Performance tests of dual-phase CO_2 cooling for particle detectors

J-H Arling[1], M Baselga[1], S Diez[1], I-M Gregor[1], P Goettlicher[1], R Gupta[1], M Hauser[2], U Parzefall[2], F Poblotzki[1], A Renardi[1], S Schmitt[1], D Sperlich[2], M Stanitzki[1] and R Stroem[1]

[1] Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany
[2] Albert-Ludwigs-Universitt Freiburg, Hermann-Herder Str. 3a, 79104 Freiburg, Germany

E-mail: alessia.renardi@desy.de

Abstract. Evaporative CO_2 cooling is becoming a popular cooling solution for large-scale, high-energy particle detectors, such as the new ATLAS Inner Tracker (ITk) for the high-luminosity upgrade of the LHC. CO_2 offers a high latent heat transfer at reasonable flow parameters and is an environment friendly alternative to many other coolants currently used. This cooling technique is used to investigate the thermal performance of prototypes from the ITk strip detector produced at DESY. The strip end-cap local support structure, called petal core, is designed to allow a good heat transfer between silicon strip modules glued on its surface and the embedded titanium cooling pipe. Studies on the thermal properties using infrared thermography have been performed to analyse the heat dissipation path which allows also to detect eventual imperfections in the assembly as part of the quality control strategy. A similar analysis was executed on a petal loaded with electrical modules to study the heat generation due to active components and its dissipation for each module under different CO_2 conditions.

1. The ITk project for the ATLAS phase-II upgrade

The ATLAS detector [1] of the High-Luminosity LHC has to be able to operate to large particle fluences due to the increase in the integrated luminosity up to $7.5 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Therefore, an upgrade of the current Inner Detector, as part of the so-called Phase-II upgrade, is required to guarantee a working detector in these conditions. The detector will be completely replaced in order to deal with the unprecedented high levels of radiation and particle rate of the collider. The Inner Tracker (ITk) [2] is an all-silicon detector: pixel and strip sensors cover the inner and outer radii, respectively. The ITk is divided into a central region, called Barrel, and two forward regions, the Endcaps. Each strip Endcap is built with six disks, each of them populated by 32 *petals*. The petal is a support structure loaded with silicon modules on both sides. It consists of three main objects: the *silicon modules* [3], the petal *core* and the *End of Substructure*(EoS) cards [4], as sketched in fig. 1. The modules are wedge-shaped and six different geometries are needed to achieve full hermiticity of the forward regions called R0 on the inner radius up to R5.

2. The CO_2 cooling technique

The evaporative CO_2 method allows to cool down the experiment working in the dual-phase regime of the coolant. The heat is transferred from the experiment to the liquid CO_2 circulating through the petals pipe and generates its evaporation allowing for a large latent heat transfer.

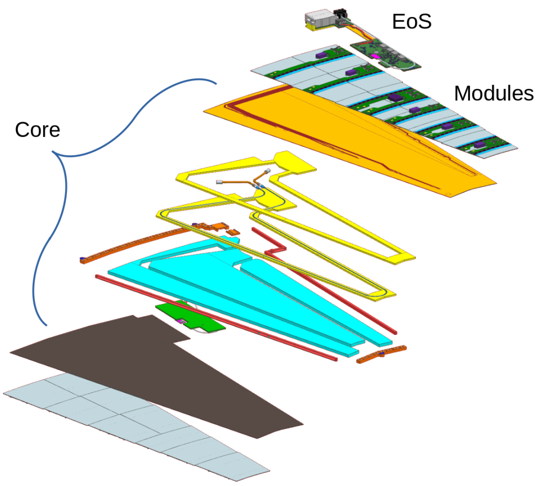

Figure 1. Exploded view of the petal structure. **Silicon modules**: the readout and power/control electronics is directly glued on top of the strip sensor. Wire-bonds are needed to bias the sensor, power the readout chips and transmit the data collected by the strips. **Core**: a carbon-fiber structure with an embedded titanium cooling pipe constitutes the mechanical support for the modules. All electrical connections are incorporated in a multi-layered copper polyimide bus tape on each petal side. **EoS**: electrical interface between petal and off-detector, these cards provide power and differential data to the modules and receiving and sending it off-detector through optical fibers.

The coolant temperature is controlled by the CO_2 pressure to provide a good cooling performance working in the wet-steam region. The dry-out scenario, an excessive evaporation of liquid CO_2 ending in a sub-optimal cooling regime, needs to be avoided during operation [5]. The usage of dual-phase CO_2 cooling for particle detectors is advantageous due to several reasons [6]:

- a large latent heat transfer is possible due to the phase change energy for the transition of liquid to gaseous CO_2 and allows low mass flows of the coolant (few g/s);
- a low pressure drop allows to use small cooling pipe diameters reducing the material budget of the cooling services in the detector, whereas the heat transfer capability is kept high;
- a practical temperature range of [-40, 25]°C→[10, 60]bar is accessible for detector cooling;
- CO_2 is a natural, non-toxic and non-flammable gas and well suited for high-energy physics applications, as it is radiation resistant and non-magnetic.

The MARTA CO_2 chiller (*Monoblock Approach for a Refrigeration Technical Application*)[7] used for the thermal analysis is able to provide dual-phase CO_2 cooling in a temperature range from -35°C to +20°C, in which the tests for the petals are performed.

2.1. Experimental setup for thermal analysis
The tests were performed first on "naked" prototype petal cores, and then on a petal core structure partially loaded with silicon module prototypes and an EoS card (only on one side). In both cases, the same setup has been used: the petal is placed inside a chamber to allow the imaging with an infrared (IR) camera; the MARTA CO_2 system is connected to the core's pipes to provide CO_2 cooling at different temperatures; the CO_2 coolant temperature and pressure is measured at the inlet and outlet; temperature and relative humidity are monitored inside the chamber; power supplies for low and high voltage are required to actively power the modules.

3. Thermal investigation on petal cores
After the construction of a petal core, a series of quality control tests are conducted to validate the assembly process. One of these tests consists of an infrared imaging thermal analysis performed at the lowest CO_2 temperatures. Here, particular emphasis is on the detection of eventual delamination defects. IR thermograms are used to measure the temperature along the pipe at $\sim$ 80 equidistant linear markers, as showed in fig. 2. Figure 3 shows a front-/backside comparison for two of the prototype cores under test ("core 07" and "core 08"). A better agreement is found for the front sides, whereas the back side of core 07 is slightly warmer.

This observation can be explained by different ambient conditions in the chamber and the uncorrected emissivity of the core surface influencing therefore the measured temperatures.

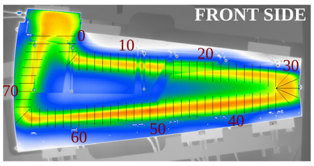

Figure 2. IR thermogram of a bare petal core with its front side at a CO_2 set point of 20 bar analysing the temperature along the cooling pipe [6].

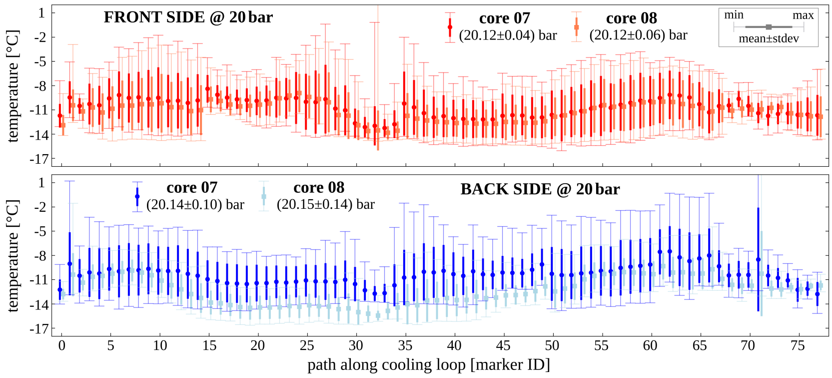

Figure 3. Temperature distribution comparison along the cooling pipe for the two core prototypes at a CO_2 set point of 20 bar [6].

A second analysis is performed on the same thermogram evaluating the module areas by ten polygonal pixel selections as depicted in fig. 4. The same observation as before can be observed in fig. 5, but for the EoS region the inverse temperature behaviour is present. Here, the reason is a known delamination defect, which proves the suitability of this method as a QC tool.

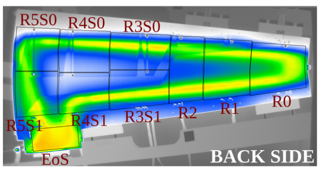

Figure 4. IR thermogram of a bare petal core with its back side at a CO_2 set point of 20 bar analysing the temperature inside the module areas [6].

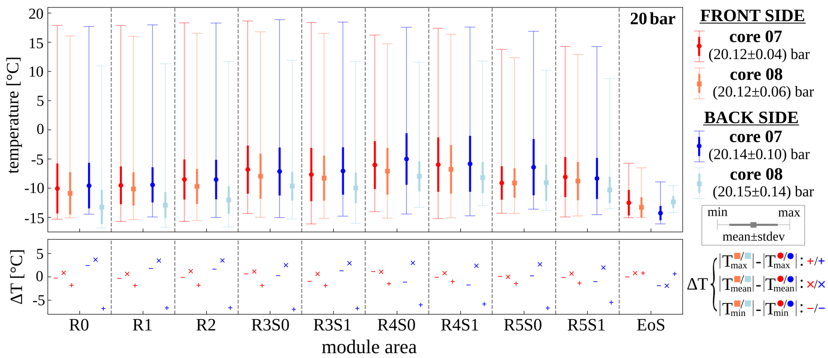

Figure 5. Temperature distribution comparison in each module area for the two core prototypes at a CO_2 set point of 20 bar [6].

4. Thermal analysis on an electrical petal

For the core loaded with modules, the same thermal analysis is repeated and the resulting IR thermogram is shown in fig. 6 for the coldest CO_2 temperature achieved (-34 °C) and all the silicon modules powered on. The absolute values do not indicate the real temperature on the petal because of the uncorrected emissivity of each component (e.g. silicon sensor, read-out chip). The temperature of each module is evaluated from the IR thermography using again polygonal regions of interest, about the same size of the relative module. The trend is plotted in fig. 7 for every tested CO_2 temperature. The average temperature is comparable for all modules and the coldest value is measured on the EoS region showing the good thermal interface for that region. The right side of R3, R4 and R5, the so-called *S0* part, is slightly warmer than the left one, the *S1* part, because of the power electronics glued on its sensor.

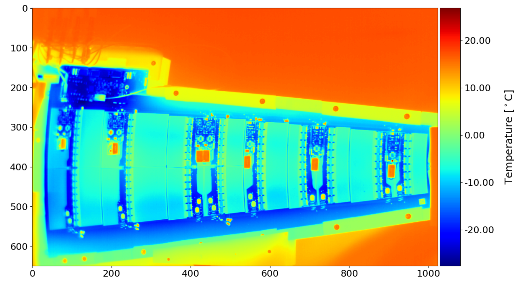

Figure 6. Example of a thermogram (1024 × 678 pixels) taken by the IR camera of the powered on petal at a CO_2 temperature of -34 °C. The cooling pipe is barely visible in the thermogram due to the thermal conductance of the silicon modules.

In order to monitor the temperature of the module electronics, Negative Thermal Coefficient thermistors (NTCs) are glued close to the electronics and read out during the CO_2 cycle with the trend shown in fig. 8. The reading values follow the same behaviour of the coolant in confirmation of the good cooling performances of the local support.

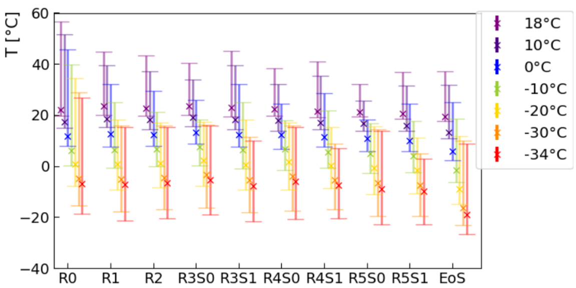

Figure 7. Temperature average and span calculated over the pixels selected for each module area at different CO_2 temperatures.

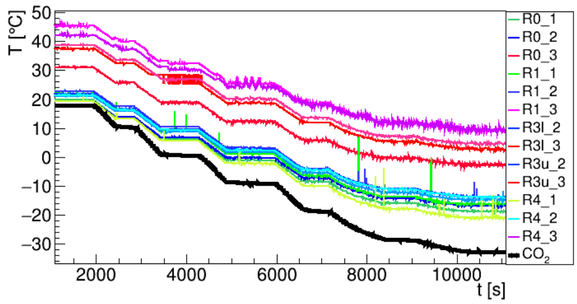

Figure 8. Measurements taken by NTCs placed next to read-out chips (green palette, *_1/_2*), on the hotter, power electronics (red palette, *_3*) and the CO_2 inlet temperature (black).

5. Conclusions

Thermal analyses were performed on ITk strip prototype local support structures to investigate how the heat is generated and dissipated by dual-phase CO_2 cooling. IR thermography proved to be a valid tool to check the thermal performance and to find eventual defects in the assembly procedure. The analysis of two core prototypes shows comparable results and it was also possible to detect delamination defects. The thermal study on a core loaded with electrical components indicates that all the modules follow the same temperature behavior with the EoS as the coldest area on the petal. These thermal studies demonstrate the validity of the petal design and the cooling approach with dual-phase evaporative CO_2, also confirmed by the NTCs readings.

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