PB03

The Effect of the Aberration on the Emittance Growth Revealed in Design Study of LEBT using Magnetic Lenses for the JHP RFQ

Satoshi Fujimura, Akira Ueno and Yoshishige Yamazaki
National Laboratory for High Energy Physics, KEK
Graduate University for Advanced Studies
1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305, Japan

Abstract

The growth of effective emittances in a low energy beam transport (LEBT) is one of the most important problems to be solved for the high-energy, high-intensity proton linacs, in the high-energy part of which the beam loss should be extremely reduced. Although a variety of LEBTs using electrostatic lenses were examined at Superconducting Super Collider Laboratory, large effective emittance growth due to lens aberrations was observed in almost of them. Therefore, we performed design studies on LEBTs with magnetic lenses in order to inject a proton beam into a 432-MHz radio frequency quadrupole linac developed for the Japanese Hadron Project. The smallest effective emittance growth (no growth in RMS emittance and small growth of less than 15% in 100% emittance) was obtained in the LEBT with two short, strong solenoid magnets (SMs). The LEBT with two triplet quadrupole magnets gave rise to the larger effective emittance growth than that with two SMs, even in the case that the beam optics was simulated in the ideal quadrupole field without higher-order components under the linear space charge force.

Introduction

A 432-MHz, radio-frequency quadrupole (RFQ) linac was developed as a pre-injector for the high-intensity proton linac of the Japanese Hadron Project (JHP) [1]. A variety of low-energy beam transports (LEBTs) for RFQs with resonant frequencies around 400 MHz have been studied extensively at Superconducting Super Collider Laboratory (SSCL) and Los Alamos National Laboratory (LANL) [2,3,4]. LEBTs with electrostatic lenses were studied at SSCL, while those with magnetic lenses at LANL. However, the results of their developments are not satisfactory for our purpose, since the measured "effective emittances" at the exit of their LEBTs were about twice as high as that measured just after the ion sources.

It is perhaps necessary to present the definition of "effective emittance" and the reason why we introduce this. How to eliminate the loss of the high-intensity, high-energy beam is one of the most important issues for the design of the high-energy, high-intensity proton linacs, since the beam loss gives rise to the radioactivity, eventually making the maintenance impossible. From this point of view the mathematically defined emittance or even the root-mean-square (rms) emittance is not an appropriate measure of the beam quality. In order to represent the quality of a LEBT we use the phase-space area surrounding the positions and gradients of all the particles with the designed TWISS parameters of the RFQ linac. We here refer to thus defined emittance as an effective emittance. Of course the parameters of the LEBT are here adjusted to obtain the lowest effective emittance.

Critically inspecting the experimental results at SSCL we concluded that the effective emittance grew in the LEBT with electrostatic lenses mostly through their lens aberrations. Since it is difficult to reduce the aberration of electrostatic lens, we had to give up the use of the electrostatic lenses. On the other hand, although the effective emittance in the LEBT with magnetic lenses at LANL was also increased (the reason is not clear from their papers), there is a hope of the improvement in this case, since one may find the way to improve the aberration of the magnetic lenses, if this is the reason for the emittance growth. At first, of course, we have to find the reason for the emittance growth in the magnetic lenses. For this purpose we performed beam-simulation studies on magnetic-lens LEBTs in the realistic magnetic field calculated by using the computer program POISSON or MAFIA [5,6].

Tabel 1
Design beam parameters in the LEBT

Proton or H^- beam energy	50 keV
Beam intensity	40 mA
Particle distribution in transeverse emittance	KV
4 times of normalized RMS emittance	1.5 π mm•mrad
TWISS parameters at the entrance	$\alpha_{xi}=\alpha_{yi}=0.00$ $\beta_{xi}=\beta_{yi}=0.043$
TWISS parameters at the exit	$\alpha_{xo}=\alpha_{yo}=-1.05$ $\beta_{xo}=\beta_{yo}=0.0473$

Design Beam Parameters and Preliminary Design Study

The design beam parameters at the entrance and exit of the LEBT are respectively listed in Table 1. These parameters were estimated or assumed, based upon the beam-simulation results in the RFQ and the measured beam parameters extracted from a volume production H− ion source at KEK [7]. It is assumed that the particles are distributed with the KV-distribution at the entrance of the LEBT (the particle distribution at the exit of the ion source (IS) is not well-known). It is thus possible to study the effect of the lens aberrations on the emittance growth, separately from the non-linear space charge effect, since the particles with the KV-distribution (uniform distribution in real space) exert only the linear space-charge defocusing force. If the particles are non-uniformly distributed, the stronger focusing force than that for the KV-distribution is required (almost the same focusing force required for a 40 mA beam with the KV-distribution is necessary in order to focus a 20 mA beam with the Gaussian-distribution). Therefore, the design peak beam intensity of the LEBT is chosen to be twice as high as the required value of the JHP linac.

As the first step, three LEBTs were preliminarily designed by using the computer program TRACE [8]. (With TRACE using linear transfer matrices, we cannot obtain any information on the lens aberration.) The design parameters of each magnet are summarized in Table 2. The LEBT is schematically shown in Fig. 1. Two solenoid magnets are used in each of the first two LEBTs, respectively referred to as BT-SM1 and BT-SM2. Two triplet quadrupole magnets (TQMs) are used in the third LEBT, referred to as BT-TQM. The following four technical restrictions were imposed on these designs; (1) a distance of 90 mm between the exit of the ion source (IS) and the first magnet is required for sufficient vacuum pumping speed just after the IS, (2) a distance of 215 mm between the two magnets is necessary for the space of

Table 2
Parameters of magnets determined by using TRACE

	BT-SM1	BT-SM2	BT-TQM
Magnet length L (cm)	10	20	20
Magnet bore radius r_{bor}(cm)	2.5	5.0	2.5
Field strength of 1st magnet	1.02 T	0.533 T	-10.2 T/m 15.9 T/m -10.2 T/m
Field strength of 2nd magnet	1.15 T	0.573 T	10.8 T/m -16.9 T/m 10.8 T/m
Total length (cm)	54	74	74
Max. beam radius r_{bmx} (cm)	1.2	1.7	2.5
ratio of radii r_{bmx}/r_{bor}	0.48	0.34	1.0

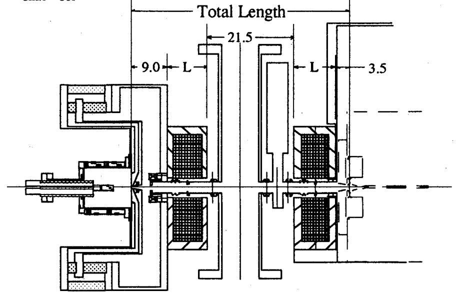

Fig. 1. Schematic view of the LEBT

the gate valve, beam diagnostics and vacuum pumping, (3) a distance of 35 mm between the second magnet and the entrance of the RFQ vane was already occupied by the end plate of the RFQ, (4) the field strength should be smaller than the value obtainable without significant saturation in iron yoke of SM or TQM.

The BT-SM1 was designed in such a way that the maximum beam radius r_{bmx} was minimized by using almost the strongest magnetic field obtainable with normal-conducting solenoid magnet. The BT-SM2 was studied in order to find out the reason for the emittance growth observed at LANL. The total length of BT-SM2 and the dimensions of the SMs in BT-SM2 are similar to those used in the LEBT developed at LANL. As seen from Table 2, the significant differences between BT-SM1 and BT-SM2 are in r_{bmx} (1.2 cm in BT-SM1 and 1.7 cm in BT-SM2) and in the ratio of r_{bmx} with the bore radius r_{bor} (r_{bmx}/r_{bor}=0.48 in BT-SM1 and 0.34 in BT-SM2). In the later section, we will investigate which parameter of r_{bmx} or r_{bmx}/r_{bor} has more effect on the lens aberrations.

In general, quadrupole magnets are considered to have smaller aberrations than SMs. This is the reason for studying the BT-TQM. Since the convergence angle of the beam injected into the RFQ is very large (about 80 mrad), the shorter quadrupole magnets is preferable in order to reduce the beam radius. On the other hand, the thin quadrupole magnet has large higher-order components due to the fringing field. In order to compromise these two conflicting requirements we set the two additional restrictions upon TQM: (1) the minimum pole length of the quadrupole magnet is equal to the bore diameter, (2) the minimum space between the two quadrupole magnets is equal to the bore radius.

Beam Optics Simulation in LEBTs

As described in the previous section, we expected that the lens aberrations play an important role in the growth of the effective emittance. In order to study the effect of the lens aberrations, we have to simulate the trajectories of particles in the realistic field, for example the solenoid magnetic field calculated with POISSON. However, it takes very long time to optimize the LEBT design by using the simulation program such as BEAMPATH [9]. Therefore, we developed the program, referred to as SHU in order to simulate the effect of the lens aberrations more easily. With SHU, we trace the trajectories of particles, the positions of which in the x-x' phase space are shown in Fig. 2 (no emittance in the y-y' phase space : y=y'=0 for every particle), undergoing the realistic magnetic field. In SHU, the particles also undergo the linear space charge force estimated only from the intensity and diameter of the beam (the axially symmetric beam with the uniform particle distribution in the real space is assumed). In order to justify the validity of the calculation using SHU, the simulated results will be compared with those using BEAMPATH.

The emittance profiles calculated with SHU at the exits of BT-SM1, BT-SM2 and BT-TQM are shown in Fig. 3a), 3b) and 3c), respectively. In these figures, the design emittance profiles injected into the RFQ and the areas of the 100% emittances are also shown with dotted lines. The 100% emittance surrounding the simulated emittance profile has the same TWISS parameters as those designed. The magnetic field distributions calculated with POISSON were used in the simulations for BT-SM1 and BT-SM2. Since the current version of BEAMPATH supports the simulation only for the ideal quadrupole field (not for the arbitrary 3-dimensional field), the ideal quadrupole magnetic fields were used in the simulations for BT-TQM in order to make possible the comparison with the BEAMPATH results. The calculated emittance profiles were matched with the design profile by slightly tuning the field strength. The beam envelopes, calculated at the same time with Figs. 3, are shown in Fig. 4. In this figure, we also show the beam envelopes when the beam intensities are 0 mA.

In order to compare the simulation results using SHU with those using BEAMPATH, we performed the simulations in BT-SM1, BT-SM2 and BT-TQM under the same conditions as before. In these simulations, we traced the trajectories of 10000 particles. The simulated emittance profiles at the exits of BT-SM1, BT-SM2 and BT-TQM are shown in Fig. 5a), 5b) and 5c), respectively. In these figures, the design emittance profiles injected into the RFQ and the 100% emittance profiles are also shown with dotted lines. As can be seen from Figs. 3 and Figs. 5, the simulation results using SHU are in good agreement with those using BEAMPATH. In this sense the use of SHU is justified in order to study the lens aberration effects. The calculated RMS and 100% normalized emittances of each LEBT are summarized in Table 3.

The results of the present simulation studies are summarized as follows;

(1) Almost no growth of the effective emittance was observed in

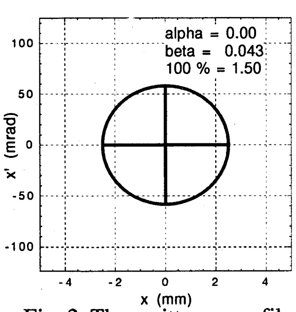

Fig. 2. The emittance profile at the entrance of LEBTs.

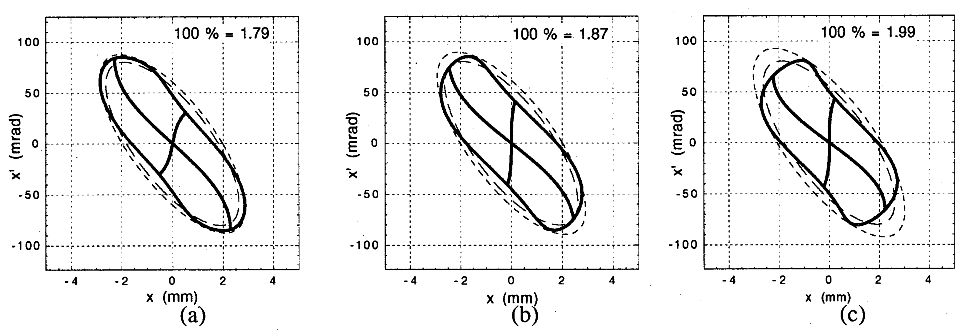

Fig. 3. The emittance profile at the exit of LEBTs estimated with SHU.
(a) BT-SM1, (b) BT-SM2, and (c) BT-TQM, respectively.

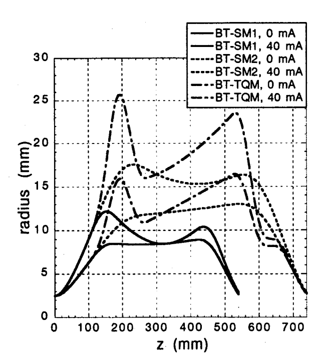

Fig. 4. beam envelopes calculated with SHU.

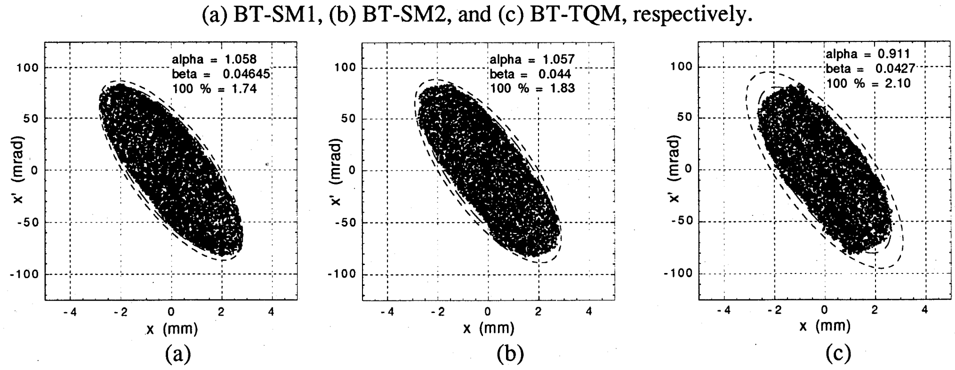

Fig. 5. Simulated emittance profile at the exit of LEBTs with BEAMPATH.
(a) BT-SM1, (b) BT-SM2, and (c) BT-TQM, respectively.

Table 3
Normalized emittances simulated with BEAMPATH.
(π mm•mrad)

	4xRMS	100 %
BT-SM1	1.50	1.74
BT-SM2	1.52	1.83
BT-TQM	1.53	2.10

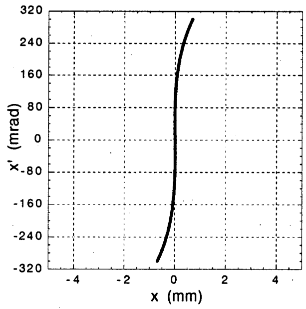

Fig. 6. Calculated emittance profile of the focused particles extracted from a point source with the ideal focusing quadrupole field.

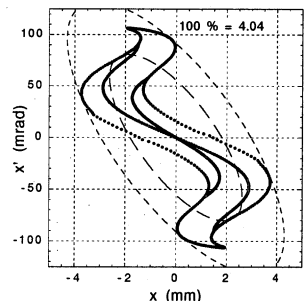

Fig. 7. Calculated emittance profile at the exit of BT-TQM with the practical quadrupole magietic field.

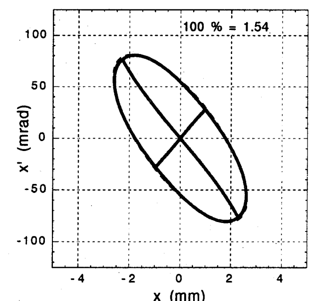

Fig. 8. Calculated emittance profile at the exit of BT-SM1 with the first order magietic field distribution.

any LEBT, when the beam intensity was 0 mA.
(2) It can be seen from Table 3 that the effect of the lens aberration was revealed on the growth of the effective emittance for the 40-mA beam, while almost no effect on the RMS emittance.
(3) The growth in BT-SM1 with two short, strong SMs was the smallest among the three LEBTs.
(4) The largest growth of the effective emittance was observed in BT-TQM in contrast to the naive prediction from its ideal quadrupole magnetic fields.

The sources of these emittance growths are discussed in the next section.

Sources of Aberrations

(1) Source of Aberration in TQM

In order to find the source of the aberration occurring in BT-TQM, we simulated the trajectories of the particles extracted from a point source in the ideal focusing quadrupole field by using SHU. In this simulation, the beam intensity was 0 mA and the particles with initial divergences of up to ±300 mrad were traced. Since the focal length of the quadrupole magnet is 7 cm, the particles were traced until 14 cm, where the particles will be focused again at one point if there is no aberration. The simulated emittance is shown in Fig. 6. It can be seen that the linear oscillation in the ideal quadrupole filed is satisfied only for the particle with initial divergence angle of within around ±120 mrad. In the BT-TQM, the simulated maximum value of the divergence angles for the beam intensities of 0 mA and 40 mA are 140 mrad and 270 mrad, respectively. The latter value is significantly higher than 120 mrad. This is the reason for the remarkable filamentation in the simulated emittance at the exit of BT-TQM.

In order to study the effect of the fringing field in BT-TQM we used the SHU together with the realistic quadrupole magnetic field calculated with MAFIA. The simulated emittance at the exit is shown in Fig. 7. The extremely large filamentation was generated due to the fringing field. The filamentation shown in this figure is very similar to that observed in the LEBT with several electrostatic quadrupoles developed at SSCL. It is thus concluded that any short quadrupole lens has large aberration due to the fringing field, when it is necessary to inject the beam with large convergence angle into the RFQ with a resonant frequency of around 400 MHz.

(2) Source of Aberration in SM

If the divergence angle of the particles exceeded ±120 mrad, the aberration described above should also occur in the SM. Fortunately, this is not the case for SM, since there is no defocusing force in the field of SM and the divergence angle is not so enlarged as above.

In order to reveal the source of the aberration observed in BT-SM1, we simulated the beam optics in BT-SM1 with the first-order magnetic field distribution (Br=-r/2*(dBz/dz)) by using SHU. The simulated emittance at the exit is shown in Fig. 8. Almost no filamentation can be seen in this emittance profile. Therefore, the effect of the aberration seen in Fig. 3a) and 5a) arises from the higher-order components of the field which are generated by the edge of the iron yoke and the fringing field. It is noted that this kind of geometrical aberrations in BT-SM1 is significantly smaller than that due to the fringing field in the realistic TQMs. The aberration in BT-SM2 also arises from the higher-order components of the field. It is seen that filamentation is magnified in proportion to the beam radius. This is the reason why the aberration of BT-SM2 becomes larger than that of BT-SM1. On the other hand, the difference of the ratio r_{bmx}/r_{bor} in BT-SM1 and BT-SM2 has not so large effect on the aberration. (The simulated emittance growth in BT-SM2 is smaller than that measured at LANL, perhaps due to the lower beam energy (35 kev) in the LEBT at LANL.)

Conclusion

Three types of LEBTs with magnetic lenses were investigated. In BT-SM1 with two short, strong solenoid magnets, the smallest effective emittance growth was obtained (no growth in RMS emittance and a small growth of less than 15% in 100% emittance). We will construct BT-SM1 in near future for this reason. BT-SM1 is suitable for precise experiment on the non-linear space charge effect, since there is only small emittance growth when the linear space charge force is assumed.

Two important mechanisms of the emittance growth in the quadrupole magnets were also comprehended. One is the aberration due to particles with large divergence angles of more than ±120 mrad. The other is large aberration due to the fringing field of a thin quadrupole magnet. We should also pay attention to these aberrations in the medium energy beam transport (MEBT) located just after the RFQ, since a number of thin quadrupole magnets are used there.

Acknowledgment

The authors wish to express their sincere thanks to Dr. Y. Batygin (Institute of Physical and Chemical Research in RIKEN) for his offer of the computer program BEAMPATH and several useful advices. They also appreciate Mr. K. Yoshino for his help in calculation of the 3-dimensional magnetic field in the triplet quadrupole magnet.

References

[1] A.Ueno et. al.,Proc. 1994 International Linac Conf., Vol. 1, (1994) 166.
[2] K.F.Johnson et. al., Proc. Lin. Accel. Conf, **AECL-10728**, Vol. 1, (1992) 64.
[3] F.W.Guy et. al., Proc. 1993 IEEE Part. Accel. Conf., **93CH3279-7**, Vol. 4, (1993) 3130.
[4] S.K. Guharay et. al, Nucl. Inst. and Meth. in Phys. Rev., A339 (1994) 429.
[5] User's Guide for POISSON/SUPERFISH group of codes, LA-UR-87-115, LANL (1987)
[6] MAFIA, The Universal Software-System for Electromagnetic CAD.
[7] Y. Mori, T. Okuyama, A. Takagi and D. Yuan, Nucl. Inst. and Meth. A301 (1991) 1.
[8] K.R.Crandall, TRACE 3D documentation, LA-11054 MS.
[9] Y. Batygin, "BEAMPATH: A Program Library for Beam Dynamics Simulation in Linear Accelerators", Proc. EPAC 92, Berlin, Vol. 1, (1992) 822.