END TO END BEAM DYNAMICS OF THE ESS LINAC

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Abstract

The European Spallation Source, ESS, uses a linear accelerator to deliver the high intensity proton beam to the target station. The nominal beam power is 5 MW at an energy of 2.5 GeV. The individual accelerating structures in the linac and the transport lines are briefly described, and the beam is tracked from the source throughout the linac to the target. This paper will present a review of the beam dynamics from the source to the target.

INTRODUCTION

The European Spallation Source, ESS, to be built in Lund, Sweden, will require a high current proton linac to accelerate protons to be used for the spallation process on which high flux of pulsed neutrons will be generated. The accelerator is a 5 MW superconducting proton linac delivering beams of 2.5 GeV to the target in pulses of 2.86 ms long with a repetition rate of 14 Hz [1], [2]. Beam current is 50 mA, which at 352.21 MHz is equivalent to $\sim 9 \times 10^8$ protons per bunch.

Both hands on maintenance and machine protection set a strict limit on beam losses and have been a concern in every high power linac [3]−[6] , therefore it is crucial, specially for high power accelerators, to design a linac which does not excite particles to beam halo and also keeps the emittance growth to a minimum to avoid losing the particles that otherwise get to close to the acceptance and eventually escape the separatrix. The ESS linac is designed carefully to minimize such effects all along the linac and transfer lines. A recent study relaxed the losses in the low energy part of the linac, mainly in the RFQ and MEBT [7], from the conventional 1 W/m.

The latest design of the linac will be presented here and the 2003 Design Update can be found in table 1 and reference [1]. In the new design it is foreseen not to exclude the possibility of a potential power upgrade of the linac. One of the scenarios for such a power upgrade would be increasing the power by increasing the energy to 3.5 GeV and/or increasing the current to 100 mA [8].

SOURCE AND LEBT

A Microwave Discharge Ion Source, MDIS, will be employed for the production of the high intensity proton beam in macro-pulses of up to 3 ms. The proton energy will be 75 keV and a current up to 80 mA is expected with an emittance of 0.3 π mm.mrad at the RFQ entrance. The absence of hot filaments significantly increases the mean time between failures with reliability close to 100% and high current stability as already experienced by other ion sources [9]. The Low Energy Beam Transport, LEBT, is composed of two magnetic solenoids together with all the necessary eqipment to prepare and match the proton beam out of the source to the radio frequency quadrupole entrance while keeping the emittance growth due to the space charge effect to a minimum. The LEBT will also house a chopper with fast rise and fall times in order to remove the heads and tails of the beam macro-pulses mantaining rise and fall times in the order of hundreds of nsec.

RADIO FREQUENCY QUADRUPOLE

The ESS Radio-Frequency Quadrupole, RFQ, will accelerate and bunch proton beams from 75 keV at the LEBT exit to 3 MeV before the MEBT entrance. The beam current is 50 mA for 4% duty cycle. The RFQ is a 4 vane-type structure running at 352.21 MHz of roughly 5 m in length divided in 5 segments of 1 m each. The peak electric fields on the vane surface has been limited to a Kilpatrick value [10] of 1.8. A transmission of more than 99% is foreseen for the nominal current and high quality beams will be delivered to the downstream rf structures of the accelerator.

MEDIUM ENERGY BEAM TRANSPORT

The major challenge of this part of the accelerator is to maintain the beam quality, low emittance and minimized halo, to limit the beam losses downstream the linac and maximize the ESS reliability. The considered versatile MEBT is designed to achieve four main goals: 1. To contain a chopper and its correspondent beam dump that could serve in the commissioning as well as in the ramp up phases, 2. To collimate by means of two collimator sections, 3. To measure the beam phase and profile between the RFQ and the DTL, along with other beam prop-

Table 1: ESS main parameters

Parameter	Unit	2003 (LP/SP)*	2011
Ion	–	Proton / H^-	Proton
Energy	[GeV]	1.334	2.5
Beam power	[MW]	5.1	5
Repetition rate	[Hz]	$16\frac{2}{3}$ / 50	14
Beam current	[mA]	114	50
Beam pulse	[ms]	2 / 0.48	2.86
Duty cycle	[%]	3.3 / 4.8	4

* Long pulse / Short pulse.

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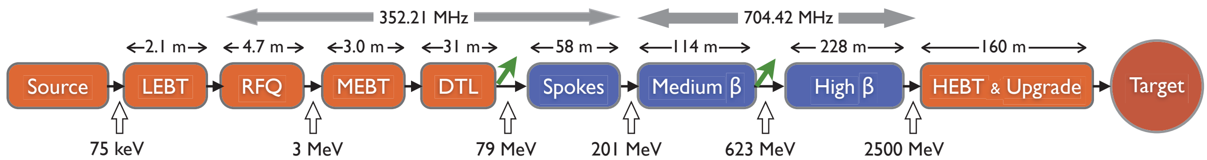

Figure 1: Block layout of the ESS segmented linac 2012 (not to scale). Orange boxes represent the normal conducting components, the blue boxes the superconducting secions, and the green arrows the branching sections.

erties, 4. To match the RFQ output beam to the DTL in all the three planes. For this purpose, in collaboration with FETS [11] project, a set of ten quadrupoles is used to match the beam characteristics transversally, combined with two 352.2 MHz *buncher* cavities, which are used to adjust the beam in order to fulfill the required longitudinal parameters.

DRIFT TUBE LINAC

The drift tube linac increases energy of the 50 mA beam to 79 MeV in four tanks in the latest design. The increased energy of the DTL is a result of requiring a smooth phase advance variation between DTL and spoke section without reducing the tune depression in any plane to less than 0.4 in DTL or spoke section. The transverse focusing is achieved by permanent magnet quadrupoles arranged in a FODO lattice leaving half the drift tubes empty for diagnostics and steerers with a maximum field of 1 mT·m to correct the beam trajectory and reduce the losses. The Kilpatrick value is limited to 1.4 which respects the Moretti criterion [12] at the low energy part as well. The pros and cons of using a shorter five DTL tanks with ramped field and higher bore radius in the last tanks are still being investigated.

SUPERCONDUCTING LINAC

The superconducting linac accelerates the beam from 79 MeV to 201 MeV using double spoke cavities ($\beta_{opt} = 0.5$) at 352.21 MHz. The phase law in spoke section is modified to improve the smoothness and continuity of the phase advance between spokes and medium β cavities. This improved smoothness is achieved by ramping the synchronous phase from $-20°$ down to $-33°$ in the last seven periods of the spoke section. The additional effect of this change is improved acceleration in the downstream structure as well as decreasing the range of required power to accelerate the beam in medium β cavities.

The five cell elliptical cavities work at twice the frequency and increase the beam energy to 623 MeV using medium β cavities ($\beta_g = 0.67$) and then to 2.5 GeV using high β cavities ($\beta_g = 0.92$). By increasing the final energy of the spoke section and reducing the geometric β of the medium β cavities excitation of the Same Order Modes, especially $4\pi/5$, is avoided at the low energy end of medium β cavities [13].

The cryomodules of the spoke and elliptical sections house two and four cavities each respectively. The transverse focusing is achieved by normal conducting quadrupole doublets. By adding a diagnostic box in between the quadrupoles as well as vacuum ports a Linac Warm Unit is formed. Each lattice period is composed of a LWU and one cryomodule in the spoke and medium β sections, or one LWU and two cryomodules in the high β section.

BRANCHING SECTIONS

Two branches are added to the linac to allow beam extraction at intermediate energies for diagnostic purposes during commissioning and operation, green arrows in Fig. 1. The first branching section, FBS, is located right after the DTL at 79 MeV and the second branching section, SBS, is in between the medium β and high β section at 623 MeV. Due to the low energy of the beam at the end of DTL the FBS has a limited length of 0.7 m. A 0.5 m long bending magnet with a field of 1.2 T bends the beam by 27° and the next quadrupole enhances the kick to clear the downstream quadrupole and the spoke cryomodule. At the end of medium β section, a drift space equal to the length of a medium β cryomodule, 5.641 m is reserved for the SBS, this space is long enough to extract the beam using a 1.8 m long dipole, similar to the dipoles used in the high energy beam transport, and bends the beam 30° by a field of 1.2 T.

HIGH ENERGY BEAM TRANSPORT

The main purpose of the High Energy Beam Transport system is to bring the beam from the exit of the linac to the target. Several functionalities are included. These contain 1. A 100 m transport section reserved for future energy and power upgrades, 2. A semi-vertical dogleg section bringing the beam 4 meters up from the underground linac level to the target ground level, 3. An underground commissioning and tuning dump area, and 4. An above ground section matching the beam to the requested footprint $(16 \times 6\ \mathrm{cm}^2)$ on target.

In order to reduce the peak current density on the target (and the proton-beam window – PBW) to an acceptable level, a beam expansion system using two octupoles has been designed. A fixed collimator mounted in front of the PBW will capture the beam halo. The trade-off between beam power on the fixed collimator and the peak current

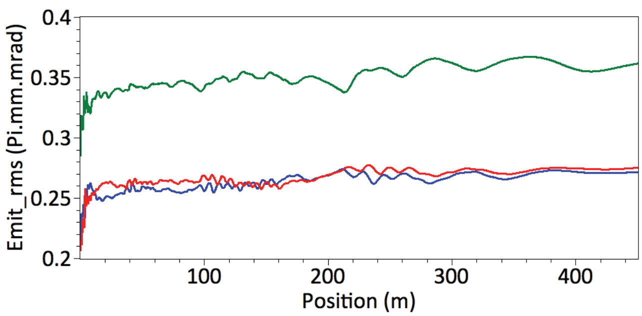

Figure 2: Normalized rms emittance evolution of the bunched beam of RFQ in the ESS linac. Red, blue, and green lines are Hor., Ver. and Long. planes respectively.

density is still to be determined. We expect a peak current density around 60 μA/cm^2 on target and beam power on the fixed collimator of 10 kW seems realistic.

BEAM DYNAMICS

The new design of the linac is focused on improving the integrity of the accelerator as a single structure. The guideline is the smoothness and monotonic variation of the average phase advance. At the same time the tune depression is being kept above 0.4, limiting the number of mismatch resonances to only two, from which one is always present irrespective of the tune depression and to avoid the second resonance one should keep the tune depression above ~ 0.6 [14]. The transverse phase advance per period is limited to 89° to reduce the percentage of the beam that due to their phase otherwise would have had a phase advance exceeding 90° per period. Since the tune depression in very close to 0.4, unless the beam is equipartitioned tune depression will be less than 0.4 at least in one plane. This limits the longitudinal phase advance per period to 73°. Though every section of the accelerator is designed by a part of the collaboration to match the phase advance of neighboring structures, a further phase advance smoothness matching is performed during the integration to assure a premium beam quality.

The Start2End (End2End) simulations are performed with 100,000 macro particles using the code TRACEWIN [15]. The 3D PICNIC space charge routine with a $10 \times 10 \times 10$ mesh is employed for space charge calculations, which are performed 15 times per $\beta \cdot \lambda$, a limit that speeds up the calculation and does not affect the results. This beam is generated at the RFQ input and transported through the linac and HEBT to the target wheel surface.

The aperture to rms beam size ratio has a minimum of 5 in the last cells of the DTL in transverse and longitudinal planes and stays above 10 and 8 in the rest of the linac in transverse and longitudinal planes respectively. The emittance growth from the end of the RFQ to the end of linac are 33%, 31% and 29% in xx', yy', and zz' planes, Fig.2.

CONCLUSION

Integrating the beam dynamics design of the linac, as one structure, have significantly improved the beam quality along the linac. Taking into account the effects of same order modes, SOMs, changing the phase law and smooth and monotonic variation of phase advance have resulted in a more robust design which is less sensitive to rf errors. Application of specific beam physics rules in the design of beam expander system have reduced the power outside of the defined footprint on target surface.

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