ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-THPHA050

DEVELOPMENT, COMMISSIONING AND OPERATION OF THE LARGE SCALE CO_2 DETECTOR COOLING SYSTEMS FOR CMS PIXEL PHASE I UPGRADE

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Abstract

During the 2017 Year-end Technical Stop of the Large Hadron Collider at CERN, the CMS experiment has successfully installed a new pixel detector in the frame of Phase I upgrade. This new detector will operate using evaporative CO_2 technology as its cooling system. Carbon Dioxide, as state of the art technology for current and future tracking detectors, allows for significant material budget saving that is critical for the tracking performance.

The road towards operation of the final CO_2 cooling system in the experiment passed through intensive prototype phase at the CMS Tracker Integration Facility (TIF) for both cooling process hardware and its control system.

This paper briefly describes the general design of both the CMS and TIF CO_2 detector cooling systems, and focuses on control system architecture, operation and safety philosophy, commissioning results and operation experience. Additionally, experience in using the Ethernet IP industrial fieldbus as distributed IO is presented. Various pros and cons of using this technology are discussed, based on the solutions developed for Schneider Premium PLCs, WAGO and FESTO IOs using the UNICOS CPC 6 framework of CERN.

INTRODUCTION

CMS Pixel Phase I Upgrade

Compact Muon Solenoid (CMS) is one of the two large multi-purpose detectors installed on the Large Hadron Collider (LHC), operating at the European Organization for Nuclear Research (CERN). The Pixel detector is the innermost CMS sub-detector and it is used for precise tracking of the particles produced by the collisions. Due to the vicinity to the interaction point (i.e. the small region where the particle collide), the radiation harm have a major impact on the lifetime of the silicon sensor. To limit the radiation ageing effect, the temperature of the silicon sensors must be kept below -10°C. In order to cope with the increase in the collision rate provided by the LHC, the CMS experiment replaced all of its Pixel detector during an extended winter technical stop in 2016/2017 year. The new detector features several important improvements including: new front-end chips, a nearly twofold increase of the active surface, reduced amount of inactive material in the tracking volume. Following the upgrade, the Barrel Pixel (BPIX) grew from 48M to 80Mchannels and the Forward Pixel (FPIX) from 18M to 45M channels. The new design of the detector, despite the larger area and increase of channels, substantially reduced the amount of material. This was achieved mainly by the introduction of a new two phase CO_2 cooling system that replaced the C_6F_{14} liquid cooling [1].

The Cooling Requirements

The cooling system needs to cope with the heat load produced by the detector electronics but also with the heat leak from the ambient environment to the cold elements of the system. For the BPIX detector, the estimated power is around 6 kW, for the FPIX is around 3 kW, while an estimation around 2kWis made for the heat leak from the ambient. For redundancy reasons, it has been decided to install two cooling plants working in parallel. However, each of the cooling plants has been designed to handle a heat load of 15 kW, which provides sufficient safety margin to provide alone the required refrigeration power to the full detector for operation in the temperature range from 15°C up to −22°C.

Tracker Integration Facility (TIF)

In order to handle the requirements of the CMS Pixel upgrade [PP1], at first stage a full-scale prototype of a 15kW evaporative CO_2 cooling system has been designed, constructed and commissioned in 2013 [2] in a dedicated surface installation called Tracker Integration Facility (TIF). The TIF cooling system prototype consist of three main units: one cooling plant core, one manifold and one accumulator. The prototype represents one half of the final cooling system which was installed in the underground area of the CMS experiment.

CMS Final

The final CO_2 cooling system comprises two individual cooling units. In normal operation, one is dedicated to the BPIX detector and the other to the FPIX detector. Each unit consists of three main sections: the Accumulator, the Plant Core and the Manifold.

- The accumulator is a vessel always filled with a mixture of liquid and vapour CO_2. It is connected to the return line of the refrigeration loop, keeping the 2-phase CO_2 returning from the detector at the same pressure as in the vessel. The accumulator pressure is regulating by the heating and cooling action.
- In the plant core, the returning two-phase CO_2 is cooled down and liquefied in a heat exchanger by a standard primary chiller, based on R507a refrigerant. Afterwards, the liquid CO_2 is pumped by a membrane pump through vacuum insulated transfer lines to a distribution manifold. The plant core is also equipped

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with a local bypass, a dumper and shut off valves used during maintenance.

- Each of the detectors (BPIX & FPIX) is served by a manifold, which is responsible for the flow distribution to the detector. In the manifold, there are manual regulation valves, instrumentation for flow measurement and pneumatic shut off vales to separate individual loops. In total, there are 16 loops, 8 per detector, and additionally one bypass loop per manifold, on which is installed the dummy thermal load used during the commissioning period.

In normal operation, the BPIX and FPIX cooling systems are separated. However, they are sized such that they can act as redundant backups for each other, in case of problems with any of the two plants.

CONTROLS

Control System Architecture

The control system for the CMS CO_2 cooling is separated for BPIX and FPIX. However, the system is equipped with one common Schneider Premium Programmable Logic Controller (PLC) and two privet EtherNet/IP networks for the distributed Input/Outputs (I/Os). The overall control system architecture is presented in Fig. 1.

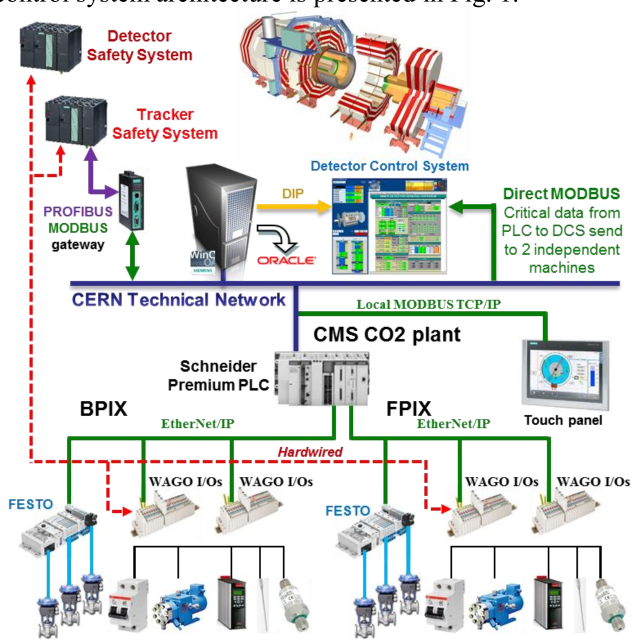

Figure 1: CMS CO2 cooling control system architecture.

Each of the cooling systems is equipped with one dedicated EtherNet/IP network card at the PLC level, two WAGO EtherNet/IP couplers for the distributed IOs and one FESTO EtherNet/IP coupler for pneumatic valve piloting. In total, the PLC manages almost 600 IOs via the EtherNet/IP protocol. The Siemens WinCC OA based Supervisory Control And Data Acquisition (SCADA) was chosen as a User Interface (UI). The control system follows the UNICOS CPC6 (Unified Industrial Control System for Continuous Process Control) framework of CERN [3] [4].

The PLC communicates to the SCADA server, placed in the CERN Control Center (CCC), through the CERN Technical Network, which is isolated from the global network, using the Modbus TCP/IP protocol. In case of a large network failure, the CO_2 cooling control system is equipped with a local touch panel, placed in the control rack, directly connected to the PLC and allowing for safe operation of the system. The touch panel software was programmed according to the UNICOS standard for the Siemens HMI (Human Machine Interface). Such user interface is very much similar to the WinCC OA SCADA UIs.

The whole cooling system is powered from the DIESEL backed network. The 24V DC hot-swappable redundant power supply, the PLC and the Siemens Touch Panel (see Fig. 2) are powered from a dedicated UPS (Uninterruptible power supply).

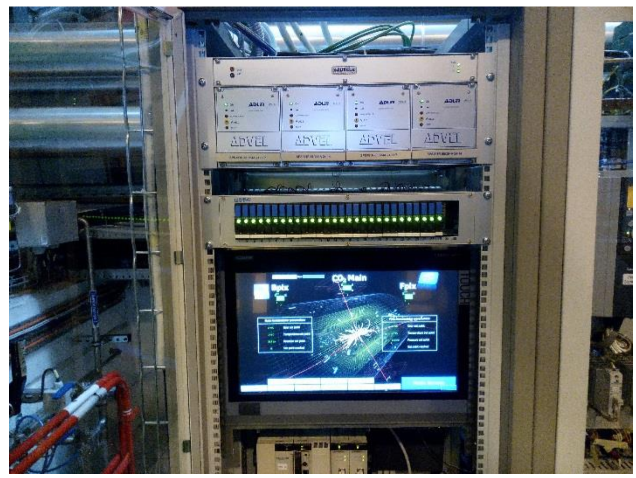

Figure 2: 24V DC power supply & distribution, Touch panel and PLC.

System Operation

During normal operation, both BPIX and FPIX cooling systems runs as separate systems. They can run with different evaporation temperature set-points and different CO_2 flow requests. Both systems are piloted by the master Process Control Object (PCO), which is the top control object in the hierarchy. In case of failure of one plant core, the PCO stops it, and when the interconnection valves in between the two plants are open, the system can continue the operation. In this scenario, the excluded plant core is removed from circulation by the pneumatic valves, the accumulator control follows the commands sent by the remaining running plant, and the running pump increases the pumping speed to deliver the requested flow to both BPIX and FPIX manifolds. This is the so-called backup option mode, where one plant operates as master and the second runs in the backup. In backup mode, there is only one common evaporation set point available for the two detectors due to the common return pressure.

Safety

In the CO_2 cooling system, during the operation but also while the system is switched off, high pressure is present.

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Each circuit section that can possibly drive to trap cold liquid is protected against excessive pressure by safety vales (set point ~ 90 bar) and a burst disk (set point 110 bar). In the CO_2 installation, there are 16 electrical heaters, serving different purposes, with power up to 7.5 kW. All the heaters are in the direct contact with the CO_2, installed in a small pipe volume and covered by thermal insulation. In order to avoid dangerous situations like overheating, rapid pressure increase or even fire, a three levels safety interlock philosophy has been applied for all electrical heaters of the CO_2 cooling systems:

- The first level is a software interlock, which stops the heater when a predefined first temperature threshold is exceeded. The temperature readout comes from the measurement of a thermocouple installed inside the heater cartridge.
- The second level are additional software interlocks, which stop all system heaters when any of the heater temperatures exceeds a predefined second temperature threshold. The measurement is based on the same thermocouple as in the first level protection.
- The third level is a hardware interlock, which cuts the power to all system heaters, when any temperature exceeds the further threshold fixed by one thermal switch. The thermal switches are installed directly on the piping.

To ensure the safe BPIX and FPIX detectors operation, but also to provide a maximum of safety for the plants and the operators, an extensive safety matrix has been applied. The CMS CO_2 cooling system exchanges critical signals with the Detector Safety System (DSS) and Tracker Safety System (TSS) via hardwired signals with “positive logic”. It was defined that the control system sends to DSS and TSS signals like “Cooling circulation is established” or “BPIX plant interlocked”, which cause actions like “Switch off/on the detector”. The CO_2 cooling station also receives signals from DSS and TSS, e.g. in case of fire in the CMS service cavern, where the system is located, or when the humidity level is too low and the system is forced to operate with high evaporation set point.

Additionally, on top of the digital signals, direct communication with TSS with analog signal exchanges has been established. Two PLCs communicate to the PROFIBUS to Modbus gateway, exchanging signals like “Detector temperature”, “Evaporation temperature set point” or “Accumulator pressure”.

Database

All the monitoring data need to be preserved for future system analysis. The CMS system is connected via the SCADA to the LHC Logging ORACLE database [5], where all the critical data are stored for long term. This allows the operators or experts for long term data analysis and debugging.

Commissioning

The cooling control system consists of about 600 I/Os and more than 240 alarms and interlocks. It was extremely helpful to use the UNICOS tools for the commissioning tables’ preparation, which were used during the I/Os check. Before the performance tests, all the I/Os were tested together with the alarms and interlocks. Most of them were verified by causing the real interlock conditions and those that could not be physically triggered were simulated. Due to the high number of interlocks and warnings, an Alarm Groups philosophy were applied. Alarms were grouped in category and in case of system failure or warning situation, the operator receive only a message with the alarm group name, to avoid a huge number of messages.

During the system performance test, where both cooling stations run with the maximum pumps speed & stroke and lowest possible evaporation temperature, it was discovered that the pumps consumed more current than expected. This caused a Frequency Inverter (FI) alarm and in the end the pump stop. After investigation with the pump manufacturer, new pump limits were implemented in the software to avoid operation in the unsafe zone, were the power consumption is too high.

Operation Experience

After the long commissioning process, the system has been connected to the detector and since 2017 is in operation. The cooling system operates stably since and without any major problem. During the first runs with the presence of the LHC beam, it was discovered that the electronics of the flowmeters, which are located in the CMS experimental cavern, randomly switched off, producing an I/O error. The problem is still under technical investigation, however most likely the flowmeters suffer from the so called “single event upset”, when a particle coming from a collision directly hits the electronic. To avoid a detector interruption during such random events, the TSS logic has been modified to handle that situation.

Distributed IOs

As mentioned before, the CMS cooling control system is based on distributed I/Os over two independent EtherNer/IP networks. The WAGO EtherNet/IP distributed I/Os has been selected as the preferred solution to handle a huge number of signals. The main advantage of using this technology was a low space consumption with respect to the PLC I/O cards, which is an important parameter when the control cabinet space is limited. It has been possible to fit almost 600 I/Os in one 43U Eurorack. Additionally, this solution reduces the cost of the control system and spare parts management.

However, a disadvantage of using EtherNet/IP together with a Schneider PLC is the lack of advanced diagnostic and complicated configuration. Also, the Schneider Unity Pro has a low level of support for third party EtherNet/IP devices like WAGO or FESTO.

SUMMARY

After the commissioning period, the described CMS CO_2 cooling system operates with the new pixel detector since 2017. Both plants are running steadily, without any major failure. The system has been prepared for operation

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24/7 and due to the redundancy approach, it is possible to keep the cooling active on the detector even during plant maintenance. The presented EtherNet/IP distributed I/Os architecture is an interesting solution especially for control systems where the space and budget are limited.

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