A STEERING STUDY FOR THE ESS NORMAL CONDUCTING LINAC

R. Miyamoto*, ESS, Lund, Sweden

Abstract

Construction of the European Spallation Source is rapidly progressing in Lund, Sweden, and preparations for commissioning of its proton linac has been underway for some time now. Accurate adjustment of accelerator components to achieve ideal beam parameters is the key to maximizing performance and safe operation for any machine. This paper presents a study of beam steering for the normal conducting part of the proton linac of ESS.

INTRODUCTION

The European Spallation Source (ESS) will be a neutron source based on a 5 MW proton linac. The facility is currently under construction in Lund, Sweden and preparations for the beam commissioning are also progressing. For such a high power machine, it is the key to successful commissioning and operation to minimize beam losses and protect its components by properly adjusting the electromagnetic elements and achieving ideal beam parameters. Figure 1 shows a schematic layout of the linac of ESS and some of the high level parameters. The initial part of the linac is consist of normal conducting structures and this paper presents a study of beam steering in this part of the linac as a part of the ongoing preparations for the beam commissioning. The ion source (IS) and radio frequency quadrupole (RFQ) have nothing to adjust the beam trajectory. The low energy beam transport (LEBT) has only two dipole magnet steerers and thus the steering in the LEBT is relatively simple. Therefore, the focus of this paper is on the steering in the medium energy beam transport (MEBT) and drift tube linac (DTL).

STEERING IN MEBT

Figure 2 shows the zero current phase advances of transverse planes within the MEBT, together with a lattice schematic. This lattice is a version in 2014 [1] and has ten identical quadrupoles and an additional one surrounding the chopper. Each of ten quadrupoles is equipped with a dual-plane BPM and additional coils to produce dipole fields and steer the beam in both plane. Please note that, after evaluations in terms of beam dynamics and engineering design, it has been decided that the chopper and the quadrupole around it is separated. Hence, from the next version, the same quadrupole as other ten will be placed right after the chopper and the numbers of BPMs and steerers per plane will be increased to eleven. To identify which BPMs and steerers are essential to achieve a good steering, cases with reduced numbers of BPMs and steerers were studied and the yellow markers in Fig. 2 represent the BPM locations of one such cases with six BPMs and steerers per plane. The

* ryoichi.miyamoto@esss.se

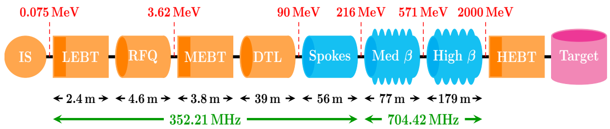

Figure 1: Schematic of the linac of ESS. Sections of superconducting cavities are in blue and those of normal conducting structures are in orange.

steerers used in this case are ones in quadrupole numbers 1, 2, 5, 7, 9, and 10.

Figure 3 shows RMS trajectories in the MEBT and the initial part of the DTL after the steering is applied to one thousand linacs with errors in the lattice elements and the parameters of the beam out of the RFQ. The layout of BPMs and steerers in the DTL used in this calculation is the new one, which is discussed in the next section. In 2014, a campaign of studies about impacts of the lattice element errors on beam quality and beam losses was conducted [2–4] and the values referred to as *tolerances* in these articles are used as the errors in this calculation. The exceptions are the dynamic errors of the cavities and inaccuracy in BPMs, to observe the effects of just the layout and the algorithm of steering. The calculations of the trajectories were done with the TraceWin code [5]. For the MEBT, the steering was done with the simplest way of minimizing the position at one BPM with one steering and performing this process one by one from the first steerer to the last (referred to as *one-to-one steering* in the following). If the layout of BPMs and steerers is adequate, this method should provide a reasonably good steering and this is indeed the case as seen in Fig. 3, even for the layout of the reduced numbers of the BPMs and steerers. The anticipated inaccuracy of the BPMs is on the order from a few hundred μm to a half mm so this will have a larger impact in the real machine. Please note that there is a small peak around ~1.2 m on the horizontal plane. This

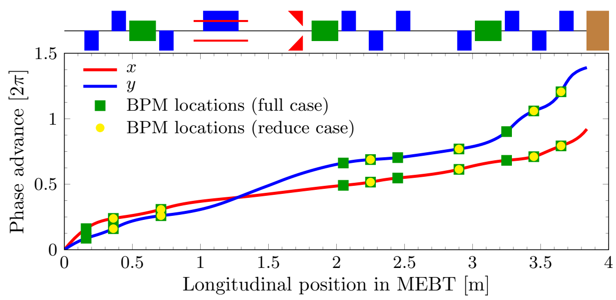

Figure 2: Zero current phase advances within the MEBT and a MEBT lattice schematic, where the blue boxes above (below) the line are the focusing (defocusing) quadrupoles, green boxes are the buncher cavities, and the red lines and triangles are the chopper and its dump.

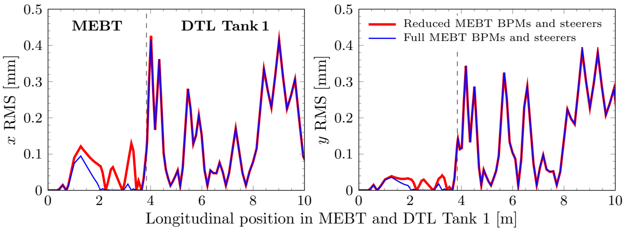

Figure 3: RMS trajectories in the MEBT and the initial part of the DTL Tank 1. The red line is for the case with reduced numbers of BPMs and steerers in the MEBT.

is due to that there is no BPM in the region of the chopper and its dump, as seen in Fig. 2, but this situation should be improved for the next version which will have an additional BPM in this region. Another important conclusion from this figure is that, for the DTL Tank 1, the errors within itself is more significant than the injection error from the MEBT.

STEERING IN DTL

The DTL of ESS has five tanks. Every other drift tubes house permanent quadrupole magnets (PMQs), forming a FODO lattice, and the drift tubes without the PMQ can house a dual-plane BPM or a single plane steerer. Further details of the DTL lattice can be found in [6]. Similar to Fig. 2, Fig. 4 shows the zero current phase advance (averaged over two planes) within the DTL and the locations of the BPMs and steerers. The top figure shows the current layout of BPMs and steerers; each tank has three BPMs and three steerers per plane, giving a total of 15 BPMs and steerers per plane. As seen in the figure, however, the Tank 1 has almost three periods of the betatron oscillation and, with only three BPMs, is is in a situation of undersampling. In such a situation, when a steerer tries to minimize the position at one BPM, there is a risk that the steerer applies a too large deflection and causes a large excursion where there is no BPM. Such an effect can be avoided by artificially applying a limit in the steerer strength and it is empirically known ~6 G m is the optimum value. Though the steering method in this way worked in the past studies [2, 3], such an method is not most ideal. This is because the optimal limit depends on the magnitudes of various errors, which may not be known in a real machine, and also a significant fraction of the Tank 1 is left blind and the trajectory in this region is not well known. Given this situation, an alternative layout of BPMs and steerers, which does not rely on the artificial limit of the steerers, is investigated and the bottom of Fig. 4 is one of such layouts. From the Tank 2 to Tank 5, the new layout repeats the patter of {**H**,**B**,**V**} separated by roughly 90 degrees in the phase advance, where **H**, **V**, and **B** denote a horizontal steerer, vertical steerer, and BPM for each. The situation of the Tank 1 is difficult since the phase advances between the two empty drift tubes are large and having the above pattern is not possible. As a compromise, a separation of ~270 degrees is also used for some combinations among BPMs and steerers. For instance, the

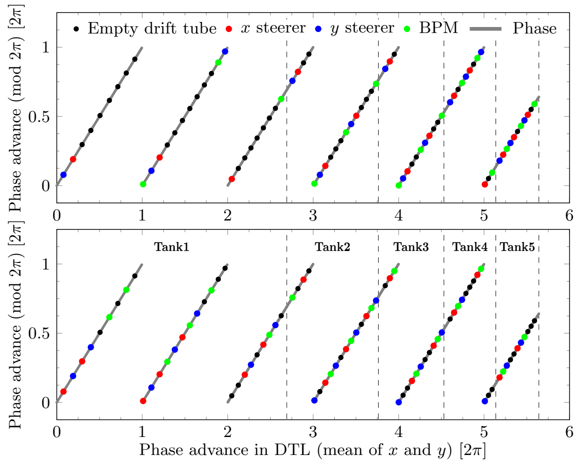

Figure 4: Zero current phase advance and the current (top) and new (bottom) BPM and steerer layouts in the DTL.

first pair of steerers is primarily looking at the second BPM which roughly separated by 270 degrees. Another example is the separation between the second and third BPMs and that between the second and third pairs of steerers are also roughly 270 degrees. In this new layout, the numbers of BPMs in each tank are 6, 4, 3, 2, and 2 (17 in total) for each and those of steerer pairs are 7, 4, 3, 2, 2 (18 in total). Please note that the last steerer pair in Tank 5 primarily looks at the first BPM in the section following the DTL and are used to improve the injection into this section.

Figure 5 shows the RMS trajectories in the MEBT and DTL over one thousand linacs, comparing the current and new layouts of BPMs and steerers in the DTL. The conditions of the errors are identical to the case of Fig. 3. The steering in the MEBT was done with the one-to-one steering as Fig. 3. For the current layout, the steering in the DTL was done for each tank as [3]. The positions at three BPMs in a tank were minimized with three steerer in the tank with the Downhill simplex algorithm implemented in TraceWin. On the contrary, for the new layout, it was found that applying steering in either one step for all the tanks or in two steps,

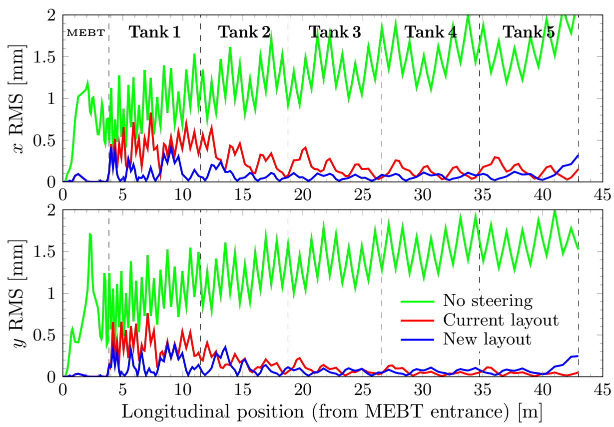

Figure 5: Comparison of RMS trajectories in the current and new layouts of BPMs and steerers in the DTL.

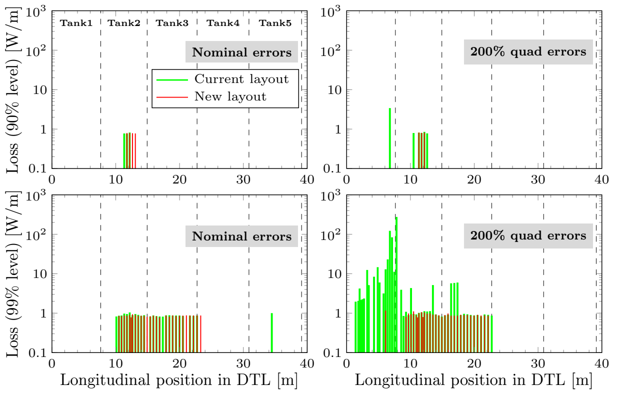

Figure 6: Confidence level beam loss densities for the current and new layouts of the BPMs and steerers in the DTL. The right column is when alignment and gradient errors of the PMQs in the DTL are increased twice.

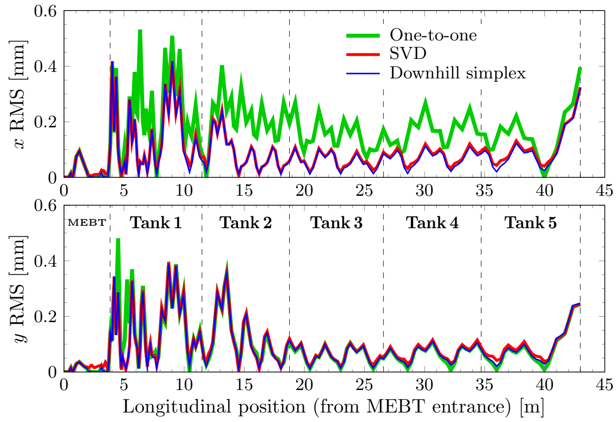

Figure 7: Comparison of steering algorithms.

first the Tank 1 and then the rest, is better. The figure is showing the result of the two steps case, where the minimization of the positions at the BPMs was also down with the Downhill simplex algorithm. Compared to the case of no steering applied (green lines), both layout provides a good steering but, as expected, the new layout could produce better trajectory in the Tank 1. The peak in the RMS is reduced almost by a half mm in both plane and in some locations the improvement is almost 1 mm.

The ultimate goal of the machine tuning for a high power machine is to reduce the beam loss so Fig. 6 compares the confidence level loss (per unit length) for the discussed two layouts. The confidence level loss of 90%, for instance, is defined as the maximum loss at each location after excluding the worst 10% cases. To simulate the beam losses, $1{\times}10^5$ macro-particles were tracked with TraceWin. The left column shows the case for the same errors as used in the calculations for Figs. 3 and 5 but this time the dynamic errors of the cavities and inaccuracy of BPMs are also taken into account. As seen in these two figures, the situation of the losses has no major difference, indicating the used set of errors are still not too close to the limit of the machine. The right column shows the case when alignment and gradient errors of the PMQs in the DTL are increased twice (uniform distributions within ±200 µm and ±1% for each). Even in such a bad case, a significant difference is only seen in the 99% confidence level but, nonetheless, this also shows that the new layout is better than the current one.

COMPARISON OF ALGORITHMS

One standard method to steerer the beam in a transport line or ring is to minimize the positions at BPMs by using the pseudo-inverse of the orbit response matrix calculated from the singular value decomposition (SVD). Figure 7 compares the RMS trajectories from the three different steering methods applied to the DTL: one-to-one steering, one based on the Downhill simplex algorithm, and one based on the SVD. The conditions of the calculations and errors are the same as Figs. 3 and 5 and the layout of BPMs and steerers in the DTL is the new one. Please note the none of the singular values of the orbit response matrix was too close to zero and all the singular values and corresponding left and right singular vectors were used to calculate the pseudo-inverse. As seen in the figure, the results based on the Downhill simplex algorithms and SVD are almost identical. The one-to-one steering gives a slightly worse result than the other two for horizontal plane but the difference is only on the order of a few hundred µm in most of the locations. Please note that the SVD is much simpler than the Downhill simplex algorithm and the steering based on it is done in one step once the response orbit matrix is measured or extracted from a model. The one-to-one steering is even simpler than the SVD and may be even performed *by hand* with no special program in the control room. Hence, if the difference is so small magnitude, the one-to-one steering is likely good enough in the initial stages of the beam commissioning and later a fine-tuning can be done with the SVD based method.

CONCLUSIONS

Beam steering in the MEBT and DTL of ESS was studied. For the DTL, an alternative layout of BPMs and steerers was considered and a few steering algorithms were compared. It was found that, if the layout is adequate, algorithms produce only small differences and even the simplest one-to-one steering provides reasonably good steering.

ACKNOWLEDGMENTS

The author would like to thank to R. de Prisco for useful discussions about the DTL.

REFERENCES

[1] R. Miyamoto et al., in Proc. of IPAC'14, THPME045.

[2] M. Eshraqi et al., in Proc. of IPAC'14, THPME044.

[3] R. De Prisco et al., in Proc. of LINAC'14, THPP042.

[4] R. Miyamoto, in Proc. of HB'14, MOPAB18.

[5] R. Duperrier et al., in Proc. of ICCS'02, p. 411.

[6] R. De Prisco et al., in Proc. of IPAC'14, THPME041.