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CO_2 cooling system for Insertable B Layer detector into the ATLAS experiment

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CO_2 cooling has become a very interesting technology for current and future tracking particle detectors. A key advantage of using CO_2 as refrigerant is the high heat transfer capability allowing a significant material budget saving, which is a critical element in state of the art detector technologies.

At CERN a new CO_2 cooling system has been constructed to serve for the cooling of the new ATLAS Insertable B-Layer (IBL) detector. Two independent cooling units, sharing one common accumulator, placed about 100m from the detector, are designed to cool 14 individual pixel staves with evaporative CO_2 at a the given pressure.

This paper describes the general system design, the innovative redundancy approach, the maintenance philosophy, the control system implementation and the commissioning results including the performance tests in the proximity of the detector. Additionally the different failure scenarios and recovery techniques including the cooling units swap procedure will be discussed.

The system tests and challenging commissioning proved precise temperature control over the long distance and expected performance. Looking forward for the IBL detector installation, the cooling system will be prepared to serve for the next Large Hadron Collider physics run starting early 2015.

Technology and Instrumentation in Particle Physics 2014
2-6 June, 2014
Amsterdam, the Netherlands

1 Speaker

1. Introduction

The high energy physics (HEP) experiments constructed to operate on the Large Hadron Collider (LHC) at CERN, sitting 100m underground, includes high precision semiconductor tracking detectors. The detector's electronics and sensing elements require a light weight and radiation-hard cooling system to ensure a stable and safe operation. The current state of the art in the detector cooling technologies is the evaporative CO_2 cooling based on the 2 Phase Accumulator Controlled Loop method (2PACL) [1]. The main benefits of CO_2 with respect to the currently used Fluorocarbons are favourable thermo-physical properties allowing to apply very small diameter tubing, as well as a reduced operation cost and environmental impact [3].

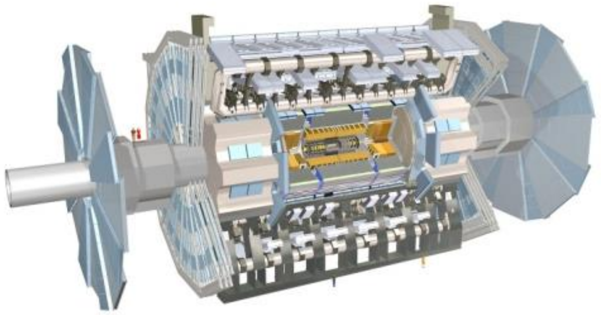

Figure 1: The Atlas experiment

The ATLAS experiment (Fig.1) being the largest general purpose detector installed at CERN with its 25m diameter, an overall length of 46m and a total weight of about 7000 tons, is under the upgrade process during the first long shut down of the LHC. One of the major upgrade tasks for the ATLAS tracking detector is the improvement of the current pixel system. The main activity was the installation of an additional new PIXEL detector called Insertable B Layer (IBL) in between existing pixel detector and the beam pipe with a very close distance to the interaction point. The IBL is the first sub-detector in ATLAS experiment using the evaporative CO_2 to remove the dissipated heat and to limit the radiation damage of the silicon sensor by keeping the sensor temperatures below -20'C.

1.1 History

The development of the evaporative CO_2 cooling systems based on the 2PACL method was initiated in HEP by NIKHEF in about 2000 by introducing a new cooling concept to the community. The first detectors equipped with CO_2 cooling were the Alpha Magnetic Spectrometer (AMS-02 launched on May 16, 2011) installed on the International Space Station and the LHCb Vertex Locator (VELO) [1]

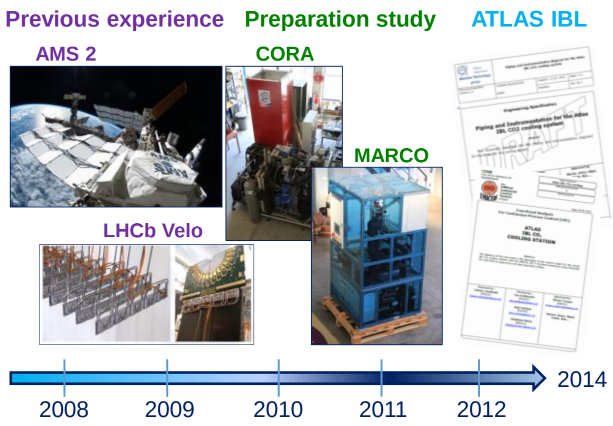

Figure 2: The 2PACL history

installed in 2008 at CERN. Further studies, research and development followed. The time scale is shown on figure 2. Since 2009 at CERN several CO_2 cooling plants where designed and manufactured in close collaboration with NIKHEF, mainly as preparatory work for future detector cooling systems. In 2010 the first stationary unit called CORA (CO2 Research Apparatus) [4] was built to serve for R&D of all LHC tracker upgrades. In 2011 the first fully automated transportable cooling unit called MARCO was manufactured to enable basic studies of a low temperature range close to the CO_2 freezing point at -56^{o}C.

The CO_2 cooling system was first proposed in 2009 for the ATLAS IBL detector then the concept prototyping was done using the CORA and the MARCO machines and the real IBL system development began in 2012.

1.2 The 2PACL concept

The 2PACL is a 2-phase pumped loop, as shown in figure 3, where, the detector evaporation temperature is indirectly controlled by the accumulator pressure. The accumulator is a vessel filled with a mixture of liquid and vapour CO_2. The return line connects to the accumulator, keeping the same pressure of the returning 2 phase CO_2, as pressure in the accumulator, regulated by cooling and heating action.

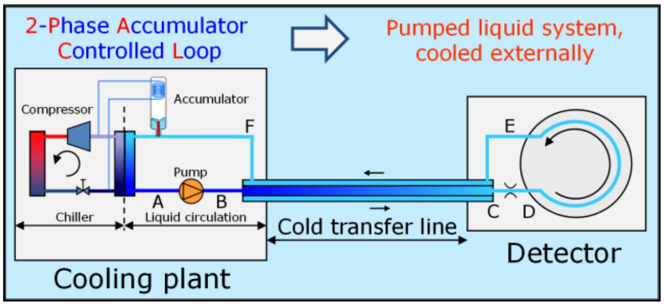

Figure 3: The 2PACL scheme

Cold liquid CO_2 is pumped to the detector where it expands to the desired pressure set point and becomes a two-phase coolant removing detector's heat. The returning mixture of vapour and liquid CO_2 is condensed and subcooled by means of a primary chiller before being pumped back into the closed loop.

2. The ATLAS IBL cooling system

The new ATLAS IBL detector is composed of 14 individual staves equipped with 3d and planar pixel sensors . It is the innermost layer of the pixel detector requiring cooling power of 1.5kW with the fully flexible and continuous detector evaporation temperature control from +20^{o}C to -40^{o}C. The cooling system has to be redundant and self-recovering in case of one unit failure. Reliability and largest possible readiness is also required to ensure 24/7 operation. Additionally as the amount of the available space to bring the coolant from the distribution system up the heart of the detector is very limited in the ATLAS experiment, a new vacuum insulated flexible transfer line technology had to be developed see section 2.1.4.

2.1 Mechanical system design

To fulfil the detector requirements the CO_2 cooling system was designed to provide cooling power of about 3kW at -40^{o}C, where 1.5kW is the heat dissipated by the detector and the rest is reserved to cover the heat losses in the system.

To provide a redundancy approach and to guaranty the shortest possible time of recovery after any kind of trip, the IBL cooling system is made of two almost fully independent systems, internally called A and B. Maintenance task on one of the sub-systems can easily be done when the other one is in normal operation and serves for the detector. Each of them is a modular sub-system comprising one cooling plant, one chiller unit and one common accumulator unit shared by both systems. The systems are equipped with a fully redundant control instrumentation, see figure 4. Additionally, both sub-systems share common interconnection piping for maintenance operations. This approach allows performing any kind of maintenance task on the one of the sub-systems when the other one is in normal operation providing service to the detector.

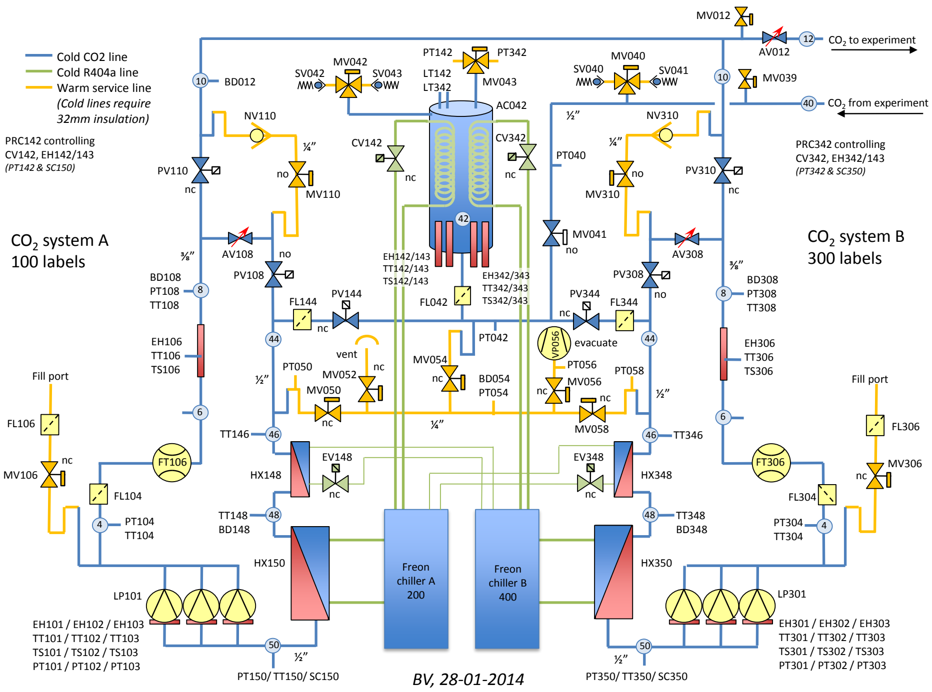

Figure 4: The IBL CO_2 cooling plant P&ID

The IBL CO_2 cooling system is located in the ATLAS experiment service cavern, see figure 5, in a radiation protected area, about 100m away from the detector cooling distribution equipment, called Junction and Manifold Box.

Figure 5: The IBL CO_2 cooling system in ATLAS service cavern

2.1.1 The cooling plant unit

The cooling plant unit is composed of several mechanical component's like: a triple head liquid membrane pump, a Coriolis mass flow meter, a direct liquid heater, a set of pneumatic actuated valves, filters, two heat exchangers, a cooling plant by-pass etc. All so called "cold" parts are encapsulated in two "sandwich" shape foam boxes: one for the liquid pump heads, the second for the CO_2 piping, see figure 6. The foam box solution provides an easy maintenance and service access to the components without a need of damaging and redoing time consumable standard insulation. Additionally, all warm mechanics and instrumentation are kept outside the foam box with an easy access at any time of operation.

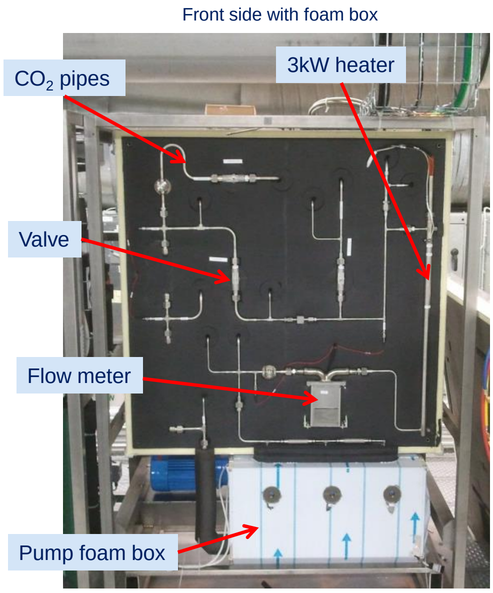

Figure 6: The Cooling plant unit

The reason to use two independent heat exchangers (HX) in each cooling plant unit is related with the redundancy principle. In normal operation mode one subsystem is running following its program, driven by the industrial Programmable Logic Controller (PLC), and controls the detector evaporation temperature. It uses the large HX using its own chiller to condense and sub cool the CO_2 before the pump. At the same time the second system can be kept in stand-by mode pumping locally liquid around over the internal by-pass. The CO_2 is cooled in the small heat exchanger and is connected to the chiller of the active system. The R404a flow is controlled by an electric shut-off valve of the CO_2 unit concerned. The flow regulation of this standby mode is passive with a thermostatic expansion valve, and so no control communication between the plants is needed. The purpose of the standby-mode is to keep the pump of the inactive system cold such that a fast start of the 2nd system is possible. When a swap is performed to a warm pump it can take hours to reach cold condition again as the whole system needs to be pressurized to liquid of ambient temperature. The so-called SWAP procedure might be triggered automatically if one unit tripped and the other one was in stand-by mode or if decided by the operator.

2.1.2 The chiller unit

The chiller unit is made as standard refrigeration equipment based on a two stage Bitzer R404a compressor. To guaranty a stable system operation and to cope with a wide range of system loads, from zero to the full IBL load switched on in a single step, the primary cooling unit is equipped with a set of features like a frequency controlled compressor, a hot gas bypass with liquid injection, a back-pressure regulator and an advanced control algorithms controlled by the cooling plant PLC. Additionally for the internal redundancy each chiller unit has two condensers: water cooled condenser used as the default and air cooled condenser for the redundancy needs in case of a water failure.

2.1.3 The accumulator

The accumulator unit is a shared component between system A and B. It is a pressure vessel equipped with two cooling spirals and four heating elements where one spiral and two heaters serve for system A and the rest for system B. Apart from that it has a dedicated local control box which allows to control all maintenance valves on the service manifold independently of the controls of the system A or B. Moreover the local box is being powered from two independent power sources: uninterruptible power supply (UPS) and normal power. Additionally it is equipped with an auto switch equipment to provide necessary power even if one of the sources fails.

2.1.4 Transfer lines and the distribution system

As the ATLAS IBL CO_2 cooling system is located into the service cavern, the overall length up to the detector is more than 100m. To connect the detector distribution with the cooling plants two solutions were introduced. The first one is the industrial standard permanent vacuum insulated coaxial transfer line covering the majority of the distance up to the top part of the detector. In this section, via the inner pipe**,** the liquid CO_2 is flowing. It is being warmed up by the returning 2 phase CO_2 from the detector, passing by the outer pipe. Like this a liquid temperature similar to the evaporation temperature is obtained, resulting in evaporation of the CO_2 when entering the detector cooling pipe. The transfer line connects up to the Junction Box which is the first line distribution component equipped with set of manual valves and a dummy load, enabling to perform the commissioning of the cooling system in the proximity of the detector without a need of connecting to it. The Junction Box also senses the in- and outlet condition of the CO_2 going to and from the distribution manifold. The second solution is provided by the usage of 14 custom made vacuum insulated flexible transfer lines from the Manifold box up to the detector (see figure 7). The principle is very similar, however because of the pipe sizes the line becomes flexible, very similar to a rigid electrical cable (see figure 8). This feature enables to pass through the difficult and tight in space routing inside the ATLAS detector. The vacuum insulated flex-line

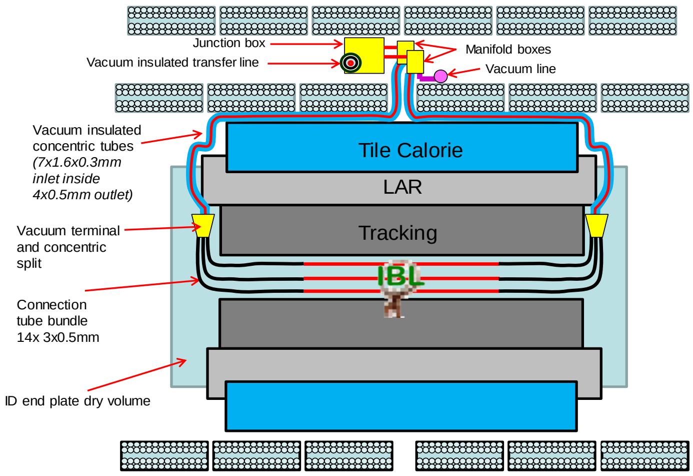

Figure 7: the flexible vacuum insulated transfer line simplified rooting

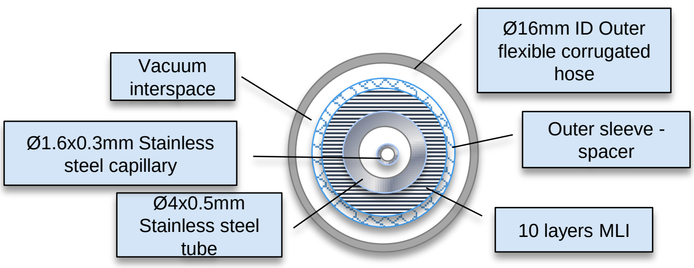

Figure 8: Cross section of the flexible vacuum insulated transfer line

solution is also applied to avoid condensation on the cooling line surface. Additionally the major difference between main CO_2 transfer line and the flexible is that the flex-line requires constant vacuum pumping. The highest evaluated vacuum level not guaranteeing safe system operation, without condensation effect, has been evaluated to be 10^{-3}mbar. In consequence the ATLAS IBL CO_2 cooling system had to be equipped with an additional, fully redundant, vacuum pump station being able to work very close the strong magnetic field. The selected solution is a combination of primary rotary backing pumps with oil diffusion pumps.

2.2 Control system design

The control system is based on industrial control and electrical components so-called off shelf components for easy maintenance and spare parts availability.

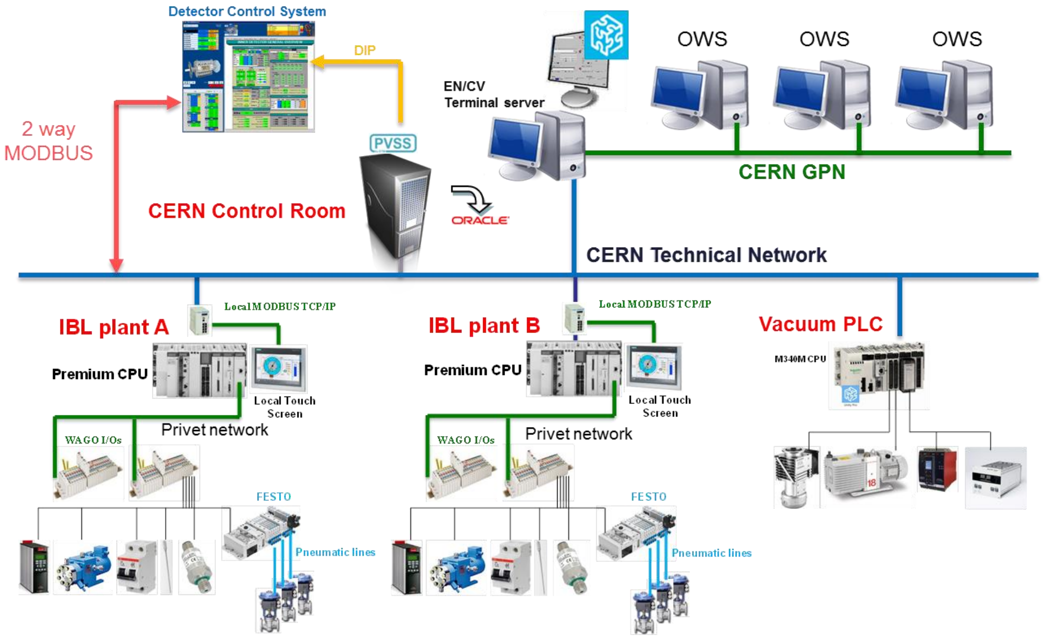

Figure 9: ATLAS IBL CO_2 cooling control system architecture

The ATLAS IBL CO_2 cooling system is driven by 3 independent Schneider PLCs: two Premiums serving for the system A&B and one 340M for vacuum system, all placed in CERN Technical Network physically detached from the outside world for the security reasons, see figure 9. Each cooling unit is equipped with about 330 I/Os. The PLCs run about 20 control loops and monitor about 360 interlocks and alarms. Industrial ETHERNET IP filed network was selected to connect the distributed system elements. The user interface is based on a SCADA (Supervisory Control And Data Acquisition), based on Siemens WinCC OA, see figure 10. The control software conforms to the UNICOS CPC6 (Unified Industrial Control System Continuous Process Control) framework of CERN [6] [7]. Communication between the SCADA server located in the CERN Control Centre, and PLCs uses MODBUS protocol. The hierarchical access control is in place being synchronized via centralized mailing lists system called e-groups. Additionally to save all the data for the later analysis our control system connects also to long term data storage data base called LHC-Logging.

The detector interfaces are accomplished in three different ways:

- Detector Control System (DCS) reads non critical data via DIP protocol,
- DCS reads/writes most critical data via direct MODBUS protocol,
- Detector Safety System reads/writes safety interlocks via hard wired signals.

Additionally for simplification reasons and to limit the amount of very detailed information transferred in between the cooling system and the master control and monitoring systems, the alarms and interlocks grouping philosophy was introduced. The ATLAS DCS or first level support team who receives alarms vial LASER system, is being limited to general alarms only. Any further detail investigation can be done via IBL CO_2 cooling SCADA system to fully understand the detailed cause of the problem.

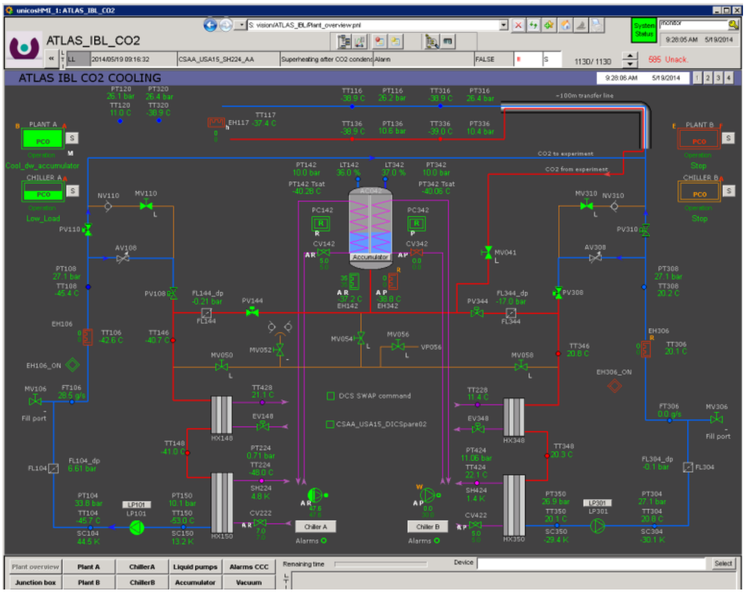

Figure 10: ATLAS IBL CO_2 cooling SCADA user interface panel example

2.3 First commissioning results

Figure 11 shows one of the tests results performed via the junction box including typical start-up sequence with -40°C user temperature set point. At the beginning system is being pressurized and liquefied. Then the condensing unit starts its operation followed by the liquid CO_2 circulation. Once achieved, the CO_2 temperature is gently, with a speed of 1°C per minute, decreased up to the desired user set point. The temperature changing speed is actually limited by the PLC to avoid the thermal shock effect on the detector. However, if needed, it can be extended or shortened if required. When the accumulator saturation pressure, being strongly related to the detector evaporation temperature, gets stable +/-0.02 bar over last 2 minutes, the dummy load was

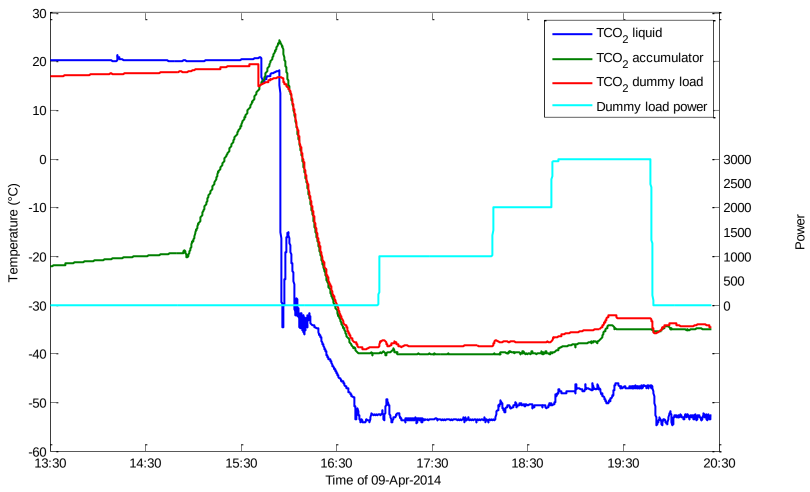

Figure 11: operation test with -40°C temperature set point

powered to simulate the IBL. The dummy load power was increased in 1kW steps from 0 up to 3kW. The test results showed stable operation with 1 and 2 kW loads. Unfortunately system was unable to get stabilised once 3kW applied with -40^{o}C set point. The automatic sub cool protection pushes up the temperature to remain sufficient margin for safe operation. At 3kW a stable operation was possible at -35^{o}C set point.

3. Conclusions

CO_2 evaporative cooling became the technical choice for the ATLAS IBL detector, thanks to its excellent thermodynamic performances and the lightweight structures it can fit into. The IBL CO_2 cooling system being under intensive commissioning, mainly via the junction box, since the beginning of 2014, has already shown first positive results. Smooth operation of both cooling plants was preceded by a wide range of electrical control and operation tests performed by the cooling team. The first observations showed that the operation with full designed load at -40^{o}C is more critical than expected. This due to a few factors like a larger heat pick-up by the pump and larger pressure drops in the return line than expected. However operation with -35^{o}C detector evaporation temperature in full power range is easily achievable. As currently the IBL detector has no radiation damages the upgrade for larger primary chiller compressor to cope with 3kW load is not needed but it stays as an open option easy to implement if needed.

Recently on 25th of June 2014 the IBL CO_2 cooling system started the trial runs with the detector connected.

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