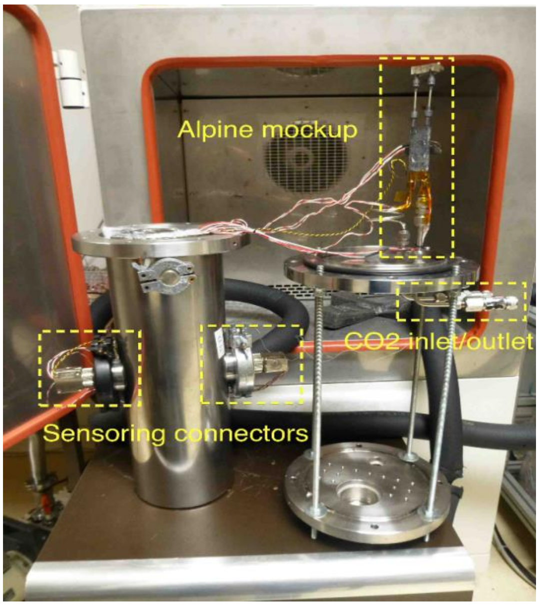
Prototype isolated with foam





To get rid of the external temperature influence, the prototypes were put in a vacuum chamber

Dismounted elements



Global view of setup

On the left picture, one can see the prototype (Alpine mockup) connected to the support structure (below) with tight feedthroughs to introduce and extract the CO2. This is the only connection with the vacuum chamber in addition to the PT100 probe cables (red and white) and the cables to transfer the electrical current for the heaters (black and yellow).

There is no protection against thermal radiation between the prototype and the vacuum chamber.

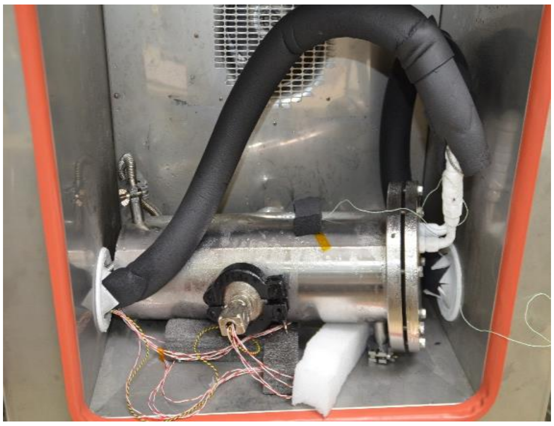
The probe cables (4 wires) have a total section of 0.32 mm2 for 1-meter length within the chamber. The wires are made of zinc-nickel alloy. The data acquisition is done with NI 9217 modules.

After careful optimisation (leak-avoidance, use of molecular pump) a pressure of ~10^{-4}-10^{-5} mbar has now been reached.

2.3.3 Addressed issues

At the beginning of the tests, a pressure drop of 10^{-1} - 10^{-2} mbar was reached in the vacuum chamber, and as such we thought that it was sufficient to neglect the heat convection and conduction through air which is absent in the simulation.

The vacuum vessel was transferred within the climate chamber. The temperatures were measured on the prototype, not heated by the heaters but cooled by CO2 (see picture).

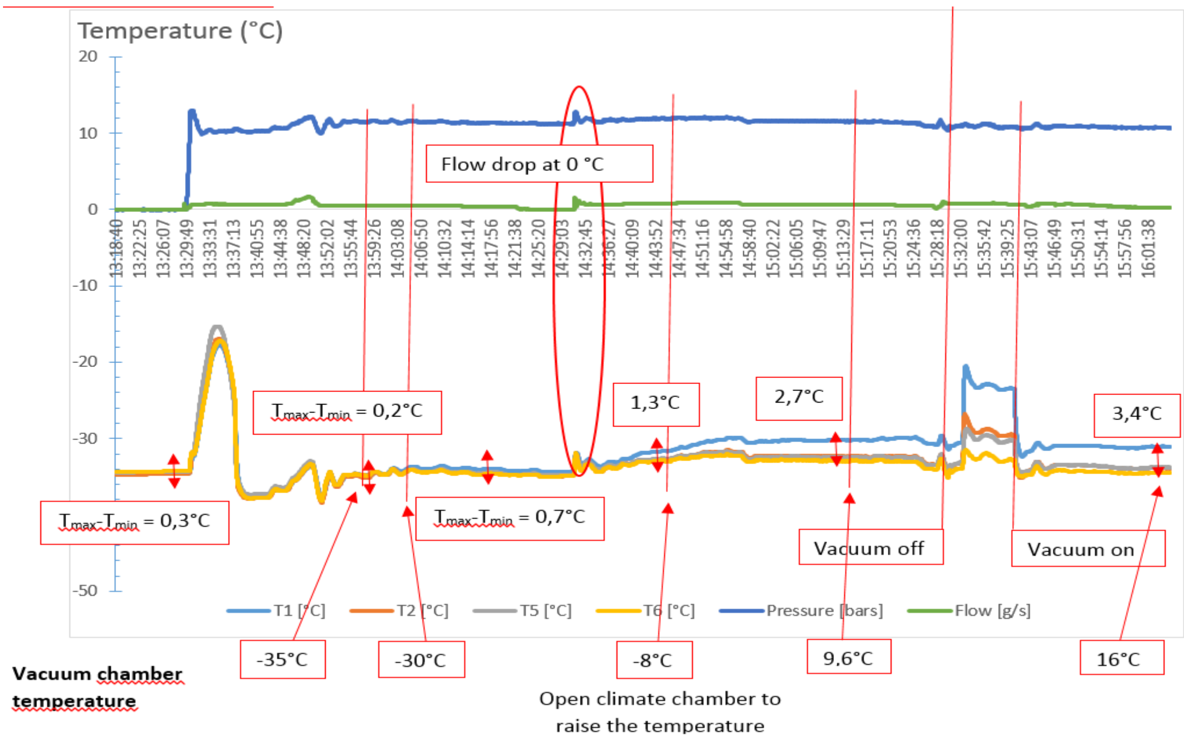


Vacuum chamber within climate chamber

The climate chamber temperature was adjusted from -35°C to +16°C. On the below plot T1 (light blue) is the highest point of the mountain and T6 on the CO2 outlet.

When the climate chamber is at -35°C the two temperatures are similar within few tenths of a degree and diverge when the chamber temperature runs away from -35°C. The precision of the temperature probes is estimated to be 0.3 °C according to the delivery spreadsheet.

At the end of the test, the vacuum is removed and the temperature difference reaches +8°C demonstrating the heat transfer through the air at atmospheric pressure.



The conclusion is that with an external environment at room temperature, and for low heat power, there is already a gradient of 3.4 °C which cannot be neglected. If we consider roughly (from measurement on this prototype that is far from being final) a 24K gradient for a 5.9W heat power, then the equivalent incoming power estimated to (5.9*[3.4/(24-3.4)]= 1 W Compared to the nominal power (5,3 W), this is 19%. But the measured gradient differs between prototypes (from 1.5 °C to 7°C). That means the parasitic heat can be much higher and is very difficult to predict.

Many options have been investigated:

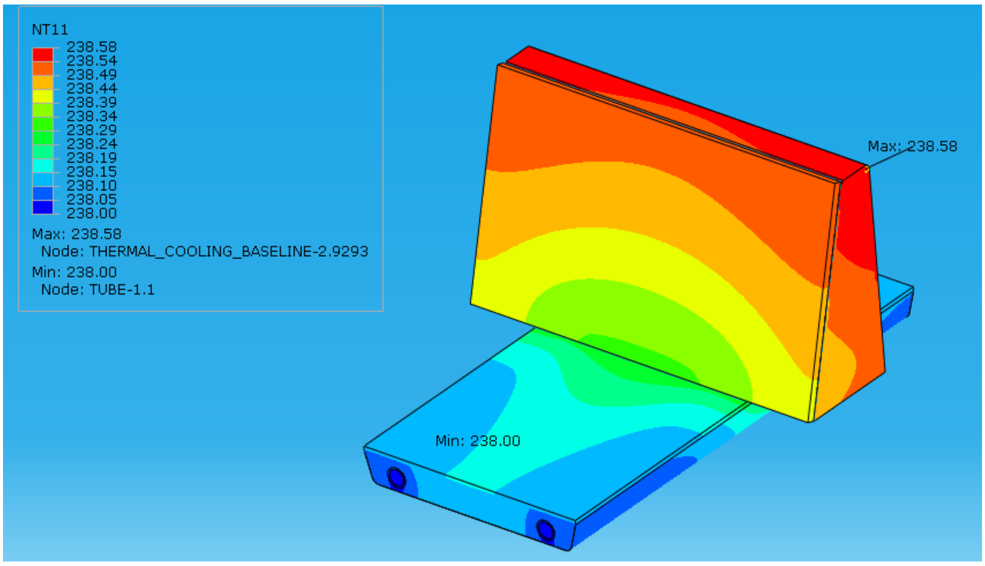
- Thermal radiation exchange between the prototype and the vacuum chamber,
- Heat transfers though the cables of the PT100 probes,
- Bias on PT100 probes through Joule effect,
- Heat exchange through convection or molecular conduction through the remaining gas in the vacuum chamber.

Results seem different depending on the prototype used. Maybe the construction of the prototype (foam, glue, graphite cover,…) has a significant influence on the parasitic effect.

2.4 Investigations

2.4.1 Radiation

A FEA computation was done with ABAQUS. The most severe case has been considered with a uniform temperature of the environment at 300K. The maximum gradient is 0.6 K, translated into 0.18 W. An analytical calculation assuming black body gives a consistent 0.2 W



More simulation should be done to evaluate the sensitivity of the parameters.

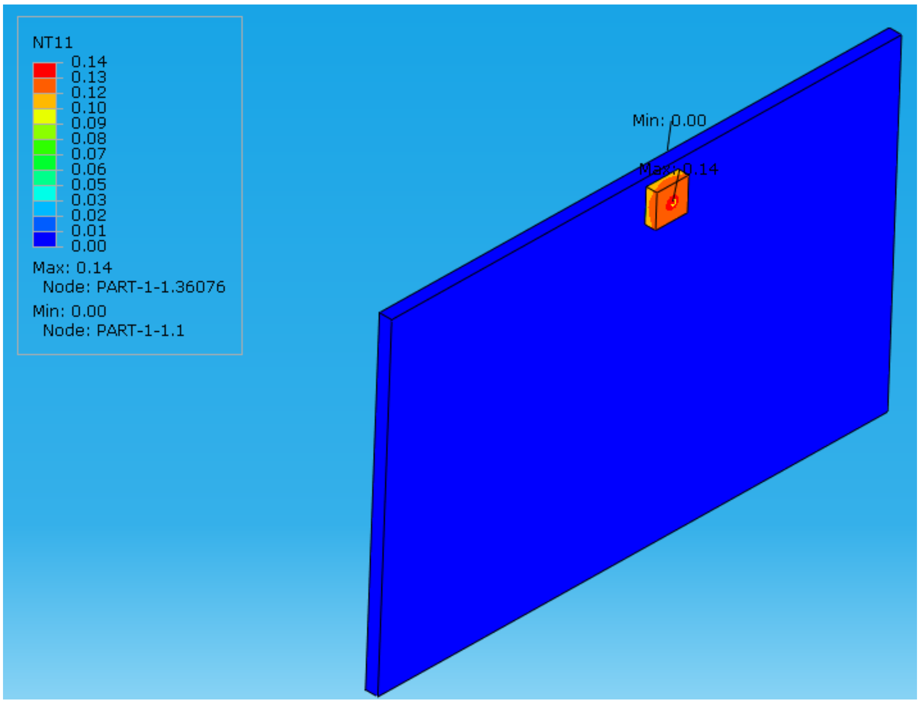
2.4.2 Heat conduction through probe cables and joule effect on PT100

We model a silicon heater, onto which a PT100 temperature probe is glued (50 µm of glue with K=1W/m.K) connected to a cable of 0.317 mm^2 section (K=100W/m.K) and a length of 1 m.

The temperature of the opposite side of the heater (the one supposed to be glued on the face plate) is fixed to 0K. The other end of the cable is fixed at 55 K (to have gradient of 55 K = 20 – (-35)).

A thermal power (joule effect) of $100*(10^{-3})^2=10^{-4}$ W is introduced on the external side of the probe.

The result of the simulation estimates a gradient of 0.15K in agreement with simple analytical calculation. On the next picture (below), the cable is hidden.



2.4.3 Convection and molecular conduction

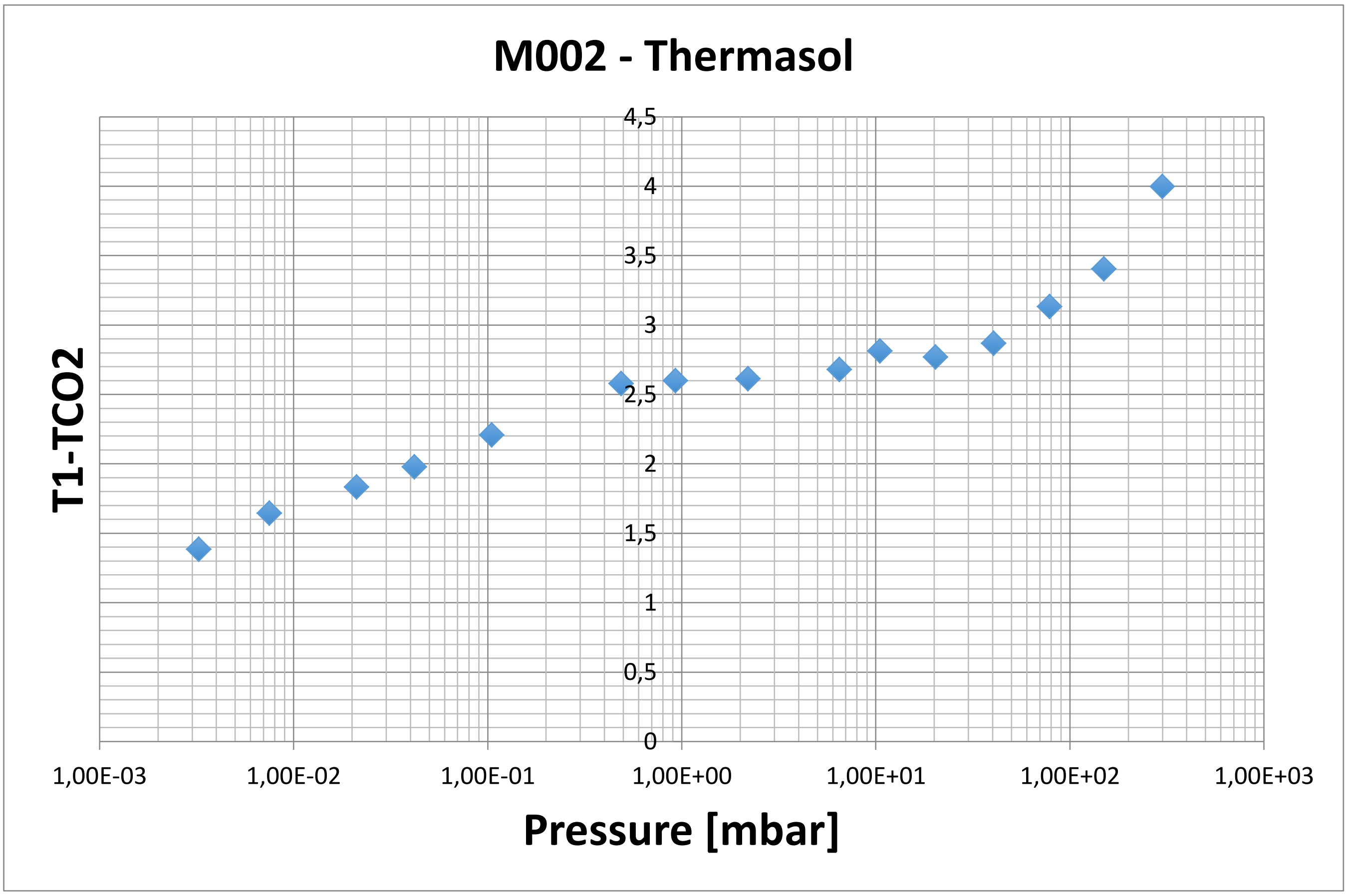
No theoretical estimation of thermal transfers induced by the remaining gas in the vacuum chamber has been performed for the moment.

Measurements have been done to estimate the temperature dependency on the residual pressure.

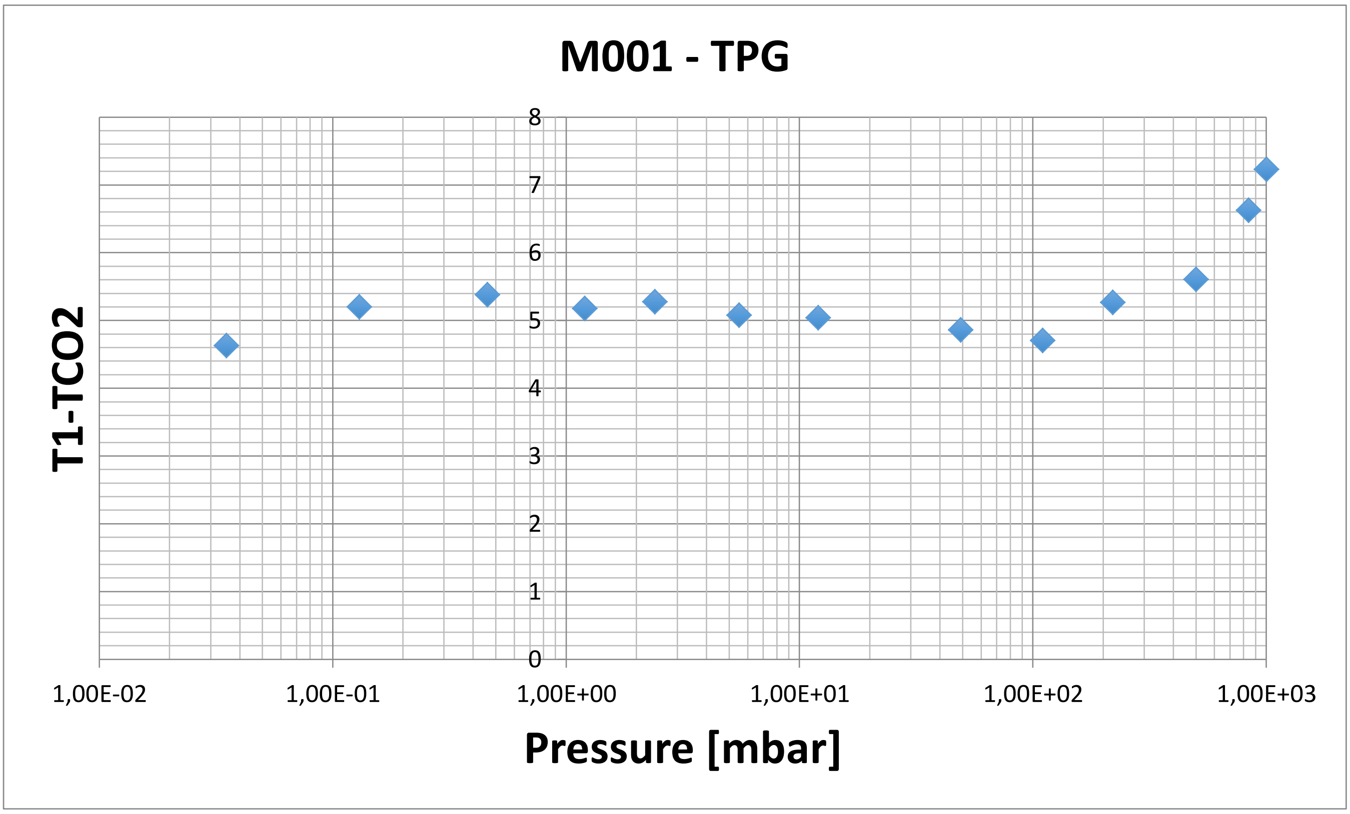
The next three plots (M002-M001-M003) display a maximum temperature gradient (top of mountain – CO2) as function of the pressure in the vacuum vessel for three different prototypes. M002 has a 30 µm graphite sheet covering all the mountain, M001 and M003 have only a 250 µm graphite plate (TPG) glued onto the mountain face, there are no covers on the foam.

For the two first plots (M002 and M001), no heating was applied. Ultimate vacuum pressure is about few 10^{-2} to few 10^{-3} mbar. For the last sample (M003), the vacuum pressure dropped down to few 10^{-5} mbar and measurements were done with 0.0, 0.5 and 1.1 W. M003 was made to evaluate the influence of mountain foam made of two parts connected by glue without graphite cover. That explain the very bad results we got. We had to use this one because M001 and M002 had to be repaired due to lots of manipulations.

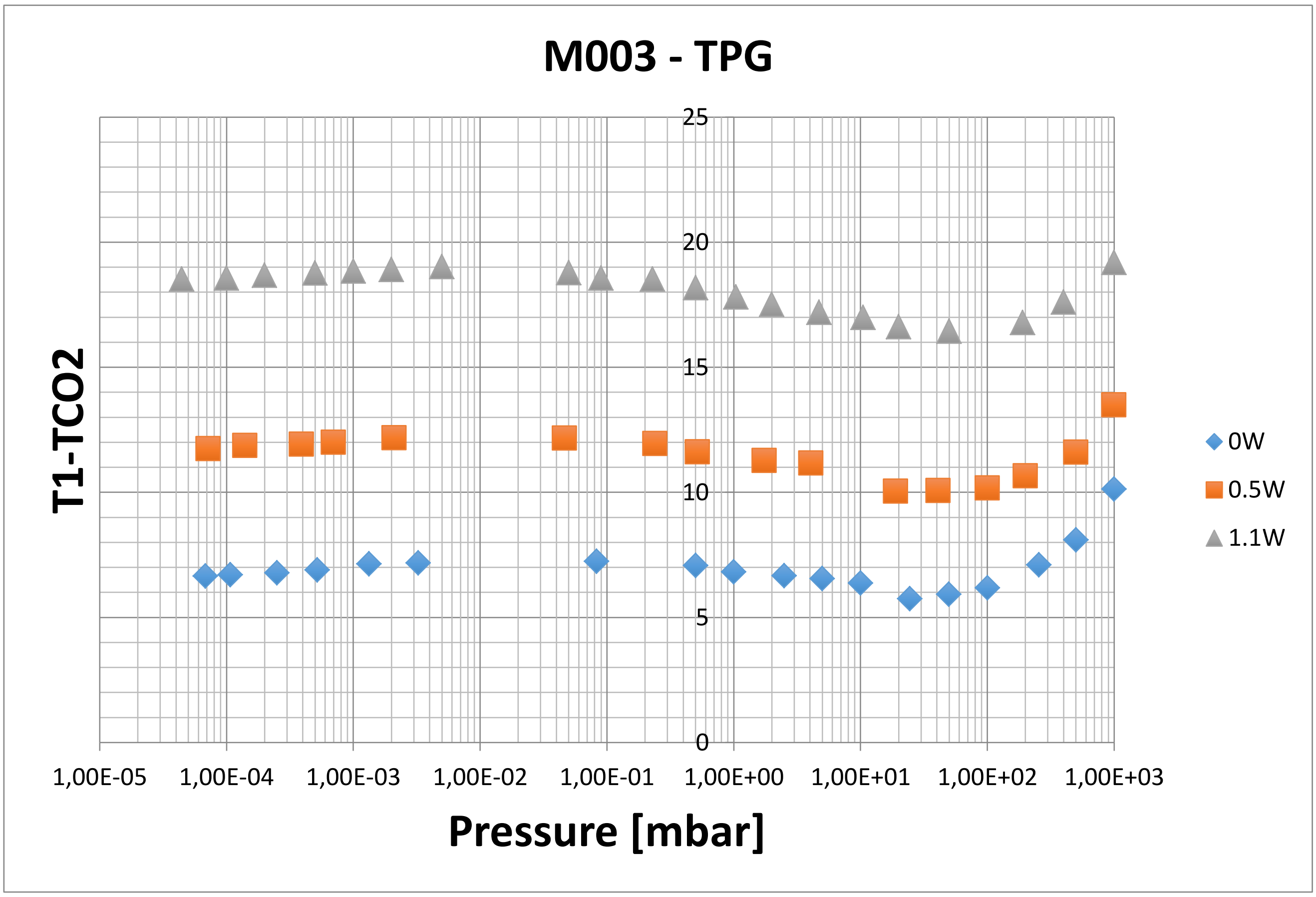
For all series of measurements, a starting pressure of 1 mbar is used, after which the pressure is decreased.



M002 - Thermasol
T1-TCO2
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
1,00E-03
1,00E-02
1,00E-01
1,00E+00
1,00E+01
1,00E+02
1,00E+03
Pressure [mbar]



M001 - TPG
T1-TCO2
0
1
2
3
4
5
6
7
8
1,00E-02
1,00E-01
1,00E+00
1,00E+01
1,00E+02
1,00E+03
Pressure [mbar]



As expected, the highest gradients mainly occur at atmospheric pressure. The gradient always decreases until 100-50 mbar. Afterwards the situations are not clear and the gradients differ from sample to sample. One can notice that:

- The TPG prototypes (M001 and M003) give higher values for the gradient (7 K) than for Thermasol (M002) (2.5 K).
- For Thermasol, below 100-50 mbar the gradient is quite stable, until 1 mbar at which point it decreases. As for TPG, the gradient tends to increase a bit, then is quite stable. Looking at M001 results we thought the gradient could decrease by lowering the vacuum pressure, but this is not the case for M003.
- When we increase the power (M003) the gradient at low pressure tends to be equivalent to the one measured at atmospheric pressure, and about 3K more than the one measured at 100 mbar !

During these tests we suspect that there is a possible leak of CO_2, since the pressure increases slightly when the CO_2 flux is switched on.

3. CONCLUSIONS

The current setup to measure thermal performances of prototypes has biases which cannot be neglected. The gradient of parasitic heat can reach 7K. This has to be compared to the current specifications ranging between 5 – 7K at nominal heat production.

Our evaluation of the radiation influence and heat transfer through the cables of the temperature probes has no significant effect to explain our observations. Investigations have to be pursued. We can notice that right now, no other prototype measurements was done under vacuum, and measurements performed on other samples (SLIM) show the same type of effects.

4. REFERENCES

Alma memo 554 – Effect of vacuum Pressure on the Thermal Loading of the Alma Cryostat- G.A Ediss – National Radio Astronomy Observatory – 25 July 2006.