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STATUS OF THE ESS LINAC

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Abstract

The European Spallation Source (ESS) under construction in Lund (Sweden) uses a 2 GeV-5 MW pulsed superconducting linac as proton driver. Normal conducting accelerating structures are used up to 90 MeV and superconducting structures up to 2 GeV. Most linac components are designed and procured as in-kind contributions by institutes/laboratories in the partner countries in Europe. Installation of the Ion source delivered by INFN-Catania started January 2018. Installation of more components and infrastructure progresses at a high pace. Commissioning of the normal conducting linac section will take place in parallel with installation of the superconducting section. Beam commissioning of the superconducting section will start in 2021, interlaced with the installation of additional high beta cryomodules. Beam will be sent to the target in 2022, initially at an energy of 1.3 GeV. Start of the User Program is scheduled in 2023, when some neutron instruments will be ready and end of construction is in 2025, with the full set of instruments operational. This paper reports the status of linac components construction, the progress with installation on site, and the overall project schedule.

INTRODUCTION

ESS will be a long pulse neutron source of the next generation with performance exceeding all similar existing and planned facilities world-wide [1]. The ESS superconducting proton linac is a key ingredient for that purpose, with a beam power of 5 MW at 2 GeV delivered in 2.86 ms pulses at a 14 Hz rate. ESS is being built north of the University town of Lund in the south of Sweden. The site layout can be seen in Fig. 1. The facility is presently (2018) under construction, with the start of user operations planned to late 2023. At the end of construction, in 2025, ESS will operate 15 instruments for neutron users.

A facility of ESS size and scope is a major undertaking both cost and scope-wise, and even more when starting from a green field. The project in general and the accelerator in particular are therefore extensively relying on knowledge and competences throughout Europe, provided as in-kind contributions. For the accelerator project, partners and contributions are listed in [1].

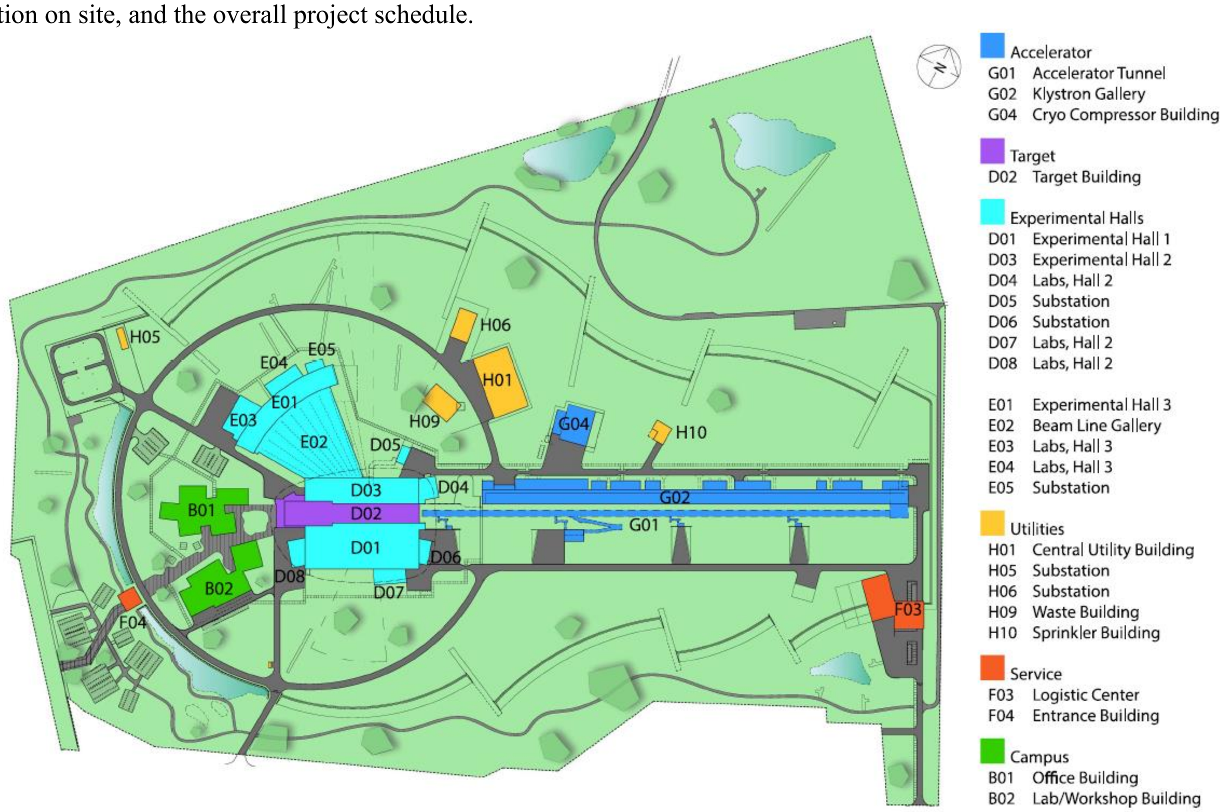

Figure 1: ESS site layout.

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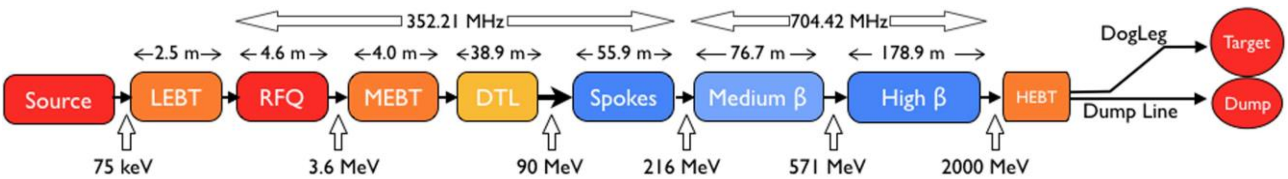

Figure 2: ESS Linac lattice overview.

ESS LINAC DESIGN

Lattice and Linac Design

The linac is approximately 450 m long. A 100 m long High Energy Beam Transport (HEBT) section at its end provides the possibility to add accelerating structures in the future. Table 1 shows the main characteristics of the linac.

Table 1: Linac General Parameters

Parameter	Unit	Value
Energy	GeV	2.0
Current	mA	62.5
Pulse length	ms	2.86
Pulse repetition rate	Hz	14
Average beam power	MW	5
Power during pulse	MW	125
Beam emittance at target, ϵ_x	π mm mrad	0.34
Beam emittance at target ϵ_y	π mm mrad	0.36

The lattice is shown in Fig. 2. It starts with the Ion source and Low Energy Beam Transport, followed by the RFQ, three bunchers in the Medium Energy Beam Transfer (MEBT) section, and five DTL tanks. This part of the linac is normal conducting. The DTL tanks are succeeded by the Spoke section, consisting of 26 Superconducting double spoke superconducting cavities in 13 cryomodules. Next come 36 six-cell superconducting medium-beta elliptical cavities in 9 cryomodules. The final section of the linac makes use of 84 five-cell high-beta elliptical cavities in 21 cryomodules. It is worth noting that 95% of the final beam energy is due to superconducting cavities, an unusually high portion. After the linac the beam drifts through the HEBT section until is it diverted towards the target using dipole magnets. Just before hitting the target the beam is swept using a magnet raster system, to illuminate the target more uniformly.

Parameters of the linac cavities and their RF sources are listed in Table 2. Up till the end of the Spoke linac section, the RF frequency is 352.21 MHz. The 4 vane RFQ accelerates protons to 3.6 MeV. After the bunchers, the five DTL tanks bring the energy to 90 MeV. The Spoke cavities section increases the energy up to 216 MeV. The medium beta and high beta sections both operate at 704.42 MHz. Beam energy is 570 MeV after the medium beta section, and 2 GeV at the end of the high beta section.

The Ion source and LEBT are designed and built by INFN Catania (Italy). They are presently at Lund and installation will be complete by Q3 2018. The RFQ is designed and built by CEA-Saclay (France), and delivery is planned during Q4 2018. MEBT bunchers are designed and constructed by ESS Bilbao (Spain), and delivery is planned during Q1 2019. INFN Legnaro (Italy) will successively deliver all DTL tanks between Q1 2019 and Q1 2020. For more details on the normal conducting linac, see [2]. Spoke cavities and cryomodules are under the responsibility of IPNO (France). They will be tested at FREIA lab in Uppsala (Sweden) before delivery at Lund. Design is finished, fabrication has started and delivery is planned between June 2019 and December 2020. Elliptical cavities come from INFN Milano (Italy) for medium beta and STFC Daresbury (UK) for high beta. CEA Saclay will take care of assembling all elliptical cavity cryomodules. The first four cryomodules will be fully tested at CEA Saclay before shipment. All the others will be tested at high RF power on the surface at Lund before installation in the tunnel. Design and prototyping of medium beta section is finalized (Fig. 3). Delivery is planned between October 2019 and August 2020 for medium beta cryomodules and between October 2020 and end 2021 for high beta cryomodules.

Table 2: Parameters for the Linac Cavities and RF Sources

Linac section	Energy (MeV)	Frequency (MHz)	Number of cavities	Temp (K)	RF power required (kW)	RF source	RF power specified (kW)
Source	0.075	-	-	300	-0		
LEBT	0.075	-	-	300	-		
RFQ	3.6	352.21	1	300	1600	Klystron	3000
MEBT	3.6	352.21	3	300	20	SSPA	35
DTL	90	352.21	5	300	2200	Klystron	3000
Spoke	220	352.21	26	2	330	Tetrode	450
Medium beta	570	704.42	36	2	870	Klystron	1500
High beta	2000	704.42	84	2	1100	Klystron/IOT	1500/1200

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RF Systems

The RF systems located in the RF gallery are providing the power necessary for getting the required accelerating fields in the accelerating structures. Their inventory is given in Table 2. RF systems are grouped in cells, each cell in the SC sections of the linac typically powering 8 cavities. A view of a medium beta cell can be seen in Fig. 4.

The 352 MHz sources chosen for the RFQ and DTL are klystrons that two major suppliers have already developed. A dual-tetrode RF transmitter powers the spoke section. Elettra (Italy) delivers these power stations.

The need for 120 amplifiers to drive the 704 MHz elliptical cavities triggered an ESS/CERN/industry collaborative project for the development of high power 704 MHz Multi-beam IOTs as high efficiency alternatives to klystrons. Two prototypes were funded by the ESS project and CERN provided a test facility. Both prototypes successfully reached nominal performance and 1200 kW power [3].

These new devices are however not mature enough for series production according to the ESS schedule and klystrons have therefore been selected for the medium and the first part of the high beta linac sections. Prototype klystrons have been ordered from 3 manufacturers. To improve the efficiency of the klystrons which will operate well below saturation power in the medium beta section, a mismatch is created in the output cavity. In the high beta section, klystrons are being ordered for the first batch of 44 cavities. The RF amplifiers for the last 40 cavities will be ordered at a later date and MB-IOTs may be the best choice at that time.

Figure 3: Cryomodule for installation tests at ESS.

The LLRF system is based on the MTCA-4 platform, and FPGA units from Struck. Overall system has been designed by Lund University. Polish Electronic Group designs, constructs, and delivers vital subsystems to the LLRF system. The phase reference distribution system has been designed and installed by Warsaw university of Technology. It is based on a coaxial line transporting both 352.21 and 704.42 MHz references to RF and beam diagnostics systems along the linac.

RF interlock systems are built by Atomki (Hungary) using an ESS design based on PLCs and dedicated fast FPGA processing for fast interlock, see controls.

IFJ PAN from Krakow (Poland) contributes to the installation of RF equipment with manpower.

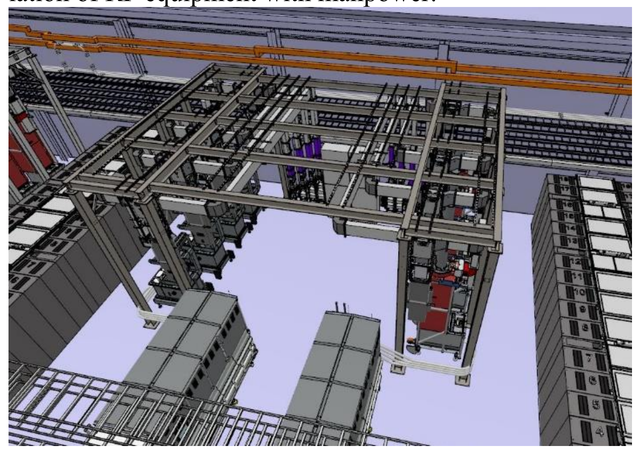

Figure 4: Medium beta cell view. Modulators are to the bottom, klystrons and waveguide systems are in the center, and the waveguides transmit RF power to the tunnel.

Cryogenic Systems

ESS uses cryogenics in three principal applications: The cryomodules require 2 K, 4.5 K, and 40 K cooling. The target moderator requires 16.5 K cooling, and many of the instruments also require cooling. Liquid helium (LHe) is used in most cases. The helium is produced by three cryoplants and an extensive distribution system [4]. The cryoplants have been built by Linde Kryotechnik (Switzerland) and Air Liquide (France). The cryogenic transfer lines are contributions from CNRS (France) and Wroclaw University of Science and Technology (Poland) for spoke linac and Medium/high beta linac/test stand, respectively.

The status Q3 2018 is that the cryoplant for the cryomodule test stand and neutron instruments and the accelerator cryoplant are both being commissioned and production of LHe has commenced. The transfer line between the cryoplant and the test stand is under installation.

Power Converters and Magnets

Power converters for the magnets in the Linac Warm Units (LWU) are contributed by INFN (Italy).

A novel modulator topology called stacked multi-level (SML) [5] is used to power the klystrons. It meets stringent requirements and provides long pulse (3.5 ms), high pulse power (11.5 MWpk) and high average power (660 kVA) while minimizing disturbance to the electrical grid. Its development was made at ESS in collaboration with Lund University. Due to its modularity and extensive utilization of standard off the shelf components, the topology brings considerable advantages in terms of compactness, cost efficiency and maintainability. A prototype was successfully built and tested in the ESS test labs.

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The SML topology is used for the three modulators of the normal conducting linac ordered by ESS Bilbao (Spain) and for the nine modulators of the medium beta section procured by ESS.

In the A2T area the raster magnets are powered by a system from our partner Aarhus University. This system scans the beam across the target in a raster, so that the target is more uniformly illuminated. See Fig. 5.

LEBT magnets are part of the Ion source/LEBT contribution from INFN Catania (Italy). MEBT magnets come from ESS Bilbao (Spain). All magnets in the Spoke section and onwards is a contribution from Elettra (Italy), manufactured by Danfysik (Denmark) and SigmaPhi (France). The rastering magnets come from Aarhus University (Denmark). STFC (UK) assembles the Linac Warm Units (LWUs) and puts the magnets into them.

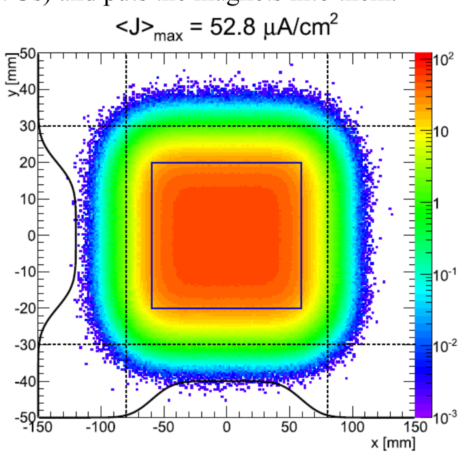

Figure 5: The intensity profile across the target after raster scanning. Note 3:1 aspect ratio on scales.

Beam diagnostics

An overview of the beam diagnostic efforts can be found in [6]. The diagnostic suite contains more than 20 system types, produced by a global collaboration of more than 20 institutes. Table 3 shows the main measurement categories and system types. The total number of diagnostic stations exceeds 450. All systems deliver measurement data via the EPICS-based control system, while a large subset also use FPGA-based processing to provide protection functions with microsecond latency.

Controls, MPS, and PSS

ESS integrated control system is based on EPICS. Information about ESS controls can be found in [7]. The Integrated Control Systems (ICS) division will provide software integration, control room, Machine Protection System, Personnel Safety System, process control, timing, and other services. ICS has adopted for data collection three hardware platforms:

- MicroTCA-4 for fast applications like LLRF and beam diagnostics with MHz and higher data rate
- EtherCAT for slower applications, up to 100 kHz
- PLC for industrial type process control

These platforms are standardized so that as few device families as possible is achieved.

Table 3: Beam Diagnostics

Category	System
Beam accounting	Doppler System
	Beam Current Monitors
	Faraday Cups
	Beam Loss Monitors (ionization, neutron)
	Aperture Monitors
Centroid	Beam Position Monitors
Distribution	Emittance measurements
	Bunch Shape Monitors
	Wire Scanners
	Beam Induced Fluorescence
	Ionization Profile
	Imaging

The purpose of ESS machine protection is to support the operational availability of ESS by preventing equipment damage. A dedicated machine protection concept [ESS-0035197] has been developed and is being implemented to mitigate the risks and achieve the high operational availability [ESS-0057245]. Several machine protection systems (MPSs) are used to implement the relevant protection functions and are connected to the Fast Beam Interlock System (FBIS) [ESS-0275481], which can stop beam within 2-4 µs through a set of dedicated actuators [ESS-0231457], like the Ion Source, LEBT chopper, MEBT chopper and timing system. The Beam Current Monitoring System (BCMs) is connected to the FBIS to ensure that pulse length, repetition rate, and beam current are not being exceeded [ESS-0178171]. The fastest reaction time of BCMs is 1-2 µs.

The primary role of the Personnel safety Systems (PSS) at ESS is to protect workers from being harmed by exposure to ionising prompt radiation generated by the proton beam and high power RF systems, during all operating modes and lifecycle phases. This will be achieved by preventing the access of personnel to the PSS controlled areas when a hazard is present and controlling access under safe conditions. All hazards within the PSS controlled areas will be identified, assessed, and analysed during the hazard identification process.

Typical hazards that shall be considered are ionising prompt radiation from the proton beam; ionising radiation (X-ray) from high power radio frequency (RF) devices; electrical hazards; high powered radio frequency hazards; magnetic field; motion/mechanical hazards; laser hazards; oxygen deficiency hazards. The PSS systems are developed and comply with IEC-61508/IEC-61511: Functional safety of electrical/electronic/programmable electronic safety-related systems. All PSS systems will be designed, manufactured, commissioned and validated to IEC61508, using proven commercial of the shelf technology.

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SCHEDULE

The schedule of the ESS project has recently been re-baselined mostly because of delays in the construction of the target station building. That is due to revised requirements related to earthquakes in the aftermath of the Fukushima incident and concerns about antagonistic threats. The start of the user program, when scientific users make use of neutrons from the source in experiments, is at the end of 2023. For this to be achieved, the accelerator is scheduled to achieve beam on target (BOT) in the middle of 2022. Accelerator readiness for beam on target is scheduled to mid 2021 (Accelerator RBOT). At this stage, 570 MeV beam shall be available, so all the needed hardware (cavities, RF, BI, etc.) need to be installed and commissioned. Fig. 6 depicts the startup steps for the accelerator.

Currently the subsystems are being delivered and installed. The Ion source and LEBT are finalized during Q3 2018, and the plan is to start running the Ion source during September 2018. In the RF Gallery, racks and structures to support waveguides, circulators, and loads are being delivered and installed. To accommodate the schedule in Fig. 6, the beam commissioning of Ion source, LEBT, RFQ, Bunchers, MEBT, and DTL 1-4 will be done in parallel with the installation of the superconducting cavities. This will be achieved installing a shield wall in the tunnel where DTL 5 will ultimately be located.

To test cryomodules and HV/RF equipment the gallery holds a test stand area. Klystrons/HV modulator for these tests are in place and the assembly of the bunker will proceed in October 2018.

The licensing process is complex and progresses thanks to tight interactions and transparent exchanges between ESS and the Swedish nuclear safety authorities for which this is a new type of facility. It is staged and takes place in parallel with testing activities. Permits for running klystrons in the test stand area as well as the Ion Source and LEBT are obtained. The next step is to get permits for operating the test stand bunker and the normal conducting linac.

SUMMARY

The ESS linac will at completion be the world's most powerful proton linac with a proton energy of 2 GeV and a beam power of 5 MW. The linac employs an unusually high portion of superconducting cavities for the acceleration, 95% of the final proton energy. Among the achievements are development of the new SML modulator topology and the MB-IOT tube amplifiers, both of which have been verified experimentally. The next step during Q3 2018 is to start commissioning of the Ion Source and LEBT, in parallel with installation of infrastructure in the RF gallery. Start of the neutron production is scheduled by mid-2022, user scientific program at the end of 2023, and end of construction in December 2025.

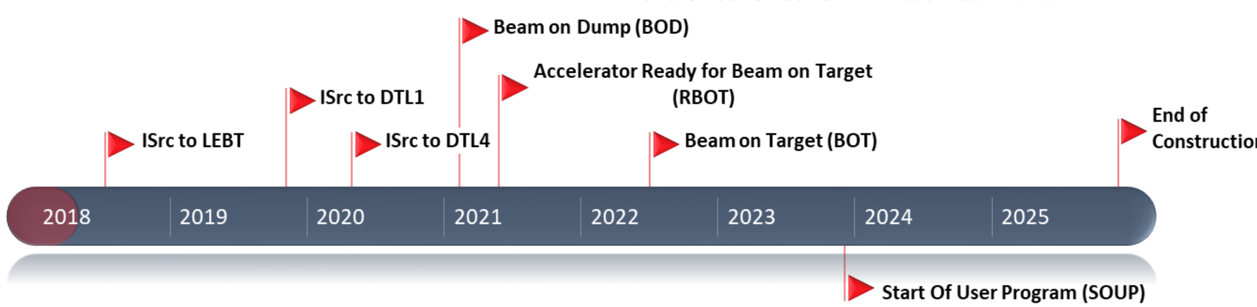

Figure 6: Overall schedule of ESS linac milestones.

ACKNOWLEDGEMENTS

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