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PROGRESSES IN THE ESS SUPERCONDUCTING LINAC INSTALLATION

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Abstract

The ESS Linac is progressing into the technical commissioning phase. The normal conducting linac up to the first 4 tanks of the DTL is being commissioned with beam. All the 13 spoke cryomodules and the 9 elliptical modules (7 MB+2 HB) foreseen for the first operation at 570 MeV on the beam dump in summer 2024 are available in Lund and waiting for the completion of the cryogenic distribution system (CDS) commissioning. The test program of all the 30 elliptical cryomodules that will enable the 5 MW potential operation after the target commissioning is progressing well, as well as the installation of the RF power stations necessary up to the 2 MW stage of the first project phase. Pilot installation of one spoke and one elliptical cryomodule in the tunnel is in progress. The talk will cover the status of the component deliveries from the partners, the CM preparation and SRF activities at the ESS test stands, with the resolution of several non-conformities, and the experience of the pilot installations and technical commissioning activities in the accelerator tunnel.

INTRODUCTION

The European Spallation Source (ESS) [1], currently under construction in Lund, Sweden, will be the world's most powerful linear accelerator driven neutron spallation source. The normal and superconducting sections of the linac (NCL/SCL) will deliver an ultimate average beam power of 5 MW at 2 GeV. The superconducting linac uses three types of cryomodules: Spoke cryomodules, medium-β and high-β elliptical cryomodules. Figure 1 shows a schematic layout of the linac, and Table 1 lists the high-level parameters for the full facility design [1] and for the configuration of its initial operation [2].

Table 1: ESS Linac High Level Parameters for the Design and Initial Operations (InitOps)

Parameter	Unit	Value
Beam power (design)	MW	5
Beam energy (design)	GeV	2
Beam power (InitOps.)	MW	2
Beam energy (InitOps.)	GeV	0.8
Peak beam current	mA	62.5
Beam pulse length	ms	2.86
Beam pulse repetition rate	Hz	14
Duty factor	%	4
RF frequency	MHz	352.21/704.42
Availability	%	95

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The NCL of the ESS linac already went through several commissioning steps and the beam was successfully sent through all four DTL tanks during 2023. For the downstream part of the linac, components are being manufactured, installed and tested. This paper first provides a summary on the ESS linac project with a focus on the progresses in the klystron gallery, Cryogenic Distribution System (CDS) commissioning, spoke and elliptical test activities, and then presents a summary and highlights of the pilot installation of one spoke and one elliptical cryomodule in the ESS tunnel.

PROJECT STATUS

This section gives an overview of the ESS linac project. Previous progress reports can be found in [2-4].

Schedule and Linac Configurations

Similarly to other facilities, ESS is based on staged commissioning phases, summarized in Table 2. As shown in Fig. 1, the linac is composed of 13 spokes, 9 medium-β, and 21 high-β cryomodules. Spoke cryomodules contain two spoke cavities whereas medium-β and high-β cryomodules house four cavities. At the beginning of the project, no high-β cryomodule was supposed to be installed for the fifth and sixth commissioning steps in Table 2 [5], to operate at the design energy of the output of the medium-β section, 570 MeV. The current plan assumes a configuration with seven medium-β cryomodules (the blue coloured ones in Fig. 1) and two high-β cryomodules for those steps [2]. This change is due to some medium-β cavity production issues and a good progress with the production of high-β cryomodules. The maximum energy remains approximately 560 MeV. The remaining cryomodules (2 medium-β and 19 high-β cryomodules) will be installed later and only some of them will be powered in order to get the 800 MeV beam energy for the initial operations phase.

Currently, a temporary shielding wall is separating the NCL from the SCL to allow beam commissioning activities on one side and cryomodule installation on the other side

Table 2: ESS Linac High-Level Schedule

	Step	Start	Energy [MeV]
1	Commissioning to LEBT	2018-09	0.075
2	Commissioning to MEBT	2021-11	3.62
3	Commissioning to DTL1	2022-05	21
4	Commissioning to DTL4	2023-04	74
5	Beam on Dump (BOD)	2024	560
6	Beam on Target (BOT)	2025	560
7	Start Of User OPerations	2026	800

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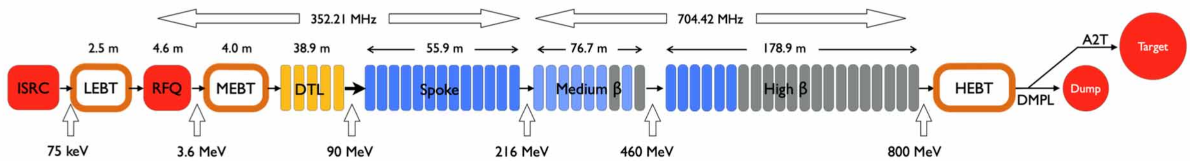

Figure 1: ESS linac schematic layout. The segments represent DTL tanks and cryomodules. The colour code helps identify the initial phase with 800 MeV and 2 MW. The cryomodules marked with the grey colour will not be powered during the initial 2 MW operations.

The delivery pace of cryomodules from the ESS project in kind partners is increasing. All the 13 spoke cryomodules are currently on site, as well as the 7 medium-β and 9 high-β. The amount of cryomodules currently at ESS is sufficient for all the commissioning stages up to SOUP.

RF AND ITS DISTRIBUTION SYSTEM

The ESS RF Distribution Systems (RFDS) contain more than 5000 pieces of waveguide components including high power loads and circulators [6]. Waveguides such as full and half height WR2300 and full height WR1150 are used to deliver the two different frequencies (352.21 and 704.42 MHz) from either 3 MW klystrons (NCL), 400 kW tetrode-based power stations or the 1.6 MW elliptical klystrons. The systems include a waveguide shutter switch to allow for local testing and isolating the accelerating cavity in the tunnel. Most of the RFDS systems are installed (see Fig. 2) and tested, with the exception of the last 40 RF loads and circulators which were deferred due to budget constraints. [7].

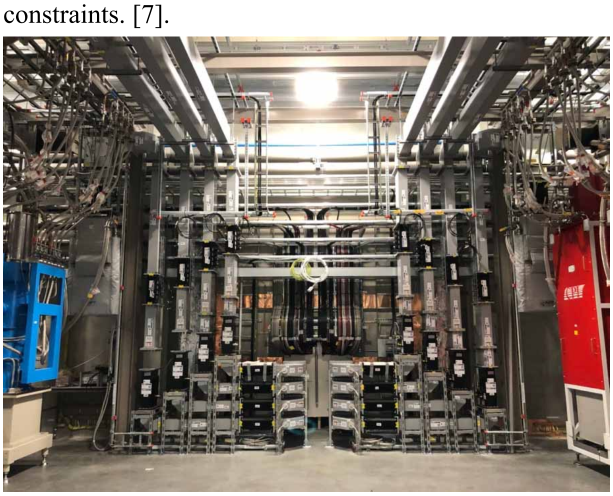

Figure 2: The cells with RFDS run between the klystrons in the RF Gallery and the cavities in the tunnel.

CRYOGENIC SYSTEM

The Accelerator Cryogenic Plant (ACCP) is designed to deliver helium cooling to the cryomodules at different temperatures. The cavity tanks are filled with liquid helium at 2 K, 4.5 K and 40 K are the temperatures for coupler cooling and Thermal Shield (TS) respectively [8, 9]. The cryogenic distribution system (CDS) connects the cryomodules and the ACCP by means of 43 valve boxes and ~400 meters long cryogenic multi-transfer lines [10]. After the ACCP successfully passed the acceptance tests and in order to test the performance of CDS and the cold compressors (CCs), an integrated test of ACCP and CDS without cryomodules connected was performed in Q4 2022/Q1 2023. [11]

The test goals were defined as follows

- even cool-down process over the CDS and the valve boxes
- testing the heat load with small mass flow, ~ 10 g/s
- pumping down the CDS vapor low pressure line steadily without CCs trip.

After several weeks of tests, the cool-down results were non-conclusive. The mechanical integrity of the system was demonstrated, together with the functional testing of controls and instrumentation. On the other hand, valve seat leaks and thermal acoustic oscillations (TAO) resulted in heat loads higher than expected.

A repair plan was then defined and carried out during the pilot installation. Valves are equipped with wipers along the stems to limit the TAO effect. Moreover, a campaign of visual inspection, re-initialisation and preload adjustment was conducted.

CM PRODUCTION AND DELIVERY

Spoke and elliptical cryomodules are French in-kind contributions [2, 4] by IJCLab and CEA Saclay respectively. Spoke cryomodules achieved their site acceptance test (SAT) at the FREIA Laboratory, in Uppsala.

ESS will have a total of 14 spoke cryomodules (13 in the linac and one spare): presently 13 modules passed SAT at FREIA and are in Lund. Incoming inspection for 12 of the 13 received modules have been completed for all the several disciplines (mechanical, vacuum, electrical and SRF). 9 medium-β (MB) and 21 high-β (HB) cryomodules will be delivered to ESS. INFN and STFC are providing the MB and HB cavities. The assembly and delivery responsibilities lie with the CEA side, as well as the high RF power test for the first three CM of each family (and prototypes). CEA Saclay is also supervising the industrial assembly in house, performed by B&S International.

SPOKE CM TEST STATUS

After SAT at FREIA the spoke cryomodules are shipped to ESS, inspected and in some cases repaired before tunnel installation. The details of the spoke cryomodule tests performed by FREIA team is presented at this conference.

Non-conformities such as exchanging the galvanised steel fasteners to stainless steel ones or the replacement of LHe level gauges are managed directly at ESS with the

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help of the in-kind partners. A more concerning issue regards the Cold Tuning System and more precisely the stepper motors. The stepper motors failed for three cryomodules during the Site Acceptance Tests at Uppsala/FREIA and were replaced before a second campaign of tests. In March 2023, a review was held at IJCLab, Orsay to assess the risks for the installation schedule as well as to define a short and a long-term mitigation plan. An "end-of-life" test to determine the largest number of revolutions of the stepper motor was conducted at IJCLab. Results are between 150k and 350k revolutions. It was then decided to open all Spoke cryomodules at ESS to modify the stepper motor temperature sensor configuration and exchange the three stepper motors that are close to their expected end of life.

ELLIPTICAL CM TEST STATUS

Elliptical cryomodules are tested at ESS Test Stand 2 (TS2). The prototype modules, both for MB and HB, and first three series cryomodules of each family are tested both at CEA, Saclay [12] and ESS, in order to:

- Provide rapid test feedback to the CEA module assembly process at its starting phase
- Verify that the main ESS requirements on accelerating field and RF pulse structure are achieved
- Validate the ESS test facility and cross check results with those obtained at CEA.

The TS2 has been commissioned in 2020 with the prototype CM0 and RF operation started in 2021. Until now, the CM00 prototype, all 7 series MB (CM01-CM07) and 2 HB (CM31, CM32) have been tested at TS2. CM33 is being tested as we write this paper and 2 next HB (CM36, CM37) are being prepared for test.

Operations at CEA are performed in open loop with manual Lorentz Force Detuning (LFD) compensation with piezo. The closed loop cavity operation and LFD LLRF algorithms are in the TS2 scope.

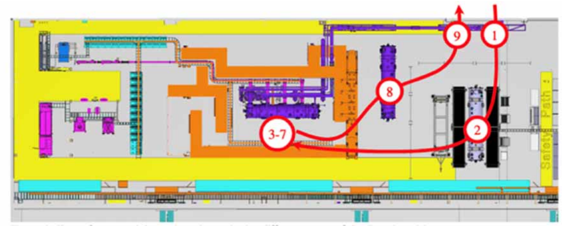
TS2 CM Test Documentation

To ensure the long-term maintenance needs of the facility, the complete design and individual component documentation, as received by the in-kind partners, is stored in the ESS central engineering documentation management system (CHESS). These include: 1) Cryomodules assembly documentation (quality) and 2) Cryomodules operation documentation (calibration data for instrumentation, like thermal sensors and accelerating field calibration constant kt). The TS2 workflow completes the existing documentation as the ESS SAT activities for the component acceptance are performed.

The sum of the multi-disciplinary incoming inspections, RF and cryogenic measurements reports, produces a final master report for documenting the overall SAT findings and resolution for possible non-conformities. [13, 14]

CM Test Cycle

The CM testing workflow is split into phases, and properly documented in ESS Document Management system. Phases and their flow are illustrated in Fig. 3 [14].



#	Phase	Areas	
		From	To
1	Cryomodule reception	G02-CXL	CM-IRA
2	Cryomodule preparation	CM-IRA	
3	Cryomodule installation	CM-IRA	Bunker
4	Cryomodule Warm Validation	TS2 Bunker	
5	Cryomodule Cold Validation		
6	Cryomodule Warm-up		
7	Cryomodule Disconnection	Bunker	CM-IRA
8	Cryomodule Preparation for Dispatch	CM-IRA	G02-CXL
9	Cryomodule Dispatch	G02-CXL	HLB Hall or Storage

Figure 3: Layout of TS2 and phases of the test activities.

Cryogenics Operations

Part of the incoming inspection concerns the cryogenic equipment. It starts with initial visual inspection and electrical checks are performed on all internal instrumentation. Then, the cryomodule is flanged to the valve box and auxiliary circuits (part of the TS2-CDS) inside the bunker. The devices functionality and diagnostics instrumentation are verified with the EPICS control system.

The tests on all cryogenic circuits are performed to identify possible leaks to ambient, insulation vacuum and beam vacuum, up to high sensitivity. The circuits are then conditioned by successive pump and purge cycles.

The cool-down process starts with cooling the thermal shield to 40 K followed by the helium tanks surrounding the cavities to 4.5 K.

Once a He-I bath liquid is established, the cool-down to a superfluid He-II bath at 2 K is engaged by reducing the pressure of the helium bath to 31 mbar. A carefully defined controller maintains a stable level and temperature (pressure) conditions for the cavity during SRF tests.

Measuring methods for the heat loads to the cryogenic system are defined in Ref. [15]. Static and dynamic heat load measurements require the cryomodule to be in a steady state condition and happen usually at the end of the testing cycle. To already improve the future linac operations, a survey for systematic errors on temperature, level and pressure measurements is conducted and documented.

The cryogenic operation is completed by safely warming up the cryomodule to ambient temperature.

PILOT INSTALLATION OF SPOKE AND ELLIPTICAL CMS

The pilot installation of one Spoke and one Elliptical cryomodule (see Fig. 4) was performed according to the schedule between March'23 and end of May'23. This pilot installation is meant to cover the complete scope of activities from the preparation of the cryomodules in the lab or test stand up to its final configuration in the ESS tunnel. Moreover, an Installation Readiness Review (IRR) was held with the different stakeholders in order to verify the sequence of the activities, the schedule and resources to perform the numerous tasks. The Cryomodule Installation

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Package Lead (CM IPL) has also the responsibility to track and register all the details of the installation in order to prepare for the serial installation of 13 Spoke CM and 9 Elliptical CM at the much faster pace of 2 cryomodules per month during the installation campaign starting in summer 2023. The general procedure for the installation is similar for the Spoke as well as the Elliptical cryomodule.

The spoke cryomodules are currently located in the ESS laboratories space where they undergo repair and preparation for the tunnel. The Elliptical cryomodules are stored in the klystron gallery after the Site Acceptance Test in the Test Stand. Prior to installation, both types of cryomodule need to have their cryogenic process pipes modified to fit the tunnel configuration. The ESS rigging and logistics teams then transport to the tunnel. The lighter (~2 tons) Spoke cryomodule, can be steered manually with a dedicated trolley, whereas the heavier (~6 tons) Elliptical cryomodule requires an automated transport trolley.

The following step is performed by the Alignment group who positions the cryomodule according to the reference system defined in the tunnel. When it comes to the Spoke cryomodule, an extra measurement is needed due a known misalignment of the CDS with respect to its original design position. To compensate the misalignment occurred during installation, the process pipe cup joints are adjusted individually. That stage requires to place the Spoke CM to its final position, measure the needed lengths, cut the existing process pipe cups and finally weld new ones with proper length.

The final welding work connects the CDS to the cryomodules. The welded connections guarantee leak tightness and reliability over time over multiple cooldown/warm-up processes. Leak tests in sniffer mode are performed soon after the welding work is finished to make sure that no big leaks are detected. In order to improve the sensitivity and the speed of the test, clamp shell tools were designed and procured. The final leak check is conducted when the insulation vacuum is pumped down.

Multi-layer insulation foil (MLI) is wrapped around the process pipes and the thermal shield before closing the jumper sleeve. The CMs are now connected to their valve boxes and the insulation vacuum can be pumped down. When conditions are met, leak checks of the sleeve and process pipes connections are performed. As mentioned above, various vacuum tests have already been conducted in TS2 to ensure leak tightness of the internal circuitry.

The RF components for the connection to the RFDS can be installed independently as soon as the cryomodule is brought in place. In contrast to the Elliptical cryomodule which has the doorknobs installed in the test stand, the Spoke cryomodule requires the doorknob installation to be performed in the tunnel.

All cable connections from the CM instrumentation to the racks in the gallery were performed at the end of the installation to limit risk of damage and to allow tests of the instrumentation controllers on the rack side.

Piping work runs in parallel to the workflow described above. The cryomodules need instrument air supply, connections to the CDS (He return line) and to the water-cooling manifolds for coupler cooling.

Figure 4: Medium Beta CM (top) and Spoke CM (bottom) of the pilot installation in the ESS tunnel.

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As was pointed out in the introduction to this section, the pilot installation goal is to detect and adapt the existing installation procedures and fix every detail for the series installation starting this summer. A lessons learned document is currently being prepared and will be followed by a second Installation Readiness Review before the installation of the remaining 12 Spoke and 8 Elliptical cryomodules. Nevertheless, we have already introduced modifications, such as simplified cable tray routing and to address pipe clashes. The correct order of the several installation packages has been analysed and the preparation work started in all linac install locations. The tight installation schedule requires also to define the necessary tooling for each step. For instance, cutting and welding activities related to the Spoke cryomodule process pipes are time-consuming in the tunnel and will be from now on prepared in the lab.

CONCLUSION

The first eight RF vertically integrated systems (RFQ, MEBT 1-3 and DTL 1-4) have been commissioned and are already in use both for full cavity conditioning and for the initial operation with beam. The RF systems have performed well with few failures and interruptions. The other RF systems are well underway with the RF systems for DTL5, half of the Spoke and MB systems already high power commissioned. The remaining systems up to HBL-020 are under test.

We presented also the status of the Spoke and Elliptical cryomodules for the ESS linac. More than the minimum number of cryomodules required (29/22) for the first phase of the project with 570 MeV operation on the beam dump are already available in Lund, either at the Ready-For-Installation state or awaiting test at TS2.

Pilot installation of one Spoke and one Elliptical cryomodule in the tunnel was conducted according to the defined schedule. A second cool-down is currently taking place in order to check the CDS repairs, as well as the cryomodules controls. The series installation of 21 cryomodules will then start from July 2023.

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