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SPIRAL2 CRYOGENIC SYSTEM THERMODYNAMIC BEHAVIOUR PREDICTION THROUGH DYNAMIC MODELING

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Abstract

SPIRAL 2 (Caen, France) is a state of the art superconducting linear accelerator composed of 26 quarter wave accelerating cavities. Each cavity is plunged in a liquid helium bath at 4.4 K itself surrounded by a thermal shield at 70 K. In this paper, a dynamic model of the cryogenic system of the LINAC is proposed. This model simulates the dynamic behaviour of the 19 cryomodules and their respective valves box connected through the cryodistribution. Model accuracy is evaluated through a comparison between simulation and experimental data. Using the model we should be able to predict the behaviour of the cryogenic system for different beam operating conditions of the accelerator. The model also highlights the link between the cryogenic system and the cavity RF losses through a dynamic estimator of those RF losses in the cavity walls. The latter could be used as a rough estimator of the quality factor of a cavity.

INTRODUCTION

SPIRAL2 accelerator aims at delivering high intensity beams for research in the nuclear fields [1]. It is built around a LINAC (LINear ACcelerator) composed of 26 quarter wave accelerating cavities. Because they are made of bulk niobium, each cavity is plunged in a liquid helium bath. The whole formed by the cavity and its helium bath is called a cryomodule. Liquid helium production and routing is ensured by a complex cryogenic system [2]. To provide the best operating condition for the LINAC it is necessary to understand the behaviour of this cryogenic system. To do so we model the overall SPIRAL2 cryogenic system. Model accuracy is evaluated through experimental comparison. A dynamic estimator of the radio frequency (RF) losses is also proposed as a direct use of the model.

MATERIALS AND METHOD

The oveall cryogenic system of SPIRAL2 is modeled using the Simcryogenics [3] library on MATLAB/SIMSCAPE environment. The model is designed to be control oriented and to allow fast simulation. It means that only the macroscopic physical behaviour (e.g., pressure variation) are considered and not the microscopic ones (e.g., flow distribution in piping). Only two sub-systems of the cryogenic system are considered in this paper: the cryomodules and the cryodistribution. An RF losses estimator is also presented as a direct use of the model.

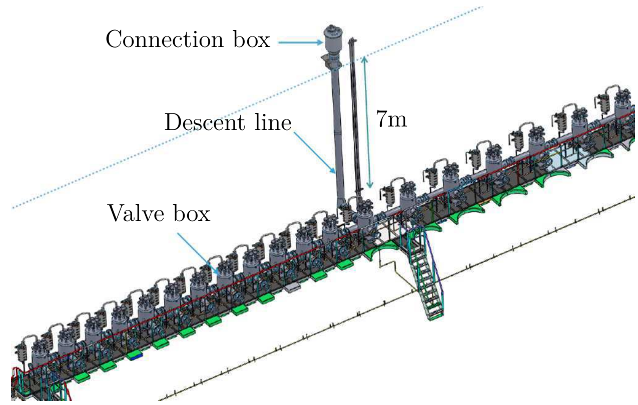

Figure 1: View of the SPIRAL2 cryodistribution without the cryomodules.

The Cryodistribution

The cryodistribution represents the link between the cryoplant and the cryomodules (see Fig. 1). It is composed of four lines: two for the cryomodule bath (supply and return) and two others for the cryomodule shield (also supply and return). The cryodistribution can be seen as multiple pipes connected together as shown in Fig. 2

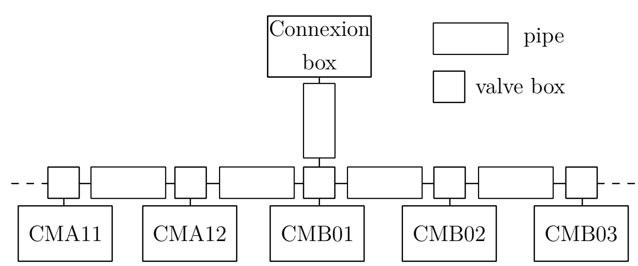

Figure 2: Decomposition of the cryodistribution in multiple pipes - *CMAi represents type A cryomodule whereas CMBi represents type B cryomodule*

To model the flow of helium in those pipes, three physical phenomena are considered:

- Friction: when a fluid is flowing in a pipe, it generates friction between the fluid and the pipe. This friction results in a pressure drop calculated through the Darcy-Weisbach equation: $\Delta P = f_D \frac{L}{D_h} \rho \frac{V^2}{2}$ with ΔP the pressure drop due to pipe friction, f_D the friction factor calculated with the Haaland approximation, L

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the length of the pipe, D_h the hydraulic diameter, ρ the fluid density and V the fluid velocity.

- Heat load: the fluid in the pipes is at low temperature (between 80 K to 4.5 K depending on the line) whereas the external environment is at room temperature. So the fluid undergoes a thermal heat load which is modeled through an enthalpy balance equation: $h_{out} \cdot \dot{m}_{out} = h_{in} \cdot \dot{m}_{in} + Q$, where h_{out} and h_{in} respectively represents pipe outlet and inlet specific enthapy, $\dot{m}_{out}$ and $\dot{m}_{in}$ respectively represents pipe outlet and inlet mass flow and Q is the external heat load.

- Gravity: as shown in Fig.1, the LINAC is 7 m underground. Consequently, there is a pressure difference between the bottom and the top of the descent line. This phenomena called hydrostatic pressure is defined by $\Delta P = \rho \cdot g \cdot h$, where ΔP is the pressure difference, ρ is the fluid density, $g = 9.81$ is the gravitational acceleration and h the height.

Once the model of the cryodistribution is established, we use it to define the boundary conditions of the cryomodule model.

The Cryomodule

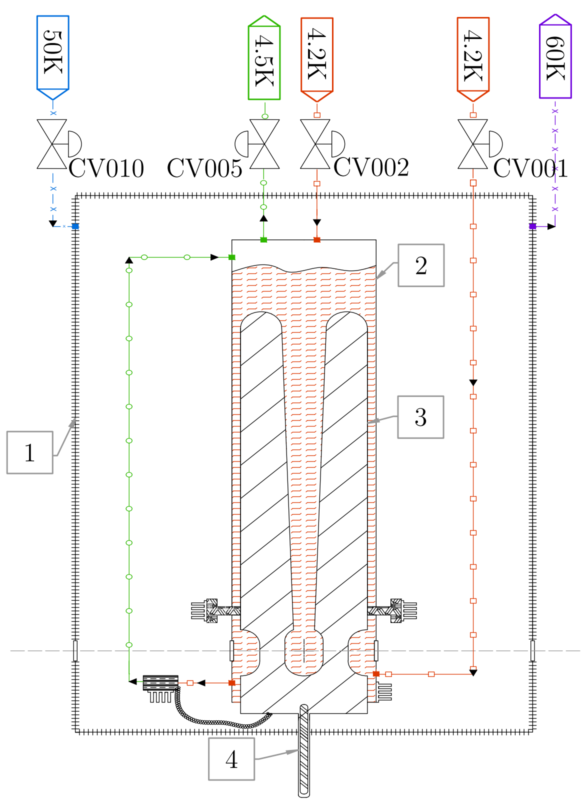

Figure 3: PI& D of type-A cryomodule and its associated valves - *1. The thermal shield, 2. The liquid helium bath, 3. The accelerating cavity, 4. The RF antenna.*

In the case of SPIRAL2 facility, there are two types of cryomodule: a type-A (see Fig. refCryomoduleCMA) and a type-B which respectively contains one and two accelerating cavities. The helium bath is controled through three valves. The valve CV_{001} is used to fill the cryomodule by the bottom during the cooldown whereas CV_{002} and CV_{005} ensure respectively level and pressure regulation in the bath. CV_{010} ensures shiled outlet temperature regulation around 70 K. For more information about the cryomodules please refer to [4] [5].

In terms of thermodynamic behaviour, cryomodule type-A and type-B are similar. The distinctions are the volume of the bath and the heat load extracted by the helium bath as shown in Table 1. The heat load can be decomposed in two parts: the static heat load which represents the influence of the outside environment on the bath and the dynamic heat load due to RF losses in the cavity walls which generate heat according to Joule effect.

Table 1: Comparison of Type-A and Type-B Cryomodule - *The static load is given in measured mean/standard deviation, the dynamic load is the maximum expected.*

Characteristics	Type-A	Type-B
Static load [W]	3.5/1.4	12.5/1.8
Dynamic load [W]	10	20
Helium bath volume [L]	20.5	91.2

The thermodynamic behaviour of a cryomodule is similar to the one of a phase separator: gravity ensures phase separation between liquid and gaseous helium whereas external heat load causes liquid evaporation. From this consideration, we use the equations of previous phase separator model [6] to describe the cryomodule thermodynamic behaviour. An alternative model is also proposed in [7]. Adaptation of this model is necessary to take into account the shape of the helium bath. Using a 3D scheme of the cryomodule, we create a function which takes the volume of liquid in the bath as an argument and outputs the corresponding height of liquid.

The cryomodule model can be used in many ways such as synthesizing controllers for the cryomodule valves, run experiences on simulation or even dynamically estimate the heat load induce by RF losses in the cavity wall as proposed in the next section.

RF Losses Estimator

The measurement of the RF losses (e.g., dynamic heat load) in cavity wall is an indicator of the cavity state. Nevertheless, in the case of SPIRAL2, it is impossible to have a dynamic measurement of those losses while the accelerator is in nominal operating mode. To solve this problem, we design a Luenberger state observer to dynamically estimate this load. This observer (see Fig. 4) is based on a linear version of the proposed cryomodule model and requires the measurement of the valves opening, bath pressure and liq-

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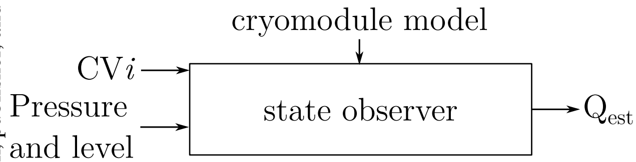

Figure 4: description of the observer - *CVi represents the valves opening whereas Q_{est} is the estimation of the dynamic heat load.*

uide helium level to work in real time. A similar work is proposed in [8] in the case of a refrigerator phase separator.

EXPERIMENTAL RESULTS AND DISCUSSION

Cryomodule Dynamic Model Validation

Cryomodule model accuracy is estimated through a comparison between experimental and simulated data. Do to so, valves CV_{002} and CV_{005} are manually controlled to induce pressure and level variations in the helium bath. Then the same valves variations are applied on the model and both simulated and measured data (i.e., level and pressure) are plotted in the same graphic in Fig. 5.

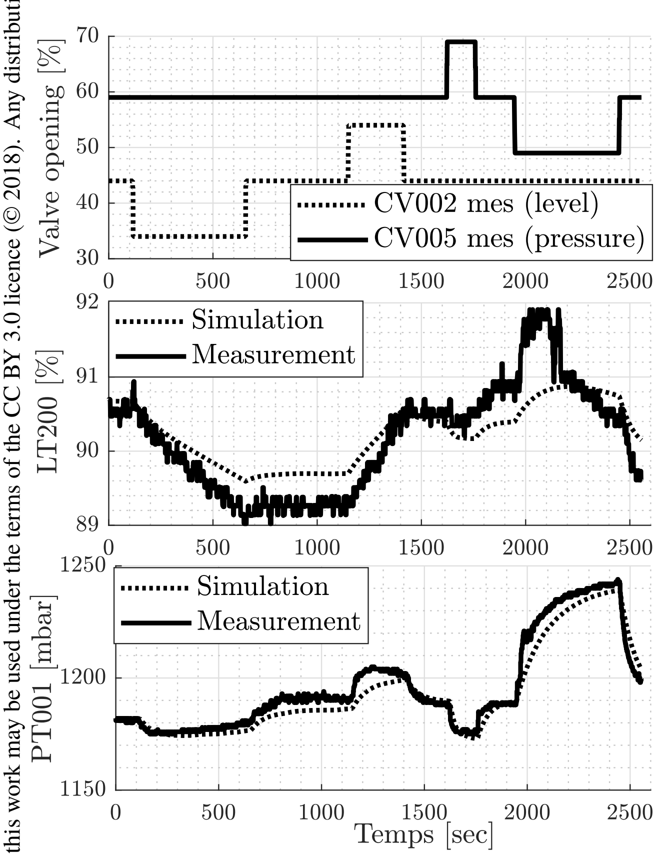

Figure 5: Comparison between experimental and simulated data for type-A cryomodule n°10.

As one can see the model globally reproduces the dynamics of the level and the pressure. The rising pike at time $t = 2000$ s on the level is most certainly due to a sensor deviation as it decreases at time $t = 2200$ s while no valves are moving. Even if it could be improved, we consider that the model is accurate enough to be used for different purposes like the design of an RF losses estimator as described in the next section.

RF Losses Estimator

The goal of the estimator (also called observer in this article) is to estimate the heat load induced by RF losses. As RF system is not fully operational, we mimic the effect of the RF losses with an electrical heater placed at the bottom of the helium bath. To estimate the accuracy of our observer, we generate a heat load step with the electrical heater while the cryomodule is in nominal operating mode. The comparison between estimated and injected heat load is plotted in Fig. 6. At time $t = 25$ s, the electrical heater is risen to its maximum at 43 W.

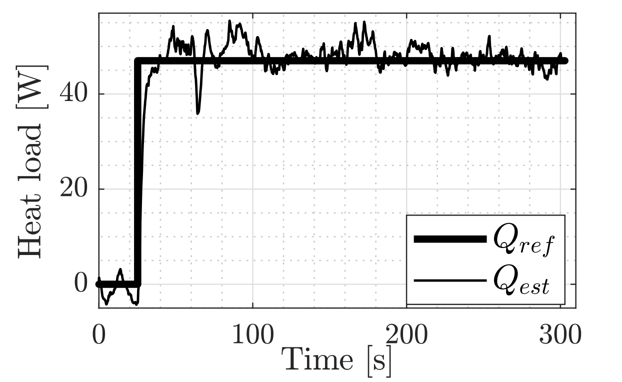

Figure 6: Comparison between injected (ref) and calculated (obs) power.

Despite the oscillations of the estimated heat load around the real value, the observer gives a correct approximation of the heat load injected through the electrical heater. It takes 10 s for the observer to react to the heat load step. The next goals are to reduce this time as much as possible as well as reducing the observer oscillations.

Knowing the RF losses in the cavity, and using equations of the BCS (Bradeen, Cooper, Schriffer) [9] theory, it is possible to have a dynamical estimation of the quality factor of the cavity.

CONCLUSION

SPIRAL2 is a superconducting linear accelerator composed of 19 cryomodules. A model of the cryomodules has been validated through a comparison between simulation and experimental data. As a direct use of the model, an estimator of the RF losses in the cavity walls has also been realized and validated experimentally. Currently, other developments involving the proposed models are in progress,

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especially the design of control algorithm for the cryomodule valves which will be tested during the next cooldown in the late August 2018.

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