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ESS DRIFT TUBE LINAC CONTROL SYSTEM COMMISSIONING: RESULTS AND LESSONS LEARNED

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Abstract

European Spallation Source (ESS) will be a neutron source using proton beam Linac of expected 5MW beam power. Designed and implemented by INFN-LNL, the Drift Tube Linac (DTL) control system is based on EPICS framework as indicated by the Project Requirements. This document aims to describe the results of the first part of the control system commissioning stage in 2022, where INFN and ESS teams were involved in the final tests on site. This phase was the first step toward a complete deployment of the control system, where the installation was composed by three sequential stages, according to the apparatus commissioning schedule. In this scenario, the firsts Site Acceptance Test (SAT) and Site Integrated Test (SIT) were crucial, and their results were the milestones for the other stages: the lessons learned can be important to speed up the future integration, calibration, and tuning of such a complex control system.

DTL CONTROL SYSTEM ARCHITECTURE

Given the nature of the project and the involvement of multiple individuals across different levels, the design and implementation of the DTL Control System must adhere to meticulous strategies and solutions, aiming to optimize both costs and time throughout the installation campaign in Sweden. For control systems, the ESS [1] project guidelines indicate EPICS [2] as the standard for this topic.

The scope of the DTL CS is to provide the required software and hardware layers to operate the apparatus. It's important to note that not all functional sub-systems within the DTL fall under the purview of the INFN-DTL CS Group. Therefore, the control system architecture presented covered only a portion of these subsystems and all the remaining ones are designed, and implemented by ESS [3].

Figure 1 represents the schematic related to the control system architecture deployed for the DTL apparatus and it follows the standard 3-layer structure where, at the lowermost layer, encompasses all functional sub-systems of the DTL and it defines the context from which the input/output (I/O) signals originate. The intermediary layer delineates the array of controllers employed for executing the necessary logic and automation within the application, spanning both hardware and software realms. Within this layer, all EPICS Input/Output Controllers (IOCs) are tasked with running both the low-level interface applications and the high-level state machines (Control System Core). The uppermost layer includes the suite of services offered by ESS-ERIC to facilitate routine operations of the Linac, such as Human-Machine Interface, Archiver service, and Alarms management system.

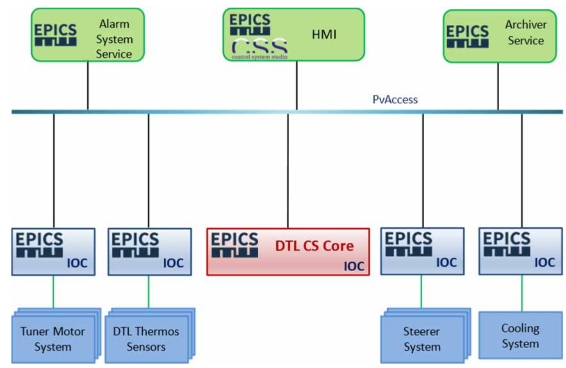

Figure 1: DTL 3-layer control system schematic.

Different functional sub-systems required different solutions for their implementation based on the design requirements and the possible technologies approved by the project. Where possible, common technologies among the systems were used to optimize development, maintenance, and costs. This approach defined the software architecture developed and the relative control system topology.

The principal technologies adopted are summarized in Table 1, while the primary details in terms of EPICS parameters are indicated in Table 2.

Table 1: DTL Functional Systems: HW, SW and Protocols

Sub-System	Technologies (HW, SW, Protocols)
High Level Control (CS Core)	• EPICS framework • No dedicated hardware
Tubes Thermos Sensors	• EPICS framework • Beckhoff hardware • EtherCAT protocol
Water Cooling Controls	• Siemens PLC low-level logic and EPICS integration
Tuning Motor System	• EPICS framework • Beckhoff hardware • EtherCAT protocol
Steerer System	• EPICS framework • Hardware provided by the tender • Serial and TCP-IP communication

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Table 2: DTL Control System – EPICS Details

	DTL Control System
Number of E3 modules	**10**
Number of EPICS IOCs	**5**
Number of Devices	Temp. Sensors: **178** Steerers: **30** Mobile Tuners: **15** Skid: **5** tank lines + **1** main line
Number of EPICS Variables	**18148** (considering all the PVs for the entire DTL)

INTEGRATION STRATEGIES AND VALIDATION PROCEDURES

Verification plans play a crucial role in the realm of control systems, providing a structured and meticulous approach to ensure the system's integrity and functionality are aligned with the intended specifications. The plan aims to confirm both the accuracy and reliability of the system operations by subjecting the control system to a series of rigorous tests and validations. These tests cover a wide array of scenarios and use cases, thoroughly examining the control system's behavior under various conditions.

Clearly defined criteria for success are established, stipulating the outcomes that each test must achieve to be deemed successful. This adherence to the verification plan serves as a safeguard, pinpointing any discrepancies or deviations in the control system's performance before it's deployed in production. Moreover, the plan encompasses considerations of interoperability, ensuring smooth integration with other systems and components.

Usually, a complete verification plan is composed of the preliminary Factory Acceptance Test (FAT) and the final Site Acceptance Test (SAT), where the system can be considered ready for production once this final test is passed with success.

Because of the dynamic nature of the project and the constraints coming from the COVID period, the DTL control system installation and validation schedule was modified and adapted to this new scenario. As a consequence, the number of validation stages increased and additional steps were defined. This approach was defined to minimize the stopping time caused by the limitation in travel and optimize the tests remotely where possible. The final validation schedule agreed between ESS and INFN-LNL is listed below:

- **1st Factory Acceptance Test (1st FAT)**: hardware and software verification using only the control system racks (performed at INFN-LNL, Italy);
- **2nd Factory Acceptance Test (2nd FAT)**: hardware and software verification using only the control system racks (performed at ESS-ERIC, Sweden) required by the need to unbundle and rebuild in the final racks' configuration the entire racks equipment;
- **Connection Test**: connection tests verification, checking the connection from the DTL tank to the racks;
- **DTL Water Cooling Control System Test**: the test covered the DTL Skid functionalities and the DTL Water Cooling system integration;

  Site Acceptance Test (SAT1): verification of the DTL Core Control System algorithms, from the low-level functionalities to the high-level orchestration. In addition, data archiving and alarm management should be ready for the SIT1 stage. The entire apparatus won't be completely available from the beginning and the different tanks composing the DTL will be installed, tested, and conditioned in different periods. For this reason, the DTL Control System SAT was split into 3 different SATs, where in every single stage a different set of tanks is going to be verified. Considering this peculiarity, the in-kind contract will be considered concluded after SAT3;
- **Site Integrated Test (SIT1)**: validation of the DTL control system with all the other functional systems provided by the other ESS groups and in-kinders. In this stage, the complete set of functional subsystems was ready to be orchestrated by the DTL apparatus.

To perform the different validation stages and in particular in actions performed remotely, two important aspects played a key role: teams' coordination and documentation. Documentation of the verification process created a comprehensive record, detailing the steps taken, tests conducted, and results obtained during the control system's evaluation. Any necessary adjustments or optimizations to the system's algorithms or parameters were identified and applied as part of the process.

CONTROL SYSTEM COMMISSIONING

The commissioning of DTL tank 1 involved several distinct steps, with each validation test being executable only upon successful completion of the preceding ones. Figure 2 illustrates the schematic of all the stages that were undertaken.

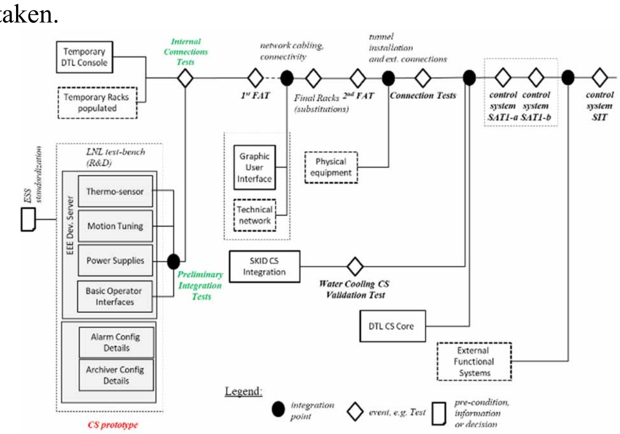

Figure 2: DTL commissioning process.

1st and 2nd FAT

The 1st FAT was performed at Legnaro Laboratories (Italy) in January 2020. The aim of this stage was to verify and validate the electrical components and ancillaries constituting the DTL controls. The entire control system was composed of 6 racks (this estimation does not include all the components devoted to skid controls). In this stage the following aspects were tested: racks internal network infrastructure, EPICS infrastructure (E3 modules and IOCs), basic Operator Interface (basically only remote I/O checks), thermo-sensor system (using potentiometers as simulated temperature sensors), tuner motor system (using dedicated bench test composed by a single motion axis: motor, encoder potentiometer, limit switches), steerer magnet power supply (using resistors as simulated load).

The absence of the DTL apparatus or an equivalent complete test-bench required the usage of simulated equipment for the factory acceptance test. Because of the pandemic event and the quarantine, all the activities related to DTL construction and installation stopped during the first half of 2020 and only at the end of the same year slowly restarted. Based on this inertia, the 2nd FAT was performed at ESS-ERIC only in May 2021.

For this validation test, two different documents were defined: the test specification plan and the final FAT report, which includes all the results obtained by the different FATs.

Connection Tests for Tank 1

The connection tests were performed at ESS-ERIC Lund in September 2021 remotely, and they covered the verification of the correct presence and cabling of the I/O (sensors and actuators) between the DTL tank and racks. The definition of this verification stage was thought to take advantage of the fragmented schedule caused by COVID and optimize the next validation stage: while during connection tests only hardware part and simple equipment online verification, the SAT stage could be focused only on the algorithm and low-level and high-level logics, which were never tested in previous stages. Thanks to the modular approach adopted during the design and implementation of the control system, along with the previous FATs, this set of tests was executed seamlessly. Because of the nature of these tests, the result was resumed on a short report which was integrated into the SAT1 final report.

DTL Water Cooling Control System Validation Test

The DTL water cooling control system was developed as part of the entire cooling system by a tender as a standalone system connected to DTL controls via the PLC-EPICS interface. The validation test performed consisted of the verification of all the equipment and ancillaries related to the cooling skid apparatus, including the local Human-Machine Interface. All the tests were performed between December 2021 and February 2022; at this stage, the acceptance test included the verification of the PLC control system functionalities and the verification of the EPICS integration layer required to have full automation. The EPICS layer used the EPICS application generated by the ESS PLCFactory tool.

SAT1-a and SAT1-b

SAT can be considered the most critical phase in the implementation of a system in its final location, and it is performed to validate the system functions as per the specified design requirements to meet the user's needs. In particular, this kind of test couldn't be performed before because of the absence of power tests during the R&D stage.

As previously indicated, the SAT1 tests validated the high-level logic implemented; it was composed of state machines devoted to supervising the functional systems (temperatures, steerers, mobile tuners, cooling) and the state machines devoted to the main orchestration (automatic operative procedures). In addition, the SAT1 was split into two sub-stages, SAT1-a and SAT1-b: this request was based on the need for software alignment with the ICS (Integrated Control System) production environment. As a consequence, SAT1-a was performed by INFN as part of the original SAT plan while software alignment and SAT1-b were performed by ESS-ERIC with INFN support. All the verifications and validations were performed between January and March 2022. The final report coming from the SAT1 included also the connection tests previously described.

SIT1

During the SIT conducted in March 2022, the DTL control system underwent comprehensive testing alongside all interfacing systems, both directly and indirectly connected to the DTL apparatus. These interfacing systems included the RF system, Machine Protection System, Vacuum system, and Personnel Safety System. This configuration allowed for the validation of high-level controls and closed loops, encompassing functional systems that were not directly developed by INFN – for instance, closed loops for mobile tuners which needed frequency detuning from RF. The ESS team led the entire validation process with support from INFN, building upon documentation from prior tests. Notably, the SIT1 tests facilitated the initiation of cavity conditioning for the DTL apparatus, delivering a significant positive impact on the project schedule.

CONCLUSION

The validation of the DTL control system progressed through meticulous phases, with innovative approaches emerging in response to pandemic challenges, all aimed at achieving the final goal. Across these stages, the pivotal SAT1-a/b and SIT1 comprehensively evaluated the logic and facilitated harmonization of the DTL with interfacing systems, leading to positive impacts on timelines. This multi-phase journey underscored the significance of resilience and adaptability in the complex implementation of this control system. The entire DTL control system commissioning will be completed after SAT3 (estimated at the beginning of 2024.

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REFERENCES

[1] ESS website, https://europeanspallationsource.se

[2] EPICS website, http://epics-controls.org

[3] M. Montis, L. Antoniazzi, A. Baldo, M. Giacchini, and T. Fay, "ESS Drift Tube Linac Control System Architecture and Concept of Operations", in *Proc. ICALEPCS'19*, New York, NY, USA, Oct. 2019, pp. 435. doi:10.18429/JACoW-ICALEPCS2019-MOPHA096