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Performance of the ALICE SPD cooling system

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Abstract. The new generation of silicon detectors for particle physics requires very reduced mass and high resistance to radiations with very limited access to the detector for maintenance. The Silicon Pixel Detector (SPD) is one of the 18 detectors of the ALICE (A Large Ion Collider Experiment) experiment at the Large Hadron Collider (LHC) at CERN. It constitutes the two innermost layers of the Inner Tracking System (ITS) and it is the closest detector to the interaction point.

An evaporative cooling system, based on C₄F₁₀ evaporation at 1.9 bar, was chosen to extract the 1.35 kW power dissipated by the on-detector electronics. The whole system was extensively tested and commissioned before its installation inside the ALICE experimental area. Since then we had to deal with a decrease of the flow in some lines of the system that imposed severe restrictions on the detector operation. Recently, a test bench has been built in order to carry out a series of tests to reproduce the misbehaviour of the system and investigate proper actions to cure the problem.

The performance of the systems and the most interesting results of the above mentioned tests will be presented.

1. The Silicon Pixel Detector (SPD)

ALICE (A Large Ion Collider Experiment) is the experiment at the Large Hadron Collider (LHC) at CERN (European Organization for Nuclear Research), designed to address the physics of strongly interacting matter and the quark gluon plasma (QGP) at the extreme values of energy density and temperature reached in ultra-relativistic nucleus-nucleus collisions [1].

The ALICE detector consists of a central barrel measuring hadrons, electrons and photons, and a forward muon spectrometer. Its overall dimensions are 16x16x26 m³ for a total weight of approximately 10000 tons.

The tracking in the central barrel is based on the Inner Tracking System (ITS), a six layer, high resolution silicon vertex detector, and the Time Projection Chamber (TPC).

The Silicon Pixel Detector constitutes the two innermost layers of the ITS [2] and it plays a fundamental role in the ALICE physics program. The SPD sensors consist of a two-dimensional matrix (sensor ladder) of reverse biased silicon diodes bump-bonded to 5 readout chips.

The basic detector module is the half-stave (Fig.1), composed of two sensor ladders, one Multi-Chip Module (MCM) and one multi-layer interconnect (pixel bus). The two sensors, 200 μm thick, are attached and wire bonded to the pixel bus, which carries data and control lines and power/ground planes. The Multi-Chip Module, located at one end of the half-stave, is wire bonded to the pixel bus and establishes the connection between the sensors and the off-detector readout electronics via optical fiber links. Two half-staves are attached head-to-head along the z direction to a Carbon Fiber Support Sector (CFSS), with the MCMs at the two ends to form a stave [3]. Each sector supports six staves, two on the inner layer, located at an average distance of 3.9 cm from the beam axis, and four on the outer layer, located at 7.6 cm. Ten sectors are then mounted together to form the SPD cylindrical barrel around the 800 μm thick beryllium beam pipe.

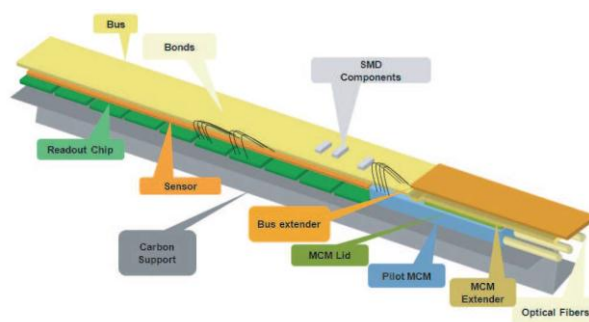


Fig. 1 The SPD half-stave with its main components.

The SPD front-end electronics dissipates ~ 23 W (nominal) in each stave, i.e. 1.35 kW for the whole detector. This power, if not correctly removed, could increase the temperature of the detector up to dangerous values at the rate of $1^\circ\text{C}/\text{s}$. A continuous monitoring of the detector's temperature is therefore mandatory and a safety interlock is set up in order to switch off the detector in case of failure of the cooling system.

1.1. The SPD cooling system

In order to remove the power dissipated by the on-detector electronics, the SPD is equipped with an embedded cooling system based on the Joule-Thomson cycle (rapid expansion at constant enthalpy and subsequent evaporation), with C_4F_{10} (perfluorocarbon) as refrigerant fluid.

The design of the cooling system was driven by several constraints, such as:

- complete removal of the power dissipated by the on-detector electronics maintaining the sensor temperature around 25°C and assuring a uniform temperature distribution along the stave, in order to reduce mechanical stresses associated with thermal gradients;
- low material budget contribution;
- cooling duct temperature above the dew point;
- long-term stability against corrosion;
- dielectric fluid or leak less operation.

The layout of the SPD cooling plant is depicted in Fig. 2. The saturated liquid C_4F_{10} coming from the condenser (7) is subcooled in a plate heat exchanger (6) before entering the pump (5), in order to avoid cavitation. The pump increases the liquid pressure so it can reach the detector (about 50 m away) still subcooled. After a hydrofilter (to remove water and HF compounds) and a molecular-sieve

filter (4), the fluid reaches the liquid manifold (3), which splits the flow in 10 lines, one for each sector. The pressure of each line can be set by a pressure regulator, and the flow is evaluated thanks to a Coriolis mass flow meter. Ten stainless steel 6/4 mm (in/out diameter) 50 m long pipes bring the fluid to the SPD detector inside the ALICE magnet: along its path the fluid loses ~100 mbar and reaches the ambient temperature (22°C). The fluid is then subcooled again in plate heat exchangers.

Before entering the detector the flow of each line is divided in six lines inside a manifold box (Fig.3, right), each one of them feeding one capillary (0.5 mm ID) and the subsequent cooling duct (1). Inside the capillaries the fluid undergoes the required pressure drop to start evaporating. At the outlet of the detector the flow is recollected in another box and, after complete evaporation provided by an electrical heater (10), it reaches the compressor (8) that forces the gas inside the condensation tank (7). The evaporation pressure is controlled acting on the compressor speed.

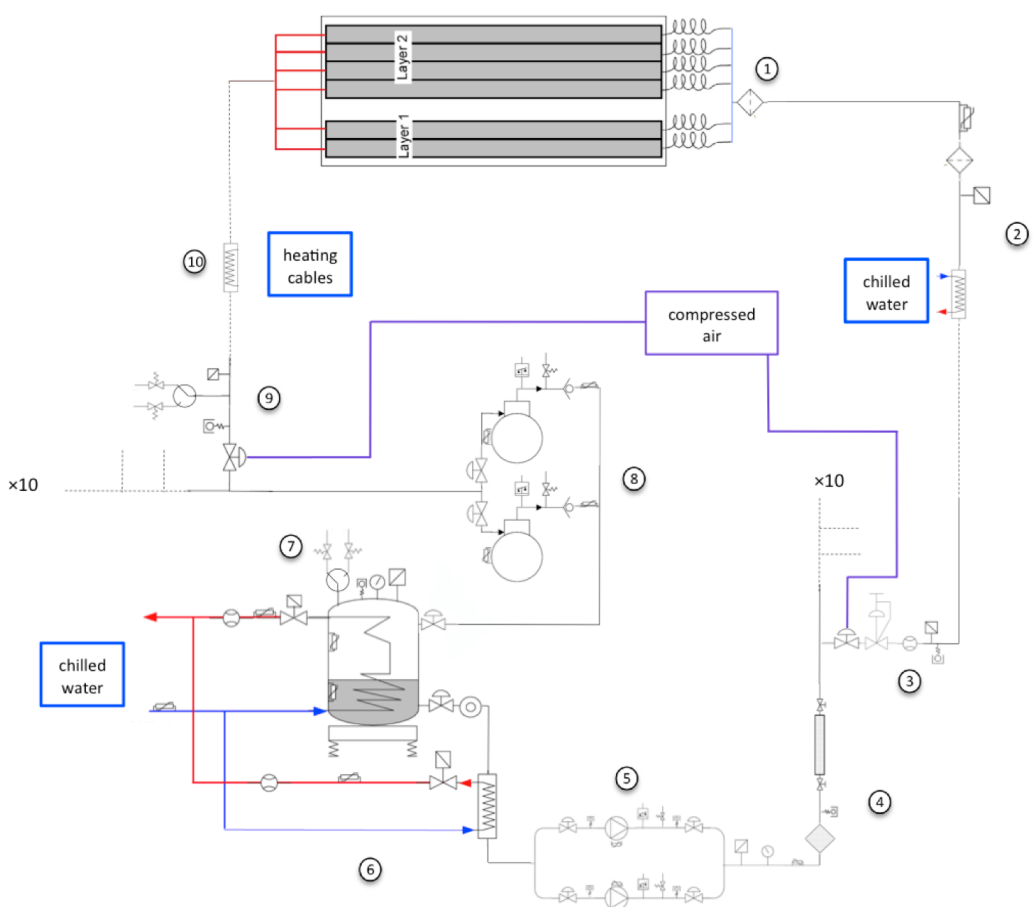


Fig. 2 Layout of the SPD cooling system

Along the lines, before the detector, two 60 µm filter are installed in series in order to protect the capillaries from pollution: one is installed in the position called PP4, 6 m away from the detector and the other in the PP3 point, 1.5 m away from the detector. The filter installed in PP4 is reachable and can be regularly replaced, while the other (PP3) is not accessible without having to disassemble part of the ALICE experiment.

Assuming an evaporation pressure of 1.9 bar, the minimum flow required in order to completely extract the 23 W of each stave is 0.3 g/s, corresponding to 1.8 g/s for one sector and 18 g/s for the whole detector.

The evaporative cooling ducts are housed in the CFSS and run underneath the on-detector electronics. The thermal coupling between the heat source and the cooling duct is established by the thermal grease (AOS 52029), also reducing the effects of anisotropic heat conduction typical of carbon substrates.

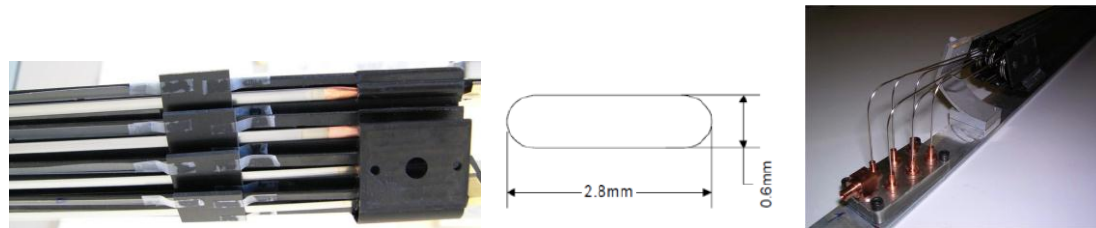


Fig. 3 The cooling ducts installed on the carbon fibre support of an SPD sector (left), the cross section of a cooling duct (center) and the inlet manifold feeding the six capillaries of a sector (right).

The cooling duct is made by a 40 μm wall Phynox (Elgiloy) tube, a cobalt based austenitic alloy highly corrosion resistant. It is obtained from a 2.6 mm ID circular tube squeezed down to a flat profile with a thickness of 600 μm in the thin dimension (Fig. 3, center) in order to increase the exchange surface. This, however, reduces to 2.5 bar the maximum pressure tolerable by the pipe before deformation.

1.2 SPD detector performances

During the whole commissioning phase preceding the installation of the detector inside the ALICE experimental hall, the system showed full efficiency (100%) and a mean temperature of the sensors of 28°C with an input pressure before the capillaries of 2.7 bar and no problem or misbehavior was observed. Each sector was individually tested and a thermal survey with an infrared camera was also performed [5].

After the installation in ALICE, the detector showed the first problems with 50% of sector #9 switched off due to high temperature. After that, also other sectors started to show the same behavior, with the cooling flow clearly decreasing in their lines. Some attempts of increasing the flow by increasing the liquid pressure were only partially successful and did not allow the full recovery of the performance. The flow in some lines continuously kept decreasing despite the pressure rising, until only 60% of the detector could be switched on.

2 Experimental setup

In order to study the problems affecting the SPD cooling system, a test bench was realized at CERN to carry out dedicated tests. The layout includes a cooling plant and a test section (Fig. 4). The cooling plant is a down-scaled replica of the SPD cooling system installed in the ALICE experimental hall except for the absence of the compressor: in this case the evaporation pressure is not set by the compressor rotational speed but it is adjusted by changing the saturation temperature inside the condenser.

The main part of the test section is the SPD dummy sector, which is a replica of the hydraulics of one of the 10 sectors that compose the SPD detector: in this case the power dissipated by the silicon sensors is simulated by some resistors located in the same position of the sensors.

The dummy sector is equipped with several measurement points: six pressure sensors installed at the end of each capillary are used to measure the pressure drop through the capillaries. Five NTC temperature sensors are installed in each of the six staves: four are installed just above the cooling duct along the axial direction in order to evaluate the development of the fluid temperature. The fifth NTC is installed on the surface of the resistor in order to evaluate the temperature gradient in the normal direction: this is also the same position where the temperature sensors are installed in the real detector.

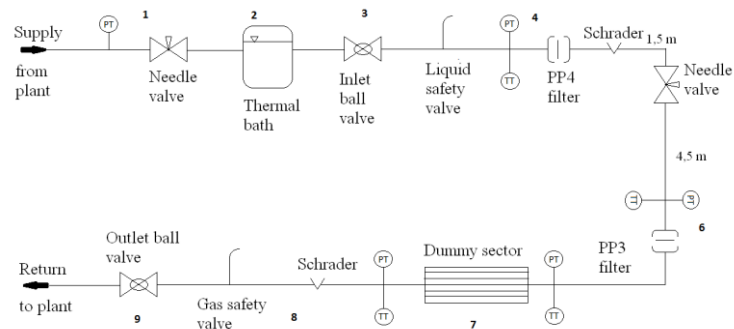


Fig. 4 Layout of the test section setup.

As can be seen in Fig. 5, the resistor is composed by a sandwich of materials in order to better simulate the thermal behavior of the SPD silicon sensors.

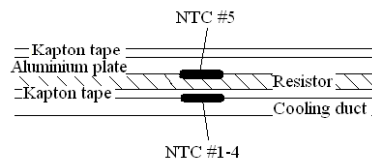


Fig. 5 Scheme of the resistors of the dummy sector.

3 Test campaign

Analyzing the reduced efficiency of the detector cooling, it seemed that the filters located in PP3 were partially clogged, causing an important decrease of the flow and thus the increase of the pressure in PP4. A SEM analysis of the filters from PP4 showed traces of graphite and metals that might indicate a similar contamination of the downstream filters in PP3.

In order to study the effects of small particles contaminating the fluid flowing inside the systems, a set of tests was performed by inserting in the lines small quantity (~0,25 g) of sized carbon particles with diameter ranging from 0,4 up to 200 μm .

The following considerations came out from these tests:

- the clogging effect of the powder is very high;
- a relatively small amount of powder can obstruct the flow up to levels compatible with those observed in the real system;
- particles can flow across the first filter and stack on the second one.

These results proved that obstruction caused by small particles on the PP3 filter mesh can explain the misbehavior of the SPD cooling system.

Another effect that could affect the behavior of the system is a premature evaporation of the fluid before it enters into the capillaries, caused by the high pressure drop located in the clogged PP3 filter, which may imply obstruction and misdistribution of the flow in the supply manifold box described above. This phenomenon was clearly observed in the test bench, where transparent pipes are used to examine the flow patterns: usually plug/slug and stratified flow were detected, as expected for the low title and small velocity.

Instabilities of the evaporation pressure and temperature were also observed when two-phase flow enters the capillaries, as can be seen in Fig. 6. In case of subcooled liquid at the inlet (Fig. 6, top), temperature profiles along the stave are steady, even increasing the power applied on the sector step

by step up to the nominal value. On the other hand, if two-phase flow was observed entering the sector (Fig. 6, bottom), temperature and pressure evaporation instabilities were registered and a higher temperature on the sensors was detected for the same power applied.

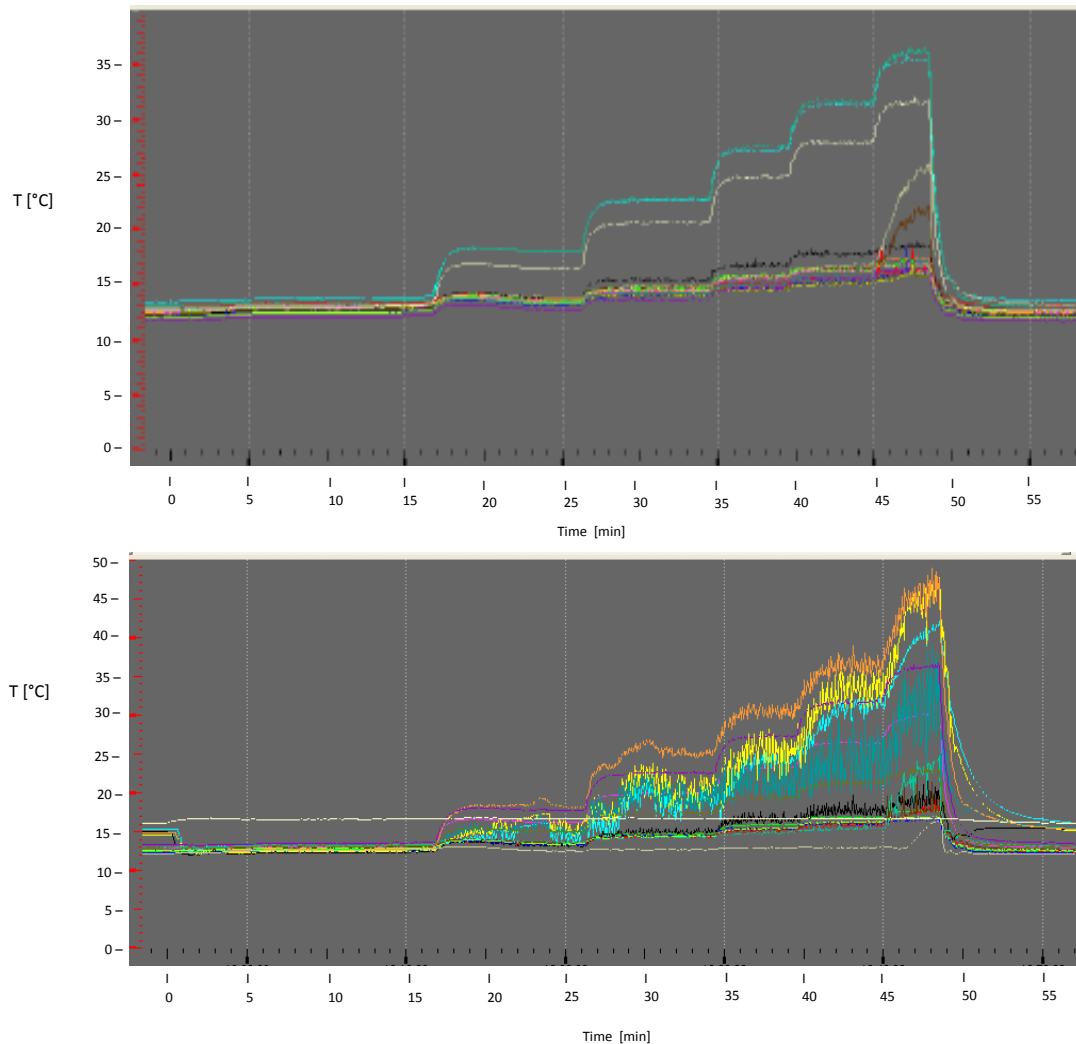


Fig. 6 Temperature profiles at increasing heat flux: normal profiles (top) and temperature instabilities due to two-phase flow entering the capillaries (bottom).

In order to verify if a higher sub cooling of the liquid could improve the performance of the system by moving its state far from the saturation zone, two kinds of test were performed: first different temperatures were set in the thermal bath and then the sub cooling position was changed along the line closer to the detector. The first test was made by setting all the parameters as they are in the cavern with the aim to evaluate the minimum flow rate to avoid two-phase flow before the capillaries. The thermal bath temperature was then set at 8°C as in the real system. In this situation the flow rate was decreased step by step by simulating the pressure drop between PP4 and PP3 with a needle valve. In this situation, two-phase flow was observed starting at 1.4 g/s, which implies that in the real system if the flow gets below this value, a two-phase state can be expected before the sector entrance, with a high chance to drastically affect the flow distribution inside the capillaries.

Another test was carried out decreasing the temperature of the bath at 4°C: in this case the minimum flow to prevent evaporation before the capillaries decreased to 1.25 g/s (Fig. 7).

The effectiveness on the flow rate of installing the sub-cooling as close as possible to the detector was also proven; however this option is limited on the real system because the detector closest accessible point is only about 6 m far away.

An attempt to reduce the evaporation of the fluid before the capillaries was carried out also increasing the pressure of the fluid in PP3 point: this was obtained by increasing the evaporation pressure and the pressure in the return line by setting a higher saturation temperature inside the condenser.

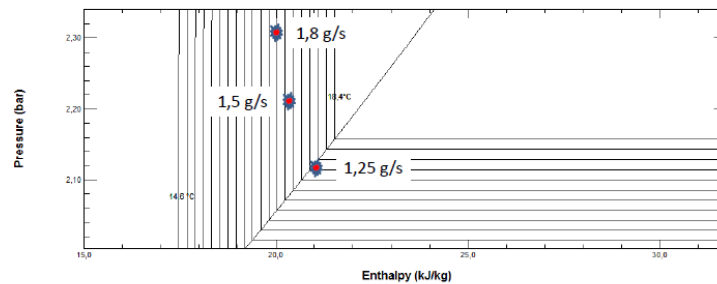


Fig.7 Results of the tests with sub-cooling at 4°C plotted on the C_4F_{10} p-h diagram

In this condition, although the temperature of the staves is expected to increase because of the higher evaporation pressure, a higher amount of power should be removed because of a better distribution of the flow. Once set the flow rate at 1.5 g/s with the flow regulation valve, the gas pressure was increased from 1.5 to 2.1 bar in steps of 100-150 mbar: the increase of gas pressure results in a higher amount of power that can be dissipated at constant flow rate, increasing from 85 W to 150 W. A confirmation of this result was then obtained repeating the same test on the real system: in this case, increasing the gas pressure from 1.65 to 1.9 bar, the mean temperature on the detector's sensors increased from 29.6 to 32.8 °C, as expected, but it was possible to switch on 6 more modules.

4 Drilling intervention

The results described above show that a clogging of the PP3 filter installed on the lines of the SPD cooling system can explain the misbehavior of the system dramatically affecting the number of half-staves that can be operated. Further studies and the very low effectiveness of all attempts to clean the clogged filters by counter-flow flushing and ultra-sound showed that to substantially improve the cooling performance the removal of the filters was mandatory. However to get access to the filters in PP3 a heavy effort is necessary because it requires a partial dismount of ALICE, which can be performed only during a long shutdown of LHC. Therefore during the last winter shutdown an intensive campaign of tests was launched in order to understand if the filters could be drilled while in place and whether this intervention would be effective to recover the cooling performance. One of the main problems in this kind of intervention is to reach the filter that is located 5 meters downstream inside the 4 mm inner diameter pipe with an 80 degrees bend in between.

For this reason, a dedicated tool was built by welding a tungsten carbide tip (Fig. 9) at the end of a 5 m long, 2,5 mm thick twisted stainless steel wire. The shape of the tip was developed step by step in order to improve the drilling procedure avoiding the breaking of the tip and/or the filter and paying attention to limit the number of residual particles, since also very small particles flowing towards the detector can obstruct the capillaries severely damaging the detector.

A careful cleaning procedure was developed and optimized, consisting of particles aspiration at the drilling point performed by inserting up to the filter a plastic pipe connected to a vacuum pump; magnetic particles collection performed by inserting up to the filter a strong magnet welded at the end of a 5 m long stainless steel twisted wire and counter flow cleaning with liquid C_6F_{14} . The whole procedure was extensively tested in order to prove its effectiveness: in particular, the cleaning

procedure was tested by placing a filter after the drilled filter and flowing liquid towards the detector like during normal operation: the filter was then analyzed at the electronic microscope in order to evaluate the number and the size of the remaining particles. At the end of the optimization process, the number of particles detected was very small (5-6) and their dimension was well below the limit to become dangerous for the capillaries.



Fig.9 Tool used for the drilling intervention.

The first intervention on the detector was performed on February 2012 and it was very successful: 3 out of 10 sectors were drilled and in all of them the flow increased up to nominal values allowing powering all the half-staves. Another intervention was performed during the following LHC technical stop on 2 other sectors confirming the previous results and increasing the cooling efficiency up to 100%. The enhanced flow rate inside the lines of the cooling system increased the number of operating half-staves from 75 up to 116, also allowing a better configuration of the modules and safer working conditions. The detector has successfully passed the first stress tests after the intervention and it is now under observation for the long term behavior.

Conclusions

The paper reports the results of the test campaign carried out at CERN in order to explain the misbehaviors observed in the cooling system of the SPD detector installed in the ALICE experiment dramatically affecting the performance of the detector. In particular a continuous decreasing of the flow in some lines of the system was observed after its installation in the ALICE experimental hall. These tests showed that a partial clogging of a 60 μm filter installed in the cooling lines and not reachable without a partial disassembling of the whole experiment could be the cause of the anomalous behavior observed.

Some attempts to solve the problem are also described but no one of these, in the end, was found to be effectively implemented in the real cooling system. As results of the test campaign a drilling intervention was then scheduled after a careful study and an extensive experimentation. This critical intervention allowed restoring the nominal flow rate in the lines of the SPD cooling system significantly improving the efficiency of the detector.

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