STATE-OF-THE-ART CRYOGENICS PROCESS CONTROL FOR THE OPERATION OF THE ESS SUPERCONDUCTING LINAC

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Abstract

This paper presents the strategy for the simultaneous cryogenic operation of the ESS superconducting linac, consisting of 43 cryomodules. It details the process logic required for different operational phases and introduces a novel control system designed to manage these complexities. Key features of the system are discussed, including multiple independent automatic control sequences, a master controller for system synchronization, failure response protocols, and operator interface design. Fully deployed in December 2024, the system played a critical role in the successful cooldown of the accelerator. The paper also addresses lessons learned during this deployment and outlines potential improvements for future operations.

INTRODUCTION

The European Spallation Source (ESS) superconducting linac [1] aims at delivering 5MW proton beams in its final design configuration, thus becoming the most powerful neutron spallation source driven by a linear accelerator. The ramping-up to the final configuration will be done in stages, the installation of the first stage was completed in 2024 [2, 3], it comprises 27 cryomodules (CM), housing a total of 82 superconducting cavities able to drive the proton beams up to 870 MeV, thus enabling 2 MW beam power.

Superconducting Linac Cryogenics

The superconducting linac is composed of three families of cryomodules, comprising 13 spokes, 9 medium-beta and 21 high-beta cryomodules. The cooling power required for operating the cryomodules is provided by the accelerator cryogenic plant (ACCP) enabling the operation of the superconducting cavities at 2K. Helium is supplied and returned to the ACCP via a cryogenic distribution system (CDS), composed of a multi-channel transfer line, an endbox and multiple valve boxes (VBox) each interconnecting to a single cryomodule forming a unified system [4].

Figure 1: Layout of the accelerator cryogenic system.

The cryoplant was supplied with its own stand-alone control system, while for the operation of the cryomodules and distribution system (CMDS), a segmented control system approach was chosen and developed, matching the physical layout of the systems (Fig. 1).

The control system for the CMDS is split in various cells, each cell comprising a CM and its dedicated Vbox. This approach allows for a modular structure that can be deployed and upgraded following the scaling-up of the accelerator through its phases, while keeping in mind a maximisation of the accelerator availability.

CRYOGENICS OPERATION DEFINITION

Strategy

Each cell of the linac cryogenic system, contains multiple cryogenic circuits and numerous devices, each requiring precise monitoring and control to perform a series of complex and coordinated cryogenic operations, in addition these operations must happen in an orchestrated way between all cells and the cryoplant.

The control system is built to support concurrent control and monitoring between cells through an integrated interface that reduces operational complexity and human intervention, while enabling operators to maintain a clear overview of system status.

The required process logic for each cell is implemented in dedicated programable logic controllers (PLC) allowing for the automated actions and transitions required to operate each cell cryogenic system, called Automated Control Sequence (ACS).

A dedicated PLC, named master, oversees and synchronizes the status of each cell, coordinating the operation of all the linac systems with the ACCP (Fig. 2).

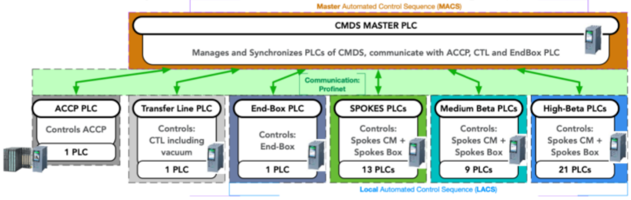

Figure 2: Control system architecture.

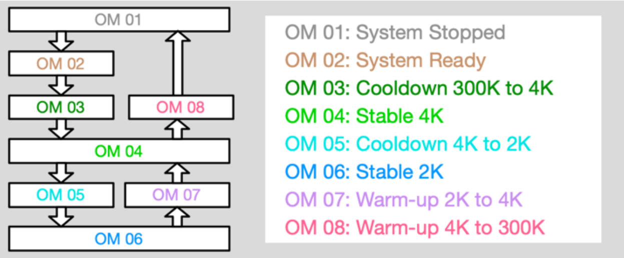

Figure 3: Simplified view of the CMDS operating modes.

The full cryogenic operation is broken-down in operating modes (OM) [5] as shown in Fig. 3, which constitute a procedure containing a series of states, each state contains actions and transitions required for full cryogenic

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operation: bringing the system from room temperature to nominal operating conditions.

Process Logic

The process logic for the cryogenic operation of the CMDS evolved from years of experience at TS2 [6-10], where the site acceptance testing of all elliptical CM (medium-beta and high-beta) is performed. A pilot implementation of CMDS control system was validated at TS2, prior to the final implementation in the linac [11].

At the core of the process logic, is a breakdown of the various circuits in key components: actuators (e.g. valves heaters) and sensors (e.g. temperature, pressure and level sensors). Some processes require constant regulation and therefore PID controllers are defined, allowing to maintain process variable setpoints (of the required sensors by performing corrections to the state of the corresponding actuators. The controllers are implemented via typical PID controllers requiring adjustment of control settings for optimal behaviour.

Each OM is made up of a sequence of states, and with every state, specific verifiable actions take place on the designated circuits. With each state, predefined interlocks or supervision logic, prevents actions to take place whenever process conditions are not satisfied. After the required actions take place (verified by feedback readings or process conditions) the transition the next step is allowed.

Finite State Machine

The methodical sequential progression of the cryogenic process makes it possible to be implemented into a finite state machine (FSM) and implementable into PLC logic. Moreover, the systematic approach to the process logic makes it that shortcomings and improvements can be easily identified and implemented.

A state reflects the status of the system at a specific moment, defined by key parameters that describe its operational characteristics. When a state is activated in the ACS, it triggers predefined actions to adjust the system based on the process needs. Interlocks may block certain actions until all required conditions are met, ensuring safe and efficient operation.

Transitions are key components of the FSM, controlling the progress between states, A transition occurs only when predefined conditions are met to ensure safe and valid. Each transition is uniquely identified by a name and number for precise control and documentation. Transition delays are also used, introducing a timed pause before advancing, these are usually employed to operations requiring time-based stabilization, or simply to generate a time-based progression of the sequence.

The correct definition of the transitions conditions is essential for maintaining a smooth operational flow and ensuring that each state is prepared to handle the subsequent demands of the process.

CONTROL SYSTEM DESIGN

At the core of the control system design, is the structured approach to the cryogenic process logic by adopting and aligning a terminology that can be easily implemented. This is an important step at reducing the risk of misinterpretation thus helping to bridge the gap between process experts and control system engineers.

Two Python scripts have been prepared to support control system programming: one for the generation of PLC code using structured control language (SCL) which is then implemented using siemens TIA portal software and a second script for the generation of operator interface screen with a visual representation of the ACS.

Each cryomodule and valve box cell is independently controlled by a dedicated PLC and is treated as an independent control unit within the CMDS. The PLC design is based on Siemens S7-1500 series CPUs, distributed I/Os (ET200 series and PROFIBUS connectivity for intelligent field devices like the cryogenic valve positioners using SIPART PS2.

All hardware modules, including power supplies, digital and analogue inputs/outputs, follow ESS standardized configurations, allowing for simplified scalability and deployment, while enhancing troubleshooting and maintenance. The software design is modular, separating key functions such as data acquisition, valve control, mode selection, alarm handling and interlock logic.

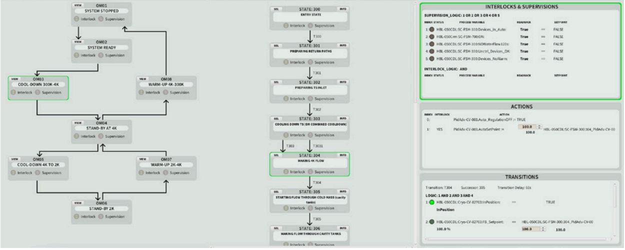
The PLCs communicate with EPICS IOC servers allowing for a unified, real-time monitoring, which in turn feed the operator interfaces for control room visibility and alarm archiving. Dedicated handler blocks manage analogue and digital device signals allowing for standard processing like scaling, alarming and fault detection.

Local Automated Control Sequence (LACS)

The Local Automated Control Sequence is embedded into the PLC logic, providing all the required automated state-machine logic for every operating mode applicable for each cryomodule and valve box cell. Moreover, it also includes the required logic for response whenever safety functions and interlocks are triggered (Fig. 4).

Embedded in the ACS logic is the possibility for adjustment of specific process setpoints, providing the operator with additional flexibility to adjust the process behaviour.

The operator is provided with various options to influence the behaviour of the process with the sequence running, the most common types are either by setting the ACS in manual and providing additional verification of the transition via a state transition ‘push’ button, by adjusting ACS transition setpoints, or by setting specific devices in manual control and taking over their behaviour.



Automated Control Sequence HBL-050

SEQUENCE STATUS

Waiting for Transition Condition

STATE ACTIVE 304

OM ACTIVE 3

TIME FROM TRANSITION 185

SEQUENCE CONTROL

Mode select: AUTO

Swich to Manual: DISABLED

Select manually: 304

OM Name: Cool-Down 300K-4K

OM Number: 3

State Name: MAKING 4K FLOW

State Number: 304

Description: Opening supply valve (CV03), verifying supply pressure conditions

State Timeout: 1728

SUPERVISION_LOGIC: 1 OR 2 OR 3 OR 4 OR 5

INTERLOCK_LOGIC: AND

Figure 4: Example of an operator screen of the LACS.

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Master Automated Control Sequence (MACS)

A master PLC coordinates the operation and communications among all PLCs, ensuring system-wide consistency, timing and safety. The system employs PROFINET and TCP/IP protocols for robust and real-time data communication.

The master automated control sequence logic allows for coordinated operation of the linac cryogenics. It receives the status of each individual LACS plus ACCP and sends transition enablers at various moments of the global sequence, thus serving as the orchestration mechanism of the overall process. Having access to the status of each LACS and ACCP it can also sent trigger for failure action on individual LACS due to events on other systems.

Safety Actions

The control system also serves as mitigation against undesired or accidental events, as part of this strategy, a structured evaluation was conducted, identifying the most probable and critical failure scenarios, assessing the severity of their unmitigated consequences, and define corresponding mitigation actions. These actions are then integrated into the control system to minimize the potential impact.

Some safety actions (SA) are solely integrated in the LACS other require the management of the MACS to exchange information. For example, in the event of a beam vacuum or insulation vacuum venting of a cryomodule, the event is detected by the specific CM PLC logic, and the safety action is triggered accordingly, while in the event of an specific type of trip in the ACCP, the information needs to be exchanged between the ACCP with the MACS PLC, and then the MACS PLC instructs the various LACS to perform the pre-determined actions accordingly.

The identification of a failure scenario, and its actions is integrated in the alarm service, annunciating in main control room that a specific event has occurred.

OPERATOR INTERFACE DESIGN

The operator interfaces (OPI) are implemented using CS-Studio on EPICS standards. It provides intuitive graphical views at various levels of complexity of the system and functionality. Below a list of the most important:

- The SRF linac layout and main cryogenics status.
- M-ACS and L-ACS status and console.
- Detailed and interactive views of the process flow schematics for each cell.
- Global controls for system actuators and controllers.
- Global and local process variable trends.
- Overview of interlock status.
- Health status of PLC and communication.

The operators interact with the system in multiple ways: by mode selection, for manual or automatic selection of operating modes, by manually control of devices if required or change of control settings.

The operators can also view historical data and trends through integrated archivers, via predefined organized sets of process variables or by rearranging of creating new sets.

The operators can also get informed about warnings and alarms through visual indicators and messages and get predefined guidance on how to resolve issues.

The standardized design philosophy ensures that the OPI's are clear, informative, and safe with the goal of minimizing operator workload and maximizing system understanding (example in Fig. 5).

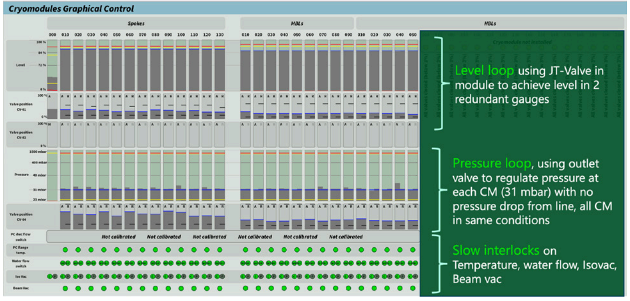

Figure 5: Example of the linac cryogenics status.

LESSONS

This novel system for cryogenic process control was deployed for the first time in the last quarter of 2024 prior to the first integrated cooldown of the ESS superconducting accelerator [12]. Since then, it has played a crucial role in allowing for a reliable operation of the accelerator.

Several improvements were implemented since its deployment that are worth mentioning, such as providing additional flexibility to the operators through global controls affecting multiple systems at once, improving the looks and feel of the OPI.

One issue that affected the performance of the cryogenic system was, electric noise which disseminated through the readout of some process variables (temperature, helium level), this behaviour triggered into various interlocks and resulted in longer time of stabilization as the logic interpreted it as real deviations in the process. This problem was solved partially with software filters applied after the readout, while the origin of the noise is being investigated.

CONCLUSION

The cryogenic operation of ESS superconducting linac is made possible by a novel control system allowing for the simultaneous operation of 43 cryomodules. The LACS, drives the process logic on each local cell, consisting of a cryomodule and its valve box, while th MACS makes sure all the cells work in unison together with the ACCP.

The system is fully scalable, allowing it to seamlessly accommodate the planed future upgrades of the facility.

The control system is built on Siemens PLCs architecture, while the code generation is done using Python scripts first: working as gateway between the process logic and the PLC logic and secondly: by automatic generation of graphic representation of operator Interface in Phoebus.

Robustness of the system is added by implementing Failure action response, which provides a coordinated mitigation in case of accidental / trip scenarios. The operator interface is designed providing intuitive graphical views at various levels of complexity of the system.

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