PROGRESS TOWARDS THE COMMISSIONING AND INSTALLATION OF THE 2PACL CO₂ COOLING CONTROL SYSTEM FOR PHASE II UPGRADE OF THE ATLAS AND CMS EXPERIMENTS

L. Zwalinski[†], V. Bhanot, M. Ciupinski, J. Daguin, L. Davoine, M. Doubek, S. Galuszka,
Y. Herpin, W. Hulek, T. Pakulski, P. Petagna, K. Sliwa, D. Teixeira, B. Verlaat
CERN European Organization for Nuclear Research, 1211 Geneva 23, Switzerland

Abstract

In the scope of the High Luminosity program of the Large Hadron Collider at CERN, the ATLAS and CMS experiments are advancing the preparation for the production, commissioning and installation of their new environment-friendly low-temperature detector cooling systems for their new trackers, calorimeters and timing layers. The selected secondary "on-detector" CO2 pumped loop concept is the evolution of the successful 2PACL technique allowing for oil-free, stable, low-temperature control. The new systems are of unprecedented scale and largely more complex for both mechanics and controls than installations of today. This paper will present a general system overview and the technical progress achieved by the EP-DT group at CERN over the last few years in the development and construction of the future CO2 cooling systems for silicon detectors at ATLAS and CMS. We will describe in detail a homogenised infrastructure and control system architecture which spreads between surface and underground and has been applied to both experiments. Systems will be equipped with multi-level redundancy (electrical, mechanical and control) described in detail herein. We will discuss numerous controls-related challenges faced during the prototyping program and solutions deployed that spread from electrical design organization to instrumentation selection and PLC programming. We will finally present how we plan to organise commissioning and system performance check out.

INTRODUCTION

New Environment-friendly, non-flammable and low-temperature detector cooling systems, shown on Fig. 1, based on the evolution of the 2-Phase Accumulator Control Loop (2PACL) [1] concept are being constructed for ATLAS and CMS experiments to cope with challenging cooling needs of the new trackers, timing detectors and silicon based calorimeters. For many years, smaller systems with cooling powers up to 15 kW have been in continuous operation at CERN for LHCb Velo, ATLAS IBL and CMS Pixel Phase I detectors. The next generation systems will have much higher cooling power needs and complexity with 310 kW for ATLAS and 550 kW for CMS and about 1000 – 1800 evaporators each. Detector temperature requirements are also shifting lower to -40 ℃. The cooling plants will be located in underground service caverns, displaced more than 120 m away from the detector proximity distribution manifolds and interconnected via concentric insulated transfer lines. The detector dissipated power removed by the oil-free 2PACL will be rejected to an R744 (CO2)-based primary refrigeration system.

The R744 refrigeration plants are located in a newly constructed surface building interconnecting the underground plants via two warm long transfer lines placed into ~90 m vertical shaft. The R744 system can pre-cool the 2PACL loop to about -53 ℃ (very close to the freezing point of
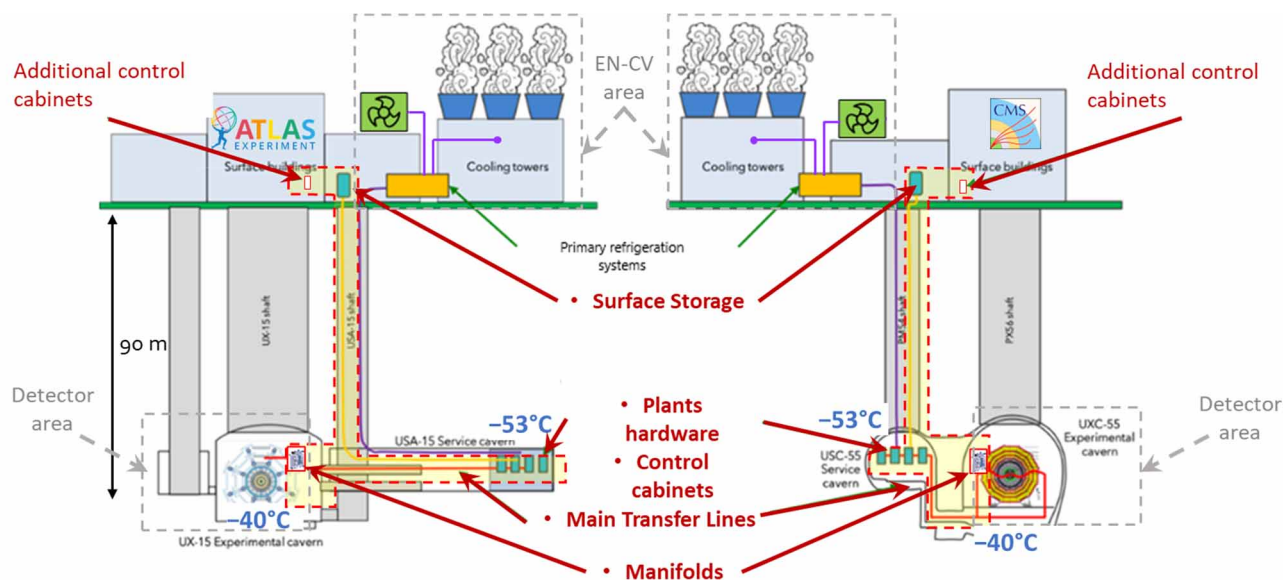

Figure 1: ATLAS and CMS CO2 cooling system overview.

CO2) and will use a combination of air cooling and water cooling. It can run on air cooling only during low heat load periods to allow for the water system maintenance without stopping the primary cooling to the 2PACL stations.

The 2PACL systems' large volume together with wide detector temperature operation range (spanning from +15 °C to -40 °C) requires large quantities of CO2. To minimise human safety impact and to fit 2PACL accumulators in limited underground space, the Surface Storage concept is being introduced for the first time ever for 2PACL applications. The surface storage tank with volume of about 12 m^3 will be actively cooled and heated to control its pressure to allow for CO2 transfer to the 2PACL plant in the underground. The cooling is realised either by a branch of the main R744 chiller or by small local backup chiller. The back-up chiller is there to keep the pressure below the maximum design pressure of the surface storage tank in case of primary chiller loss.

In total, the following number of cooling plants will be installed:

ATLAS:
- 6+1 backup 2PACL systems, and,
- 6+1 R744 slices,

CMS:
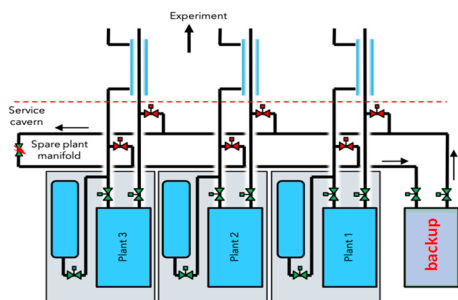- 8+1 backup 2PACL systems, and,
- 12+1 R744 slices.

Figure 2: 2PACL cooling plants interconnection.

No interruption of the CO2 flow to the detector is acceptable either in case of power cut or in case of individual cooling plant failure, in order to minimise possible silicon damage due to warm up. This is why CO2 systems are designed as N+1 (Fig. 2) redundant, with power supplied via UPS backed-up by diesel, both for 2PACL and part of R744. This enlarges the lifetime of the detector by ambient heat pickup removal even when detector power is off.

INFRASTRUCTURE

Mechanics

The mechanical N+1 redundancy shown in Fig. 2 is done by interconnecting each 2PACL system, via a common rail manifold, with one backup cooling plant. Backup plant will continuously circulate liquid CO$_2$, ready to replace any failing cooling plant. The accumulator vessels, by cooling and heating actions, directly control the detector pressure

and hence evaporation temperature, will stay always connected to their respective sub-detectors.

Control System Architecture

High system reliability requires robust distributed control system architecture spread in between surface and underground. The core process control and interaction between different sub-systems is being realised by redundant and powerful master M580 Schneider Programmable Logic Controllers (PLC) located on the surface. Each individual cooling system composed of the cooling plant, the accumulator unit and the distribution manifold will have its own slave PLC located underground and will communicate with its own deported I/Os via dedicated local RIO redundant loop. Master will interact with slaves via main RIO redundant fibre optic-based communication ring ensuring continuous operation in case of one link being broken. Short communication distance will use CAT 5e Ethernet cables. The architecture overview is presented in Fig. 3. In total, 18 PLCs will be installed for both ATLAS and CMS 2PACL cooling system.

The control system infrastructure will be based on 108 individual control and power cabinets designed at CERN using E-Plan 8 electrical design software, 63 for CMS and 45 for ATLAS with large majority located in underground service caverns. The design is standardised in between the two experiments both in the cabinet's organisation and components selection.

The 2PACL sub-system instrumentation is localized either in the plant or accumulator skid or 120 m away inside the experimental cavern at the manifolds located in the detector proximity. All shared system elements and common instrumentations are redundant.

The control software conforms to CERN's Unified Industrial Control System (UNICOS) [2] framework and uses Siemens WinCC OA as Supervisory Control And Data Acquisition (SCADA) layer.

PLCs are connected to the CERN Technical Network to ensure physical separation from the outside world. Communication with the Detector Control System (DCS) will use the DIP protocol of CERN [3] to interchange non-process-critical data like the startup sequence status, cooling system key parameters and detector temperatures. Safety crucial information will be exchanged between cooling control system and Detector Safety System (DSS) via hardwired positive logic. DSS will be equipped with a dedicated state table to execute safety actions to the detector high and low voltage power supplies. In the same manner key process signals will be exchanged in between the 2PACL and the R744 primary system.

The 2PACL systems are overseen by two operator layers. As first the 2PACL specialised intervention team and second the CERN Technical Infrastructure operators located in CERN Control Centre. The 2PACL SCADA will ensure continuous link to CCC via the LHC Alarm SERvice (LASER) [4] for all major and minor alarms. The CCC TI will always call a 2PACL expert in case of an alarm. MOBICALL will also be established.
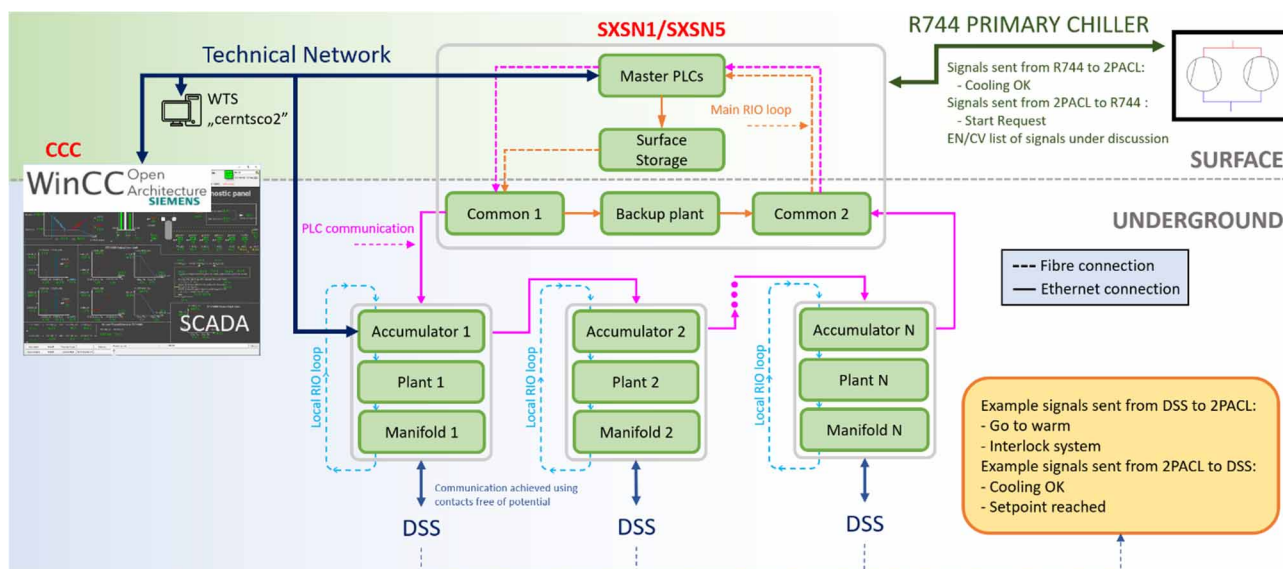
Figure 3: The ATLAS and CMS 2PACL cooling control system overview.

Electricity

To ensure continuous 2PACL cooling system operation independently of national French and Swiss electrical network state and to cope with various maintenance operations of the upstream infrastructure, careful risk analysis has been carried out to adopt best newly constructed 2PACL electrical network.

Each 2PACL cooling control rack in underground hosting PLC components will be equipped with redundant 24 V DC power supplies. One is always connected to normal power and the other one is connected to a safe experiment power source with Uninterruptible Power Supply (UPS) and backed-up by a diesel generator. This will ensure that all instrumentation will always be readable. The surface redundant PLCs are located in two separate cabinets each connecting to UPS backed-up by diesel. Multiple high power key components like the membrane pumps and the accumulator heaters will also be connected to UPS backed-up by diesel as their continued operation is crucial to ensure stable temperature of silicon sensors. Special cases are ATLAS warm nose heaters that pre-condition the CO_2 just before entering the evaporator, connects only to diesel as a short unavailability is not crucial for the process.

Power distribution swich boards upstream to 2PACL will be equipped with re-powering options to a different source, to ensure minimal detector cooling down time in case of a major failure. The simultaneity safe power needs have been estimated to 430kW for ATLAS and 555kW for CMS.

PROTOTYPING PHASE

DEMO

The DEMO facility is made up of one large-capacity 3-head cooling plant (the Lewa LDG3 pump), one smaller-capacity one-head plant (the Lewa LDG1 pump), an accumulator unit, a surface storage simulator, and a R744 primary system nicknamed "System A". DEMO is a 1:1 size pre-production and test system for both mechanics and controls. This CERN based facility is shown in Fig. 4. All the individual components and instruments are tested under real operational conditions, and at cooling loads up to 100 kW. The load on the cooling plant mimics the detector and is achieved by two Dummy Load skids. Each skid is equipped with two 25 kW heaters, controlled valves and instrumentation piloted by two independent M340 Schneider PLCs based on CERN's UNICOS framework. The System A R744 chiller is a prototype for the final primary chiller, and is the first ever R744 unit built at CERN. It served as a prototype and proof-of-concept for future multi-stage R744 primary systems of ATLAS and CMS.
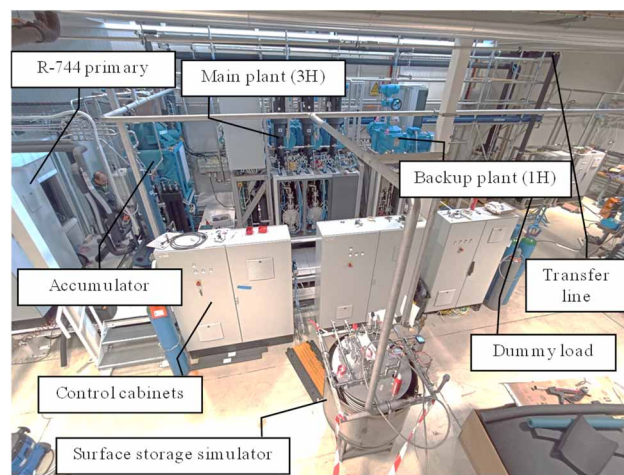

Figure 4: DEMO cooling plants.

DEMO Control Challenges

During the pre-production testing phase, CERN's EP-DT team built a smaller scale control system that incorporated all functionalities foreseen for the final implementation. This allowed us to mimic and test all the functionalities related to the control system architecture robustness and component's reliability. One of the key modifications introduced thanks to DEMO test program is implementation of the individual PLCs for the 2PACL sub-system,

initially not foreseen. We expected to be capable to load all program into two master PLCs. However, master PLCs capacity showed to be insufficient when scaling from DEMO full system program.

For the 2PACL controls hardware, a key lesson learned during the DEMO tests was the selection of different-than-initially thought heater elements and control mechanism. In previous CO_2 detector cooling systems, where accumulator individual heater power were in the range of 2-5 kW, the fine tune power control was achieved using simple PID controller with Pulse Width Modulation (PWM) signal sent to zero-crossing Solid State Relay (SSR). This simple and cost-efficient solution showed to be inefficient for the large heater powers of 25 kW required for the new ATLAS and CMS systems. The minimum PWM pulse length was generating far too large power steps compared to what was required by the process fine control. Much better performance with minimum power steps of 100 W has been achieved thanks to the 3-phase EPack^{TM} (Silicon Controlled Rectifier) power controller. An additional advantage of this device is the heater bake-out mode adopted as custom software built at CERN together with manufacturer. This allows for non-intrusive improvement of the heater's insulation resistance which is frequently jeopardized in low-temperature applications as the air humidity tends to penetrate into the heater's insulation powder (hygroscopic MgO). In this mode, power control is replaced by voltage control that is limited to 50 V. Additionally, a temperature controller implemented in the PLC program stays active in order to avoid overheating.

The logic for each system (accumulator and plant pair) will be identical, except for the variable names which denote the system to which the variable belongs. This allows us to generate sections of PLC code using templates. The templates are separated by object type and contain a list of features that can be implemented. For calculated variables, the features include basic operations such as addition, subtraction, and multiplication, as well as some more complex calculations such as CO_2 saturation temperature by a logarithmic formula. The concept is that each calculation is written only once in the template and then called by the logic generator as needed, specifying the corresponding input variables.

There are also templates for the actuator logic. These are separated into different object types (analog, analog digital, on off, etc.) based on the function of the actuator. Then for each actuator type, we define features that are commonly needed.

These templates have been developed in DEMO to cover all the logic needs that are foreseen for the final systems. Using these templates will provide two main benefits: reducing the amount of programming time needed for each system; and ensuring that the logic will be identical between the systems. It also decreases the time of troubleshooting.

Similarly, the SCADA panels can be automatically generated by creating one 'master' panel and using parameters to identify the individual systems. Once the master panel is defined, it can be referenced for each system with the corresponding system name defined as the parameter value. This allows for consistency across all systems and reduces the editing time of each panel.

DEMO Commissioning and Main Achievements

DEMO has been steadily tested through 2022 and 2023. Scaling up 2PACL cooling systems has led to non-trivial challenges in terms of new instrumentation, control methods and startup procedures. The first phase of commissioning focused on qualifying new components. This included developing a new level measuring method, studying heat exchanger performance, verifying new types of valves and developing heater control loops. In the second phase of commissioning, we focused on qualifying system operation as a whole, and here we describe one such qualification test.

As mentioned in the Introduction, the 2PACL systems for Phase-II have a backup plant which can instantly take over from any malfunctioning plant. Once the broken plant is ready to be brought back into circulation, it must take over from the backup. A test of this take-over was carried out and the results are shown in Fig. 5 below.
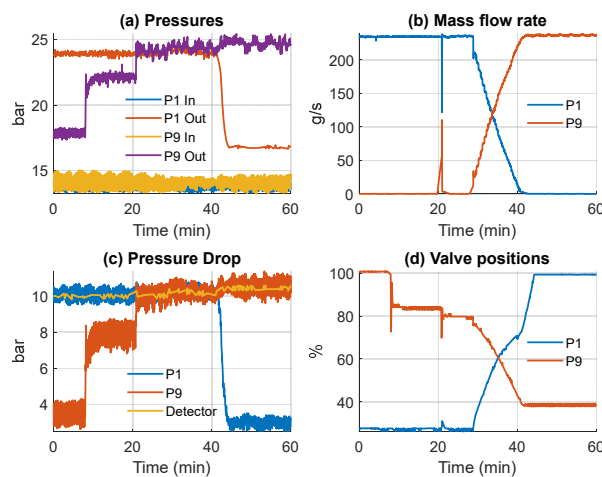

Figure 5: DEMO cooling plants take over test.

In this test, P1 (Plant 1) was the Backup and P9 must take over. Initially, P1 supplies flow to detector (Fig. 5(b)). Detectors are pressure-drop controlled (setting a pressure drop sets the flow rate) and we see that the pressure head across P1 matches the detector (Fig. 5(c)). P9 initially starts circulating flow internally (Fig. 5(a) purple line). The setpoint is for P9 outlet pressure to be *just under* P1 pressure (to avoid accidental take-over). Once stable flow in this condition is obtained, P9 pressure is raised slightly *higher* than P1, and we see in Fig. 5(b) that the flow rate of P1 slowly goes to 0, while P9 slowly takes over. This process is very gentle (around 15 minutes), and the detector is unperturbed throughout, indicating a successful result.

DEMO Specific Control Logic Implementation

New concepts like the surface storage and associated accumulator logic allowing for an active system filling or emptying have been implemented and tested at DEMO.

General

Device Control

The accumulator is always kept at lower pressure than surface storage to make filling possible with a control valve. Emptying is realised by a control valve connected to the pump discharge side. The discharge is kept always above the surface storage pressure using a 3rd control valve in the main flow. Due to the limitation for the accumulator pressure, high temperature operation of the detector is not possible in the conventual accumulator control way. To reach higher detector temperature setpoints in this case, a Back Pressure Regulator (BPR) has been introduced at the detector return line before the accumulator vessel.

Accumulator saturation temperature control is based on a single split-range PID controller, with cooling and heating request split in between two injection valves (on the primary cooling side connected to two heat exchangers on top of accumulator vessel) and two cast aluminium active heaters. Split range concept is explained in Fig. 6.
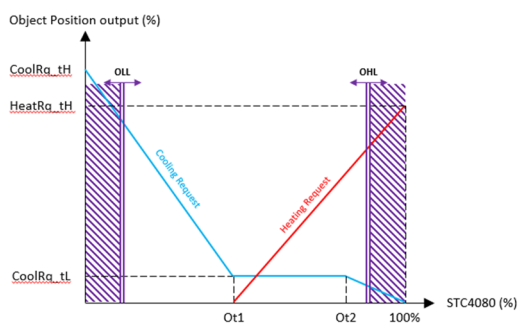

Figure 6: Accumulator split range PID controller.

The accumulator controller has active boundary limitation to compensate potential deviation and to keep proper control of the system. The dynamically calculated output high limit (OHL) is based on heater internal core temperature to avoid overheating while dynamic output low limit (OLL) is using active plant pump subcooling to ensure liquid CO_2 is pumped.

Both the accumulator and the plant are respecting and following with their own stepper logic (see Fig. 7), allowing for automatic changeover of the system operation modes and executing different operation scenarios like the operation in the 2PACL mode with or without the surface storage or stand-by mode for backup plant. Stand-by is a preparatory state for the backup plant being ready to kick in at any time in case of another plant failure.

PLANS FOR FINAL SYSTEM COMMISSIONING AND SYSTEM PERFORMANCE CHECK OUT

With experience gained in the DEMO facility, the CERN EP-DT group prepares for the final systems installation which will begin in 2024 for CMS and in 2025 for ATLAS. Each cooling plant, accumulator and manifold system will strictly pass via the I/O check, alarms check-out, safety chains sign off and instrumentation verification. At this stage the systems will be connected sequentially with two 50 kW dummy loads. In case of CMS the dummy load will be located in the cooling plant proximity and in case of

ATLAS about 150 m away in service cavern. The difference is due to available space and main transfer lines availability (MTL). The semi-automatic performance scan will start with dummy load changing load conditions and allowing for steady state measurements. At second stage 2PACL plants and accumulators will be connected with the manifold distribution system inside the experimental cavern. The manifolds are equipped with dummy load heaters which will allow to repeat full the performance scans in the detector proximity. The systems will face continuous commissioning one by one.
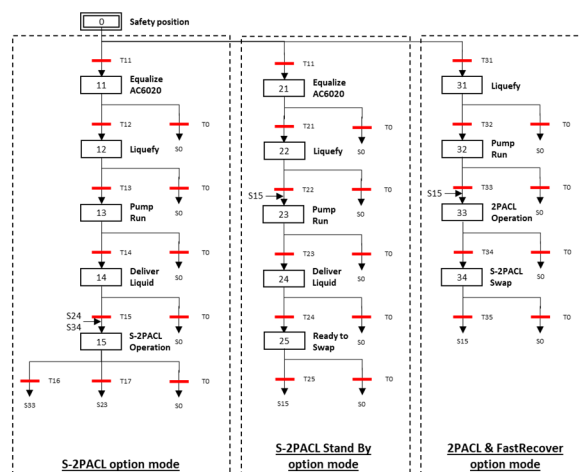

Figure 7: 2PACL cooling plant stepper.

CONCLUSIONS

During the last two years the CERN EP-DT CO_2 cooling team consolidated numerous results from a large-scale DEMO prototype commissioning phase. The outcome of the DEMO exercise has been implemented in final designs for all controls, the first 60 control cabinets are currently under production. The cooling plants and accumulators are designed and are currently in the tendering phase. This has brought us very close to the production of upcoming cooling plants and their installation and commissioning at ATLAS and CMS experiments.

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