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INSTALLATION AND COMMISSIONING PROGRESS OF THE 2PACL CO_2 COOLING CONTROL SYSTEMS FOR PHASE II UPGRADE OF THE ATLAS AND CMS EXPERIMENTS

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Abstract

In the scope of the High Luminosity Program of the Large Hadron Collider at CERN, the ATLAS and CMS experiments are progressing in the installation and commissioning of their environmentally friendly low temperature detector cooling systems for their new trackers, calorimeters and timing detectors. The selected "on-detector" cooling solution is the CO_2 pumped loop concept which is the evolution of the successful 2PACL technique allowing for oil-free, stable, low-temperature control. These systems are of unprecedented scale and largely more complex for both mechanics and controls than installations of today. This paper will present a control system overview, applied PLC architecture and the installation and commissioning progress achieved by the EP-DT group at CERN over the last years. We will describe in detail homogenized solutions which spreads between surface and underground and have been applied for future CO_2 cooling systems for silicon detectors at ATLAS and CMS. We will describe in detail applied multi-level redundancy for electricity distribution, mechanics and controls. We will discuss numerous controls-related solutions deployed for electrical design organization, instrumentation selection and PLC programming. We will finally present how we organized early control system commissioning as initial step for LHC Long Shut down 3.

INTRODUCTION

The detectors of the two largest experiments at the LHC, ATLAS and CMS, are getting upgraded to cope with challenging requirements set by the High-Luminosity LHC. The core part, composed of tracking and timing layers, together with calorimeters for CMS, will be fully silicon-based detectors requiring cold operation at temperatures as low as -40°C. To cope with challenging cooling needs, Detector Technology Group at CERN in the Experimental Physics Department, since 2009 has been developing CO_2 cooling systems, of various size and complexity, based on the 2-Phase Accumulator Control Loop (2PACL) [1] concept. Multiple smaller installations with cooling powers up to 15 kW, have been in continuous operation at CERN for the LHCb Velo and UT, ATLAS IBL and CMS Pixel Phase-I detectors. The Phase-II upgrade detectors 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. These new, more efficient systems will replace the older cooling circuits that used synthetic refrigerants, significantly reducing the environmental impact of detector cooling.

The cooling systems are located in the underground service caverns where the 2PACL cooling plant and most of the control cabinets are located, displaced more than 120m away from the detector proximity distribution manifolds and interconnected via concentric insulated transfer lines, shown in Fig. 1. Due to the larger system volume, and to ensure smooth operation in all temperature conditions that span from +15°C to -40°C, additional Surface Storage tanks will be installed at surface of ATLAS and CMS, interconnecting with underground via two thermally insulated transfer lines. This 'Surface Storge' is 12-cubic-meter storage vessel ensuring CO_2 fluid exchanges in a thermosiphon loop between itself and the underground cooling infrastructure following the detector power needs.

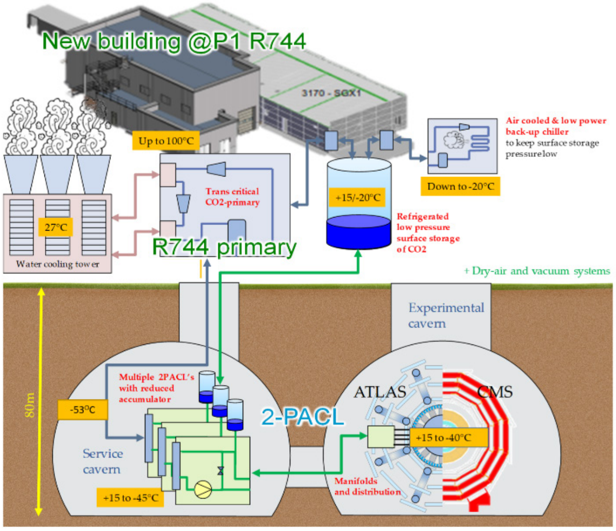

Figure 1: 2PACL system general layout.

The detector's dissipated power removed by the oil-free 2PACL will be rejected to an industrial-like R744 (CO_2)-based primary refrigeration system operated by the Cooling and Ventilation Group of the Engineering Department at CERN. The R744 plants are in newly constructed surface buildings and they interconnect with 2PACL via two warm, long transfer lines of about ~90m length. The R744 systems pre-cool the 2PACL to about -53°C (very close to the freezing point of CO_2).

In total, the number of cooling plants to be installed is as follows:

ATLAS:

- 6 (+1 backup) 2PACL systems, and,
- 6+1 R744 slices,

CMS:

- 8 (+1 backup) 2PACL systems, and,
- 12+1 R744 slices.

No interruption of the detector cooling is acceptable in case of power cut or in case of individual cooling plant failure, in order to minimize possible silicon damage due to warm up. 2PACL cooling plants are thus designed as redundant ‘N+1’, with safe electrical power supply. The 2PACL accumulators are not redundant N+1 as they are high pressure vessels but do have redundancy of instrumentation, heaters and heat exchangers. The Surface Storage vessel is additionally equipped with a local backup small R744 chiller, also connected to safe power source, to keep the vessel pressure always low.

INFRASTRUCTURE

Mechanical Redundancy

Each 2PACL system composed of the cooling plant, accumulator unit and the associated manifold connects via a ‘common-rail’ interconnection piping to the backup cooling plant. Interconnection piping is a complex and dense pipe-work installation, hidden tightly below the compact false floor space, allowing for continuous operation of the backup plant, which is always ready to replace any failing cooling plant. The accumulator vessels, by cooling and heating actions, directly control the detector pressure and hence evaporation temperature, and will stay always connected to their respective sub-detectors.

Control System Architecture

Reliability requirement set by the experiments originated a robust, distributed control system architecture which spans both the surface and underground. The core process control and interaction between different sub-systems is being realized by redundant and main M580 Schneider Programmable Logic Controllers (PLC) (BMEH586040) located in a new surface building hosting also the primary R744 system. Each individual 2PACL cooling system (composed of the cooling plant, the accumulator unit and the associated detector proximity distribution manifold) has its own M580 Schneider PLC (BMEP583040) located underground and communicates with its own deported I/Os via a dedicated local Remote Input Output (RIO) redundant loop. The Main PLCs interact with slaves via core RIO redundant fiber optic-based communication ring, ensuring continuous operation in case of one link being broken. Short communication distance is using CAT 7 (S/FTP) Ethernet cables. The architecture overview is presented in Fig. 2.

The dummy loads skids, which mimic the detector thermal load for system performance commissioning, are using one M340 Schneider PLC each. In total, 24 PLCs will be installed for both ATLAS and CMS 2PACL cooling system.

An additional innovation is the implementation of 2 redundant manageable ethernet switches, in central point of underground infrastructure, creating a double-star architecture. This is achieved via Rapid Spanning Tree Protocol priority definition. The benefit over the double ring topology previously foreseen is that one system can be switched off for maintenance reasons without impacting rest of the installation and without sacrificing communication redundancy.

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.

For security reasons all the PLCs connect 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 using hardwired positive logic to Detector Safety System (DSS). In the same way, the signals exchange is established with R744 primary cooling system.

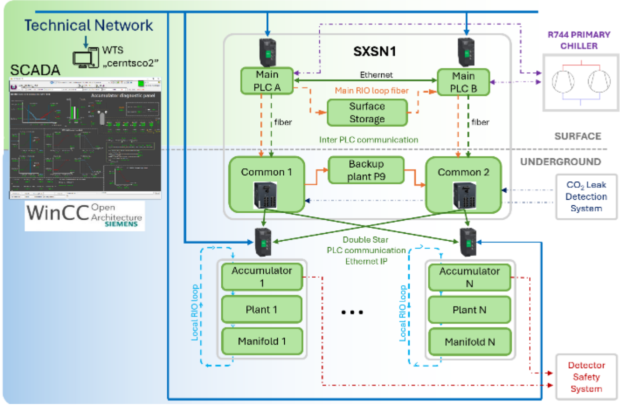

Figure 2: ATLAS control system architecture.

Overall, the 2PACL cooling control system consist of:

- 6888 Inputs Outputs in CMS,
- 5560 Inputs Outputs in ATLAS,
- 85 Inputs Outputs in each out of five 50 kW dummy load skid installed in ATLAS (2x) and CMS (3x)

Redundancy for Electricity Distribution

High level electricity redundancy has been achieved thanks to fruitful collaboration with CERN Engineering Department, Electrical Engineering Group who supported extensive study determining solution for continuous 2PACL system powering in various maintenance and failure scenarios but not limited to the 2PACL only but considering also the upstream infrastructure. Redundant feeders, switchboard redundancy and organization, source repowering bridges, UPS backed up by diesel, load balancing have been implemented.

PLC Logic Development

PLC development follows the latest release of CERN UNICOS standard. 14 different python source files, dedicated for CO_2 development, were created to organize the different templates allowing full generation of individual PLC programs. They are organized per object type and

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include all field object logic but also calculated variables distributed over different PCO (Process Control Object). These functions are reusable across the full project and allow standardization of logic definition for CO_2 applications. This library, version controlled on GIT, is developed for the current project but will also be reusable for future applications. Additional templates were also established to generate, for example, alarms panels on SCADA or list of equipment and calculated variables to be tested during commissioning in a .csv file.

The logic generated with UNICOS and the library of python templates is imported into a base program in Schneider Control Expert. The base program is configured with communication scripts that define the variables which are communicated between the main PLC and the dedicated 2PACL PLCs. These scripts are generalized to be reusable between all 14x 2PACL units and reduce development time.

Instrumentation Selection

High energy physics low temperature CO_2 cooling system instrumentation selection was a challenging part of the Phase-II 2PACL project. The thermofluid properties of CO_2, the low-temperatures operation, together with radiation and magnetic field in the experimental caverns make selection highly demanding. Industrial suppliers frequently lack experience and test data compatible with our domain, harsh environment and extreme boundary conditions. CERN, together with ATLAS and CMS teams, has selected instrumentation based on more than 15 years of experience, material compatibility and stress testing in endurance condition, and radiation and magnetic field tests. This applies to manual and automatic shut-off valves, control valves, pump membranes, pressure transmitters, differential pressure transmitters, level measurement sensors, electrical heaters, heater controllers etc. Lighter criteria have been applied for the equipment located permanently in the service caverns where no major radiation or magnetic field is present. Multiple studies, often with the support and active participation of the manufacturer, led to either development or redesign to achieve a compliant product. Fruitful collaboration with companies like LEWA, Endress+Hauser, Parker, SWEP and Schneider Electric will broaden available solutions for similar applications in the future.

Following tests organized on the first systems fulfilling new requirement for Phase-II, control valves from Parker were selected in several locations for the plant and accumulator. A new driver was developed by Parker and following our requests additional functionalities were introduced to correspond to our needs. As an example, coil winding short-circuit detection and loss-of-request signals were added to the default configuration of the driver after being approved by the manufacturer. Additionally, fail-safe position after loss of power were defined with both fully close or fully open options without the need to change any wiring between the distinct configurations.

INSTALLATION

During the recent Year-End Technical Stop (YETS) of the LHC 2024/2025, CERN engineers and technicians, in collaboration with the ATLAS and CMS teams, began installing the first 2PACL plants and their accumulators in the underground service caverns of the two experiments. Each cooling plant, weighing approximately 5 tons, is a critical component of the High-Luminosity ATLAS and CMS upgrades, set to begin operations in 2030.

The installation of 2PACL units at CMS began in October 2024 and completed in time with 9 cooling plants, 8 accumulators and two 50 kW dummy load skids at the end of July 2025, shown on Fig. 3. At ATLAS, an initial installation phase holding one backup cooling plant, one accumulator, and two 50 kW dummy load skids took place during this year's YETS, shown in Fig. 4, with full deployment planned for the upcoming Long Shutdown 3 (LS3). The installation of the associated equipment will continue through 2025 in CMS and during LS3 in ATLAS, followed by an extensive commissioning phase to ensure system reliability when connected to the detector.

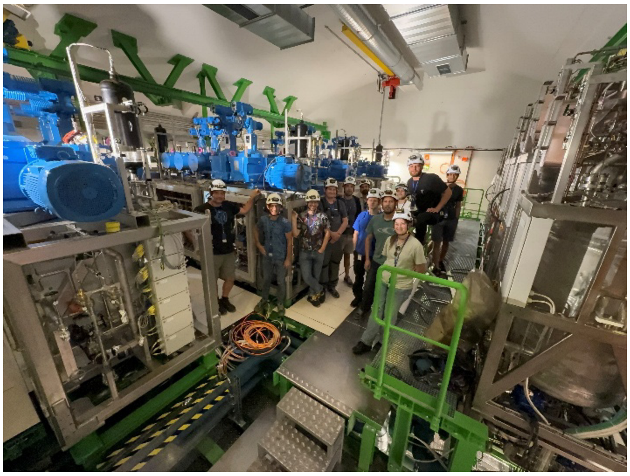

Figure 3: CMS underground installation.

Figure 4: ATLAS underground installation.

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In parallel to the pipework, cooling plant, and accumulator skid installations, controls related activities also took place. At CMS, 60 controls and power distribution cabinets (manufactured by two external suppliers PPA Slovakia and Hajru Elekter Estonia) were installed by a CERN technical teams, with 4 cabinets at the surface and 56 in the underground service cavern. In ATLAS, 21 of the planned 46 cabinets manufactured by PPA Slovakia have been installed so far. The remaining installations of controls infrastructure will take place during LS3, once space becomes available following the decommissioning of the currently operational (and co-located) cooling systems. The controls and power distribution cabinets were built as footprints of CERN electrical E-plan based and 3D CATIA designs.

Two fully independent teams laid down kilometers of cables allowing them to interconnect deported cabinets with the cooling systems patch panels. The ATLAS is completed, and CMS continues cables connection during 2025 with today status shown on Fig. 5.

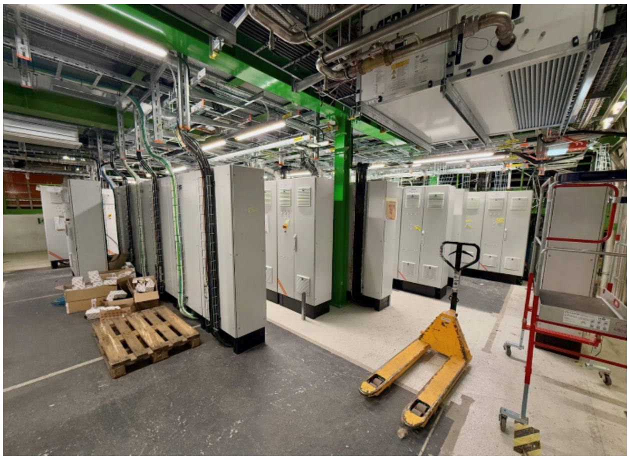

Figure 5: CMS underground control cabinets.

COMMISSIONING

After successful installation of the cooling plants, accumulators, control cabinets, main transfer lines and the dummy loads, hardware commissioning began following the schedule shown in Fig. 6.

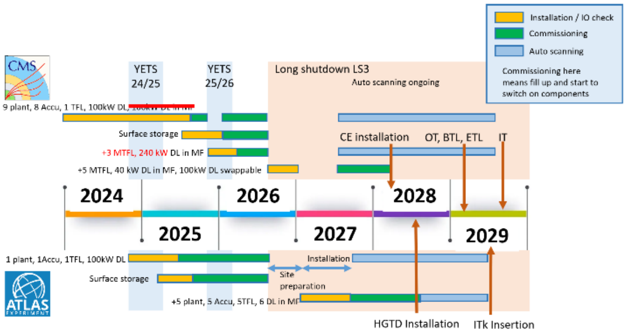

Figure 6: Installation and commissioning schedule.

For all control cubicles an extensive Factory Acceptance Test (FAT) took place in the presence of CERN staff at the manufacturing premises. The test consisted of verification of manufacturing reports, visual inspection and simplified I/O test with a PLC program to sign-off correctness of the wiring and components configurations in the cabinets. The verification team used dummy sensors connected to the cabinet's terminals to mimic final system responses. This will ensure that time and risk taken for underground installation is minimized. Still, even though the cabinets and cooling skids were delivered at CERN prewired to their patch panels and are carefully checked during their FAT, on-site connections can also lead to errors. Upon cable connection completion, parallel ATLAS and CMS I/Os commissioning and calculated variables verification have started with the first PLC program loaded for ATLAS plant P9 and accumulator A5. CMS, being by far the larger installation, will continue through all of 2025. Next step was the full PLC logic testing in a man-in-the-loop manner before automatic procedures take over for 24/7 performance testing.

Performance Testing and Plans

After receiving commissioning safety clearance in the first days of August 2025, the ATLAS A5 accumulator was filled with 47 kg of CO_2 for the stand-alone tests, achieving first cooldown on August 4th. Multiple problems were identified like the level probe being mounted in reverse, leaking heater-control valves and a wrong safety position of some valves. These are being solved and will be propagated to other accumulators installed in CMS. After step-by-step activation of the control loops and limiters, the PID tuning will be performed. In standalone tests, particular attention is being given to level probe calibration based on differential pressure measurement of static height. Additionally, accumulator cooling and heating actions are carefully checked as they ensure stable detector evaporation temperature control. In particular the gas return line of R744 transcritical primary system must always remain warm to avoid condensation on the not thermally insulated pipes.

The next step is 2PACL cooling plant startup. The system will be liquefied via accumulator pressurization, R744 primary will build up subcooling in front of the pump which will be switched on to establish CO_2 circulation. Stable flow will be ensured through careful differential pressure control along the cooling loop, at plant-level first, then transfer line connected to the accumulator but also between the surface storage and cooling plant. When these are verified, 2× 50 kW dummy load will be switched on to mimic the detector heat load. At a later stage all possible detector operation scenarios with different system conditions will be checked using auto scanning functions allowing for 24/7 commissioning.

CONCLUSION

During last year's ATLAS and CMS experiments progressed significantly with the installation and commissioning of their new 2PACL based environmentally friendly low temperature detector cooling systems for their new trackers, calorimeters and timing detectors. All 106 control cabinets have been produced and largely installed on both sites. Dozens of cables were laid down and connected. The I/O commissioning is advancing well together with the first performance tests in ATLAS starting in August 2025. This is the beginning of endeavor which will continue during LHC LS3 aiming to deliver in due time the key detector cooling system for Hi-Lumi LHC era of ATLAS and CMS experiments.

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