MAGNET OPTICAL AND BEAM MATCHING ISSUES IN A MEDIUM ENERGY BEAM TRANSPORT LINE OF SNS LINAC *

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Abstract

A Medium-Energy Beam Transport (MEBT) line is employed in the SNS linac. The MEBT lattice consists of fourteen electromagnetic quadrupoles and other devices. The quads have very small aspect ratios, and they are densely packed. Significant fringe fields and magnetic interference cause difficulties in beam matching. We have performed 3D simulations of the magnets, computed their optical properties, and compared their performance with what predicted by simple hard edge models. This paper reports our findings and a general solution to the problem.

INTRODUCTION

The SNS accelerator contains a MEBT line, which matches a 2.5 MeV H^- beam from an RFQ to a DTL and performs other functions. As shown in Fig. 1, the MEBT employs two kinds of quads: six in the middle section have an aperture of 42 mm and eight in the other two sections have an aperture of 32 mm. Their steel length is 45 mm. The design uses empirical hard edge models for the quads, i.e. the hard edge length equals to the steel length plus the half of aperture. This yields 6.6 cm for MEBT42 and 6.1 cm for MEBT32. In addition, the MEBT also contains four rebuncher cavities, a chopper system, and various beam diagnostic devices.

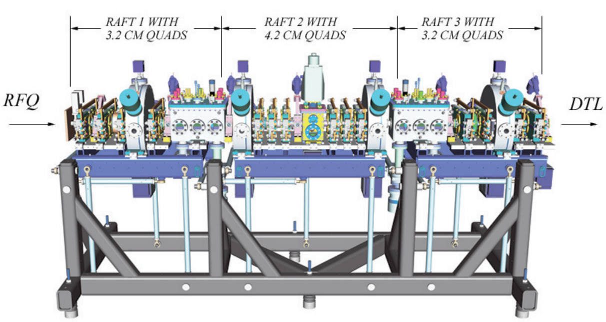

Fig. 1: SNS MEBT lattice (Courtesy: LBNL design)

The MEBT line was designed and developed by LBNL [1], and has been working since SNS commissioning. However, there probably has never been a good matching condition. Diagnostics often show significant discrepancy in beam envelope amplitudes between measurements and the design calculations. This mismatch usually increases beam emittance and may even cause particle losses. Moreover, it leads to unknown operation conditions in the DTL and subsequent accelerator sections. The problem was realized from the very beginning of the project [2], but has not been adequately addressed so far.

Our studies show that the empirical hard edge models are incorrect when used in MEBT matching calculations. The MEBT42 and MEBT32 quads have an aspect ratio of 1.07 and 1.41, respectively. Significant fringe fields affect particle optics. In addition, the MEBT quads are densely packed in the lattice. The central distance between two quads is as small as 10 cm for the MEBT42 assembly and 14.5 cm for the MEBT32 assembly, respectively. Magnetic interference changes optical properties of the quads. Our results are presented below.

MAGNETIC FRINGE FIELDS

The effect of magnetic fringe fields on particle optics in the MEBT quads is studied in 3D computer simulations and analyses. A MEBT42 model at 250 A built with OPERA-3d/TOSCA [3] is shown in Fig. 2.

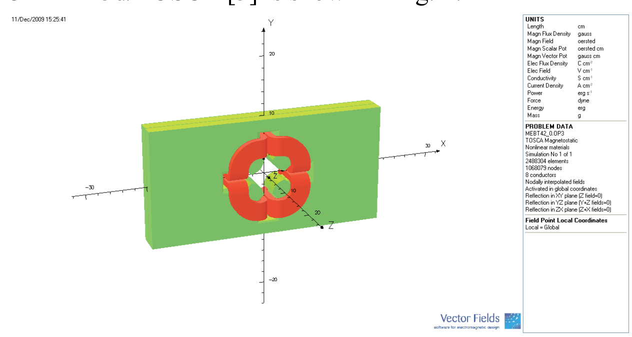

Fig. 2: 3D simulation model of a MEBT42

By employing the technique of 3D multipole expansion [4], we can find magnetic field distributions in the quad from simulation data. In Fig. 3 we plot the linear quadrupole term and a few higher-order terms. The simulation data on a cylindrical surface of R=1.7 cm radius for the 3D multipole expansion are also included.

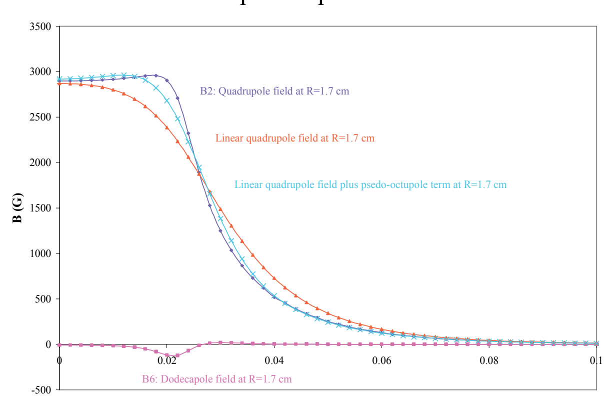

Fig. 3: Field distributions in a MEBT42 quad.

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The linear quadrupole field in Fig. 3 leads to the linear focusing function. The particle trajectories and the transfer matrix elements can be found from the equations of motion which are integrated from z=-0.2 to z=0.2 m to cover all fringe fields. Then, we derive an equivalent hard edge model for the quad. This results in a hard edge length of 9 cm for MEBT42 and 8 cm for MEBT32. A comparison among different models of MEBT42 is made in Fig. 4. The difference in the transfer matrix elements between the linear model and the design hard edge model is as large as 18.5%.

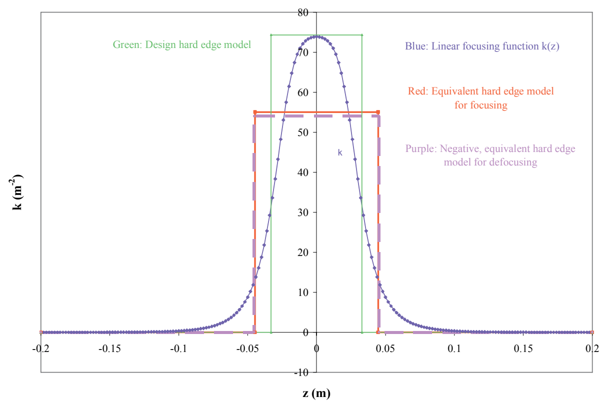

Fig. 4: Various representations of a MEBT42.

MAGNETIC INTERFERENCE

When two quads are close to each other, their magnetic fields overlap. The integrated gradient of each quad is reduced since its flux lines are terminated by the adjacent iron core. We have built 3D simulation models to study the effect on particle optics due to magnetic interference. An example is shown in Fig. 5, which contains a full MEBT42 quad at 250 A and a MEBT42 iron core. Their distance is 10 cm from center to center.

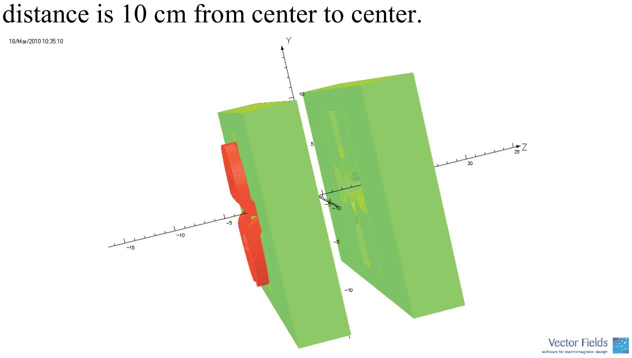

Fig. 5: A MEBT42 interfered by its neighbor.

We obtain the linear quadrupole field from simulation data and derive the linear focusing function, which differs from the one in Fig. 4. As plotted in Fig. 6, this difference determines the degree of the interference. The particle trajectories and matrix elements are computed from the interfered focusing function, from which an asymmetric hard edge model sandwiched in two drift spaces of unequal distances can be derived [5]. Numerical data show that the difference in the transfer matrix elements between the linear model and the design hard edge model in the MEBT42 assemblies could be as large as 33.6%.

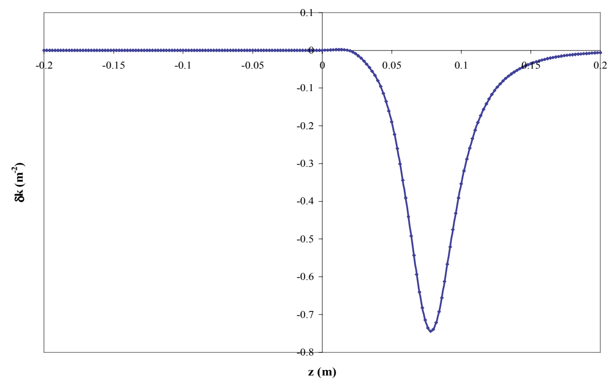

Fig. 6: Perturbation to MEBT42 linear focusing function.

ERROR PROPAGATION

With the design hard edge models, the beam envelope deviates progressively more from what is predicted by the linear optics as the beam propagates through the lattice. In order to demonstrate this error propagation and accumulation, we have built two simulation models for two quad assemblies, containing the first four MEBT32 quads and the following three MEBT42 quads. The magnet currents in the models follow a production current setting. Concatenation of the two assemblies forms the first half of the MEBT lattice. By applying the technique of 3D multipole expansion and linear analyses, we obtain the linear focusing functions and the equivalent hard edge models for the two assemblies, as plotted in Fig. 7.

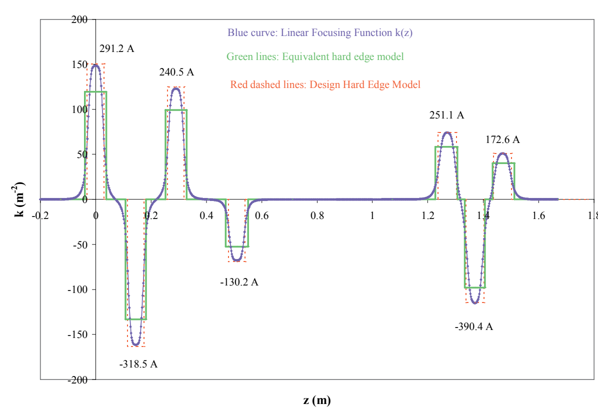

Fig. 7: Representations for the first half of MEBT lattice.

The beam envelope is computed with the linear model and the design hard edge model shown in Fig. 7. Space charge effects are ignored. The results are plotted in Figs. 8(a) and 8(b). The envelope amplitudes from the two models are close in the first a couple of quads, and deviate gradually after more quads. The difference does not monotonically increases. It appears that the envelope amplitudes from the two models are close at the center of the lattice. But, their slopes differs greatly at the same point, where the relative difference in X_m' is about 50% while Y_m' from the two models even has different signs. These differences will further propagate and accumulate in the second half of the lattice, and eventually invalidate the beam matching solution at the end of the MEBT lattice by the design hard edge models.

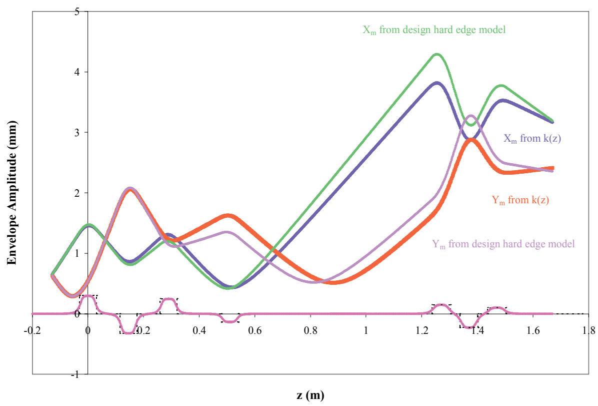

Fig. 8(a): Beam envelope amplitudes from two models.

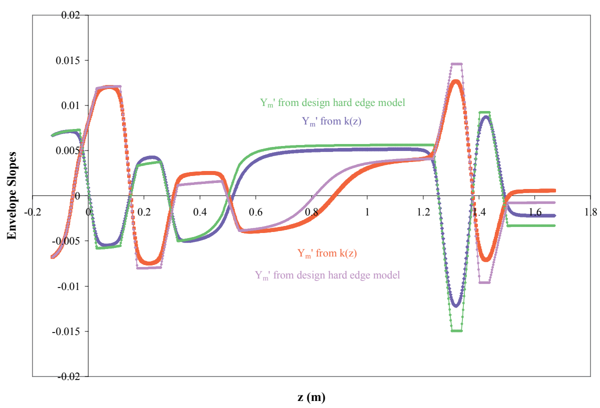

Fig. 8(a): Beam envelope slopes from two models.

SOLUTION

Calculations to find magnet currents for matched beam conditions in a lattice require a procedure opposite to the example in Fig. 7. Since the magnet currents vary during iteration, there are no correct hard edge models for magnets with overlapped fields.

A general solution to this problem is to generate a z-dependent transfer function $f_i(z)$ for each quad, which is defined as the linear focusing function per unit current. This function should take into account both magnetic fringe fields and interference. The shape of this transfer function should remain unchanged and its amplitude varies linearly with the driving current. This transfer function is generated through a 3D magnet simulation model such as the one shown in Fig. 5. As long as the quad and its neighbors do not run into saturation, the transfer function thus generated can be superimposed with its neighbor's during optimization process of beam matching calculations. For the MEBT lattice, we obtain the linear focusing function as

$$k(z)=\sum_{1}^{14} C_i f_i(z-d_i)\,.$$

Here C_i is the current of the i-th MEBT quad, and d_i is the central distance between the i-th quad and Q1. This approach requires that the overlapped, smooth transfer functions can be accepted in lattice design codes.

MEBT lattice matching with the superimposed transfer functions is illustrated in Fig. 9. It is done manually by trial and error adjusting of the magnet currents. No space charge is included. The matching goal at the middle and the end of the lattice is indicated by the crosses. The magnet currents during matching calculations are kept below 300 A in order to avoid the complication from magnet core saturation. The result looks reasonably good. Off course, a more realistic and accurate matching computation with this method requires the modification of existing simulation codes and automatic iterations, which is an ongoing task.

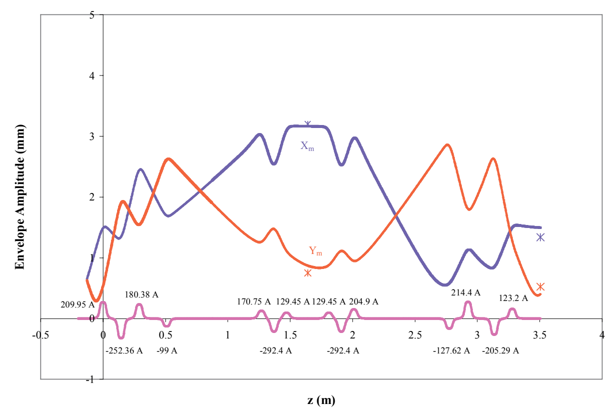

Fig. 9: A beam matching example.

SUMMARY

Significant fringe fields and strong magnetic interference in the SNS MEBT line cause much difficulty in beam matching. No suitable hard edge models of quads exist for beam matching. Our proposed remedy consists of two steps. First, the z-dependent transfer function for each quad should be generated from 3D simulation models that take into account magnetic fringe fields and interference. Second, the existing design codes should be modified in order to accept overlapped smooth transfer functions.

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