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DESIGN OF BEAM-TRANSPORT LINE BETWEEN THE RFQ AND THE DTL FOR THE JHP 1-GeV PROTON LINAC

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Abstract

A beam-transport line between the RFQ and the drift tube linac (DTL) for the Japanese Hadron Project (JHP) was designed using three recently developed computer codes. One of the codes, called LEBT, takes into account the particle-to-particle (P-P) electric forces among all particles for a space-charge calculation. The calculated results show no increase in the transverse emittance and about a 20% increase in the longitudinal emittance for a 20-mA bunched proton beam. The properties of the beam line have been studied in connection with the effects on the final beam qualities after a long acceleration with the 1-GeV proton linac. The effects of a transverse mismatch at the DTL injection are discussed.

Introduction

In a recently designed injection scheme into a proton drift tube linac, a radio-frequency quadrupole linac (RFQ) is usually used instead of a conventional Cockcroft-Walton generator. The utilization of an RFQ brings many advantages, as follows: 1) The longitudinal phase spread is so small that the longitudinal emittance in the DTL can be improved. 2) The number of particles located near to the edge of the longitudinal acceptance of the DTL is greatly reduced, resulting in a good effect on the reduction of beam losses in a high-energy part of the linac. 3) The transverse emittances can be limited to some upper value, since the RFQ is regarded as being a kind of filter for the transverse emittances. 4) A higher injection energy into the DTL can be chosen. Therefore, the most complex part of the DTL, due to its short unit-cell length, is no longer required. Thus, the mechanical structure of the injection part of the DTL, including the fabrication of the quadrupole magnets, can be simplified. 5) The effects of space-charge in the beam line between the RFQ and the DTL can be reduced as the injection energy into the DTL becomes higher. However, the space-charge effects are not negligibly small for a 20-mA bunched beam of 3 MeV.

The design of the beam-transport line between the RFQ and the DTL (named MEBT) is very important in the sense that the beam quality in the low-energy part of the long linac mainly determines the characteristics of the beam in the high-energy part of the linac. Therefore, a degradation in the quality of the RFQ beam is not allowed in the MEBT. As for matching in transverse phase space, the emittances of the beam at the exit of the RFQ are normally within the acceptance of the DTL, although they have some mismatched twiss parameters. The transverse emittance growth in the DTL is sensitive to the transverse matching at the injection part. This suggests that the beam-diagnostics system in the MEBT is very important in order to achieve matching with a reasonable tuning method: comparing the experimental results with the calculated one. As for matching in longitudinal phase space, it is not considered here, since the design of the DTL for the Japanese Hadron Project (JHP) [1] has adopted a rather high accelerating field (3 MV/m) for the injection part, inevitably resulting in some mismatching in the longitudinal phase space. However, detailed simulations of the acceleration in the DTL and the CCL (coupled cavity linac) have revealed that the effects due to the longitudinal mismatching were negligibly small from the viewpoint of the final beam quality at an energy of 1 GeV. Therefore, the transport beam line (MEBT) between the RFQ and the DTL for the JHP was designed so as to fulfill the following requirements: 1) there is almost no degradation of the beam quality in the MEBT, 2) transverse matching for a 20-mA beam can be achieved, and 3) there is sufficient space for installing beam diagnostics.

Design tools

Four computer codes are utilized for designing the MEBT: one is the MAGIC code [2], and the other three (named BTSCF, BTFIT and LEBT) were written by the author. The MAGIC is useful for designing a beam-transport line for a 0-mA beam. Thus, it is used both for designing at the first stage and for checking the results from the other three codes at the final stage. The BTSCF code calculates the optics of the beam line with a transfer matrix, including space-charge effects. The BTFIT code, an extended version of BTSCF, searches for the focusing strength of four quadrupole magnets in order to achieve transverse matching of the beam. The LEBT code, a multi-particle simulation code, calculates particle motion by solving a second-order differential equation by the Runge-Kutta method of fourth order. The code takes into account the particle-to-particle (P-P) electric forces among all particles for the space-charge calculation. It is therefore run on a supercomputer, because much time is required to compute space-charge effects on a scalar computer. It is used for both evaluating the emittance growth in the MEBT and confirming the results calculated with the other codes.

Design procedures

The design procedures for determining the MEBT parameters are as follows:

1) At first, roughly approximated beam line parameters are chosen in order to calculate the longitudinal motion including space-charge forces for the design beam current. Two codes, BTSCF and LEBT, are used for determining both the length of the MEBT and the parameters of the buncher. They are adjusted so that the energy and phase width at the exit of the beam line are equal to those at the entrance of the beam line.

2) The number of quadrupole magnets is determined for a given length of the beam line.

3) The MAGIC calculates the zero-current parameters. The twiss parameters of the output beam from the RFQ and those of the DTL acceptance are used as the input and output parameters, respectively.

4) Both the bore radius and the length of the quadrupole magnets are determined so that the maximum magnetic filed gradient may not greatly exceed 40 T/m, thus avoiding saturation in an iron yoke.

5) The BTFIT code determines the quadrupole gradients for obtaining a 20-mA matched beam on the basis of the results of the MAGIC calculation.

6) The LEBT code confirms the calculated results mentioned above. It also examines both the emittance growth and any change in the field energy of the bunch. The bunched beam generated by the RFQ simulation [3] with the PARMTEQ code is used as the injection particles.

7) Finally, the output beam from the LEBT code is injected into the DTL and CCL accelerators in order to examine the properties of the output beam after all acceleration through the following linac.

8) Some iterations among the procedures mentioned above are performed in order to find satisfactory parameters, if necessary.

Design of the MEBT

The optimized design of the MEBT is summarized in Table 1. The beam line (1643.5 mm in length) comprises eight quadrupole magnets and an rf buncher. Figure 1 shows the square root of the β-functions for the beam line. The maximum β-function is 2.2 m, corresponding to a beam radius of 5.2 mm for a normalized emittance of 1.0 πmm•mrad. A bore radius of 17.5 mm, more than three-times the beam radius, is chosen, giving a maximum surface magnetic field of 7.5 kG for the quadrupole magnets. The circles plotted in Fig. 1 show the results of the LEBT code calculation. In spite of the many assumptions used in the BTSCF code, the results calculated with both codes agree with each other approximately.

The variation in the energy and phase spreads along the beam line are shown in Fig. 2. It can be seen that the effects of space-charge noticeably appear in the longitudinal motion. An rf buncher (9-mm gap-length and a 115-kV rf voltage) is placed at a position 860 mm downstream from the entrance of the beam line. In the design, a small beam radius in the buncher is realized, so that the effects of an rf defocusing force in the gap might be small.

The calculated emittances for a 20-mA beam with the LEBT code are listed in Table 2. Although there is no transverse emittance growth, there is longitudinal emittance growth by 20%. The field energy of the bunch decreases by 13% in the MEBT. The ratio of the field energy to that of an equivalent uniformly distributed bunch decreases by 4%, which means that the charge distribution becomes more uniform at the exit of the MEBT.

Effects of rf fields in the buncher

The equivalent focusing force of the rf buncher amounts to 41% of that of the following quadrupole magnet. Thus, it can not be neglected in finding the matched parameters of the beam line. The rf defocusing force dose not cause any transverse emittance growth so long as it remains a linear force in the transverse direction. It is therefore important to make the beam size small in the rf buncher, thus avoiding the non-linear part of the defocusing force. The magnitude of the rf defocusing force varies according to the particle position in the bunch, even if the radial positions are equal. The LEBT code exactly estimates the effects mentioned above as well as those due to the transverse distribution of the electric field in the gap. In fact, the LEBT simulation shows no transverse emittance growth for the optimized design.

Table 1 Parameters of the MEBT calculated with the BTFIT code for both 20-mA and 0-mA bunched beams.

No	Name	Length mm	Total length	Gradient T/m 20mA		Gradient T/m 0mA
1	LD1	90	90		drift	
2	QF1	60	150	38.926	F	38.926
3	LD2	120	270		drift	
4	QD1	50	320	33.462	D	33.462
5	LD3	260	580		drift	
6	QF2	50	630	28.173	F	28.173
7	LD4	80	710		drift	
8	QD2	50	760	25.617	D	20.00
9	LD5	200	960		drift	
10	QF3	50	1010	13.33	F	13.00
11	LD6	120	1130		drift	
12	QD3	50	1180	18.99	D	21.60
13	LD7	180	1360		drift	
14	QF4	70	1430	32.51	F	32.34
15	LD8	60	1490		drift	
16	QD4	70	1560	42.88	D	37.37
17	LD9	83.5	1643.5		drift	

In the longitudinal direction, there is a non-linear force arising from the sinusoidal accelerating voltage. In the design, half of the full-phase width amounts to 55 degrees at the rf gap (the 90% half width is about 32 degrees). Therefore, some particles located near to the edge part of the bunch are accelerated by the voltage that contains a more non-linear portion of the accelerating field. This effect causes some deformation of the longitudinal emittance. The LEBT code calculation shows a longitudinal rms-emittance growth rate of 22% and a 90%-emittance growth rate of 15%. However, a 100% emittance decreases by 17%. The effects of the longitudinal emittance variation in the MEBT on the final beam quality after acceleration by the DTL and CCL are discussed in the next section.

Effects of a degradation of the beam quality in the MEBT

There is some degradation in the emittances (Table 2) along the MEBT, especially in the longitudinal emittance. For evaluating the degradation of the beam quality in the MEBT, it is reasonable to calculate the effects on the final beam qualities

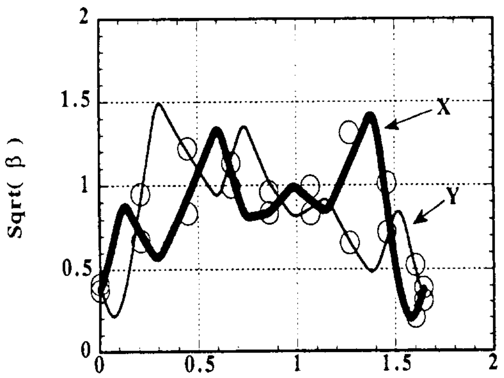

Fig. 1 Square-root of the β-functions for the MEBT calculated with the BTSCF code. The circles indicate the results of the LEBT code calculation.

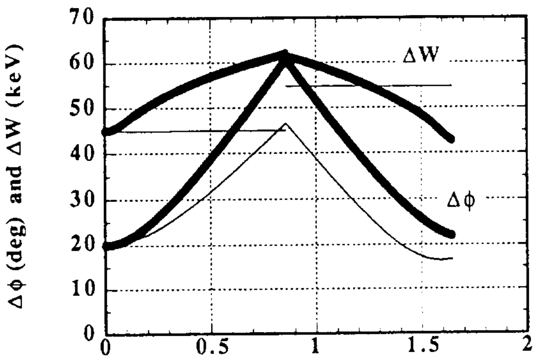

Fig. 2 Variation in the energy and phase half-spreads along the beam line calculated with the BTSCF code. The wide lines correspond to a 20-mA beam, while the narrow lines correspond to a 0-mA beam.

after successive acceleration by the DTL and CCL. Two kinds of beam simulations along the DTL and CCL were performed with a 20-mA beam. One used the output beam with the PARMTEQ code (named direct-injection) as the injection particle into the DTL. The other used those with the LEBT code (named LEBT-injection). (The injection beam into the LEBT code was the output of the PARMTEQ code.) The transverse emittances of the injection particles were transformed in order to exactly match the transverse acceptances of the DTL. The acceleration in the DTL and CCL was performed using the PARMILA and PROEND codes [4], respectively. Table 3 summarizes the results of the simulations. It can be seen that the longitudinal emittance for LEBT-injection is larger than those for direct-injection by 32%; however, both the transverse emittances and the energy spread are nearly equal in both simulations. Figures 3 shows the output longitudinal emittances for both simulations. Although the output longitudinal emittance for LEBT-injection is larger than that for direct-injection, it seems not to be a peculiar or dangerous distribution in the longitudinal output emittance for LEBT-injection. Moreover, the difference in a 100% longitudinal emittance is only 7%. This means that there is almost no difference in the beam quality from the viewpoint of the beam-loss problem in the high-energy part of the linac. It is therefore concluded that the degradation of the longitudinal emittance in the MEBT is negligibly small from the viewpoint of the output beam quality at an energy of 1 GeV.

Mismatching due to the codes

The twiss parameters calculated with the LEBT code is slightly different from those with the BTSCF code. The main reason for the differences is that the LEBT code includes the particle-particle interaction among a few thousands of particles explicitly, while the BTSCF code takes approximate account of the effects. Therefore, the LEBT code can treat the effects of the particle distribution within a bunch; however, the BTSCF code assumes a uniform distribution throughout the calculation. Moreover, the space-charge form factors [5] in the BTSCF code are used on the condition that the transverse beam sizes for both transverse directions are not greatly different from each other. This is not valid for MEBT. Thus, when the asymmetry of the transverse beam sizes becomes large, the associated errors in the calculation become large. Finally, the LEBT code deals with an rf acceleration more precisely than that in the BTSCF code. As a result, the twiss parameters obtained by the LEBT code calculation, using the MEBT parameters determined by the BTSCF code, is slightly different from the DTL acceptance. Figure 4 shows the difference in the emittance shapes at the exit of the MEBT for both the exactly matched parameters calculated with the BTSCF code and for those obtained by the LEBT code. Two simulations in the DTL were performed in order to examine the effects of the difference in the twiss parameters mentioned above. One used the input beam obtained by the LEBT code calculation (named mismatched-injection). The twiss parameters of the beam are slightly different from those of the DTL acceptance. The other used the input beam that was transformed so as to have the twiss parameters equal to those of the DTL acceptance (named matched-injection). The results are given in Table 4. It can be seen that the transverse emittance (90%) in the x-direction for mismatched-injection is larger than that for matched-injection by 7%; however, those in the y-direction for both simulations are nearly equal. More detailed studies are required in order to examine the reason for the emittance growth in the x-direction and no emittance growth in the y-direction. It can be said, so far, that an emittance growth below 10% is expected in mismatched-injection, arising from a difference in the calculated results between the BTSCF and the LEBT. Therefore, some modifications of the focusing strength are required in order to exactly match the beam of the LEBT code with the DTL acceptance.

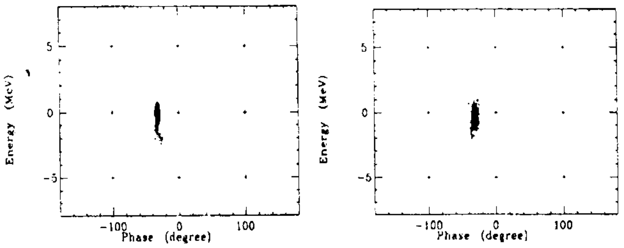

Fig. 3 Calculated output longitudinal emittance for a 20-mA beam after acceleration by the DTL and CCL. The left one is the direct-injection. The right is the LEBT-injection.

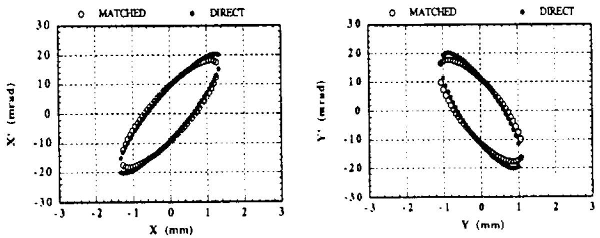

Fig. 4 Comparison of the emittance shapes into the DTL. The black circles indicate the output beam with the LEBT code. The white circles indicate the exactly matched beam with the DTL acceptance.

Table 2 Emittance in the MEBT calculated with the LEBT code .

	ε_x (πcm•mrad)		ε_y (πcm•mrad)		ε_w (πMeV•deg)	
	rms	90%	rms	90%	rms	90%
Entrance	0.0251	0.104	0.0262	0.108	0.060	0.297
Exit	0.0253	0.102	0.0264	0.108	0.073	0.342

Table 3 Comparison of the output emittances (90%) for a 20-mA beam between the simulation with direct-injection and with LEBT-injection. The injection particles were accelerated by the DTL and CCL. The energy spreads (90% full) are also listed.

	ε_x πcm•mrad	ε_y πcm•mrad	ε_w πMeV•deg	Δw MeV
Direct-injection	0.124	0.111	3.72	1.44
LEBT-injection	0.119	0.115	4.92	1.56

Table 4 Comparison of the output emittances between matched-injection and mismatched-injection into the DTL.

	ε_x(πcm•mrad)		ε_y(πcm•mrad)		ε_w(πMeV•deg)	
	rms	90%	rms	90%	rms	90%
Matched	0.0262	0.109	0.0278	0.115	0.159	0.704
Mismatched	0.0287	0.117	0.0272	0.115	0.161	0.714

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