EVAPORATIVE CO_2 COOLING SYSTEM FOR THE UPGRADE OF THE CMS PIXEL DETECTOR AT CERN

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ABSTRACT

Carbon dioxide (CO_2) has gained interest for evaporative cooling of high-energy particle physics detectors. Silicon tracking detectors need to be maintained at sub-zero temperature to increase their lifetime in the presence of radiation, with a material budget allocated to infrastructure as small as possible to allow maximum transparency for particle tracking.

Evaporative cooling is clearly a good method to meet these goals, and CO_2 coolant is an excellent option as it can withstand a large amount of radiation and has excellent thermal behavior in small diameter tubes. For these reasons, this technology has been selected for the next generation CMS Pixel detector. The design requirements for this new system are a coolant minimum temperature of -20°C and a total cooling power of about 15 kW. Following successful applications in AMS and LHCb Velo projects, the 2-Phase Accumulator Controlled Loop method (2PACL) has been chosen and adapted to the higher cooling power requirement of the CMS Pixels.

This paper describes the general design of the Pixel cooling system, both inside the detector and at the plant level. On-going tests of the in-detector evaporators and long transfer line prototypes are detailed, showing how the present design will be validated.

This development is part of the CMS Pixel Upgrade project, and it is being carried out in the framework of the CMS Pixel Collaboration.

1. INTRODUCTION

Particle detectors are used in high-energy physics research to register the products of particle collisions inside accelerators. One of the two multi-purpose detectors at the Large Hadron Collider (LHC) is the Compact Muon Solenoid (CMS), operating at the European Organization for Nuclear Research (CERN). The innermost sub-detector of CMS is the Pixel detector, which is used to record the tracks of particles issued from the collisions. Due to the close proximity to the interaction point, radiation damage has a significant impact on the lifetime of the silicon pixel sensors. Lowering the temperature of silicon sensors below 0°C significantly reduces the negative effects of radiation.

The CMS Pixel detector is due to be replaced by a new, upgrade pixel detector in ~2016, and a two-phase CO_2 cooling system has been chosen to cool the next generation sensors, replacing the C_6F_{14} liquid cooling of the present detector. Evaporative CO_2 cooling is a major innovation for the pixel upgrade. It provides high cooling efficiency in a minimal amount of material, leading to a reduction of passive material in the tracking volume, and hence significant improvement in particle tracking performance. CO_2 refrigerant has excellent thermo-dynamical properties, allowing the use of very small tubes and is substantially cheaper than fluorocarbon refrigerants, while featuring a much lower impact on the environment.

The design of a LHC detector cooling system must consider both the process aspects and the local evaporator efficiency, including all constraints imposed by harsh environmental conditions (magnetic field and radiation) and high reliability for non-accessible parts. Prediction models for the performance of detector evaporators are coupled with validation tests, and linked to the infrastructure validation process, to ensure reliable operation in all configurations.

2. THE CMS PIXEL DETECTOR

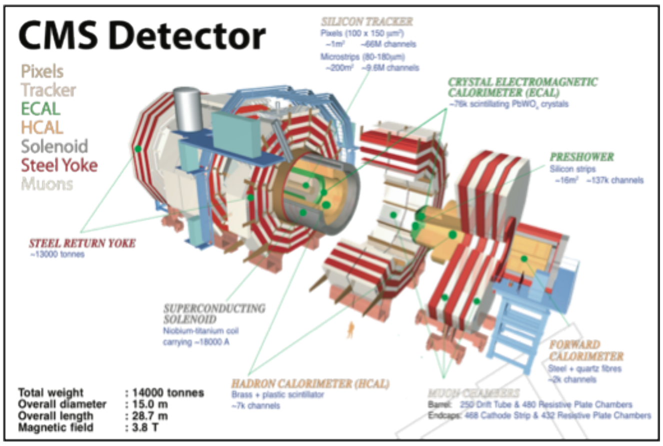

Figure 1: Schematic view of the CMS detector, with its various sections in retracted positions.

The CMS (Compact Muon Solenoid, Figure 1) is one of the two large, multi-purpose detectors analyzing the proton-proton collisions at the CERN Large Hadron Collider (LHC) (The CMS collaboration, 2008). At the heart of CMS is a 4T superconducting solenoid. The bore of the magnet accommodates the calorimeters and the inner tracker. The tracker, that measures the trajectories of all charged particles emerging from the collisions, is entirely based on silicon sensors. In the outer part, the sensors are segmented in micro-strip sense elements of approximately 0.1×100 mm2 size, while the inner three layers of pixelated sensors, with pixel size of 0.10x0.15 mm2, provide the high granularity required to resolve the high density of tracks near the interaction (proton-proton collision) point.

CMS is installed in a facility about 100 m underground. Two caverns host the equipment needed for the detector functions. One is dedicated to the primary services infrastructure and remains accessible during accelerator operation and data taking. The second cavern, housing the particle physics detector and its on-board infrastructure, is not accessible during operation (for about 250 days a year) due to its exposure to ionizing radiation from the LHC beam.

2.1 The pixel detector and its upgrade

The pixel detector, located at the center of CMS, provides high-precision tracking of charged particles in the vicinity of the interaction point. The present detector, conceived over 10 years ago, consists of three cylindrical barrel layers (BPIX) in the central region supplemented by two forward disks (FPIX) at each end. BPIX contains 48 million pixels covering a total area of 0.78 m^2. FPIX has 18 million channels covering an area of 0.28 m^2.

With the planned increase in the collision rate provided by the LHC, which is expected to exceed the original design figure before 2020, the detector will begin showing significant degradation. Therefore, an upgrade has been planned for ~2016 (Kästli, 2010). The new detector will feature several important improvements including: (i) new front-end chips with increased readout capability to cope with the higher data volume generated by the increased collision rate, (ii) a nearly twofold increase of the active surface through the introduction of a 4th barrel layer and a 3rd forward disk at each end (Figure 2), providing one additional pixel coordinate to greatly increase the robustness of track reconstruction, especially in the high particle density environment, (iii) reduced amount of inactive material in the tracking volume.

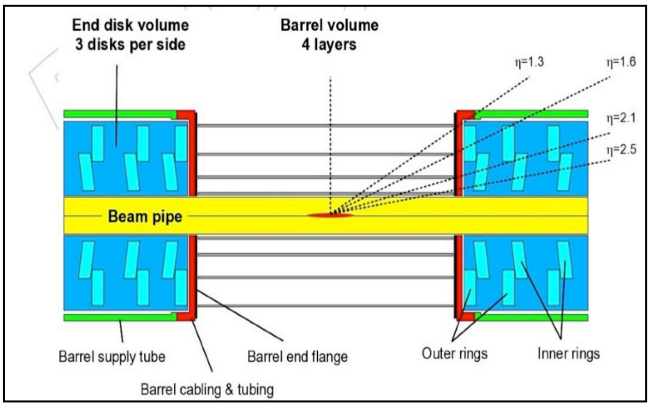

Figure 2: Schematic view of the upgraded pixel system, featuring 4 barrel layers and 3 forward disks at each end.

The amount of material in the tracking volume is the main limitation in performance of the current CMS Tracker. Despite the larger area and increase in number of channels of the upgrade detector (from 48M to 80M in the BPIX, and from 18M to nearly 45M in the FPIX), the new design will have a substantially reduced amount of material. This is primarily achieved by the introduction of CO_2 cooling, which is therefore one of the most crucial elements of the upgrade project.

2.2 The cooling requirements

The cooling system must remove the thermal load from the detectors as well as heat leaking from the ambient environment to the cold parts of the system, especially through the insulated pipe bundles between the cooling plant and the detector. At present, the maximum power estimates are 6 kW for the BPIX, 3 kW for the FPIX, and about 2 kW for the heat leak from ambient. The design for the cooling plant targets 15 kW of total cooling capacity, providing ample safety margin.

The range of temperature required for the coolant depends on the requirements for the commissioning phase and for long-term operation. In the commissioning phase, when the detector volume may not be sealed, the operating temperature must remain above the ambient dew point in the CMS cavern, i.e. >11°C, to avoid any condensation. Therefore, 15°C is set as the maximum coolant temperature. During operation, the silicon sensors need to be kept at a temperature below 0°C to mitigate radiation damage effects. To fulfill this requirement, a coolant temperature of −20°C is chosen as the lower limit of the operation range, while the in-detector cooling design will ensure a temperature difference less than ~10°C between the sensors and the coolant.

The CO_2 cooling must re-use the copper transfer pipes, now used for C_6F_{14} cooling, which join the cooling distribution racks on the cavern balconies with the first patch panel on the CMS detector. The relatively small layer of insulation (12 mm thickness of Spaceloft®) installed around the pipe bundles was designed and qualified to prevent surface condensation for coolant temperatures down to −20°C, thus compatible with the new coolant temperature requirements.

3. THE COOLING SYSTEM DESIGN

The high up-time desired for the data taking process of a particle physics experiment imposes demanding requirements in terms of robustness and reliability, since access is normally impossible, and maintenance and repairs are excluded, during most of the detector lifetime. Such reliability can only be achieved by a very rigorous approach during design, production and qualification of all related services, including the cooling system.

In addition, the design of the detector cooling system must take into account the harsh environmental conditions in which the plant and the detector are located, including the strong magnetic field and radiation. The CMS Pixel detector sits inside the 4T CMS solenoid, so no active component can be installed in the detector. On the cavern balconies next to the detector, fringe fields can reach values of 600 mT, excluding the installation of non-magnetic field tolerant equipment. Moreover, radiation tolerant components must be chosen for any part installed in the experimental cavern, consequently limiting the range of materials and the type of electronics for instrumentation.

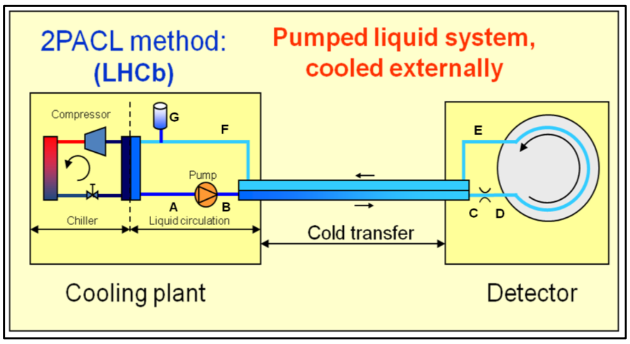

Figure 3: 2PACL schematic

3.1 The CMS pixel cooling plant

The process design chosen for the CMS pixel cooling system is the 2-Phase Accumulator Controlled Loop (2PACL, Verlaat, 2007) originally developed for the Thermal Control System of the Alpha Magnetic Spectrometer Tracker (Van Es, 2009), and later implemented in the Vertex detector of the LHCb (Large Hadron Collider beauty experiment), as reported by Verlaat et al. (2009).

The 2PACL has no active components inside the detector. The process is completely controlled from the cooling plant, which can be located at a relatively large distance from the detector (ideally in an accessible and radiation-free zone), while only small-diameter tubing is required inside the detector volume. The main components of the cooling plant are a vessel, a pump, a heat exchanger, and a primary cold source. A scheme of the system is shown in Figure 3.

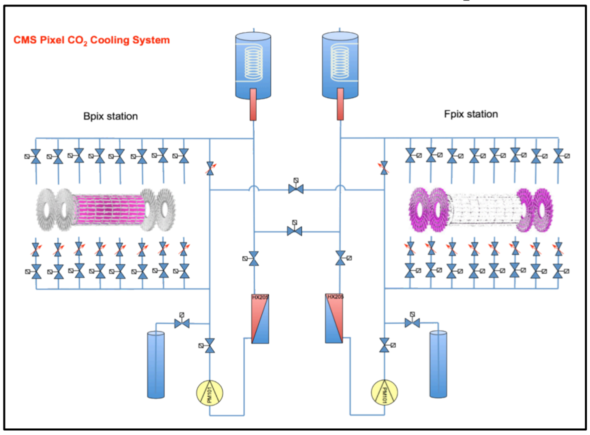

Figure 4: CMS Pixel CO_2 cooling system schematic

A redundant concept has been developed to insure that any failure of the main plant components will not cause downtime in the data taking with the detector. In addition, the two-fold redundancy can be extremely useful for maintaining the detector cold during cooling plant maintenance. As shown in Figure 4, the designed cooling system consists of two identical units. Each unit is sized to provide sufficient cooling power for the entire detector, i.e. 15 kW. Under normal operating conditions, BPIX and FPIX will each use a separate unit, but they can be connected to the same unit when needed.

Copper tubes with 12 mm ID, now used for C_6F_{14} single-phase cooling and operating at pressures less than 10 bar, are already installed between the cooling plant and the patch panels inside the CMS detector. The pipes were originally qualified by a pressure test at 20 bar. The pipes have subsequently been covered by several thousand cables and optical fibers, so they cannot be easily replaced and hence must be re-used. Following an extensive test program, these pipes have been qualified for an operational pressure of 70 bar, approved by CERN safety.

To ensure the cooling efficiency of in-detector evaporator loops, the design of the system must establish that the onset of evaporation occurs immediately before the inlet to the detector, but not too early along the pipework. On the other hand, the vapor quality (the ratio of mass flow of vapor and total mass flow (vapor+liquid)) at the exit of each detector loop should never exceed a value of 0.5-0.6 in order to prevent the so-called "dry-out" condition, i.e. a sudden temperature increase due to the absence of liquid along the pipe walls. In order to achieve these thermo-dynamic constraints, the CO_2 will be supplied in a sub-cooled state at the detector inlet, and then pre-heated to saturation by the ancillary electronics components upstream of the detector in the pixel support tube (Figure 5). Sub-cooling can be guaranteed by keeping the supply and return coolant at the same temperature. In previous applications of the 2PACL system, this was achieved by using concentric pipes between the detector and the plant. In the pixel upgrade project, the heat transfer between supply and return pipes will be guaranteed by coupling the supply and return pipes within the same insulated bundle.

The tests described in §5 will determine whether a concentric heat exchanger is needed at the detector inlet, and the minimum flow range that can be sustained in the large copper pipes without evaporation occurring in the supply sections of the circuit.

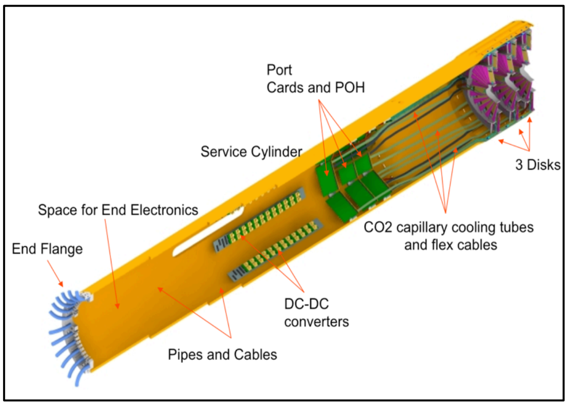

Figure 5: CAD model of the FPIX support tube with the three (half) disks

3.2 The on-detector cooling layout

Both BPIX and FPIX are served by four main cooling loops arriving from the plant at each end of the detector (12 mm ID copper pipes). Manifolds located in front of the detector support tubes (Figure 6) allow the parallel supply/return of up to 4 detector cooling loops in BPIX and up to 2 detector loops in FPIX. Detector loops connected to a single main loop are designed so they have very similar operation parameters, even under changing thermal load conditions. Unavoidable small

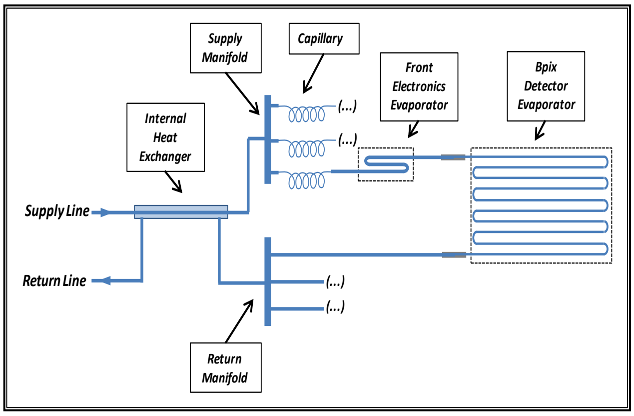

Figure 6: Pixel Barrel cooling schematic

differences in thermodynamic behavior between the different loops will be mitigated by the presence of capillaries after the manifolds (Figure 6).

The total length of the small diameter evaporators, taking into account the full path between the capillaries and the detector along the support tube, varies between 10 and 25 m, while the sections inside the detector have lengths between 7 and 9 m. Within the inner part of the detector, the choice of the pipe materials and sizes strongly influences cooling performance. The best candidates for both pixel sub-systems are stainless steel round pipes, with a wall thickness of 50 to 100 µm and inner diameters of 1.5 to 3 mm, with sizes determined by calculations and verified by experimental data (§4 and §5).

4. THE DETECTOR EVAPORATOR TESTS

The balancing of flow between different detector branches is a key factor in the cooling system design, as dry-out phenomena must be avoided in all possible operating conditions. For this reason, it is important to predict the pressure drop, heat transfer coefficient and the flow pattern along the detector evaporators where the fluid properties and flow regimes are changing.

For this purpose, a new calculator, named CoBra, was developed. It divides the detector tube into small and equal length sections where it is assumed that the flow region and fluid properties are constant. In sections where a liquid phase is present, the pressure drops and the heat transfer coefficient in liquid are calculated using the Darcy-Weisbach and Dittus-Boelter formulas. When two-phase flow is present, a phenomenological model for pressure drop and heat transfer coefficient prediction is used, based on flow pattern maps (Cheng et al. 2008). The CoBra calculator has been used to evaluate different designs for both the FPIX and BPIX detectors, and to guide the final choice of pipe sizes and lengths. Results of the calculations performed on the most recent BPIX and FPIX configurations are shown in figures 7 and 8.

In both cases, an inlet coolant temperature of -20°C and a flow rate of about 2 g/s results in a maximum ΔT between coolant and external tube surface of less than 10°C. This satisfies the requirement for a pixel sensor temperature below 0°C, but only if the thermal contact between the tube and the sensor is very efficient. In order to increase the margin on this part of the thermal contact chain, developments are on-going to further decrease the ΔT between the coolant and the external tube surface. Calculations have also been compared

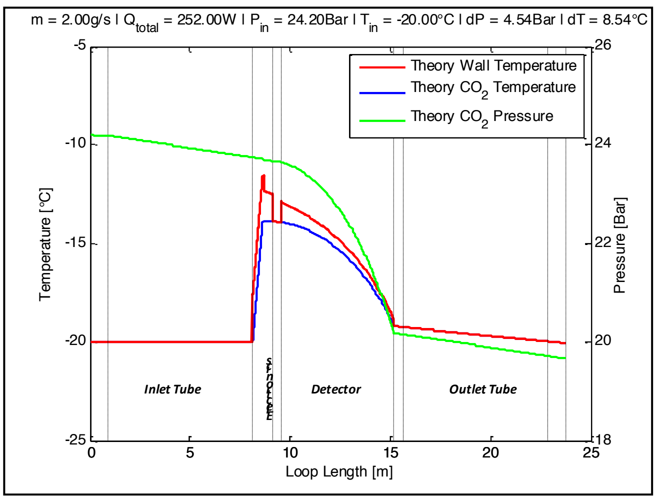

Figure 8: One BPIX cooling loop temperatures and pressure

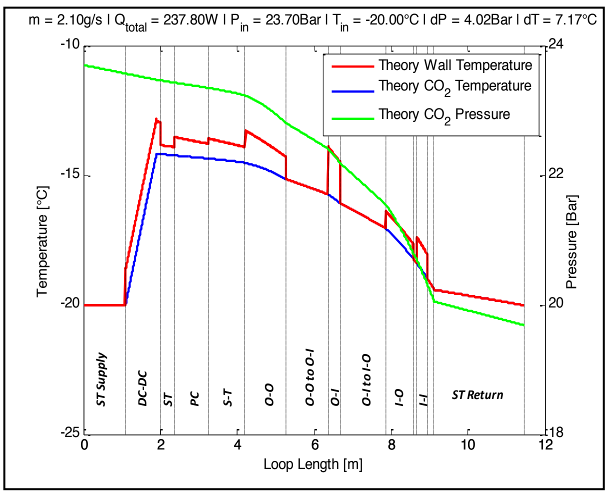

Figure 8: One FPIX cooling loop temperatures and pressure

with experimental data, as described in the following paragraphs.

4.1 The test set-up for detector thermodynamic studies

Several detector mock-ups have been built, tested, and the results compared with theory, in order to evaluate the cooling performance of cooling loops experimentally. To simulate the detector heat load, electric current has been applied to the detector tubes, taking into account the electrical resistance and length of the tubes. All tests feature multiple heat-loads and flow rate combinations. The tube wall temperature is recorded along the full length of the evaporator, as shown in Figure 9 for the most recent mock-up of one BPIX cooling loop. The mock up is connected to a small CO_2 cooling set-up which provides liquid CO_2 in a range of +20 to -30°C to the cooling tube inlet.

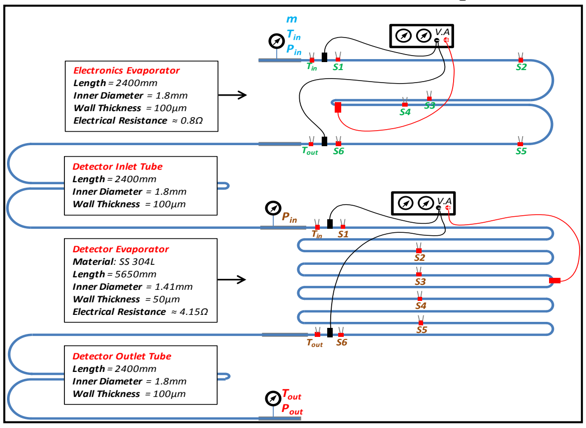

Figure 9: BPIX cooling mock-up schematic

4.2 Experimental results and comparison with calculation

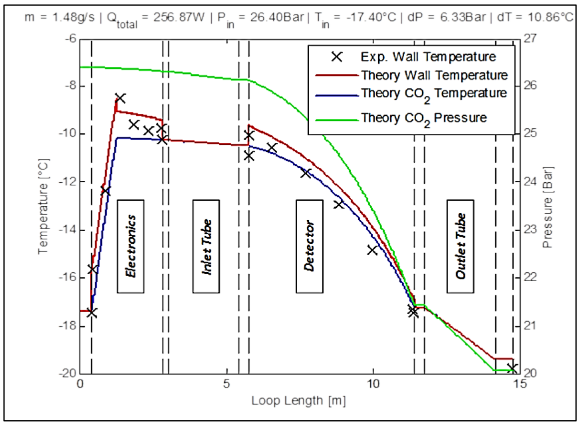

Figure 10: BPIX cooling loop mock-up, CO_2 experimental and theoretical temperature and

In Figure 10, the theoretical values of temperatures (fluid and tube wall) and pressure are plotted in continuous lines versus the evaporator length of the BPIX mock-up. Crosses correspond to the measured values of the wall temperature, showing very good agreement with the theoretical data issued from the CoBra calculator. The first meters of evaporators correspond to the pre-heating region inside the detector support tube. In this region, the ancillary electronics heat the sub-cooled CO_2 and bring it to a saturated state at the entrance of the detector evaporator (2 m), thus guaranteeing 2-phase flow in the most critical region.

The flow pattern map is a very useful tool as it allows the identification of each flow regime in the evaporator tube. The plots from the calculator indicate the presence of liquid phase (L) and intermittent flow (I) at the ancillary electronics (Figure 11), followed by annular flow (A) at the detector evaporator (Figure 12). It's also shown that in these conditions, the flow regime at the end of the detector evaporator is very near to the dry-out (D) zone. This has to be avoided as this regime is

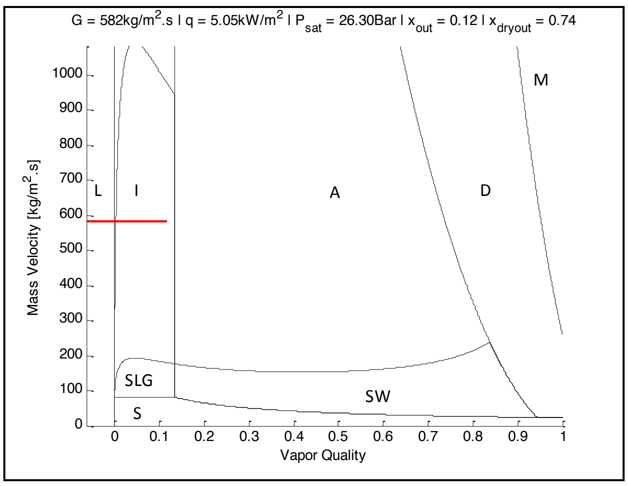

Figure 11: BPIX cooling, flow pattern for the electronics pre-heating region

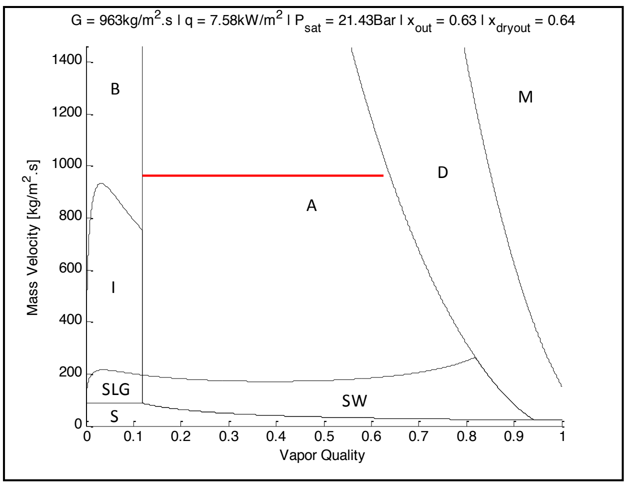

Figure 12: BPIX cooling, flow pattern for the detector electronics region

characterized by a very low heat transfer coefficient that will increase the detector temperature significantly.

5. THE LONG TRANSFER LINES TESTS

The pipework used for liquid C_6F_{14} to cool the present Pixel detector will be re-used for the evaporative CO_2 cooling of the detector upgrade. Four bundles of 9 copper pipes each (12 mm ID) are routed along the experiment from the cooling plant to the Pixel detector. The pipe average length is 32 m and includes horizontal, vertical and inclined sections.

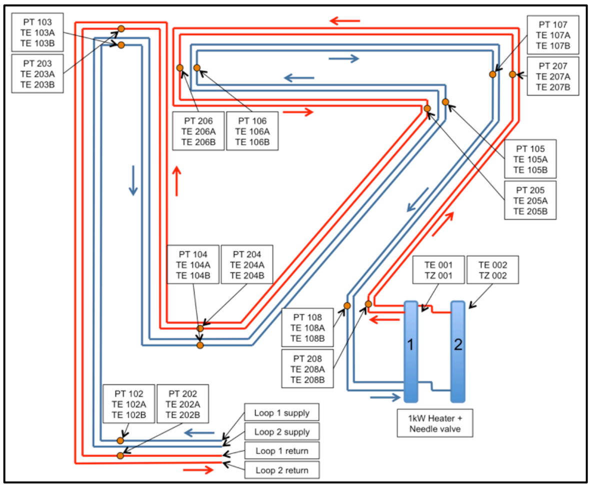

Figure 13: CMS piping mock-up

Currently, pipes are grouped in bundles of inlet or outlet pipes, in order to minimize the heat exchanged between them. For the CO_2 evaporative system, each bundle of pipes will contain an equal number of inlet and outlet pipes, in order to maximize their heat exchange, thus allowing CO_2 to be supplied in a slightly sub-cooled state at the detector inlet. On each side of the experiment (plus and minus Z), one bundle will supply the FPIX and the other will supply the BPIX. Of the 9 available pipes per bundle, 4 will be used for the sub-cooled CO_2 supply, 4 for the 2-phase CO_2 return and 1 will be kept as a spare.

5.1 The experimental set-up

One of the main constraints of this upgrade is the mandatory use of the existing copper piping. Given the size of these copper pipes with respect to the CO_2 mass flow (needed to cool down the sensors and evacuate the heat produced by the front-end electronics), the fluid speed might become too low and the environment heat pick-up sufficiently high to cause boiling of the CO_2 before the detector inlet. To avoid this phenomenon, a bypass tube may be installed in front of the detector to allow a larger flow, and thus increase the fluid speed in the transfer lines.

In order to study the flow behavior, a full-scale mock-up representing the CMS piping has been built in our laboratory, reproducing the installed lengths, bends and insulation thicknesses. The mock-up features one bundle with two separate complete cooling loops. On each loop, a heater, sized to reproduce the detector load, and a needle valve, that will create a pressure drop similar to that of the detector tubes, are used to simulate the detector. An additional pipe that can be connected to another system has also been installed on a part of the path. It will be used to study the impact of the external services temperature on the CO_2 behavior. The mock-up is connected to an experimental CO_2 cooling unit that can deliver up to 15g/s of sub-cooled liquid CO_2, and has a cooling power of 2 kW at -45°C.

One of the two test loops is fully instrumented with pressure and temperature sensors connected to a LabVIEW based acquisition system. By recording the pressure changes along the tubes and after each orientation change, we will be able to measure the thermodynamic behavior of the 2-phase CO_2 flow. The flow will then be tuned for safe and stable operation in the evaporator.

5.2 Test program

Tests will focus on three main parameters: the fluid temperature, the mass flow supplied to the experimental set-up, and the power delivered by the dummy loads. For these tests, the fluid temperature will be varied from +20°C to -20°C (operating range of the future detector cooling), the mass flow rate from 0 to 15g/s (maximum capacity of the test-stand pump), and the power from 0 to 600W (maximum estimated dissipated power on one detector cooling loop).

The test program will be carried out in several steps, varying one parameter at a time. For each combination, the pressures and temperatures along the instrumented pipe will be recorded and post-processed to determine the flow conditions at the inlet and outlet of the detector simulator. After careful analysis of the flow conditions, we will determine the optimal flow rate in the copper pipes that leads to a boiling of the CO_2 just before the inlet of the detector.

6. CONCLUSIONS

The CMS Pixel detector will be upgraded in ~2016. Based on the success of AMS and LHCb Velo in the use of CO_2 evaporative cooling (featuring the 2-PACL principle), the same method has been chosen for the cooling system of the new CMS Pixel detector. The design of the system is in an advanced state and components will be selected once the detector design and assessment of the re-use of the transfer lines are completed.

The tests of in-detector evaporators have started with the BPIX structures and good agreement has been found between experimental results and corresponding calculations. The FPIX structures will be available and tested in our lab soon. With the CoBra calculator, we can already simulate the behavior of the FPIX evaporators before the tests.

The mandatory re-use of the existing copper piping has been taken into account, and measurements on a dedicated test set-up will begin soon. These measurements are the key inputs needed to continue the design of the cooling plant. They will allow us to determine whether a bypass in front of the detector is needed. From these results, we will calculate and freeze all the parameters of the installation and begin the final design phase of the cooling system.

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