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CONTROL SYSTEM OF THE SPIRAL2 SUPERCONDUCTING LINAC CRYOGENIC SYSTEM

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Abstract

The SPIRAL2 cryogenic system has been designed to cool down and maintain stable operation conditions of the 26 LINAC superconducting resonating cavities at a temperature of 4.5 K or lower. The control system of the cryogenic system of the LINAC is based on an architecture of 20 PLCs. Through an independent network, it drives the instrumentation, the cryogenic equipment, the 26 brushless motors of the frequency tuning system, interfaces the Epics Control System, and communicates process information to the Low Level Radio Frequency, vacuum, and magnet systems. Its functions are to ensure the safety of the cryogenic system, to efficiently control the cooldown of the 19 cryomodules, to enslave the frequency tuning system for the RF operation, and to monitor and analyze the data from the process. A model based Linear Quadratic regulation controls simultaneously both phase separators the liquid helium level and pressure. This control system also makes it possible to perform a number of virtual verification tests via a simulator and a dedicated PLC used to develop advanced model based control, such as a real time heat load estimator based on a Luenberger Filter.

INTRODUCTION

Cryogenic System

Spiral2 accelerator delivers high intensity beams of various ions for research in nuclear fields. It is mainly composed of a LINAC (LINear Accelerator) composed of 26 accelerating cavities installed in 19 cryomodules, made of bulk niobium and immersed in a liquid helium bath.

The cryogenic system, as shown in Fig. 1, is split in two levels: at the ground level stands the cryoplant with its refrigerator and helium collecting system, and in the underground accelerator tunnel, the 19 valves boxes form the cryogenic lines and feed the cryomodules with liquid helium [1].

Type-A and Type-B Cryomodules

The type-A and type-B cryomodules respectively contains one and two accelerating cavities. The helium bath is controlled through three valves shown in Fig. 2. The valve CV001 is used to fill the cryomodule by the bottom during the cooldown whereas CV002 and CV005 ensure respectively level and pressure regulation in the bath, which are measured by the LT200 and PT001 sensors. CV010 serves the shield outlet temperature regulation around 60 K.

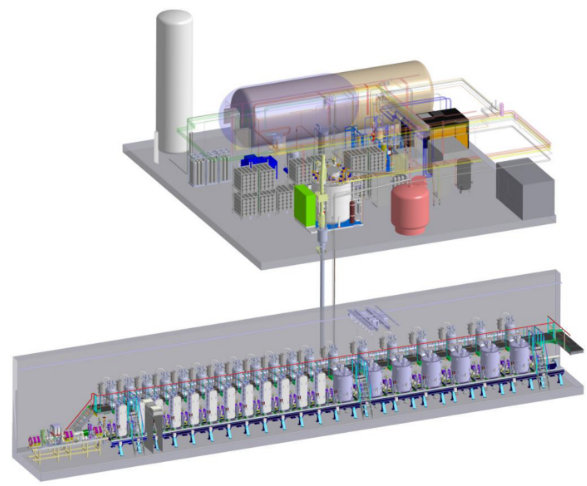

Figure 1: View of the Spiral2 cryogenic system.

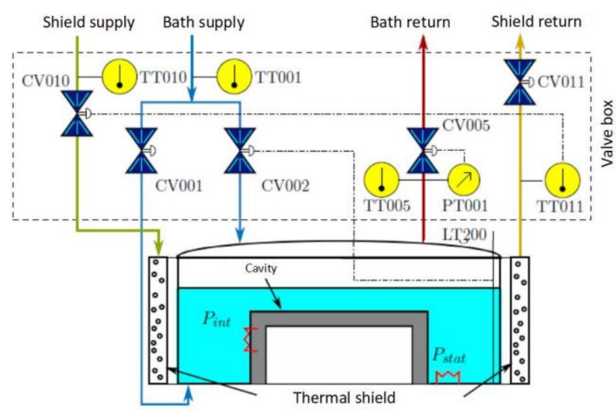

Figure 2: Type-A cryomodule and its associated valves and sensors.

ARCHITECTURE OF THE CONTROL SYSTEM

Liquid helium production and routing, as well as the automated safeties and the controls of the helium liquid bath, are ensured by a PLC-based control system. Data are issued from those PLCs to the Spiral2 Epics system for storage.

The core of the Linac cryogenics control system illustrated in Fig. 3 is made up of a fleet of 20 Siemens PLCs, one for each cryomodule and another one serving as a hub to ensure communication between the cryomodules and the outsides systems, three WinCC Pro supervisions, 1 workshop terminal, 26 brushless motors driving the Frequency Tuning Systems (FTS) of the RF cavities. In addition, there

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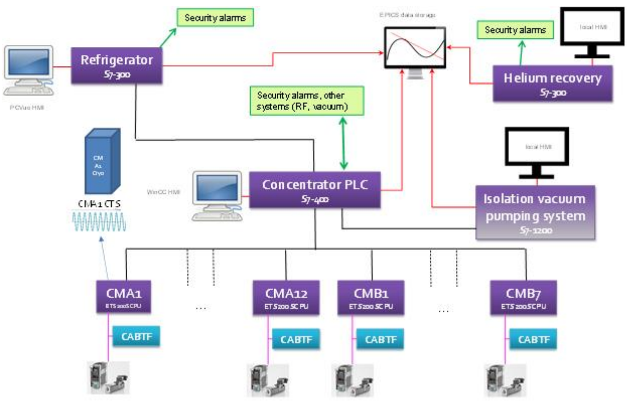

Figure 3: Control system architecture.

are nearly 70 instrumentation boxes for the control of temperatures, pressures and helium levels, vacuum pressures, heating supplies. Orders, sensors feedback and others data are exchanged via the private cryogenic network, which is completely autonomous with independent supervision. During power cuts, batteries make it possible to secure the cryogenic automated system (PLC, supervision and network) and to keep control at all times.

The cryoplant works with its own control system: Siemens PLC and PCVue user interface. Other dedicated Siemens PLCs and their local user interface are used for gas recovery management, for the isolation vacuum pumping system of the Linac, and for the vacuum system of the hot sections and RF cavities

MAIN FUNCTIONS

The functions of the concentrator PLC and19 cryomodules PLC are shown in Fig. 4. The PLCs provide controls independently for each cryomodule by opening or closing the valves and reading process measurements: pressure and level controls, cooldown and warmup regulation. Additionally, the FTS is managed by the same PLC. The orders are made manually by cryogenics operators from the HMI.

Sequential Function Chart

The cryogenics control of the cryomodules is mainly based on sequential steps shown in Fig. 5, each defining a working mode.

- X1: Hot mode, cryomodule is at ambient room temperature.
- X2: checking of the FTS state.
- X20 and X21: waiting cooldown order.
- X22 and X23: the shield and cavity are cooled separately at 60K and 4K. Input valves are opened to immerge the cavity.
- X4: normal mode, the cavity is immerged in the liquid helium bath at 4K. Only this mode allows the activation of the RF fields in the cavity.
- X5: Safety mode: Following a major fault of the cryomodule, helium input is closed and the output valves are completely opened.
- X6: Stand by, the cavity is regulated at a higher temperature to reduce the helium consumption.

Human Machine Interfaces

Three redundant WinCC Pro supervisions are running on virtual machine. Those HMIs are located in a cryogenics

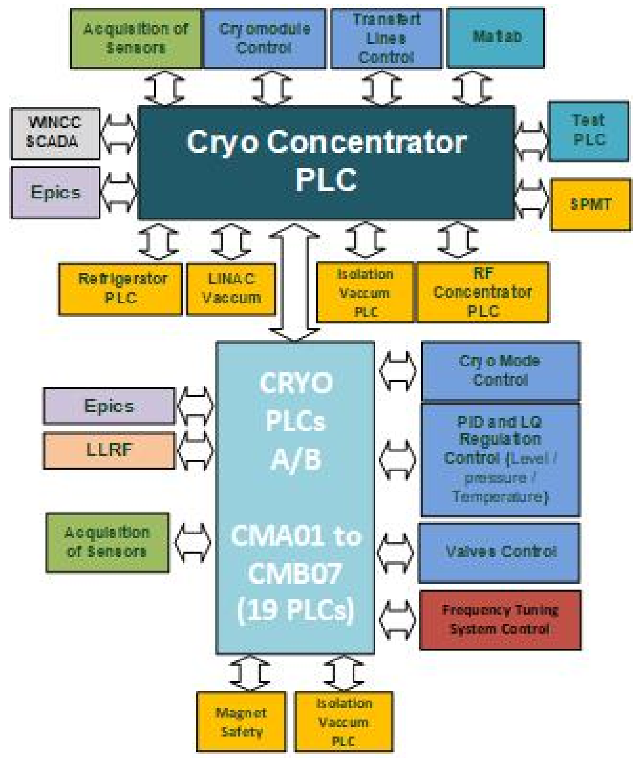

Figure 4: PLCs functions.

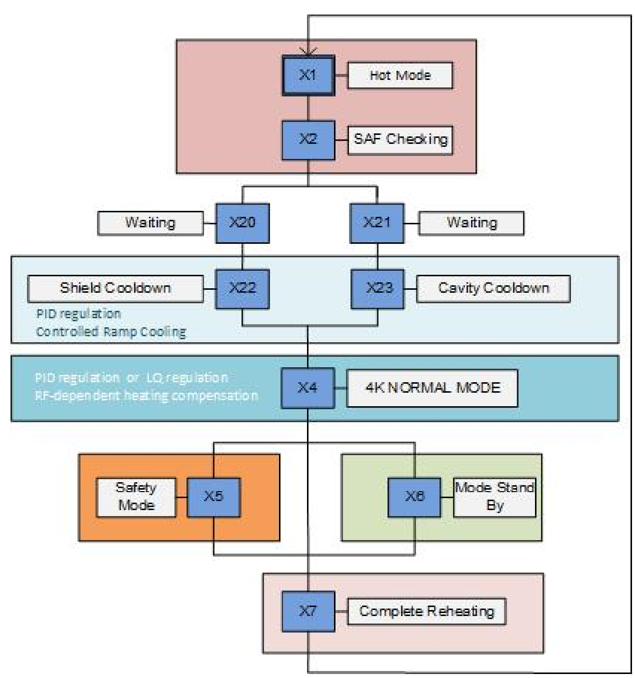

Figure 5: SFC of the cryogenics modes.

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dedicated control room, and are also reachable from distance. They include all the necessary data to drive the cryogenic system, and display the associated commands of the connection box, from transfer lines to cryomodules (see Fig. 6). It is made up of around 200 pages and 6000 variables. The alarms are archived.

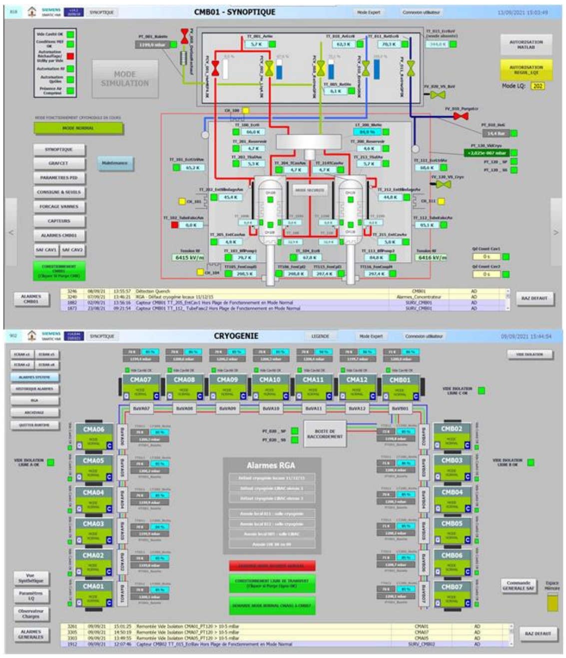

Figure 6: Cryogenics system supervision.

Frequency Tuning System

As the resonance frequency of the superconducting cavity is dependent to its volume, a mechanical device is used to adapt it in real time according to the RF regulation requirements. In the case of type-B cryomodule, the volume is modified through the insertion of a diver inside of the cavity, and in the case of the Type-A, a plier controlled by a screw enable the distortion of the 4 K cold cavity itself. On each cavity, those devices are managed through a single axis motion by the cryomodule PLC, following the phase shift instruction issued by the LLRF. As the deformations of the cavity are only possible at 4 K, hot and cold operating areas are defined (see Fig. 7) according to the cryogenic mode, to prevent any mechanical deterioration as well as any premature wear of the motorization system. In the tuning area, FTS can be positioned around a theoretical tuned position F0, around which it is moved to regulate the RF field.

Simulation

A simulation mode, with a dedicated window on the HMI supervision, was implemented to overwrite commands and sensors feedback on demand. This mode proved itself useful in the commissioning of the cryogenic system, to check every working mode and every safety conditions. This simulator is still used, mainly for the operations of the yearly maintenance phases.

Liquid Helium Bath Control

RF regulation is strongly dependent of the liquid helium bath pressure range (1200 ±2 mbar), and obviously to the immersed state of the cavity. In its earlier version, this requirement is managed by the cryomodule PLC with two PID controllers: the liquid helium bath pressure is regulated through the opening percentage of the output valve (CV005), and its level through the opening percentage of the input valve (CV002). Those controllers working in parallel are managed from a dedicated HMI window (see Fig. 8) where the cryogenics operators can tune the PID parameters and adjust the setpoint.

Moreover, during the cooldown steps, another PID controller regulate the cavity temperature by opening the CV001 valve. The cooling of the Linac is completely controlled with the application of an automatically sliding temperature set point. As shown in Fig. 9, the descent is slowed down from 300K to 150 K and then accelerated from 150K to 4 K in order to limit the time in the critical temperature range 150–50 K.

Dynamic Heat Load Compensation

All control parameters are only valid inside a certain range of conditions, expressed in term of heat load. The cavity RF fields being different for the variety of ions accelerated in Spiral2, the cryogenic bath load will also vary. To avoid permanent optimization of the control parameters, it has been decided to work always at the maximum heat load working point, which is defined as the heat load when the cavity is at its nominal RF field, 6.5 MV/m gradient. Hence, when RF is off, electric heaters are used to mimic the RF load inside

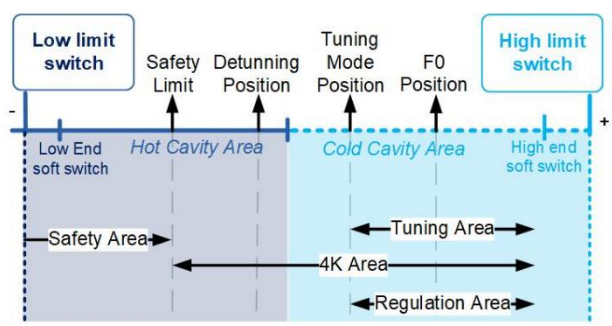

Figure 7: Type-A cavity FTS operating areas.

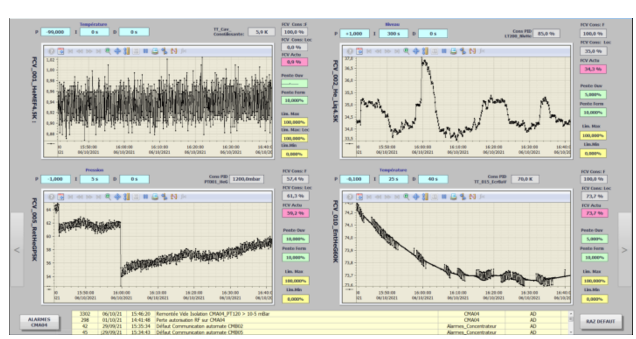

Figure 8: PID parameters supervision.

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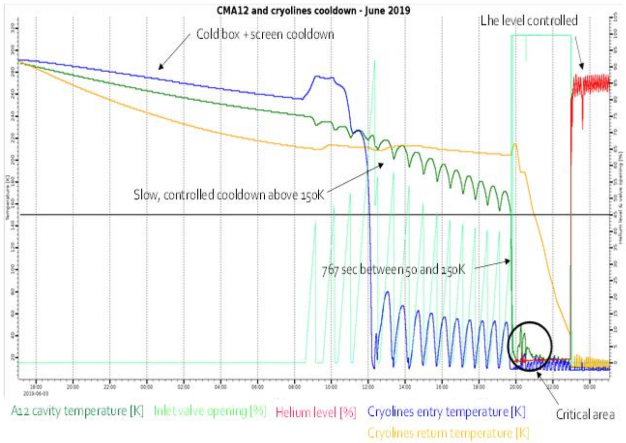

Figure 9: Cooldown of a type-A cryomodule.

the helium baths. Moreover, to keep the liquid helium distribution balanced, the heat load working point is evened up for all the type-A (12.275 W) and type-B (27.47 W) cryomodules. A feedback of the RF field level allow the cryomodule PLC to deliver the correct electrical power to the heater in order to reach those heat load setpoints.

MODEL BASED TOOLS

Cryogenics Modelling

The type-A and type-B cryomodules were modeled using the Simcryogenics [2, 3] library on MATLAB/SIMSCAPE environment. In order to be simple enough to be usable with a PLC, the cryomodule model is linearized to provide the state space equation, linking the opening of the valves and the liquid helium bath state.

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$
$$x = [\rho \; e]^T$$
$$u = [\mathrm{CV002}\; \mathrm{CV005}]^T$$
$$y = [\mathrm{LT200} \quad \mathrm{PT001}]^T$$

With ρ the density of the liquid helium bath, *e* the internal energy, CV002 and CV005 the opening of the input and output valves, LT200 and PT001 the helium liquid level and pressure measurements. The state space matrix are computed via a MATLAB graphic interface and transferred from MATLAB to the cryomodules PLCs.

Linear–Quadratic Controller

The linearized model, paired with a disturbance estimator (see Fig. 10), is used to provide a Linear Quadratic (LQ) controller of the liquid helium level and pressure [3].

The feedback gain K and the estimator gain *L* are computed with MATLAB tools, through the minimization of the quadratic criterion *J*.

$$J = \int x'Qx + u'Ru$$

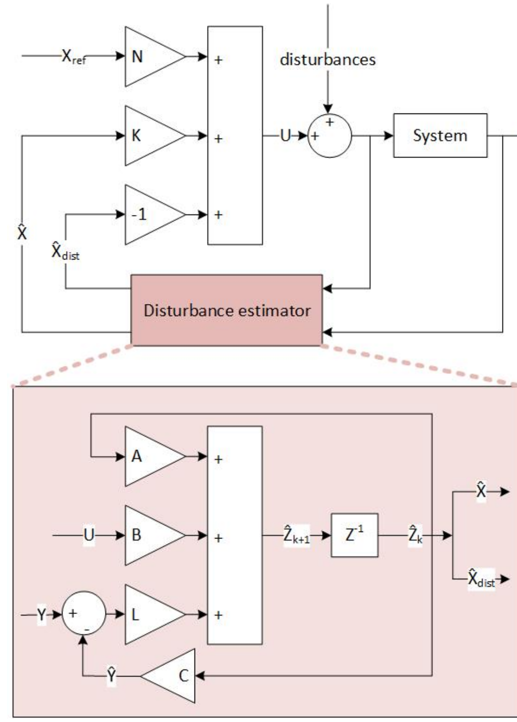

Figure 10: Block diagrams of the LQ controller.

$$Z = [X \quad Y_{dist}]^T$$
$$Z_{k+1} = AZ_k + BU_k + L(Y_k - \hat{Y}_k)$$
$$Y_k = CZ_k$$

The weighting of the variations of the sensors and actuators, as well as the weighting of estimations and errors, are adjustable with a dedicated HMI. The gains are then transferred to the cryomodule PLC with the state space matrix.

This regulation, as it uses knowledge of internal coupling between the liquid helium heat load regarding to the input and output helium flow, shows significantly better performance regarding the pressure stability, especially in the normal 4 K cryogenic mode, than the two separate PID controllers that were firstly used. However, as it is based on a linearization of the modeling around one single working point, its performance is strongly dependent to the distance of the ongoing heat load to this theoretical point. On the contrary the PID regulations can still be robust enough to be used in degrade situation or in the cooldown steps, so it is always possible to manually switch to these controllers.

Heat Load Estimator

The measurement dynamic heat losses, e.g. the variations of the heat load, is an indicator of the cavity state, which could itself be an indicator of the RF losses, or of the beam losses. As it is impossible to have a dynamic measurement of those losses while the accelerator is in nominal operating mode, a state observer was designed [4] (see Fig. 11) and implemented in a dedicated PLC to work in real-time,

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without risks of slowing down the cryomodules PLCs. This estimator PLC communicate with a selected panel of cryomodules PLCs to read the measurement of the CV002 and CV005 valves opening, and liquid helium bath pressure and level.

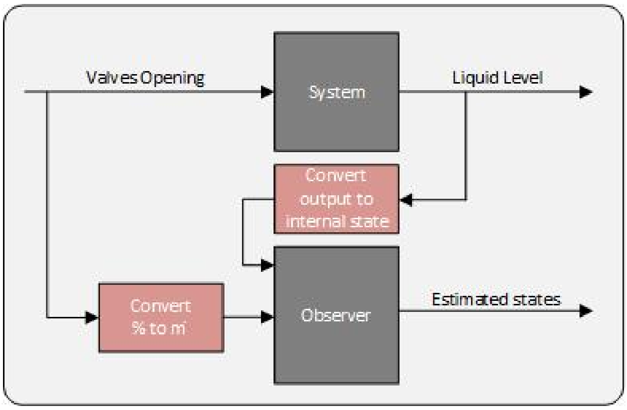

Figure 11: Block diagram of the estimator.

The linearized state space equation is augmented to include the heat load in the state vector. The estimator use a conversion of the input and output valves opening into mass flow, and any estimation error is attributed to a variation of the heat load.

First tests showed that this estimator is able to deliver a slow but correct enough estimation of the heat load, as illustrated by the Estimator 1 in Fig. 12. However it is too dependent on the output valves opening value, which are disturbed by thermo-acoustics oscillations. Others strategies of estimation are being studied to mitigate the weight of those disturbances. For instance the estimator 2 in the Fig. 12 also aims at computing the error of the output mass flow, in addition to the attribution of the error of estimation to the heat load. The result is slower, but, as it is less dependent on the CV005 working point variations, its performance concerning the offset error is improved.

Future improvements on the cryogenic system are expected to mitigate the thermo-acoustic phenomena, and thus to stabilize the CV005 and allow the estimator to provide faster and/or more reliable heat load estimations.

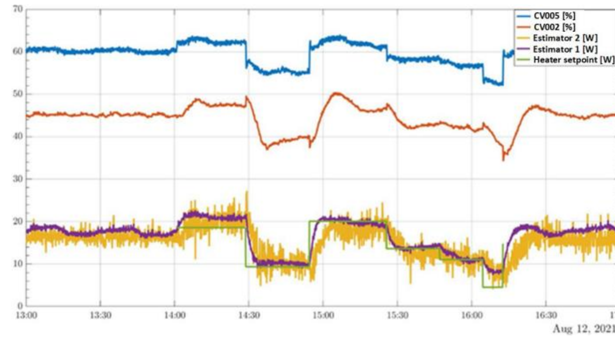

Figure 12: Estimated Heat Load.

In the long term planning, the goal is to design a software sensor able to provide dynamic heat load data from every cryomodule, working with several Kalman and/or Luenberger estimators with different response time. Those data could be useful for the beam tuning and other analysis about the cryogenic system performance.

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