BEAM PHYSICS DESIGN OF THE ESS MEDIUM ENERGY BEAM TRANSPORT

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Abstract

A radio frequency quadrupole (RFQ) and drift tube linac (DTL) in the proton linac of ESS are connected with a medium energy beam transport (MEBT). The MEBT removes low quality bunches in the head and tail of a macro-pulse with a chopper and houses diagnostic devices to characterize and adjust the beam out of the RFQ for the DTL. These must be achieved within a relatively short space and without significant degradation of beam quality due to the space-charge force, imposing a challenge on its lattice design. This paper presents a beam physics design of the MEBT in the ESS Linac, which satisfies its requirement while preserving a decent beam quality.

INTRODUCTION

The European Spallation Source (ESS) is a neutron source based on a 5 MW proton linac, build in Lund, Sweden. Figure 1 shows the present linac layout [1]. The main function of the medium energy beam transport (MEBT), located between the radio frequency quadrupole (RFQ) and the drift tube linac (DTL), is to house a fast chopper to remove bunches in the head and tail of a 2.86 ms macro-pulse. These bunches are generated during the transient times of the upstream sections and likely to have wrong parameters, and thus impose a risk of beam losses unless otherwise removed. The chopper is used for machine protection too [2]. The MEBT also houses scrapers to remove halos on the transverse planes [3] and diagnostics devices [4] to characterize the beam out of the RFQ and adjust it for the DTL. Housing all these devices in a relatively limited space, while maintaining reasonable beam quality and achieving a good matching to the DTL, imposed a challenge to the lattice design but was eventually achieved and this paper presents the beam physics aspect of the present lattice design. All the simulations are done with the TraceWin code [5] starting from $\sim 1 \times 10^6$ particles generated from a RFQ simulation with Toutatis code [6] and the space-charge force is calculated 25 times in every [(relativistic-β) × (wavelength)] with 3D PICNIC routine [7] with a 10 × 10 × 10 mesh size.

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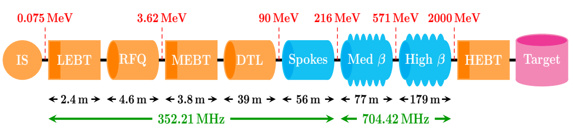

Figure 1: Schematic layout of the ESS Linac. Orange (normal temperature) and blue (superconducting) colors indicate a temperature of a section.

MEBT LATTICE

Design Criteria

In contrast to the RFQ and DTL being an integrated structure, the MEBT is consist of separate quadrupoles and buncher cavities and cannot focus the beam as strong as the RFQ and DTL. This makes it very hard, if not impossible, to completely avoid degradation of beam quality within and or near the interfaces of the MEBT. Emittance growth of a 10-20% level could occur for a MEBT of a high current linac [8, 9], but this level of degradation is commonly accepted as a small price to pay for various functions provided by a MEBT and this is also the case for the ESS MEBT. Due to various constraints, a MEBT often cannot have a periodic structure and, in such a case, the well known rule of thumb of beam physics for a design of a periodic structure cannot be used, making the design even harder. Given these situations, the design of the ESS MEBT is done in a pragmatic manner by first laying out necessary components based on the best guessed mechanical constraints and then making adjustments to optimize beam quality as possible.

Figure 2 shows a schematic layout of the present ESS MEBT lattice (top) as well as the beam envelopes (3σ) and apertures. The primary constraints of the layout are the ~90 cm space for the chopper and its dump and the other 35 cm space (starting at 2.54 m) for diagnostics devices such as an emittance meter. A quadrupole triple is used to focus the beam out of the RFQ so that it goes through the space of the chopper and dump and also the beam size of the vertical plane (the plane for the chopping) at the location of the dump is small enough to guarantee a good chopping efficiency. The beam expands after the dump and so another triple is used to focus the beam again before entering the space for diagnostic devices. The four quadrupoles in the last part are used to match the four transverse Courant-Snyder parameters

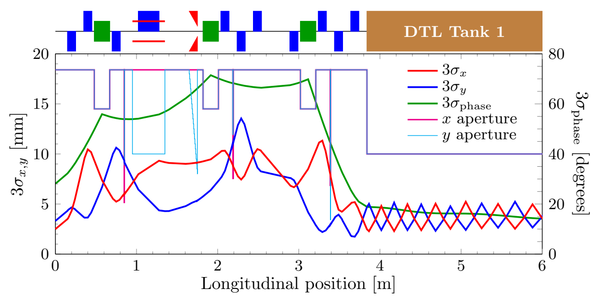

Figure 2: Schematics layout of the MEBT lattice (top), beam envelopes (3σ), and apertures. In the schematic, blue boxes are quadrupoles, green boxes are buncher cavities, red lines are chopper plates, and red triangles are a chopper dump.

to the ideal values of the DTL. While maintaining all the conditions mentioned above, it is also tried with the magnet lattice that the transverse beam sizes do not become too large or small throughout the MEBT to avoid beam losses and the enhanced space-charge force degrading beam quality.

The situation is similar for the longitudinal plane but simpler. Longitudinal focusing is provided by three buncher cavities. The second and third ones are used to match the two longitudinal Courant-Snyder parameters and the first one is used to control the bunch length throughout the MEBT. A too long bunch is affected by the nonliterary in the buncher cavity field and a too short bunch enhances the space-charge force, and both case degrades beam quality. Thus, like the case of the transverse plane, the bunch length is controlled not to become too long or short.

Scraper

In Fig. 2, tight apertures at 0.95, 1.915, and 3.39 m correspond to three scrapers. It is planned that one scraper system consists of four blades (two per plane) and acts on both plane. A study showed that the scraper is not very effective unless it could remove particles near 3σ [3] and this requires one scraper blade removes ~1.3% of the beam. A preliminary thermomechanical calculation indicated this is achievable and even more particles may be removed [3] but, to avoid optimistic estimations at this stage, the scraper blades are positioned to remove the half of the required ~1.3% of the beam in the following simulation.

Chopper

The present plan for the chopper system is to design a system similar to that of CERN Linac4; an electric deflector is surrounded with a large aperture quadrupole. This additional quadrupole enhances the deflection and also provides additional focusing on the other plane of chopping. Assuming the electric deflector has the same dimensions as the system of Linac4 (40 cm length and 2 cm gap), the required voltage for the ESS MEBT is 4 kV. If the voltage is higher than 4 kV, the deflection angle is too large and the beam may touch the deflector. One of the hardest parts of a fast chopper design lies in a fast high-voltage switch and achieving 4 kV with a rise-time as fast as a bunch spacing (2.84 ns for the ESS Linac) is challenging. The rise-time of the Linac4 chopper is ~2 ns but its maximum voltage is ~1 kV [10], and the two identical units are used to achieve the necessary deflection. If the rise-time is relaxed to ~10 ns, there are commercially available switches which could go up to 4 kV and one of them was tested for a chopper of RAL-FETS [11]. A study showed that the beam losses due to *partially-chopped* bunches for the 10 ns rise-time occur only in the DTL and the peak loss is only at the level of 10^{-2} W/m even under pessimistic assumptions [12]. Based on these, the chopper voltage and rise-time are presently specified as 4 kV and 10 ns for the ESS MEBT.

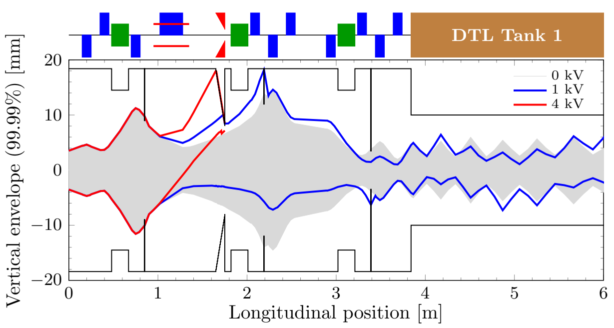

Figure 3: Vertical envelopes (99.99%) for the chopper voltages of 0, 1, and 4 kV cases.

Figure 3 shows vertical envelopes enclosing 99.99% of particles for the cases of 0, 1, and 4 kV chopper voltages. As seen in the figure, the chopper efficiency is better than 99.99% for the 4 kV case. The 1 kV case represents the worst cases of the partially-chopped bunches. A large fraction of this bunch enters the DTL but its envelope is not much worse compared to that of the nominal bunch (gray) thanks to the second and third scrapers removing some particles. The situation is worse without the scrapers and this bunch touches the aperture of the DTL and causes beam losses. In this way, in addition to improve beam quality, the scrapers also improve the situation with the partially-chopped bunches as well as the chopping efficiency.

MATCHING TO DTL

Table 1 lists the RMS normalized emittances and Courant-Snyder parameters of the all three planes from the tracking simulation at the entrance and exit of the MEBT, together with the ideal values at the DTL entrance. This shows the output beam is fairly well matched to the ideal values. The matching used be done with the envelope calculation of TraceWin code, which only includes the linear part of the space-charge force, and the result was rather poor particularly on the longitudinal plane. It is commonly understood that the matching on the longitudinal plane is of more concern since the beam losses are due to dynamics on the longitudinal plane. Hence, a simple algorithm to perform the longitudinal matching based on the tracking is developed and this allowed the almost perfect longitudinal matching seen in the Table.

Table 1: RMS normalized emittance (ϵ) and Courant-Snyder parameters (β and α) at the entrance and exit of the MEBT. The third column is the ideal values for the DTL entrance.

Parameters	Entrance	Exit	Exit (ideal)
ϵ_x [π mm mrad]	0.253	0.283	0.283
ϵ_y [π mm mrad]	0.252	0.288	0.288
ϵ_z [π mm mrad]	0.361	0.373	0.373
β_x [m]	0.210	0.214	0.223
α_x	−0.052	1.335	1.431
β_y [m]	0.371	0.762	0.796
α_y	−0.310	−4.167	−4.295
β_z [m]	0.926	0.413	0.413
α_z	−0.481	0.126	0.126

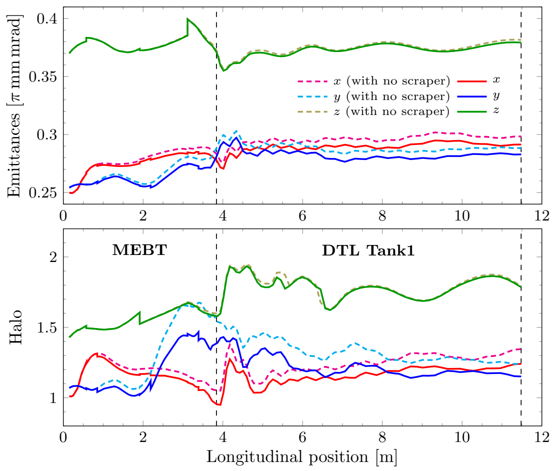

Figure 4: Evolutions of emittances (top) and halo parameters (bottom) in the MEBT and the first DTL tank.

BEAM PROPERTIES

This section sees some beam properties of the presented MEBT. Figure 4 shows evolutions of RMS normalized emittances and halo parameters defined in [13]. Because these parameters may abruptly change right after the DTL entrance, the longitudinal position is extended till the end of the first DTL tank. As already seen in Table 1, the transverse emittance growths are on an acceptable level of 10-15% and the longitudinal one is only about 3%. The emittances show no abrupt change in the beginning of the DTL. On the contrary, the halo parameters are showing abrupt changes on all the planes in the beginning of the DTL but the overall levels are not significant. The improvement from the scrapers are clear in the figure and they suppress not only the halos but also emittance growths.

Figure 5 shows the particle distributions at the MEBT exit. The non-elliptical structures are clearly present in the distributions. This is certainly an unwanted effect but hard to completely avoid in presence of the strong space-charge force, and what is shown is the best achieved thus far for this lattice. The points with magenta color represent additional particles in case no scraper is used. The improvement by the scrapers is clear also in this figure.

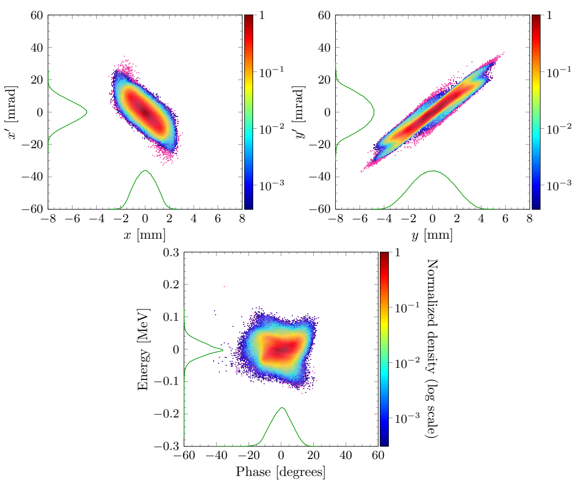

Figure 5: Particle densities at the MEBT exit. Magenta points represent additional particles in case of no scraper.

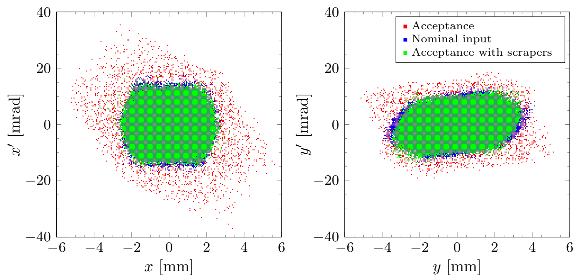

Figure 6: Acceptances of the transverse planes at the MEBT entrance with and without the scrapers.

Considering particles at 5σ in one transverse plane as an example, each scraper is separated by 40-50 degrees on the horizontal plane and 100-110 degrees on the vertical plane. Thus, in addition to compensate the degradation occurring within the MEBT itself as seen in Fig. 4, the three scrapers as one system could provide an efficient cleaning in the phase space in case the beam out of the RFQ includes halos. Figure 6 compares the acceptances of the transverse planes at the MEBT entrance for the cases with and without the scrapers. The blue points represent the nominal simulated distributions out of the RFQ as a reference. It is clear in the figure that the scrapers could efficiently clean particles in all the directions in the phase space.

The presented lattice is also checked that it has no sensitive behavior against statistical errors in the components as a part of a study done for the entire linac [14].

CONCLUSIONS

Design and beam properties of the current ESS MEBT lattice are presented. Various requirements and mechanical constraints as well as a high peak current imposed a challenge but a design with reasonably good beam qualities is successfully achieved.

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