BEAM DYNAMICS AND DESIGN OF THE ESS LINAC

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Abstract

The European Spallation Source, ESS, will use a linear accelerator delivering high current long pulses with an average beam power of 5 MW to the target station at 2.5 GeV in the nominal design. The possibilities to upgrade to a higher power LINAC at fixed energy are considered. This paper will present a full review of the LINAC design and the beam dynamics studies.

INTRODUCTION

The European Spallation Source, ESS, is a high current proton LINAC to be built in Lund, Sweden. The design is based on previous studies done by ESS-Scandinavia [1] and ESS-Bilbao [2] teams. In the new design the average beam current and the final beam energy have changed by at least a factor of two from the 2003 ESS design values (5 MW, 1 GeV, 150 mA, 16.7 Hz) [3]. Decreasing the beam current and increasing the beam energy simplifies the linac design and increases the reliability as well as leaving the upgrade scenario by increasing the beam current possible.

In the new design LINAC delivers 5 MW of power to the target at 2.5 GeV, with a nominal current of 50 mA. It is designed to include the ability to upgrade the LINAC to a higher power of 7.5 MW at a fixed energy of 2.5 GeV, by increasing the current from 50 to 75 mA. Increasing the beam current implies that in case of fixed power couplers the energy gain per cavity will decrease, to reach the fixed energy of 2.5 GeV extra cryo-modules will be added in the area reserved for this purpose, as illustrated in Fig. 1.

LINAC STRUCTURES

Proton Source and LEBT

It is foreseen to use an ECR, electron cyclotron resonance, proton source to produce up to 90 mA of beam current at 75 keV. The source will deliver pulses as long as 2 ms with a repetition rate of 20 Hz. One of their advantages is that they can operate in low vacuums of $O(10^{-4})$ Torr, enabling them to deliver very high currents. The absence of hot filaments increases the mean time between maintenance significantly [4]. These sources function is very reliable manner in terms of availability and current stability.

The Low Energy Beam Transport, LEBT, system is composed of two magnetic solenoids, it transports and matches the 75 keV beam out of source to the radio frequency quadrupole, RFQ, while minimizing emittance growth. The LEBT is equipped with magnetic steerers to adjust the beam position and angle at the RFQ injection point, and includes beam diagnostics to measure the beam parameters between source and RFQ. Depending on the rise time of the source and the beam quality during the rise time a slow chopper might be added to deflect the low quality head and tail of the beam.

Table 1: Primary Parameters of Accelerating Structures

System	Energy MeV	Freq. MHz	β_{Geo}	No. of modules	Length m
Source	0.075	–	–	–	2.5
LEBT	0.075	–	–	–	1.6
RFQ	3	352.21	–	1	4.7
MEBT	3	352.21	–	–	1.0
DTL	50	352.21	–	3	19
Spokes	240	352.21	0.54	15	61
Low β	590	704.42	0.67	10	59
High β	2500	704.42	0.84	14	169

RFQ and MEBT

The first stage of the acceleration in ESSLINAC will be performed by a radio-frequency quadrupole, RFQ. This four-vane RFQ operates at 352.21 MHz and boosts the proton beam from 75 keV to 3 MeV while it shapes the beam in a train of micro-pulses. The quality of the proton beam out of RFQ will have a significant impact on the particle dynamics throughout the rest of the LINAC. ESS has consequently put important R & D efforts in designing the RFQ. The RFQ is expected to maintain the transverse emittance of the beam, control and reduce the generation of halo, and shape the beam longitudinally to improve the efficiency of acceleration in the following structures. In addition very low loss in the RFQ walls is mandatory to prevent sparking and a possible thermo-mechanical stress.

A Medium Energy Beam Transport, MEBT, composed of four electromagnetic quadrupoles and two buncher cavities, at 352.21 MHz, matches the 3 MeV beam out of RFQ to the acceptance of the Drift Tube LINAC, DTL. Not requiring a chopper the MEBT will be the shortest possible to avoid the longitudinal blowup of the beam. At this energy, 3 MeV, neutron production is not an issue and pre-collimation can be easily performed, if necessary.

There are proposals to avoid the MEBT completely and couple the RFQ to the DTL directly, this option needs to ramp the voltage in RFQ, requiring a varying ρ, to match its phase advance to the one of DTL, and subsequently the acceleration

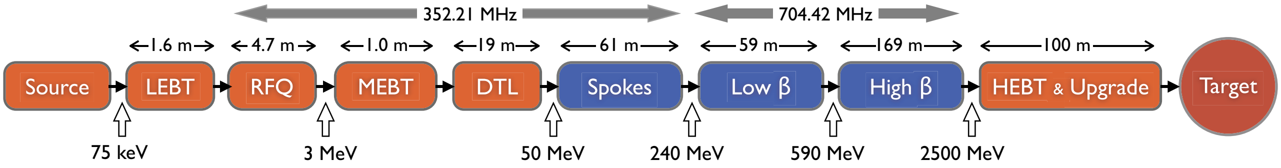

Figure 1: Block layout of the ESS LINAC (not to scale).

in DTL can start in a higher synchronous phase providing more efficient acceleration [5].

DTL

The DTL uses Permanent Magnet Quadrupoles, PMQ, for the transverse focusing of the beam, and the focusing is done in an FFDD lattice. DTL has a frequency of 352.21 MHz and will accelerate the beam over the range of 3 MeV to 50 MeV in three tanks each being fed by a single klystron delivering 1.3 MW to the first tank and 2.5 MW to the second and third tanks. RF field perturbations caused by static manufacturing errors are compensated by fixed post couplers that are installed in front of every third drift tube in the first tank, every second drift tube in the second tank, and before every drift tube in the third tank, making almost the same number of fixed post couplers per tank.

Spoke Resonators

Superconducting spoke resonators at the relatively low frequency of 352.21 MHz have the advantage of providing a large longitudinal acceptance, and the less the number of spokes, the larger is their velocity acceptance. In addition to that the large transverse acceptance that is a result of relatively large apertures compared to normal conducting structures makes them the preferred accelerating structure at this range. This is expected to significantly reduce beam losses and radio-activation. Superconducting spoke resonators also reduce power consumption enormously with respect to the usual normal conducting structures. Another advantage is the flexibility to phase and tune spoke resonators independently making them less sensitive to single cavity failure.

There are 15 periods using superconducting double spoke resonators with geometric β of 0.54 each period being consisted of a quadrupole doublet followed by three cavities. Depending on the choice of magnets and cryo-module, few periods can be housed in a single cryo-module.

Elliptical Cavities

To reduce the size of the cavities in the high energy part of the LINAC, lower their manufacturing cost, and decrease the cryogenic heat load a frequency jump is performed at the end of spokes resulting in the superconducting elliptical cavities that operate at the second harmonic with a frequency of 704.42 MHz. Two families of five cell cavities will be used, with medium β cavities accelerating from 240 MeV to 590 MeV and high β cavities from 590 MeV to 2500 MeV. The ESS elliptical cavities have medium and high geometric βs of 0.67 and 0.84 , respectively when optimized for the nominal beam current of 50 mA, while if the LINAC was optimized for the high current these values would have been 0.63 and 0.75 for the low and high β cavities, such a LINAC would need the minimum number of modifications for the upgrade scenario [6]. The low beta cryo-modules contain four cavities, and the high beta cryo-modules houses eight cavities. Each cavity is fed by a single power coupler delivering 0.9 MW of power to the beam. An inter-cavity distance of 400 mm nullifies the crosstalk between neighbor cavities, and accommodates both the main power couplers and also higher order mode couplers in case the latter is proven necessary.

A quadrupole doublet per period, each period being house in one cryo-module, will focus the beam in transverse plane in both low and high beta regions. There are ongoing studies to clarify between the use of superconducting or normal conducting quadrupoles, the former may result in a non-segmented architecture with a continuous cryostat (e.g. SPL) [7] and will have a lower static heat load, while the latter will dictate a highly segmented architecture with many warm-to-cold transitions (e.g. SNS) [8], with the advantage of a shorter mean time to replace defective cryo-modules. Doublet quadrupoles have the advantage of simpler cryo-module design and easier installation, and will result in a much shorter LINAC than singlets in case of normal conducting magnets. Superconducting quadrupole doublets can be installed either inside the same cryo-module or inside a separate cryo-modules designed to house them.

BEAM DYNAMICS

After design and optimizing of structures to achieve the best acceleration in each individual section, the optics in LINAC is adjusted to have a ratio between transverse to longitudinal phase advances which does not excite any resonances, at the same time the phase advances in all the three phase space planes are always kept below 90 degrees per period. It is noteworthy to mention that the matching between adjacent structures is done by smoothing the phase advance variation per meter. Then a series of multi particle end-to-end beam simulations is performed to find and remove bottlenecks, to pin-point the sources of halo production along the Linac and reduce their effect, and to improve the beam quality at the end of the Linac. The CEA codes, GenDtl and GenLinWin are used to optimize and generate the structures, and then Toutatis and TraceWin codes are used for multi particle simulations [9]. The beam distribution is generated at the RFQ entrance having $50,000$ macro particles with a Gaussian distribution cut at $3 \times \sigma$.

More than 99% of the particles entering the RFQ are transmitted through and accelerated to the right energy, without any growth in the rms transverse emittance for a 50 mA beam and which decreases to almost 99% if the current is increased to 75 mA. Even for a completely matched beam RFQ generates some minor halo at the beginning of acceleration. A collimator to remove this halo could be included in the MEBT where neutron production cross section is still negligible. The required klystron power is about 0.95 MW and 1.05 MW for the ESS nominal and the potential upgrade current respectively. It is shown that the total transmission reaches a maximum for a given klystron power and more power does not increase the transmission [10].

The Kilpatrick limit is chosen to be $K_p = 1.8$ with the possibility to increase to $K_p = 1.9$. To achieve the best performance it has been decided to bunch the beam as adiabatically as possible using a long gentle buncher section, and careful varying of the minimum aperture, a, allows to avoid resonances between planes, and conserve the transverse focusing.

The DTL accelerates the beam out of RFQ and MEBT without any losses in the absence of errors, when the phase advance is matched smoothly between the MEBT and DTL and then between DTL tanks, both for nominal and for upgrade current. The FFDD lattice is intrinsically more forgiving against quadrupole misalignments [11], and can be matched much easier to both upstream and downstream structures because of its longer period length. A zero current phase advance ratio of 1.5 (transverse to longitudinal) gives a satisfactory transverse confinement of the beam within the drift tube apertures and maintains nicely the longitudinal shape of beam.

To achieve a large longitudinal acceptance the synchronous rf phase at the entrance to the first DTL tank is set to -30 degrees. As the bunch gets longitudinally focused the synchronous phase gradually increases to -20 degrees in the middle of first tank to increase the real estate gradient. The lower space charge forces at the higher energies, as in the spoke resonators, allows the synchronous phase to increase from -20 deg to -15 deg. To minimize the effect of frequency jump at injection to elliptical cavities the bucket size is kept constant at this transition, by decreasing the synchronous phase and gradient in elliptical cavities [12], where the frequency is twice the upstream structures. The phase increases rapidly from -30 degrees to -15 degrees in the low beta section, and increases smoothly to -13 degrees in the high beta section, towards the end of the Linac.

The longitudinal acceptance of the three DTL tanks combined is more than 50 times the rms emittance at DTL injection and for the three SC structures it is more than 160 times the area of the matched beam emittance, as shown in Fig. 2, the large acceptance in the SC structures indicates the effectiveness of the method used during the frequency jump, on top of that one may conclude that such a structure is more tolerant to single cavity failures.

The transverse apertures are larger in the downstream superconducting structures. A varying phase advance ratio between 1.1 and 1.3 (transverse to longitudinal) is used in general to avoid resonances, by varying the ratio of phase advances gradually within each structure the phase advance per meter in the neighboring structures can be equalized to avoid impulses to the beam due to discontinuity in the average focusing force. Lowering the phase advance ratio relaxes the transverse plane and results in emittance exchange from the longitudinal to the transverse planes, as shown in Table 2. The rms beam envelopes shown in Fig. 3 are kept less than 4 mm all along the Linac, resulting in an increasing aperture to rms ratio which consequently decreases the beam loss and machine activation. More than 99.9% of the particles shown in Fig. 4 are confined within 5 mm of radius. The outermost of particles do not exceed a radius of 20 mm for the end-to-end beam, and in case of a Gaussian beam generated at the injection to MEBT the particles will stay confined within a radius of 10 mm.

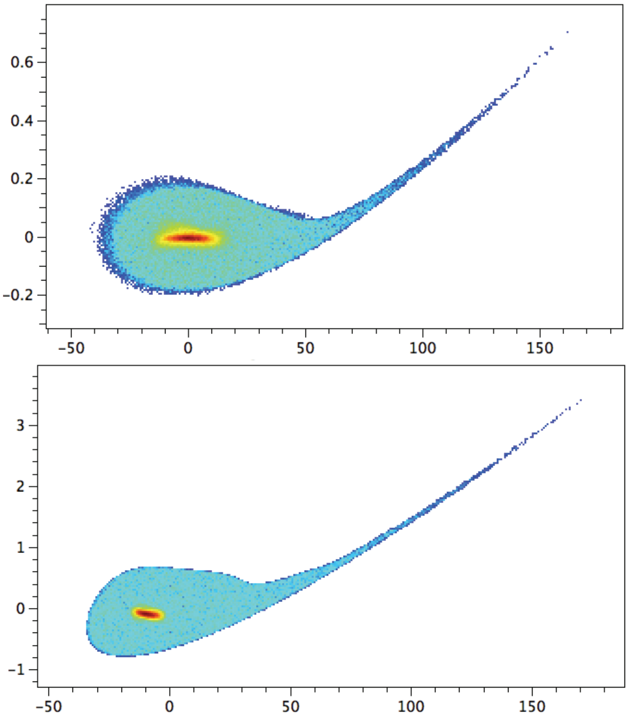

Figure 2: Superposition of the matched beam emittance on the total acceptance of each structure. The ordinate is the difference from input energy in MeV and the abscissa is the phase in degrees. Top: DTL tanks, Bottom: SC structures.

Table 2: Normalized rms emittances along the Linac at the exit of each structure, for the 50 mA beam generated at RFQ input.

Structure	ϵ_x π mm mrad	ϵ_y π mm mrad	ϵ_z π mm mrad
LEBT	0.2	0.2	–
RFQ	0.206	0.205	0.274
MEBT	0.243	0.215	0.275
DTL	0.240	0.230	0.314
Spokes	0.244	0.254	0.330
Low β	0.260	0.272	0.307
High β	0.257	0.268	0.328

SUMMARY AND CONCLUSION

A review of the ESS Linac design and beam dynamics activities has been presented. Transverse focusing in all three DTL tanks is performed using an FFDD lattice for its robustness against errors and to better match the period length to the adjacent structures. A single family of half wave spoke resonators each fed by an independent power source is used to accelerate the beam in the medium energy range. Acceleration continues using five cell elliptical cavities working at twice the frequency.

Since the main part of emittance increase is the MEBT to avoid spoiling the very high quality of the beam out of RFQ in the MEBT, direct coupling of the RFQ to DTL has to be studied for its cons and pros.

The number of cavities per cryo-module as well as the geometric betas of cavities is optimized to have the most efficient acceleration in the elliptical cavities while maintaining the best beam quality. All normal conducting structures, RFQ and DTL, and superconducting structures, spokes and ellipticals, are designed to be capable of accelerating 50% more current without any need for significant change in the installed equipment.

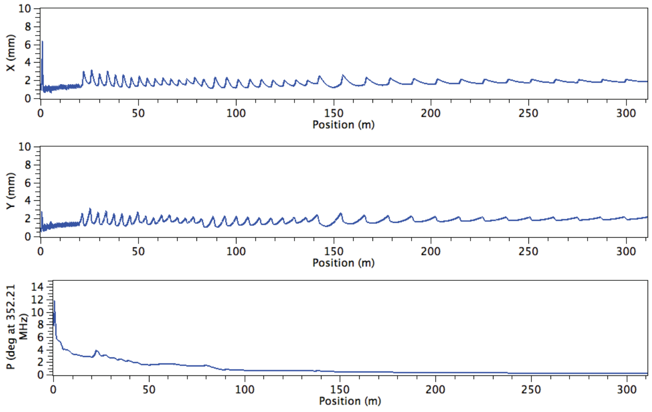

Figure 3: RMS beam size envelopes along the length of the Linac in the horizontal (top), vertical (middle) and longitudinal planes (bottom). The longitudinal phase spread is plotted using a reference frequency of 352.21 MHz.

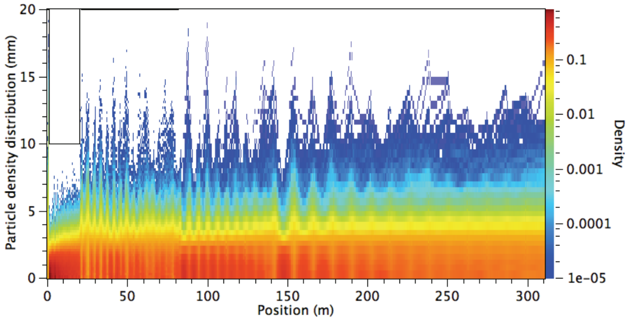

Figure 4: Beam density along the length of the Linac for a beam generated at the entrance of RFQ with a Gaussian distribution cut at $3 \times \sigma$.

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