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Commissioning and Operational Performance of the ESS Linac Cryomodules Cryogenic Control System: Achievements and Future Prospect

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Abstract. The Cryomodules are essential components of the European Spallation Source (ESS) accelerator, connecting spoke cavities to medium- and high-beta elliptical cavities in the SRF Linac. They create a superconducting environment at 2K, enabling proton acceleration from 90 MeV to 2.0 GeV. Each Spoke Cryomodule contains two double-spoke cavities, while MBL and HBL cryomodules house four elliptical cavity packages. In total, ESS will install 13 SPK, 9 MBL, and 21 HBL cryomodules. Cryogenic circuits are controlled using sensors, heaters, and valves managed by a Programmable Logic Controller (PLC), integrated with EPICS via the Controls Network. After individual cryomodule commissioning, system-wide control coordination was implemented using a Master PLC with Automatic Control Sequence (ACS) and safety features. These controls were integrated into the CMDS master system, enabling simultaneous operation across all cryomodules and the distribution system. In December 2024, the commissioning was successfully completed, cooling the ESS Linac to 2K. This paper outlines the challenges of integrating cryomodule controls into CMDS, highlights the coordination achievements via the Master PLC, and discusses initial system operations during the cooldown phase. Plans for further developments in Accelerator Cryogenic Controls are also addressed.

1. Introduction

The European Spallation Source (ESS) is a multidisciplinary research facility designed to provide the world's most powerful neutron source. Located in Lund, Sweden, the ESS accelerator is fundamental for producing high-intensity neutron beams to support scientific research in fields such as materials science, biology, and energy technology [1]. A critical component of this infrastructure is the Superconducting Radio Frequency (SRF) Linac, which relies on 43 cryomodules—13 Spoke (SPK), 9 Medium-Beta (MBL), and 21 High-Beta (HBL)—to accelerate protons from 90 MeV to 2.0 GeV. These cryomodules must operate at cryogenic temperatures of 2K to maintain superconducting conditions.

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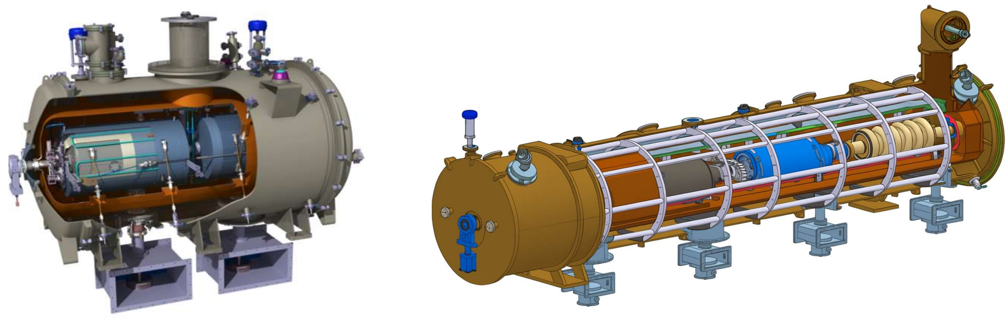

Figure 1. SRF Linac Cryomodules conceptual model - Spk (left), ELL (right)

The complexity and scale of the cryogenic environment demand a robust and automated control solution. To meet this need, a distributed cryogenic control system was developed using a Programmable Logic Controller (PLC) architecture integrated into the Experimental Physics and Industrial Control System (EPICS) framework. Each cryomodule includes sensors, actuators, heaters, and automatic valves, all coordinated through an individual control system.

A pivotal element in the successful commissioning of this infrastructure was the implementation of the *Automatic Control Sequence (ACS)*, coordinated centrally by the CMDS Master PLC. The ACS operates using Finite State Machine (FSM) logic, defining specific operational states, transitions, and actions for each cryomodule. Transitions only occur when predefined conditions are met, often with built-in delays for system stability. Safety interlocks and supervision mechanisms are embedded to ensure safe progression and to halt operations in the presence of faults, even though Safety Functions and Interlocks (SFI) function independently of the ACS logic [2].

Integrating the individual ACS units into a centralized Master ACS within the Cryomodule Distributed System (CMDS) allowed for synchronized and automated operation across all cryomodules and the cryogenic distribution network [3]. The operator interface provides real-time supervision with clear, intuitive controls for both global system oversight and detailed module-level management, significantly improving operational safety and efficiency.

The final commissioning phase culminated in December 2024 [4], with the successful cooldown of the SRF Linac to 2K. This marked a major milestone, validating the integrated control approach and highlighting the importance of the ACS in achieving stable and coordinated cryogenic operations. The development and deployment of this system not only addressed critical operational needs but also overcame key challenges, offering valuable lessons for large-scale cryogenic automation in advanced research facilities.

2. CMDS Control System Architecture

The Cryomodule Distributed System (CMDS) at the European Spallation Source (ESS) is built upon a hierarchical and modular control system designed to ensure the synchronized, safe, and efficient operation of all cryogenic components in the SRF Linac [5]. At the core of this architecture is the CMDS Master PLC, which serves as the central coordination unit, responsible for supervising and synchronizing all local control units across the facility. Each cryomodule and its associated valve-box are managed by a dedicated local PLC, which handles real-time control of sensors, actuators, heaters, automatic valves and Local ACS. These local PLCs operate independently but follow command sequences coordinated by the Master PLC. The Master PLC ensures consistent signal exchange, state synchronization, and global process alignment across the entire cryogenic system.

In addition to the cryomodule PLCs, the Master PLC is interconnected with specialized PLCs responsible for other key cryogenic subsystems, including the ACCP (Cryoplant interface), the Cryogenic Transfer Line (CTL), and the Endbox. This interconnected network enables comprehensive coordination of cryogen distribution, cooldown procedures, and fault management across all subsystems.

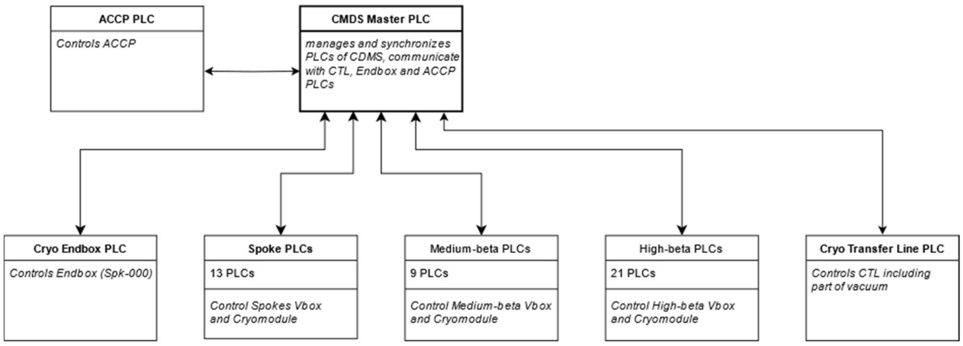

Figure 2. Hierarchical control system showing Master PLC, local PLCs and integration.

Communication across architecture is facilitated through the PROFINET between the PLCs and via Experimental Physics and Industrial Control System (EPICS) [6] to provide centralized supervisory control and data acquisition. Operators interact with the system via user-friendly interfaces that offer both global overviews and detailed control views at the cryomodule level. The architecture supports closed-loop control, enabling real-time monitoring and automated adjustments of key parameters such as temperature, pressure, level, and flow to maintain optimal cryogenic conditions.

At the core of this automation is the Automatic Control Sequence (ACS), which uses Finite State Machine (FSM) logic within the CMDS Master PLC to drive and coordinate the execution of cryomodule operations across all integrated systems.

3. Automatic Control Sequence (ACS)

The Automatic Control Sequence (ACS) is a core component of the cryomodule control system at the European Spallation Source (ESS), providing the structured automation necessary for reliable and synchronized operation of all cryogenic processes [7]. Integrated into the CMDS Master PLC, the ACS is built on Finite State Machine (FSM) logic, which guides the system through a predefined series of states, ensuring that each cryomodule transitions in a controlled, sequential, and fault-tolerant manner.

At its core, the ACS is designed to provide consistent, step-by-step progression through the various operational states of each cryomodule, defined by a set of parameters and conditions that reflect the cryomodule's physical and operational covering initialization, cooldown, steady-state operation, and fault recovery. Each state is uniquely status.

Each operational mode within the ACS defines a set of states and transitions that direct the cryomodule through a specific process, such as cooldown or warm-up. A state represents a stable condition of the system, characterized by a unique identifier, a descriptive name, an explanation of its function, and a timeout period. If the conditions required for the state are not fulfilled within the given time, the system flags an error, preventing progression until corrective action is taken.

Transitions are logical links between states and occur only when all predefined conditions are satisfied [6]. These transitions can include operational delays, known as transition delays,

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which are applied after conditions are met but before moving to the next state, ensuring system stability. Within each state, actions are performed to control devices such as valves and heaters. These actions are subject to interlocks—logical constraints that prevent execution unless certain safety and process criteria are met.

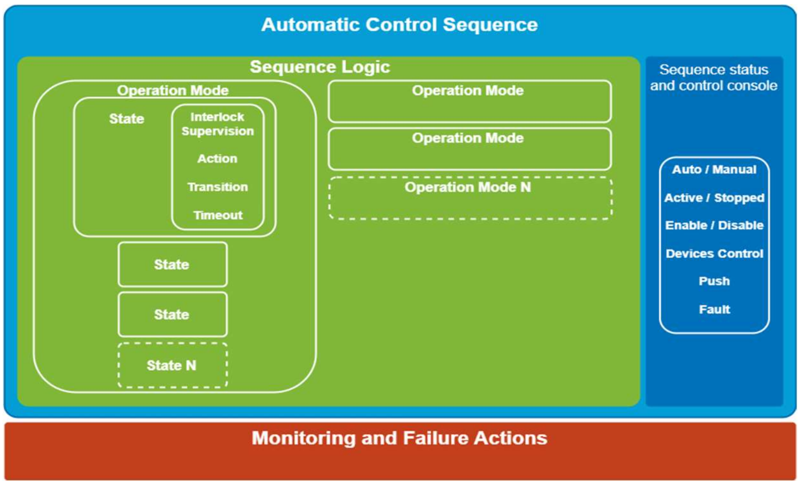

Figure 3. Automatic Control Sequency Logic Diagram

The system also incorporates a robust supervision mechanism, which continuously monitors faults and alerts operators to any irregularities. When a fault is detected, the ACS halts its progression and remains in the current state until the issue is resolved and acknowledged. This ensures that all operational anomalies are addressed before the system continues, reinforcing both safety and reliability.

Although Safety Functions and Interlocks (SFI) operate independently from the ACS logic, their behaviour is closely linked to its operation [8]. These functions are always active, regardless of whether the ACS is running, and they serve to monitor critical conditions. If any monitored parameter deviates beyond acceptable limits, the SFIs can interrupt ACS execution. In some scenarios, the behaviour of these safety systems may depend on the ACS operation mode, further highlighting their interdependence.

The ACS follows strict design rules to guarantee safe and predictable system behaviour. One of the foundational principles is Exclusive Activation, which ensures that only one step or state is active at any given time—parallel or simultaneous actions are strictly avoided. This provides a clear and conflict-free execution path. Another key rule is Sequential Progression, requiring that the ACS advance step-by-step in a predefined order, including dedicated waiting steps where necessary to manage timing and synchronization. Additionally, all devices involved in the ACS must be set to Automatic Mode, ensuring that every component is properly configured for automated control. This condition is essential for full system functionality and seamless execution of the control sequence.

Together, these structural elements and design rules form a robust, scalable, and fault-tolerant automation framework. The ACS has been instrumental in the commissioning of cryomodules at ESS, enabling coordinated operations, precise process control, and safe system behaviour across the entire cryogenic infrastructure.

However, to fully realize the benefits of this structured control logic, it was essential to move beyond isolated cryomodule automation. The next step in enhancing system performance was the integration of all individual ACS units into a centralized coordination platform, managed by the

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CMDS Master PLC. This integration enables the synchronization of all cryomodules and cryogenic subsystems, ensuring a coherent and unified approach to automation throughout the facility.

4. CMDS and ACS

4.1 Integration

The integration of the individual Automatic Control Sequences (ACS) into the central Cryomodule Distribution System (CMDS) Master PLC represents a pivotal advancement in the automation architecture of the ESS cryogenic infrastructure [8]. By connecting all cryomodule PLCs—including their valve boxes, the endbox, and the cryogenic distribution lines—with the CMDS Master, the system achieves a fully coordinated and synchronized control environment.

This centralized integration allows the CMDS Master PLC to oversee and harmonize the behaviour of every cryomodule's ACS, ensuring that operations such as cooldowns, transitions to steady-state, or warm-ups happen in a logically sequenced and globally aware manner. It minimizes operational conflicts, avoids overlapping actions between modules, and supports efficient load management on the Cryoplant and distribution subsystems.

One of the key benefits of this integration is the implementation of a unified operator interface [9], which consolidates control and monitoring across the entire cryomodule network. Designed for clarity and ease of use, the interface provides real-time system oversight with intuitive screens that allow users to navigate from high-level facility views down to detailed, per-module diagnostics and commands. This structured visualization enables operators to monitor the overall system status while also managing individual cryomodules as needed—enhancing responsiveness, safety, and operational insight.

In effect, the integration of ACS logic into the CMDS control layer transforms a collection of independently functioning systems into a cohesive, centrally managed automation framework [5]. This approach supports reliable system-wide coordination, accelerates commissioning and recovery procedures, and reinforces the overall safety and efficiency of the ESS cryogenic operations.

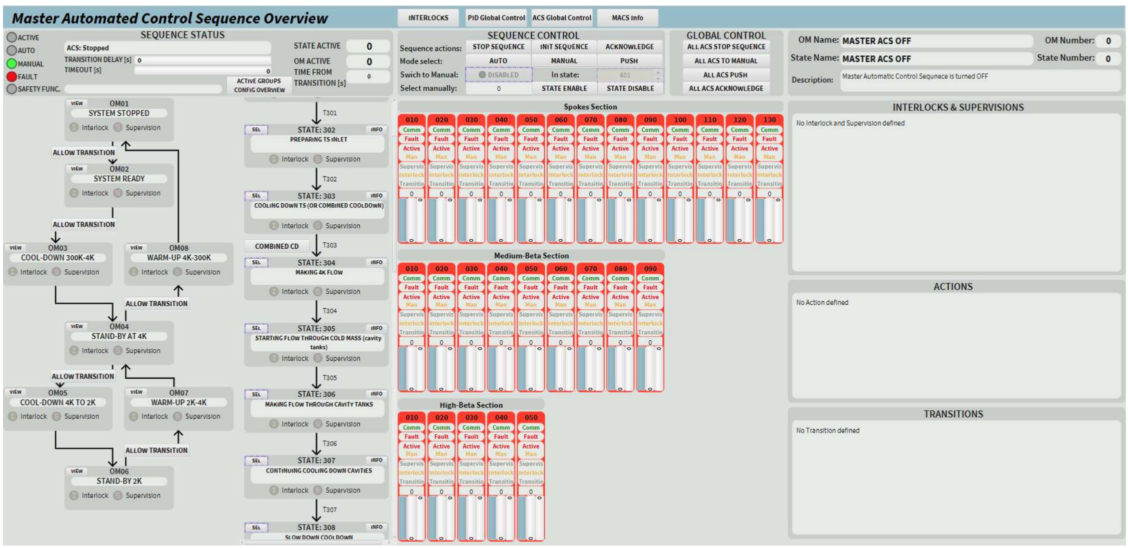

Figure 4. CMDS Master and Cryomodule ACS Operator Interface

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4.2 COMMISSIONING

The commissioning phase of the CMDS and ACS control system marked a critical step in ensuring the reliable and safe operation of the cryogenic infrastructure. It began with the verification of each CMDS PLC device [4], followed by testing the communication logic among PLCs and validating the Automatic Control Sequence (ACS) functionality across all cryomodules [10]. Next, the interfaces for Safety Functions and Interlocks (SFI) were tested—first between the CMDS Master PLC and the ACCP (Cryoplant) PLC, and then between the CMDS Master and the individual CMDS PLCs[11].

This commissioning process followed a structured testing procedure divided into four key stages:

1. General Verification: Ensured that the necessary infrastructure was in place to support the CMDS, ACS, and SFI control systems.
2. Functional Verification: Confirmed proper integration of the ACS with the control system, validated signal exchange with the Operator Interface (OPI), and verified that the control logic was implemented according to specifications.
3. Constraints Verification: Assessed hardware compatibility, device control, setpoint management, error handling, and the correct activation of safety constraints and interlocks. Finally,
4. Interface Verification: Validated communication reliability, time synchronization, and EPICS integration between ACS and CMDS PLCs, as well as proper fault detection under error scenarios.

The successful completion of these steps provided a robust foundation for centralized coordination of all cryomodules through the CMDS Master PLC—laying the groundwork for full system integration. This integration not only streamlined automation but also revealed critical technical insights during development and operation, exposing both the strengths and the challenges of deploying such a distributed control architecture. These experiences form the basis for a deeper look into the key challenges faced and the achievements made throughout the CMDS and ACS implementation process.

4.3 1st LINAC Cool Down

The successful commissioning of the ESS cryogenic control infrastructure demonstrated the effective integration of 47 PLCs into a synchronized and reliable system. Through the implementation of a structured Automatic Control Sequence (ACS), robust interlocking logic, and central Master PLC, the system achieved coordinated and safe operation across all cryomodules. Challenges such as communication management, debugging of complex sequences, and system safety were overcome through iterative improvements, interface enhancements, and continuous testing.

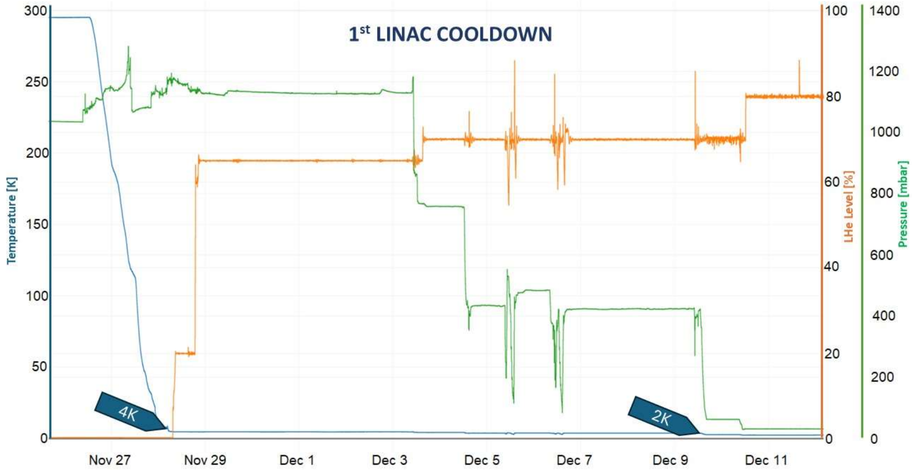

Figure 5. 1st LINAC Cool Down Progress

This solid foundation enabled the successful execution of the first ESS LINAC cooldown in winter 2024. Despite technical difficulties, including sensor failures, cold compressor trips, and valve regulation issues, the system achieved stable 2K conditions across most cryomodules. The experience validated the ACS framework and highlighted areas for refinement, reinforcing the system's reliability and setting the stage for future operational cycles.

5. CHALLENGES AND ACHIEVEMENTS

The development of the CMDS and ACS control infrastructure introduced significant challenges, particularly in achieving synchronized coordination among 43 distributed PLCs across cryomodules/valve boxes, plus the Cryoplant (ACCP) and endbox systems. Ensuring consistent finite state machine (FSM) behaviour, precise timing, and reliable communication was essential for integrated control.

Debugging the Automatic Control Sequence (ACS) revealed subtle issues such as misconfigurations and code typos that impacted system stability. Integrating new features without disrupting existing functions required cautious planning, especially within the EPICS environment, all while maintaining stringent safety through robust interlocks and supervision logic.

Despite the complexity, key advancements included improvements to the FSM code generator, development of simulation models, enhanced interlocking logic, and redesigned HMIs. These achievements laid a solid foundation for future system refinements and more efficient commissioning strategies.

6. Future Activities

Looking ahead, the next major phase will focus on the installation, integration, and commissioning of six additional High Beta (HBL) cryomodules in the ESS Linac, scheduled for summer 2025. These activities will follow the validated framework established during the initial commissioning, leveraging the CMDS and ACS architecture to enable a smooth and coordinated integration process. Lessons learned from the first cooldown and previous deployments will guide the refinement of procedures, sequence adjustments, and test strategies to streamline the ramp-up of new modules.

In parallel, efforts will continue to enhance system resilience by introducing redundancy at the field level. This includes integrating devices from different manufacturers to mitigate risks associated with hardware failures or vendor-specific limitations. These improvements aim to strengthen system reliability, ensure long-term maintainability, and future-proof the control infrastructure for the evolving demands of the ESS accelerator.

7. Conclusion

The commissioning of the CMDS and ACS systems at the European Spallation Source (ESS) successfully addressed complex challenges involving the integration of 43 PLCs and devices across a distributed architecture. Through careful design, robust communication, and FSM-based control logic, the system achieved synchronized, safe, and reliable operation. Key improvements included enhanced interlock logic, refined operator interfaces, and the introduction of new functionalities without disrupting existing processes. These efforts culminated in the first successful LINAC cooldown to 2K in winter 2024, despite technical issues such as sensor faults and compressor trips. The experience not only validated the system's performance but also laid a strong foundation for future operations and continued system evolution.

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