Cooling for the LHCb Upgrade Scintillating Fibre Tracker

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As part of the LHCb Phase-II upgrade programme, the existing downstream tracking systems will be replaced by a new scintillating fibre tracker read out by multi-channel silicon photomultipliers (SiPM). To ensure high tracking performance over the entire experiment's lifetime, the SiPMs will be operated at sub-zero temperatures, down to -40°C. The proposed SiPM cooling system is outlined and the design considerations which led to the choice of the monophase liquid cooling solution are described. The requirements on the cooling system are discussed, along with the constraints the thermal considerations impose on the mechanical design of the tracker modules. The prospective refrigerants (C_6F_{14} and 3M Novec thermal fluids) are compared with each other, with an emphasis on their effect on the environment. The SiPM cooling system consists of the remote cooling plant, insulated transfer lines, the local distribution pipework and the cooling structures inside the read-out boxes spread over twelve 5×6 m^2 tracker planes. The main design challenges of this system are associated with its large linear extent and severe restrictions on the geometrical envelope and, hence, insulation. Since the SiPM themselves produce very little heat, the thermal load of the entire system, estimated as 13 kW, is mostly passive. Main system design parameters, as well as the latest results of the thermal mock-up tests, are summarised.

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1.Introduction

The LHCb detector [1] is a single-arm forward spectrometer designed to perform high-precision flavor physics measurements at the CERN LHC. As part of the proposed LHCb upgrade [2] for the LHC Phase 2, the existing downstream tracking systems will be replaced with a new scintillating fibre (SciFi) tracker read out with multi-channel silicon photomultipliers (SiPMs), as described in the SciFi Tracker TDR [3].

The tracker (Fig. 1) consists of twelve 5×6 m^2 layers, arranged with the average spacing of about 70 mm along the beam. Every layer consists of two half-planes, each composed of half a meter wide “modules” containing ribbons made of 0.250 mm diameter scintillating fibres. Each module has two identical read-out boxes (ROB) at the top and at the bottom, where the fibres are interfaced with the SiPMs. The ROB encases 16 SiPMs, together with their cooling structures and the front-end electronics. Fig. 2 shows a prospective 128-channel SiPM array.

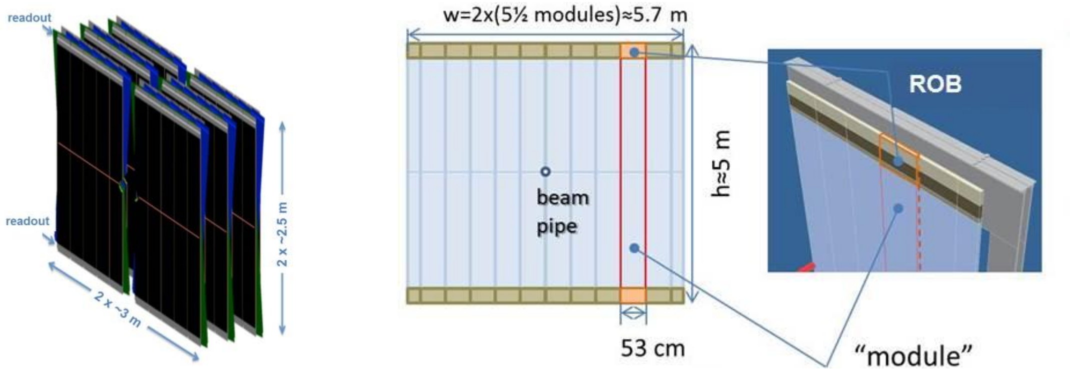

Figure 1: Left: schematic view of the SciFi tracker with 3 stations of X-U-V-X planes. Middle and right: a SciFi layer composed of “modules” each having the read-out boxes at the top and bottom ends. In X-planes the modules are vertical, while in stereo-angle U- and V-planes they are tilted at ±5°.

2. SiPM cooling

2.1 System requirements

It is crucial for the SciFi Tracker to operate the SiPMs at low temperature, in order to reduce their thermal dark count rate (DCR). The light yield from the fibre ribbons is relatively low (on average, about 20 detected photons per MIP) and will decrease with time due to the radiation-induced attenuation in the fibres. Thus, to keep the tracking efficiency high, the hit detection thresholds must be as low as possible (of the order of a few photoelectrons). At this level, the DCR can give rise to a competing hit rate which will increase with time due to the neutron-induced radiation damage in silicon, as explained in Refs. [3, 4]. The only way to mitigate this effect is cooling, as the DCR depends exponentially on the temperature and drops by about a factor two for every 10 K decrease in the temperature of the SiPM die [4].

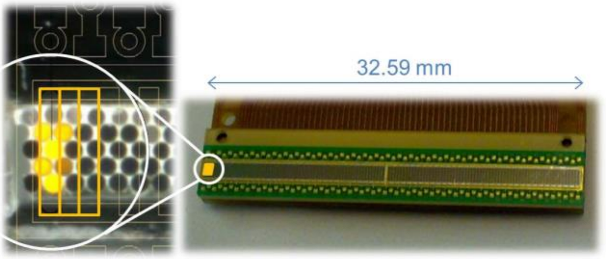

Figure 2: A custom-made 128-channel SiPM array with 0.25×1.32 mm^2 cells matching the fibre diameter and the thickness of the 5-layer ribbon. The SiPM signals are transfered to the front-end electronics via a flex PCB bonded to the SiPM package. There will be about 4600 such arrays in the whole SciFi tracker.

It has been estimated that for a satisfactory tracking performance by the end of the experiment's life, the SiPMs will have to be operated at down to -40°C [2]. Although the overall system thermal load is mostly passive (SiPMs produce very little heat, on average ≪1 W per ROB), this requirement is quite challenging because of the large linear extent of the SiPM arrays – about 150 m in total – and a tight space envelope inherited from the existing tracker, leaving no room for evacuated guard volumes.

Apart from the working temperature, there are requirements on the temperature uniformity in space and stability in time, because of a sharp dependence of the SiPM breakdown voltage (and hence the gain) on the temperature. Groups of 4 SiPM chips will have common gain and threshold adjustments and these settings will be fixed between calibrations. Within such groups, the temperature profile has to be uniform and stable within about 1°C [3]. The cooling system modularity should match the modularity of the tracker; in particular, every ROB should have its own cooling structure. The system should be safe for people and hardware and, possibly, environment-friendly.

The existing 128-channel SiPMs can only be cooled externally, through a thermal contact with an external heat exchanger. The efficiency, long-term stability and compactness of the cooling structures, the effects of thermal strains and sharp themperature gradients across the SiPM-fibres interface, vapor-tightness of the SiPM enclosure, potential moisture condensation on the outer surface and the heat load – all these factors have to be taken into account by the thermal design of the ROB, to a large extent driving its construction. Since SiPMs are situated outside the tracker acceptance and the expected integrated ionisation dose and neutron fluence are small for most of construction materials, there are no particular restrictions on the choice of ROB materials, except for their compatibility with the chosen cooling technology.

2.2 The choice of the cooling technology

With these requirements and observations in mind, we considered several cooling technologies as candidates, including Peltier cooling with low-temperature heat pipes, chilled air with vortex tubes and liquid-based options, both 2-phase and monophase.

[2] In the beginning of the operation, the SiPM temperature might be higher.

[3] This can be relaxed for the new generation of SiPMs having a weaker temperature dependence of the gain [4].

The preferred solution is a monophase liquid cooling, with serial connection in a branch combining 6 consecutive ROBs in every quarter-plane, as shown in Fig. 3.

The considerations behind this choice were as follows:

- Liquid cooling is an established technology, permitting use of commercial off-the-shelf components (pumps, chillers etc.) and offering more flexibility in the choice of refrigerants, compared to the evaporative cooling.
- It has a big reserve in cooling power and offers a lot of room for optimisation to satisfy the requirements on the temperature uniformity and stability.
- It is the simplest and least expensive option, requiring a minimal amount of additional equipment at the detector side. There are no compelling reasons to use the 2-phase option, more appropriate for inner detectors with severe restrictions on material budget. The thermoelectric cooling option is disfavoured because of the need to dissipate the heat produced by the discrete Peltier coolers which have a very low efficiency at the required temperature difference of 60°C.

The main drawback of the monophase liquid cooling is the need of cold transfer and interconnection lines which will include flexible sections for the movable half-planes.

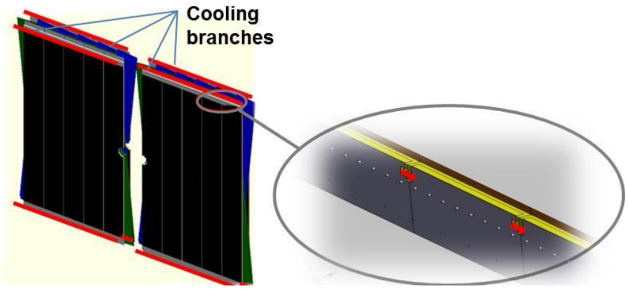

Figure 3: Serial connection of six ROBs in a a cooling branch. The entire detector cooling system will have 48 independent branches.

The serial connection of the ROBs somewhat compromises the modularity concept, but allows to reduce by a factor of 6 the number of connections and the total mass flow. The expected coolant pressure and temperature drops along the branch are about 1.2 bar and 1.6 °C, respectively.

2.4 Refrigerants

Perfluorohexane C_6F_{14} [5a], a popular refrigerant fluid used in many detector cooling systems at above cryogenic temperatures, has a number of advantageous features, like a high radiation resistance, chemical inertness, low pour point (-90°C), low toxicity, non-flammability and low viscosity. Its high dielectric strength and volatility make it safe for equipment in case of leaks. On the negative side, it is a potent greenhouse gas with the global warming potential (GWP) of 9000 [5b]. Among alternatives to perfluoro-carbons are 3M^{TM} Novec thermal management fluids [6]. In particular, the fluoro-ketone Novec 649 has all thermophysical properties at -40...-50°C very similar to those of C_6F_{14}, but features a GWP≈1. We tentatively chose it as a baseline option for our backup solution.

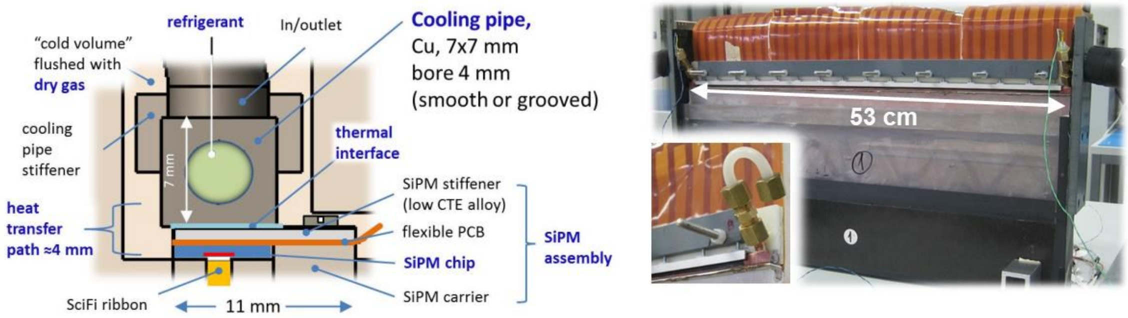

Figure 4: Left: schematic view of the SiPM-cooling interface region. Right: the mock-up module with the front cover removed, exposing the cold pipe, the pipe pressing mechanism and the dummy flex PCBs. The insert shows a detail of the cooling pipe edge with the outlet prepared for the serial connection with another module.

2.3 Thermal ROB mock-ups

A possible realisation of the liquid cooling inside the ROB is illustrated in Fig. 4, showing the internals of a full-scale thermal mock-up module which is currently under test at CERN. Several such mock-ups, following the SciFi ROB concept described in Ref. [3], have been constructed.

The heat exchanger (a square 7×7 mm^2 copper "cooling pipe" with a 4 mm bore) is pressed against the SiPM assemblies, each consisting of the photodetector itself, a flexible PCB running through the insulation to the front-end electronics, and a metallic stiffener[4]. The about 4 mm thick heat transfer path between the liquid refrigerant and the SiPM silicon dye is composed of several layers of different materials. The design goal is to optimise the heat flow through this path, and minimise the temperature difference between the fluid and the SiPM. The interface layer between the cooling pipe and the SiPM stiffener, apart from providing a good conformity and thermal conductivity, also serves to absorb the mechanical stress due to the difference in thermal expansions of the cooling structures and the end-piece. Silicone-based thermal pad (used in the mock-ups) or a thin sheet of a pyrolitic graphite are suitable for this purpose.

The cold structures are surrounded by a narrow space for flushing with a sufficiently dry gas, to prevent frost formation inside the cold volume. The rest of the SiPM enclosure is filled with Rohacell insulation and covered with an external aluminium sheet playing the role of a heat spreader eliminating superficial cold spots.

The mock-up modules have realistic cooling structures but the parts that are not critical for the thermal tests – the SiPM assemblies and scintillating fibres – are replaced by dummies. The dummy SiPMs are made of FR4 strips with calibrated PT1000 sensors glued-in at the level of the SiPM dies. Simplified flexible PCBs have the surface

[4] The mock-up units have aluminium stiffeners, also performing as heat spreaders for the dummy SiPMs. A real SiPM assembly might use stiffeners of a low-CTE alloy matching the thermal expansion of the SiPM assembly.

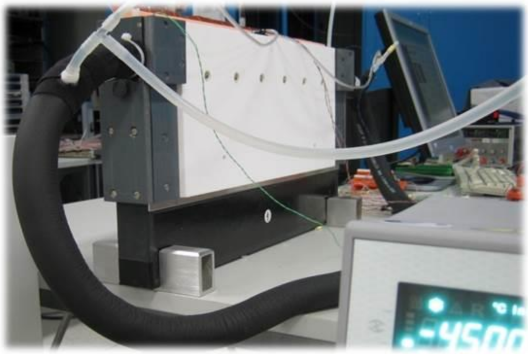

Figure 5: A mock-up modules under test.

density of copper similar to real flexes; at the far end they can be coupled to linear heaters simulating the electronics.

The test setup (Fig. 5) is equipped with a laboratory circulating chiller and external cirquits to control and monitor the fluid flow rate. The results presented in the next section are obtained with C_6F_{14}.

2.4 Mock-up test results

The mock-up tests provide a valuable input for engineering designs of the ROB and the cooling plant. They permit one to tune the refrigerant flow rate, assess the insulation efficiency, measure the heat load of ROBs, the temperature difference ΔT_{SiPM} between the fluid and SiPMs, the pressure and temperature drops between inlet and outlet (ΔP and ΔT_{io}).

The fluids foreseen for our application are poor heat conductors (k <0.1 W/m K) and efficient heat transfer in the cooling pipe can be only achieved if the flow is mostly turbulent. Therefore, an optimisation is required among several design parameters: the cooling pipe diameter, ΔT_{SiPM}, ΔP and the flow rate (the latter two, essentially, define the properties of the circulation pump). Fig. 6 shows the results for a single mock-up module with a 4 mm (inner diameter) pipe, which, according to simulations, is close to optimal for our application. As expected, at a linear fluid velocity v >1 m/s (>20 g/s), the flow becomes mostly turbulent, which secures an efficient heat transfer between the fluid and the pipe wall and, consequtively, a small and uniform ΔT_{SiPM} over the entire pipe. A transition from a mostly laminar to a turbulent flow is clearly visible in Fig. 6a showing the measured SiPM temperature profiles along the module at the fluid

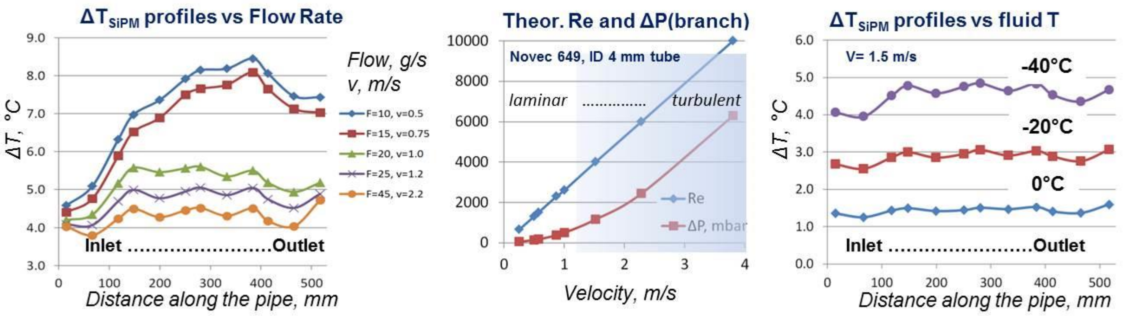

Figure 6: Temperature profiles for different fluid flow regimes. (a) Observed ΔT_{SiPM} profiles along the pipe for the fluid at -45°C and different flow rates. (b) Theoretical dependencies of the Reynolds number and the pressure drop over a cooling branch of 6 ROBs, on the fluid velocity. (c) Observed ΔT_{SiPM} profiles for different fluid temperatures at v =1.5 m/s.

temperature of -45°C. The heat transfer efficiency starts to saturate above v ≈1.5 m/s, the remaining observed temperature non-uniformity of less than 1°C (due to the high turbulence after the 90° inlet ankle and inhomogeniety of the thermal interfaces) being perfectly tolerable. Further increase of the flow rate will not significantly improve ΔT_{SiPM} but result only in a rise of the pressure drop ΔP, as Fig. 6b suggests. Fig. 6c shows the evolution of the ΔT_{SiPM} profile as function of the fluid temperature. At the desired average SiPM temperature of about -40°C the ΔT_{SiPM} does not exceed 5°C.

The heat load P is evaluated by a simultaneous measurement of the mass flow rate F_m and the temperature drop ΔT_{io} of the fluid, $P = F_m \times \Delta T_{io} \times C(T)$, using the known heat capacity $C(T)$ of the fluid as function of its temperature T. The measured value for a single module at T=-45°C and the fluid mass flow of 30 g/s is 10–13 W, in a reasonable agreement with CFD simulations predicting 7–10 W per module. The corresponding pressure drop is ΔP ≈0.2 bar per module. More accurate measurements will be possible with several modules connected in series. A pessimistic value of 20 W/module is used for the conceptual design of the cooling plant, briefly described below.

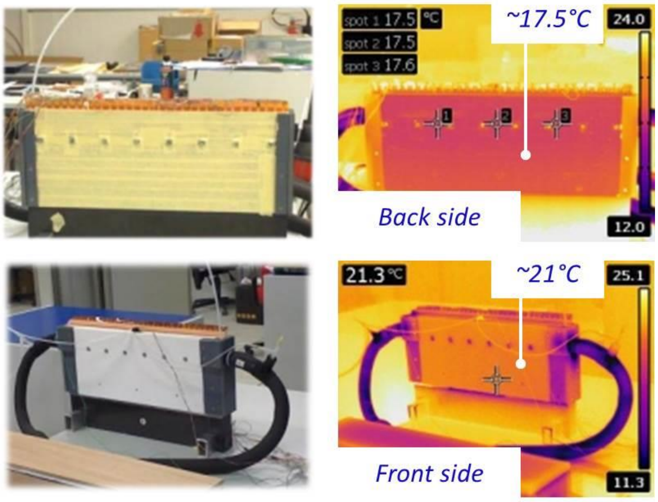

Figure 7: The IR images of the mock-up module running at -50°C. Top: no extra insulation, the alumunium skin is covered with a paper tape; bottom: additional 10 mm layer of Rohacell insulation is added on top of the aluminium skin.

Fig. 7 shows the IR images of the mock-up module running at -50°C. It is seen that the concept of aluminium sheets as heat spreaders works very well. The temperature of the external surfaces is safely above the dew point (about 10°C) in the LHCb cavern. With an extra insulation on top of the skins, the surface temperature becomes close to the ambient (and the heat load drops by 10–15%). The expected cold spots on the uninsulated inlet and outlet lids and, especially, at the module edges will be the subject of further design work.

2.5 SiPM cooling infrastructure

A conceptual design of the SiPM cooling infrastructure is illustrated in Fig. 8. The remote cooling plant is based on an industrial chiller developing the cooling power of 13 kW at -55°C and permitting to control the fluid temperature to within ±0.1°C. Half of the cooling power will be dissipated in the pair of 100 m long transfer lines between the cooling plant and the detector site. The design pressure and temperature drops in each of the transfer lines are about 0.7 bar and 1°C, respectively. The circulation pump

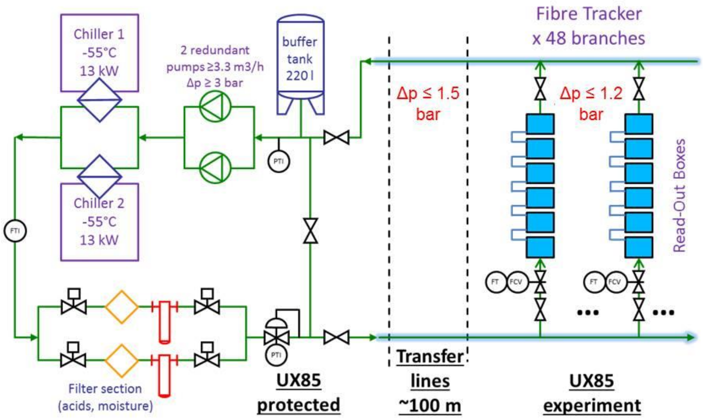

Figure 8: Schematic diagram of the SiPM cooling infrastructure for the SciFi Tracker.

should provide an overpressure of ≥3 bar and a flow rate of ≥3.3 m^3/h (or about 36 g/s in each of the 48 cooling branches). The cooling plant also includes a filtering station to remove moisture and acids from the refrigerant. The principal components of the cooling plant are duplicated. The total amount of refrigerant is 330 kg (this corresponds to a total volume of 210 l at 20°C or 180 l at -50°C).

3 Summary

A large cooling system is being developed for the new LHCb SciFi Tracker, with the combined length of the cooled photodetectors of about 150 m, running at a temperature of down to -40°C. A monophase liquid cooling technology with an environment-friendly refrigerant will be used. The results yielded by the ongoing thermal mock-up tests support the design parameters included in the project's TDR [3].

Among the subjects requiring further investigation are: a validation of the prospective refrigerant Novec 649; ROB edge insulation; the effects of the warm front-end electronics, vapor barriers for the ROB; and a number of the infrastructure-related issues, like the design of low-loss transfer lines and flexible interconnection pipes.

References

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