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The liquid cooling system of the LHCb Inner Tracker: Design constraints and considerations

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Abstract

This note gives an overview of the design of a liquid cooling system for the silicon microstrip based Inner Tracker detector at LHCb. We compare the thermal performances of different liquid coolant options for the Inner Tracker by calculating the heat exchange parameters in a simplified cooling geometry under certain boundary conditions. The layout of a cooling system based on C_6F_{14} is presented and the necessary cooling parameters like massflows and pressure drops are evaluated.

1 Introduction

The use of silicon microstrip detectors for the Inner Tracker at LHCb requires the design of a cooling circuit. Since the hybrids carrying the front-end electronics have to be located as close as possible to the silicon sensors, the cooling system has to remove efficiently the dissipated chip heat. Moreover, the silicon sensors are being operated in a radiation environment with accumulated 1 MeV eq. neutron fluences of up to 10^{13} $1/\text{cm}^2$ after 10 years. Since radiation effects in the bulk silicon lead to an increase in leakage currents, the silicon sensors have to be kept cold in order to avoid any additional shot noise contributions from enhanced leakage currents. Fluence estimations [1] and leakage current evaluations show, that the shot noise contribution to the total noise can be kept below 5%, if the silicon sensor temperature are kept below 5°C. In a previous note [2], the thermal performance of different ladder designs have been evaluated by using the method of finite element analysis. The fundamental cooling principle of a liquid cooling system of cooling the ladder from one end through so called cooling balconies was studied. It was found out, that this concept will work, if either a high thermal conductive carbon fiber is located underneath the silicon, or if a strong convective cold nitrogen flow is provided.

In this note we focus on the layout of a liquid cooling system for the 3 tracking stations (IT1-IT3) of the Inner Tracker by investigating some of the cooling design parameters in detail. The note is organized in the following way: In the first section, an overview of the basic design parameters is given. The next section contains a detailed summary of some of the available coolant options and evaluates their cooling performace in detail. Certain design aspects like the material compatibilty, the radiation hardness and the radiation length contibutions are given.

2 The basic cooling system parameters

We consider three Inner Tracker silicon stations (IT1, IT2 and IT3) behind the LHCb dipole magnet for the cooling system design. One Inner Tracker station consists of 4 quadrants mounted in a cross shaped way around the beam pipe [3]. An Inner Tracker quadrant contains a total of 28 silicon ladders arranged in 4 planes. The silicon ladders are mounted with one end on a cooling plate with an embedded cooling passage, in which a liquid coolant is circulated. The conductive thermal path between cooling plate and ladder hybrid is established by small cooling balconies, which provide in addition aligment and referencing features. The design, material specifications and material studies for balconies and cooling plate can be found in [4].

The ladders of one Inner Tracker quadrant are enlcosed in a light-tight box made out of a polyurethane foam material with aluminium and kevlar cladding to provide electrical and thermal insulation to the outside world. Since the box walls are designed to be rather thin, thermal losses through the insulating polyurethane ocurr. The permanent heat flux from the outside experimental hall into the box volume depends on the thermal insulation value of the box wall, the box surface area and the temperature difference between inside and outside. A detailed description of the design and construction and thermal measurements on a prototype detector box can be found in [5].

The expected total power dissipation in one Inner Tracker box, consisting of 28 ladders, has three contributions:

1. heat dissipation from the chips: It is assumed that one Beetle chip dissipats 0.5 W, meaning 1.5 W per hybrid, i.e. 28 × 1.5 W= 42 W per box.

2. silicon bulk heat production after irradiation: a maximum of 0.5 W per ladder after 10 years of LHCb operation is expected, if the silicon is kept at room temperature. The bulk heat production in silicon is strongly temperature dependent and can be supressed to less than 0.1 W by operating the silicon between 0°C and 5°C.

3. thermal losses through the box: If the box is kept cold at $T = 0°$C, a heat dissipation of 30 W from the outside experimental hall at $T = 22°$C through the box walls is expected. The heat flux is proportional to the temperature difference between box temperature and ambient and assumes 6 mm thick polyurethane foam walls as it is presently foreseen in the design.

All three contributions to the total power dissipation within one box are shown in figure 1 as function of the box temperature and for a constant ambient temperature at $T_{amb} = 22°$C. Under the assumption of a maximum contribution of (3), meaning that the box is kept cold at $T = 0°$ C, the total dissipated power of a Inner Tracker box, which has to be removed by the cooling system is $P_{tot} = P_{chips} + P_{Si} + P_{box} = 42\ W + 28 \times 0.1\ W + 30\ W = 75\ W$. Here, we assume, that the leakage currents after 10 years of running produce a power dissipation in the silicon of 0.1 W per ladder only.

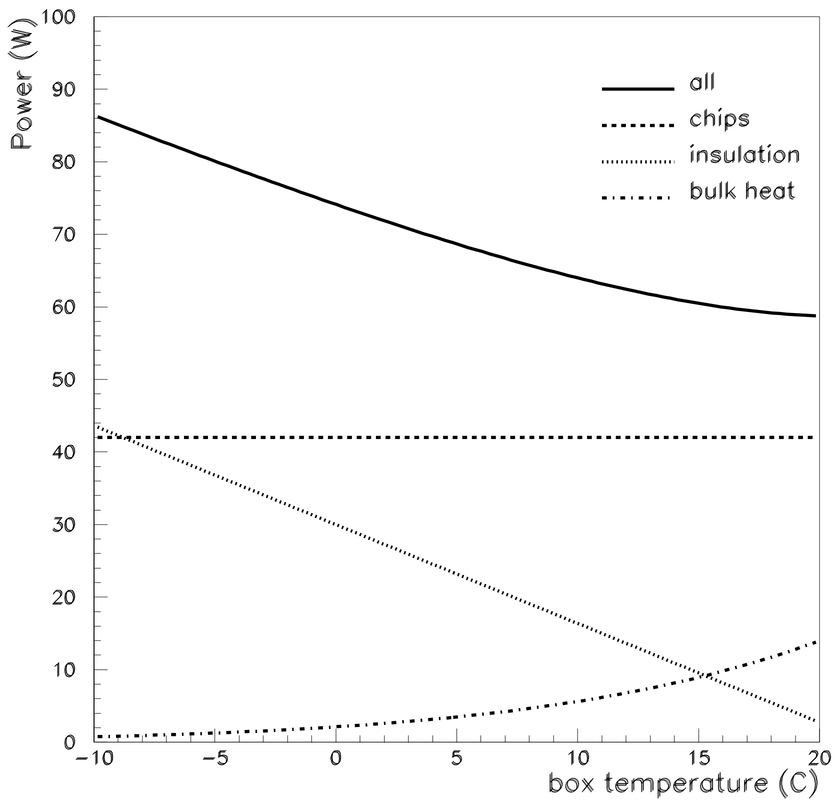

Figure 1: The different contributions to the total power dissipation inside one Inner Tracker box as a function of the box temperature. The outside temperature of the experimental hall is assumed to be $T_{amb} = 22°\text{C}$. The box wall thickness is taken to be 6 mm.

Since the box and the ladders will be kept at such low Temperatures, the bulk heat production in silicon can then be neglected.

In summary we expect that the cooling system of the LHCb Inner Tracker has to remove 75 W per box quadrant, 300 W per station and finally a total of 900 W for all three IT1-IT3 stations.

3 The choice of the coolant

The properties of some standard liquid coolants, partially commercially available, have been compared and their cooling performances have been evaluated for a simplified Inner Tracker cooling geometry by investigating the flow of the different coolants in a 1.5 m long pipe. This length corresponds roughly to the length of a cooling passage inside one box of a station without counting the supply lines to the box. As mentioned previously, we expect that one box of the Inner Tracker has a thermal load of 75 W. The cooling pipe which is assumed in the calculation has a circular cross section with an outer diameter of 5 mm and a wall thickness of 0.25 mm.

3.1 Performance parameters of the cooling

The cooling efficiency has been evaluated by comparing several parameters: the mass flow which is required to reach a certain heat transfer coefficient, the velocity of the coolant in the pipe, the average wall temperature and other dimensionless numbers, which are widely being used to describe the coolant performances. In order to choose an appropriate coolant and to better interpret the aforementioned quantities some important criteria are listed below:

- The mass flow $\dot{M}$
  the mass flow is directly proportional to the chiller size.

- The flow speed v
  very high values of v translate into high pressure drops along the pipe and a higher probability of cavitation, especially when the pipe geometry changes abruptly. Also vibrations could be build up. On the other side however, low values of v do not provide enough convective heat transfer inside the coolant and may lead to problems with removal of air bubbles at the start-up.

- The average wall temperature T_{wall}
  the average wall temperature corresponds to the working temperature which is available for the conductive thermal process of the silicon and hybrid cooling. A low value of T_{wall} for a given inlet and outlet coolant temperature has to be pursued.

- The heat transfer coefficient $h_c = \frac{(\dot{Q}/A)_w}{(T_w - T_m)}$
  with $(\dot{Q}/A)_w$ being the wall heat flux through the pipe and T_m the mean bulk temperature of the fluid, which is the coolant temperature at any cross section which would be attained by the fluid if from that cross section onwards the pipe surfaces were perfectly insulated and no heat transfer or removal occurred. An efficient cooling system should aim for high values of h_c so that only small differences between T_w and the mean bulk temperature T_m are reached.

- The Reynolds number $Re = d \cdot \dot{M}/\mu$
  where d is the hydraulic diameter[1] and μ is the dynamic viscosity of the fluid. The Reynolds number relates the viscous and inertial forces and determines the transition from a laminar to a turbulent flow. Usually, for flow through pipes, the transition Reynolds number is observed to have a value of around 2000-2500.

[1] the hydraulic diameter is $d = 4 \cdot crosssection/circumference$

- The Prandl number $Pr = c_p \cdot \mu/\lambda$
where c_p is the specific heat capacity. The Prandl number signifies the relative speed with which momentum and energy are propagated trough the medium. The higher the Prandl number at a specified Re the steeper the temperature gradient at the wall.

- Nusselt number $Nu = h_c \cdot d/\lambda = (d/kA)/(1/h_c A)$ the physical meaning of the Nusselt number can be interpreted as the ratio of two thermal resistances at an area A through which the heat flows: The thermal resistance which would be offered by the fluid if it was stationary and heat flowed only by conduction through it, and the thermal resistance associated with the heat transfer coefficient at the wall surface of the pipe. The cooling system has to aim for high values of Nu, since it indicates a more efficient convection in the coolant implying a larger mass of the coolant participating in the heat transfer.

3.2 Compilation of coolants

The following coolants have been compared:

- Standard mixtures of water with 20% and 34% volume fraction ethylenglycol (EG) with minimal working temperatures of $-10°$C and $-20°$C respectively

- A mixture of water with 20% volume fraction methanol with freezing point of $-17°$C

- The commercial available 3M coolants PF5060 (C_6F_{14}) and PF5080 (C_8F_{18})

- The high performance silicone polymer coolant Syltherm from Dow chemical

- The aliphatic hydrocarbon solvent PF^{TM}-200IG from P.-T. Technologies

- The aliphatic hydrocarbon blend Dynalene HF-LO from Loikits Industrial Services

Table 1 gives a summary of the coolant properties at a reference temperature of $-10°$C. The data for the aqueous liquids and the fluorocarbons have been compiled by the CERN ST/CV group [10]. The data for the aliphatic hydrocarbons are taken from [6] for PF-200IG and from [7] for Dynalene HF-LO.

The perfluorocarbons C_6F_{14} and C_8F_{18} are clear, colourless liquids which partially replaced the older chlorfluorocarbon (CFC) coolants in refrigeration applications. Contrary to the CFC which exhibit a very high ozone depletion potential, the perfluorocarbons are non-ozone depleting. However, they possess a high global warming potential and their atmospheric lifetime is around 3000 years. C_6F_{14} is the preferred coolant choice for the CMS conductive silicon cooling system and the Atlas TRT detector,

Table 1: Compiled parameters for different coolants at T=-10°C.

$T = -10^{\circ}$C	20% EG	34% EG	20% Meth.	C_6F_{14}	C_8F_{18}	Syltherm	PF-200	Dynalene
density ρ [kg/m^3]	1038	1066	976	1766	1863	870	790	783
specific heat c_p [J/kg·K]	3850	3553	4072	998	998	1570	2303	1947
therm. cond. λ [W/m·K]	0.498	0.464	0.458	0.0611	0.066	0.117	0.159	0.114
viscosity μ [kgm^{-1}s^{-1}]	5.2E-3	8.1E-3	5.4E-3	1.13E-3	2.75E-3	2.5E-3	1.9E-3	3.1E-3

since its material compatibility and radiation resistance are very good. Furthermore, it is not flammable as well as non-irritating to the eyes and skins and practically non-toxic orally.

The aliphatic hydrocarbon PF-200IG is used as a coolant by the recently upgraded Silicon-, Rich- and Drift chamber detectors of the CLEO experiment [6]. The aliphatic hydrocarbon PF-200IG is an industrial solvent and degreaser and is electrically non-conductive with no ozone depletion potential and low global warming potential. The big disadvantage however, is its flammability with an auto-ignition point of 100°C. This aliphatic hydrocarbon is a complex combinations of normal paraffins consisting of a straight chain of non-aromatic saturated hydrocarbons having carbon numbers in the range from C-5 through C-20. At ambient temperatures and pressures, PF-200IG is a colourless liquid with a faint petroleum odour. The Dynalene coolant HF-LO [7] is also a clear, colourless blend of hydrocarbons which will ignite and burn at elevated temperatures of 340°C. Dynalene HF-LO may cause skin and eye irritation.

3.3 Results of the coolant calculations

Since a coolant flow in a cooling pipe has more than one free parameter, reasonable boundary conditions have to be set. As it was mentioned before we have treated the flow in the tracker passage in a very simplified model of a 1.5 m long circular pipe having outer dimensions of 5 mm and wall thickness of 0.25 mm. The walls of the pipe are assumed to be smooth so that no additional roughness factors had to be applied when calculating the pressure drops. Also, the bendings and fittings are neglected here. The coolant temperature at the entrance was set to -10°C and the dissipated power in an Inner Tracker quarter station is taken to be 75 W. The flow in the cooling pipe is assumed to be fully developed and the equation by Hausen for a laminar flow ($Re < 2300$) and the Dittus-Boelter equation for fully-developed turbulent flows ($Re > 2300$) have been used [8].

In order to compare the coolants two different boundary conditions have been analysed: In the first condition a temperature gradient of the coolant between inlet and outlet of $\Delta T = 1$°C is set whereas the second condition fixes the pressure drop in the duct to be $\Delta p = 0.3$ bar. The last condition is motivated by the idea of running the fluid in the tracker cooling passages at subatmospheric pressure. This allows a much more safer operation for aqueous coolant solutions in case of a leak in the cooling pipe.

Table 2: Performance of the coolants for temperature drop between inlet and outlet of $\Delta T = 1°C$. The inlet temperature of the coolant was at T=-10°C.

$\Delta T = 1°C$	20% EG	34% EG	20% Meth.	C_6F_{14}	C_8F_{18}	Syltherm	PF-200	Dynalene
flow speed [m/s]	0.96	1.01	0.96	2.17	2.06	2.80	2.10	2.51
mass flow [g/s]	19.5	21.1	18.4	75.1	75.2	47.7	32.5	38.5
pressure drop [bar]	0.1	0.15	0.1	0.34	0.41	0.40	0.21	0.33
Reynolds number	955	672	870	16935	6965	4866	4365	3154
Nusselt number	7.9	6.4	8.1	178.3	121.2	83.5	70.7	71.0
Prandl number	40.1	61.3	47.9	18.5	41.6	33.6	27.5	53.2
T_{wall} [K]	267.6	267.7	267.8	264.9	265.5	265.1	264.9	265.5
h_c [W/m^2·K]	786	751	736	2179	1600	1954	2249	1617

Table 3: Performance of the coolants for a constant pressure drop along the cooling pipe. The inlet temperature of the coolant was set to $T = -10^{circ}$C.

$\Delta p = 0.3$ bar	20% EG	34% EG	20% Meth.	C_6F_{14}	C_8F_{18}	Syltherm	PF-200IG	Dynalene
flow speed [m/s]	2.0	2.1	2.23	2.1	1.7	2.3	2.6	2.5
mass flow [g/s]	41.4	42.2	42.8	71.5	62.7	39.8	40.7	38.5
T_{outlet} [K]	263.35	263.45	263.5	264.05	264.2	264.2	263.8	263.9
Reynolds number	2034	1343	2023	16129	5804	4055	5456	3154
Nusselt number	10.4	10.5	11.1	171	105	72	85	71
Prandl number	40	61	47.9	18.5	41.6	33.5	27.5	53.16
T_{wall} [K]	266.3	266.5	266.3	265.0	265.9	265.5	264.6	265.5
h_c [W/m^2·K]	1039	971	1021	2095	1382	1688	2688	1616

In our cooling performance evaluations, we will focus mainly on the criterion of achieving a low temperature T_{wall} at the cooling pipe wall by avoiding to large pressure drops. The lower T_{wall} is - at a given inlet temperature - the more efficient is the the heat transfer. A low T_{wall} also guarantees a low temperature working point for the successive cooling of the remaining cooling components like cooling plate and balconies.

Table 2 shows the performance results for the different fluids under the condition of a constant temperature gradient between entrance and exit of the cooling pipe. The results for the case of a constant pressure drop are listed in table 3.

Generally, all three water based solutions (20% EG, 34% EG and 20% Meth.) behave very similar. Their biggest advantages are a very high specific heat and a much higher thermal conductivity than the other coolants. However, in order to run below 0°C, an admixture of ethylenglycol or methanol to water is necessary which increases the viscosity tremendously. The flow of all three aqueous solutions was for both investigated conditions laminar or close to the turbulent transition region at $Re \approx 2300$, meaning that the predominant mechanism for the heat transfer is the conduction within the fluid. Consequently, the achieved Nusselt and heat transfer numbers are very low and the wall temperature of the cooling pipe is around 3K higher than the temperature at the input. Since convection gives much higher Nusselt and heat transfer numbers, an efficient coolant should run in a turbulent way, as the achieved heat transfer numbers for the fluorocarbons C_6F_{14} & C_8F_{18}, the Syltherm coolant and the PF-200IG coolant indicate. The convective heat transfer mechanism relies on molecular mixing and so a much larger fraction of the fluid is participating to the heat exchange, meaning that less fluid mass is circulated uselessly.

It has to be pointed out, that the water based solutions can be operated in a turbulent regime as well in order to reduce the effective working point temperature T_{wall}. By setting the the difference between inlet and outlet to $\Delta T = 0.25°\text{C}$ only, the three coolants reach values of $Re \approx 2600$. However, these coolants have not yet fully developed their turbulent flow under such conditions and hydrodynamic calculations on heat transfer and pressure drops are difficult to make. If one relies on such turbulent calculations, high pressure drops of 1 bar or more along the straight sections of the cooling pipe are expected, which is unnecessary high compared to the other fluids. Therefore, we rather tend to limit the pressure drop to the absolut necessary values.

The highest heat transfer numbers and the lowest values for T_{wall}, the working temperature for the cooling, can be achieved by using either the cooling C_6F_{14} or the hydrocarbon coolant PF-200IG. PF-200IG would even give a little lower pressure drops than C_6F_{14} in case of the constant temperature condition. The Reynolds numbers of the two coolants are different however, and demonstrate that the fluorocarbon liquid would run in a much more turbulent way than PF-200IG which may possibly cause a higher risk of cavitation. Moreover, the usage of PF-200IG has the advantage of a much longer radiation length (see next section), but a careful study of its radiation tolerance has to be made. The big concenr with PF-200IG however, is its flammability and its related safety aspects. CERN may allow flammable coolants for use at LHC only under very strict safey requirement.

The second best performing coolant is C_6F_{14}. Since C_6F_{14} is the prefered choice for the CMS silicon tracker and Atlas TRT detector at LHC, material compatibility data and informations on radiation hardness exist and is described in detail in the next sections. Moreover, experienced CERN support from the CERN cooling group in case of C_6F_{14} is available helping us in the final design and layout of the cooling system. We therefore consider C_6F_{14} as the baseline choice for the liquid cooling system.

The cooling performance calculations for the chosen geometry in case of C_6F_{14} for different massflows are summarized in figure 2. The temperature difference of the coolant between outlet and inlet is shown in the upper graph as a function of the circulating massflow and for different power dissipation settings within one IT1-IT3 box. Each curve corresponds to one power setting. The lower part of figure 2 shows the difference between inlet temperature and effective wall temperature, which is the available working point temperature for the cooling of all subsequent elements in the cooling chain. In order to keep the temperature differences small and to make the cooling more efficient, a mass or volume flow for C_6F_{14} of 150 l/h should be used. Such a high volume flow will limit the temperature gradients between the inlet & outlet to be less than 1K and will give reasonable average wall temperatures of only 1.5-2K above the inlet temperature.

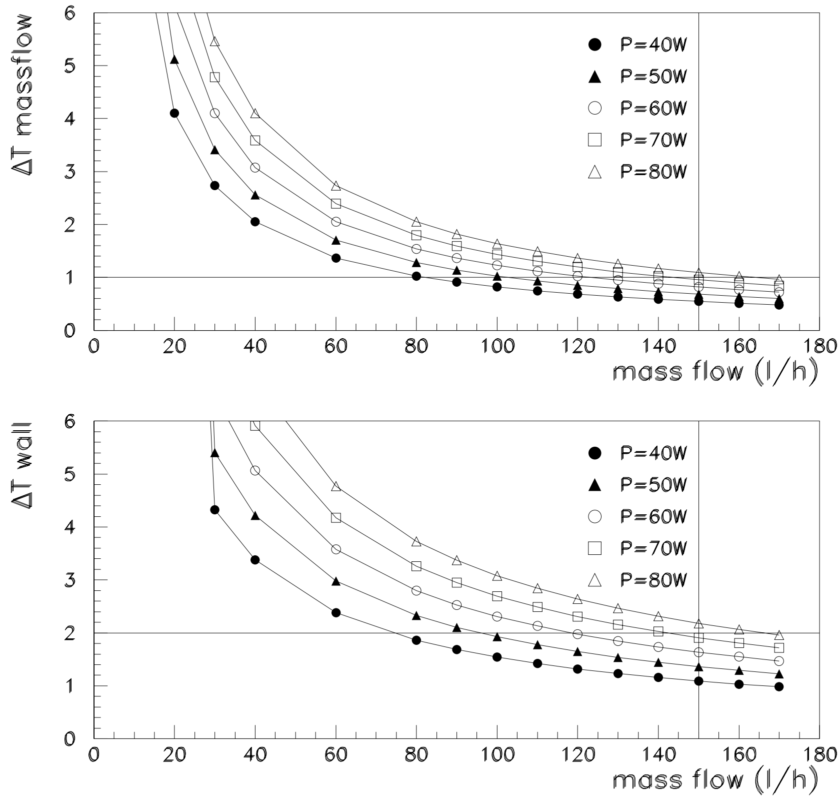

Figure 2: The temperatur difference ΔT between outlet and inlet (ΔT massflow) and between cooling pipe wall and inlet as function of the circulating massflow and for different power settings within one IT1-IT3 box. The cooling parameters of C_6F_{14} used in this calculation have been evaluated at a fixed temperature of $T = -10°\mathrm{C}$.

Table 4: Radiation length for some of the coolants in [cm]

Coolant	X_0 [cm]	rel. X_0 in I.T. [%]
water	36.1	0.31
ethylenglycol (EG)	35.1	0.32
water + 34%-Vol EG	35.8	0.32
C_6F_{14}	19.1	0.59
C_8F_{18}	17.5	0.65
PF-200IG	52	0.22

3.4 Radiation length issues

The radiation length has impact on the coolant choice as well. For a 1.5 m long cooling passage with outer diameter of 5 mm and wall thickness of 0.25 mm an Aluminium cooling pipe would contribute with 0.56% of X_0 per IT-Station in the material budget of the so-called hybrid area, which is used as a reference surface area. The coolant itself has a non-negligible contribution. Table 4 compares the radiation lengths of some of the coolants.

All solutions which are based on water and either EG or methanol have very similar radiation lengths close to 36 cm, depending on their EG content. Their contribution to the material budget based on the 1.5 m long Inner Tracker cooling passage would amount to 0.32%, i.e lower than the Al-pipe. Due to their high fluor-content the fluorocarbons C_6F_{14} and C_8F_{18} have significantly lower radiation length. They contribute with 0.59 - 0.65% in the material budget. Since the hydrocarbons contain primarily H- and C-atoms their radiation length is outstandingly high. The radiation length of PF-200IG has been studied [6] by 20keV Photons, finding it 45% longer than water. For the mentioned 1.5 m long duct, PF-200IG contributes then with only 0.22%.

Although C_6F_{14} has a lower radiation length compared to PF200-IG and the other water-based solutions, the total contribution to the material budget in the hybrid area is rather small due to the small cross section of the pipe. It has to be noted, that the balconies will dominate the material budget in that area which is assumed to have a total radiation length of 8% for the complate IT1-IT3 station. Since we do not gain much by lowering the coolant contribution from 0.6% (C_6F_{14}) to 0.32% (EG) or even 0.2% (PF-200IG) we accept the larger dead material contribution of C_6F_{14}.

3.5 Material compatibility and radiation hardness

The material compatibility of perflourocarbons with various metals and plastic materials has been investigated in the past, since they have been considered and used as coolant agents in silicon detectors and radiator media for Cherenkov detectors [9]. In the future

LHC experiments, C_6F_{14} will be used as the liquid coolant in the CMS pixel and silicon strip detector system as well as in the ATLAS TRT detector.

The overall material compatibility of the perflourcarbons was found to be very good with most metals, plastics and elastomers and no corrosion effects on metals have been reported. Slight discoloration effects have been only observed with bright copper, but not with Aluminium or stainless steel [11]. The material compatibility to plastics and elastomers was measured in terms of volume and weight change after several weeks of exposure [11, 10]. Plastics and elastomers with a high degree of compatibilty to perflourcarbons were: acryl, butyl, chlorosulfonated polyethylene, nitrile or chloroprene elastomeres. Silicone elastomers have also been found to be compatible. In most applications, the aforementioned materials should behave entirely satisfactory with perflourcarbons. Other materials like Teflon, polypropylene, nylon and PVC should be avoided however, since they cause larger volume swells and strong discolorations. We consider therefore the selection of suitable materials for use as hoses, gaskets etc as no big problem.

Irradiation studies of C_6F_{14} with γ's from a Co-60 source and with neutrons have been carried out [12, 13] in order to study the radiation hardness of the fluid. The neutron irradiation was performed to investigate the radioinduced activity of nuclides. Small samples of C_6F_{14} and other perflourocarbons were irradiated up to $3 \cdot 10^{13}\ cm^{-2}$ with fast neutrons to simulate the expected environment at LHC. The neutron irradation study showed the creation of radionuclides in C_6F_{14} with ^{18}F being the main longest lived radioisotope. The activity levels for this radionuclide is in the range of $10^4 - 10^5$ Bq/g during circulation, which is believed to be acceptable [13]. After γ irradiation with ^{60}Co and an absorbed dose of 3 MRad, about 1% by weight of liquid C_6F_{14} had been chemically modified. Some polymeric deposits containing C, F and O are formed with thickness less than 0.4 μm on alumiunium or stainless steel tubes after an irradiation of 6 MRad. Several purification methods of C_6F_{14} have also been successfully tested in order to clean the cooling agent 'online'. These cleaning methods will significantly lower the number of damaged C_6F_{14} molecules within the circulating system.

There was also a recent radiation hardness study at Fermilab [14] which indicate that the C_6F_{14} cooling fluid will withstand doses up to 20MRad without dissociating. The measured F^--ion trace content after this exposure was less than 17ppm. The coolant exhibited a very good radiation hardness and showed almost no corrosive attack to most metals.

The aliphatic hydrocarbon coolant PF-200IG has been described by the manufacturer as non-corrosive to metals such as aluminium, cooper, magnesium and stainless steel [6]. The authors of [6] conducted an investigation of the material compatibility of PF-200IG with Beryllium and found no visibly dicernible changes after a period of three months at ambient temperature and pressure and light exposure. Furthermore the compatibility to elastomere tubing and variuos other plastic tubing was successfully tested.

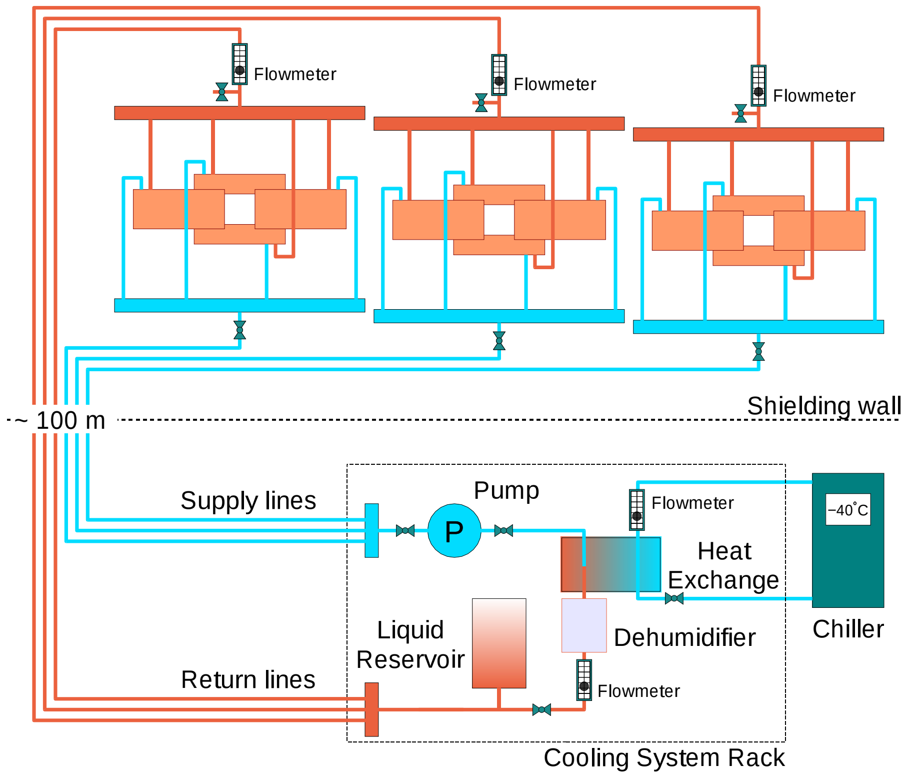

Figure 3: Schematics of the Inner Tracker cooling setup.

4 A layout of the Inner Tracker cooling system

Due to the system modularity of the Inner Tracker, each IT1-IT3 station behind the LHCb dipole magnet will be served independently with own supply and return lines. The service lines have to be routed from the chiller to the outer tracker stations and then in parallel to the four detector boxes of each IT1-IT3 station. The location of the chiller is on a platform behind the shieding wall of the LHCb experimental hall [15]. The distance between chiller location and Inner Tracker stations will be between 70 m and 100 m. This means that we will have easy acces to chiller and pumps in case of failures. However, the hydraulic impedance of the system will be higher.

A vacuum insulation for the 2×100 m long service lines will be realised, in order to insulate the coolant well enough. Between the supply and return lines a parallel circuitry connecting the four detector boxes of each individual IT1-IT3 stations is chosen.

The proposed liquid cooling system consists of two separate circuits and is shown in figure 3. The first circuit is a powerful chiller connected to a heat exchanger mounted in the cooling system rack behind the LHCb shielding wall. The second circuit includes the rack itself, the three IT1-IT3 stations, manifolds and piping routed inside the experimental hall.

The pressure drop along the aluminium pipe cooling circuit of 5 mm diameter inside

Table 5: The main design parameters and spcifications of the Inner Tracker cooling system

total dissipated heat in 3 IT1-IT3 stations	900W
total volume of C_6F_{14}	350 l
chiller power	5kW
pump capacity	4 bar at 3000 l/h
temperature range	$-40°$C to $20°$C
temperature accuracy	± 0.1 K

an Inner Tracker box does not exceed 1 bar at a design masflow of 150 l/h. This number contains also the estimated pressure drops ocurring at the four bendings of the cooling pipe. An up to 5 m long supply line of 10 mm diameter made out of a thick enough silicone hose will be routed over the Outer Tracker station. The estimated pressure drop loss will be less than 0.5 bar at the same massflow. Since four supply lines per station are used in a parallel mode, the pressure drop in each branch is the same. The resulting mass flow per station is then 4×150 l/h=600 l/h. The three stations in total will then individually served by parallel cooling lines capable of 600 l/h. By having vacuum insulated pipes of 30 mm diameter for the common supply line, the pressure drop in this section can be limited to 2 bar for a length of 2×100 m. The main design parameters of the cooling system are mentioned in table 5.

Various equipment is necessary to run, monitor and control the liquid cooling system. The equipment includes a chiller, capable of 5 kW, the heat exchanger unit, a dehumidifier unit, manifolds, piping, flow meters and flow indicators, temperature, pressure and humidity gauges. In addition there will be a dry gas system to prevent the formation of condensate and ice. The dry gas will purge the Inner Tracker boxes. We have estimated the costs of the Inner Tracker cooling system to be CHF 150k.

5 Summary

This note has summarized the important design aspects for a liquid cooling system of the silicon microstrip based Inner Tracker detector of the LHCb experiment. The performance of different coolants have been addressed by considering its flow in a cooling pipe under certain boundary conditions. The important cooling performance parameters like Nusselt number, wall temperature of the cooling pipe and achieved heat transfer numbers have been investigated. The prefered choice for the coolant is the perflourocarbon C_6F_{14}, which is also being used for the ATLAS TRT detector and for the CMS silicon tracker. The liquid offers a high degree of compatibility with other material and provides enough radiation resistance. For an effective cooling, C_6F_{14} has to run in a turbulent regime inside the cooling pipes. The achieved heat transfer numbers are high enough to provide a low enough cooling pipe wall temperature as working point for the subsequent conductive cooling of the cooling plate, balconies and ladders.

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