ESS NORMAL CONDUCTING LINAC COMMISSIONING RESULTS

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Abstract

The European Spallation Source is designed to be the world's brightest neutron source once in operation, driven by a 5 MW proton linac. The linac consists of a normal conducting front end followed by a superconducting linac. The normal conducting part has been commissioned in several stages, with the latest stage involving all but one DTL tank now in 2023. During this commissioning period, we successfully transported a 50 µs pulse of the nominal 62.5 mA beam current. We will present an overview of the commissioning results, with a focus on what we achieved in this latest stage.

INTRODUCTION

The European Spallation Source (ESS) is a long pulse neutron source driven by a 5 MW proton linac [1]. The facility is currently under construction in Lund, Sweden. A rotating tungsten target is bombarded by a 2.86 ms long proton beam pulse at 2 GeV beam energy 14 times per second. The Start of User Programme (SOUP) is planned for 2026.

The protons are accelerated through a 600 m long linac, comprising of a normal conducting front-end (NCL) followed by a super-conducting linac (SCL) performing the bulk of the acceleration. The front-end RF is at 352.21 MHz, same as the first class of SC cavities (Spokes). After that we have two elliptical cavity families running at twice this bunching frequency.

The NCL has been installed and commissioned in several stages over the past years [2–6]. The latest and final stage of dedicated NCL commissioning was performed in the second quarter of 2023.

Main Goals of Commissioning Run

The primary goal of each commissioning stage is to have all necessary sub-systems integrated and commissioned, and show the ability to transport and accelerate the nominal beam. Except for the LEBT FC, the beam destinations used cannot receive the full proton pulse length (or more generally, the average charge deposition), but we are still able to prove transport of the nominal beam current which can give us confidence in the transverse beam optics. Transporting a 50 µs pulse is expected to be sufficient to prove that we can provide a stable RF for the full pulse. The ESS accelerator will nominally operate at 14 Hz, which is also important to test, in particular during reliability studies and for RF.

A "safe to be lost" beam mode called probe beam has been defined with a 6 mA, 1 Hz, 5 µs envelope. To verify ability to transport we then have other beam modes which vary one or several of the envelope parameters up to 62.5 mA, 14 Hz, 50 µs which were used during the commissioning run.

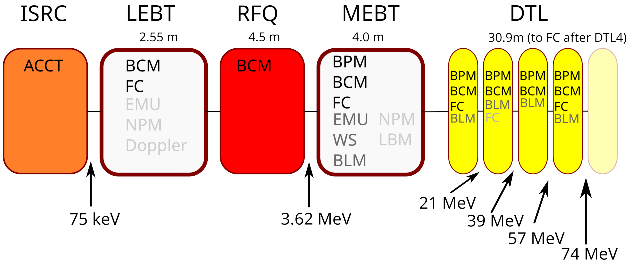

Figure 1: The ESS normal conducting linac during commissioning, with diagnostic systems for each section indicated. Dark grey indicates partial availability, while light grey indicates not ready. All RF in the NCL run at 352.21 MHz. The final energy out of the 5th DTL tank is 90 MeV.

The beam modes are an underlying concept for machine protection at ESS and the operator choice is enforced via an interlock implemented through the Beam Current Monitor (BCM) system. To prevent damage, some beam modes had special restrictions or were not allowed for certain beam destinations.

NORMAL CONDUCTING LINAC

The NCL comprises an ion source (ISRC), a low-energy beam transport (LEBT), a radio-frequency quadrupole (RFQ), a medium-energy beam transport (MEBT) and finally a drift-tube linac (DTL). During the final stage of NCL commissioning, 4 out of 5 DTL tanks were installed, while a temporary shielding wall (TSW) was installed in the location of the 5th tank. This wall ensured that work could continue uninterrupted in the rest of the tunnel, downstream of the NCL (and wall). The total linac length was around 42 m, and the layout is depicted in Fig. 1. The diagnostics used are discussed in more detail in Ref. [7].

ISRC and LEBT

The ion source is a plasma discharge ion source with a voltage gap of 75 kV. Three magnetic coils are available to

Table 1: ESS Linac High-level Schedule

Step	Start	Energy [MeV]
Commissioning to LEBT	2018-09	0.075
Commissioning to MEBT	2021-11	3.62
Commissioning to DTL1	2022-05	21
Commissioning to DTL4	2023-04	74
Commissioning to dump	2024	570
Commissioning to target	2025	570
Start of user operations	2026	800

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adjust the plasma, effectively manipulating the quality and stability of the extracted beam. The nominal pulse out of the ion source is 6 ms, about twice the final proton pulse in the linac. This is due to the slow rise time of the proton current, which is chopped off in the LEBT. H_2 and some H_3 content are also expected out of the ion source, but these species will not be focused as well by the LEBT solenoids and hence are not matched into the RFQ. The source is designed for a nominal proton current of 74 mA but is capable of producing a total current of 100 mA.

The LEBT has two focusing solenoids each containing two internal H/V correction coils for beam steering. Between the magnets, we have a diagnostic tank including the LEBT chopper to control the pulse length and a 6-blade iris to control the beam current.

RFQ

The RFQ is a 4-vane of 4.5 m length, divided in 5 segments. The beam is accelerated from 75 keV to 3.62 MeV, with expected capture efficiency above 90 %. The RFQ nominally operates at 120 kV.

MEBT

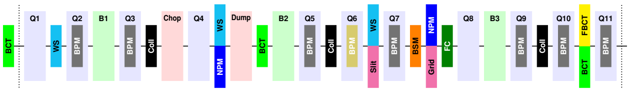


Figure 2: The MEBT synoptic layout.

The MEBT is shown in Fig. 2. It serves as a matching section for the DTL, as well as an essential diagnostic section. Additionally, a second fast chopper station is installed. Eleven quadrupoles are available for transverse tuning, each including an H/V coil for trajectory correction, and 3 bunchers for longitudinal focusing and matching to the DTL. A collimator is installed as well for cleaning any transverse tails from the front-end.

DTL

Five DTL tanks bring the energy from 3.62 MeV up to 90 MeV, before beam continues into the SCL. During the commissioning the first 4 tanks were installed, providing a nominal beam energy of 74 MeV. There are a total of 154 drift tubes through the 4 tanks, with every second containing a permanent magnet quadrupole (PMQ) to provide a FODO lattice for transverse focusing. Some of the other drift tubes contain a corrector magnet or a BPM, while the remaining are empty. After the 4th tank, there was a drift followed by the FC housed inside extra shielding during this commissioning campaign.

Diagnostics

The essential beam diagnostics needed to allow beam commissioning are considered to be BCMs, FCs (or more generally, beam stops), and BPMs. These were available at the start of beam commissioning, with to some extent final checks to be done with beam.

We have one FC in the LEBT, one in the MEBT, and in the DTL we have one after tank 2 and one after tank 4. During the commissioning the one after tank 2 was not available, but we could proceed without it. The FC after tank 4 was installed with a drift section, approximately 1 m after the end of the tank. It has a degrader foil in front of the cup, and there was concerns that the DTL1 exit energy of around 21 MeV could cause fatigue. Therefore, we operationally limited the activities with this beam energy during the commissioning stage. Beam stops for the NCL commissioning are discussed further in Ref. [8].

There are 7 BPMs in the MEBT and a total of 13 in the 4 DTL tanks. Additionally, a fast BPM in the MEBT dedicated to measure the beam energy. These were all generally available. The signal from several BPMs in the DTL as well as the last BPM in the MEBT was difficult to interpret, likely a result of RF interference. The BPM gain settings had to be adjusted several times during commissioning, and adapted to changes of the beam current. The experience gained will be valuable for the next commissioning rounds and later operation.

We have one ACCT that measures the beam extracted from the source, one BCM at end of LEBT, one at the end of RFQ, another two in the MEBT and one after each DTL tank. These were all available and most of their functions were connected to the machine protection system (MPS). There is also a fast BCM (FBCM) available towards the end of the MEBT.

COMMISSIONING SCHEDULE

This is the 4th commissioning run of the ESS front-end since the first beam was extracted in the fall of 2018, as listed in Table 1. We currently expect to have a finished beam line to the beam dump at the end of the linac by the end of next year, with beam to target to follow in 2025.

Commissioning of the RF could start already in February, while the first beam of this commissioning run was extracted in the middle of April. We had a total of 3 months available for beam commissioning before we had to stop beam activity in order to ensure enough time for the DTL4 FC to cool before dismantling. During this cool-down, we had some additional time that we could run beam to the MEBT FC.

RESULTS

The overall goal of this beam commissioning run was to demonstrate the ability to accelerate the nominal 62.5 mA beam through the NCL. Among our beam modes available for NCL commissioning we have 5 µs and 50 µs pulse lengths. The intention of the latter is to verify RF feed back and feed forward stabilize as well. We achieved a transport of the 62.5 mA, 50 µs beam with good transmission in the first week of July 2023.

Trajectory

During the DTL4 commissioning we had a total of 20 BPMs installed in the NCL. Before performing a trajectory correction we verified the polarity of the correctors and the BPMs. For that, we measured trajectory differences for each corrector and compared with model predictions of the expected signatures. In total, we found 1 BPM in DTL3 with the polarity of the horizontal plane swapped. Additionally, 4 correctors, distributed between the tanks, had wrong polarities. All of them were corrected at the beginning of beam commissioning. We then attempted to correct the trajectory from MEBT to DTL4. The BPMs 1, 3, and 4 in DTL1 had a lot of RF background and the measurement presented large offsets and could not be used. We did manage to correct the trajectory to the centre of all the remaining BPMs, as shown in Fig. 3. For the trajectory correction, we used a model-based response matrix for the BPMs and used SVD in order to invert the resulting matrix to determine the corrector shifts. The final trajectory has an RMS of less than 200 µm in both planes.

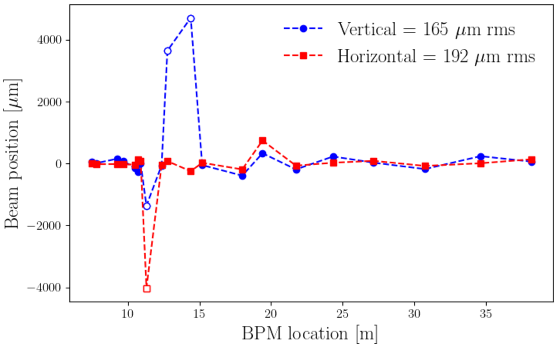


Figure 3: Final corrected trajectory from MEBT to DTL4. The BPMs not used in the correction due to signal issues are marked in white.

Longitudinal

The main activity of a linac commissioning is obtaining the correct amplitude and phase parameters for the accelerating cavities. For this commissioning we had 3 buncher cavities in the MEBT and 4 DTL tanks to configure.

MEBT Bunchers For the MEBT bunchers, we used a model-based response matching to the downstream BPMs. If we denote bunchers C and BPMs B, our MEBT layout is B1-C1-B2-C2-B3-B5-FC-C3-B6-B7-B8 (B4 is a special fast BPM used for energy measurement). This layout is also shown in Fig. 2.

This means that for the first buncher, we only have one BPM unless we turn off the second buncher. This BPM is also quite close to the buncher and may see some RF noise. For buncher 3 we had to take out the MEBT FC and have DTL4 FC as the beam destination.

Manually setting the 3 bunchers would typically take 30 minutes to 1 hour. Towards the end of the commissioning we had an automated logic that would set the buncher parameters in around 3 m (depending on scan granularity). The buncher scans have been presented in past commissioning runs [9]. This commissioning run focused on a fast and reliable automated logic.

One of the questions for automation of the buncher scans was if we need to detune downstream bunchers, or if it is sufficient to turn them off and use a low current short pulse beam which means low beam loading effects. Our results so far indicate that we can expect a difference below 1° for the phase matching.

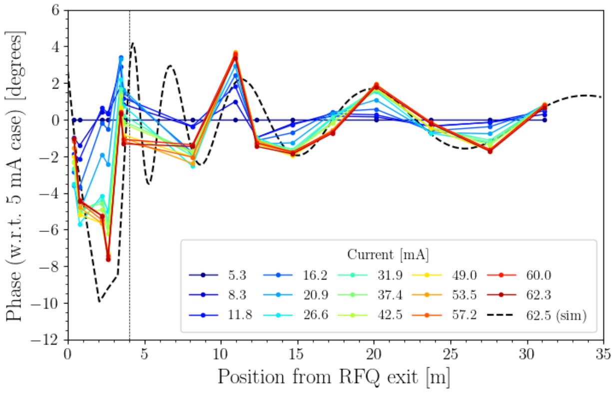
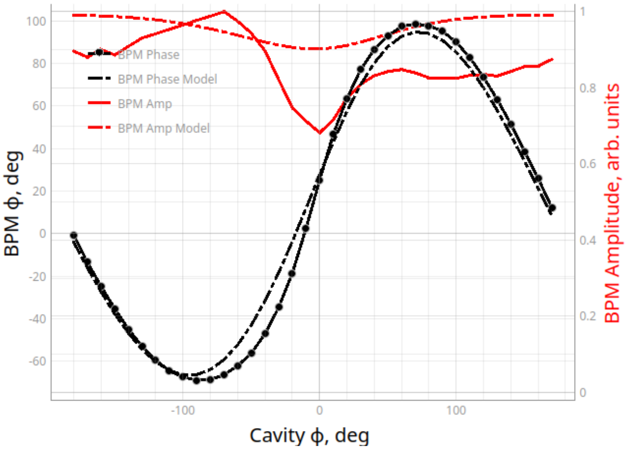


Figure 4: Phase shift out of the RFQ as a function of beam current.

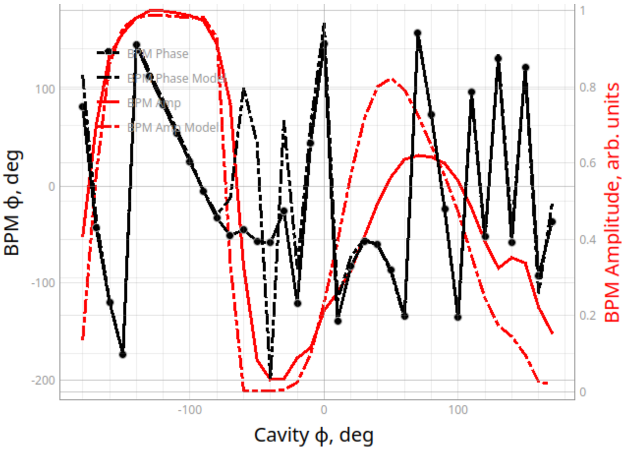
During the commissioning run a strong current dependency of the initial beam phase out of the RFQ on beam current was observed, as indicated in Fig. 4. This effect has not been fully understood yet, but as seen in the figure, the oscillation and damping of the beam phase with energy match well to the model if we assume the initial phase offset of the beam. We believe this effect needs to be understood if we want to continue with the strategy of running phase scans with a low current beam and operate with a high current.

DTL The DTL tanks have internal BPMs, 6 in the first tank, 3 in the second, and 2 in the tanks 3-5. The first BPM in each tank has a good signal for basically all phases, and the phase response is sinusoidal-like since there are not as many gaps before this BPM. During the commissioning campaign, we found that this BPM signal is effective for setting the correct phase and amplitude of the cavity, matching to model-predicted BPM response. It has the added benefit that compared to a ToF we do not need to turn off (or detune) downstream tanks.

The second internal BPM to a tank is harder to match since it does not see BPM for all beam phases, and due to the high number of wraps of the signal. Nevertheless, a fitting algorithm was successfully developed [10] where we unwrap the simulated signal instead of wrapping the measured signal. This was developed using PyORBIT [11] for modelling instead of the OpenXAL model we traditionally use. Adding the second BPM in the fitting provided an improved matching, in particular on amplitude. Analyzing the reliability of the matching across the measurements done, we largely found that the estimated set amplitudes for the DTL tanks were stable. The same was true for phase, with the exception that on occasion we had upgrades to the system that would reset the reference phase value. For DTL1 we see in particular for the BPM1 that the phase response does not exactly correspond to model predictions, as seen in Fig. 5.



(a) BPM1



(b) BPM2

Figure 5: DTL1 phase scan example. Black curves show phase, red curves BPM amplitude response. The dashed lines indicate the simulated (expected) response from model.

Transverse

The MEBT has a slit-grid type EMU installed, as well as 3 wire-scanners for measuring the transverse profile. Towards the end of the commissioning run we were able to get some detailed scans of the horizontal beam profile with the EMU.

We used the nominal 62.5 mA beam current over a 30 µs pulse to measure the profile, expanding the beam somewhat by leaving some quadrupoles in the MEBT off. The measurement is shown in Fig. 6.

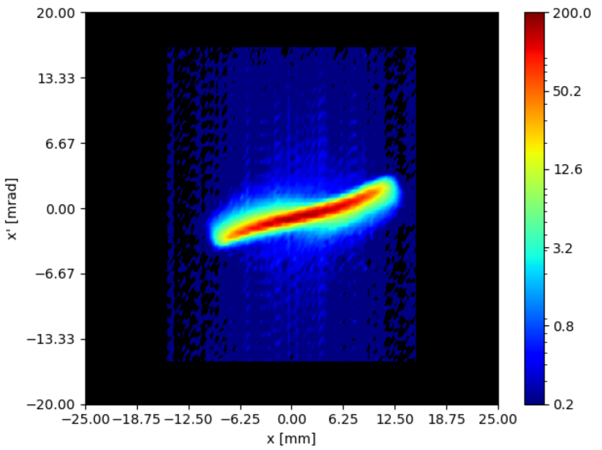


Figure 6: Measurement of the horizontal beam profile from the MEBT EMU, for a 30 µs pulse length at nominal beam current.

Good background subtraction is generally a major challenge in the analysis of transverse profile measurements, since an overly aggressive cut will artificially reduce the estimated RMS beam size. For our EMU, we believe background signal at the core of the beam, extended towards higher angles due to scattered protons at the slit. Based on that we applied a Gaussian fit to the background which we subtracted, followed by a signal cut. In Fig. 7 we see that when we subtract the Gaussian shaped background we have a dramatically improved emittance estimate for low signal cuts. We further observe that different bias voltages converge at a lower signal cut. For reference, we expect a transverse emittance of around 0.25 mm mrad from the model.

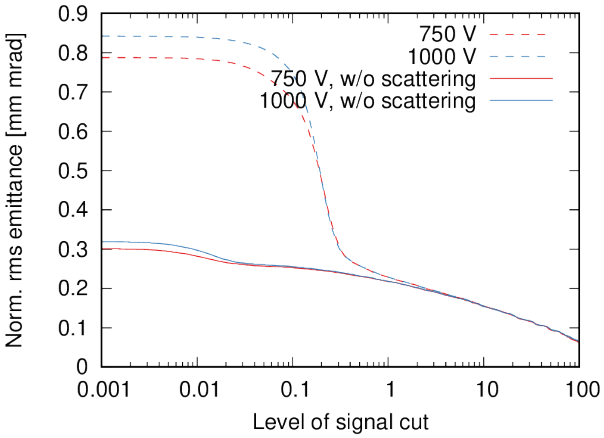


Figure 7: The estimated beam emittance as a function of signal cut applied. Dashed lines show only a signal cut, while for solid lines we have first made a Gaussian fitted background subtraction. Measurement was repeated for two different bias voltages.

The measured beam pulse has been chopped in the LEBT, where space-charge neutralization plays an essential role in the beam optics. The head of the chopped pulse will not see the same build-up of electrons, therefore having a lower degree of neutralization and a mismatch into the RFQ. This build-up is expected to be around 20 µs [12]. In Fig. 8 we show the transient of the emittance and Courant-Snyder α. We see a clear stabilization after about 15 µs.

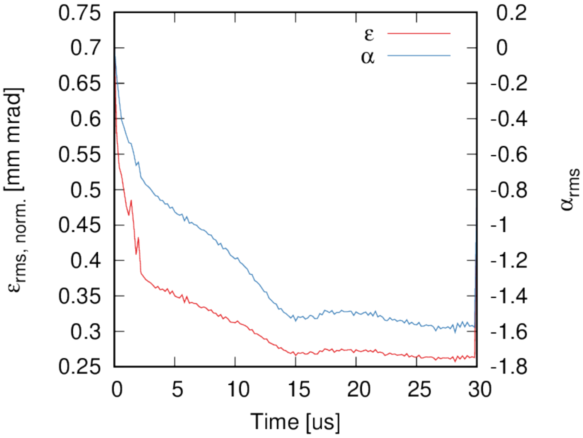


Figure 8: The transient of the emittance from the EMU measurement.

DISCUSSION

During this beam commissioning campaign, we successfully achieved our main goal which was to transport and accelerate a 50 µs beam pulse at nominal current to the end of DTL4. We further made good progress in our understanding of the machine behavior and the stability of our matching strategy. There are optimizations needed on e. g. matching into the DTL, and we will need to understand the beam phase current dependency out of the RFQ.

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