CONCEPTUAL DESIGN OF THE ESS LINAC

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Abstract

A three year design update for the European Spallation Source (ESS) LINAC is just starting. A review of this work is presented. Acceleration in the medium energy part of the LINAC using spoke cavities has been optimised, and the rest of the machine has been redesigned to incorporate this optimisation. The ESS LINAC will deliver an average power of 5 MW to the target in the nominal design. The possibility to upgrade to a higher power LINAC of 7.5 MW has been included in all design features.

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-Bibao [2] teams. The LINAC delivers 5 MW of power to the target at 2500 MeV, 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 2500 MeV, by increasing the current from 50 to 75 mA after adding extra cryo-modules in the area reserved for this purpose, as illustrated in Figure 1. All the components are designed to not need significant changes in case of this potential power upgrade.

LINAC STRUCTURES

Source and LEBT

The ESS LINAC will use an electron cyclotron resonance (ECR) proton source to deliver macro-pulses of up to 2 ms in length and currents of up to 90 mA. The nominal pulse repetition rate is 20 Hz, but the source frequencies as high as 33 Hz are viable. ECR sources have the advantage that they can work in vacuums of order 10^{-4} Torr, enabling very high currents. Also, the absence of hot filaments significantly increases the mean time between maintenance [3]. ECR sources are very reliable in terms of current stability and availability.

The magneto-static Low Energy Beam Transport (LEBT) system is composed of two magnetic solenoids transports. It matches the 75 keV beam out of source to the radio frequency quadrupole (RFQ) while minimising 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.

RFQ and MEBT

The RFQ - the first structure to shape the bunches - has a significant effect on the quality of the beam distribution throughout the rest of the LINAC. Adiabatic bunching of the continuous beam from the source is performed in the first meter of the RFQ. Special care has been taken in the design 1: to maintain the emittance during the bunching and accelerating processes and 2: to increase the transmission efficiency, not only to preserve the highest intensities but also to avoid losses on the vanes that cause microscopic deformations and initiate sparking. The normal conducting four vane RFQ resonates at 352.21 MHz and increases the beam energy from 75 keV to 3 MeV within 4 meters. A low Kilpatrick ratio of 1.8 has been chosen, in order to enable pulse length and repetition rate adjustments, in the future.

The medium energy beam transport (MEBT) that follows the RFQ uses four electromagnetic quadrupoles and two bunching cavities to match the beam in all 3 dimensions into the acceptance of the drift tube linac (DTL) in the shortest possible length. At this energy, 3 MeV, neutron production is not an issue and pre-collimation can be easily performed, if necessary.

DTL

The DTL works at the same frequency as the RFQ, accelerating the proton beam from 3 MeV to 50 MeV in three tanks. Each tank is fed by a single klystron - 1.3 MW in the first tank and 2.5 MW in the second and third. 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

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	352.2	–	1	4.0
MEBT	3	352.2	–	–	2.5
DTL	50	352.2	–	3	19
Spokes	200	352.2	0.45	14	52
Low β	500	704.4	0.63	10	57
High β	2500	704.4	0.75	19 (21*)	215

*High power LINAC

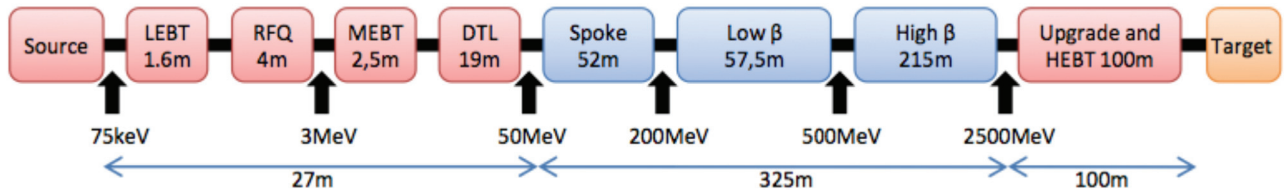

Figure 1: Block layout of the ESS LINAC (not to scale).

third tank. Transverse focusing is achieved by permanent magnet quadrupoles arranged in an FFDD lattice.

Spoke Resonators

The most major recent change in the LINAC design reduced, from two to one, the number of families of superconducting half wave spoke resonators that are used in the acceleration section after the DTL from 50 MeV to 200 MeV [1]. The 14 cryo-modules with a geometric β of 0.45 consist of a quadrupole doublet followed by three double-spoke cavities. Superconducting spoke resonators at the relatively low frequency of 352.21 MHz have the advantage of providing a large longitudinal acceptance, in addition to the large transverse acceptance that results from relatively large apertures compared to normal conducting structures. This is expected to significantly reduce beam losses and radio-activation. Superconducting spoke resonators also reduce power consumption enormously. Another advantage is the flexibility to phase and tune spoke resonators independently.

Elliptical Cavities

The superconducting elliptical cavities operate at 704.42 MHz. Two families of five cell cavities will be used, with medium β cavities accelerating from 200 MeV to 500 MeV and high β cavities from 500 MeV to 2500 MeV. They are very similar in design to Superconducting Proton Linac (SPL) cavities, except that ESS cavities have medium and high geometric βs of 0.63 and 0.75 , respectively [4]. These geometric betas are optimized for the high power upgrade LINAC, requiring only two more cryo-modules to be added. The low beta cryo-modules contain four cavities, and the high beta cryo-modules contain eight cavities. Each cavity is fed by a power coupler delivering 1 MW of power, 90% of which is available for acceleration. An inter-cavity distance of 400 mm nullifies the crosstalk between cavities, and accommodates both the main power couplers and also higher order mode couplers.

Transverse focusing in both low and high beta regions is provided by quadrupole doublets. A non-segmented architecture with a continuous cryostat (e.g. SPL) would have a lower heat load, while a highly segmented architecture with many warm-to-cold transitions (e.g. SNS), would have a shorter mean time to replace defective cryo-modules. Doublet quadrupoles have the advantage of simpler cryo-module design and easier installation, and are more compact than singlets if they are normal conducting. Superconducting quadrupole doublets can be installed either inside the same cryo-module or inside separate cryo-modules designed to house them.

BEAM DYNAMICS

A set of end-to-end beam simulations are performed after the structures have been optimised to achieve the best acceleration in each individual section. The goal of these simulations is to find and remove bottlenecks, to reduce beam halo production along the LINAC, and to improve the beam quality at the end of the LINAC. The CEA codes, GENDTL and GENLINWIN are used to generate the structures, and then TOUATIS and TRACEWIN are used for multi particle simulations [5]. Ion source simulations have not yet been started. Instead, 50, 000 macro particles with a Gaussian distribution are generated and launched at the entrance to the RFQ.

More than 95% of the particles entering the RFQ are transmitted through and accelerated to the right energy, with 18% growth in the rms transverse emittance for a 55 mA beam. The RFQ generates a halo even for a completely matched beam. A collimator will be included in the MEBT in order to remove this halo. The DTL accelerates the beam without any losses in the absence of errors, when the phase advance is matched smoothly between the DTL

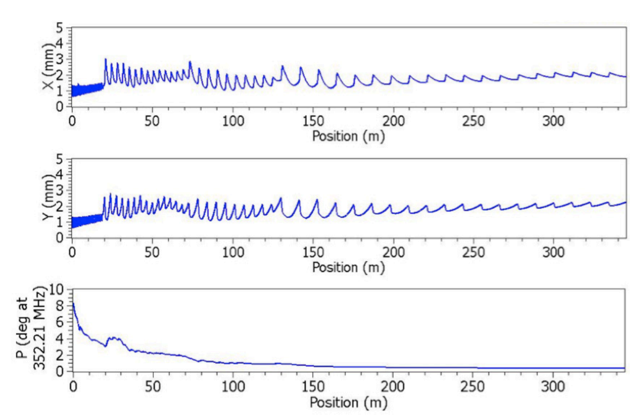

Figure 2: RMS beam size envelopes along the length of the LINAC in the horizontal (top), vertical (middle) and longitudinal planes (bottom). The longitudinal phase spread is plotted using a reference frequency of 352.21 MHz

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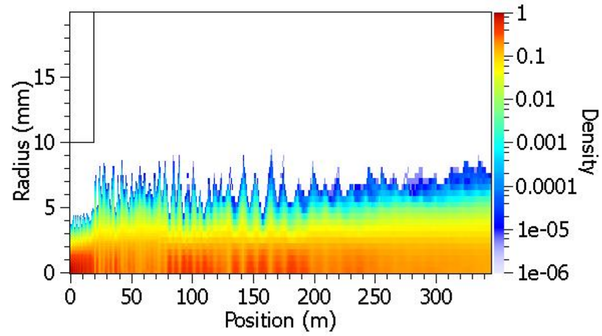

Figure 3: Beam density along the length of the LINAC

tanks, both in nominal and in upgrade current and power conditions. The FFDD lattice is intrinsically more tolerant to quadrupole misalignments [6], and is more easily matched to both upstream and downstream structures because of its longer period length. A phase advance ratio of 1.7 (transverse to longitudinal, at zero current) gives the best transverse confinement of the beam within the drift tube apertures.

The synchrotron phase at the entrance to the first tank is -30 degrees, in order to have a large acceptance. It gradually increases to -20 degrees in the middle of first tank for better acceleration. Space charge forces are weaker in the spoke resonators, permitting the synchrotron phase to increase from -20 deg to -15 deg. The bucket size is kept constant at the frequency transition, in order to minimise the disruption [7]. In order to achieve this goal the synchronous phase in the elliptical cavities is initially set to -30 degrees, twice the lower frequency phase. It increases rapidly 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 transverse apertures are larger in the downstream superconducting structures. A lower phase advance ratio of 1.25 (transverse to longitudinal) is used in general to avoid resonances, except at the beginning of the superconducting structures where the longitudinal phase advance reaches 80 degrees per period. Here a lower phase advance ratio is used, in order to not exceed a transverse phase advance of 90 degrees per period. 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 Figure 2 are kept less than 3 mm all along the LINAC, increasing the aperture to rms ratio and decreasing beam loss and machine activation. More than 99.9% of the particles shown in Figure 3 are confined within 5 mm. The outermost of particles do not exceed a radius of 10 mm.

SUMMARY AND FUTURE WORK

A review of the ESS LINAC design activities has been presented. The focusing in all three DTL tanks uses an FFDD lattice to match the period length in adjacent structures. A single family of half wave spoke resonators is used

Table 2: Normalized rms emittances along the LINAC at the injection point of each structure, for the 55 mA beam in RFQ and 50 mA in the rest.

Structure	ϵ_x π mm mrad	ϵ_y π mm mrad	ϵ_z π mm mrad
RFQ	0.2	0.2	–
DTL	0.239	0.234	0.617
Spoke	0.245	0.242	0.645
Low β	0.248	0.260	0.634
High β	0.257	0.267	0.623
Transferline	0.262	0.270	0.620

to accelerate the beam in the medium energy range. Acceleration continues using elliptical cavities working at twice the frequency.

The number of cavities per cryo-module is optimised 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 substantial change.

The possibility of reducing the pulse length and increasing the beam current to achieve the same nominal power is under study, as also is an ultimate upgrade to 15 MW that would require major modifications in many rf systems.

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