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ESS COMMISSIONING PLANS

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Abstract

The ESS linac is currently under construction in Lund, Sweden, and once completed it will deliver an unprecedented 5 MW of average power. The ion source and LEBT commissioning starts in 2018 and will continue with the RFQ, MEBT and the first DTL tank next year and up to the end of the fourth DTL tank in 2020. This paper will summarize the commissioning plans for the normal conducting linac with focus on the ion source and LEBT and application development for both commissioning and operation.

INTRODUCTION

The European Spallation Source, currently under construction in Lund, Sweden, will be a spallation neutron source driven by a superconducting proton linac [1]. The linac accelerates a beam with a 62.5 mA peak current and 4% duty cycle (2.857 ms pulse length at 14 Hz) up to 2 GeV and thus produces an unprecedented 5 MW average beam power. The superconducting linac has a normal conducting (NC) linac as its injection, which consists of an ion source (IS), radio frequency quadrupole (RFQ), drift tube linac (DTL), as well as low and medium energy beam transports (LEBT and MEBT) and accelerates the generated proton beam from 75 keV to 90 MeV. A schematic layout of the (ESS) linac is shown in Fig. 1.

Beam commissioning of the ESS linac will be conducted in stages [2–4]. The first and upcoming stage is for the IS and LEBT, planned to start in the summer of 2018 and continue until fall. Commissioning of the NC linac up to the first DTL tank should happen at end of 2019 and up to the fourth tank in the first quarter of 2020. This paper presents the updated plan of the NC linac beam commissioning with a major focus on the IS and LEBT commissioning, high level applications development and beam parameters.

NC LINAC OVERVIEW

IS and LEBT

The IS and LEBT are in-kind contributions from INFN-LNS [5]. Table 1 lists a possible set of operational parameters of the IS. Note that the operational parameters are ultimately determined after all the sections of the linac are installed and tested. The proton current larger than the nominal 62.5 mA is to take into account possible beam losses in the LEBT and RFQ. The off-site commissioning confirmed that the IS is indeed capable of producing this level of current [6]. The pulse length longer than the nominal 2.857 ms is due to the required ~3 ms stabilization time of the IS. The excess ~3 ms in the leading part is removed by a chopper in the LEBT, before the beam enters into the RFQ.

Table 1: ESS IS Possible Operational Parameters

Parameter	Value	Unit
Energy	~75	keV
Peak current (total)	~85	mA
Peak current (proton)	~70	mA
Proton fraction	~80	%
Pulse length	~6	ms
Pulse repetition rate	14	Hz
Duty cycle	~8	%

The LEBT is a focusing channel with two solenoids. Each solenoid also houses coils of dipole correctors (*steerers*) for both planes. Tuning of the linac requires a beam with a much lower power than the nominal 5 MW. Standardized sets of limits in the current, pulse length, and repetition rate have been defined as *beam modes* [7] and an important function of the LEBT is to produce the beam modes by adjusting the current and pulse length with its iris and chopper.

The LEBT also houses a suite of beam diagnostics devices. Most of them are either in the permanent tank, between the solenoids, or in the commissioning tank, temporary placed in the position of the RFQ (Fig. 2). The beam current monitor (BCM) and Faraday Cup (FC) are used for current measurements. The first BCM actually monitors the current extracted from the high-voltage power supply and thus indirectly provides the total current of the IS. The Doppler detector measures fractions of ion species from Doppler shifts of the light induced by the beam. In total four cameras (Non-invasive profile monitors or NPMs), one for each plane at two locations, also detect the beam induced light and measures the beam profile and centroid position. An Allison scanner type emittance measurement unit (EMU) measures the phase space distribution in either the permanent or commissioning tank. The commissioning tank also houses a temporary beam stop, which could stop the beam with a full peak current and duty cycle, at its end.

RFQ

The RFQ is an in-kind contribution from CEA-Irfu and will be delivered to ESS in the last quarter of 2018. It consists of five sections with a total length of 4.6 m and accelerates the proton beam from 75 keV up to 3.6 MeV. The RFQ design was optimized for a high transmission (> 97%). The maximum total power coupled into the RFQ is expected to be 1.6 MW [8]. The only diagnostics in the RFQ section is a BCM attached to the exit wall and right before the MEBT.

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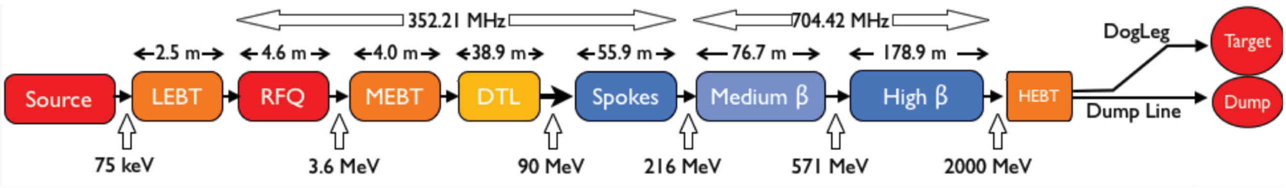

Figure 1: Schematics of the ESS linac. The red/orange section represent the warm parts of the linac while the blue are the superconducting/cold sections.

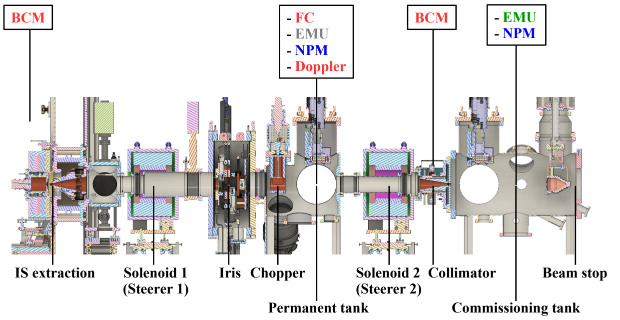

Figure 2: Schematic of the LEBT during the IS and LEBT beam commissioning. The EMU can be also housed in the permanent tank (indicated by the grey text).

MEBT

The MEBT section follows the RFQ and most of its components are in-kind contributions from ESS Bilbao [9]. It is 4 m long and includes eleven quadrupoles, three buncher cavities, one fast chopper, one beam chopper dump and three vertical blades used as collimators. It also contains steerers in every quadrupole as extra windings for both planes. When the beam pulse length is adjusted with the slow chopper in the LEBT, an extra 20 µs is left in the leading part. This extra 20 µs part remains in the RFQ and is removed by the fast chopper in the MEBT. This is because the space charge neutralization effect in the LEBT has a finite build-up time, estimated up to 20 µs, and this part of the pulse is expected to have wrong beam parameters.

The transverse lattice of the MEBT is separated into two parts at the chopper dump. The initial part produces a waist in the vertical plane (plane of the fast chopper's deflection) and a parallel beam in the horizontal plane, in a section between the fast chopper and its dump. These are to guarantee a good efficiency of chopping as well as a good transport in a relatively long section with only one week quadrupole focusing in the horizontal plane. When the beam passes through the fast chopper dump, it is diverging in both planes. The transverse lattice after the dump refocuses this expanded beam and matches to the following DTL. Three buncher cavities maintain the bunch length within the MEBT and match the longitudinal Twiss parameters at the DTL entrance. The first buncher cavity defines the mean bunch length throughout the MEBT and the other two are used to achieve the matching.

As far as diagnostics goes, there are seven BPMs, two NPMs, one FC, two BCMs, two Fast BCMs (FBCMs), a set of 3 wire scanner profile monitors (WS), one EMU and a Longitudinal Beam Profile Monitor (LBM). The BPMs in the MEBT and downstream the linac can also be used as phase monitor. A schematics of the MEBT elements can be seen in Fig. 3.

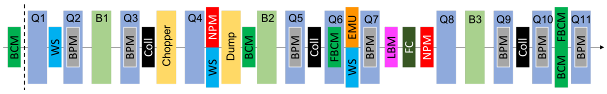

Figure 3: Schematics of the MEBT.

DTL

The DTL will de delivered by INFN-LNL [10]. It is a 38.8 m long system, divided in five tanks. Each tank is a standalone structure, composed of four 2 m long modules made of stainless steel with internal electro-copper deposition. Every other drift-tube is equipped with permanent magnet quadrupoles (PMQs), forming the FODO layout (transverse focusing channel). Some drift-tubes not housing a PMQ are equipped with a BPM or a single plane steerer. A BCM is present in each inter-tank section and a FC every twos tanks. In the DTL the beam is further accelerated from 3.6 MeV to 90 MeV and no adjustment in the transverse focusing is possible, given the nature of its quadrupoles. A schematic of the DTL diagnostics and steerer elements can be seen in Fig. 4.

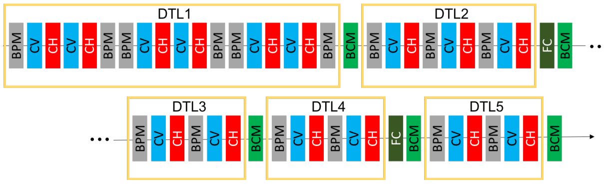

Figure 4: Layout of the DTL diagnostics and steerers. Drift-tubes with a PMQ or no additional element are omitted.

NC LINAC INSTALLATION SCHEDULE

Installation of the IS and LEBT components was finalized in May 2018 (Fig. 5). Hardware commissioning of the components has been on-hold due to lack of electrical power in the tunnel but is anticipated to commence in the summer. An exception for the yet-started hardware commissioning

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is the control system, which is based on the EPICS framework and an in-kind contribution from CEA Saclay [11]. Its acceptance test was successfully performed already as a part of the off-site commissioning in September 2017. Also on ESS site, trial connections to EPICS channels from the local control room, using temporary power, were successfully conducted in April 2018, making it ready for the full re-verification as soon as the power becomes available in the tunnel. A readiness review for the IS and LEBT, focusing on the safety aspect, follows completion of the hardware commissioning, and pass on the review allows to start the beam commissioning, planned to begin end of August and run for 3 months.

The RFQ is scheduled for delivery and installation in fourth quarter of 2018, but RF conditioning and beam commissioning can only start in the second half of 2019 due to the unavailability of the RF system. The first four DTL tanks are also scheduled for delivery and installation in 2019. The beam commissioning of the RFQ, MEBT, and first DTL tank will be conducted together, while commissioning up to the fourth DTL tank will continue in 2020, after the full RF system for the NC linac is installed.Up to this point, the beam will be stopped with the FCs in the MEBT and between the DTL tanks and a temporary shield wall will be placed after the DTL tank 4 (taking the space of DTL tank 5), allowing the beam commissioning of the NC linac while installation work in the superconducting part of the linac happens in parallel.

Since the RFQ and MEBT will be installed and commissioned together, this means that the beam out of the RFQ must be characterized with diagnostics devices in the MEBT. For some hadron linacs, for instance CERN LINAC4, the IS, LEBT, and RFQ were commissioned by itself without the following sections and the output beam of each section was characterized with a common movable test bench [12]. The movable bench was also considered for the beam commissioning of the ESS NC linac [13] but is not currently in the plan due to the limitations in budget and schedule.

BEAM COMMISSIONING STRATEGY

The initial phase of every beam commissioning consists of verification of systems which require the beam presence, such as beam diagnostics devices. Afterwards, a series of characterization and optimization activities should follow and the beam commissioning is concluded with long-term stability tests. The main activities during the commissioning for the NC linac are listed in the following subsections.

Figure 5: IS and LEBT installed in the ESS linac tunnel.

Beam Modes

As already stated, several sets of beam modes are defined to be used during the beam commissioning and general linac tuning [7] (see Table 2). The probe mode has the lowest beam power and is used mainly for the very first check of the system and hardware and the beam threading, the process to correct the trajectory and deliver the beam to the designated beam stop. The fast tuning and slow tuning modes are used to characterized the beam and achieve the desired beam parameters and thus the main types of modes during the beam commissioning. The fast tuning mode is mainly for setting the phases and amplitudes of cavity fields. The slow tuning mode could have a pulse length up 50 µs and this is meant to provide a good quality signal to invasive diagnostics devices, such as FCs and WS profile monitors. The slow tuning mode will be also used to set the low-level RF (LLRF) feed-backs and feed-forwards loops for the cavities. All beam modes mentioned above can be sent to any of the beam stops in the NC linac, however they are constrained by the total dose produced for the FCs at the DTL inter-tanks [14], which can restrict the amount of time that each one can be used. The other available beam modes listed in [7] can only be stopped at the tuning dump or target and thus will not be used for the NC linac tuning.

IS and LEBT Phase

Prior to the delivery to ESS in December 2017, the IS and LEBT were successfully commissioned with the beam at INFN-LNS [5, 6, 15, 16]. Given this successful off-site commissioning, the re-commissioning of the IS in Lund begins with verification of the IS beam characteristics (see Table 1), observed during the off-site commissioning, followed by fine-tuning adapting to the needs of the following sections.

Having steerers and NPMs at two locations for each plane in the LEBT allows a simple beam steering based on the measured trajectory responses. Ideally, we would like to cancel both position and angle errors at the RFQ interface and this requires the position error being canceled in the middle of the second solenoid. The location of the first set of cameras is not far from the second solenoid and thus we are not far from this ideal situation.

The RFQ transmission is very sensitive to the beam parameters at its entrance. Once we have the RFQ, good matching is achieved by simply scanning the solenoids and identifying the strengths for the best transmission. During the IS and LEBT beam commissioning, an EMU is placed in the commissioning tank, ~15 cm from the LEBT-RFQ interface. Due to a strong space charge and never-known space charge compensation level in this region, reconstructing the transverse phase space distribution at the interface can be difficult. On the other hand, once the RFQ is connected, this EMU

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Table 2: List of Beam Modes for the NC Linac Tuning

Type	Destination	Main usage	Peak current [mA]	Pulse length [µs]	Repetition rate [Hz]
Probe	Any beam stop	Initial check Beam threading	6	≤5	≤1
Fast tunning	Any beam stop*	RF check	6-62.5	≤5	≤14
Slow tunning	Any beam stop*	Invasive measurement LLRF setting	6-62.5	≤50	≤1

* Subject to maximal dose limit for DTL FCs during NC linac commissioning.

is no longer available. Therefore, our strategy during the IS and LEBT beam commissioning is to collect EMU data for a range of the two solenoids field strengths, where simulations predict good matching. This allows us to look back the data of the emittance meter for a given (or at least close) condition of the IS and LEBT, even after the RFQ installation.

The input current to the RFQ has to be adjusted so that the output becomes the linac-wide nominal value of 62.5 mA. This is because the sections after the RFQ are not designed for more than 62.5 mA. Transmission through the RFQ is not known during the IS and LEBT beam commissioning and this requires the preparation of several configurations of the IS and LEBT for different currents. Because of the iris, the IS itself does not need to fine-tune the current. However, extracting an excess amount of the beam could spoil the emittance [17], so it is still ideal to extract just the right amount of current from the IS and minimize the use of the iris for production of the nominal current. The permanent tank, after the first solenoid and iris, houses the FC, Doppler detector, and EMU. This allows to characterize the beam parameters against the IS configuration as well as the amount of N_2 gas injection (for enhancing the space charge neutralization effect) and helps to prepare candidates for the final IS setting.

Capability to produce the beam modes has to be verified during the IS and LEBT beam commissioning, before the beam is sent to the rest of the linac. For the chopper, its efficiency has to be carefully verified to prevent the chopped part of the pulse leaking into the RFQ. During the initial power ramp-up phase of linac operations, the beam power is managed with current, whereas the pulse length and repetition rate are fixed to the nominal values of 2.857 ms and 14 Hz due to users demand. This requires multiple configurations of the linac for different currents, already from the LEBT, and thus the matching process of the NC linac has to be re-done for intermediate currents as well, once we are ready to send the beam to the dump.

RFQ Phase

After the IS and LEBT, the RFQ and MEBT will be commissioned together. For the RFQ, the only parameter to adjust is the amplitude of the field to achieve the desired output energy of 3.62 MeV. The output energy is reconstructed from time-of-flight measurements, combined with scans of the buncher cavities, with BPMs in the MEBT. After setting the amplitude of the field, the transmission should be verified.The efficiency of any RFQ is never perfect and the output beam includes particles not properly accelerated. There is one BCM at the and the end of the RFQ and the other around the middle of the MEBT, behind the chopper dump (see Fig. 3). These two BCMs are used to distinguish the transmissions of the particles with the right energy and the rest. This is based on the result of a study that, for the ESS RFQ, most of the particles with wrong energies have the IS output energy of 75 keV and they are lost before the third quadrupole. At this point, we revisit and fine-tune the setting of the IS and LEBT so the output current of the RFQ becomes the linac-wide nominal value of 62.5 mA.

MEBT and DTL Phase

After the IS and LEBT are commissioned and the RFQ transmission is verified, a full commissioning of the next sections should start. For the MEBT and DTL, the beam threading is done with steerers and the BPMs (see Fig. 3 and 4). The layouts of the steerers and BPMs in the MEBT and DTL are such that the simple 1-to-1 steering works. For the cases when some of BPMs and or steerers are not available, our high level application for the steering is also capable of a SVD based correction.

The MEBT and DTL are the first sections which require to set the amplitudes and phases of the cavities with the phase scan method. The first step in setting the RF is to find the rough region of RF phase and amplitude to set the klystron. The RF group will have a rough idea of the amplitude, based on the measured RF power and design shunt impedance. Each cavity should be scanned in the vicinity determined by the rough estimate described above, by ±10-20 degrees. The phase difference (difference in arrival time) will be measured with a pair of downstream BPMs and compared with the calculated signature field maps for each cavity. An additional output from this technique is knowledge of the input (and output) beam energy. The fitting results are typically quite sensitive to beam energy (i.e. within 100-300 keV [18]) and this can be used during the MEBT first buncher scan to calibrate the RFQ output energy.

As stated in one previous sections, the transverse lattice of the MEBT is separated in two in terms of its function. The initial part requires adjustments of the beam sizes for achieving good transmission and chopping efficiency, and the second part has to achieve good Twiss parameters for matching at the DTL interface. The three WSs and one EMU should provide enough information to achieve these requirements together with a model. For the longitudinal plane, there is only one profile monitor (LBM). Thus, to reconstruct the Twiss parameters and emittance and achieve the longitudinal matching to the DTL section, measurements with different settings of the buncher cavities are needed. Since the quadrupoles of the DTL are made of permanent magnets there is no degree of freedom to adjust the optics and preform any kid of matching along this section.

HIGH LEVEL APPLICATIONS

Beam physics high-level applications are crucial tools for efficiently achieving desired machine performance. The applications for the ESS linac [19] are built on the OpenXAL framework [20]. This framework was initially developed at SNS and it has been transformed into a collaborative project between several laboratories. ESS is an active contributor to the project for developments of both (the core of) the framework itself and new applications.

The latest developments related to improving the ESS-specific online model (JELS) are listed below:

- machine description is now imported from the official lattice repository, which uses the TraceWin [21] format.
- the calculation for the RF fieldmap element was optimized 30% in speed by using a first order integrator.
- two new elements where created for the LEBT. Both 3D and 2D (cylindrical coordinate) filedmap elements were introduced for a solenoid, based on the above-mentioned first order integrator for an RF fieldmap.
- a new element representing a whole DTL tank was introduced and it uses the same definition for the Transient Time Factor as TraceWin.

All new elements were benchmarked against TraceWin, as well as the full accelerator lattice, and results were in very good agreement. For more details, see [22].

A new framework for physics applications is being developed based on JavaFX and JacpFX [23] and it is planned to port all new applications once the framework is ready. For the moment a version that adds a tool bar with the same functionality as the OpenXAL Swing version. Current available functionalities in the new framework include: the logbook posting capability and a link to the User documentation Wiki is already being used. An expansion of the FXapplication framework, as it is called, is expected to be released still this year [24].

Ion Source and LEBT Phase

For the IS and LEBT beam commissioning, a high-level application, which allows to visualize beam parameters and control the IS and LEBT components, has been developed [25]. In this application the trajectory and envelope along the LEBT and the commissioning tank are calculated and displayed for given initial conditions, together with readings from diagnostics (NPMs and EMUs). From the application it is possible to manipulate some of the magnets and power supplies from the source and LEBT and it is also possible to perform a simple matching based on diagnostics readings.

A generic multi-dimensional scanner application, whose main use cases include the LEBT solenoids scan, was also developed. For the Scanner Application a new widget has been developed to quickly select multiple channels to read or write to. The application allows to scan a sub-space of multiple parameters, defined with common mathematical operations, and stores data in a XML file as other OpenXAL applications. There is currently no analysis of the data acquired, so the users are for now expected to develop their own external tools

These two applications were already tested in the control room by connecting to the virtual machine and are ready for the next step of testing with the real control system.

Ion Source to DTL Phase

For the next commissioning step a trajectory correction application is under development. Two correction methods are included: a 1-to-1 and a SVD correction. The matrices used can be extracted from the machine model or can be measured. and the overall trajectory can be corrected to the BPM zeros or to a predefined reference trajectory. To complement this application a Trajectory Display Application was also developed.

The next step for the high level applications is a phase scan application for the MEBT buncher cavities and DTL tanks. This application is responsible for setting the phase and amplitude of a cavity by comparing the measured and simulated time-of-flights among BPMs. Another important application to be developed is the one responsible for the transverse matching, using the data(s) from the WSs and EMU to evaluate the optics in the MEBT and matching into the DTL.

CONCLUSION

Beam commissioning of the ESS linac starts soon in summer, 2018, from the IS and LEBT. This paper presented the strategy for the NC linac commissioning with a major focus on the IS and LEBT commissioning, high level applications development and beam deliverables. Some highlights from the preparation works of installation and testing for the IS and LEBT were also presented.

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