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PRELIMINARY STUDY ON THE CRYOGENIC CONTROL SYSTEM WITHIN RF SUPERCONDUCTIVE LINAC PROJECTS

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Abstract

Several RF Superconductive LINAC projects are underway in different laboratories around the world, with various objectives such as research in physics, irradiation tests, production of radioisotopes for medical purposes. Superconducting operation of the accelerating cavities requires them to be maintained at cryogenic temperatures (2K - 4K) by the use of cryogenic fluids. This requires a complete cryogenic control system, including sensors, actuators, local controllers and PLCs. We describe the process by which the preliminary design of the cryogenic control system for the accelerator's cryomodules and valve boxes may be built. It starts with the functional and performance requirements of the system, followed by the definition of use cases and the study of the necessary cryogenic instrumentation. This leads to a preliminary design of the architecture of the cryogenic control system using Siemens hardware, as well as cryogenic sequences describing standard phases of operation of the LINAC. We also discuss how to take advantage of the modularity of cryomodules for control system implementation and some recent developments in PLC simulation.

INTRODUCTION

In general, the cryogenic infrastructure installed on a SC Linac includes 3 major layers (Fig. 1):

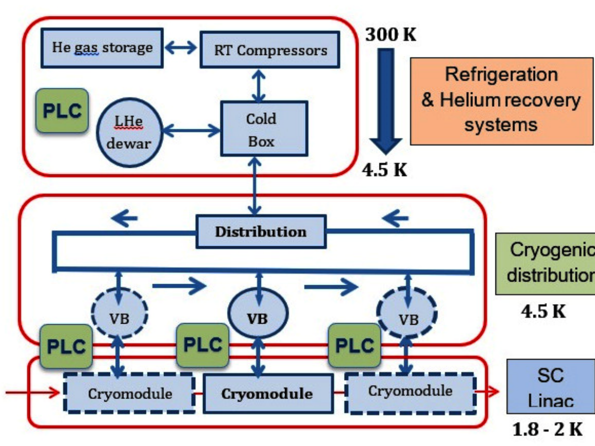

Figure 1: SC Linac, main cryogenic components.

- Refrigerator, helium recovering and storage systems
- Cryogenic distribution: multi lines connecting the refrigerator to the SC Linac.
- SC Linac components (Cryomodules, Valve Boxes)

All the 3 layers are controlled, for cryogenic operation, by industrial PLC systems. A standard solution adopted in many facilities is to install a PLC for the control of each pair {Cryomodule + Valve Box}. This is a major requirement in order to adapt to the different accelerating gradients and associated dynamic losses.

In this paper we focus on the control system (PLC) of the pair {Cryomodule + Valve Box}. For the prototyping phase, a close development is to control only a pair (CM+VB). In this case the CM + VB are installed in a test room, connected to different cryogenic supply systems (LHe dewars, He pumping systems, …) but using most of the sensors and actuators that will be installed in the final SC Linac.

PHYSICAL EQUIPMENT, SENSORS, ACTUATORS, INTERFACES

Safe operation and stability of the SC Linac Cryogenic systems (Cryomodules and Valve Boxes) are two major requirements for all the operation phases. The associated control system based on PLC must assume this responsibility. Other important requirements are the connection of these “local” PLC to the overall Linac security systems (machine protection system MPS, personnel protection system PPS) and to the facility infrastructures (electrical distribution, cooling, HVAC, vacuum systems, etc.)

All the operation process are based on dedicated sensors and actuators installed within the SC Linac Cryogenic systems, connected through special interfaces to the PLC. On the other side, using supervisory tools and networks, the PLC must be interfaced to the high-level control process (databases, MPS, PPS, infrastructures etc.) using adapted IOC (Input/Output Controllers) operating under EPICS [1] software environment.

Sensors within the Cryomodules and the Valve Boxes, are difficult to be replaced in short delays, and need to be redundant. Other redundancy that may be considered are the process controllers (complete PLC or partial critical hardware as CPU and I/O systems), data networks and associated power supplies.

In parallel with the major control role and safety aspects, the Cryogenics Instrumentation will deliver interesting measurements for the SC Cavities and RF Couplers

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operation, in particular using the following sensors: cryogenic temperatures, Liquid Helium levels, Helium gas mass flow, pressures … All these measurements will help analysing the static and dynamic losses, the sensitivity to pressure perturbations, and in general the anomalous behaviour of SC cavities, and associated components.

Another important aspect is the high radiation levels within the SC Linac Tunnel where all Cryomodules and Valve Boxes are installed. This high radiation levels are originated by beam losses and anomalous operation of SC cavities (field emission). Some facilities have entered in long term operation phases (i.e. CEBAF,SNS,LHC, …) and have observed these critical consequences, with increased number of machine trips or adoption of lower operational accelerator gradients in the SC cavities.

Presently, for new facilities, important installation improvements have been adopted:

- Battery supply installed in the PLC crates
- PLCs and controllers installed in radiation-free areas
- Instrument interfaces can be installed in the tunnel or close to the instruments if radiation-tolerant electronics cards are available.
- Use of radiation tolerant interface cards for: Vacuum gauges, Pt thermometers, low voltage power supplies.
- Other possibility of installation of these interfaces, in smaller interconnecting tunnels (shafts) between Linac tunnel and technical equipment gallery

FROM GENERAL REQUIREMENTS TO CRYOGENIC AND CONTROL SYSTEM DESIGN

In this section, we describe a method to define a local control architecture and operating sequences starting from global requirements on the cryogenic control system (related to the considered accelerator and its performance, safety and reliability objectives).

Step 1 : General Requirements

At a first level, all the different functions desired for the system must be listed see Fig. 2. They are classified into the following six categories:

- pre-start checks; measurements; regulations; interfaces with auxiliary systems; monitoring; maintenance and exceptional cases.

In the table below, we list some main functional requirements for each category. At this level, we do not yet introduce quantified performance targets.

Category	ID	Stakeholder requirements
1-Checking before start	101	Be able to check that all instrumentation works properly
	102	Detect that vacuum level is sufficient before start
	103	…….
	104	…….
2-Measurements	201	Helium temperature measurements at inlet and outlet of each component
	202	Helium pressure measurements at inlet and outlet of each component
	203	Helium level measurement in the cavity cooling bath
	204	Estimate potential losses in the cavities
	205	…….
3- Regulation	301	Regulate the pressures in function of time
	302	Regulate the temperatures in function of time
	303	Regulate the mass flow depending on thermal load
	305	Stability of electrical current (CW)
	306	…….
4-Auxiliary systems	401	Integrate/send information from/to cryogenic supply system
	402	Integrate/send information from/to Machine Protection System
	403	Integrate/send information from/to various vacuum systems
	404	…….
5-Monitoring	501	Parameters shall be monitored and controlled by a user interface in real time
	502	Parameters shall also be controlled by this user interface
	503	Be able to implement and launch cryogenic sequences
	504	Include data reference data for regulation in this interface
	507	Vizualize the general state of the overall system by a color code
	508	Vizualize the states of all sub-systems by a color code
	509	Be able to store data and acess it
6-Exceptional cases / Maintenance	601	…….

Figure 2: Stakeholder requirements generic table.

Step 2 : Use Cases Definition

The second step is to divide and group the previously defined requirements into functional use cases. At this stage, we distinguish three categories of use cases:

1- Use cases related to the operational sequences of the cryomodule (contains for example Preliminary tests, Conditioning, Cooldown and Warmup sequences, Maintenance) ; 2- Measurements and Regulations (e.g. Bath pressure, Bath level, Temperature) ; 3- Recording, Storing, Displaying data

Step 3 : Hardware Definition

The next step is to define the hardware (see Fig. 3) that must be used to meet the use cases listed above. Thus, it is classified according to the same use cases. In general, except for some particular cases, each sensor or actuator is associated with a signal conditioner. For each type of measurement, we treat in a global way the acquisition chain: sensor, conditioners, cables, communication protocol with the PLC. We indicate for each acquisition chain the following characteristics:

1- Communication protocol between the signal conditioner and the PLC (or directly from the sensor in the case of platinum temperature sensors ; 2- The typical performances of the hardware regarding the following parameters : response time, accuracy, sensitivity, calibration issues, hardness to radiations and magnetic fields ; 3- The number of sensors needed for the desired application.

We detail here the example of the use case "Temperature measurement below 20 K". We define the acquisition chain necessary for its realization, giving information on the sensors and signal conditioners required, the communication protocols to be used, and the performance of this hardware in the environment considered (for example the effect of ionizing radiation or magnetic field on the quality of measurements).

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				Control chain			Technical characteristics		
	Use Case	Technology	Category	signal conditionner	Connection sensor - signal conditionner	Communication signal conditioner - PLC	Category	Typical performance	Qty/CM
1	Measure Temperature of the 2K circuit	Cernox Cold thermometer	Sensor	CABTR	4-wire connection (firstly grouped in 24-wires feedthroughs, then separated with regard to each sensor)	Group all Profinet outputs of the CABTR into a single Profinet connection to the PLC	Response Time	Sensor : 1.5 ms @ 4.2 K CABTR : 20-100 ms	n
							Accuracy	Sensor : ± 5 mK up to 4.2K, ± 25mK after many thermal shocks CABTR : < ± 1 mK	
							Sensitivity	10^3-10^4 ohm/K @2K	
							Calibration	Individual calibration is mandatory for every sensor ; Recalibration is impossible until maintenance operations	
							Effect of Magnetic Field	ΔT/T = 1-3% @ T = 2K, B = 2-8 T, insignificant for B < 1 T	
							Effect of Ionizing Radiations	Ionizing radiations' effects on accuracy : deviation up to 25mK at T = 2K with 5.10^5 Gy	

Figure 3: Example of hardware requirements for measuring sub-20K temperatures.

Step 4 : Architecture of the Cryo Control System

All this preparatory work allows us to produce a fundamental document : a system architecture proposal, see Fig. 4.

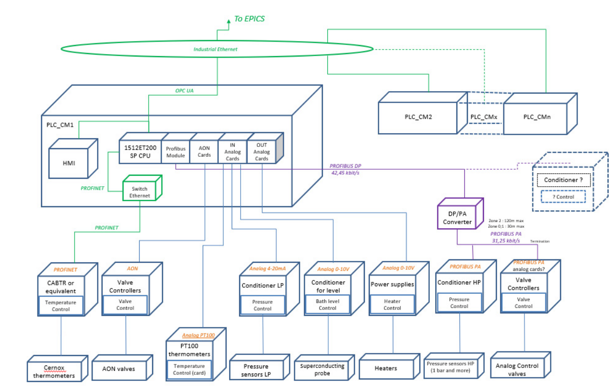

Figure 4: Generic system architecture for the cryogenic control system at field level.

IMPLEMENTING CRYOGENIC SEQUENCES IN MULTIPLE SIMILAR PLCS

In this section, we use the Siemens' framework [2] to describe a programmation method for implementing the previously described architecture. All cryomodules controlled by a PLC are integrated in a single TIA Portal project. Thus, we have access to a common library for all similar cryomodules' PLCs.

The first step is to create a project template in the "Master copies" directory, in which the entire PLC program for a single cryomodule can be found. This will allow to duplicate the project for each cryomodule from a PLC project template. Then, each program component (FC, FB) is placed in the library, under the "Types" directory. This main library is unique to all the projects. The programmer has therefore the possibility to update simultaneously all the PLC projects (cryomodules 1 to N) from the main library.

NEW PERSPECTIVES FOR PLC DEVELOPMENT AND SIMULATION

State of the Art

Some existing, or under construction, facilities (in particular CERN [3], ESS, XFEL in Europe) have made important improvements on the field of reliability and performance of Control Systems for Cryogenic equipment. Currently, the cryogenic control system follows the standard automation pyramidal structure of the International Electrotechnical Commission (IEC-62264) and is based on industrial components deployed in all control layers : 1- Instrumentation layer ; 2- Control layer ; 3- Supervision layer ; 4- Maintenance & Operation Management System layer.

CERN has developed a special Platform: UCPC (UNICOS Continuous Process Control). It helps to identify the origin of a failure, predict what could happen in the near future, etc. UCPC is an open-source platform providing objects libraries and including Siemens [2] PLCs libraries in the control layer, and WinCC flexible libraries in the supervision layer. An interesting tool "Generator" was developed using a step-wise methodology. Today the LHC cryogenic tunnel applications are automatically generated, while the non LHC cryogenic systems and the LHC refrigerators are manually developed.

Presently, in recent performance analysis, the availability for the LHC cryogenic control system is estimated to be more than 99.8%. At the European Spallation Source ERIC (ESS) in Lund Sweden, the PLC Factory was developed to automate programming of all repetitive tasks of the facility.

Recent Developments

Two recent developments can help the development of future projects :

- Development of Process Modelling, and integration of the components' Models into the regulation loops of Cryogenic Systems controlled by PLC. An interesting example has been recently tested at the Spiral 2 Linear Accelerator [4]. The models were developed with MATLAB/SIMSCAPE tools, and introduced into the PLC programs for regulation of the Helium level of each SC cavity. Heat load estimator were also developed..
- Machine Learning Platforms. Recently CERN Control Group has developed a platform based on the recent advances of machine learning techniques adapted to complex systems and improve their evolution. Model algorithms could be introduced into the PLC programs to develop prediction tasks parameters, that could play a major role on optimization of operation and improvement of the systems reliability and availability [5].

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