Dynamic modeling and control of the SPIRAL2 cryomodules

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Dynamic modeling and control of the SPIRAL2 cryomodules

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Abstract. SPIRAL 2 (Caen, France) facility aims at delivering high intensity of rare isotope beams. The linear accelerator (LINAC) of the SPIRAL 2 facility is composed of 26 superconducting accelerating cavities distributed into 19 cryomodules cooled down with liquid helium at 4.4 K. A dynamic model of the cryomodules and their associated shields and valves thermodynamic behavior is proposed. This dynamic model is validated through comparisons between simulation and experimental data. Since the model is developed with the Simcryogenics library for MATLAB/Simulink environment, It is convenient for control loops design. Using the model, advanced control algorithms have been developed in order to achieve the cryomodule's pressure stability required for beam acceleration. This paper presents the dynamic model, experimental versus simulation results as well as the control outcome.

1. Introduction

SPIRAL2 [1] is a state of the art superconducting linear accelerator composed of 26 quarter wave accelerating cavities [2]. One of the main goals of SPIRAL2 is to accelerate light and heavy ions (e.g. $^{58}Ni^{18+}$, $^{40}Ar^{14+}$, $^{4}He^{2+}$). As accelerating heavy particles requires a lot of energy, it's more efficient (in terms of energy consumed by the whole accelerator) to use superconducting accelerating cavities than to use non superconducting ones. In the case of SPIRAL2 those cavities are made of bulk niobium which have a critical temperature of 9.2 K. They have a precise geometry designed to optimize their accelerating coefficient, consequently they have not be deformed. To maintain the superconducting state, the cavities are immersed in a liquid helium bath at 4.4 K and 1.2 bar. Nevertheless, the pressure inside of the helium bath could vary because of perturbations. Those pressure variations result in mechanical deformations of the cavity which decrease their performances. In this article we propose an original solution to maintain pressure oscillations below $\pm 5\ mbar$: first we model the cryogenic system, then using the model we develop algorithms to control the valves acting on the helium bath.

2. The cryomodules

The accelerating cavity and its associated cryogenic system is called a cryomodule. In the case of SPIRAL2 there are two different types of cryomodule: namely a type A and a type B, as shown in Figure 1.

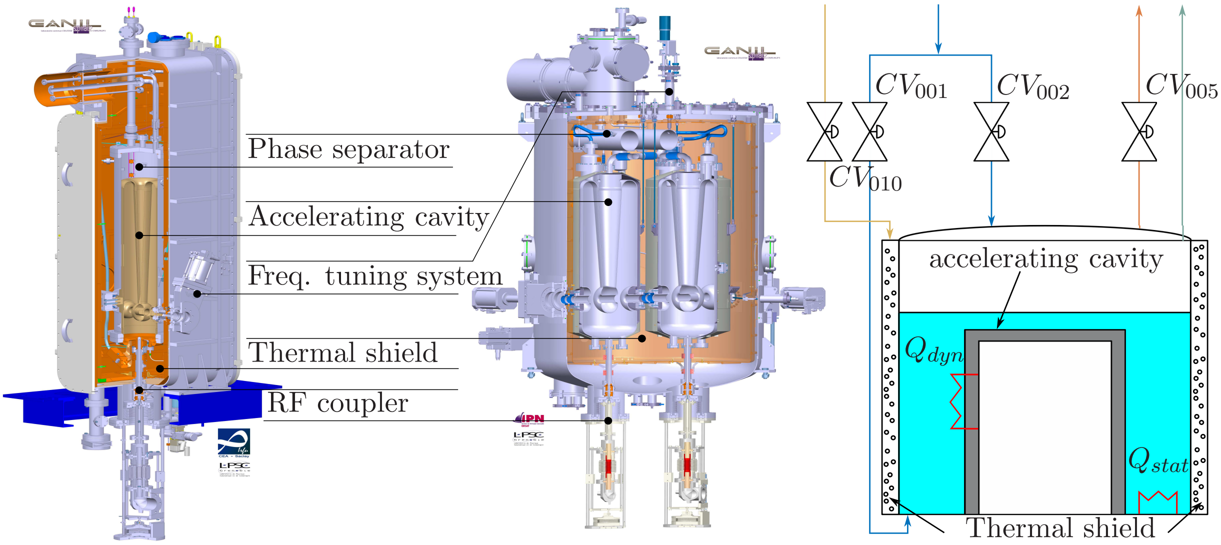

Figure 1. Cut view and schematic view of type A and type B cryomodules - *on the left a type A and a type B cryomodule with respectively one and two accelerating cavites on the right a schematic view of the cryomodule and its associated valves. Q_{stat} and Q_{dyn} refer to static and dynamic heat load*

In terms of thermodynamics the main differences between type A and type B cryomodules are the volume of liquid and the heat loads extracted in the helium bath (see Table 1. The heat loads can be decomposed in tow parts: the static and dynamic heat load. Static heat load is caused by the exchange between the helium bath at 4.4 K and its surrounding. Dynamic heat load is due to the RF losses in the accelerating cavities which generate heat according to Joule effect.
The cryogenic system of the cryomodule is controled by four vales (see figure 1). The latter are described in list 1. CV_{001} is only used during cooldown whereas CV_{002}, CV_{005} and CV_{010} are regulation valves used in nominal cryogenic operation mode.

List 1. The valves purposes

- CV_{010} regulates the shield outlet temperature around 60 K
- CV_{001} fills the cryomodule with liquid helium during the cooldown
- CV_{002} regulates the liquid level in the cryomodule around 90 %
- CV_{005} regulates the pressure in the cryomodule around 1.2 bar

Table 1. Comparison between type A and type B cryomodule - *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

3. Modeling

In this section we describe the physical equations used to model a cryomodule and its associated valve box. The same equations are used to describe the physical behavior of a type A cryomodule and a type B cryomodule. Only the heat loads applied to the bath and the volume are changed as detailed in Table 1. All models introduced in this section are realized with the Simcryogenics [3] library on MATLAB/Simscape environment.

3.1. The cryogenic valves

Two equations for mass flow calculation through a valve are given by the ANSI/ISA-75.01.01 [4] standard: one for compressible fluid and the other for incompressible fluid. In our case, as CV_{001} and CV_{002} are dealing with liquid helium or two phase flow (almost incompressible) whereas CV_{005} is dealing with helium gas (compressible) we define a unique valve model that is valid for both compressible and incompressible cases.

Hypothesis: the expansion through the valve is considered isenthalpic and there is no mass accumulation in the valve.

Using [4] we express the mass flow through the valve in the case of a compressible and incompressible fluid:

$$\dot{m}_{comp} = Kv \cdot CV \cdot (1 - \frac{X}{3 \cdot X_C})\sqrt{\rho_{in} \cdot P_{in} \cdot X} \tag{1a}$$

$$\dot{m}_{incomp} = Kv \cdot CV \cdot \sqrt{\rho_{in} \cdot (P_{in} - P_{out})} \tag{1b}$$

$$X = \min\left(\frac{P_{in} - P_{out}}{P_{in}}, X_C\right), \quad X_C = \frac{\gamma}{1.4} \cdot X_t, \quad X_t = \frac{P_{in} - P_{out}}{P_{out}} \tag{1c}$$

Where $Kv = 7.59 * 10^{-3}$ is a conversion coefficient from imperial to international system of units, P_{in} and P_{out} respectively the inlet and outlet pressures, ρ_{in} the fluid density at valve inlet, $\gamma = C_p/C_v$ the heat capacity ratio and CV is the flow coefficient. To create a unique valve model valid for both compressible (1a) and incompressible (1b), fluids we used the helium property called isothermal compressiblity. It quantifies the change of the volume of a system as the pressure changes while temperature remains constant. It's defined by $\beta_T = \frac{1}{\rho}\left(\frac{\delta\rho}{\delta p}\right)_T$. Isothermal compressibility value is used to determine which equation (i.e. compressible or incompressible equation) is most likely to be used. To do so, the helium isothermal compressibility is normalized between 1 and 0. 1 refers to compressible fluid and 0 to incompressible fluid. Finally, this factor is used in a weighted average to define the mass flow trough the valve:

$$\dot{m} = \overline{\beta_T} \cdot \dot{m}_{comp} + (1 - \overline{\beta_T}) \cdot \dot{m}_{incomp} \tag{2}$$

With $\overline{\beta_T}$ between 0 and 1. This last equation allows us to deal with compressible and incompressible fluid with a smooth transition between the two cases with a unique valve model.

3.2. The cryomodules

A cryomodule could be seen as a phase separator undergoing external heat loads. As phase separator behavior has already been described in [5], we just remind the main equations and focus on the cryomodule specificity.

Hypothesis: the helium bath is in thermodynamics equilibrium, consequently density and internal energy are homogeneously spread in the bath.

Applying mass and energy balance on the helium bath it is possible to define the time variation of density and internal specific energy:

$$\dot{\rho} = \frac{\dot{m}_{in} - \dot{m}_{out}}{V} \qquad \dot{u} = \frac{h_{in} \cdot \dot{m}_{in} - h_{out} \cdot \dot{m}_{out} + \sum_i Q_i}{\rho \cdot V} - u \cdot \frac{\dot{\rho}}{\rho} \tag{3}$$

With ρ the mixture density, V the volume, $\dot{m}_{in}$ and $\dot{m}_{out}$ respectively the inlet and outlet mass flows, u the mixture specific internal energy, h_{in} and h_{out} respectively the inlet and outlet specific

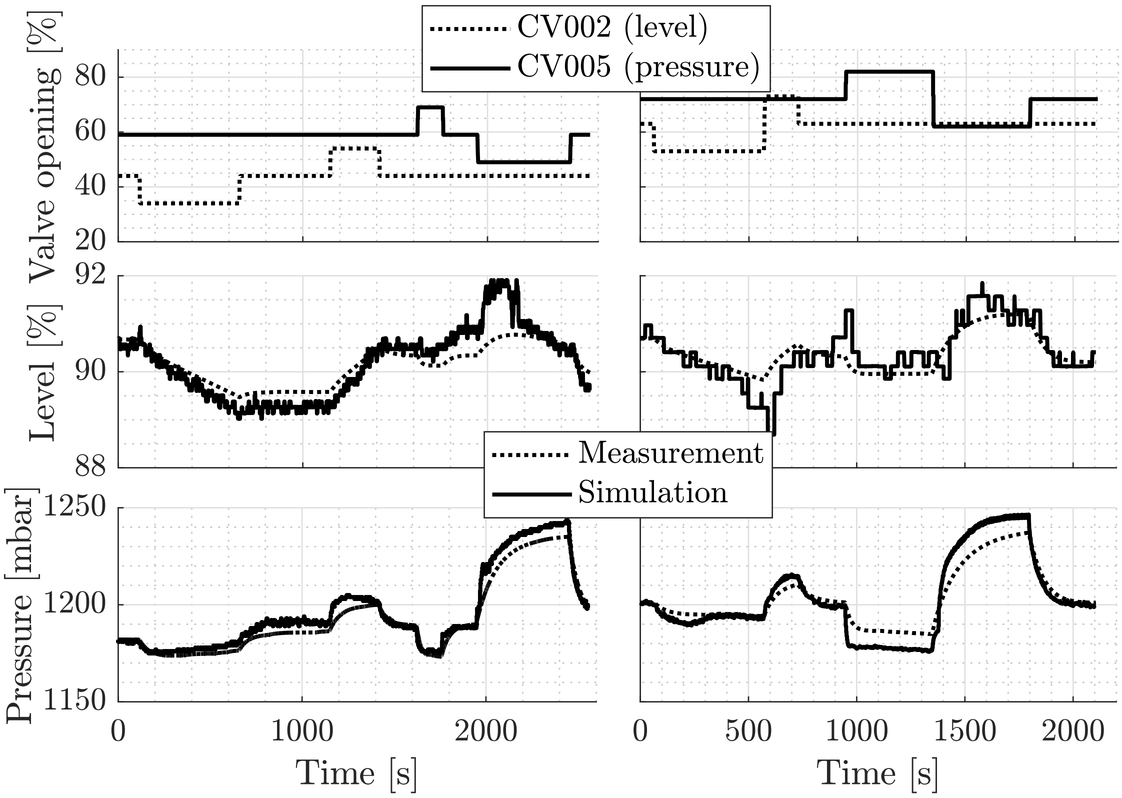

Figure 2. Comparison between experimental and simulated data for type A n°10 (on the left) and a type B n°2 (on the right) cryomodule - *On the top: the resulting variation applied on the valves; In the middle: the resulting variation of liquid level; On the bottom: the variation of pressure*

enthalpy and $\sum Q_i$ the total the heat load acting on the helium bath.
From there we express the pressure and the liquid level contained in the cryomodule. As u and ρ are independent parameters, pressure and vapor mass fraction are directly interpolate from helium property tables using HEPAK, then the liquid level is deduced from vapor mass fraction and bath geometry.

4. Experimental comparison

Evaluating the model accuracy consists in three parts: first we have to perform an experiment in order to have a measurement of the cryomodule behavior, then we have to simulate the same experiment on the model, finally we compare experimental and simulated data. The experiment consists in acting on the valves CV_{002} and CV_{005} and measuring the variations induced on the pressure and liquid level of the associated helium bath. The comparison between experiment and simulation is shown on figure 2.

The main point of interest for us is to ensure that the model reproduces the dynamics of the system. More precisely, the direction and amplitude of variation should be the same on simulated and measured curves. For the purpose of the model, getting the right variation is

more important than getting the right steady state.
Based on this comparison, we consider that the model is precise enough to be used in the synthesis of control algorithms for the cryomodule control valves as described in the next section.

5. Control of the cryomodule regulation valves

Currently the control of the helium supply and return valves is ensured by two PID (Proportional Integral Derivative) regulators which get trouble to reach the required pressure stability of ± 5 $mbar$ in the helium bath. To solve this problem we propose to replace the PID by a LQ regulator. This latter is synthesized using a linear model obtain through a linearization of the cryomodule model described in the previous section. The performances of this new regulator is evaluated on the non linear model of the cryomodule and compare to the one of the PID. Figure 3 shows a response of the LQ regulator to a heat load perturbation of 5 W at time $t = 5$ s, the same response obtained with a PID regulator tuned with MATLAB tools is also plotted for comparison. As one can see, the LQ shows better performances than the PID in terms of perturbation rejection time and pressure amplitude variation, fulfilling the ± 5 $mbar$ requirements for the cryomodule.

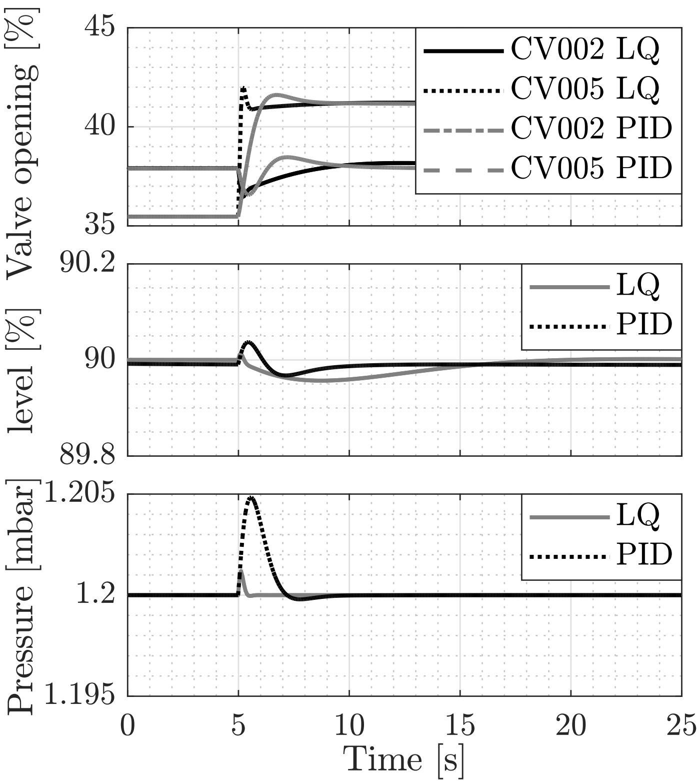

Figure 3. Comparison of LQ and PID response to a perturbation of 5W at time t=5s

6. Perspective and conclusion

The LINAC of the SPIRAL2 accelerator is composed of 26 accelerating cavities immersed in helium bathes. The pressure variation of those bathes has to be better than ± 5 $mbar$ in order to avoid mechanical deformation of the cavities. To do so we developed a model of the cryomodules that is used to synthesize a LQ regulator. As the model has been validated through experimental validation and the LQ regulator has been validated through simulation. During the next cooldown, which start in the late august 2018, LQ regulator will be directly tested on the cryomodule.

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