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The 23-GEV/C Beam Transfer and Absorber Lines for the Superconducting Super Collider

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Naifeng Mao, John McGill, Rodney Gerig, and Karl Brown

Abstract

The beam optics of the 12-GeV/c proton beam transfer line between the Low Energy Booster (LEB) and the Medium Energy Booster (MEB) at the Superconducting Super Collider is presented. The beam is extracted from the LEB vertically and is injected into the MEB through a vertical Lambertson magnet and a horizontal kicker. The beamline has high flexibility for amplitude and dispersion function matching. Effects of various errors in the transfer line are studied, and a beam position correction scheme is proposed. The beam optics of the 12-GeV/c absorber line transporting the beam from the LEB to an absorber during the LEB commissioning is also presented.

1.0 INTRODUCTION

The 12-GeV/c LEB–MEB transfer line[1] at the Superconducting Super Collider (SSC) transports 12-GeV/c proton beam from the Low Energy Booster (LEB) to the Medium Energy Booster (MEB). The MEB[2] is the third of the SSC accelerators and the largest of the resistive magnet synchrotrons. It accelerates protons from an injection momentum of 12 GeV/c to a top momentum of 200 GeV/c. The 12-GeV/c beam is extracted from the LEB vertically and is injected onto the MEB closed orbit in the MEB injection insertion region through a vertically bending Lambertson septum magnet and a horizontal kicker.

The tune point of the LEB may vary to a certain extent, and six tune points are selected to represent the possible range of tuning. The beam centroid position and lattice functions of these two boosters may also vary because of various errors in their lattices. Therefore, the optics design of the LEB–MEB transfer line must consider the basic optical problems, such as amplitude function matching and dispersion function matching, over a range of LEB extraction and MEB injection conditions.

The misalignments and field errors of the transfer line magnets are sources of beam centroid position, amplitude function, and dispersion function mismatching, all of which can cause emittance growth. In order to obtain a high luminosity in the collider, the emittance growth has to be minimized. The effects of different kinds of errors along the transfer line are studied, and a beam position correction scheme is proposed.

Relating to the transfer line, there is an LEB absorber line that transports the proton beam extracted from the LEB to the LEB beam absorber during the LEB commissioning. The beam optics of this line is also discussed.

2.0 LAYOUT OF THE TRANSFER LINE

The general layout of the LEB–MEB transfer line, including the elevation view and plan view, is shown in Figures 1 and 2. The total length from the extraction point of the LEB to the injection point of the MEB is about 249 m.

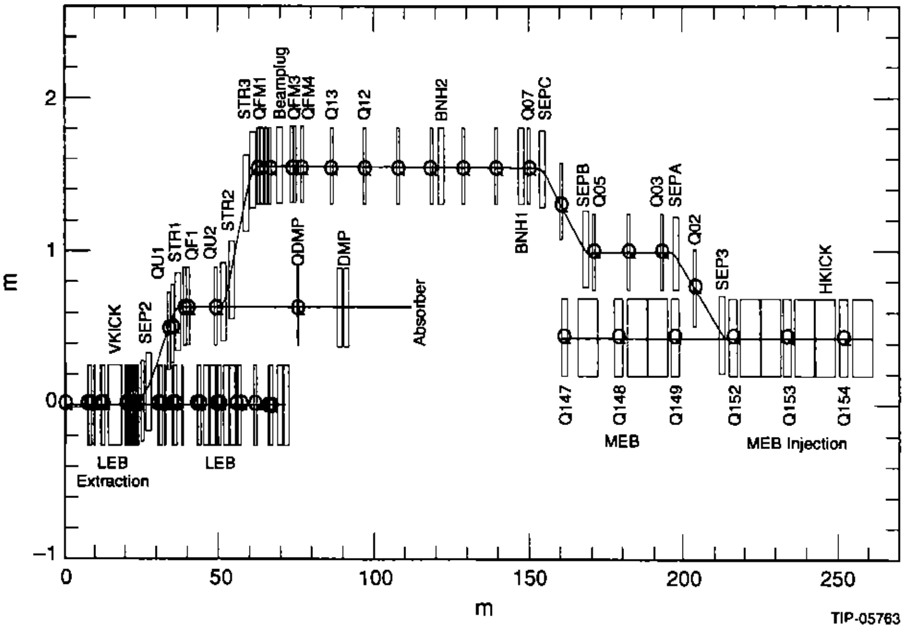

Figure 1. Layout of the LEB-MEB Transfer Line (Elevation View, LEB630 and LEB917).

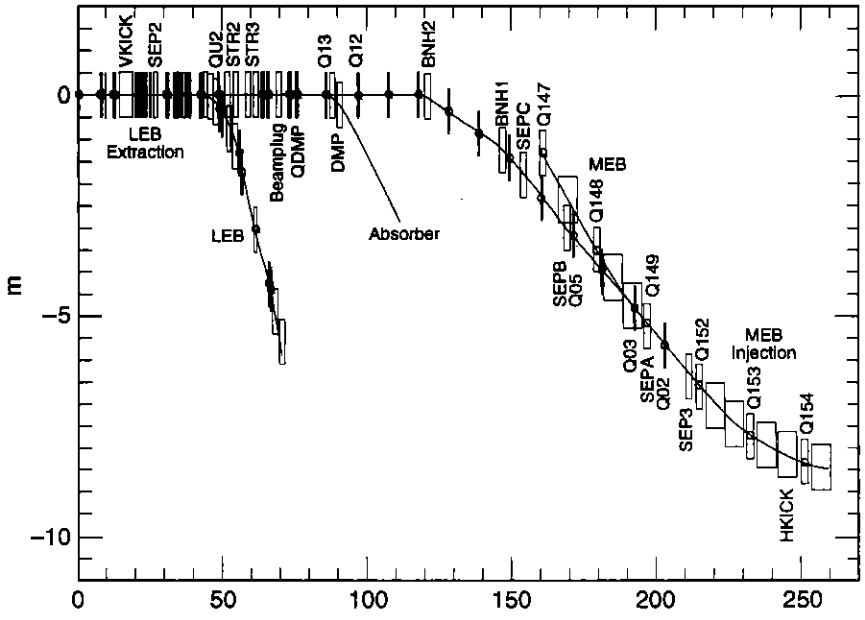

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Figure 2. Layout of the LEB-MEB Transfer Line (Plan View, LEB630 and LEB917).

The LEB extraction straight, which consists of a vertical kicker (VKICK, Figures 1 and 2), five bump magnets, and two septum magnets (SEP1 and SEP2), vertically extracts the beam from the LEB. Vertical extraction leads to the need for vertical dipoles in the transfer line; furthermore, it introduces the differential elevations of these two boosters. The elevation difference between them is about 0.46 m.

The MEB injection system[3] injects the beam into the MEB through the Lambertson septum magnet (SEP3, Figures 1 and 2) and the horizontal kicker (HKICK). The injection insertion adopts the standard FODO quadrupole spacing and uses missing dipoles to provide spaces for the beam transfer line, septum magnet, and kicker. The injection philosophy is as follows. The septum magnet (SEP3), located just upstream of the focusing quadrupole Q152, bends the beam up by 2.173° onto the MEB closed orbit plane. The horizontal kicker (HKICK), located just upstream of the focusing quadrupole Q154, completes the injection process, placing the beam onto the proper MEB horizontal closed orbit. This scheme takes advantage of the defocusing quadrupole Q153, located between the septum magnet and the horizontal kicker. The defocusing quadrupole bends the injection beam outward in the horizontal plane, thereby lessening the necessary strength of the injection kicker.

The transfer line itself has 10 standard dipoles (each 2 m in length, and mostly H-type) and 24 standard quadrupoles (each 0.5 m in length) to transport the beam from the LEB to the MEB, and to complete the amplitude function matching and dispersion function matching. In order to keep the field strength or gradient within a reasonable extent, dual-dipoles and dual-quadrupoles are used if need be, each consisting of two standard magnets.

The first five vertical dipoles (dipole STR1, and dual-dipoles STR2 and STR3) separate the transfer line from the LEB ring entirely in the vertical direction, and raise the beam centerline by about 1.57 m. On the MEB side, the last three vertical dipoles (SEPC, SEPB, and SEPA) and the

Lambertson septum magnet (SEP3) lower the beamline to the MEB elevation, and make the beam move in the horizontal plane. The vertical dipoles introduce vertical dispersion into the transfer line and make vertical dispersion function matching easy. The other two dipoles (BNH2 and BNH1) are horizontal bending magnets. These two dipoles introduce horizontal dispersion and make horizontal dispersion function matching possible.

The 24 quadrupoles, among which QU1, QF1, QFM1, QFM2, and QFM3 are dual-quadrupoles, are divided into three sections: a vertical dispersion function η_y-matching section (5 quadrupoles, QU1, QF1, and QU2); an amplitude function β-matching section (7 quadrupoles, QFM1 through QFM4); and a FODO section (12 quadrupoles, Q13, Q12 through Q02). The FODO section also plays the role of dispersion function η-matching, while lattice functions of these two boosters vary.

3.0 AMPLITUDE AND DISPERSION FUNCTION MATCHINGS

The amplitude function β and dispersion function η along the transfer line for one LEB tune point (tune E) are shown in Figure 3. The β functions have a maximum value of 103 m, and in most of the transfer line are only 75 m or less. This means that the transfer line has a low sensitivity to errors in the magnets. The FODO section, downstream of the β-matching section, transports the beam for more than 120 m, through a set of dipoles, to the MEB injection insertion region. Because of the space limitation in the transfer line, the parameters of the FODO array are slightly different from the MEB lattice, and a small but unimportant β function beating within this section appears.

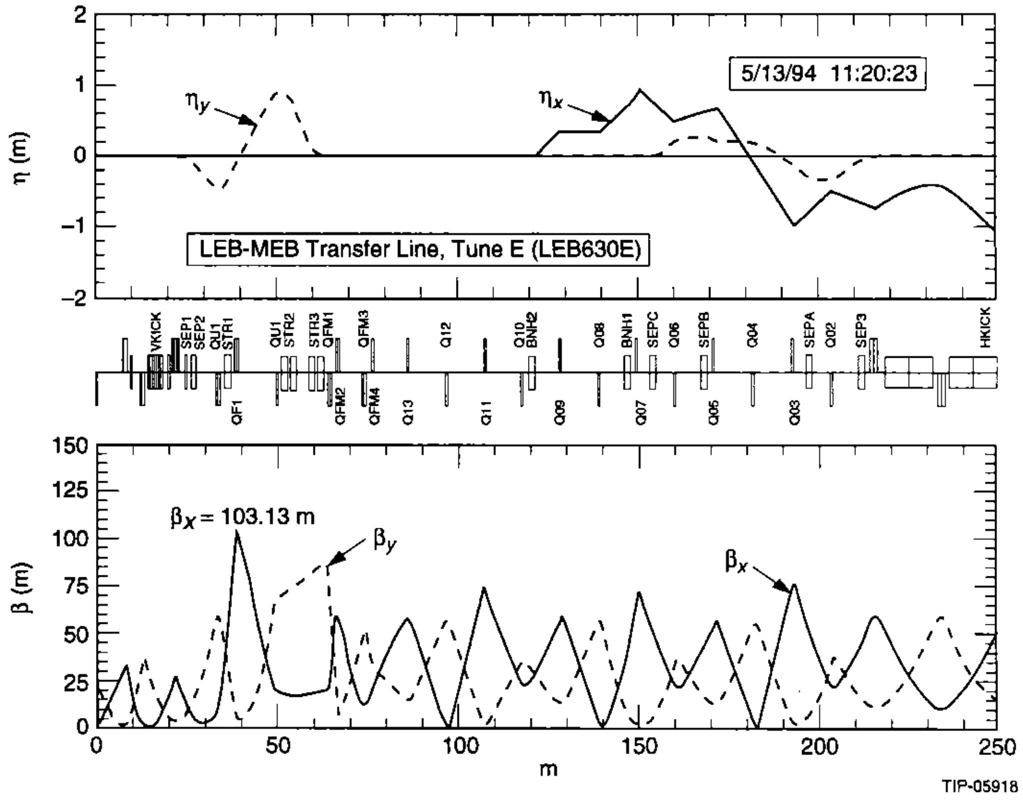

Figure 3. β and η Functions of the LEB–MEB Transfer Line (LEB630E).

The design β and η functions at the LEB extraction point and MEB injection point are listed in Table 1. The transfer line plays an important role in β and η function matching between these two boosters.

Table 1. Design β and η Functions.

	LEB Extraction Point (Tune E)	MEB Injection Point
β_x (m)	4.722	51.0927
α_x	–0.0895	–2.095 88
β_y (m)	22.223	14.4093
α_y	0.3698	0.731 054
η_x (m)	0	–1.063
η'_x	0	–0.049
η_y (m)	0	0
η'_y	0	0

3.1 Amplitude Function Matching

The amplitude function β-matching is performed by the β-matching section of quadrupoles QFM1, QFM2, QFM3, and QFM4. These four adjustable quadrupole components are necessary to complete the β_x, β_y, α_x, and α_y matching. The maximum β value of 103 m appears within this section.

In addition, the β function variations due to field errors and magnet misalignment in these two boosters are also considered. These variations may cause β function mismatching at the MEB injection point; the corresponding emittance dilution factor[4] is

$$F_\beta = 1 + 0.5(\beta_2/\beta_1)\left((1 - \beta_1/\beta_2)^2 + ((\beta_1/\beta_2)\alpha_2 - \alpha_1)^2\right)$$

$$= 0.5\,(\beta_1\gamma_2 + \beta_2\gamma_1 - 2\alpha_1\alpha_2)\,,$$

where

$$\gamma = (1+\alpha^2)/\beta,$$

subscript 1 refers to the nominal values, and subscript 2 refers to the actual values. If emittance growth of less than 1% is required, $|\alpha_2-\alpha_1|$ should be less than 0.141 when $\beta_1=\beta_2$, and β_1/β_2 should be between 1/1.063 and 1.063 when $\alpha_1=\alpha_2$ in the horizontal plane. Because these matching requirements are not easy to meet, a correction for β-mismatching is necessary. The analysis results[5] show that it is possible to use the β-matching section to complete the correction for 20% β variation of the LEB, and 5% β_x variation and 10% β_y variation of the MEB. The β functions along the transfer line after the correction for a combination of MEB 5% α_x, β_x and 10% α_y, β_y errors are shown in Figure 4. The maximum β_x function downstream of the β-matching section increases to 94 m, but the corresponding beam size is still within the magnet aperture.

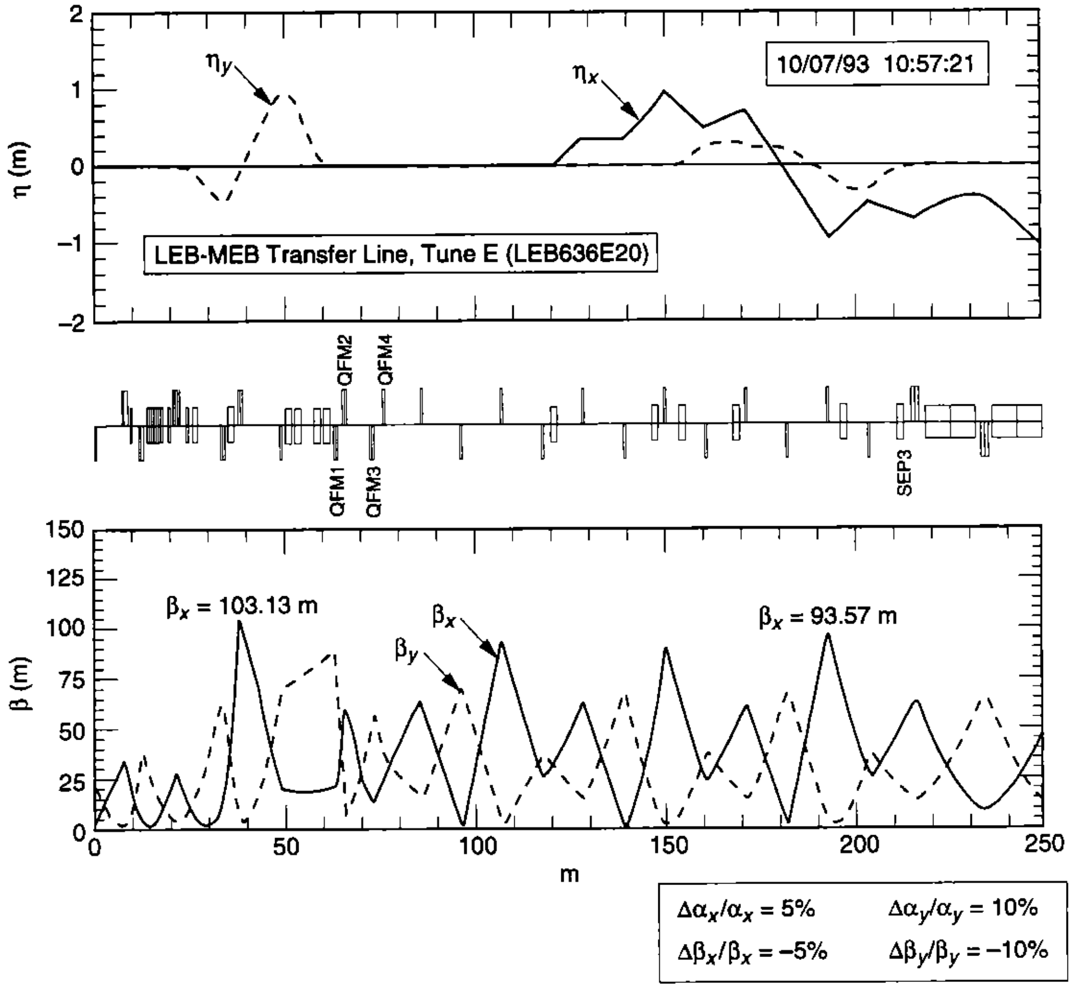

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Figure 4. **β Functions Along the Transfer Line with Correction for MEB $\Delta\alpha_x/\alpha_x = +5\%$, $\Delta\beta_x/\beta_x = -5\%$, $\Delta\alpha_y/\alpha_y = +10\%$, $\Delta\beta_y/\beta_y = -10\%$ Variations.**

The β-matching section of the transfer line is located in a region of the transfer line where the η functions are zero, so that the β-function matching has no effect on the η functions.

3.2 Dispersion Function Matching

The dispersion functions in the horizontal plane are $\eta_x = \eta'_x = 0$ at the LEB extraction point and $\eta_x = -1.063$ m, $\eta'_x = -0.049$ at the MEB injection point (Figure 3 and Table 1). Matching the nominal η_x and η'_x functions is accomplished by fixing the positions and bending angles of the two horizontal dipoles (BNH2 and BNH1).

If the horizontal η functions of these two boosters vary, the matching can be regained by adjusting the gradients of one or two pairs of quadrupoles in the FODO section in an orthogonal way.[6] The two quadrupoles of each pair are separated by 180° phase advance, and the transfer matrix between them is $-I$. For η_x matching, a phase advance approximate to $(n+1/2) \times 180°$ between this pair and the MEB injection point is required; and for η'_x matching, a phase advance approximate to $n \times 180^\circ$ is required. To achieve matching, the η_x functions at the positions of the paired quadrupoles should be different. This occurs if a horizontal dipole is located between the paired quadrupoles. In the LEB–MEB transfer line, quadrupoles Q11 and Q07 are chosen for η_x matching, Q13 and Q09 for η'_x matching. The gradient adjustment for the two paired quadrupoles is of opposite sign. A gradient adjustment of about 5% is needed for an LEB horizontal dispersion variation of $\Delta\eta_x = 0.1$ m.

In the vertical plane, this transfer line is an achromatic transport system: $\eta_y = \eta'_y = 0$ at both the LEB extraction point and MEB injection point. η_y matching is performed by the η_y-matching section (quadrupoles QU1, QF1, and QU2). Two of the three adjustable quadrupole components are for η_y and η'_y matching, and the other for producing a horizontal beam waist. If η_y functions of these two boosters vary, the remitting can also be achieved by adjusting the gradients of one or two pairs of quadrupoles in the FODO section, as discussed for η_x matching. Obviously, this transfer line has a high flexibility to match different conditions.

The beam optics is calculated with the program TRANSPORT.[7]

4.0 ERROR EFFECTS AND CORRECTIONS

The magnet misalignment and field errors in the transfer line cause errors in beam centroid position, β function, and η function. The tolerance of the misalignment and field errors is mainly constrained by two factors: the limited magnet aperture and the allowed emittance growth. The latter is more stringent, as the allowed emittance growth is only a few percent.

In order to study the effect of various errors on emittance dilution and to develop a position correction scheme, a statistical method is used. The corresponding code EAC[8] independently analyzes the effect of errors and develops the position correction scheme on the basis of the linear optics design using the code TRANSPORT. EAC also has a post-processing package to generate various types of graphics, such as beamline geometrical layouts, plots of β and η functions, beam envelopes, and so on, as shown in Figures 1–3.

4.1 Beam Centroid Position Mismatching and Correction

Two types of errors cause beam position mismatching. One is dipole field instability, and the other includes all the systematic errors, such as magnet misalignment, field setting errors, the centroid position displacement, and angular deviation of the LEB extracted beam.

The transverse emittance dilution factor due to the beam centroid position and angular mismatching (Δy and $\Delta y'$ at the MEB injection point, taking the vertical plane as an example) is given by

$$F_y = \frac{\varepsilon}{\varepsilon_0} = 1 + \frac{1}{2} \times \left[\frac{\Delta y_{\text{eq}}}{\sigma_0}\right]^2 ,$$

where

$$\Delta y_{\text{eq}} = \sqrt{\Delta y^2 + (\beta \Delta y' + \alpha \Delta y)^2} .$$

For an MEB injection normalized emittance $\varepsilon_0 = 0.6$ π-mm-mrad (collider operation mode), the beam rms half width $\sigma_0 = 0.8$ mm. If an emittance growth of less than 1% is required, Δy_{eq} should be as small as 0.1 mm. In practice, beam position corrections are needed to control the emittance growth.

A detailed analysis has been made of the beam centroid mismatching caused by the dipole field instabilities.[9] The fractional errors assumed in the analysis are as follows: 1×10^{-2} for LEB extraction kicker (VKICK) and MEB injection kickers (HKICK); 2×10^{-3} and 1×10^{-3} for the LEB extraction septum magnets SEP1 and SEP2, respectively; and 1×10^{-4} for the MEB injection Lambertson septum magnet (SEP3) and the 10 dipoles of the transfer line itself. The analysis shows that the centroid mismatching in the vertical plane is $\Delta y_{eq} = 1.0$ mm, corresponding to 76% emittance growth. In order to control the emittance growth in the MEB, an injection damping system in the MEB is considered.

The rms values of the systematic errors of the transfer line, which cause the beam centroid position displacement and mismatching, are:

1. quadrupole transverse displacement $\mathrm{DIS}(x) = \mathrm{DIS}(y) = 0.25$ mm, rotation angle about the z axis $\mathrm{ROT}(z) = 1.0$ mrad;
2. dipole rotation angle about the z axis $\mathrm{ROT}(z) = 1.0$ mrad, field error $\Delta B/B = 1 \times 10^{-3}$;
3. LEB extracted beam position error $\Delta x = \Delta y = 0.5$ mm, angular deviation $\Delta x' = \Delta y' = 0.1$ mrad.

In the statistical analysis of the systematic error effect,[10] 1000 seeds are randomly selected, and the corresponding beam position displacements along the beam transfer line are simulated. Figure 5 gives an example of the beam position displacements (dashed lines) along the transfer line in both horizontal (x) and vertical (y) planes. It can be seen from the figure that the maximum displacement is larger than 10 mm. Obviously a beam position correction scheme is absolutely necessary for errors of this magnitude.

The proposed correction scheme consists of dipole correction magnets (correctors) and beam position monitors (BPMs). The scheme is designed through statistical simulation—that is, randomly choosing magnet misalignments and field errors, then calculating the necessary corrector strengths and the centroid displacement along the transfer line. In most of the transfer line, a "one (corrector)-to-one (downstream BPM)" correction mode is used, meaning that each corrector corrects the beam centroid displacement where the BPM is located. But at the end of the transfer line, a "two-to-two" correction mode needs to be used. This mode corrects both beam centroid displacement and angular deviation.

Figure 5 shows a correction scheme for the transfer line, which requires 14 BPMs and 17 correctors. Among these BPMs are 10 single-direction BPMs (4 for the x direction and 6 for the y direction) and 4 dual-direction BPMs (for both x and y directions). In addition to these BPMs, two dual-direction BPMs, located upstream and downstream of the MEB injection kicker (HKICK) in the MEB injection insert, are also used to give the beam position information for the transfer line position correction. Among these correctors, eight adjust the beam position in the horizontal plane, and nine adjust in the vertical plane. Three main dipoles (two horizontal dipoles BNH2 and BNH1, and one vertical dipole STR1) and two vertical septum magnets (SEP2 and SEP3) also play a role in the position correction.

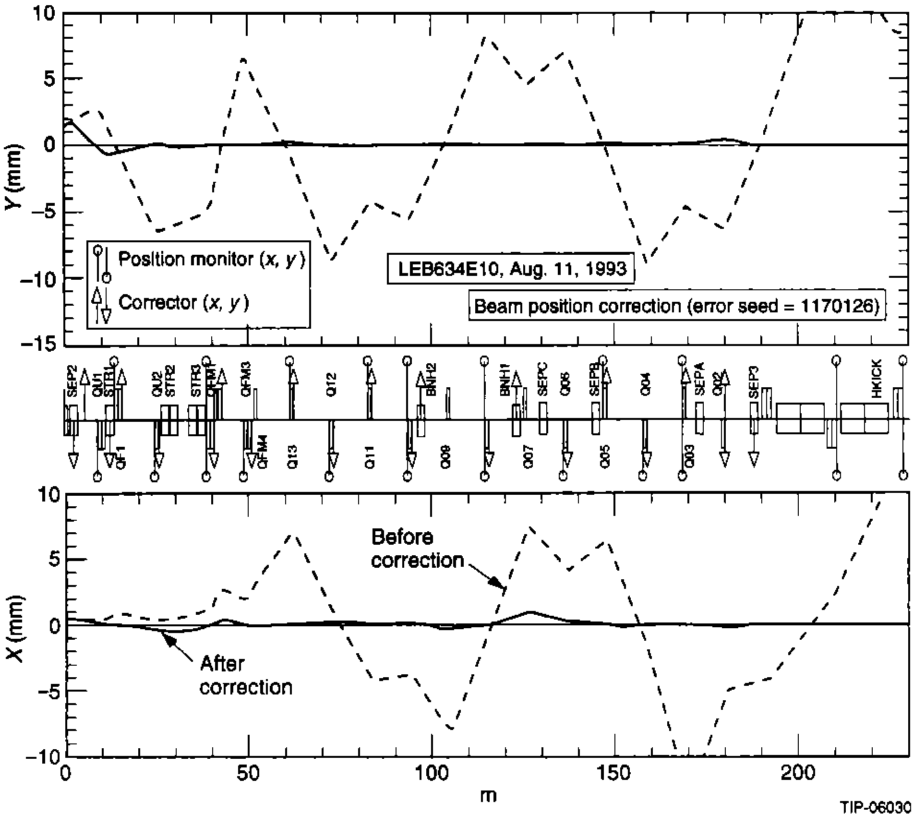

Figure 5. Beam Position Correction Scheme of the LEB–MEB Transfer Line (LEB634E10).

Based on the correction scheme mentioned above, the position displacements along the transfer line in both the horizontal and vertical planes are simulated. The results show that the maximum displacement after the correction is about 2.1 mm. The equivalent position displacements Δx_{eq} and Δy_{eq} at the MEB injection point are less than 0.02 mm, corresponding to an emittance growth of less than 0.1%. The maximum corrector strength required for this correction scheme is 0.7 mrad.

4.2 Amplitude and Dispersion Function Mismatching and Corrections

The major error in the transfer line that causes amplitude and dispersion function mismatching is quadrupole gradient error. The gradient tolerance of transfer line quadrupoles is required to be 0.1%.[11] Accordingly to the statistical simulation[5] in which the gradient errors of all quadrupoles are randomly chosen with an rms value of 0.1% (1000 seeds), the emittance dilution in the MEB, as shown in Figure 6, is about 0.4% for 99% of the seeds. This meets the emittance budget requirement.

The analysis also shows that the η-function mismatching caused by the quadrupole gradient errors of 1×10^{-3} will lead to an emittance growth of less than 0.1%.

In order to prevent dipoles in the transfer line from interfering with MEB magnets, vertical dipoles SEPA and SEPB (Figure 1) have to be of C-type with openings facing down. These C-type dipoles have a strong quadrupole component. The effect of this component on the amplitude function mismatching, dispersion function mismatching, and phase space dilution is studied.[12] The result shows that the emittance growth will be much less than 0.1% if dipole SEPC is of C-type with opening facing up and if quadrupole Q05 is slightly readjusted in gradient.

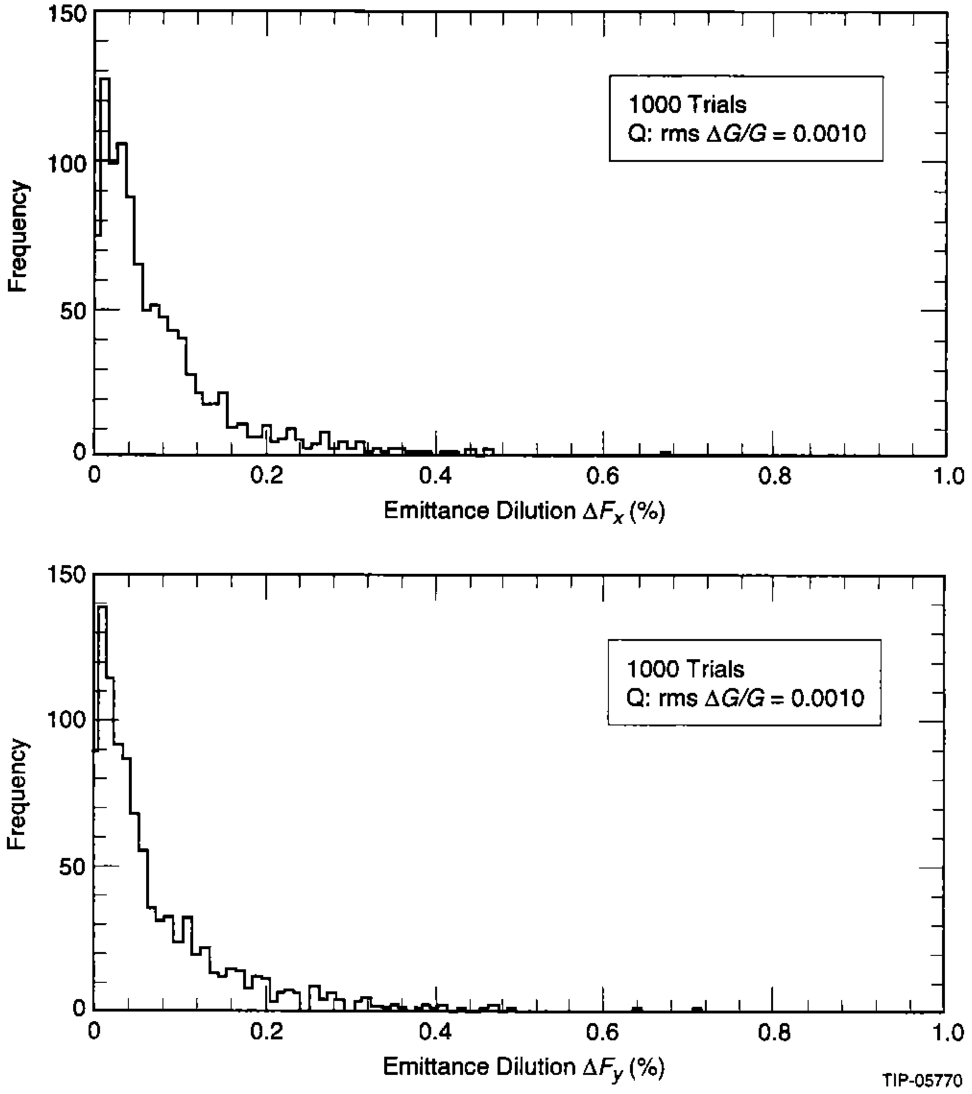

Figure 6. Emittance Dilution Due to Transfer Line Quadrupole rms Gradient Error of 0.1%.

5.0 LEB ABSORBER LINE

In addition to the LEB–MEB transfer line, there is an LEB beam absorber (beam dump) line, as shown in Figures 1 and 2, that transports the 12-GeV/c proton beam from the LEB to the absorber during the LEB commissioning. The absorber line separates from the transfer line at the entrance of dual-dipole STR2. All the dipoles, quadrupoles, correctors, and BPMs located upstream of STR2 are shared by both lines. And all the magnets located downstream of quadrupole QU2 in the transfer line are turned off while the absorber line is in operation. Safety-critical devices[11] preventing the unwanted beam from entering the MEB tunnel during the LEB commissioning include dual-dipoles STR2 and STR3 (power supply turns off, fail safety) and a beamplug (in the beam path between dual-quadrupoles QFM2 and QFM3, compressed air turns off, fail safety).

The absorber line itself consists of one dual-dipole (DMP) and one quadrupole (QDMP). The total length from the extraction point of the LEB to the absorber is about 112 m. The dual-dipole separates the beam from the transfer line in the horizontal plane, and the quadrupole focuses the beam in the horizontal plane and makes it have a circular beam spot in the absorber. Figure 7 shows the amplitude function β and dispersion function η along the absorber line for one LEB tune point (tune E).

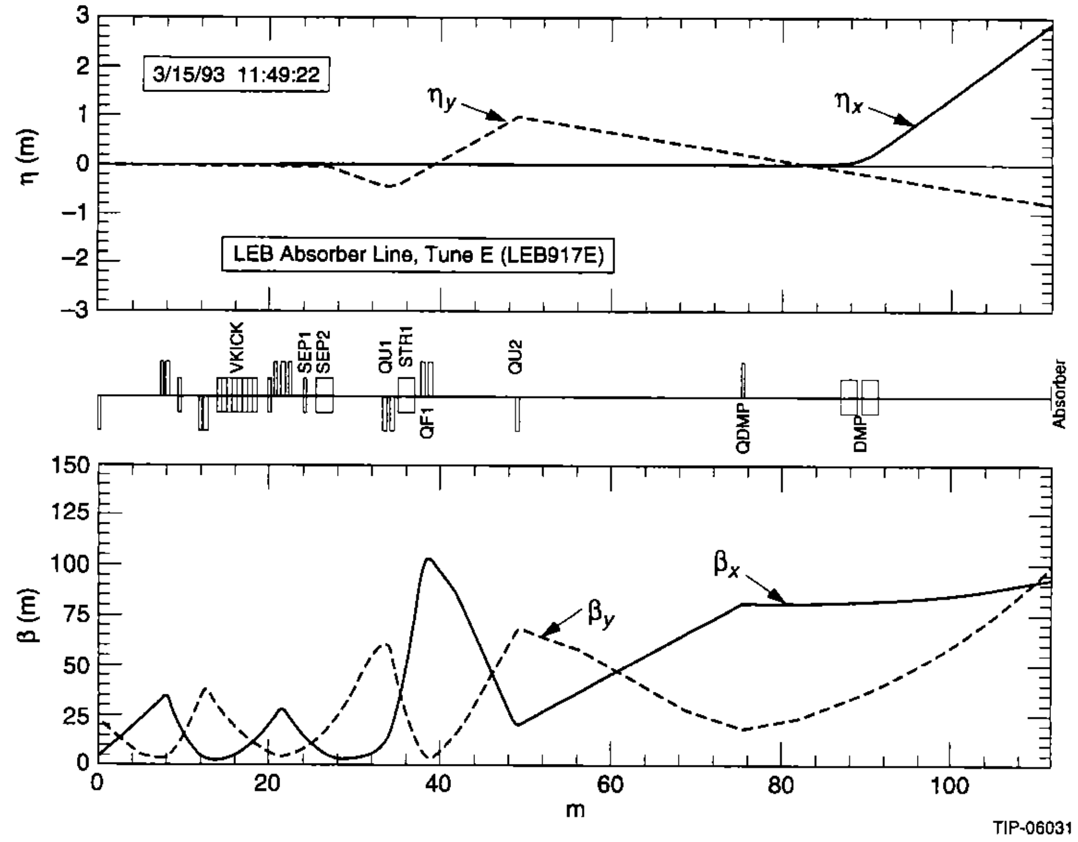

Figure 7. β and η Functions of the LEB Absorber Line (LEB917E).

Based on the beam centroid position correction scheme of the transfer line, the correction scheme of the absorber line is studied.[10] Since emittance growth control is meaningless to the absorber line, only the limited magnet aperture is considered. The correction scheme of the absorber line is shown in Figure 8. Here the dual-dipole DMP serves as a corrector. Two additional BPMs are arranged along the line: one horizontal BPM located upstream of quadrupole QDMP and one dual-direction BPM located upstream of the absorber. The statistical simulation results show that the maximum displacement along the line is 2.1 mm after the correction, and the maximum corrector strength required is 0.7 mrad, consistent with the values for the transfer line.

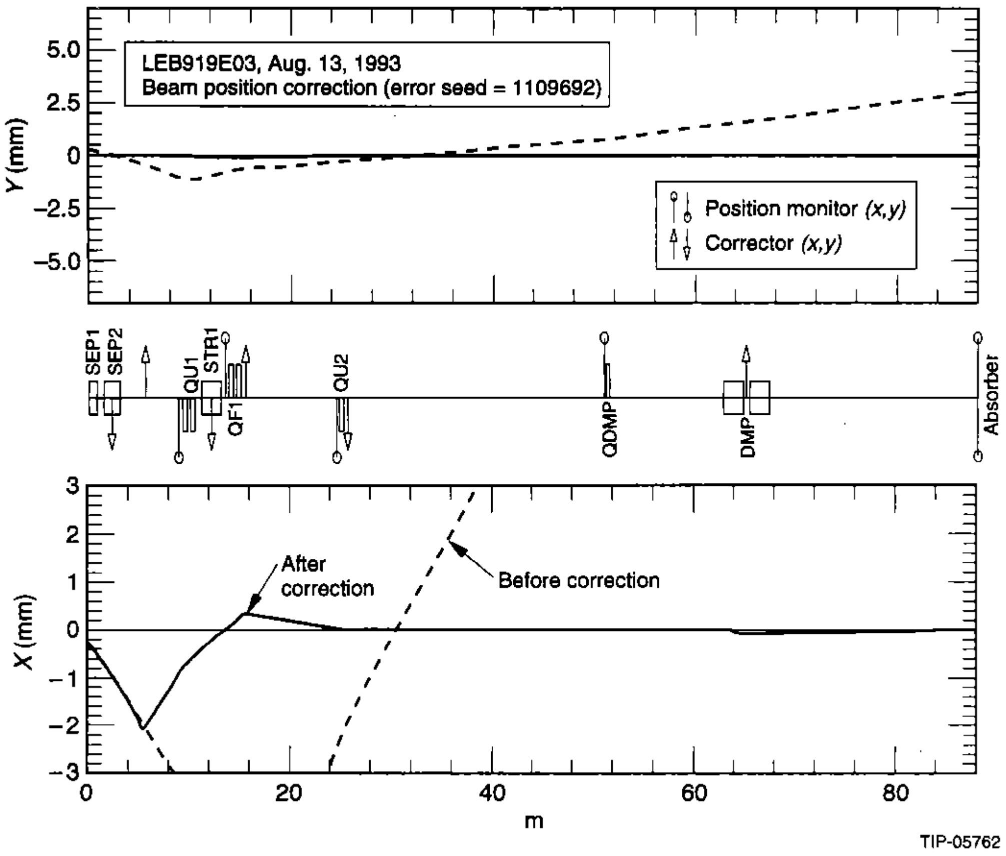

Figure 8. Beam Position Correction Scheme of the LEB Absorber Line (LEB919E03).

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