

## Dynamic Simulation of a 1.8K Refrigeration Unit for the LHC

Bradu B., Gayet P., Niculescu S.I. \*

CERN, 1211 Geneva 23, Switzerland

\*Laboratoire des Signaux et Systèmes, UMR 8506 CNRS-Supélec, 91192 Gif-sur-Yvette, France

A new simulation toolkit has been successfully developed at the European Organization for Nuclear Research (CERN) and applied to existing cryogenic installations as, for example, the 1.3kW @ 4.5K cold-box of the Compact Muon Solenoid (CMS) experiment and the central CERN helium liquefier. The simulator is based on different interconnected simulation tools and provides simulations of cryogenic systems with their control and supervision. In this paper, we present an application to a complete 2.4kW @ 1.8K refrigeration unit for the LHC. It includes the cryogenic centrifugal compressors coupled to the warm compression station.

### INTRODUCTION

For the first time, the European Organization for Nuclear Research (CERN) is cooling the 27km of superconducting magnets at 1.9K with superfluid helium for the Large Hadron Collider (LHC). Along the LHC ring, there are 8 cryogenic plants (four built by Air-Liquide and four by Linde), each of them is able to cool down a sector of 3.3km using a 18kW@4.5K refrigerator coupled to a 2.4kW@1.8K refrigeration unit.

The use of high efficiency cryogenic centrifugal compressors (also called cold compressors) is necessary to build such a large scale cryogenic system below 2K [1]. These refrigeration units at 1.8K have been successfully commissioned in 2005 using a test facility [2], but the control of cold compressors is a difficult task due to their complex dynamic behaviours on large operating ranges and tests at real scale are impossible for the LHC.

The simulation environment and the thermodynamic and hydraulic models developed for 4.5K cryogenic systems have already proved their efficiency and their ability to provide pertinent dynamic simulations during transients, as for instance, the simulation of the CMS cryogenic system [3] or of the CERN central helium liquefier. We have derived models for 1.8K refrigeration units including models of the cryogenic centrifugal compressors and models for long cryogenic distribution lines.

### SIMULATION ENVIRONMENT AND MODELLING

#### Simulation architecture

A simulation environment called PROCOS for *Process and Control Simulator*, has been developed at CERN to perform dynamic simulations of large scale cryogenic systems [3]. This environment is based on the CERN cryogenic control standard called UNICOS (*Unified Industrial Control System*) [4] in order to reproduce in simulation the three layers of the real architecture as it is shown in the Figure 1. The supervision layer remains the same with operator consoles, Programmable Logic Controllers (PLCs) which perform the control are replaced by PLC simulators (software) provided by manufacturers and the cryogenic plant is replaced by a cryogenic process simulator integrating all physical equations of the system. The modelling is achieved on an industrial modelling and simulation software, EcosimPro 4.4, using differential and algebraic equations.

Helium properties are estimated by linear interpolations from large properties tables obtained with the specialized helium library HEPAK<sup>®</sup> offline and then integrated in the simulator to increase the simulation speed. Component models are divided in two main categories, those imposing a pressure and those imposing a massflow in the system. Components calculating a pressure have to be connected to components calculating a massflow and vice-versa in order to obtain a consistent global model of the system to have as many equations as unknown variables.

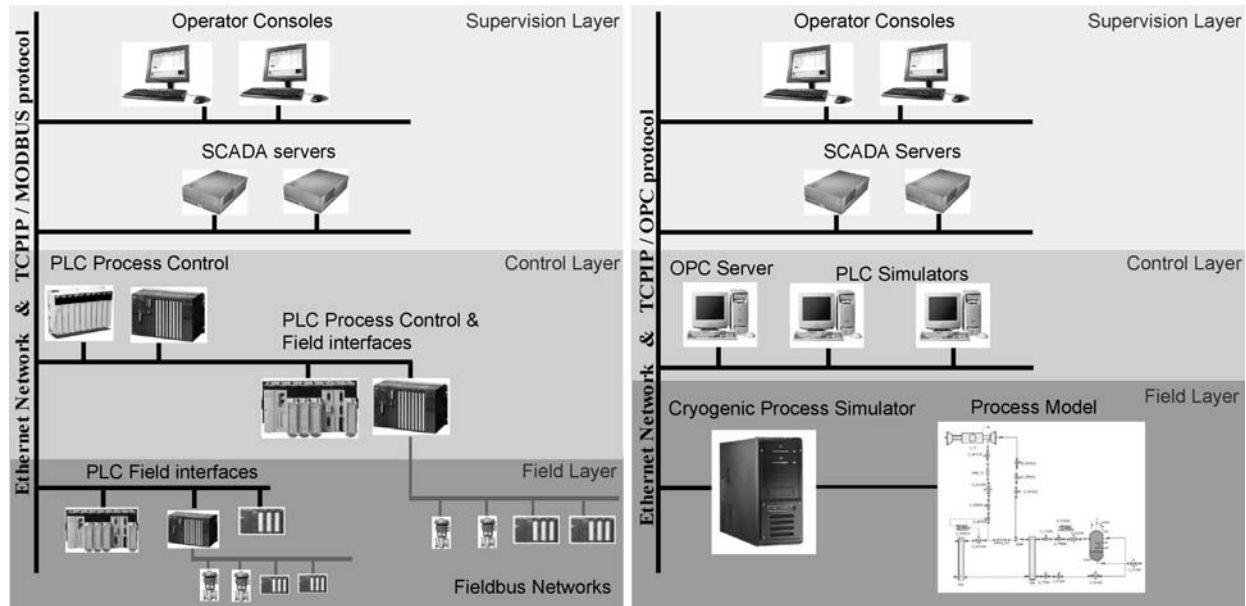


Figure 1 The real and the simulated control architecture for cryogenic processes

### Volume components

Cryogenic components containing a non-negligible volume like heat exchangers, pipes, phase separators or adsorbers perform mass and energy balances to compute their internal pressure and temperature, see equations (1) and (2). Here,  $M$  represents the mass of helium in the component,  $m_{in}$  and  $m_{out}$  the inlet and outlet massflows,  $E$  is the total energy of the working fluid,  $u$  is the internal energy and  $h$  is the enthalpy. Next,  $Q_k$  represents heat transfers to the working fluid; it is calculated according to the component. To compute convective heat transfers between the working fluid and its enclosure, we use equation (3) where  $M_w$ ,  $Cp_w$ ,  $T_w$  and  $S_w$  are respectively the mass, heat capacity, temperature and internal surface of the enclosure. The heat transfer coefficient  $h_c$  is dynamically computed with the Colburn formulation, generally used for turbulent flows with high Reynolds number. Radiative heat transfers are integrated in equation (4) where  $C$  is a coefficient related to the total emissivity of the component.

$$\frac{dM}{dt} = \dot{m}_{in} - \dot{m}_{out} \quad (1)$$

$$\frac{dE}{dt} = \frac{dM}{dt} \cdot u + M \cdot \frac{du}{dt} = \dot{m}_{in} \cdot h_{in} - \dot{m}_{out} \cdot h_{out} + \sum Q_k \quad (2)$$

$$Q_{conv} = M_w \cdot Cp_w \cdot \frac{dT_w}{dt} = hc \cdot S_w \cdot (T - T_w) \quad (3)$$

$$Q_{rad} = C \cdot (T_2^4 - T_1^4) \quad (4)$$

### Flow components

These cryogenic components impose a massflow according to a pressure drop at their boundaries like valves, turbines, warm compressors or cold compressors. Massflows in valves are computed according to a classical CV (valve coefficient) formulation and turbine models are using a St Venant's equation. Note that sonic flows are taken into account. Warm compressors are volumetric machine, so the massflow simply depends on the density of helium.

To simulate a 1.8K refrigeration unit of LHC, we had to include a model for cold compressors which are not volumetric machines. The model uses the internal pressure field of compressors to calculate the massflow. This characteristic, provided by manufacturers, is represented in Figure 2 for a typical cold compressor. It defines the compressor operating points according to three correlated variables: the pressure ratio  $pr$ , the reduced massflow  $m_r$  and the reduced speed  $N_r$ , respectively represented in equations (5), (6) and (7).

$$pr = \frac{P_{out}}{P_{in}} \quad (5)$$

$$\dot{m}_r = \frac{\dot{m}}{\dot{m}_d} \cdot \sqrt{\frac{T_{in}}{T_{in_d}}} \cdot \frac{P_{in_d}}{P_{in}} \quad (6)$$

$$N_r = \frac{N}{N_d} \cdot \sqrt{\frac{T_{in_d}}{T_{in}}} \quad (7)$$

Reduced values depend on the design values (represented by subscripts ‘d’) of each compressor. The model computes the massflow as a function of the pressure ratio, the speed and the input temperature. The output temperature after compression is calculated with the isentropic efficiency of compressors given by manufacturers according to the operating point on the pressure field.

Pressure fields are given for relatively high rotational speeds (from a reduced speed of 50% to 120%) but there is no information about compressor behaviour at low rotational speeds. Hence, we have extrapolated some operating points for low speeds from available experimental results to simulate the start of compressors, up to a reduced speed of 50%.

Cold compressors have to operate in a safe region between the choke line and the surge line and this constraint reduces the operational range (the nominal point is only at 20% from the surge line). This constraint represents one of the reasons for which the control is so difficult. The optimal operating area is around the nominal point to have the best isentropic efficiency.

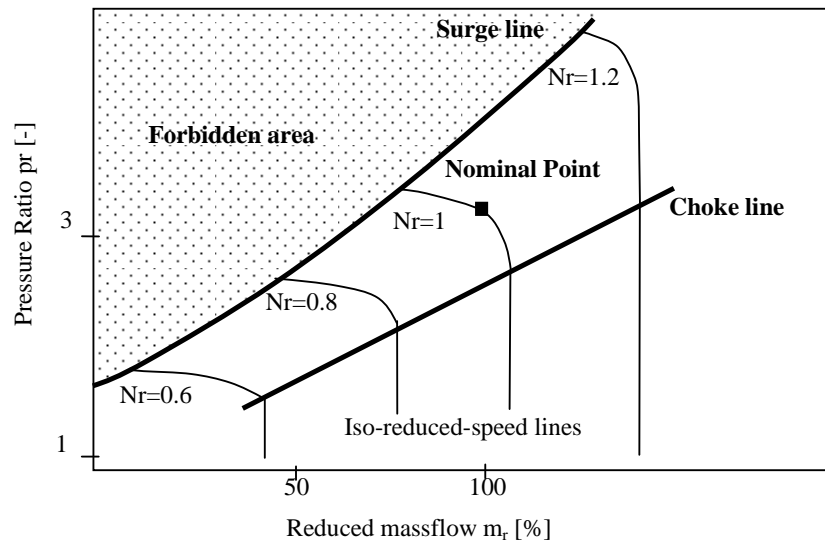


Figure 2 Typical pressure field of a cold-compressor

## 1.8K REFRIGERATION UNIT

A 1.8K refrigeration unit for the LHC allows pumping gaseous helium over 3.3km sector from atmospheric pressure until 14.5 mbar in order to decrease the temperature of the LHC magnet helium baths from 4.5K down to 1.8K following the saturation line of helium. These units pump gaseous helium through the line B of the Cryogenic Distribution Line (QRL) which is connected to the LHC magnets.

The Air-Liquide system uses three cold compressors in series and two oil lubricated screw compressors in parallel to compress warm helium until 3.2 bar. Two heat exchangers are used to transfer heat from the high pressure side to the low pressure side and finally one turbine expands helium at 1.3bar before sending it to the 4.5K refrigerator, see Figure 3. The Linde system works on the same principles but it uses four cold compressors, the warm compressors are in series and there is one additional turbine.

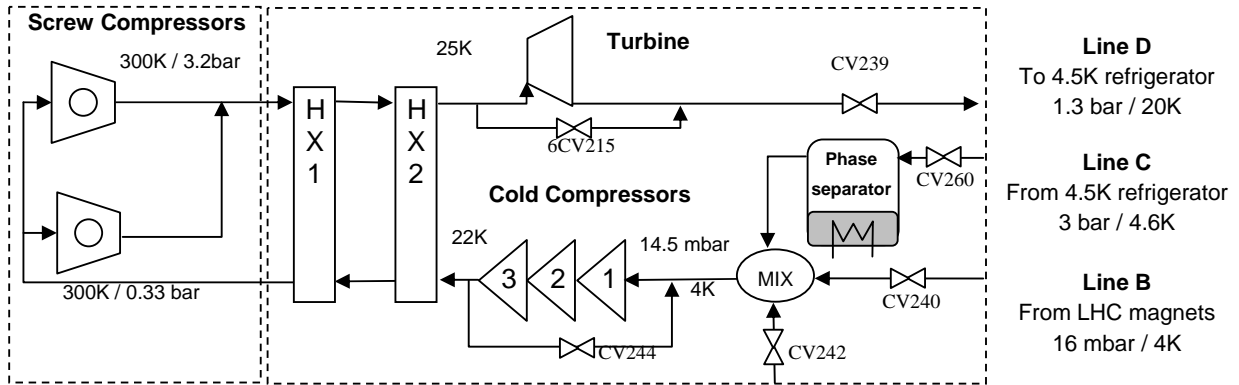


Figure 3 A 1.8K refrigeration unit for the LHC coupled to a warm compression station (Air-Liquide)

## SIMULATION RESULTS

### Simulation in Capacity Check mode

First simulations of the 1.8K refrigeration unit connected to the warm compression station have been performed in *capacity check* mode. This operation mode allows to test the refrigeration unit without being connected to the line B of the QRL. In this case, cold compressors are pumping the bath in the internal phase separator of the unit which is supplied in liquid helium by the 4.5K refrigerator, see Figure 3.

Differences have been observed between theoretical pressure fields and real measurements. Sensor errors on the real plant were rejected and we conclude that the differences came from bad iso-speed lines of pressure fields. Hence, iso-speed lines were adjusted in pressure fields in order to fit the real data obtained during the different test campaigns made at CERN and at CEA. After these modifications, we obtained simulations close to observations and the general dynamic behaviour of the refrigeration unit was correct and realistic, see, for instance, Figure 4 where results are presented during a pumping between 160mbar and 14.5mbar in *capacity check* mode. Simulations are compared to a real run performed in November 2006 at the point 6 of the LHC.

For this simulation, boundary conditions of the model are the pressure and temperature in the line C (3bar / 4.6K), the pressure in the line D (1.3bar) and the heater power in the phase separator.

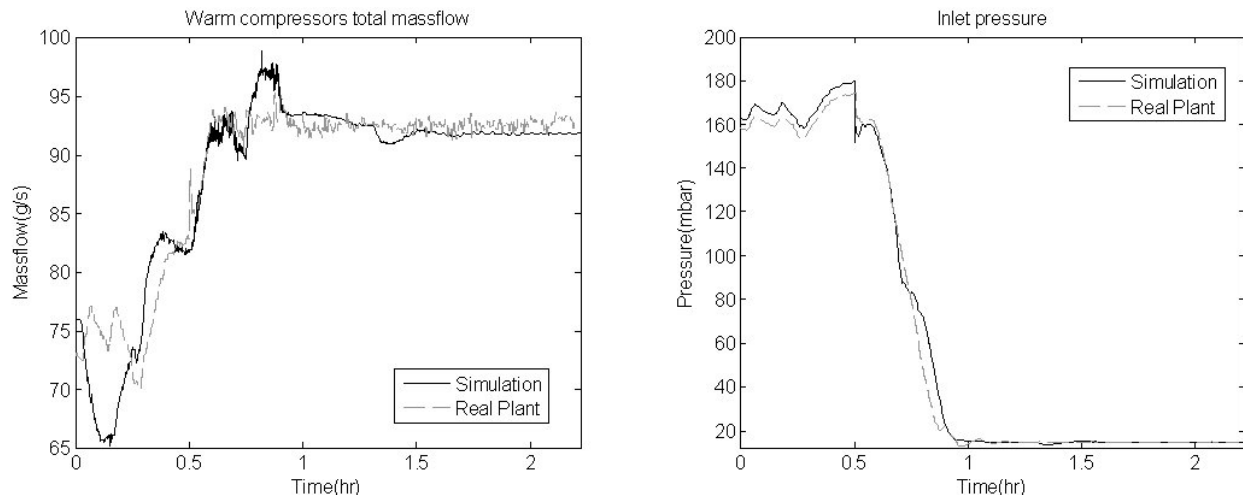


Figure 4 Massflow and inlet pressure in simulation compared to real data in capacity check mode

### Simulation in Pumping mode

After the validation of the cold compressors models in *capacity check*, the cryogenic distribution line (QRL) has been included in the model to simulate the final cooldown of the LHC magnets from 4.5K down to 1.8K.

The line B model of the QRL/sector is discretized with a finite difference method over the 3.3km to take into account the spatial dynamic along the line. The line is then divided in 31 cells of 107 meters each, corresponding to the different 1.9K cryogenic loops allowing to cooldown the LHC superconducting magnets. These cryogenic loops are fed from line C, and return to line B through subcooled heat exchangers. The complete simulation model with the boundary conditions is represented in Figure 5.

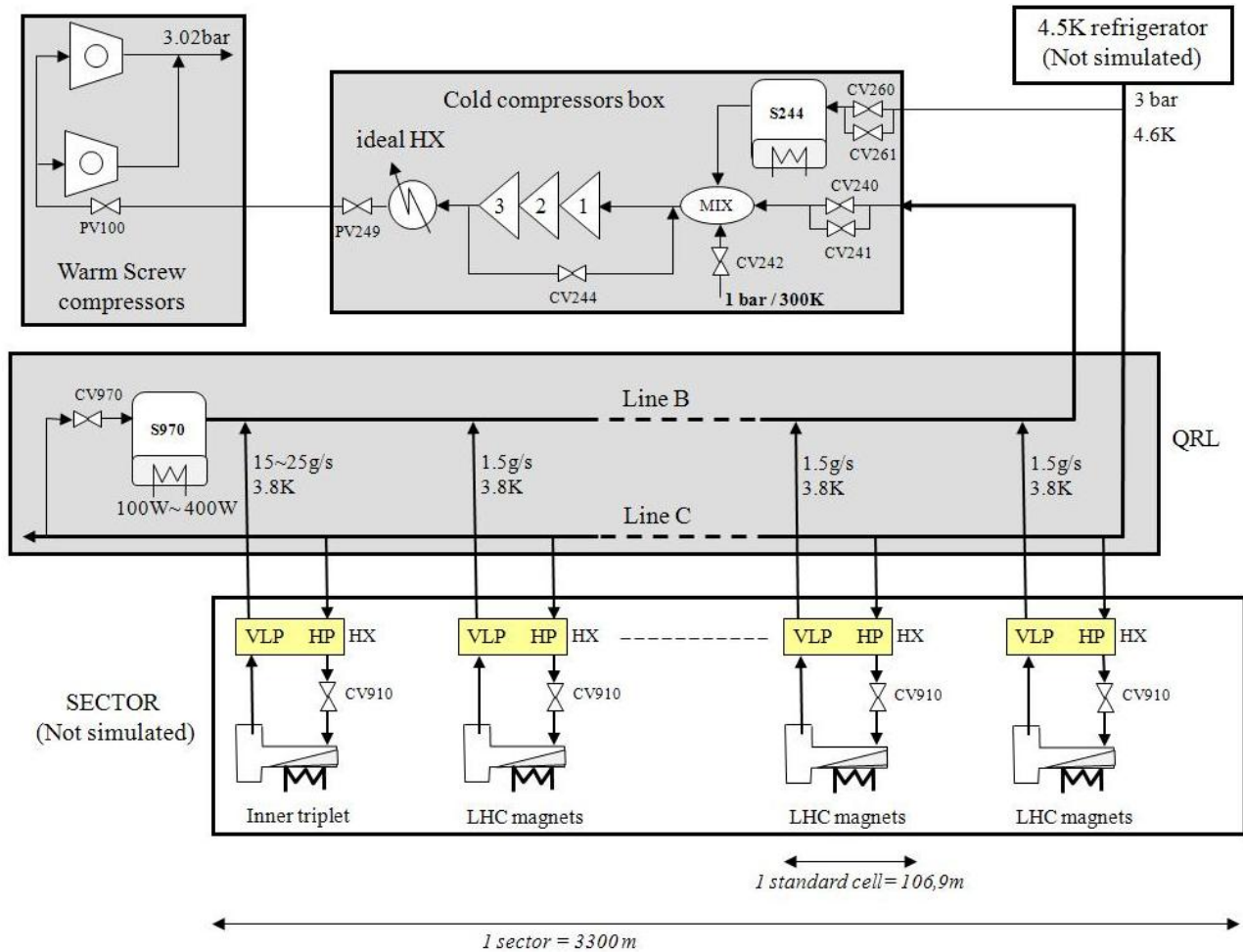


Figure 5 Simulation model in pumping mode with boundary conditions

The cold compressor box model is simplified for this simulation in order to alleviate numerical calculations. Only the low pressure side is modelled, considering that the high pressure remains constant due to the good efficiency of the regulations observed on the real plant. The output pressure of warm compressors and the helium return flows coming from LHC standard cells (6 dipoles and 2 quadrupoles) and from the inner triplet (3 special magnets) are considered as boundary conditions in the model.

The simulation results have been compared with the final cooldown of the sector 5-6 of the LHC in April 2008, see Figure 6. They agree with the real data, the transients are well simulated and the simulation speed (25 times faster than the real time) is more than satisfactory. The control of cold compressors is well reproduced in simulation but the output temperatures of cold compressors are lower in simulation than on the real plant due to isentropic efficiencies which are over estimated.

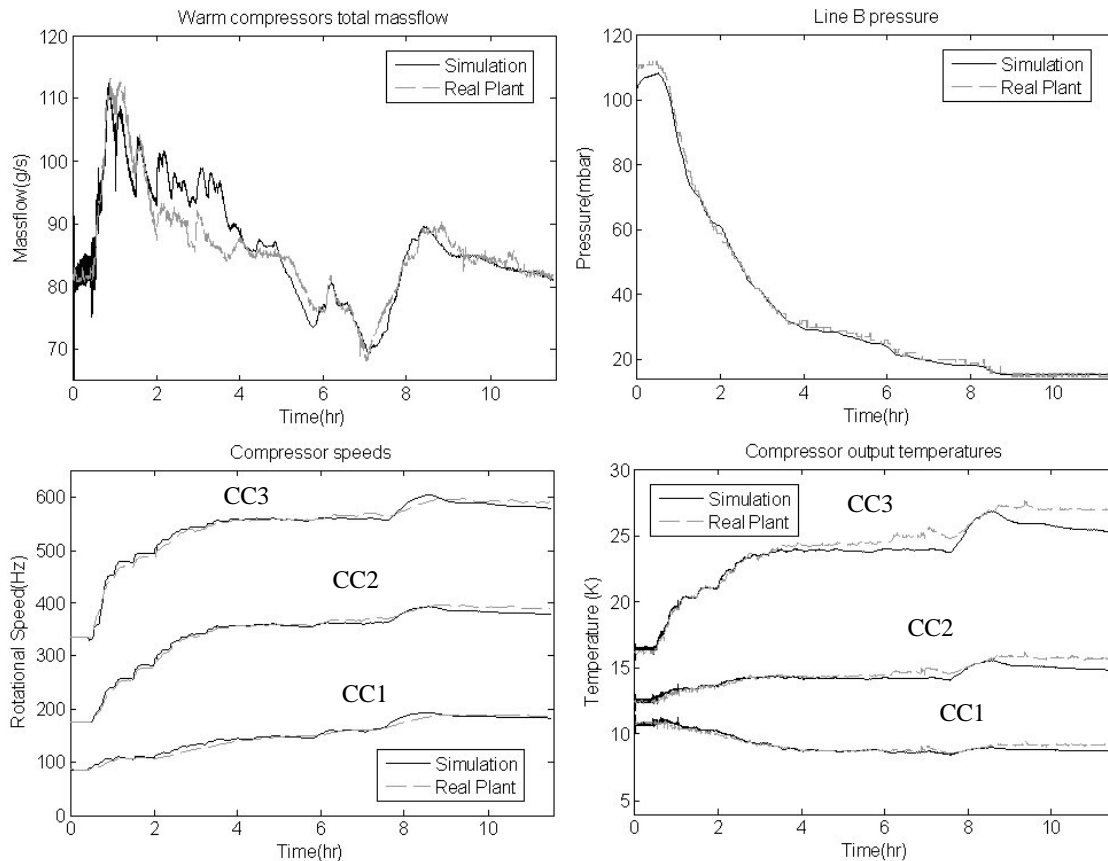


Figure 6 Main simulated variables during the pumping through the line B compared to real data

## CONCLUSION AND PERSPECTIVES

The good agreement between the real data and the simulations performed in the present study allows us to qualify the different component models for large scale cryogenic systems below 2K.

Hence, as the control of cold compressors is a delicate task and the LHC operation does not suffer perturbation, the proposed simulator is the best solution available to validate improved control strategies. Moreover it helps improving our knowledge on the process, in particular on the valid operating ranges.

In the future, a model of LHC magnets including the 1.9K cryogenic loops will be connected and thus we will be able to extend the optimization work on the complete LHC process.

## AKNOWLEDGMENTS

Authors wish to thank people who have shown a particular interest in the development of these simulations applied to the LHC cryogenic systems from CERN AT/CRG, especially Francois Millet for his support.

## REFERENCES

1. Claudet, S., Recent progress in power refrigeration below 2 K for superconducting accelerators, Particle Accelerator Conference, Knoxville, Tennessee, USA (2005)
2. Millet, F., Claudet, S., Ferlin, G., Performance assessment of 35 cold hydrodynamic compressors for the 1.8K refrigeration unit, Cryogenic Engineering Conference, Keystone, Colorado, USA (2005)
3. Bradu, B., Gayet, P., Niculescu, S.I., Modeling, simulation and control of large scale cryogenic systems, International Federation of Automatic Control World Congress, Seoul, Korea (2008)
4. Gayet, P., Barilliere, R., UNICOS : a framework to built industry-like control systems, principles and methodology, Int. Conf. on Accelerator and Large Expt. Physics Control Systems, Geneva, Switzerland (2005)