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IMPLEMENTATION AND EXPERIENCE WITH THE PILOT CMDS CONTROL SYSTEM AT TS2, IN VIEW OF OPERATING THE ESS LINAC CRYOGENICS

N. Elias†, W. Bińczyk, A. Fontoura, E. Asensi, J. Zhang, K. Arada, M. Skiba, P. Nilsson, P. Arnold, European Spallation Source, Lund, Sweden
P. Halczynski, W. Gaj, IFJ-PAN, Kraków, Poland

Abstract

This paper introduces the strategy for operating the cryogenic system of the ESS superconducting linac, emphasizing the integration of individual cryomodules and valve boxes within a unified system. The study focuses on the practical implementation of this strategy at Test Stand 2 (TS2) as a pilot project, validating the proposed control system in a real-world setting. The paper evaluates the primary goals which include performing functional tests, successful implementation, identifying control system shortcomings, and collecting valuable operator feedback for continuous improvement.

INTRODUCTION

The superconducting linac of the European Spallation Source (ESS) is currently under construction in Lund, Sweden. The first run is planned for the last quarter of 2024, where a total of 27 cryomodules (CM) housing 82 superconducting cavities will be submerged in a superfluid helium bath at a temperature of 2K, under these conditions the proton beam can be accelerated up to 870MeV [1].

In its final configuration the accelerator is expected to comprise a total of 43 CM allowing for a beam energy of 2GeV and 5MW beam power [2].

The Accelerator Cryogenics System Architecture

The cooling power required for operating the superconducting cavities is produced in the accelerator cryogenic plant (ACCP). It is supplied and distributed through a cryogenic distribution system (CDS) comprised of a multichannel transfer line, an end box and valve boxes (VBox) interconnecting to each CM forming a unified system.

CMDS Integration

A CM and associated VBox houses various cryogenics circuits and dozens of devices each requiring monitoring and control to execute a series of complex and controlled actions. The integrated operation of these components is paramount for the seamless functioning of the linac.

The various cryomodules and valve boxes part of the cryo-module and distribution system (CMDS) have to be operated in an orchestrated manner. Without an automatic control sequence (ACS) this process would require a substantial number of operators to promptly execute actions, as well as to monitor the system.

The goal for the linac cryogenics is to have these operations automated, allowing multiple devices to be actuated simultaneously following a pre-determined ACS. Operators are still required to monitor the system, acknowledge faults, or take control in case of specific needs.

INTEGRATED CONTROL SYSTEM STRATEGY FOR LINAC CRYOGENICS

Integrated Control System Architecture

The ESS Integrated Control System (ICS) utilizes a distributed control and computing setup centralized around EPICS software. This structure ensures smooth integration across the facility. The system's architecture is layered, defining clear interfaces between physical processes, equipment, control elements, programmable logic controllers (PLCs), communication networks, supervision systems, and human operators. This layered approach facilitates comprehensive management and interaction across various components of the facility [3].

Master PLC as a Strategy for Coordinating Cryogenics Operation

The various systems composing the accelerator cryogenics are controlled by independent PLCs. One PLC per Valve box and Cryomodule cell to allow independent operation and increase redundancy. This strategy also streamlined the installation and commissioning of the control system following cryomodules installation.

A Master PLC is introduced as a way to centralize the necessary coordination function as a global system.

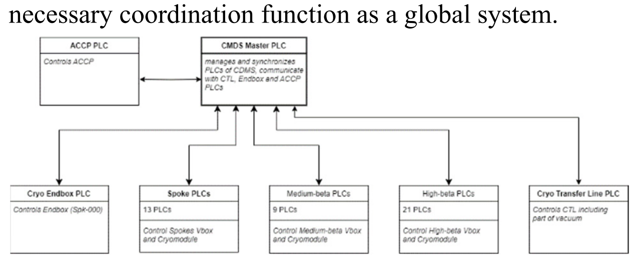

Figure 1: Master PLC coordination between systems.

The Master PLC main function is to manage the signal exchange between the various PLCs (Fig. 1), providing seamless data flows and synchronization whilst ensuring that the whole system is operating in a unified way by using a dedicated PLC-PLC Profinet network.

PILOT IMPLEMENTATION AT TS2

TS2 Environment

The TS2 is a state-of-the-art facility dedicated to perform the site acceptance testing of all Elliptical

† nuno.elias@ess.eu

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Cryomodules [4, 5]. Designed to verify the performance of cavities and cryomodules whilst simulating conditions similar to those in the accelerator. It ensures that all cryomodules meet the rigorous operational demands they will face once installed in the main accelerator. The test bunker at TS2 is constructed with a similar cross-section to the LINAC tunnel, ensuring that the cryogenic interfaces and thermodynamic conditions closely mimic those in the actual accelerator environment [6, 7].

TS2 has a dedicated cryogenic plant (TICP), which ensures that similar thermodynamic conditions can be realistically achieved in the cryomodules under test as when mounted in the linac, where cool-down, stabilization and warm-up cycles are required to evaluate the cryomodule cryogenics performance [8].

TS2 Controls Setup

The control system at TS2 is equipped with a Siemens S7-1500 CPU, facilitating advanced control and monitoring capabilities. This CPU is connected through a PROFINET communication network to an ET200MP Remote Input/Output Module, and it utilizes PROFIBUS communication to manage cryogenic valve positioners.

The CPU's integration with the Experimental Physics and Industrial Control System (EPICS) is managed through an Input/Output Controller (IOC) running on a virtualized Industrial PC (IPC). This setup enables robust remote monitoring and control capabilities from the Operator Panel Interfaces (OPI).

The IOC's primary responsibilities include managing data transfer between system components. It feeds critical operational data to the Archiver and Alarm services and facilitates data exchange between the PLC and the OPI, ensuring seamless operation and quick response to any system anomalies.

TS2 also acts as the foremost site for implementing innovative design solutions prior to deployment in the accelerator, such as defining the Automated Control Sequence. The technical setup provides a robust framework for testing the ACS's integration with existing systems and for simulating various operational scenarios, thereby identifying potential improvements before broader deployment.

The Automated Control Sequence

Over the past 4 years of manual operational experience at TS2 [X, X], the needed cryogenic process was improved, streamlined and made more resilient to abnormal scenarios. This experience allowed a simplified breakdown of actions and transition conditions into a sequential process.

The ACS is subdivided into operating modes (OM). Each OM is a collection of states and the needed transitions connecting them, constituting a procedure for transitioning the cryomodule systems from one stable state to another.

A state represents the current condition or status of a subsystem, component, or process. Each state is defined by a specific set of parameters, variables, or attributes that describe the operational characteristics of the system at a given moment. States are crucial for monitoring the system's performance and ensuring that it functions within the defined operational parameters.

The system follows a sequential progression with waiting steps, ensuring a methodical flow, constituting what is called a Finite State Machine (FSM).

When a state is activated in the ACS, it triggers a series of pre-defined actions tailored to manage or adjust the system according to its process needs. Importantly, some actions may be interlocked, which prevents them from executing despite the state's activation. This safety mechanism ensures that certain operations only proceed when all necessary conditions are satisfied, thereby preventing unsafe or inefficient system behavior.

Transitions are elements within the FSM, dictating the shift from one state to another. A transition occurs only when predefined conditions are met, ensuring that the system's progression is based on safe and correct operational statuses. Each transition is uniquely identified by a name and number for precise control and documentation. Some transitions, known as empty transitions, do not have programmed conditions and serve specific operational strategies or system testing purposes. Transition delays are also employed, setting up a timer that must expire before the system progresses to the next state, which is critical for operations requiring time-based stabilization or preparation.

Managing these transitions carefully is essential for maintaining a smooth operational flow and ensuring that each state is prepared to handle the subsequent demands. In practice, when a transition is activated, the steps associated with the current state are deactivated, and those pertinent to the successor state are initiated. If transition conditions are not met, the current step remains active, maintaining the system in its current state until conditions change.

ACS Implementation at TS2

The implementation of the ACS at TS2 was systematically organized to optimize both the design and operational effectiveness of the cryogenic processes.

The creative process began by establishing the general architecture of the system, which involved defining the necessary operating modes to achieve the intended process goals. This strategic phase set the groundwork for the detailed development of each OM [9].

Within each operating mode, the cryogenic process was meticulously split into manageable discrete actions, conditions, or verifications. This simplification was guided by years of accumulated operator expertise, ensuring that the system's design was both practical and efficient. From this foundation, a sequential progression of states, transitions, and potential fault conditions were systematically developed.

To minimize the discrepancy between process definition and control system execution, a simple semantic structure was adopted. This approach facilitated clear and consistent communication across the development team.

A shared spreadsheet document with robust version control was employed as the primary tool for representing each OM. Each sheet in the document corresponded to a specific state, with systematic data entry fields designed to ensure

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that all necessary information was captured clearly and could be easily managed by subsequent automation scripts.

Two main scripts were used in the system's automation:

- fsmgen: This script is responsible for the generation of the Programmable Logic Controller (PLC) code using Structured Control Language (SCL), which is then implemented using Siemens TIA Portal software. This script transforms the structured data from the spreadsheet into functional control code, streamlining the development process.
- bobgen: This script is used for the generation of the Operator Panel Interfaces (OPIs), commonly referred to as operator screens. This script ensures that the interfaces are intuitive and meet the operational needs of the system, enhancing usability and efficiency.

Through these innovations, the implementation of the ACS at TS2 not only adheres closely to the defined process parameters but also leverages advanced automation tools to reduce manual coding errors and accelerate system development.

OPERATOR ENVIRONMENT

The design of ACS related operator screens and control interfaces are focused on enhancing usability and real-time monitoring capabilities.

The sequence console (Fig. 2) provides the operator with the high-level status of the ACS (e.g., active state number, presence of faults, transition delay progress bar or system status mode). It allows for flexible control of the sequence, allowing the operator to stop or start the sequence, or set the sequence to auto, manual, or assisted auto where each step is confirmed through a 'push' button.

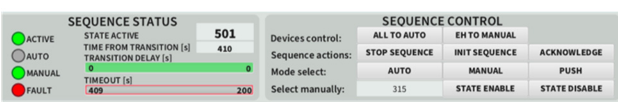

Figure 2: Sequence console.

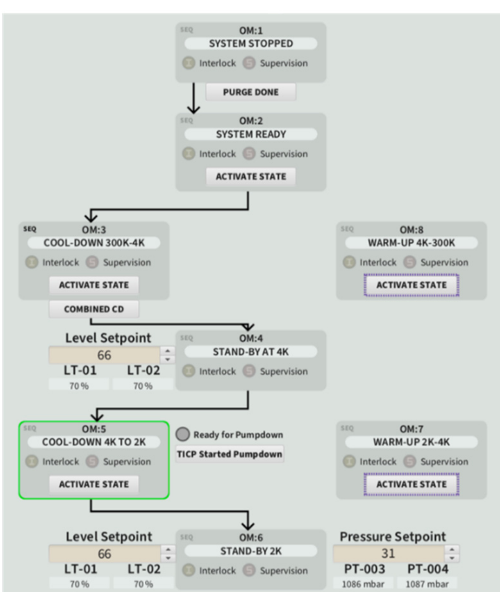

Figure 3: Operating modes display.

The operating modes layout is displayed as high-level information on the operator screen (Fig. 3) It highlights the active OM and outlines the possible process routes available. In specific modes the operator needs to activate buttons the start the following mode. Also available to the operator are relevant setpoints that can be modified within a stable OM.

A clear and intuitive view of the sequence structure within the OM is available to the operator (Fig. 4). The state information panel provides the operator with visual information on interlock and supervision conditions that need to be satisfied for the state to progress. Actions and transitions of the state are also contemplated in the panel integrating consistent color schemes to indicate similar types of information or alerts.

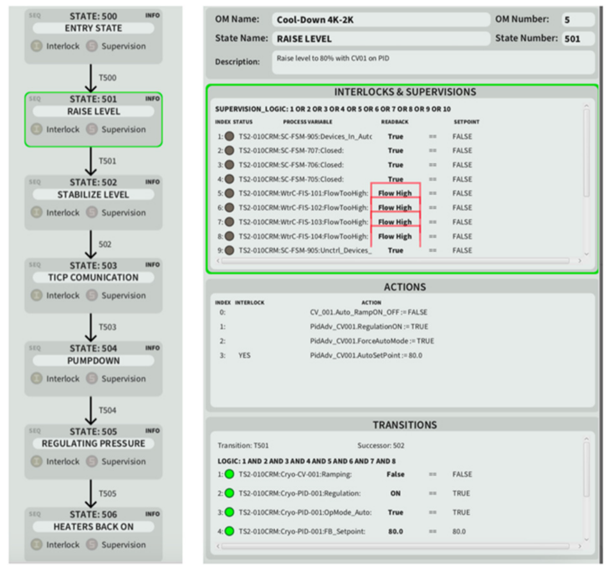

Figure 4: Sequence visualization (left) and state information panel (right).

RESULTS

The pilot CMDS control system was successfully implemented at TS2 during CM09 SAT, allowing for the complete cool-down to 2K, verifying six out of eight OM.

Operators feedback confirms that the necessary functions for the linac implementation are being addressed.

The design shows the required robustness, flexibility, responsiveness and aesthetics, offering a common point-of-truth between process and controls integration.

Based on these results, recommendations for future improvements have been identified and are being addressed, such as: Customized device controls fine-tuned to suit the specific requirements of the ACS, ensuring seamless integration and optimal performance; Empowering operators with the capability to make necessary adjustments to setpoints, thereby enabling real-time optimization and responsiveness to changing conditions or demands; Implementing robust safeguards and proactive measures to anticipate, detect, and address potential failures, ensuring system reliability, uptime, and operational continuity.

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