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REDESIGN OF THE VELO THERMAL CONTROL SYSTEM FOR FUTURE DETECTOR DEVELOPMENT

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Abstract

The Detector Technologies group at CERN has developed a Two-Phase Accumulator Controlled Loop (2PACL) [1] test system for future detector development, using reused hardware from the LHCb Vertex Locator (VELO) Thermal Control System [2]. The fluid, electrical and control systems have been redesigned and simplified by removing redundant components because it is no longer a critical system. The fluid cycle was updated to allow both 2PACL and integrated 2PACL [3] cycles to be run and the chiller was replaced with an air-cooled unit using hot gas bypass to achieve a high turndown ratio. The electrical systems were upgraded to improve usability and practicality. The control system logic is being developed with the CERN's Unified Industrial Control System (UNICOS) framework. This paper presents the details of the design and implementation.

INTRODUCTION

The Vertex Locator (VELO) Thermal Control System (VTCS) is the first CO_2 detector cooling system used at CERN to cool LHCb's VELO sub-detector. Following the successful use of CO_2 cooling in the VTCS and AMS-02 [4] on the International Space Station the number and capacity of CO_2 based detector cooling systems has increased significantly with installations in the LHCb, ATLAS and CMS experiments at CERN. The VTCS was retired and replaced with a new system in 2019 [5]. The Detector Technologies (DT) group decided that the system could be refurbished and used for the development and testing of future detectors for ATLAS on the surface.

The system was partially redesigned to prepare it for the new role. The electrical system was replaced to ensure it met the department's standards. The control logic has been rewritten with a new program developed under the Unified Industrial Control System (UNICOS) framework [6]. The fluid systems have remained largely unaltered with only the position of the accumulators being changed. All redundant components have been removed and a mode that runs the integrated two-phase accumulator controlled loop (I2PACL) [7] have been added. The chiller has been replaced to make it more suitable for surface applications without available underground infrastructure.

FLUIDIC SYSTEM

The original fluid systems were designed with redundancy in each layer to make sure no single failure would cause the detector's cooling supply to stop because the silicon tracking sensors of the detector degrade quickly at temperatures above 0 °C after they have been exposed to radiation. These redundant elements have been removed from the new system because a failure of the cooling system in a test environment is acceptable because the sensors have not been exposed to radiation [8].

The VELO detector consists of two halves that sit on either side of the beam. The VTCS was designed with two independent, two-phase accumulator controlled loops (2PACL), one for each side. A third pump was installed to act as a backup for either side in the event of a pump failure [2]. This pump along with the pipes and valves that supplied it have been removed. Two valves were left in because they provide mechanical support for the surrounding pipes and convenient access for maintenance of the system.

The new system will retain the two independent 2PACL, shown in Fig. 1, loops to maximise its versatility and minimise the changes that need to be made to the CO_2 system. To improve the responsiveness of the controllers to changes in the process, in-flow temperature sensors are being added. The accumulator heat exchanger previously connected to the backup chiller will be used to allow the system to run in the simpler Integrated 2PACL (I2PACL) mode [7].

Integrated 2PACL

Since the development of the VTCS the DT group has made improvements to the two-phase process: integrated 2PACL. This removes the need to actively cool the accumulator, reducing the complexity of the fluid and control systems. In an I2PACL system, the sub-cooled CO_2 leaving the pump flows through a heat exchanger in the accumulator, shown in Fig. 2.

Removing the need for a controlled external cooling source simplifies the control of the accumulator's saturation pressure, thus allowing the saturation temperature of the accumulator to be controlled with the heater alone. The heater provides the energy equal to the heat capacity of the liquid CO_2 and by controlling the power the pressure is regulated (Fig. 3).

The accumulators contain two condensing spirals, which were used by the main and backup chillers. One of these condensing spirals will now be used for the I2PACL mode; the other will be supplied from the chiller to control pressure in 2PACL mode.

Chiller

The primary water-cooled chiller and backup air-cooled chiller, will not be reused. Cold water is a service supplied in the caverns at CERN but is not readily available in other

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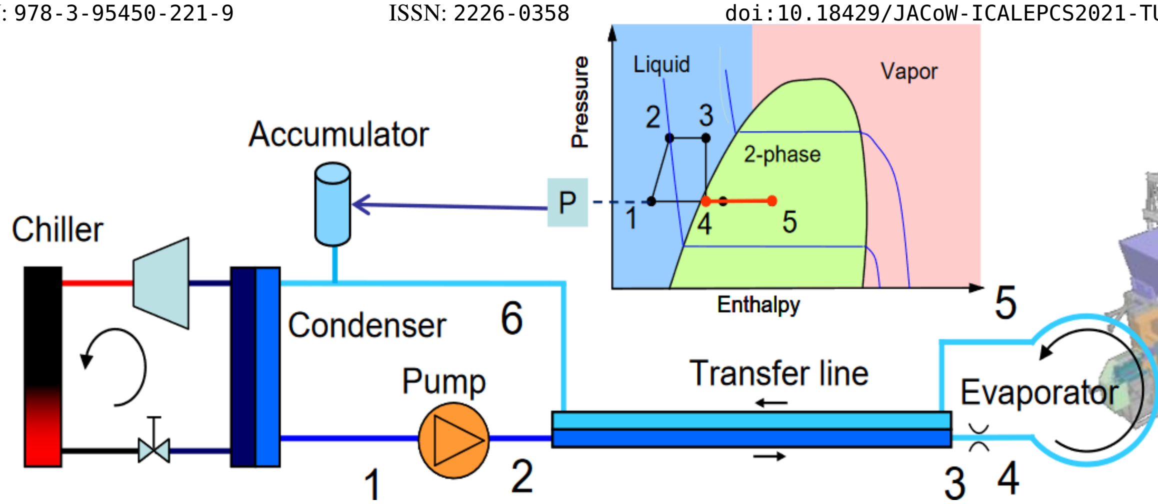

Figure 1: 2PACL system diagram [9].

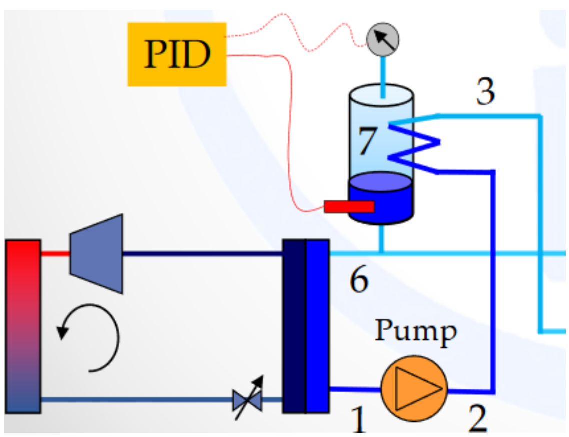

Figure 2: I2PACL system [10].

parts of the site, making the old primary chiller problematic to re-use on the surface.The backup chiller's capacity is only 1 kW which is too low. They will be replaced with a new 3.15 kW air-cooled chiller.

The chiller is based on a commonly used design that the group first developed for the Light Use Cooling Apparatus for Surface Zones (LUCASZ) systems, shown in Fig. 4 [10]. Hot gas bypass and cold liquid injection valves allow the chiller to continue running when varying or low loads are applied to it. This is unusual in refrigeration systems as they are typically designed to operate at a fixed load. In this case, the load will be variable and the chiller needs to be capable of running normally at any load that is applied to the system.

The chiller will use R449a to replace R404a which is prohibited from being used in new systems from 2020 by the European Fluorinated Gas Regulation to reduce the climate impact of refrigeration systems [11]. The adaptation to R449a required some minor modifications to the design and control to accommodate the differences in the characteristics of the two refrigerants.

ELECTRICAL SYSTEM

The electrical systems were examined to determine what could be re-used from the original system and what would require upgrading. The electrical hardware in VELO was installed in rack mounted boxes with connectors on the back. These boxes were replaced with a simplified electrical system where all the electrical components are mounted vertically in the cabinet behind the front door, as shown in Fig. 5.

This design is advantageous because it makes the components more visible and accessible. The status of circuit breakers can be seen and set or reset without disconnecting any cables or removing components from the cabinet. The flat layout also allows for signal cables and power cables to be more easily isolated from each other, reducing the impact of electrical noise on other components. A new electrical design was developed using the original system as a baseline. The design was constrained by the available area of the panel, 500×1500 mm, and by the project budget. Using components that are in good condition from the VTCS or were in spare stock at the time will reduce the cost.

CONTROL

The control architecture has been completely redesigned using CERN's UNICOS continuous process control framework [6] to make sure it meets CERN's standards and will be easily maintainable and modifiable in the future. The system will be controlled through Siemens WinCC OA for supervisory control and data acquisition (SCADA) which will operate on CERN's Technical Network (TN) as shown in Fig. 6.

The PLC is a Siemens S7-400 station that will be reused with changes to some modules. The CPU was upgraded to one with a greater work memory to accommodate the larger size of programs developed using UNICOS. An incompatible controller card was removed and replaced with an analogue output (AO) module. The current system configuration is shown in Table 1.

The spare channels were retained because we already had all the IO modules apart from the analog outputs and

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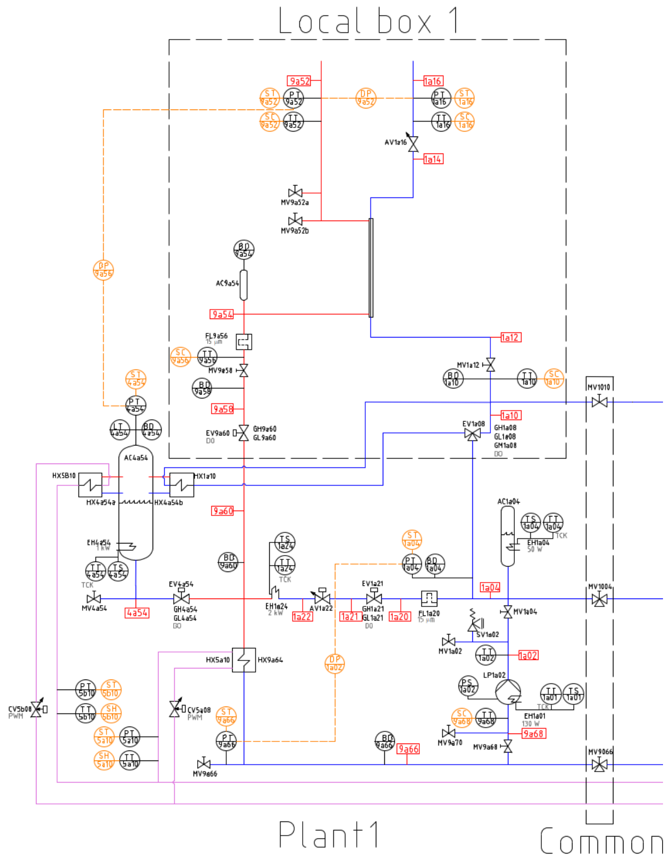

Figure 3: CO_2 P&ID diagram.

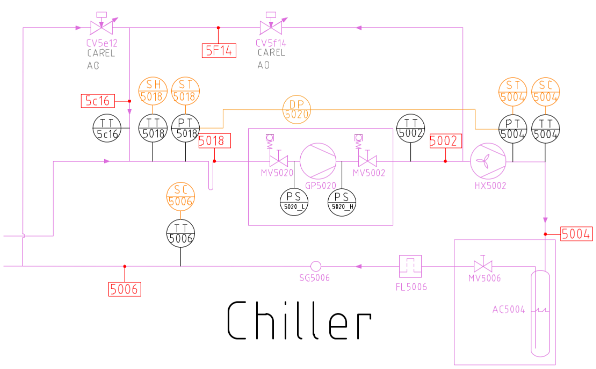

Figure 4: Chiller P&ID.

Table 1: PLC IO Channels

IO type	Used	Total
Digital input	63	96
Digital output	41	96
Analog input	47	64
Analog output	2	8

they were connected to IO terminals in the cabinet. They also provide a comfortable buffer against the failure of an individual card. The S7-400 platform is reaching end of life, if a IO card failed it would be possible to switch to a spare unit and continue operating while a replacement is found.

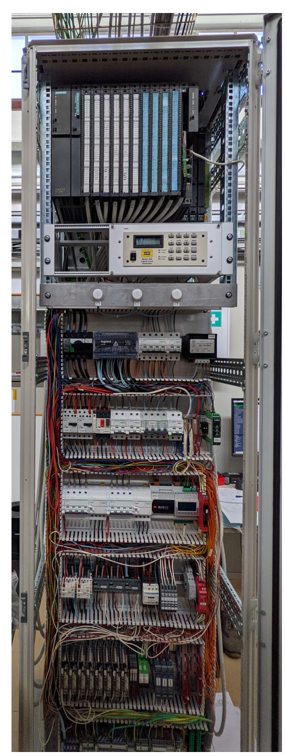

Figure 5: New power distribution panel.

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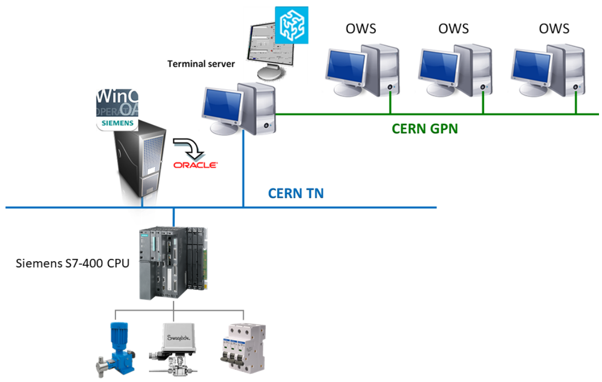

Figure 6: Control system architecture.

Program Structure

UNICOS applications are made up of process control objects (PCO) each representing a separate unit within the system. A PCO can be made up of actuators or other PCOs as shown in Fig. 7. This system has a top-level PCO called CO2. The chiller is its own PCO containing all its actuators. Each 2PACL system is identical and has it's own PCO which contains the CO_2 actuators and allows the systems to operate independently. Each local box has its own PCO which is contained by the respective plant PCO and controls the flow of CO_2 from that PCO.

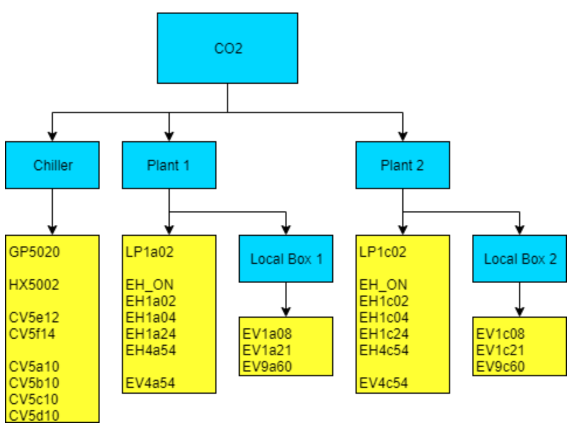

Figure 7: PCO structure.

The state of a PCO will be determined by the state of the parent PCO. If this is in Stop mode then the dependant PCO's will also be stopped. If a parent PCO is in Run mode, the dependant PCO's will be allowed to run subject to its normal run conditions. The two CO2 plants can run independently of each other. The chiller will start when one or both CO2 plants are requested to run.

Safety

The use of liquid CO_2 in a closed system introduces several important safety concerns which the system design must mitigate. The control system must ensure that no cold liquid CO_2 is trapped in a confined space. If this happens the pressure will increase dramatically as the CO_2 heats and boils, causing the pipe to burst or safety systems to activate and the CO_2 will be vented from that section. This could cause damage to the system and harm anyone who is in the vicinity.

Experiments will be manually connected to and disconnected from the local box. This process requires manual intervention by the operator. The design must protect both the operator and the hardware from potential operator error. If the operator opens a local box valve at the improper time CO_2 could be vented into the atmosphere. This poses an asphyxiation hazard to the operator.

The Stop or Safe position of controlled valves is set to open except for the local box shutoff valves, which will close. This ensures that there is always a path for CO_2 to return to the accumulator, but isolates the local box from the rest of the system. When an experiment is disconnected, the PLC will wait until only vapour is present in the transfer line before allowing the operator to continue.

If the system is stopped without disconnecting the experiment or an emergency stop is triggered, the local box shut-off valves will close with liquid still inside. This is important to simplify the shutdown procedure and allow an experiment to remain connected. A pressure vessel, AC9a54 shown in Fig. 3, will be added to allow any liquid CO_2 trapped in the local box to pressurise without causing any damage. It will have the same volume as the tubing in the local box and be placed above the accumulator and transfer line. This ensures that there is only vapour present at all times.

Start-Up and Experiment Connection

The chiller and both CO_2 plants have no start-up sequences. They start running when that state is requested and any interlocks are cleared. The Local Box has a more detailed process depending on the mode it is running in. These are shown in Fig. 8 with the transitions explained in Table 2.

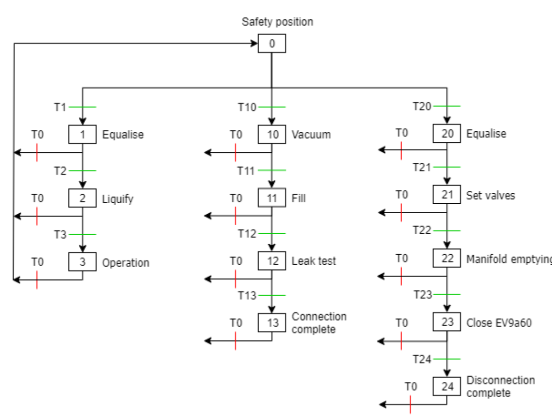

Figure 8: Stepper for the Local Box PCO.

Normal operation For normal operation of the local box the local box PCO changes the set point of the CO_2 plant to equalise the pressure difference across the valves before opening. Following this, the loop is liquefied before the set point is changed back to the user set point.

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Table 2: Transition Condition Descriptions

Transition	Condition description
T0	Stop request
T1	Device connected and run mode
T2	Pressure difference within limits
T3	Liquid CO2 is circulating
T10	Device disconnected and connect mode
T11	Vacuum applied
T12	Device filled with CO2
T13	Leak test OK
T20	Device connected and disconnect mode
T21	Pressure difference is within limits
T22	CO2 return valve open
T23	Super-heating in the local box
T24	Plant valves closed

Connection procedure The connection process is a manual process that is performed by the user. The PLC uses the sensors in the Local Box to monitor the steps that the user performs and ensures that they are all followed properly.

Disconnection procedure To disconnect an experiment, the Local Box is first emptied of liquid CO_2 . This is done by reducing the accumulator set point to its minimum allowable value and waiting for super-heating to be detected in the local box. This removes as much CO_2 from the local box as possible and allows the user to vent and disconnect the local box safely.

CONCLUSION

The VTCS has been significantly simplified and optimised to fulfil its new role for the group. The new design follows the most recent norms and standards of CERN and the DT group to ensure that it can be maintained or modified as needed to continue supporting the group's research.

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APPENDIX

The system documentation will be uploaded to the Engineering Data Management System (EDMS) and will be available at: https://edms.cern.ch/. The project is named DTCS and can be found under: CERN-0000219585.

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