ISBN: 978-3-95450-255-4 ISSN: 2226-0358 doi: 10.18429/JACoW-ICALEPCS2025-WEPD061

SIMPLIFYING CRYOGENIC PROCESS CONTROL AT ESS LINAC THROUGH AUTOMATION: DEVELOPMENT AND INTEGRATION OF AN AUTOMATIC CONTROL SEQUENCE

W. Bińczyk†[1,2], D. Domagała[1], N. Elias[2], M. Skiba[2], E. Asensi[2], A. Fontoura[2], H. Cardona[2,4], N. Baskar[2], A. Rizzo[2], P. Arnold[2], J. Zhang[2], P. Nilsson[2], P. Hałczyński[3], W. Gaj[3]
[1]S2Innovation, Krakow, Poland
[2]European Spallation Source, Lund, Sweden
[3]IFJ-PAN, Krakow, Poland
[4]AFRY, Stockholm, Sweden

Abstract

This paper presents the Automatic Control Sequence (ACS) developed and implemented to simplify the control of cryogenic processes in the linear accelerator (LINAC) at the European Spallation Source (ESS), which includes 27 cryomodules and 43 valveboxes. The main objectives of the project were to reduce the risk of human error and minimize manual operations — while maintaining full decision-making authority in the hands of the operator. The sequence is designed through interdisciplinary collaboration, with Excel serving as a database for information exchange in human readable form. A custom Python script is then used to generate PLC code in SCL programming language based on the defined logic. The final sequence is deployed on a master PLC and 43 dedicated PLCs, fully integrated with the EPICS control system and interconnected via Profinet for optimized system synchronization. A user-friendly operational interface was developed using CS-Studio, serving as both a monitoring and control layer. It provides visibility across all levels of the control system — from individual devices, through local PLC sequences, up to inter-system synchronization. This paper provides an overview of the development of the Automatic Control Sequence and discusses key lessons learned in this process as well as possible future improvements in cryogenic control at ESS.

INTRODUCTION

Cryogenic systems are indispensable for superconducting accelerators. At the European Spallation Source (ESS), stable cryogenic conditions ensure that superconducting radio-frequency (SRF) cavities remain below their critical temperature, enabling efficient acceleration of high-intensity proton beams. The accelerator complex ultimately aims for 5 MW of beam power, supported by 27 cryomodules and 43 valveboxes integrated into the linear accelerator (LINAC). Each cryomodule must be carefully cooled to 2 K, maintained within tight stability margins and synchronized with the ACCP [1].

Manual Control Challenges

Prior to the introduction of ACS automation, cryogenic operations were almost entirely manual. Operators carried out lengthy procedures consisting of valve actuation, heater adjustments, and pressure monitoring. These operations were often repeated, resulting in a substantial burden during testing in Test Stand 2 (TS2), which is a CRMs commissioning installation [2, 3]. As reported during commissioning campaigns and activities performed in cryomodules, manual procedures carried several risks:

- High workload for control room operators, who had to track dozens of concurrent actions.
- Increased risk of human error, such as mis-timed manipulations.
- Inconsistency between different operators, which sometimes led to variations in cooldown and warm-up results.
- Increased risk of failure during night shifts.

This operational reality motivated the design of an Automatic Control Sequence (ACS). The ACS sought to simplify the control of cryogenic processes, reduce operator workload, and improve reliability and reproducibility. Importantly, its design philosophy emphasized that automation should support, not replace, operator authority.

SYSTEM OVERVIEW

As shown in Fig. 1, the cryogenic infrastructure of the ESS LINAC is composed of three interlinked subsystems:

- Accelerator Cryogenic Plant (ACCP). Provides helium at the necessary temperatures and pressures.
- Cryogenic Distribution System (CDS). Transports helium from the ACCP to the accelerator tunnel, including transfer lines and 43 valveboxes, one for each cryomodule.
- Cryomodules (CRM). Distributing helium flows and regulating cavity conditions.

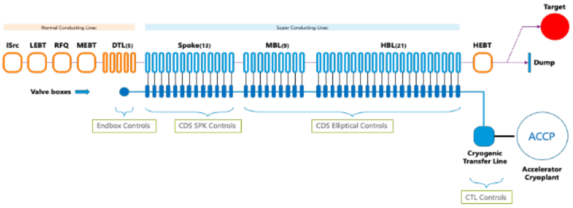


Figure 1: Overview of the system parts.

---

† wojciech.binczyk@s2innovation.com

ISBN: 978-3-95450-255-4 ISSN: 2226-0358 doi: 10.18429/JACoW-ICALEPCS2025-WEPD061

The controls are implemented using Siemens S7-1500 PLCs. Each valvebox has its own local PLC, and additionally there is the master PLC which coordinates their activities. Communication is carried out over a dedicated Profinet network, chosen for its robustness.

This distributed architecture provides modularity and resilience, because the local PLCs can independently manage valvebox operations, while the master PLC ensures global coordination and propagates interlocks. However, without automation, the same structure demands high levels of operator attention to maintain synchronization—a key challenge the ACS addresses [4, 5].

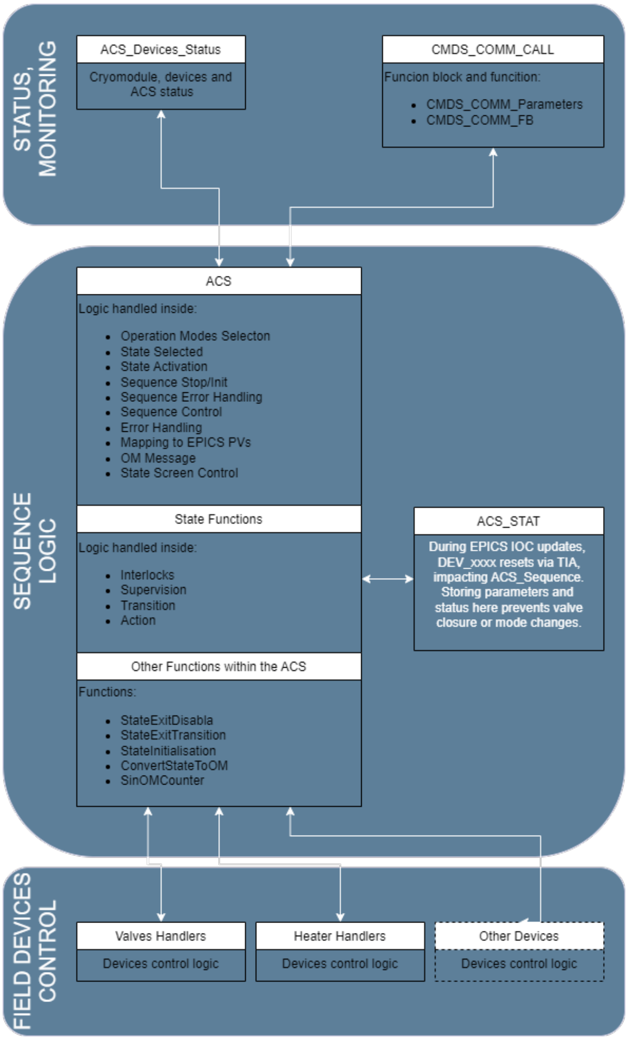
Initial Cryogenic Commissioning

Before connecting the CRMs, the CDS underwent extensive pre-commissioning and initial cooldown campaigns. Tests were first performed on the valveboxes with endcaps instead of CRMs attached, enabling leak detection, calibration of sensors, and validation of valve performance. In December 2022, the first integrated cooldown of the ACCP together with the CDS was carried out, bringing the system from ambient temperature to 8 K in roughly 1.5 days. These early operations revealed thermo-acoustic oscillations and valve seat leakages, which were subsequently mitigated through hardware modifications.

In a subsequent campaign, two pilot CRMs (one elliptical and one spoke) were connected to the CDS. The system was cooled down to 2 K using both warm and cold compressors of the ACCP, marking the first successful validation of the full distribution system with CRMs in place [6]. These staged cooldowns were crucial milestones, providing operational experience and resolving technical issues before the large-scale LINAC installation [7]. By December 2024, a total of 27 CRMs had been installed and commissioned, providing the operational basis for the first beam operations of the ESS SRF Linac [8].

ACS ARCHITECTURE AND WORKING PRINCIPLES

The Automatic Control Sequence (ACS) for the Cryomodule Distribution System (CMDS) is structured (see Fig. 2) according to the principles of a finite-state machine (FSM), which provides a rigorous and deterministic framework for cryogenic process control. This formalism ensures that transitions between operating conditions occur only under well-defined prerequisites, while preserving flexibility for operator intervention.



During EPICS IOC updates, DEV_xxxx resets via TIA, impacting ACS_Sequence. Storing parameters and status here prevents valve closure or mode changes.

Figure 2: ACS components hierarchy and overview.

Finite-State Structure

The FSM decomposes cryogenic procedures into discrete states, each representing a thermodynamic condition of the system. Typical examples include Cooldown from 300 K to 4 K, Stable at 4 K, or Maintain 2 K steady state. Within each state, a set of control actions is defined—such as valve actuation, heater operation, and regulation setpoints—accompanied by timeouts and descriptive parameters.

Transitions connect states, which are activated only when explicit conditions are fulfilled, typically involving pressure, temperature, or flow thresholds. Transitions may incorporate delays or be suspended entirely if interlock conditions are violated. The ACS therefore guarantees sequential progression of steps, precluding parallel or undefined activities, and halts the sequence whenever a supervision condition indicates instability or other potential failures.

ISBN: 978-3-95450-255-4 ISSN: 2226-0358 doi: 10.18429/JACoW-ICALEPCS2025-WEPD061

Operating Modes

Groups of states form higher-level Operating Modes (OMs), each encapsulating a complete cryogenic procedure. At ESS, the ACS defines OMs covering the full CRM lifecycle: System Stopped, System Ready for Cooldown, Cooldown 300 K–4 K, Stable at 4 K, Cooldown 4 K–2 K, Stable at 2 K (with optional RF/beam operation), and Warm-up modes returning the system to ambient conditions

This hierarchical organization allows complex processes to be initiated as single operational commands, while preserving full visibility into intermediate states.

Design Constraints

To ensure safe and reproducible operation, the ACS adheres to strict design constraints:

- *Exclusive activation* – only one state may be active at any given time; parallel execution is prohibited.
- *Sequential progression* – advancement is strictly ordered, with waiting states providing methodical flow control.
- *Stable terminal state* – the final state of Operation Mode defines a safe, steady operating condition.
- *Device autonomy* – all field devices must be set to automatic mode before sequence initiation.

Distributed Control

Execution of the ACS is distributed across the CMDS control system. Local PLCs govern valvebox- and cryomodule-level instrumentation, ensuring responsiveness to local conditions. The Master PLC supervises a global coordination, propagating interlock signals and synchronizing progress across multiple CRMs. Importantly, individual CRMs can be excluded from a cooldown sequence in the event of a failure, without interrupting the cooldown of the entire accelerator. Conversely, a single CRM can be cooled down independently and subsequently synchronized with the rest of the system. This layered control scheme combines the reliability of local autonomy with the consistency of centralized oversight.

Operators remain part of the control loop through the supervisory interface. Three execution modes are supported: fully automatic progression, assisted operation requiring confirmation of transitions, and manual control permitting direct step selection. This arrangement balances determinism with operator flexibility, ensuring that routine procedures advance reliably while preserving the ability to intervene under exceptional circumstances.

DEVELOPMENT OF THE AUTOMATIC CONTROL SEQUENCE (ACS)

The ACS was developed through interdisciplinary collaboration between cryogenics engineers, control specialists, and operators. This teamwork ensured that the automated logic captured both the technical requirements of the cryogenic plant and the practical realities of daily operation. The collaboration was structured around three main pillars.

Excel as the Specification Hub

The starting point was a structured spreadsheet in which each sheet represented an Operating Mode (OM). Rows captured states and transitions, while columns specified actions, interlocks, delays, and exit conditions. This approach provided all stakeholders with a transparent and editable specification and established a single, authoritative source of truth for the sequence logic.

Python-Based Code Generation

A dedicated python script is used to parse the .xslx files and to automatically generate Structured Control Language (SCL) code for Siemens PLCs. A second script is used to create operator interface panels in CS-Studio from the same specification. This workflow (see Fig. 3) minimized manual coding effort, improved consistency, and ensured perfect alignment between the implemented control logic and the user interface.

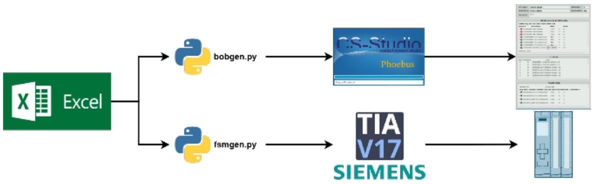


Figure 3: Workflow overview.

Iterative Testing

The ACS was piloted at a cryogenic test TS2, where six of the eight planned Operating Modes were successfully validated, including cooldown and steady-state operation [9, 10]. In the first release, the following Operating Modes were implemented: System Stopped, System Ready, Cooldown 300 K–4 K, Stand-by at 4 K, Cooldown 4 K–2 K, and Stand-by at 2 K. In the next step, the ACS was repeatedly validated on each Local PLC to verify correct code implementation and to identify any potential sequence oversights.

INTEGRATION INTO THE CONTROL INFRASTRUCTURE

The ACS was embedded within the ESS control system environment. Each PLC communicates with an EPICS input-output controller (IOC), making ACS data accessible for archiving, alarms, and higher-level applications. This integration ensures that cryogenic operations are visible across the entire accelerator facility and can be correlated with other subsystems.

User panels (see Figs. 4 and 5) were created using CS-Studio Phoebus. Three types of panels are central to the operator experience:

- *Sequence console.* Displays the active state, timers, and any detected faults. Operators can switch between automatic, assisted, or manual execution.
- *OM overview.* Provides a graphical map of all Operating Modes, highlighting active state.

- *State details.* Show the interlocks, actions, and conditions governing each state, using consistent color coding and layout conventions.

This design improves transparency: operators can easily see what the ACS is doing and why, reducing hesitation in trusting the system.

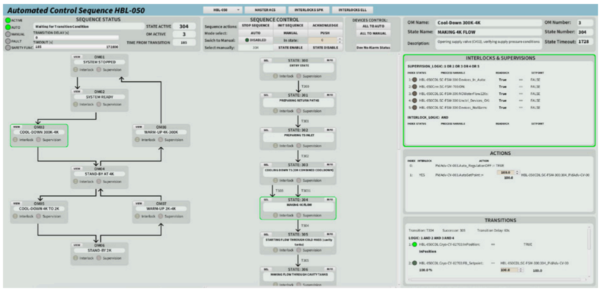


Figure 4: Local ACS OPI, graphically representing state.

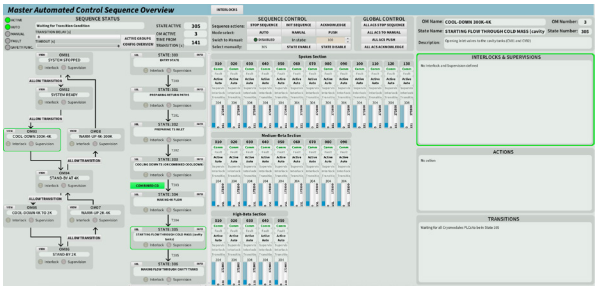


Figure 5: Master ACS OPI.

RESULTS AND ACHIEVEMENTS

The ACS was applied during the first integrated cooldown of the ESS LINAC, successfully managing 27 CRMs and their corresponding valveboxes under coordinated control. The experience demonstrated that the ACS is not only a practical tool but also an essential component of large-scale cryogenic operations. Several key outcomes were observed:

- *Reduction of human error risk.* By enforcing formalized transitions and conditional checks, the ACS eliminated skipped steps and significantly reduced operator mistakes possibility. Each state required verification of preconditions, ensuring that unsafe or incomplete operations could not proceed.
- *Increased efficiency.* Synchronization across multiple CRMs shortened overall cooldown times and reduced idle waiting. For the 2024 campaign, a single operator was able to oversee and control all cryomodules, a feat that would have been impossible with purely manual operation. The LINAC was cooled to 4 K within three days (see Fig. 6) and stabilized at 2 K within one week, marking a performance level unattainable without automation.
- *Operational consistency.* Automated execution guaranteed that procedures were carried out identically across shifts and operators, enhancing reproducibility and improving reliability of system performance.
- *Retention of operator authority.* Despite a high degree of automation, operators remained central to the process. Assisted and manual modes allowed for intervention whenever conditions required it, thereby maintaining confidence in the system and ensuring safe fallback mechanisms.

Operators' feedback during commissioning confirmed that the ACS reduced workload while preserving the ability to intervene when necessary. This balance between automation and human oversight proved to be essential in building trust in the system and in securing stable operation of the superconducting LINAC.

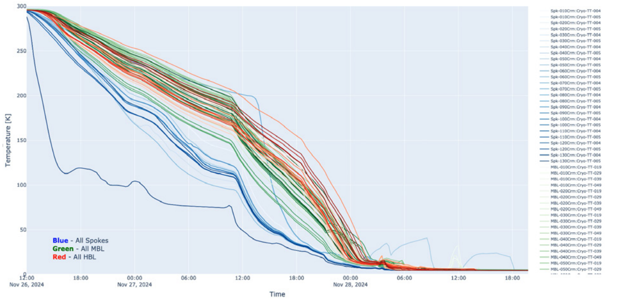


Figure 6: Temperatures of 27 cryomodules during cooldown using ACS.

LESSONS LEARNED AND FUTURE WORK

Lessons Learned

Several important lessons emerged from the development and commissioning of the Automatic Control Sequence (ACS):

- *Excel as sequence definition interface*. Simple spreadsheet-based tools proved to be highly effective for bridging different engineering disciplines, ensuring transparency, traceability, and a shared understanding of the control logic.
- *Automation in safety-critical systems* requires careful design. Preserving manual authority was indispensable both for maintaining operator trust and for safeguarding overall system integrity.
- *Standardization enhances usability.* Consistent layouts and color schemes in operator interfaces significantly improved usability and facilitated more efficient operator training.

Future Improvements

Although the ACS has already demonstrated its effectiveness, further enhancements are both possible and desirable:

- *Dedicated sequence definition interface***.** Introduction of a specialized interface for defining and managing operational sequences will allow clearer configuration, reduce the risk of errors, and improve the overall flexibility of system control.
- *Transition to a structured database.* Replacement of Excel with a dedicated yaml-based database, complemented by a custom dedicated editor, is planned to enable streamlined and error-free modifications while

maintaining consistency across all system components.

- *Enhanced diagnostics and logging.* More advanced diagnostic tools and logging mechanisms will improve fault detection, facilitate troubleshooting, and support systematic performance analysis.
- *Refinement of operator interfaces.* Continued improvements to operator panels will simplify complex procedures, making the system more intuitive and less error-prone.

The principles of the ACS may be expanded to additional cryogenic subsystems, thereby supporting ESS’s long-term objective of operating at its full 5 MW beam power.

CONCLUSION

The Automatic Control Sequence represents a significant advancement in cryogenic process control at ESS. By combining finite-state machine logic, automatic code generation, and full integration with EPICS and CS-Studio, the ACS has improved reliability, efficiency, and consistency across a large and complex cryogenic system.

Most importantly, the ACS achieves these improvements without removing the operator from the loop. Automation handles repetitive, error-prone tasks, while operators retain decision-making authority and intervention capability. This balance—automation for efficiency, human oversight for safety—is central to the success of the project.

As ESS advances toward higher power operations, the ACS provides a foundation for scalable, reliable cryogenic control. Its design principles may also serve as a model for other large accelerator facilities facing similar challenges.

REFERENCES

[1] R. Garoby *et al.*, “The European Spallation Source Design,” *Phys. Scr.*, vol. 93, no. 1, p. 014001, Dec. 2017. doi:10.1088/1402-4896/aa9bff

[2] E. Asensi Conejero *et al.*, “Commissioning the Control System for Cryomodule Cryogenics Distribution System in Test Stand 2”, in *Proc. ICALEPCS'19*, New York, NY, USA, Oct. 2019, pp. 204. doi:10.18429/JACoW-ICALEPCS2019-MOPHA009

[3] E. Asensi Conejero *et al.*, “The Cryomodule Test Stands for the European Spallation Source”, in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 1064-1067. doi:10.18429/JACoW-IPAC2017-MOPVA089

[4] E. Asensi *et al.*, “Design, development and commissioning of the control system for the cryogenic distribution system at ESS,” *IOP Conf. Ser.: Mater. Sci. Eng.* , vol. 1301, no. 1, p. 012078, May 2024. doi:10.1088/1757-899x/1301/1/012078

[5] E. Asensi *et al.*, “Design, implementation, and preliminary testing of the interlocks and safety functions for the CMDS (cryomodule and cryogenic distribution system) master system at the European Spallation Source ERIC,” *IOP Conf. Ser.: Mater. Sci. Eng.* , vol. 1327, no. 1, p. 012186, May 2025. doi:10.1088/1757-899x/1327/1/012186

[6] P. Arnold *et al.*, “Commissioning of the cryogenic distribution system of the ESS superconducting linac,” *IOP Conf. Ser.: Mater. Sci. Eng.* , vol. 1301, no. 1, p. 012084, May 2024. doi:10.1088/1757-899x/1301/1/012084

[7] A. Fontoura *et al.*, “Commissioning of the Cryogenic control system for Cryomodules at ESS SRF Linac,” *IOP Conf. Ser.: Mater. Sci. Eng.* , vol. 1327, no. 1, p. 012166, May 2025. doi:10.1088/1757-899x/1327/1/012166

[8] H. Przybilski *et al.*, “ESS installation progresses”, in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 2736-2738. doi:10.18429/JACoW-IPAC2024-WEPS19

[9] N. Elias *et al.*, “Implementation and experience with the pilot CMDS control system at TS2, in view of operating the ESS LINAC cryogenics”, in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 3754-3757. doi:10.18429/JACoW-IPAC2024-THPS13

[10] N. Elias *et al.*, “The testing experience of the cryomodules for the ESS beam on target phase at 2 MW capability”, in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 1949-1952. doi:10.18429/JACoW-IPAC2024-WECN3