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How digital twins can help with operator training, an example with ATLAS and CMS detector's cryogenics at CERN

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Abstract. This paper presents the implementation of a cryogenic process simulator applied to A Toroidal LHC Apparatus (ATLAS) and the Compact Muon Solenoid (CMS) experiments at CERN (European Organisation for Nuclear Research). Building upon the development of a digital twin of the complex LHC accelerator cryogenic system, this work extends its application to the specific needs of the ATLAS and CMS experiments and their dedicated cryogenic systems. These particle large detectors rely on superconducting magnets, each weighting hundreds of tons, which must be maintained at 4.5 K. The cryogenic simulator replicates the helium refrigerators and the proximity system connected to the detectors reproducing real operational case scenarios, enabling cryogenic operator training for both routine and special operations. This digital twin is using identical features as the real infrastructure, integrating multiple layers forming the process control system: the simulation model, Programmable Logic Controllers (PLC), and Supervision Control And Data Acquisition (SCADA) system, that shares data in real time between them. The objectives of this digital twin are threefold: first, to provide a comprehensive off-line training tool for the operators, second to improve the knowledge on the installations and third, to simulate and evaluate the reactions of the cryogenic plants in new scenarios or configuration changes before implementation.

1 Introduction

The CERN (European Organization for Nuclear Research) operates since 2008 A Toroidal LHC Apparatus (ATLAS) and the Compact Muon Solenoid (CMS) detectors using the most powerful particle accelerator of the world, the Large Hadron Collider (LHC) at 6.8 TeV. Both ATLAS and CMS are operating superconducting magnets maintained at 4.5 K employing helium refrigeration plants.

ATLAS and CMS's refrigerators are controlled by multiples PLCs, a system relatively complex controlling more than 2000 I/O each. The PLC system is using the UNICOS (UNified Industrial COntrol System) architecture, a CERN framework allowing to joint the supervision, the control and the field layer (composed of sensors, actuators, ...) [1].

In order to avoid unnecessary magnetic cycles, the cryogenic conditions shall be granted at the detector magnet level all along the physics run year. As part of the safety system (power failure...), the magnet will ramp down from its top intensity to zero in a controlled manner. In case of a critical loss (loss of current leads cooling...) the magnet can be discharged in a short time through a process called fast dump. It carries the risk of damaging the magnet due to the sudden increase in temperature generated by the strong eddy currents.

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Following an increase in the number of fast dumps in the CMS and ATLAS experiments in 2023, a task force within the cryogenic group was initiated. Its mandate was to : 'review and ensure the slow dump process, including a full stop of the cryogenic plant, regardless of the cause'. For this purpose, different approaches were developed, one of which was to set up a simulator to better train operators.

This simulator would serve several roles: training operators, optimizing the process before any consolidation, validating improved control strategies and to test the automatic PLC logic sequence initiated during a slow dump event.

2 Description of ATLAS and CMS cryogenic systems

2.1 CMS cryogenics

The helium compressor station is made up of four oil-lubricated screw compressors in two stages, two of which operate at the same time in series and two serving as hot spares. Coupled with an oil-removing system, they allow 207 g/s of dry helium to be compressed from 1.03 bar to 17 bar.

The liquefaction of helium is realised in a cold box composed of 3 Air Liquide© gas bearing turbines, 6 heat exchangers, 2 adsorbers (80 K and 20 K) and 1 phase separator with a capacity of 120 L. It is located underground near the detector cavern [2]. It has been designed to provide 860 W to cool the magnet at 4.5 K, 4.5 g/s of liquefaction for the current leads and 4500 W between 60 K and 80 K for the thermal shield. It is controlled by more than 10 regulation loops of which 2 are managed by Air Liquide© intern PLC dedicated to the turbines.

The CMS's magnet uses a Nobium Titanium conductor, embedded inside a high purity aluminum matrix. The main part of the coil is 12.4 m length and 0.3 m thick, for a diameter of 6.36 m. It weights 220 $tons$, receives up to 400 W in nominal mode plus an additional 70 W during a normal ramp up or down of 1 A/s, and has to be cooled accordingly. For this a phase separator provides helium liquid to 8 cooling circuits composed of 24 tubes. Cooling method consists in a thermosiphon loop, the helium circulates naturally by the difference of density between the liquid and the two-phase flow.
In case of failure, a 6000 L liquid helium storage is used to allow a slow discharge of the 2.7 GJ of magnetic energy stored in the magnet.

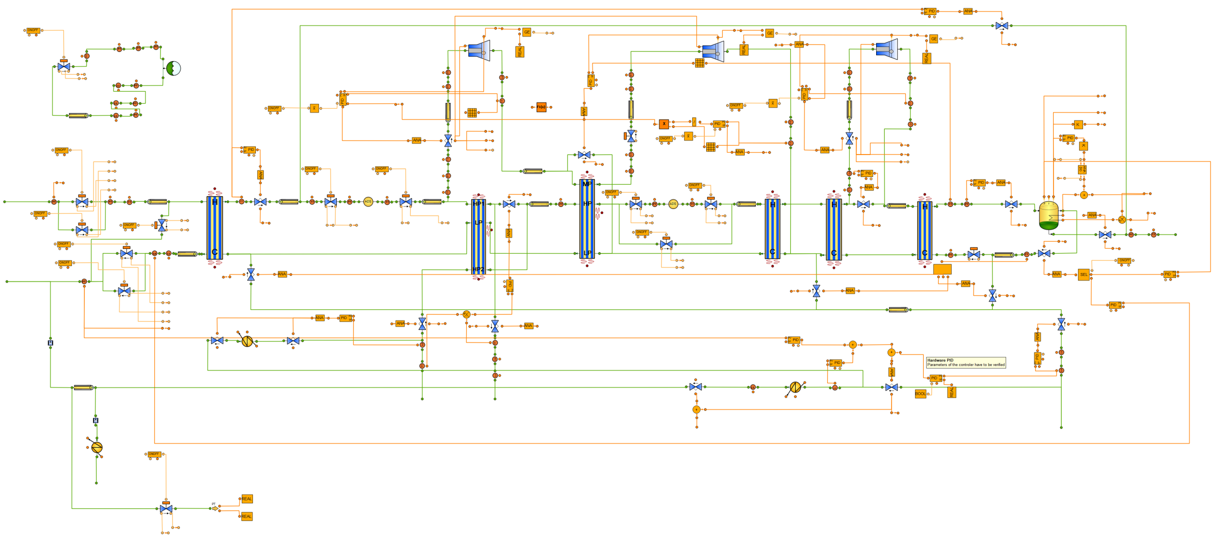

Figure 1: EcosimPro model of the CMS cold box

2.2 ATLAS cryogenics

Similarly to CMS, the Main Refrigerator (MR) compressor station is made of six oil-lubricated helium screw compressors in two stages, with four running during the standard operation: three on the low stage and one on the high stage. This station can compress up to 480 g/s of dry helium from 1.05 bar to 17.8 bar.

A second compressor station with two compressors is used to provide a 14 bar pressure for the shield refrigerator. ATLAS uses two separate cold boxes, one for the thermal shields and one for the two

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parts of ATLAS, the solenoid and the toroid magnets[3]. The shield refrigerator was designed to provide 10 kW cooling power at 80 K while the main refrigerator was designed for 6.4 kW at 4.5 K with 11 g/s of liquefaction for the current leads. It uses the same configuration as CMS, with 3 turbines, 6 heat exchangers, 2 adsorbers and a phase separator.

The solenoid system weights about 5 *tons*, generates a field of 2 *Teslas* and stores up to 38 MJ of magnetic energy. It is cooled using saturated liquid helium provided via thermosiphon loops where helium circulates naturally within the loops due to density differences, similar to the CMS approach. This method ensures a stable and uniform temperature along the entire solenoid.

The toroid system is composed of a barrel toroid and two end-cap toroids, forming an open geometry magnet system weighting more than 1300 *tons* of which 690 *tons* are the cold mass. These large coils are cooled by forced-flowed helium using cryogenic helium pumps with up to 1200 g/s capacity, ensuring uniform distribution in the large volumes of the toroid. The total thermal load for the toroid system reaches approximately 1.3 kW@4.5 K during operation, requiring careful thermal management to maintain superconducting conditions.

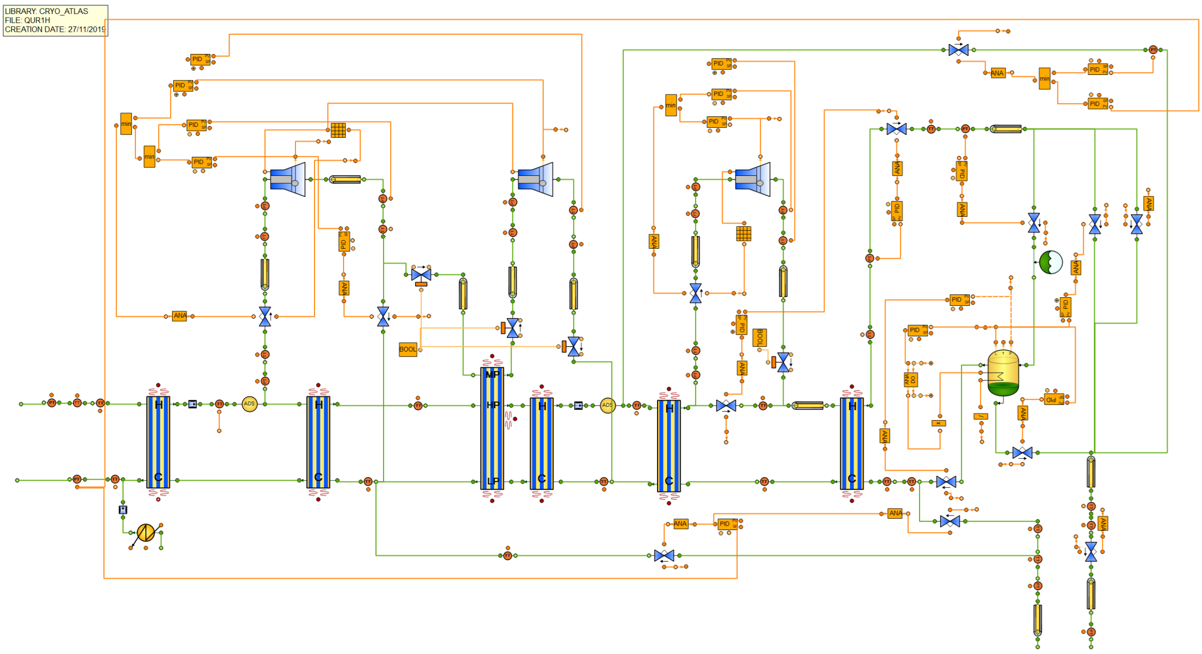

Figure 2: EcosimPro model of the ATLAS cold box

3 Model Description

The cryogenic modeling has been achieved using EcosimPro and the CRYOLIB library[4], a dynamic simulation software designed for modeling complex system. It allows solving large differential-algeabric equation systems, useful in complex modeling such as cryo-simulation. It has an object-oriented approach that consists of different physical components modeled and linked together to build large models. Objects can be divided in four parts :

- Resistive components, reacting to a pressure difference to deliver a flow rate (turbines, valves, ...)
- Capacitive components, storing fluids and calculating pressures (pipes, tanks, ...)
- Hybrid components, composed alternatively of resistive and capacitive components, allowing thermal transfer (heat exchanger)
- Control components, regulating, controlling, and exchanging with real logic controllers

To avoid algebraic loop such that the obtained model is consistent, and to facilitate equation solving, resistive and capacitive components have to be placed alternately.

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3.1 Scope of the model

Most of the cryogenic system has been modeled for both ATLAS and CMS. Elements not impacted by the helium process dynamics (oil circuits, vacuum, ...) were not modeled and instead defined as boundary conditions. The Table 1 presents the number of valves, sensors, and Proportional–integral–derivative (PID) controllers that have been modeled.

	Valve	Temperature sensor	Pressure sensor	PID controller
CMS Simulated	53	36	48	32
CMS Real plant	110	78	61	39
ATLAS Simulated	51	57	72	37
ATLAS Real plant	189	158	105	61

Table 1: Actuators, Sensors, Controllers simulated

The vast majority of sensors and actuators that are not simulated are part of the compressor station's oil system. The latter is not simulated, but considered as a boundary condition delivering an oil flow at a certain pressure and temperature.

The modeled valves aim to closely replicate real-world behavior. To achieve this, their characteristics were obtained from the technical specifications. Valves for which parameters were not specified were modeled to best approximate reality by comparing valve openings under nominal operating conditions.

In total, the CMS model contains 8226 equations with 547 output dynamics and derivatives while the ATLAS model contains 14264 equations with 988 output dynamics and derivatives.

4 The PROCOS (PROcess and Control Simulator) approach

In 2007, CERN developed a simulation tool named PROCOS [5] (PROcess and COntrol Simulator). It is a system architecture based on the standard UNICOS, adapted to process simulator. It is composed of three layers : the supervision, the control and the process, replaced by the simulated field. It means that the large majority of values normally measured by sensors are replaced by simulated ones, with the EcosimPro model.

The PROcess and Control architecture includes interconnected components that create a simulation environment for CERN's cryogenic processes, while allowing the easy configuration switch between the ATLAS and CMS configurations. The real process is managed by multiple Schneider PLC, with data exchanges through generic interfaces (illustrated in Figure 3) using the OPC-UA protocol for communication between the server and the model. All essential process information stored in the PLC are transferred to a data server (SCADA) over an Ethernet network using the Modbus protocol. Supervision clients, which employ WinCCOA software, can connect to the data server to retrieve process information and send commands to the PLC for manual operations.

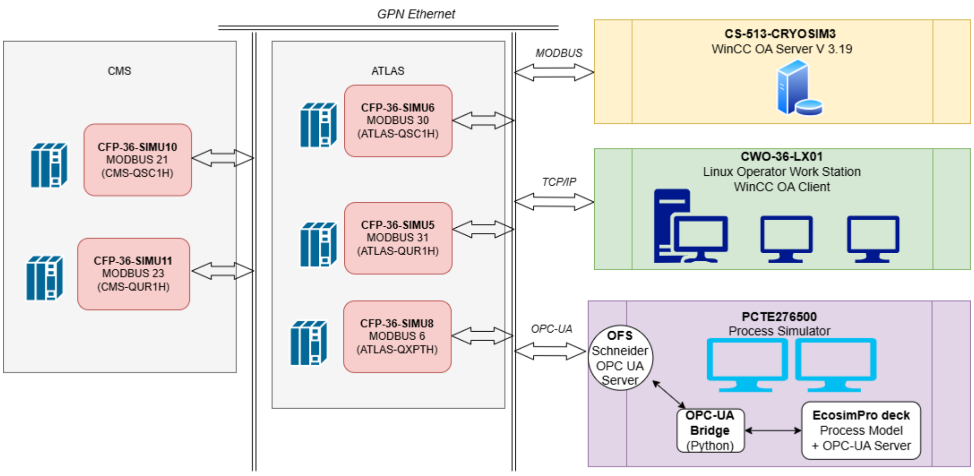

Figure 3: PROCOS architecture for the ATLAS and CMS simulators

The model contains the same PLC I/O names as the field sensors, allowing the OPC-UA server to be configured automatically to establish the link between the model and the PLC. One of the major difference is the speed: the simulation speed is not constant therefore requiring a synchronisation for ramps and timers in the PLC. To increase fidelity, the PID controllers are fully simulated in the model and only the main parameters and outputs are exchanged with the PLC to ensure consistency.

This simulation environment is particularly well-suited for operator training, as it uses the same supervision interface as the actual plant, significantly reducing development time. Additionally, these programs can be directly validated in their operational environment, allowing comprehensive testing of all interlocks, sequences, and closed-loop systems.

To exchange between the model and the PLC, the CERN Industrial Control group developed a python tool called OPCUA-bridge, based on the asyncua library, creating the two OPC connections (PLC-bridge and bridge-model). We decided to reuse this tool for the simulator as it would provide data exchange similar to the real approach, ensuring the smooth exchange of data and the time synchronisation between the model and PLCs. During the work on the CMS and ATLAS models, several performances issues were solved, improving the performances by up to 60 times during steady phases.

5 Steady state validation

Each model went through a steady state validation using the 4.5 K initial state in order to get the T-s diagrams. Two configuration have been tested : the comparison with **design** (given by the manufacturers specifications) and with a **measured point** during standard operation. Comparison with field data is more difficult due to changes in parameters since the installation and the lack of sensors in some places.

5.1 CMS

Figure 4 shows a good reconciliation for the steady state mode. The average relative error is close to 1%. This accuracy confirms that the temperature gradient and pressure repartition in the cold box are correct, thus, the global system is consistent.

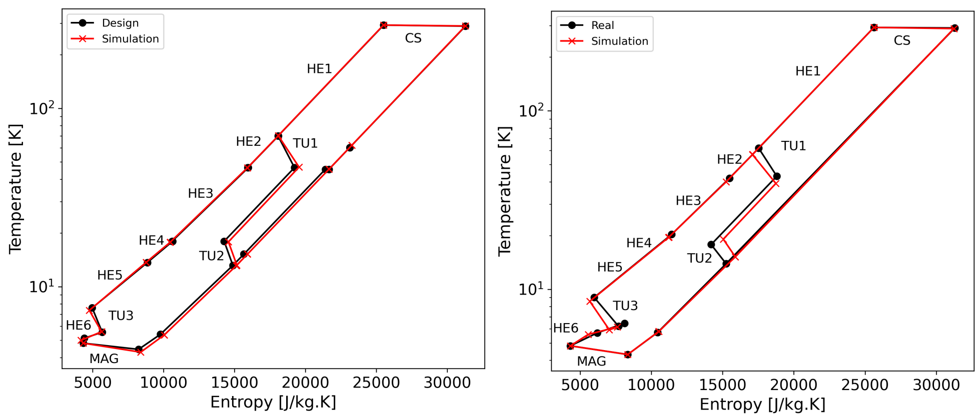

Figure 4: T-s diagrams for CMS: Simulation Vs design point (left) and field data in 2024 (right)

5.2 ATLAS

Very much like CMS, Figure 5 shows a good reconciliation for the steady state mode. The average relative error is close to 1%. This accuracy confirms that the temperature gradient and pressure repartition in the cold box are correct, thus, the global system is consistent. The only notable changes are near 4.5 K where the entropy cannot be calculated as accurately as given by the model.

With the system changes over 20 years, comparing to the real state required some changes in the model. The turbines efficiencies have been recalculated to reflect actual performance, some valves opening have been forced and some set points modified. There are, however, some differences in the T-s diagram and the mean error is larger than previously, reaching 3%. These discrepancy can be attributed to the heat loads along the cold box due to vacuum degradation, greatly underestimate, as well as the degradation of exchanger efficiency during operation. Nonetheless, these differences are unlikely to affect the dynamic

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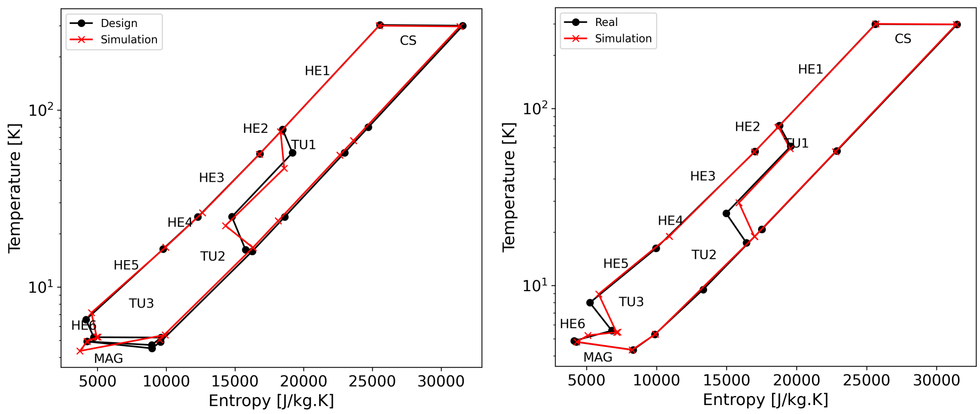

Figure 5: T-s diagrams for ATLAS: Simulation Vs design point (left) and field data in 2024 (right)

simulation, where system dynamics are the primary focus. These simulations revealed issues on the real process: flow sensors indicating incorrect values, and an overall increase in the thermal load.

6 Dynamic simulation validation and use cases

After validating steady state scenarios, we needed to check for the response of the systems during transients and standard procedures. Such scenarios start on a defined initial state and dynamic boundaries conditions are applied over time if necessary depending on the scenario. Results were compared to measured values to validate the benchmarks.

6.1 Initial State

The simulator requires initial states to operate, and four have been selected. These scenarios are defined by both their ”physical” state—which includes the configuration of valves, fluid, and thermal components—and their ”control” state, characterized by the sequence position of each control object. Both states must be saved to allow for simulator reconciliation.

- The 300 K starting state with client at 80 K, allowing future operators to practice starting the compressor station and familiarize themselves with cold box connection procedures.
- The 20 K state allows training for the final phase of the magnet's cold start-up, with the first drops of liquid appearing in the magnets.
- The 4.5 K state, intended for frequent use, enables operators to train for all expected and unexpected scenarios presented in the following section from the nominal steady-state.
- (ATLAS specific) The 4.5 K state with cryogenic pump on, intended for standard steady state operation, with ramp up and down of the magnet, and slow dump.

6.2 Scenarios, Results and discussions

Before implementing the model in the simulator, some scenarios have been tested, they allowed to validate the global behavior of the model's dynamics. The main scenarios were the start and regulation of the compressor station, the cool-down of the cold-box, the connection and cool-down of the magnet, and the final steady state with cold magnet used for model benchmark. Among the scenarios mentioned, we propose here to detail one for CMS and one for ATLAS.

To validate the simulator's overall performance, several planned and unplanned scenarios were proposed and verified either by benchmarking or by an operator. Planned events are pre-scheduled, regardless of whether the plant is in operation. They include compressor station start-up and regulation, cooling down of the cold box and magnet, magnet current ramp-up and down, turbine filter regeneration and cryogenic pump start.

Unplanned events typically occur during a major system failure and often require additional computing power due to their complexity. Key unplanned events include a compressor trip, turbine trip, and fast ramping down of current in the magnet (resulting in a significant thermal load). These events have been modeled to simulate the cryogenic process until it returns to normal conditions.

6.2.1 CMS Turbine's filter regeneration sequence This operation is performed at nominal conditions with the magnet at 4.5 K. The regeneration of turbine filters is a scheduled operation involving the shutdown of turbines 1 and 2 for a set period, during which the circuit is reheated and purged. Before starting this procedure, operators increase the intermediate cryostat level by 5% as a precautionary margin. During these two periods, the booster mode of turbine 3 is activated: its rotational speed is increased, and the opening of the turbine bypass valve is adjusted from 8% to 5%. The aim of this simulation is to validate the behavior of the cold box under transient conditions, specifically during liquefaction demand and turbine shutdown.

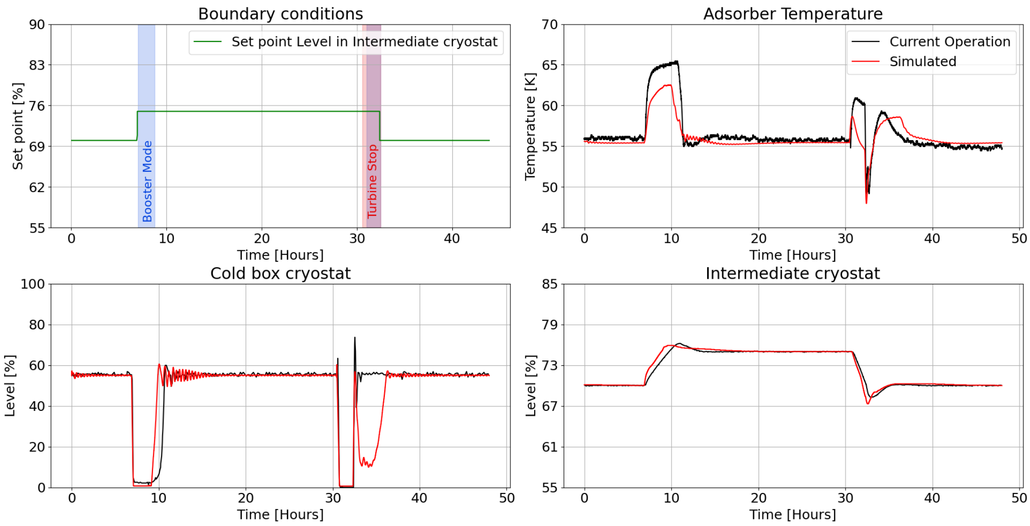

Figure 6: CMS Dynamic benchmark, turbine's filter regeneration procedure

During the filling of the intermediate cryostat, we observe in Figure 6 the increase of the adsorber's temperature due to the liquefaction happening. Once the cryostat reaches its new setpoint, the cold box returns to its normal conditions until we stop the turbines. With the turbines off, our cooling power drops leading to the decrease in cryostat's level and increase in temperature in the cold box.

When comparing to the simulation, the overall dynamics are consistent. The cold box cryostat displaying some differences due to the previously mentioned issues. Similarly, the adsorber temperature exhibits a lower amplitude than observed in reality. This slow rising of the temperature matches the second drop of level in the cold box cryostat following the turbine stop, we are not sure yet what is the cause but it's coinciding with the intermediate cryostat filling and differences in pipping and/or valve openings could be one of the sources. We fill faster at the cost of the level in the cold box.

6.2.2 ATLAS Cryogenic pump startup The cryogenic pump is restarted during the cool-down operation, for example after the yearly technical stop, when the system is in liquid. This operation requires a stabilization plateau both in flow and temperature to allow a smooth restart of the pump. Typically, the pump is started at 50 Hz, kept in this configuration for around a day and then increased to its nominal value at 72 Hz. The circuit stabilizes after the initial startup and isn't affected much by the increase to 72 Hz so we didn't simulate that far. The aim of this simulation is to validate the behavior of the phase separator and the response of the cold box during the startup of the pump, especially during the initial thermalization and filling of the lines which consumes a lot of liquid.

We start from the stable 4.5 K state and after a few seconds, we start the pump and immediately see the level in the phase separator drop consistently with the reality.

Although some differences appear, the overall dynamics are concordant. The difference in levels seen in Figure 7 can be explained by the Dewar intake, likely too small, make the filling slower and the excess liquid created ends up in the phase separator of the main refrigerator hence the higher level. The valve between the Dewar and the phase separator also remained nearly closed for longer, leading to a drop in

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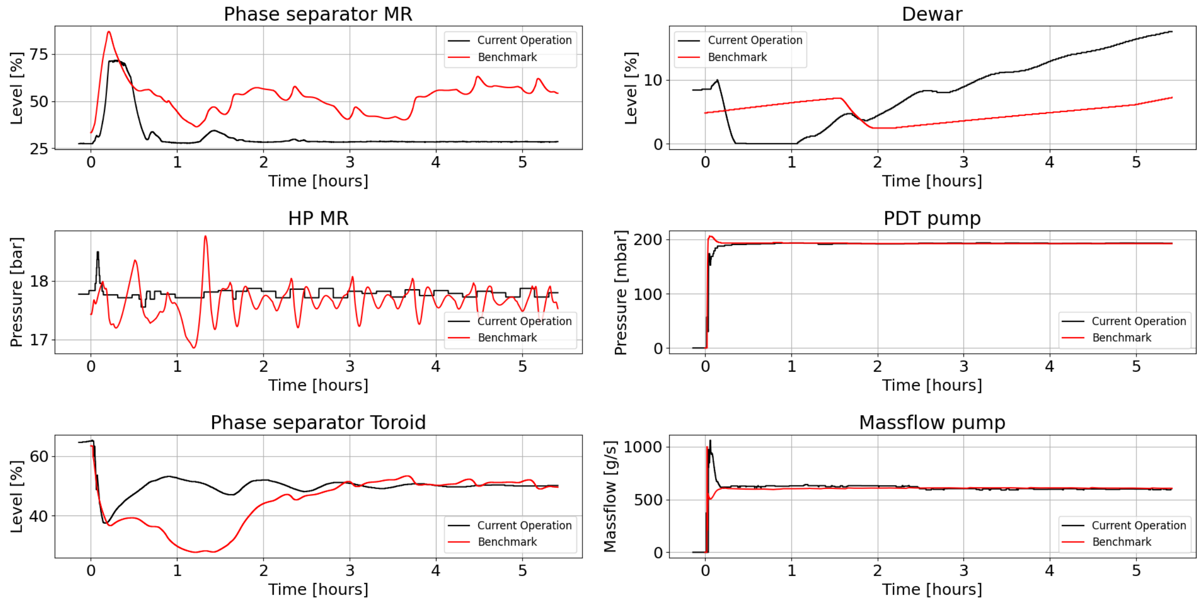

Figure 7: ATLAS Dynamic benchmark, cryogenic pump startup

level bigger than the reference but once the valve was opened we can see the recovery time matches. The oscillation of the HP line is partially explained by the filtering of the signal (filtered in SCADA, unfiltered in the model), the second source is the pressure in the LP line being slightly higher than expected, leading to less charge from the gas tanks.

7 Conclusion

Both ATLAS and CMS cryogenic system simulators were successfully developed and validated, demonstrating their reliability and robustness. The results obtained are conclusive, with steady-state validation showing an average relative error close to 1 % and transient simulations aligning well with real operational data. This confirms the simulator's reliability for operator training, control strategy validation, and process optimization. The simulator has already been implemented and tested during a training session at the end of 2024, setting up the stage for the training plan during 2025.

Moving forward, further improvements are planned to enhance the system's fidelity. The inclusion of hardware logic as well as the procedures for the operators will allow the creation of a complete path of training for the operator on both detectors, reducing the odds of an incident and improving the response of the team during unforeseen events.

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