BEAM COMMISSIONING PLANNING UPDATES FOR THE ESS LINAC

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Abstract

The European Spallation Source (ESS) is a flagship research facility currently under construction in Lund, Sweden. It is driven by a 2 GeV linac, accelerating a 62.5 mA proton beam at a 4% duty cycle. With an average beam power of 5 MW, when completed the ESS linac will become the world's most powerful. In this paper we summarise the latest beam commissioning plans from the ion source to the target, highlighting the individual phases, the beam dynamics challenges as well as the scheduling strategy.

INTRODUCTION

The global neutron science landscape has seen a dramatic change over the last two decades with new machines like J-PARC and SNS becoming operational and existing facilities like ISIS and SINQ greatly expanding their user capacity. However, with several ageing experimental reactors due for retirement, the demand for beam time is now at an all-time high. In this wider context, the European Spallation Source now under construction in Lund, Sweden, comes not just to meet this demand, but to enhance and expand neutron science. When completed, ESS will deliver a record-breaking 5 MW proton beam to the target, providing the brightest neutron flux in the world in a state of the art facility [1,2].

Nevertheless, while the project is inspiring and visionary, the challenges of delivering and commissioning such a machine cannot be underestimated. An aggressive timeline will see the installation and commissioning starting later this year, the first 570 MeV protons in 2019 and the first beam to the target in 2020. The user programme is expected to start in 2023. In preparation for beam commissioning, remarkable efforts are being made both locally and by our in-kind partners with significant progress made in planning and installation, radiation safety and licencing, as well as beam diagnostics and control software. This paper will further outline the beam physics plans and procedures being developed for beam commissioning [3].

MACHINE DESCRIPTION

The ESS linac baseline design specifies a final proton energy of 2 GeV, with a beam current of 62.5 mA, a 14 Hz repetition rate and a pulse length of 2.86 ms. These are mostly user driven requirements and equate with a 5 MW average beam power on target. A summary of the main machine parameters is presented in Table 1, while a schematic linac layout is shown in Figure 1. The accelerator consists of a 3.62 MeV front end, a normal conducting section (NC) up to 90 MeV and a superconducting section (SCL) up to final energy. The front end is characteristic for many high power linacs and starts with an ion source (IS) followed by a low energy beam transport line (LEBT) that transports and matches the beam to a 352.21 MHz four-vane RFQ. After the RFQ, a medium energy beam transport line with a fast chopper (MEBT) prepares the beam for further acceleration. The MEBT also offers the last opportunity to control the beam parameters in terms of current and pulse length before injection into the DTL section that makes up the rest of the NC part of the linac.

The DTL is followed by the superconducting linac that has three sections with three different cavity types: spoke cavities (SPK) up to 216 MeV, medium-beta cavities (MBL) up to 571 MeV and finally high-beta cavities (HBL) up to 2 GeV. Further downstream, a high energy beam transport line (HEBT) is part of the beam transport system to the target. It follows the same lattice configuration as the HBL, but it employs empty slots for cryomodules thus opening opportunities for potential upgrade scenarios. At the end of the HEBT a dipole for upward bending is envisaged. When the dipole is off, the beam will be diverted to the dump line (DMPL) terminating with a tuning dump. When the dipole is on, the beam enters the dogleg section where a second dipole will bend it back towards the target. The final accelerator to target area (A2T) ends with a raster system where the beam is scanned onto the target over a rectangular region by fast oscillating dipole magnets.

BEAM COMMISSIONING STRATEGY

Planning

Several installation and commissioning stages are planned for the linac. Initially, all components will be installed with the exception of the HBL cryomodules. This will deliver a beam at 571 MeV and 1.4 MW and the machine will be operated in this state in 2019. From 2020, the HBL cryomodules will be installed and the performance will be gradually increased. A recent value engineering exercise has recommended powering only 11 of the 21 HBL cryomodules, thus reducing the beam energy to 1.3 GeV and the power to 3 MW

Table 1: Main Parameters of the ESS Linac

Parameter	Value	Unit
Average Beam Power	5	MW
Maximum Beam Energy	2	GeV
Peak Beam Current	62.5	mA
Beam Pulse Length	2.86	ms
Beam Pulse Repetition Rate	14	Hz
Duty Cycle	4	%
RF Frequency	352.21/704.42	MHz
Machine Availability	95	%

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ISBN 978-3-95450-182-3

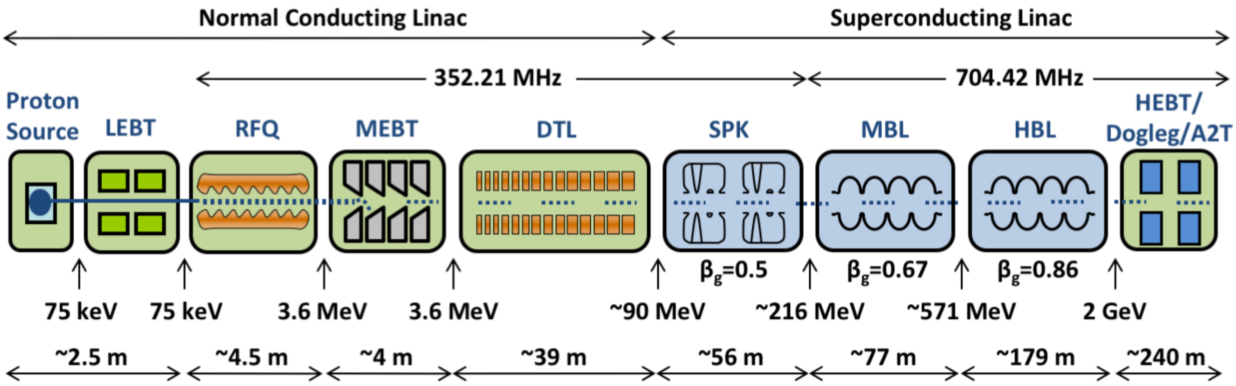

Figure 1: Schematic layout of the ESS linac.

during the initial operation period. The recovery of scope will be done during the the user operation phase with minimum disruption expected [4].

The beam commissioning will initially aim to transport a probe beam at 6 mA to the designated dump and test the polarities of the BPMs, dipole correctors and quadrupoles. Then the phases and amplitudes of all RF cavities are set in succession. The beam centroid position is adjusted at this stage with further fine tuning planned after transverse matching if necessary. The matching involves the measurements of the RMS beam size and profiles with interceptive devices and is performed at the transition between sections as well as at certain additional locations in the MEBT and A2T. This step is further repeated for each beam current configuration. Finally, when the operators are satisfied with the centroid position and matching convergence for a particular current setting, the duty cycle is progressively increased by increasing pulse length and the level of beam loss is verified.

Beam Operation Modes

It is clear that commissioning, tuning, as well as operation will require machine flexibility and therefore a range of working modes are planned [5]. The *probe mode* is the lowest power mode with a peak current of 6 mA, a pulse length ≤5 µs and a repetition rate of ≤1 Hz. It is intended for the initial system and hardware check. The *fast tuning mode* has a repetition rate of 14 Hz, a pulse length ≤5 µs and can be used for the entire range of beam currents. It is aimed mainly at setting the phases and amplitudes in RF cavities. Similarly, the *slow tuning mode* has a longer pulse length (≤50 µs and) at ≤1 Hz and is meant to provide a good signal quality to diagnostic devices like Faraday cups (FC) and wire scanners (WS) as well as help the LLRF setup. The beam in these modes can be fully stopped by the target, the tuning beam dump located at the end of DMPL and any of the FCs located in the LEBT, MEBT, DTL, SPK and MBL. To verify beam loss, higher power modes are necessary. The *long pulse mode* will operate at low repetition rates (once a minute), but pulse lengths and currents up to the nominal values. The power, in this case, can no longer be accommodated by the FCs and the tuning dump design has been recently updated to take the full pulse length [6]. A summary of all the proposed beam modes can be seen in Table 2.

IS and LEBT

The IS and the LEBT are an in-kind contribution by INFN-LNS. Assembly and commissioning have already started in Catania, Italy with delivery to ESS scheduled for late 2017 when the entire setup will be recommissioned. A microwave discharge IS design has been adopted with a proton fraction of at least 75%. The LEBT consists of two solenoids which focus and match the divergent IS beam to the RFQ. The degree of space-charge compensation in the LEBT is estimated at 95%. The effect of the space-charge compensation level on beam parameters will be evaluated with an emittance measurement unit (EMU) located between the two solenoids. In addition, solenoid scans can help identify the matching conditions that give the best transmission through the RFQ. The LEBT is also equipped with an iris for beam scraping and a chopper to remove the transient part of the beam pulse (up to 3 ms). The deflected beam is stopped by a cone-shaped structure placed at the entrance of the RFQ. Since space-charge compensation takes ~20 µs to reach a stable state, the initial part of the remaining pulse will have the wrong parameters and will be chopped with a fast chopper in the MEBT section. Additional windings placed in the solenoids will be used for steering, helped by two non-invasive profile monitors which will measure the beam transverse centroid position.

RFQ and MEBT

The RFQ and MEBT will be installed and commissioned at the same time, using the diagnostics in the MEBT to characterise the RFQ beam. The MEBT lattice consists of eleven quadrupoles with steering windings, three rebunching cavities, a fast chopper and a chopper beam dump as well as a comprehensive set of diagnostics. The field amplitude in the RFQ is set using the MEBT beam position monitors (BPMs) and time of flight measurements will determine the correct output energy of 3.62 MeV. Once the energy is fixed, the transmission is verified with beam current transformers (BCT) and the propagation of particles with the wrong energy is checked.

Table 2: Main Beam Operation Modes of the ESS Linac

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 Tuning	Any Beam Stop	RF Setting	6 - 62.5	≤ 5	≤ 14
Slow Tuning	Any Beam Stop	Invasive Measurements LLRF Setting	6 - 62.5	≤ 50	≤ 1
Long Pulse	Tuning Dump Target	Beam Loss Check Lorentz Detuning Check	6 - 62.5	≤ 2860	$\leq 1/30$
Production	Target	Neutron Production	6 - 62.5	2860	≤ 14

Beam threading in the MEBT is done using steering in the quadrupoles and the BPMs. Additional transverse beam information is available from the three WS and the EMU unit envisaged for the MEBT. Longitudinal information is obtained using a bunch shape monitor (BSM) thus providing a complete 6D beam measurement for improved matching into the DTL. The fast chopper functionality is checked with a specially configured BPM and a fast beam current transformer (FBCT) capable of measuring single bunch currents. The MEBT also includes three vertical plane collimators placed at different locations to remove halo particles.

DTL

The DTL will accelerate the beam to 90 MeV using five tanks. Commissioning will commence in 2019 and current plans will see installation of SCL components and DTL beam commissioning work done in parallel. This will require temporary shielding between the DTL and SCL sections. Each tank uses permanent magnet quadrupoles (PMQs) in a FODO configuration. This allows a compact, efficient DTL design and provides empty drift tubes for BPMs or single plane steering. Using PMQs also limits the inter-tank transverse matching options and therefore the DTL setup only involves dipole steering corrections and field phase and amplitude scans. The beam commissioning will be using low power beam modes as at this stage the beam stop is a FC. Once the downstream accelerator sections are installed up to the tuning beam dump, higher power modes will be tested and power gradually increased.

SCL and HEBT

The SPK, MBL and HBL sections of the superconducting linac employ a similar lattice configuration with one quadrupole doublet and one cryomodule per period. Dipole steering, BPMs as well as other diagnostics devices are placed between the two quadrupoles in the doublet, together forming the linac warm unit (LWU). A total of 13 cryomodules are planned for the SPK section with two cavities per cryomodule. The MBL and HBL sections have a four cavity per cryomodule configuration, with 9 cryomodules for MBL and 21 for HBL. This leads to a total of 146 cavities and suggests that setting up the phases and amplitudes in the cavities will be a major commissioning task.

Three LWUs at transition from DTL to SPK as well from SPK to MBL will house WSs and a fourth unit in SPK will also house a BSM to allow transverse and longitudinal matching. As the lattice structure in the MBL and HBL is identical, no matching is planned at this transition. The HEBT section that follows after the HBL has 16 periods, retaining the same lattice structure as in the MBL and HBL, but without any acceleration. At the transition to the A2T section, three WSs are employed to facilitate matching.

Dogleg and A2T

The dogleg line will transport the beam to the A2T section. This is achieved with a six period achromatic doublet focussing channel. Further on, the A2T will manipulate the beam such it meets the target requirements. The lattice consists of four quadrupoles that expand the beam size in a controlled manner and define the beam size on target, followed by four fast dipoles per plane that sweep the beam centroid and form the raster system and finally two additional quadrupoles that control the phase advance. A combination of BPMs, WSs and imaging devices are used to configure, setup and control the operation of the raster process.

CONCLUSION

The beginning of beam commissioning for ESS is fast approaching, with only months left until the first equipment is delivered and installed in the tunnel. This paper has briefly reviewed the procedures, available diagnostics, commissioning plans and the current status of each section from a beam physics point of view. We believe a robust system is in place to allow a smooth initial machine start-up.

ACKNOWLEDGEMENTS

The authors would like to thank B. Cheymol, R. de Prisco, Y. I. Levinsen, O. Midttun, A. Ponton, H. D. Thomsen for useful discussions and suggestions.

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