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STATUS OF THE NORMAL CONDUCTING LINAC AT THE EUROPEAN SPALLATION SOURCE

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Abstract

The construction of the European Spallation Source (ESS) accelerator is in full swing. Many key components have been delivered from our in-kind partners and installation, testing and commissioning is making remarkable progress. The first machine section to be commissioned with beam is the Normal Conducting Linac (NCL). When completed, a 14 Hz, 2.86 ms proton beam up to 62.5 mA will be transported from the Ion Source (IS), through the Low Energy Beam Transport (LEBT) line, the Radiofrequency Quadrupole (RFQ), the Medium Energy Beam Transport (MEBT) line and the five Drift Tube Linac (DTL) tanks up to 90 MeV where it will be injected in the first superconducting module of the machine [1]. This paper will highlight recent progress across the NCL, present briefly the first commissioning results and discuss the upcoming phases as well as challenges in delivering a machine capable of meeting the requirements for a next generation spallation neutron facility.

NCL DESCRIPTION

The world's most powerful linear accelerator is currently under construction in Lund, Sweden. At full completion, a 62.5 mA proton beam at 14 Hz and 2.86 ms will be accelerated up to 2 GeV. The resulting average beam power of 5 MW will be used to drive the production of spallation neutrons, enabling ESS to become a flagship research facility and to carry out world class science. While progress is being made across the board, from accelerator to target and neutron instruments [2], the NCL is the first section of the machine to transition from installation to integrated testing and commissioning with beam.

IS and LEBT

The NCL starts with a microwave discharge ion source producing a 75 keV proton beam that is further transported through the LEBT. The LEBT is a transport channel consisting primarily of two magnetic solenoids with steerers, an electrostatic chopping system, an iris, two repellers, a collimator and an extensive suite of diagnostics (Faraday Cup – FC, Beam Current Monitors – BCMs, Allison Scanner Emittance Measurement Unit – EMU, Beam Induced Fluorescence Non-Invasive Profile Monitor – NPM and a Doppler-shift spectroscopy system). The IS and the LEBT are in-kind contributions from INFN Catania in Italy.

RFQ

After the LEBT, a 4.6 m long, four-vane RFQ operating at 352.21 MHz, bunches and accelerates the beam up to 3.62 MeV. A BCM measures the beam current at the end of the RFQ. The RFQ is an in-kind contribution from CEA in France, while its RF system was provided by ESS-Bilbao in Spain.

MEBT

The subsequent MEBT is a transport line intended to match the beam to the DTL and consists of 11 quadrupoles with steerers, three buncher cavities, a fast chopping system, collimators and additional diagnostics to further characterise

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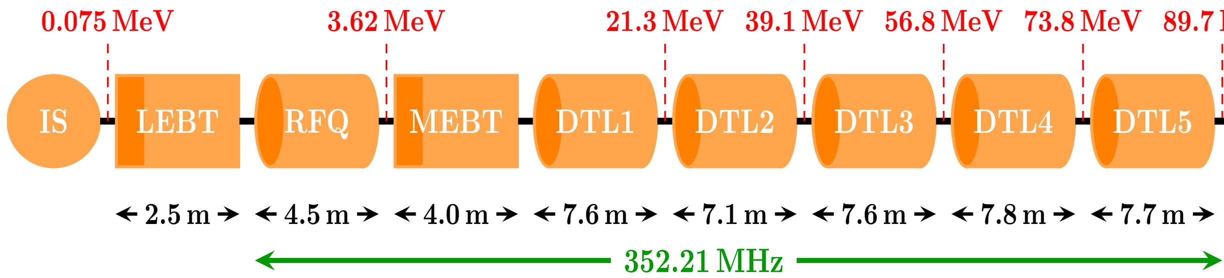

Figure 1: Schematic layout of the ESS Normal Conducting Linac.

the beam (FC, Beam Position Monitors – BPMs, BCMs, Wire Scanners – WS, a Bunch Shape Monitor – BSM, EMU, NPMs). The MEBT is also a contribution from ESS-Bilbao.

DTL

After the MEBT, five DTL tanks will accelerate the beam to ~90 MeV. The tanks operate at 352.21 MHz and make use of permanent magnet quadrupoles placed inside drift tubes for transverse focusing. Some drift tubes are also equipped with steerers and BPMs, while BCMs are placed between the tanks for current measurement. FCs are also placed at the end of DTL tanks 2 and 4. The DTL is an in-kind contribution from INFN-Legnaro and INFN-Torino, while the final assembly takes place at ESS [3]. The RF systems are provided by ESS-Bilbao. A schematic layout of the entire NCL can be seen in Figure 1.

INSTALLATION, TESTING AND COMMISSIONING PHASES

The delivery of the entire accelerator scope is a staged approach intended to establish first beam to new destinations as soon as possible. To enable the commissioning of the NCL to proceed in parallel with the installation of the superconducting linac (SCL), a temporary shielding wall was installed in the tunnel to separate these two sections. In addition, to allow a more focused use of resources only essential diagnostics are made available initially, with the ambition of deploying more devices as we advance. Each

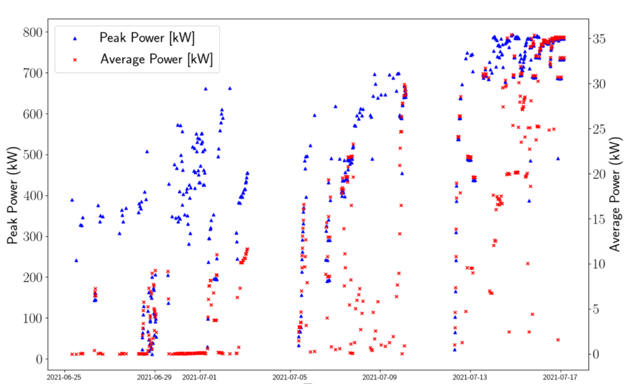

Figure 2: Evolution of the peak and average power in the RFQ during initial conditioning.

phase goes through a period of installation and infrastructure completion, followed by local and integrated testing, RF conditioning of cavities and finally commissioning with beam.

Ion Source and LEBT Commissioning

Beam to the LEBT was established for the first time at ESS in 2018 after the IS and the LEBT were delivered to Lund from INFN Catania. As these were the only beamline components installed in the tunnel at the time, a temporary diagnostics box was added to the end of the LEBT to allow a more complete characterization of the beam. These results are reported in [4–6].

RFQ Conditioning

The next step was to start conditioning the RFQ. This required a different level of effort not only on managing the deliveries from our in-kind partners, but also on completing the local support infrastructure, the deployment of the personnel safety system and the technical hardware integration. Ensuring that adequate conventional and radiation safety procedures are in place before starting, was also essential. This phase was particularly challenging for a green field facility like ESS, and establishing control room operations marked a major transition point from installation to commissioning and operations.

The first RF pulse was sent to the RFQ on the 9$^{\text{th}}$ of June 2021, and conditioning activities lasted approximately 8 weeks. The power is injected into the RFQ via two couplers that were previously conditioned up to 1 MW each at CEA in Saclay. For nominal operation with beam ~1 MW of RF power is needed (729 kW for the cavity to achieve nominal voltage and 225 kW for beam loading). At the end of the conditioning period, stable operation above the nominal power was demonstrated over a sustained period as well as the ability of the cooling skid to maintain cavity frequency within ±1.5 kHz. The evolution of peak and average power with time can be seen in Figure 2 [7, 8].

Beam to MEBT Faraday Cup

After the RFQ conditioning was completed, a short period of intense testing, pre-start reviews and dry-runs followed, in preparation for commissioning with beam. The baseline goal was to send a probe beam (6 mA, 5 µs, 1 Hz) to the MEBT FC and make all baseline systems operational. Beam

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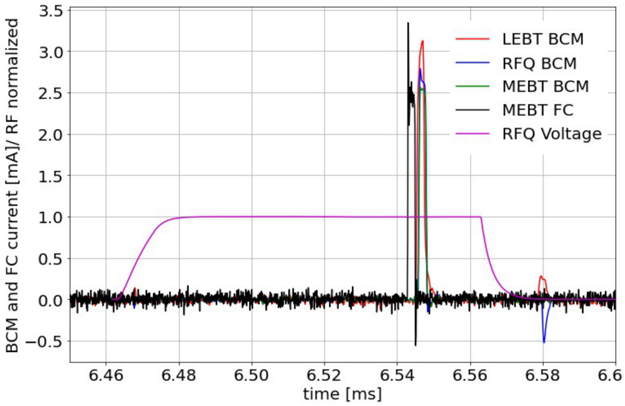

Figure 3: First beam pulse sent to the MEBT FC.

to the LEBT FC was re-established on the 10th of November 2021 and the first proton pulse of 3 mA and 5 µs was sent through the RFQ on the 26th of November 2021 as presented in Figure 3. For this phase, the three buncher cavities in the MEBT were unpowered, as their respective RF systems were not fully deployed. In addition, limited availability of diagnostics devices (only FC, BPMs and BCMs were operational on day one), coupled with the need to validate critical hardware and protection functions for the first time, imposed the need to apply administrative operational limits and take a very cautious approach in ramping up beam power. At the same time the commissioning team had to handle inevitable hardware faults and reduced availability of tools and functionalities, so at the end of the commissioning run in 2021, only the pulse length was increased to 50 µs but not the beam current. However, two more short commissioning runs were arranged in 2022 when a 62.5 mA, 5 µs beam at 1 Hz, was sent to the MEBT FC. This allowed to complete a more systematic characterization of the IS, LEBT and MEBT, testing of the RFQ with LLRF as well as extensive debugging and optimisation. Transmission through the RFQ was measured at over 95% and the beam energy at 3.6 MeV.

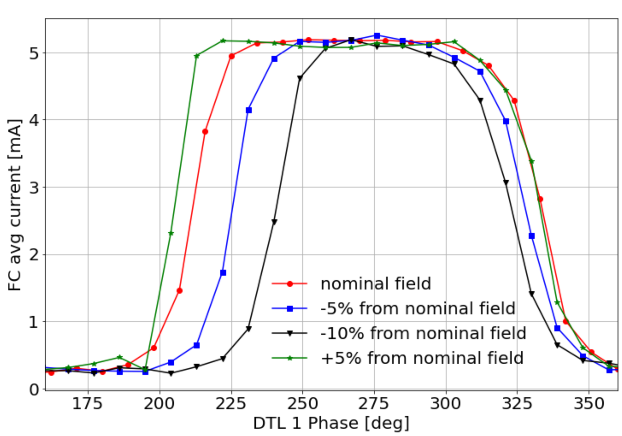

Figure 4: Preliminary DTL1 phase acceptance scans.

DTL1 Conditioning

The first DTL tank was installed in August 2021 and connection to utilities, local as well as integrating testing with the cooling skid, controls and the RF system continued throughout 2021 and early 2022. Critical interlocks, signal calibration and communication between systems were extensively verified. The RF system which is identical with the RFQ RF system, both sharing a common modulator, was tested independently at low and high power before connection. The first RF pulse to DTL1 was sent in March 2022 and progress continued gradually aiming at reaching nominal field and a duty cycle adequate for supporting the next commissioning phase with beam (3 MV/m, 100 µs, 1 Hz). Once this was achieved, focus was shifted to increasing the duty cycle. At the time of writing, DTL1 can run stably at 2.85 MV/m, 3.2 ms and 14 Hz, which is very close to the nominal parameters. This is encouraging progress given that the available time for conditioning was limited to 10 shifts per week (except for a two week period of 24/5) and often had to be shared with other concomitant activities. In addition, progress has been made on deploying and testing LLRF functionality to support closed loop operation with beam.

Beam to DTL1 Faraday Cup

After DTL1 conditioning was started, intense efforts were made in preparation for sending beam through the tank. This is possible as a FC enclosed in concrete shielding has been temporarily installed at the end of DTL1. As in earlier phases, extensive integrated testing of all additional systems was carried out, including the new FC, BCMs, BPMs and WSs, as well as the three MEBT bunchers and their respective RF systems. The first beam to the FC at 3 mA, 5 µs, 1 Hz, was established on June 1st 2022, after all cavities were roughly phased. Results from preliminary DTL1 phase acceptance scans can be seen in Figure 4. Commissioning activities are ongoing, aiming at testing individual systems and at improving the overall performance of the machine.

NEXT STEPS

Beam commissioning activities to the DTL1 FC will come to an end in the summer of 2022, when a longer shutdown period will allow the installation of three additional DTL tanks. A FC will be installed at the end of DTL4 and will serve as the new beam destination. We estimate that RF conditioning activities of tanks 2, 3 and 4 will begin in early 2023 and beam commissioning soon after. At the end of that phase, the temporary shielding wall in the tunnel will be removed to allow the installation of DTL5, as well as connection to the SCL.

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