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Design, construction and commissioning of a 15 kW CO_2 evaporative cooling system for particle physics detectors: lessons learnt and perspectives for further development

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Since 2000, a few particle physics detectors have been using evaporative Carbon Dioxide (CO2) for their low temperature cooling systems, showing exceptional performances and stability in their full range of operation. The excellent physical, thermal and fluid dynamic properties of CO2, coupled to its radiation hardness, make of this fluid a very interesting option for the cooling systems of the next generation vertex and tracking detectors.

In order to match the requirements of the CMS Pixel Phase I upgrade, a 15 kW cooling system featuring evaporative CO2 has been designed, constructed and commissioned in 2013, as a full-scale prototype of the final system.

This paper describes the challenges during the design and construction phases, highlights the performance achieved during commissioning, and describes optimization of the design for the final system. Results of the performance tests, including stability of the temperature regulation while power cycling are illustrated as well.

An outlook on further scaling up is given in view of designs for higher cooling power, as needed for the next generation of tracking detectors for the LHC experiments.

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1.Introduction

Since 2000, two particle physics detectors have been using Carbon Dioxide (CO_2) for their low temperature cooling systems. The experience gained by the community with the systems operating on the AMS Tracker and the LHCb Velo has lead to a huge interest for this technology, which is increasingly adopted for future silicon tracking. In this paper we describe the design, construction and performance results of the most powerful CO_2 cooling system designed so far for HEP experiments, developed for the Phase I Upgrade for the CMS pixel detector. Considerations are given on further scaling up, based on the experience gained so far and the state of the art of the technology.

2.CO_2 cooling for high energy physics experiments

CO_2 as a refrigerant is increasingly used in industry for its environmental friendly properties and its reduced cost with respect to standard refrigerants. Its strong radiation hardness, coupled with the non-conductivity and non-corrosive behavior make this fluid an excellent candidate for the cooling of experiments in high-energy physics. Moreover, when CO_2 is used in an evaporative cycle, the excellent heat transfer coefficient, together with the low viscosity, allow for very small size of the evaporators inside the detector, thus reducing the total material budget dedicated to this aspect. For this reason, several experiments are progressively adopting this technology for the cooling systems of their vertex detectors.

2.1The 2PACL concept and its recent applications

In industrial applications, CO_2 is used as coolant in standard vapor-compression refrigeration cycle, based on the Joule-Thomson effect and as a distributed 2-phase brine in pumped cycles with limited operating temperature ranges. Since 2000, a new concept of CO2 cooling has been developed in the Nikhef laboratories for the AMS Tracker detector, the so-called " Two Phase Accumulator Controlled Loop" (2PACL) [1] In this thermodynamic cycle layout, CO_2 is pumped in liquid phase from a cooling plant to the detector, where it partially evaporates extracting the heat produced by the electronics, before coming back to the cooling plant in a vapor-liquid mixture. A pressure vessel, called accumulator, regulates the evaporating temperature by means of a double regulation loop acting alternatively on heating or cooling elements. All active components do sit at the cooling plant, which can be located in an accessible area far away from the detector.

Following the huge interest developed in the last years within the HEP community, several 2PACL systems have been designed and built. At CERN, in the Detector Technology group of the Physics Department (CERN PH-DT), small scale (100 W) portable CO_2 cooling units for laboratory use [2] have been developed, as well as larger cooling systems, featuring evaporating temperatures down to -40°C [3] and cooling powers up to 15 kW. The most powerful system (15 kW at -20° C) has been designed for the CMS Pixel upgrade detector and will be illustrated further in this paper.

3.The cooling system for the CMS Pixel Phase I Upgrade

The Compact Muon Solenoid (CMS) experiment at the LHC is planning a full replacement of its Pixel detector for the year 2016 [4], in order to cope with the planned increase in the collision rate provided by the LHC. The new detector will feature several important improvements including: (i) new front-end chips with increased readout capability, (ii) a nearly twofold increase of the active surface through the introduction of a 4th barrel layer and a 3rd forward disk at each end (Figure 1), providing one additional pixel coordinate to greatly increase the robustness of track reconstruction (iii) reduced amount of inactive material in the tracking volume.

The latter is the main limitation in performance of the current CMS Tracker and despite the larger area and increase in number of channels of the upgrade detector, growing from 48M to 80M in the Barrel Pixel (BPIX) and from 18M to nearly 45M in the Forward Pixel (FPIX), the new design will have a substantially reduced amount of material. This is primarily achieved by the introduction of CO_2 cooling, which is therefore one of the most crucial elements of the upgrade project.

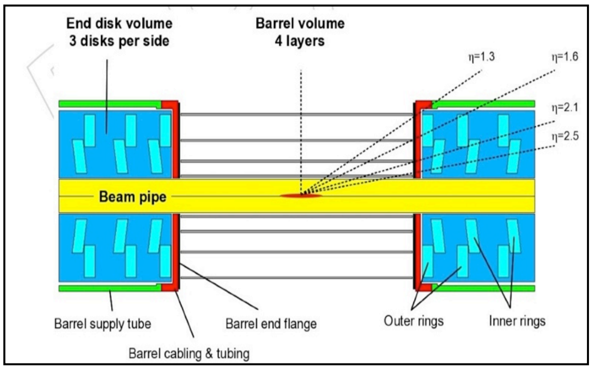

Figure 1: The layout of the CMS Pixel Phase I Upgrade detector

3.1The cooling requirements

The cooling system must remove the thermal load from the detectors as well as the heat leaking from the ambient environment to the cold parts of the system. The maximum power estimates are 6 kW for the BPIX, 3 kW for the FPIX, and about 2 kW for the heat leak from ambient. The cooling system has been designed to cope with a total power of 15 kW, providing ample safety margin.

The range of temperature needed for the coolant depends on the requirements for the commissioning phase and for long-term operation. In the commissioning phase, when the detector volume may not be sealed, the operating temperature must remain above the ambient dew point in the CMS cavern, i.e. >11°C, to avoid any condensation. Therefore, 15°C is set as the maximum coolant temperature. During operation, the silicon sensors need to be kept at a temperature well below 0°C to mitigate radiation damage effects. To fulfill this requirement, a coolant temperature of −20°C is chosen as the lower limit of the operation range, while the on-detector local thermal management design will ensure a temperature difference lower than ~10°C between the sensors and the coolant.

FPIX and BPIX may need to set a different operating temperature, in particular during the phases of checkout and commissioning. Nevertheless, the same CO2 coolant supply temperature can be accepted for limited operation periods. Coupling this requirement with the request to maintain a 24/7 operation of cooling even during maintenance periods, a conceptual design has been prepared where two cooling plants, each one dimensioned to provide the full refrigerating power required for both sub-detectors, are operated in parallel. During normal operation, each of them serves the manifold distributing cooling to one half of the detector. In case of maintenance or failure of one of the two plants the other one can feed both sub-detectors (Figure 2).

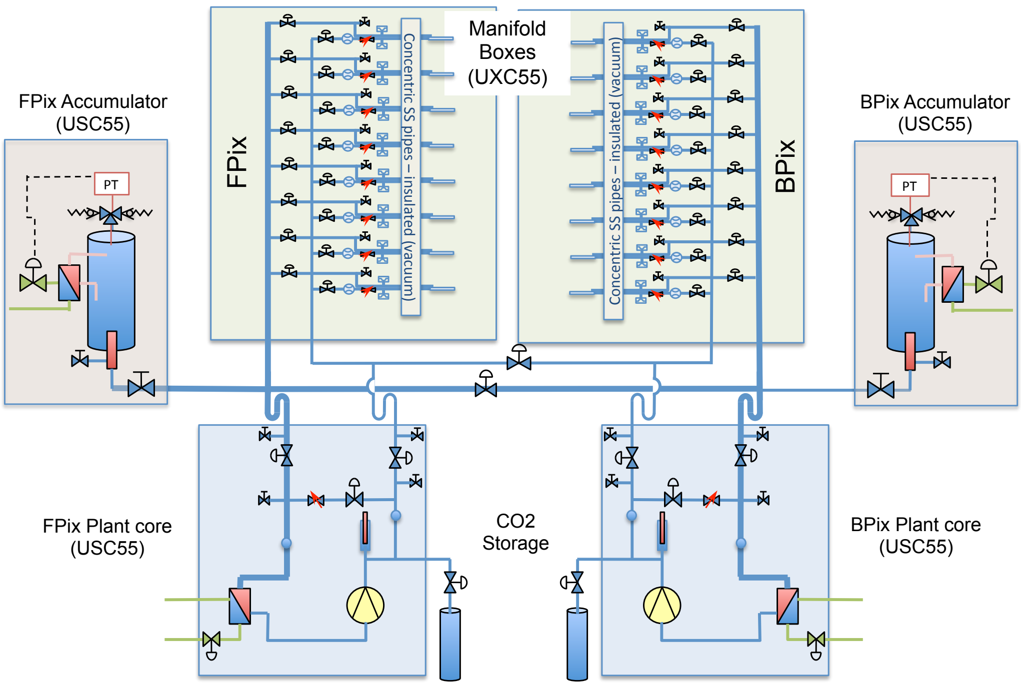

Figure 2: The general layout of the CMS Pixel phase I upgrade CO2 cooling system

3.2 The project strategy

The Phase I Upgrade Pixel detector will be installed in CMS during an extended winter technical stop in 2016/2017. The whole installation will follow a very tight schedule, where the present detector and its cooling system will be dismounted and the new detector installed and quickly connected to the new CO2 cooling plant for checkout and operation. Given the short time available for commissioning of the detector, the cooling system needs to be fully operational ahead of the installation. The request is then to have an operational cooling plant installed in the experimental premises by the end of 2014. In order to achieve such a result, a full-scale prototype of the cooling system has been built in 2012/2013 and commissioned in a surface laboratory at the CMS Tracker Integration Facility (TIF) during 2013/14 [5].

4.The TIF full scale prototype

The TIF full scale cooling plant prototype comprises four main blocks: one cooling plant core, one vacuum insulated transfer line, one manifold and one accumulator. The prototype thus represents one half of the complete cooling system to be installed in the underground premises (Figure 3). For easiness of construction, three of the four blocks are built as stand-alone, the transfer lines in sections. Both the cooling plant core and the manifold blocks are enclosed in a thermal insulated box, constantly flushed with dry air, in order to avoid condensation even without local insulation of each component inside the box. The accumulator is insulated with traditional insulation foam.

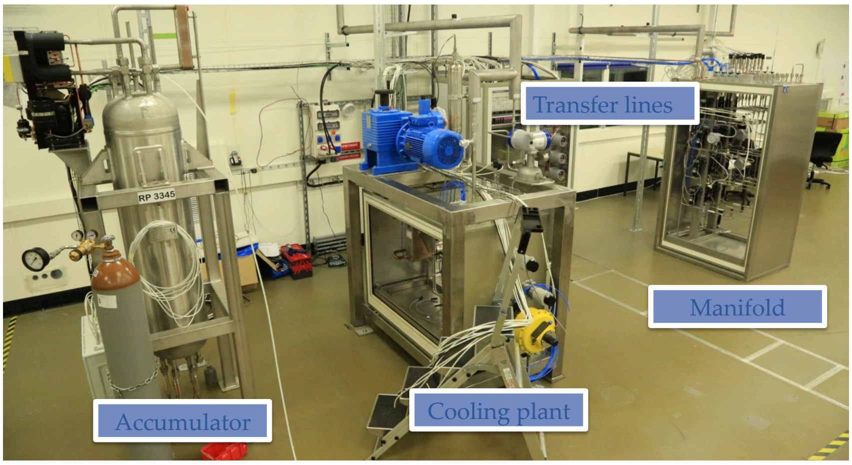

Figure 3: The TIF CO_2 cooling system

4.1The design process

Once the general layout of the system defined, together with the main functionalities for operation, the components have been only selected within the market of industrially qualified elements for the following design conditions:

- Service pressure = 110 bar (thus requiring components that can withstand 157 bar testing pressure)

- Minimum operating temperature = -40 C (which is the evaporating temperature of the primary circuit, thus including a large margin for the other components)
- Compatibility with a magnetic fringe field of about 600 Gauss (for components in the manifolds)

Under such requirements, the selection has been particularly complex and many components had to be further qualified with ad-hoc tests at CERN. For the pump selection, the market survey highlighted a unique pump type complying with all requirements. This is a Lewa membrane pump, very similar to the one mounted on the LHCb Velo cooling system, which has proven so far excellent performances and strong reliability. The bigger model available provides a flow rate of up to 150 g/s, ample enough with respect to the 120 g/s needed to extract the full power and maintain a good margin with respect to dry out. The pump has been purchased with the additional option of a remote head, so that the motor can be mounted outside of the thermal enclosure of the cooling plant and does not contribute to the total heat balance of the circuit.

4.2The construction process

The construction process followed all the requirements set by the European Pressure Directive (PED [6]) on pressurized equipment. The PED rates equipment in five categories, with increasing level of danger measured on their stored energy, and requires more stringent controls in the production of higher category equipment. In order to increase the reliability of the system, all the cooling plant and manifold welds have been controlled as in class I devices, despite the fact that, based upon the volumes and the pressure used, the system falls into class 0. Welds have been performed with an orbital welding machine, they have been fully visually inspected and 10% of them verified with x-rays. After welding, all parts have been cleaned and assembled into the insulated boxes before the leak and pressure test. Helium sniffing mode leak test has been passed with a threshold of 10^{-8} mbar*l/s.

The cooling plant and the manifold have been connected between them by means of coaxial vacuum insulated transfer lines. In such transfer lines, the innermost pipe contains the liquid CO_2, the outer one the vapor-liquid mixture of the return and a third pipe act as vacuum jacket, shielding the process line from the environmental heat. Coaxial vacuum insulated lines are common industrial products for cryogenic fluids, but they typically include a process pipe and a vacuum jacket only. Because of the particular requirements of three pipes one into the other, their design has been validated at TIF before ordering the same type for the underground premises.

4.3The control system [7]

The process is piloted by a single Schneider Premium Programmable Logic Controller and monitored by Siemens WinCC OA SCADA (Supervisory Control And Data Acquisition) system. The control software conforms UNICOS (Unified Industrial Control System Continuous Process Control) CPC 6 framework of CERN. Both PLC and SCADA server are placed into the CERN Technical Network, physically detached from the outside world, for the security reasons. The TIF control system is equipped with 216 I/Os connected into the PLC via Ethernet IP industrial fieldbus. To limit the amount of required cabling the distributed I/Os connect to privet Ethernet IP network via WAGO and FESTO couplers. On the software side the access control philosophy, long-term data storage and communication to Detector Control System via DIP protocol have been established.

The electrical part of the control system is based on the standard industrial off the shelf components for reliability and maintenance reasons.

5.Commissioning and performance tests

In order to verify the full functionalities of the TIF cooling plant ahead of connection of any detector part, a thorough program of commissioning has been followed. After the basic verification of all I/O and electrical connections, all elements of the plant have been singularly tested, and finally the whole plant has been commissioned covering all the range of expected operational conditions.

5.1 Commissioning of single components

A series of sequential tests have been conducted on all single components, including valves and regulation elements. Particular attention has been focused on the pump performances and the accumulator behavior. For the pump verification, the working conditions calculated by the supplier have been reproduced during tests and found to be fully representing the pump behavior in the whole pressure/flow range of operation. On the accumulator, two alternative options for the cooling element of the pressure regulation loop described in §2.1 have been implemented and tested: an internal spiral where R404a circulates inside the vessel, or an external heat exchanger, cooled as well by R404a. In the first configuration, the gas is directly condensed into the vessel by the cooling spiral, in the second configuration, the gas present in the accumulator exits from the top connections, is redirected to the heat exchanger, where it condenses, and the liquid drops afterwards back into the vessel. The tests focused on the velocity of both systems in reducing the pressure into the accumulator. Both systems performed identically, with a peak speed for the maximum flow of R404a being of about 1.5 bar/min. Seen these results, the option of the external heat exchanger has been chosen for the future accumulators, since it allows access to the cooling component, outside of the vessel and a possible upgrade in case of need.

5.2Tools for general plant commissioning

Once the basic components tested one by one, the commissioning program has continued with the verification of the plant general functionalities, followed by the full performance tests. The nominal conditions to be tested, for an evaporating temperature of -20 C, correspond to a power of maximum 1 kW on each manifold cooling loop, 8 kW on each cooling plant when operated on its own manifold and 15 kW on one cooling plant operated as backup of the other.

To perform these tests, two different set-ups equipped with dummy heating loads have been built and used at different stages. The first set-up comprises 4 dummy detector-cooling loops, each one with an independent heater, whose power can be regulated up to 2 kW. The second set up features a unique dummy load, whose power can be regulated up to 15 kW.

5.3Results

The first tests have been performed with one cooling loop only, simulating the maximum load the single detector-cooling loop can be charged with. As visible in Figure 4, the regulated temperature inside the detector evaporator (green line) remains perfectly constant while a varying load is applied (orange). The same results in terms of stability while varying loads are obtained by testing the four available loops in parallel, up to a total load of 8 kW. Later on, in order to verify the performances of the cooling plant when used

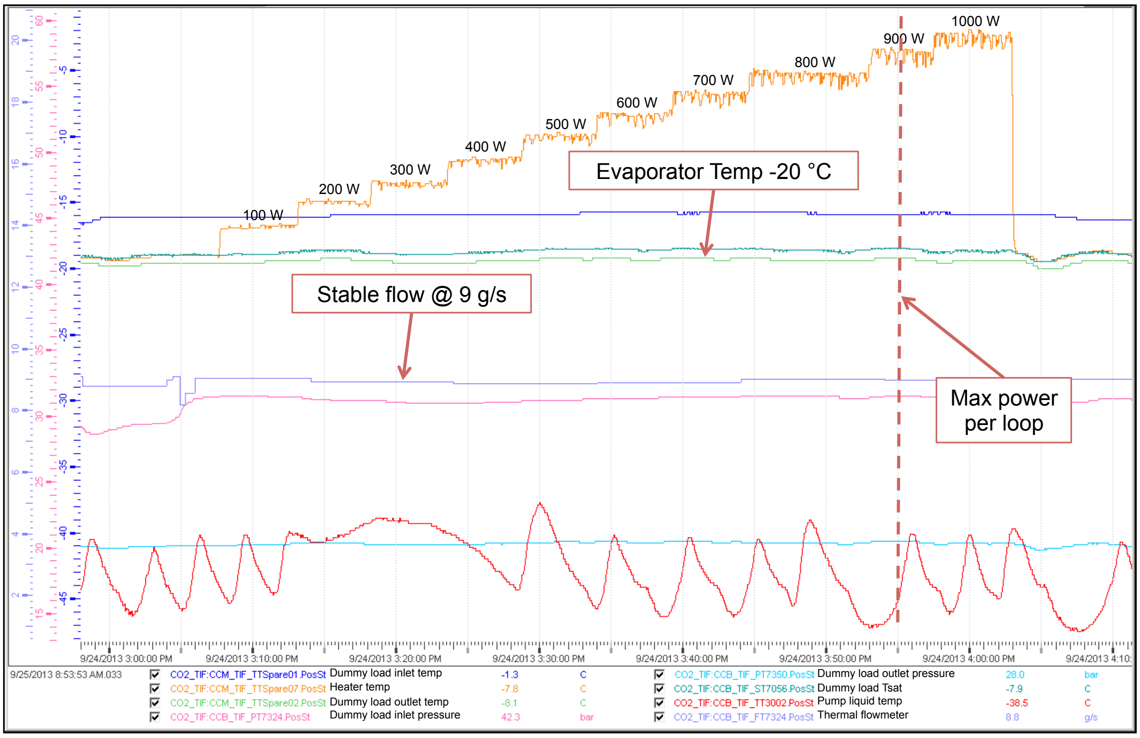

Figure 4: The single loop tests at CMS-TIF

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for both halves of the detector, the bigger dummy load has been used, setting a total flow rate of 120 g/s and varying the load up to 15 kW. Once reached the nominal set point, the stability of the temperature during operation stays within 1 degree around this value, allowing for full validation of the chosen components and proving the design performances in the most constraining operation settings, i.e. -20°C and 15 kW (Figure 5).

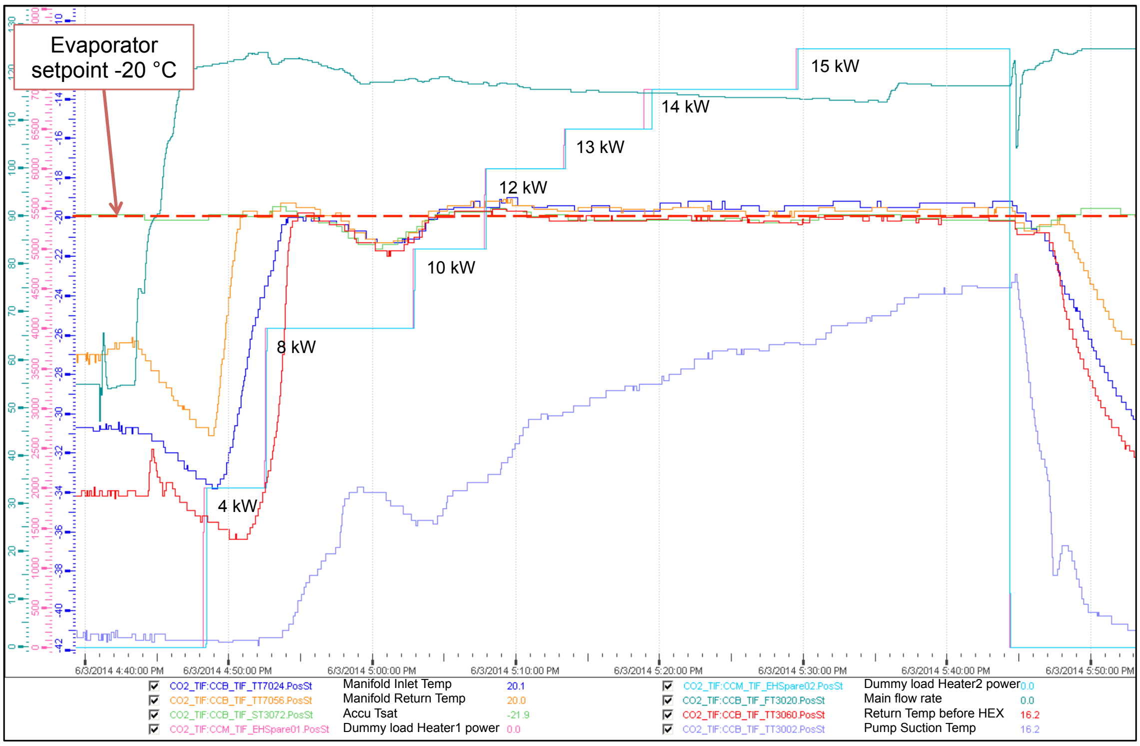

Figure 5: The full performance test at CMS-TIF

6. Lessons learnt and scaling up strategy

The results of the commissioning tests have allowed for a full revision and validation of the cooling system design before construction of the final system. The components selected for the TIF prototype plant have been endorsed, or replaced when found not suited for the desired performance; all design parameters have been verified; and choices between alternative technical options have been made for the final plants. Evaluating the perspective of long term testing of the final system before the detector will be installed, the 15 kW dummy load has been integrated in the design of each manifold, thus allowing for a thorough evaluation of overall performances also in the underground premises.

In consideration of the huge interest for the further development of CO2 cooling systems in the community of high energy physics detectors, in particular for system with increased power and lower operating temperature, a possible scaling up strategy has been developed starting from the experience gained with the TIF cooling plant. All components present in the installation can in principle be adopted for lower temperature ranges, being all qualified for -40° C. In order to achieve higher cooling power, the main issue would be the selection of a new pump. The same model used in the TIF cooling plant is also distributed with a triple head configuration, where the total flow corresponds to about 45 kW of cooling power. This seems to be now the maximum size that can be easily achieved with fully industrial components, proven for CO_2 operation in the experimental areas. A modular approach with 3 or 4 of cooling systems in parallel would allow for the total power nowadays being discussed for the major LHC detector upgrades.

7.Conclusions

Following the request for a fully redundant CO_2 evaporating cooling system, featuring 15 kW at -20°C, for the CMS Pixel Phase I Upgrade, a new cooling plant has been designed. A full-scale prototype has been built and commissioned on surface premises. The excellent results of the commissioning and performance tests have proven the perfect match of the system to the user requirements. The analysis performed on the newly built system has allowed for further improvement of the design for the construction of the final system, now on-going at the CERN PH-DT workshop. A modular concept, with few cooling systems operating in parallel, each one featuring about 45 kW, is proposed for future applications.

References

[1] Verlaat B., *Controlling a Two-Phase CO_2 Loop Using a Two-Phase Accumulator*, ICR07-B2-1565, International Conference of Refrigeration, Beijing, China, 2007

[2] Verlaat B. et al, *TRACI, a multipurpose CO2 cooling system for R&D*, in proceedings of *10th IIR-Gustav Lorentzen Conference on Natural Working Fluids 2012 (GL2012), Delft*

[3] L. Zwalinski et al., *CO2 cooling system for Insertable B Layer detector into the ATLAS experiment*, in proceedings of *TIPP2014 conference* PoS(TIPP2014)224

[4] Kästli H-C., *CMS pixel upgrade Project*, in proceedings of *19th International Workshop on Vertex Detectors* – PoS (VERTEX 2010) 039

[5] J. Daguin, J. Noite, P. Petagna, H. Postema, P. Tropea, B. Verlaat, *Evaporative CO2 cooling system for the upgrade of the CMS Pixel detector at CERN*, in proceedings of *10th IIR-Gustav Lorentzen Conference on Natural Working Fluids 2012 (GL2012), Delft, pp. 1066-74*

[6] http://ec.europa.eu/enterprise/sectors/pressure-and-gas/documents/ped/index_en.htm

[7] Zwalinski L. et al, *The Control System for the CO_2 cooling plants for Physics experiments*, 2013, in proceedings of *14^{th} International Conference on Accelerator and Large Experimental Physics Control Systems, San Francisco USA, 2013*