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COMMISSIONING PROGRESS OF THE ESS LINEAR ACCELERATOR

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Abstract

The European Spallation Source (ESS) is in the final stages of commissioning its linear accelerator (linac), which will deliver a high-power proton beam for neutron production. The commissioning process involves progressive testing of subsystems, including the ion source, radio-frequency quadrupole (RFQ), and superconducting cavities, to ensure stable and reliable beam operation. Key challenges include beam dynamics optimization, machine protection, and high-power RF system integration. Within this presentation an overview of the commissioning status, key milestones achieved, and expectations for the first beam on target, marking a significant step toward full facility operation will be given.

THE ESS FACILITY

The European Spallation Source is a pan-European project with 13 European nations as members, including the host nations Sweden and Denmark. The ESS facility is under commissioning in Lund, while the ESS Data Management and Scientific Computing centre (DMSC) is located in Copenhagen. The construction of the facility began in the summer of 2014 and we expect to see the first neutrons at the start of 2027 (see Fig. 1). ESS is the fourth facility of its kind to be constructed, after the completion of the SNS in the United States, J-PARC in Japan, and CSNS in China. All three facilities have MW capabilities, but the design beam power of ESS will be the highest of the three [1]. The linac is designed to produce neutrons through spallation with an average flux comparable to that of the continuous ILL source, while maintaining a low pulse repetition rate that enables the production of high-flux, low-energy neutrons.

The ESS facility is a huge and highly complex jigsaw puzzle. The 13 ESS member states contributed to the construction of ESS via financial and in-kind contributions, exchanging knowledge and know-how. An in-kind contribution may cover technical components, design documentation, personnel needed to perform installation and testing, or other services.

The ESS linac

A schematic overview of the high-power linac currently being built [2] at ESS can be seen in Fig. 2. A proton beam at 75 keV is produced in the Ion Source (ISrc), focuses in the Low Energy Beam Transport (LEBT) section and readily accelerated by a four-vane Radio-Frequency Quadrupole (RFQ), which is the first accelerating structure of the ESS LINAC. The 3.62 MeV bunched beam pulse matched in the Medium Energy Beam Transport (MEBT) to the Drift Tube LINAC (DTL) section, comprised of five DTL tanks accelerating the beam up to 90 MeV.

Figure 1: Photo of the ESS site from June 2022. Construction work is finished and it is possible to see the linac (orange), the Target building (yellow) and the long instruments hall (green).

Downstream of the DTL the accelerating structures are superconducting, and this part of the accelerator is referred to as the Superconducting LINAC (SCL). Three families of superconducting RF-cavities are used at ESS. The cavities are arranged in cryomodules with LINAC Warm units (LWUs) in between, each housing a quadrupole doublet and beam diagnostics. 26 Spoke-cavities (SPK) arranged two in each cryomodule, operating at 352.21 MHz, take the beam to 216 MeV. Both the 36 medium-β cavities (MBL) and 84 high-β cavities (HBL) are arranged four cavities per cryomodule and operate at a frequency of 704.42 MHz, twice the SPK frequency, and togehter bring the beam to a maximum energy of 877 MeV. Note that during the 2025 commissioning, only 5 cryomodules of HBL, were installed and operational. For the commissioning of 2026 one of the Spokes cavities tuning motor presented issues and the cavity could not be used for acceleration, reducing the final maximum achievable energy to 862 MeV. The High Energy Beam Transport (HEBT), is a contingency space for future upgrades, currently housing quadrupole doublets and beam diagnostics. After the HEBT section it is possible to send beam to the tuning beam dump, which accepts a maximum power of 12.5 kW, or to the ESS Target, the only destination that can take the full design power.

The ESS Target

The spallation process at ESS will take place when the accelerated protons beam hits the tungsten bricks of the 4.9 tonne target wheel, producing neutrons for scientific experiments across multiple disciplines [1]. The first step in this process is production of high-energy neutrons through a spallation process involving proton beam interaction with a tungsten target. The target is a 2.6 m diameter stainless steel disk containing bricks of tungsten. It weighs almost five tonnes. The wheel rotates at 23.3 RPMs, in time with

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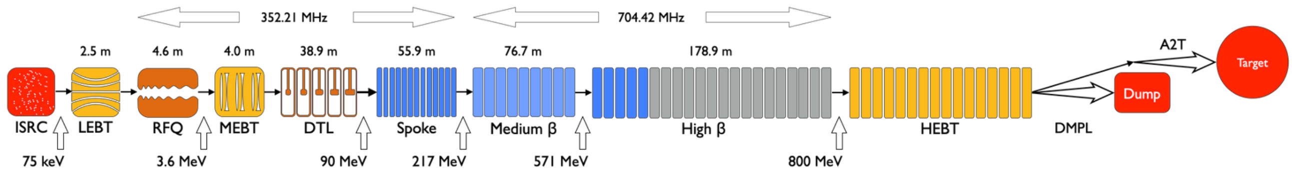

Figure 2: ESS linac schematic layout. Each segment in the DTL and SC sections denotes a DTL tank and a cryomodule. The shown figure shows the configurations for the initial operations, where five high-β cryomodules are included, allowing the capability of 800 MeV beam and 2 MW final power.

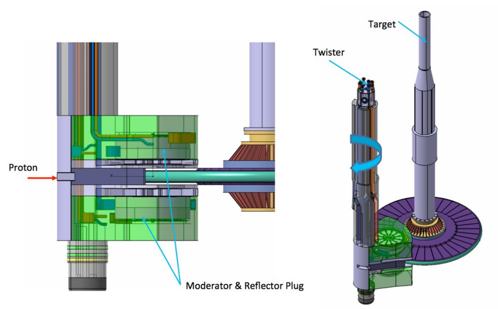

Figure 3: Schematic layout of the ESS target wheel and moderator plug.

the arrival of the proton beam painted across the exterior of the wheel shroud. The neutrons, created in the spallation process, travel at 10 % of the speed of light, are then slowed down to roughly the speed of sound, an energy level usable by the scientific instruments. This is achieved using a para-hydrogen and water-based moderator and a beryllium-lined reflector [3]. The moderator-reflector system is housed in a replaceable plug, the moderator reflector plug (MRP), and also includes cryogenic hydrogen and water-cooling systems. Finally those slower neutrons are delivered to the instruments through beam ports. Figure 3 shows an schematic of the target and moderator at ESS.

The ESS Instruments

At the European Spallation Source (ESS), fifteen specialized scientific instruments are currently being installed. Each instrument is designed to capture specific types of scientific data [4]. The 15 instruments have been selected to span a broad range of experimental techniques and scientific fields. Future plans include expanding the instrument suite to 22, presenting additional scientific opportunities at ESS. Table 1 shows the first 6 instruments that will be ready when we achieve beam on target in 2027 in addition to the Test Beamline (TBL), responsible for measuring the first neutrons and cross-check the neutron spectra produced.

COMMISSIONING HISTORY

For a large machine such as the ESS linac, an obvious challenge of commissioning is to verify functionalities of all the systems. This is one of the reasons for the staged commissioning, to discover system-related issues as early as possible [5, 6].

The ESS linac project has adopted an ambitious schedule, and the priority has been put on starting the user operations

Table 1: ESS Instruments Ready for First Beam in 2027

Instrument	Technique
ODIN	Engineering
LOKI	Large Scale Structures
NMX	Protein Crystallography
SKADI	Large Scale Structures
DREAMS	Diffraction
BIFROST	Spectroscopy

Table 2: ESS Linac Commissioning Stages

Step	Stat	Energy (MeV)
Commissioning to LEBT	2018	0.075
Commissioning to MEBT	2021	3.62
Commissioning to DTL1	2022	21
Commissioning to DTL4	2023	74
Commissioning to Dump	2025-26	800
Commissioning to Target	2027	800

as soon as possible. This lead to the decision of not using any temporary beam dump nor test-bench (except during commissioning of the IS and LEBT). Instead, a comprehensive suite of diagnostics was included in the linac and the beam was stopped by Faraday cups (FCs) during commissioning of the NCL. The FCs and beam dump are designed up to 50 µs for 1 Hz and 5 µs for 14 Hz. The beam dump is also capable of stopping one nominal pules but only every half minute. This situation imposes a challenge that testing will be limited in duty factor before the beam is sent to the target. The other limitation of the project has been resource availability, especially for the systems integration to the control system. Diagnostics devices for profile and emittance measurements have been affected, and their reliable operation has not yet been established. RF systems have been also affected; when the commissioning up to the MEBT started, only the open-loop operation was supported for the RFQ and the buncher cavities in the MEBT were still missing their low-level RF system. Because of these situations described above, commissioning activities have been focusing to establish low power beam to the intended destination and to verify critical systems. Currently we are running commissioning to the dump and the plan is to increase the pulse length 50 µs and push the current as close as possible to nominal values in order to test systems as RF feedback and feedforward in place and Beam Loss Monitors (BLMs), for example. Table 2 presents a comprehensive list

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of all commissioning stages so far as well as the max beam energy achieved.

SYSTEMS INSTALLATIONS

In the Target, the focus is now shifting from installation to integration testing. With essentially all components in place and the moderator cap sealed, the Target team has started the Neutron Factory (NF) test – a full, end-to-end verification of all target systems working together. The NF test will run for the rest of 2026 and also after the new Moderator Plug ins installed. The purpose of the NF Test is to demonstrate Beam on Target readiness by cold commissioning all target systems together.

Extensive installation work continues in the Active Cell Facility to support future remote handling of activated target monolith components. Good progress is being made in the in the manufacturing of the casks needed to exchange activated components when neutrons are produced – a key requirement when ESS is in operation. The casks for the moderator-reflector plug and the proton beam window are planned for delivery in 2026, to be followed by site acceptance testing.

In the accelerator, during the summer in 2025, 6 extra cryomodules (24 cavities) were installed in the linac [7]. In parallel, in the klystron gallery, RF modulators and klystrons are begin installed and tested. This work in paving the way to a 3 MW capable linac. Also during 2025 all Beam Loss Monitors (BLMs) were installed, tested and calibrated. This new instrumentation suite are now ready to be used and commissioned with beam.

LESSONS LEARNED

A few minutes before midnight on 25 November 2025 a brief glitch in the incoming power to ESS led to significant issues in both the accelerator and target areas. The power interruption caused the accelerator cryoplant to trip, which affected the cryogenic distribution to the cavities in the tunnel. Several cryomodule burst discs released helium into the tunnel. The main control room crew together with rapid on-site response by on-call staff quickly stabilized the cryoplant and helium supply to the accelerator. The burst discs have been replaced, and one spoke cryomodule was being thermally cycled to address a local blockage but overall, the superconducting accelerator was quickly thermally stable.

The power glitch also stopped the water moderator circulation pump in the MRP in the middle of ongoing neutron factory tests. The flow of cooling water stopped, but the cryogenic flow from the cryogenic moderator system continued, which led to ice build-up inside the water moderator channels that fully blocked the cooling channels. This likely caused one or more cracks in the channel walls or elsewhere in the system leading to water leakage into and resulting loss of vacuum in both the monolith vessel and the cryogenic transfer line insulating vacuum. After a thorough investigation the current moderator was deemed unrepairable and a decision was taken to way to the new moderator coming from Jülich, our German in-kind partner.

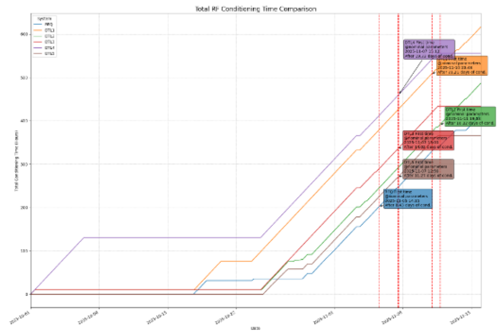

Figure 4: Total RF conditioning time of NCL cavities.

This accident created a shift of about 9 months on the schedule to beam on Target, which is now expected to happen in the first quarter of 2027.

RF CONDITIONING WITH LONG PULSES

RF conditioning of the NCL cavities began in January of 2025 [8], except for DTL 5 all cavities have undergone conditioning during earlier commissioning campaigns. The accumulated conditioning time of a selection of NCL cavities can be seen in Fig. 4. Several cavities reached the nominal RF pulse with less than 1 month of 24/7 RF conditioning. The average conditioning time for previously conditioned cavities was ~27 days of RF Operation. The RF windows of the DTLs have experienced issues with arcing, the root cause is believed to be insufficient TiN coating of the alumina ceramic. This has been experienced during previous commissioning campaigns. This RF window was replaced during the summer installation and maintenance period, the replacement window has undergone refurbishment at the manufacturer, where the alumina ceramic was removed from the mechanical assembly of the window and received a cleaning and re-coating ensuring 10 nm of TiN was homogeneously distributed across the ceramic.

After tuning, calibration and verification of SCL, cavity conditioning in open loop at full pulse length of 3.2 ms started, with respect previous conditioning only a few cavities showed minor degradation and required slightly longer conditioning time. At the end of SCL conditioning, all cavities were configured in closed loop operation according to beam physics requirement with respect to field gradient (based on phase scan result from 2025 commissioning), with manual operation of piezo, since at the time of conditioning Lorentz Force Detuning (LFD) algorithm was not yet fully integrated in the LLRF [9, 10].

During cavity conditioning multiple field emission (FE) bursts were observed, causing simultaneous signals in all arc detector fibers connected to the photomultiplier tubes (PMTs) in the gallery triggering multiple interlocks [11]. Analysis confirmed that these events were radiation-induced, consistent with earlier findings from Test Stand 2 cryomodule testing performed with the CEA in-kind SRF team. The phenomenon occurs when electrons emitted from the coupler region travel toward the cavity, producing bremsstrahlung radiation, which in turn activates the optical fibers of the

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arc detection system. Although the coupler diagnostics are designed to detect optical light from arcs, the system is also sensitive to this radiation-induced signal, explaining the simultaneous interlocks across multiple channels even when only a single cavity is powered. For ESS this effect is intrinsically connected to the extra long RF pulses, the impact of those disruptions has an detrimental effect on the reliability and up-time of the linac.

RESULTS FROM BEAM COMMISSIONING TO THE DUMP

Between 2025 and 2026 we ran several months of beam commissioning to the tuning beam dump. In Table 3 a comparison of the design beam parameters and the beam parameter used beam commissioning are presented. During the 2025 we did not run beam above the minimum specs, also called probe beam, while for 2026 are working to increase the beam pulse length and current about the probe.

Table 3: ESS High-Level Parameters for Production and Probe Beam Modes During BOD (Beam on Dump) Commissioning 2025

Parameter	Unit	Beam Mode	
		Production	Commisioning
Beam Power	MW	2	$2(200)\cdot10^{-5}$
Beam energy	GeV	0.8	0.8
Beam current	mA	62.5	6 (62.5)
Pulse length	µs	2860	5 (50)
Rep. Rate	Hz	14	1
Duty cycle	%	4	$5\cdot10^{-4}$

Phase Scans

Timing synchronization of all the cavities has to be established one-by-one by scanning the phase and amplitude of each cavity. For the phase scan of all cavities in the linac, except DTLs, the phase of the cavity under study was scanned while the phase difference between two downstream Beam Position Monitors (BPMs) was recorded, this last one is proportional to the beam energy gain. The measured data were then compared to the expected energy gain over the same range of cavity phases, as calculated from a field map of the cavity and phase and amplitude required to achieve the design energy gain and synchronous phase were determined. An example of measurement and fit with the calculated set phase value can be seen in Fig. 5. For the setting of the DTL we use the reading of a single internal BPM in order to set the cavity phase and amplitude. During the commissioning in 2026 we discovered a strong correlation between NCL BPMs measured position and phase, this issue was fixed and as a result the phasing of the front end improved drastically and today we have a better agreement between model and measurement.

Beam energy measurements were conducted using a fast oscilloscope to measure the time of flight between two BPMs in the HEBT section. By blanking downstream cavities, energy measurements of the beam could be conducted from the last SPK onwards. The resulting energy measurements after each cryomodule, starting from the last SPK module, can be seen as a blue curve in Fig. 6 for the baseline reaching 810 MeV for both commissioning periods, 2025 and 2026, showing a great improvement in terms of achieving the design energy. This improvement is in part due to a better phase scan routine as well as better loop optimizations which guarantee a flatter field on the SCL cavities if compared to the 2025 campaign [5].

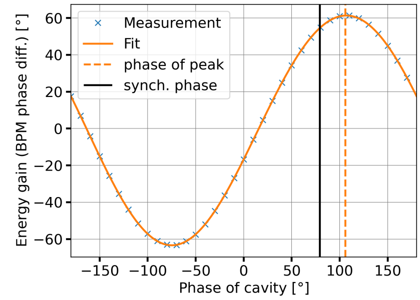

Figure 5: Example of a phase scan measurement of one of the SCL cavities.

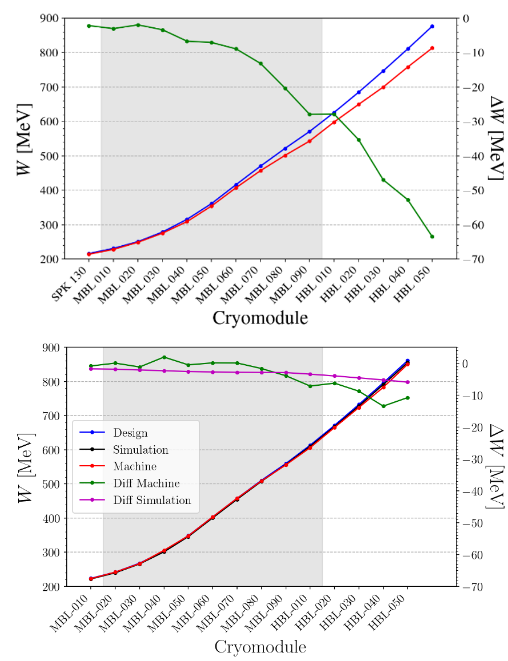

Figure 6: Comparison between the horizontal emittance from the models and form measurement showing we can see differences in Twiss paramenters between the two cases.

Emittance Measurements

A suite of instrumentation to measure beam size and emittances is available in the MEBT section of the ESS linac [12]. During the commissioning in 2026 we started a benchmarking camping in order to cross check emittances and twiss parameters using different techniques, namely: quad scan, 3 wires method and using an slit and grid system (EMU). The

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beam size was measured for a beam currents of 6 and 60 mA and the resulting emittance compiled and shown on Table 4. More understanding over the measurement limitations is needed however we can already see that the twiss parameters of the beam out of the RFQ for 60 mA (see Fig. 7) are not the ones expected from design, specially in horizontal plane.

Table 4: Comparison Between Normalized Emittance Measured Using Different Methods and Also the Design Values for the MEBT at ESS

Method	ε_y (πmm mrad)		ε_x(πmm mrad)	
	6 mA	60 mA	6 mA	60 mA
Quad Scan	0.04	0.37	0.19	-
EMU	0.68	0.18	0.10	0.19
3 wires	0.15	0.10	0.18	0.07
Design	0.09	0.25	0.10	0.25

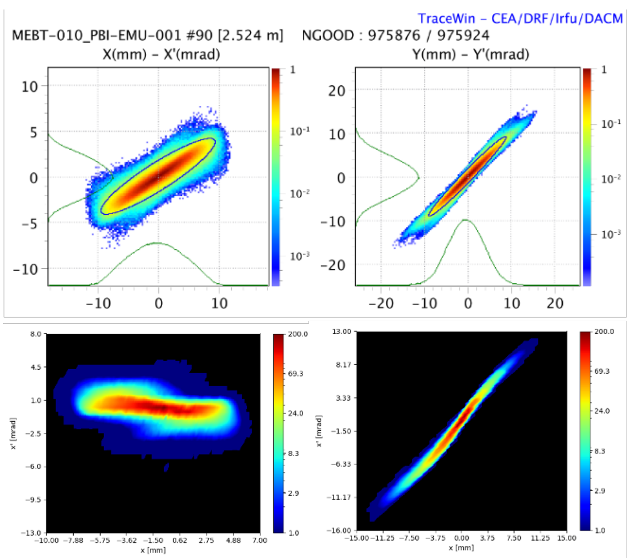

Figure 7: Design and measured emittances for 60 mA case. Measurement is done using a slit and grid system. Notice, specially in the horizontal plane, that the Twiss parameters between measurement and model are quite different.

Beam Loss Experiment

For beam loss, longitudinal dynamics is far more important than the transverse [6]. The amplitude and phase of each cavity is set one-by-one with time-of-flight measurements and model fitting (as explained in section Phase Scan). For ESS the tolerances are set to (0.5 %, 0.5°) for rms values in amplitude and phase and those error are shared by the set-point error (from the beam-based measurement) and RF systematics. For the beam simulation it is not possible to see losses with such small error, so a enhanced simulation set was performed where those errors were increased to (2.0 %, 2.0°) and results are presented in Fig. 8. Notice that the bulk of losses happen around the interface between MBL and HBL section and are mainly for protons with 200 MeV, which corresponds to end of the Spokes energy. During

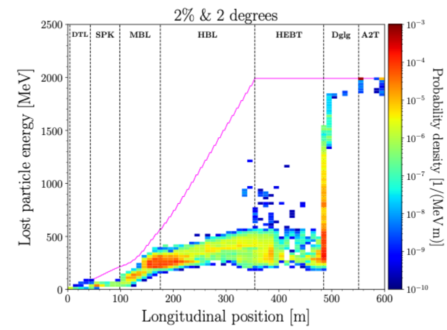

Figure 8: Simulated losses from the ESs linac for enhance RF errors.

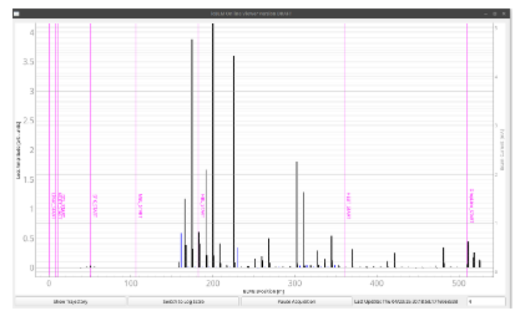

Figure 9: Measured losses using BLMs when the RFQ phase was changed by 18°. The losses match quite nicely the expected losses due to RF errors presented in Fig. 8

the commissioning in 2026 and using the BLMs, not fully installed and calibrated, we changed the RFQ phase by 18° (Fig. 9 and observed losses record n the BLMs, as expected the bulk losses happened around MBL and HBL interface. More studies and explorations of BLMs and looses are expected to be performed still this year to understand the loss patterns and mechanisms at the ESS linac.

OUTLOOK

A lot of progress was achieved at ESS during the last year. Installations are ongoing in the instruments halls and with 6 instruments on the road to be ready for beam on Target In 2027. Target was fully assembled and integration tests were ongoing until the accident in November 2025, when the the MRP was damaged. Since it was not possible to repair the old moderator the new one is expected to arrive at ESS site in the 4th quarter of 2026 and the test for the neutron factory to be finalized in 2027 in time for beam on target. On the accelerator side, installations for 3 MW capability is ongoing and a second round of commissioning to the dump is running until the summer of 2026. The linac will be ready for beam on Target in early 2027.

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