Thermal Performance of the Petal Prototype

Anja Beck, TU Dortmund, Germany

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Abstract

Contents

1 Introduction

The high-luminosity upgrade for the LHC planned to be ready to run in 2026 imposes new challenges on detectors. For instance, an enhanced luminosity is immediately related to elevated radiation levels which constitute heat development. To avoid a thermal runaway and ensure reliable measurements, the electronics must be held at a constant temperaturewhich requires some kind of cooling system for all detector components.

Which year should I put?

How cold should it be?

1.1 Petal

During my time in the DESY summer school, I participated in testing the thermal performance of the inner tracking detector of the ATLAS experiment. Figure 1 illustrates its position within the big detector and the planned upgraded design. The parts studied at DESY are the so-called petals that are assembled perpendicularly around the beampipe to track particles with low transversal energy. Figure 2 displays a picture of the tested petal prototype.

Maybe without the last sentence.

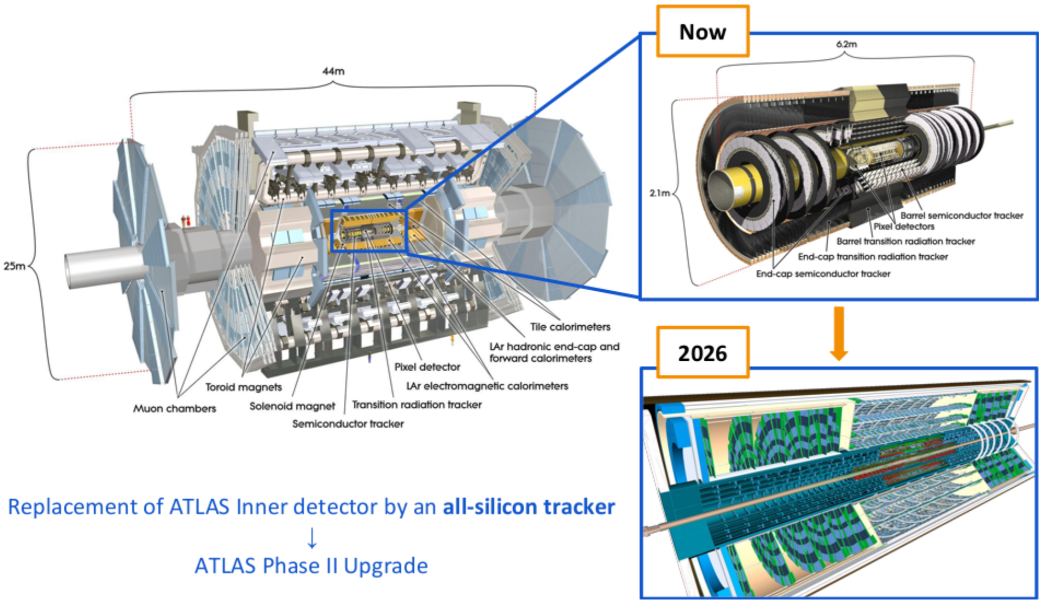


Figure 1: Schematics of the upgrade of the ATLAS inner tracking detector.

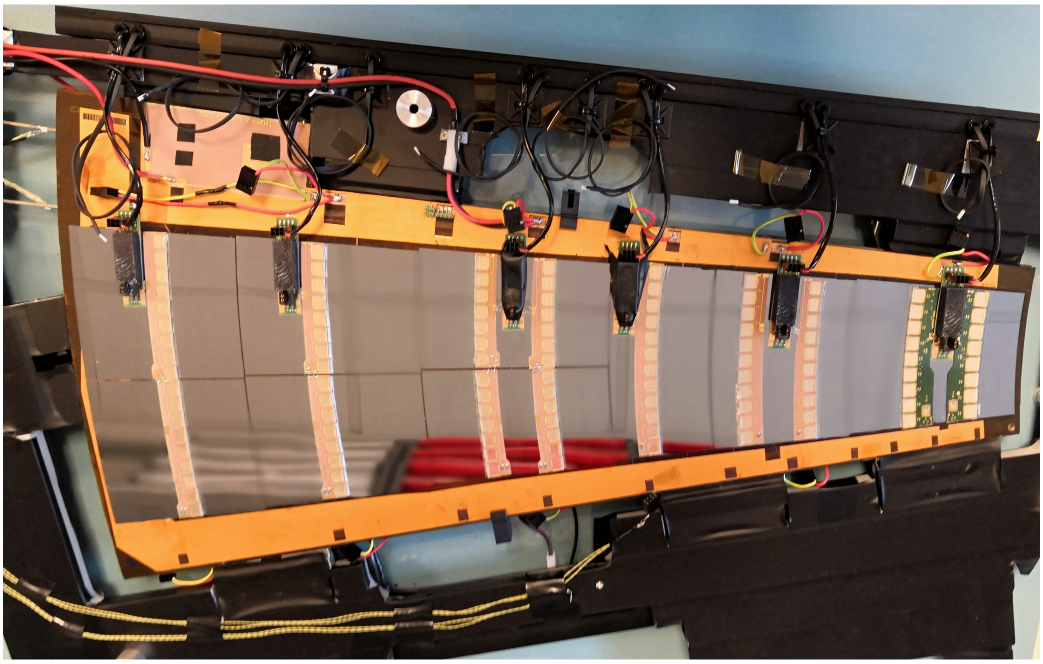


Figure 2: Picture of the tested petal prototype.

1.2 Cooling System

Figure ?? shows a prototype of the bare cooling loop. The cooling system is based on the energy taken by a phase change. Liquid CO_2 is pumped into the cooling loop where some of it evaporates if exposed to heat. This evaporation takes energy (enthalpy of evaporation) which is taken from the heat source.

Find better wording.

2 Infrared Theory

To assess the thermal performance of the petal, we measure the emitted radiation in the infrared (IR) spectrum. To properly evaluate the data measured with the IR camera, we need to understand the behaviour of IR radiation and camera software. This section gives an overview over these topics.

2.1 Emissivity

Every body emits IR radiation depending on its temperature. Light in the IR spectrum behaves identical to the more intuitive visible light. This means that surfaces can emit, absorb, and reflect IR radiation. Being purely interested in the *emitted* power, we need to minimize reflection in the IR region. The emissivity ϵ describes the ability of a surface to reflect IR radiation. It is a value between 0 and 1, where 0 corresponds to total reflection, whereas 1 corresponds to no reflection. So, to achieve good results using IR measurements, we cover the petal with a high emissivity coating. The determination of the exact emissivity value for the chosen paint is described in section 3.

Is it really only IR or is there an emissivity for all ranges?

2.2 Conversion from Temperature to Power

To fully comprehend and also for being able to check the camera data, a theoretical relation between the emitted power and temperature is crucial. As we are trying to approach an ideal black body using the high emissivity paint, Planck's law for black body radiation,

$$p(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{\exp\left(hc/(\lambda k_\mathrm{B} T)\right) - 1} \,, \tag{1}$$

can be a good start. The IR camera measures radiation over a range of wavelengths, so we need to integrate this and obtain

Describe variables!

$$F(T) = \int_{\lambda_\mathrm{min}}^{\lambda_\mathrm{max}} \frac{C_1}{\lambda^5} \frac{1}{\exp\left(C_2/(\lambda T)\right) - 1} \, \mathrm{d}\lambda \,. \tag{2}$$

Taking account of reflections of the ambiance, we propose the following equation

$$P(T) = \underbrace{\epsilon F(T)}_{\text{emission}} + \underbrace{(1-\epsilon) F(T_\mathrm{amb.})}_{\text{reflection of ambiance}} \,. \tag{3}$$

Describe variables!

2.3 Comparing Manual and Camera Computations

Different Wavelength Ranges

Different Emissivities

Fit with Global Scaling Factor

3 Emissivity Measurements

This section treats the determination of the emissivity of the paint. To do so, we need the paint to be next to a surface of known emissivity. We use high emissivity tape with $\epsilon_{\mathrm{T}} = 0.95$. In terms of equation (3), we can then write

$$P_{\mathrm{P}} = \epsilon_{\mathrm{P}} F(T_{\mathrm{P}}) + (1 - \epsilon_{\mathrm{P}}) F(T_{\mathrm{amb}}) \ ,$$
$$P_{\mathrm{T}} = \epsilon_{\mathrm{T}} F(T_{\mathrm{T}}) + (1 - \epsilon_{\mathrm{T}}) F(T_{\mathrm{amb}}) \ .$$

Assuming that both areas have the same real temperature because of their proximity and therefore emit the same amount of IR radiation, we set $P_{\mathrm{P}} = P_{\mathrm{T}}$. After rearranging, we obtain an equation for the emissvity of the paint

$$\epsilon_{\mathrm{P}} = \epsilon_{\mathrm{T}} \frac{F(T_{\mathrm{T}}) - F(T_{\mathrm{amb}})}{F(T_{\mathrm{P}}) - F(T_{\mathrm{amb}})} \ . \tag{4}$$

The first part describes the used set-up and the second part outlines the calculations.

3.1 Set-Up

As the petal will later be used at temperatures below 0 °C, also the thermal performance tests need to be adapted to low temperatures. Therefore, we measure the emissivity of the paint on the cold side of a Peltier element. Figure 3 shows the used Peltier. To ensure a low humidity to avoid ice formation, the Peltier sits in a cardboard box with dry air flushing that only leaves a hole for the camera lens.

3.2 Results

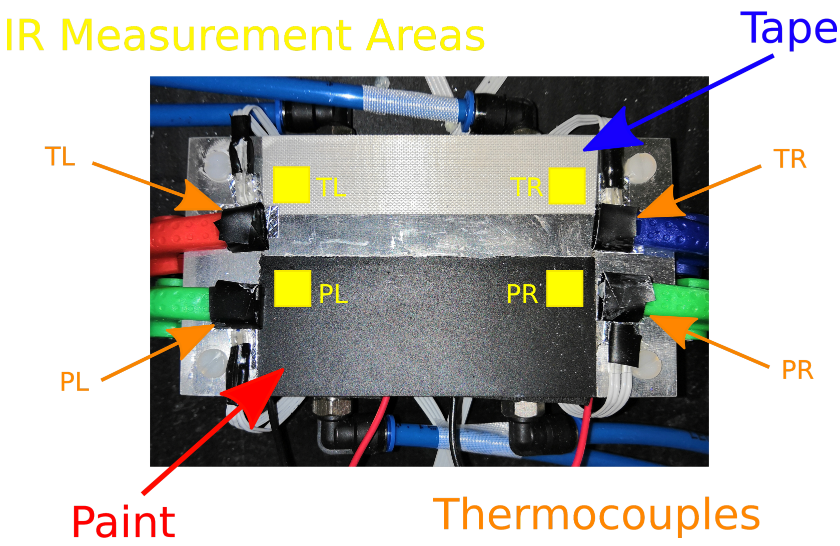


Figure 3: Peltier element used for measuring the emissivity of the paint. We see the cold side with a taped and a painted area. There are also for thermocouples (type: pt100) which are named according to their position (e.g. TL means tape left). Additionally there is an IR camera measurement area next to each of the thermocouples.

4 Understanding the Camera Software

When reaching the camera sensor, the IR photons induce a current. The software interprets this signal and displays the corresponding temperature. According to the user's manual, these computations are based on equation (3) (see section 2.2). As described in section 2.2, we are not yet able to reproduce the camera data with it.

Check how this goes!

To gain confidence in the software nevertheless and intuition for crucial variables in infrared measurements, we conducted studies using the camera software. Figure 4 shows the result. To obtain it, we took one of the thermograms taken during the emissivity measurements described in section 3 and chose one measurement point (paint right). We then manually set different ambient temperatures and varied for each of them the emissivity, keeping all other variables constant. In brief, the plot shows the dependence of the object temperature on ambient temperature and emissivity.

What temperature was the thermogram taken at?

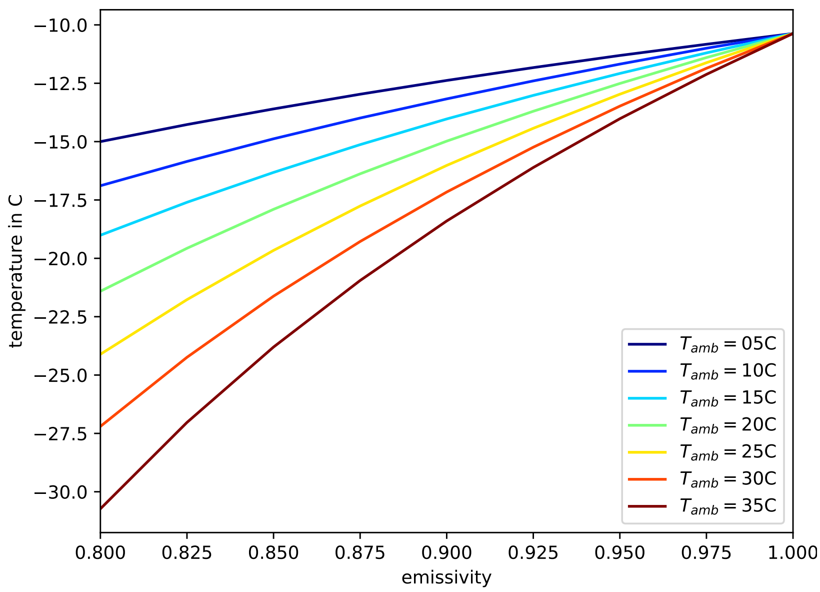


Figure 4: Object temperature on the paint for different emissivities and ambient temperatures computed by the software.

Figure 5 shows the same plot using the same thermogram but using tape right as measurement point. As pointed out by the red dotted line, the emissivity for this measurement with real $T_{\text{amb}} = 21.9\,°\text{C}$ and real surface temperature $T_{\text{pt100}} = -11.54\,°\text{C}$ should roughly be 0.96. This is close but not identical to the manufacturer value of 0.95.

Comment this result.

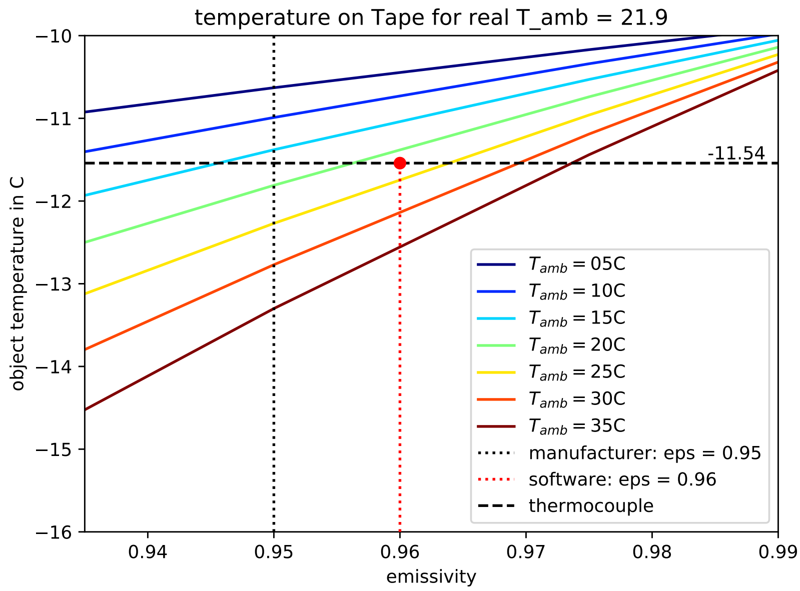
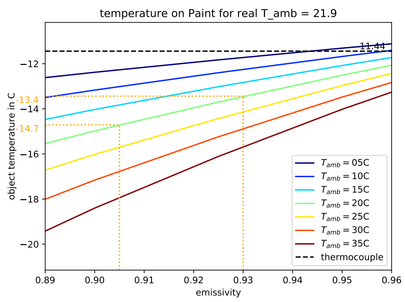


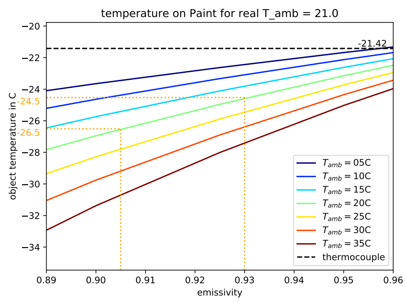
Figure 5: Object temperature on the tape for different emissivities and ambient temperatures computed by the software.

If we go back to the paint, we can use this kind of plot to evaluate the impact of the uncertainty in the emissivity value (see section 3) on the temperature measurement. Figure 6a shows again the dependency of temperature on the paint on ambient temperature and emissivity. Assuming $T_{\text{amb}} = 20\,°\text{C}$, the emissivity range and the following temperature range is being highlighted by the orange dotted lines. More precisely, the emissivity range of $0.905 \leq \epsilon \leq 0.930$ determined in section 3 leads to a temperature uncertainty of just above $1\,°\text{C}$ at a real surface temperature of roughly $T_{\text{pt100}} = -10\,°\text{C}$ (see 6a). For colder temperatures around $T_{\text{pt100}} = -20\,°\text{C}$, the following temperature uncertainty rises to $2\,°\text{C}$.

Comment on this result.



(a) $T_{\text{pt100}} = -11.44\,°\text{C}$.



(b) $T_{\text{pt100}} = -21.42\,°\text{C}$.

Figure 6: Object temperature on the paint for different emissivities and ambient temperatures computed by the software, including a display of the effect of an uncertainty in the emissivity on the temperature for an ambient temperature of 20 °C.

5 Tests on the Petal

5.1 Preparations

5.2 First Results

6 More

References

[1] Study of ... *Author name*