FIRST PRINCIPLES MODELING OF THE LARGE HYDRON COLLIDER'S (LHC) SUPER FLUID HELIUM CRYOGENIC CIRCUIT

Rafal Noga[(a)], Cesar de Prada[(b)]

[(a)] Cryogenics Group at AT Department, CERN; Room 36-2-002; 23 Geneva 1211; Switzerland
[(b)] Department of Systems Engineering and Automation; Universidad de Valladolid; Facultad de Ciencias; c/ Real de Burgos s/n. 47011Valladolid; Spain

[(a)] rafalnoga@)hotmail.com, [(b)] prada@autom.uva.es

ABSTRACT
The Large Hydron Collider (LHC) at CERN is the largest particle accelerator in the world. It uses more than 1600 superconducting magnets that will be maintained at operational temperature equal to 1.9K by Super fluid Helium Cryogenic Circuit. This document presents a first principle nonlinear model of the circuit to be used in the development process of a Nonlinear Model Predictive Control (NMPC) of LHC Standard Cell temperature. First, general information on the context of the project and the motivation for the development of the model are presented. Then, the Super fluid Helium Cryogenic Circuit is described with details and the modeling process of the circuit is presented step by step. Finally, the model is adjusted with the experimental data, the results of the model simulation are evaluated and the future work is proposed.

Keywords: LHC, Standard Cell, super fluid helium, cryogenics, first principle modelling

1. INTRODUCTION

The basic functions of beam guiding and focusing in the Large Hydron Collider (LHC) at CERN are performed by more than 1600 superconducting magnets in order to produce strong magnetic fields..

The NbTi windings of the magnets must be maintained at operational temperature equal to 1.9K in order to minimize energy losses maintaining the cables under superconducting conditions. This is done by the Super fluid Helium Cryogenic Circuit

The experiments, performed on the String and String2 LHC Prototypes from 1995 to 2003, showed that the regulation of the LHC magnets temperature is a challenge, mainly due to presence of strong nonlinearities together with frequent changes of the operation point, inverse response on the control input manipulation and variable dead time of the response.

PID controllers used to control the temperature have poor performance. A MPC controller was developed, tested and showed a great potential to improve the temperature control of the first 53 meter long "Half Cell" String Prototype. Unfortunately the MPC controller could not be commissioned on the 107 meter long "Full Cell" String2 Prototype because of the mismatch between the distributed parameter process dynamics and its lumped parameter model used in the controller.

This document presents development of a new, “first principle" nonlinear model of the Super fluid Helium Cryogenic Circuit of a LHC Standard Cell to be used in the process of development of a Nonlinear Model Predictive Control (NMPC) of the superconducting magnets temperature.

In the next section, the Super fluid Helium Cryogenic Circuit is described and some aspects of the modeling are presented. Then, the model is adjusted with the experimental data from the String2 experiment. Finally, the results of the model simulation are evaluated and the future work is proposed.

2. SUPERFLUID HELIUM CRYOGENIC CIRCUIT OF A STANDARD CELL

The task of the Super fluid Helium Cryogenic Circuit of a LHC Standard Cell is to stabilize the windings temperature of eight magnets comprised in the Standard Cell. This is done by placing the magnets into a static bath of pressurized super fluid helium that has very high thermal conductivity and penetration abilities. The heat is removed from the bath by a 107m long bayonet heat exchanger (BHX) running along the bath, with saturated helium flowing inside and evaporating thus providing cooling, see figure 1.

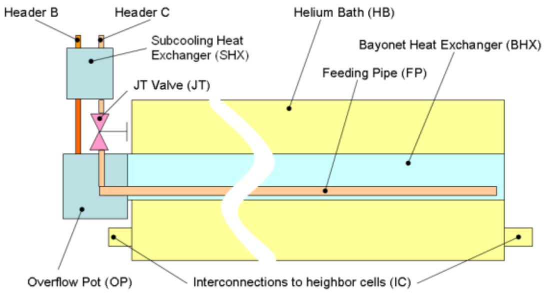

Figure 1: Simplified scheme of the Standard Cell Cryogenic Circuit

The liquid helium to be used in the BHX is taken from the header C at 4.6 K and 3 bar, cooled down to

2.2K in a sub-cooling heat exchanger (SHX), in counter-flow with 1.8 K, 16mbar helium vapor leaving the BHX. Then the pressurized He II at 2.2K, 3bar is expanded to about 16mbar via the assembly of a Joule-Thompson (J-T) valve and a small diameter feeding pipe (FP) placed inside the BHX, that deposits both the saturated helium and the vapor created during the expansion at the opposite (to the JT valve) end of the BHX. Then the saturated He II flow inside the BHX in opposite direction, towards the JT valve evaporating and absorbing heat from the HB.

The flow of evaporating helium, thus the amount of heat that it can absorb, is regulated via the JT valve position. The BHX is sized to work as partially wetted - helium flowing in the exchanger evaporates completely before reaching the opposite end of the BHX.

The vapour at about 1.8 K created in the BHX together with the vapour created during the expansion in the JT-FP assembly is pumped out to the Header B in order to keep the very low vapour pressure (16 mbar) in the BHX, that determines the saturation temperature of super liquid helium flowing through the BHX, thus the minimal achievable temperature of the helium bath.

The description is illustrated with a simplified scheme, see Figure 2.

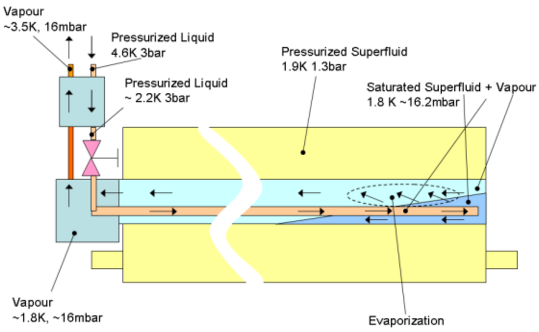

Figure 2: Simplified helium flow in the Standard Cell Cryogenic Circuit

The temperature of the HB in the String2 Phase 3 Prototype was measured at 8 points along the Standard Cell corresponding to each magnet position.

Experiments performed during the String Experimental Programme showed that the circuit dynamics includes: asymmetric inverse response of the bath temperature on a JT valve manipulation (where temperature excursion varies in function of its direction), variable dead-time depending mostly on the heat load situation, and non-uniform magnet temperature across the string of magnets due to a constrained longitudinal heat transfer (Chorowski 1998).

3. MODELING THE SUPERFLUID HELIUM CRYOGENIC CIRCUIT

The purpose of the model is to enable prediction of future temperature values of the Standard Cell Helium Bath that is defined by heat flows in the magnets, their geometry and material properties. After few significant simplifications of the magnet representation, like considering a uniformly distributed corrected mass of helium, its entropy can be calculated as:

$$\frac{\partial(\rho H(x,t))}{\partial t} = \frac{\partial q_l(x,t)}{\partial x} + \frac{\partial q_t(x,t)}{A} \tag{1}$$

where q represent longitudinal and transversal heat flow throw the HB.

Using a finite volume approach for spatial discretization of the one-dimensional model of the magnets the change of enthalpy of a discrete segment of the bath is proportional to the sum of all heat fluxes interchanged with the sector:

$$\frac{d(H_i(t)m_i)}{dt} = \sum Q_i(t); i \in <1...20> \tag{2}$$

Relation between the enthalpy and temperature has been tabularized.

The heat transfers, illustrated in the Figure 3, are:

- static heat loads into the HB that originate at ambient temperature
- dynamic heat loads into the HB originating at magnet components
- heat exchanged between the HB and BHX that cools the HB
- heat flowing from the FP into the HB, responsible for the asymmetric inverse dynamic response of the cooling loop
- longitudinal heat flow through the HB due to its non uniform temperature at the interface of two HB sectors
- heat exchanged through interconnections at the extremities of the HB;

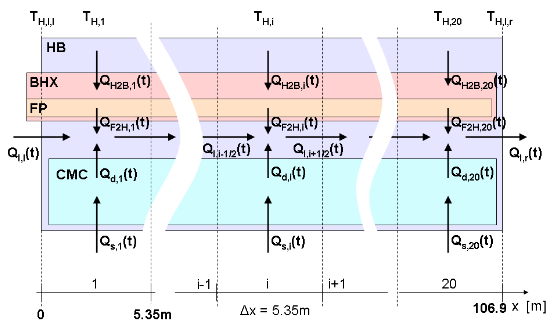

Figure 2: Heat flow in the Standard Cell Cryogenic Circuit

3.1. Counter-flow heat exchange in super fluid helium

Longitudinal Heat Transfer in the bath of HeII is very effective due to the enormous heat conductivity of super fluid helium at moderate heat flux. The mechanism of heat transfer in super fluid has been described (Bottura and Rosso 1999). In the one-dimensional case like for the HB, using the pseudo conduction term, called Super fluid Thermal Conductivity Function F(T;p), the heat flux q in the super fluid can be related to the temperature gradient

$$q^n = -F(T,p)\frac{\partial T}{\partial x} \qquad (3)$$

Between the heat flux and the temperature gradient exist a stiff bidirectional relation as temperature of the HB sector if a function of heat flows. This causes instabilities in the numerical integration of the simulation as the gradient goes to 0. For this reason a modified expression for the longitude heat flow between discrete sectors is used in the model:

$$Q_{l,i} = \begin{matrix} -A(F(T)\frac{dT_i}{dx})^{0.33}; \frac{dT_i}{dx} > 1e-7 \\ -Aconst.\frac{dT_i}{dx}(F(T))^{0.33}; \frac{dT_i}{dx} < 1e-7 \end{matrix} \qquad (4)$$

3.2. Heat transfer to the Bayonet Heat Exchanger. Kapitza conductance

The heat is evacuated from the HB to the Bayonet Heat Exchanger by conduction across the wall of the 107m long Bayonet Heat Exchanger (BHX) tube running all along the Standard Cell that is limited by the transversal thermal conductance C_{th} between HB and BHX:

$$Q = (T_1 - T_2)C_{th} \qquad (5)$$

that is dominated by Kapitza conductance of liquid-solid interfaces justifying neglecting of the bulk thermal resistance of BHX wall

$$C_{th} = C_K A T^3 \qquad (6)$$

where the Kapitza coefficient C_K has been measured for the BHX.

Finally the heat transfer between the HB and the BHX for the i-th sector of the Standard Cell depends on the surface A corresponding to wetted area of the BHX.

The investigation of the II-phase helium flow in the BHX showed that the saturated HeII would mostly operate in the stratified flow regime (Lebrun 1997) thus the wetted area of a BHX sector can by directly calculated from the level h (corresponding to mass) of helium present in the BHX sector:

$$A = \Delta x 2r \arccos(\frac{r-h}{r}) \qquad (7)$$

4. MODEL ADJUSTING AND SIMULATION

Model contains nine coefficients representing unknown model parameters determining its dynamics. Values of seven coefficients have been estimated by minimalization of a quadratic error function, calculated based on differences between simulated values of magnet temperatures and the corresponding experimental data from the String2 Phase3 experiment. Two other parameters have been hand fitted, because no specified, accurate error functions have been defined as far.

4.1. Restoring the experiment configuration

During the experiment the extremities of the Standard Cell instead to other cells were connected to an electrical feed-box DFBX and to a magnet return box MRB, both introducing additional heat flows throw the interconnections that have to be modeled.

The static heat load present during the String2 experiment has to be estimated in order to set the operational point of the simulation. It is done in a very simple way using an observer containing the model of the cryogenic circuit. In the observer configuration, the control input of the model is the static heat load, to be estimated, and the outputs are the magnet temperatures. The regulation error of the temperature is feed into the PI controller that calculates the estimated value of the static heat load.

4.2. Experimental data accuracy

The data coming from three String2 experiments has been used to validate the model. The performed experiments consisted on the JT valve manipulation (experiment “Nominal”), introducing additional heat to the magnets (experiment “Heatload”), and both actions performed sequentially (experiment “Mixed”).

The accuracy of the special thermometers measuring the magnet temperatures below 2K is +/-10mK, which is comparable to small variation of magnets temperatures. To improve the accuracy of the simulation the offset of the temperature measurement is estimated by observation of the temperatures in case when the BHX is full of saturated helium and all the temperatures should be equal.

4.3. Sequential estimation of model parameters

The model parameters have been optimized sequentially one after another using NAG single variable optimization routine e04abc (based on quadratic interpolation), (Nag 2008). The optimal coefficient value in each iteration has been found with relative tolerance

$$Tol(\bar{x}) = 1\% \qquad (8)$$

The sequential optimization allowed precise optimization with quadratic error functions specified separately for each parameter, taking into account the temperature error only at points where the parameters influence is most visible. For example, the total mass of helium in the magnets has been estimated regarding only the increase rates of magnets temperatures in response on additional heat load introduced during the experiment.

The order of optimization of the parameters is very important, because some parameters influence significantly the temperature response of the model in all operating states, and other only at some specified points. The parameters with wider influence on the model behavior, that stronger influence the optimal values of other parameters, are optimized first. For example, the total mass of helium in the magnets that has been mentioned above has been estimated at the beginning, because it determines the general dynamics of the model.

That is the reason, why the experiment with an extra heat load is used first during the optimization – the absence of valve manipulation during the experiment makes possible optimization of many model parameters, at the same time excluding errors related to inappropriate modeling of super fluid helium dynamics, will be optimized later in the sequence.

The model parameters have been estimated in following order (see the Figures 4 and 5, where the described below zones of interest of model temperature response are pointed),

1. effective cross-section of the magnet determining the values of longitude counter-flow heat flux, regarding static temperature distribution
2. effective friction factor of the very low pressure channel of the sub-cooling heat exchanger, influencing the pressure in the BHX, thus the temperature of the saturated helium in the heat exchanger
3. effective mass of super fluid helium in the magnet, described in an example above
4. rangeability value of the JT valve, determining the estimated value of the static heat load, has been estimated regarding the total energy rest in the magnets after the experiment, thus the the differences between magnet temperatures at the beginning and at the end of experiment
5. effective viscosity parameter of the super fluid helium in the Bayonet Heat Exchanger has been found based on observation that in the experiment with additional heat load, the dynamics of magnet temperature response at the end of the magnet string opposite to the JT Valve, where the super fluid helium is deposited, depends on the static distribution of saturated helium in the bayonet heat exchanger tube, thus on its effective viscosity
6. effective heat conductivity between Inner Pipe and the Helium Bath, determining the heat flow between them, and
7. effective friction of the two-phase helium flow in the Inner Pipe, determining the pressure distribution along the pipe, have been found regarding the inverse response of the magnet temperature during JT Valve manipulation.

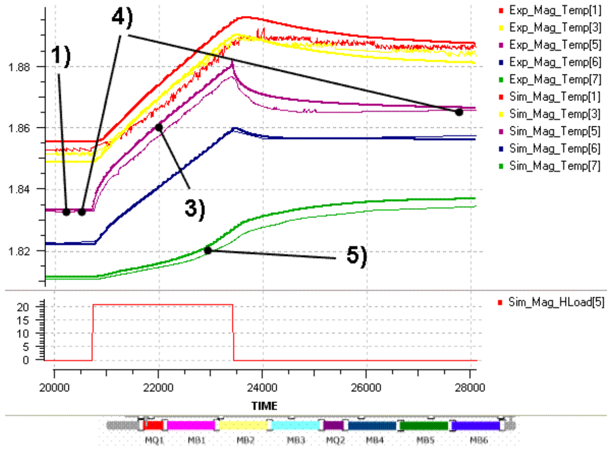

Figure 4: Model simulation: experiment « Heat Load»

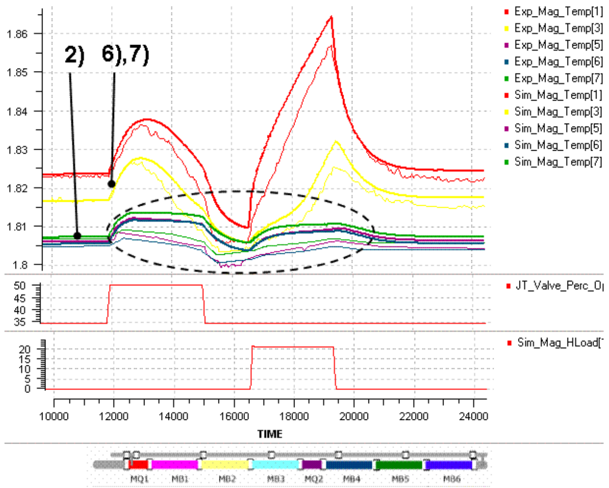

Figure 5: Model simulation: experiment « Mixed»

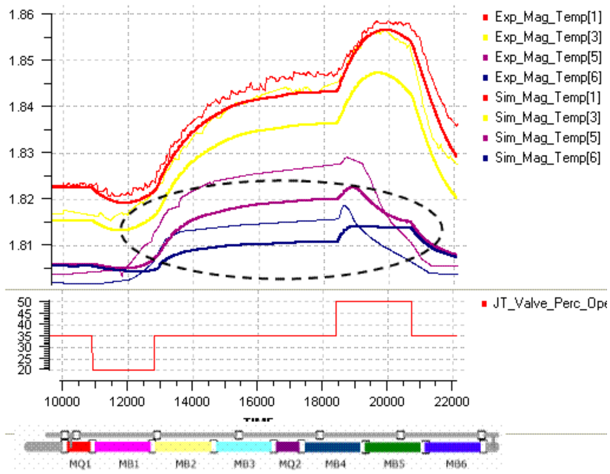

Figure 6: Model simulation: experiment « Nominal»

5. RESULTS AND FUTURE WORK

Model has been validated with three sets of experimental data corresponding to the three experiments performed on the String2 Prototype. This data is reliable for model validation because it represents distinct operational scenarios, moreover the data from experiments “Mixed” and “Nominal” has not been used to model adjusting.

The results of simulation (bold lines) and the experimental data (thin lines) for the three experiments are presented in the Figures 4, 5 and 6.

The simulation results are very close to the experimental data, but some problems remain unsolved.

Probably the wrong modeling of the pressure profile inside the pipe feeding helium inside the BHX causes inappropriate changes in vapor mass flow inside the BHX that could be the reason for temperature simulation errors in magnets opposite to the JT Valve, see areas encircled by dashed lines in Figures 5 and 6.

The way of calculation of helium temperature after sub cooling in the SHX has not been already found, thus experimental values are used during the simulation and model cannot be used to predict magnet temperatures.

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AUTHORS BIOGRAPHY

Rafal Noga; Ph.D. student at the University of Valladolid, Spain. Actually works on the project “Non-linear Model based Predictive Control (NMPC) of the Large Hydron Collider’s (LHC) Super fluid Helium Cryogenic Circuit” at CERN, Switzerland.

Cesar de Prada; Professor of Systems Engineering and Automatic Control with the University of Valladolid, Spain. Current topics of interest include modelling and simulation, predictive control and process optimization.