Dynamic modeling and control of the SPIRAL2 cryomodules

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I. Context

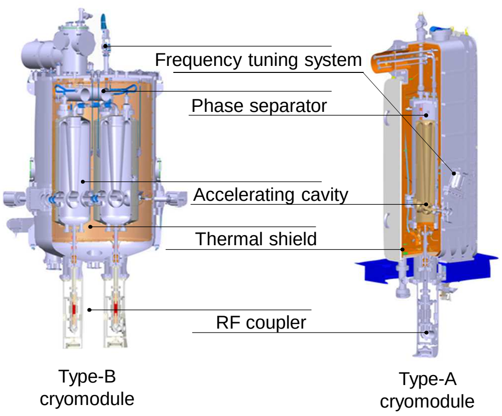
SPIRAL2 [1] is a state of the art superconducting linear accelerator composed of 26 quarter wave accelerating cavities [2]. In the case of SPIRAL2, those cavities are made of bulk niobium which is a superconductor below 9,2 K. The cavities have a precise geometry designed to optimize their accelerating coefficient. Consequently they have no to be deformed. For their superconducting state to be maintained, the cavities are submerged in a liquid helium bath at 4,4 K and 1,2 bar. The pressure inside the helium bath could vary because of perturbations. Pressure variations result in mechanical deformations of the cavities which decrease their performances. In this article we, present an original solution to maintain pressure oscillations below ± 5 mbar : first we model the cryogenic system, then using the model we develop algorithms to control the valves acting on the helium bath.

II. The cryomodules

The accelerating cavity and its associated cryogenic system is called "cryomodule". In the case of SPIRAL2 there are two different types of cryomodule: namely a type A and a type B (Fig. 1). The thermodynamic behavior of the cryomodule is modeled using the Simcryogenics [3] library (Fig. 2) on MATLAB/Simscape environment. The equations used in the model are similar to those of a phase separator [4]. The helium bath of the cryomodule is controlled through three valves (Fig. 2): CV001 is only used during cooldown whereas CV_{002} (bath supply) and CV_{005} (bath return) are respectively used to regulate level and pressure. CV_{010} (shiled supply) control the shiled outlet temperature and CV_{011} (shield return) is fully open in nominal operating mode. Model accuracy is evaluated through a comparison between measured and simulated data (Fig. 3). The measured data are obtained by manually acting on the valves CV_{002} and CV_{005}.

Figure1. Overview

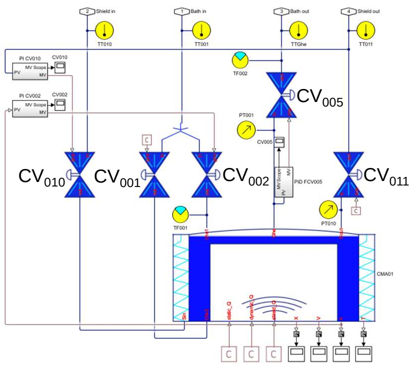
Cryomodule cut view



Properties	Type A	Type B
Static load (measured mean/standard dev.)	3,5 W/1,4W	12,5 W/1,8W
Dynamic load (theorical maximum)	10 W	20 W
Helium bath volume	20,5 L	91,2 L

Figure 2. The model

Simcryogenics view of the cryomodule



- Density variation over time

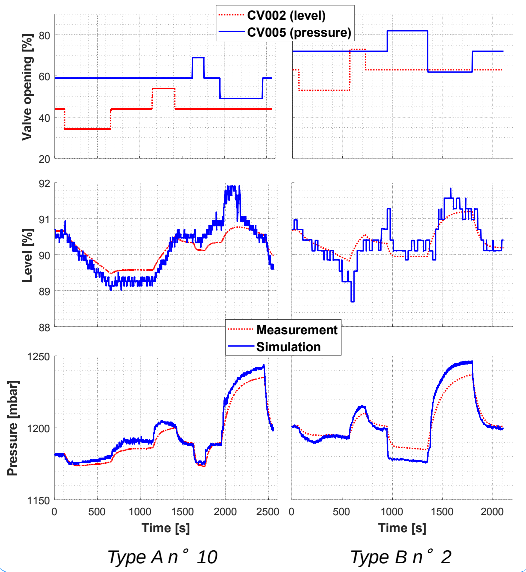
$$\frac{d\rho}{dt} = \frac{\left(\frac{dm_{in}}{dt} - \frac{dm_{out}}{dt}\right)}{Vol}$$

- Internal energy variation over time

$$\frac{du}{dt} = \frac{\frac{dm_{in}}{dt} * h_{in} + \frac{dm_{out}}{dt} * h_{out} + Q - \frac{d\rho}{dt} * u}{\rho * Vol}$$

Figure 3. Simulation vs measurement

Comparison between simulated and measured data with imposed valve opening

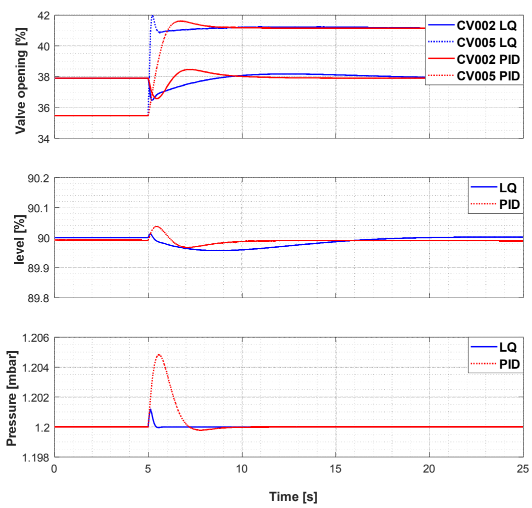


III. Pressure and level control

Currently, the control of the supply and return valves is ensured by two PID (Proportional Integral Derivative) regulators which struggle 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 (Linear Quadratic) regulator. The latter is synthesized with a linear model obtain through a linearization of the proposed cryomodule model. The performances of this new regulator are evaluated on the non linear model of the cryomodule and compared to those of the PID. Figure 4 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 variation, fulfilling the $\pm$ 5mbar pressure requirement

Figure 4. LQ vs PID regulator



IV. Conclusion

The SPIRAL2 linear accelerator is composed of 26 accelerating cavities plunged in helium baths. The pressure variations of those baths need to be reduced bellow ± 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. The model accuracy 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.

V. References

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