

BEAM DYNAMICS DESIGN OF 3 MEV MEDIUM ENERGY BEAM TRANSPORT FOR BEAM INTENSITY UPGRADE OF J-PARC LINAC

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Abstract

The J-PARC linac will extend its beam intensity in year 2014 by the introduction of a 50 mA sustainable front-end part; a 50 keV negative hydrogen (H^-) ion source (IS) and a 3 MeV radio frequency quadrupole (RFQ). Since the replacement will make the variation of the RFQ extraction beam profile, we design the lattice of the medium energy beam transport line (MEBT) which locates behind the front-end part. For the high intensity accelerator facility like J-PARC, a space-charge induced emittance growth is severe especially for low energy region. In order to take the emittance growth into the lattice design, we developed new design scheme with a 3D particle-in-cell simulator. From the obtained lattice, we study the feasibility of the elements in MEBT. In this paper, we introduce the design procedure and the design of the MEBT lattice.

INTRODUCTION

J-PARC is a high intensity proton accelerator facility designed for a MW-class beam. The accelerator complex is currently comprising a 181 MeV linac, a 3 GeV Rapid Cycling Synchrotron (RCS) and a 30 GeV Main Ring (MR). In the injector linac, a 50 keV H^- beam is extracted from an IS, then it is accelerated by a 3 MeV RFQ, a 50 MeV DTL, and a 181 MeV Separate-type DTL (SDTL) [1]. All cavities are operated at the frequency of 324 MHz. We adopt the equipartition condition for DTL and SDTL. Since all quadrupole magnets are electromagnets, we can flexibly control their field gradient. The peak current and design beam power of the linac is 30 mA and 36 kW at present. This power will be extended to 133 kW in order to achieve the design beam power of 1 MW at the RCS extraction. As a part of the power extension, we will replace the front-end part (IS and RFQ) to handle a 50 mA beam in the next year. This replacement causes the variation of the RFQ extraction beam profile, and it requires us to design the MEBT lattice for the 50 mA operation.

The present lattice is determined with an envelope calculation. For the high intensity accelerator, the space-charge induced emittance growth is significantly large especially in low energy region like MEBT. Actually, the emittance growth of MEBT is estimated by a 3D particle-in-cell simulation, and growth rate is about 20 % in the present 30 mA lattice. However, the envelop calculation does not take this emittance growth into account, and it causes the mismatch of the DTL injection beam. It motivated us to conduct the

transverse and longitudinal matching of MEBT with a 3D particle-in-cell simulation.

OUTLINE OF MEBT

The MEBT is about 3 meter long transport line connecting RFQ and DTL. MEBT has two major functions. One is the transverse and longitudinal beam matching between RFQ and DTL. Eight quadrupole magnets and two 324 MHz buncher cavities are placed in MEBT for the matching with various beam diagnoses as shown in Fig. 1. The other issue is a shaping of a beam pulse. Because the RF frequency of 3 GeV RCS is 0.938 MHz and it is different from the frequency of the linac, a part of the beam pulse stays out of the RCS RF buckets. This part is finally lost inside RCS, the beam pulse should shape as fit to the bucket to mitigate the beam loss in RCS. This additional pulse structure is formed by the RF chopper system.

The RF chopper system consists of an RF chopper cavity [2] and a scraper which is placed at 0.72 m downstream of the cavity. The chopper cavity deflects the unnecessary beam horizontally by 324 MHz sinusoidal RF wave, then it is absorbed in the scraper. The beam rejection power of the chopper system deteriorate as the longitudinal beam width becomes broad. The new RFQ simulation by LINACSRfqSIM [3, 4] indicates that the longitudinal beam emittance of 50 mA is larger than that of the present RFQ by 20 % [5]. Moreover, we have measured the longitudinal full beam width by this chopper system where we have successfully observed the beam tail in the order of 10^{-7} . The result indicates the existence of the broad beam tail [6].

MEBT MATCHING

In order to determine the MEBT lattice with taking the emittance growth into consideration, we performed the matching with a 3D particle-in-cell code IMPACT [7]. In the simulation, the initial particles are launched at MEBT entrance. We employ 100,000 macro-particles and $32 \times 32 \times 64$ meshes in the space-charge calculation. In the simulation, we adopt the Lorentz integrator with the step width of around $\beta\lambda/100$. No error is assumed. The initial distribution is obtained from the RFQ simulation by LINACSRfqSIM [5].

Procedure

We have conducted the MEBT matching with the three stages as follows:

1. The first stage is the determination of the field gradients of the quadrupole magnets in DTL. As we men-

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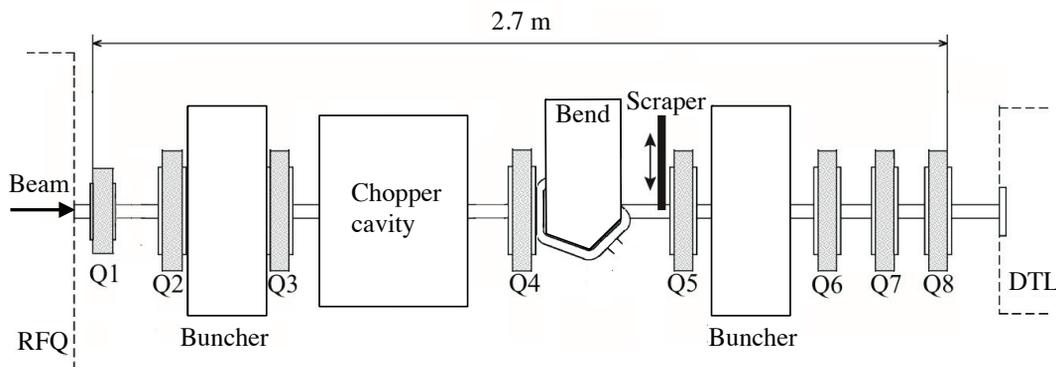


Figure 1: Schematic layout of MEBT. Eight quadrupole magnets are denoted as Q1 to Q8. The RF chopper cavity is placed between Q3 and Q4 and the scraper is just Q5 upstream.

tioned above, we adopt the equipartition condition in this section. Since the effective gap voltage (E_0TL) of all RF gaps in DTL are fixed to design, the field gradients is mathematically determined from the ratio of the transverse and longitudinal emittances. Therefore, we simulate the emittances of the DTL entrance, then calculate the GL products with the equipartition condition.

- The second stage is the optimization of the field gradients of Q1 to Q3 in MEBT. We determine these parameters as the beam transmission of the chopper cavity becomes maximum. The chopper aperture is the narrowest in MEBT and there is no transverse focus element for 0.7 meter around the chopper cavity. Therefore, the injection beam profile to the chopper cavity severely affects the beam transmission.
- The third stage is the optimization of field gradients of Q4 to Q8 and E_0TL s of the two buncher cavities (BNCHs). The mismatch factor [8] at the DTL entrance is the probe of the optimization of these parameters. In the simulation, we obtain the Courant-Snyder parameters in the middle of the 1st and 3rd drift tubes in DTL, and obtain the mismatch factor from the parameters. We perform the calculation of the mismatch factor with thousands of parameter sets, and then the optimization is stopped when the mismatch factor is reached to around 10^{-4} .

The initial parameters, field gradient for eight quadrupole magnets and E_0TL for two BNCHs, are obtained from an envelope calculation. For the optimum parameter search in the second and third stages, we adopt downhill simplex method. After the third stage, we may find emittance at the DTL entrance which is different from that assumed in the first stage. If the difference of the emittances is larger than 1 %, we repeat the whole procedure with the new emittance. We iterate the procedure until the emittance difference converges in 1 %.

Matching results

After the iteration of several times for the procedure in the last subsection, we obtain two parameter sets as listed in Tab.1 and 2. One solution (denoted as “Strong”) is characterized with stronger buncher amplitudes, and the other (“Weak”) with weaker amplitudes.

AREAS TO UPDATE

We are checking the specifications of each components in MEBT whether they sustain an operation after the intensity upgrade. Concerning the quadrupole magnets, we confirm that all field gradients are in the available range and we can handle 50 mA beam without any upgrade. Whereas, it is noticed that we need the upgrade of the bunchers and the RF chopper system.

In the obtained parameter set, the beam transmission of the chopper cavity is maximized by the second stage. Nevertheless, the transmission is about 90 % due to the insuf-

Table 1: The field gradient list of MEBT quadrupoles for 50 mA operation. The unit is Tesla per meter.

(T/m)	Q1	Q2	Q3	Q4	Q5
Strong	-27.81	22.75	-14.20	7.98	-10.33
Weak	-27.08	23.33	-13.66	8.13	-10.08

(T/m)	Q6	Q7	Q8
Strong	15.96	-15.22	4.70
Weak	16.15	-15.70	4.88

Table 2: The E_0TL list of MEBT bunchers for 50 mA operation. The unit is MV. The row “Strong” shows the parameters for strong longitudinal focus and “Weak” is the case of weak focus.

(MV)	BNCH01	BNCH02
Strong	0.206902	0.178443
Weak	0.160624	0.152672

Table 3: The transverse and longitudinal emittances list. The unit of transverse emittance is mm-mrad and longitudinal one is MeV-deg. The row “Entrance” shows the emittances at the MEBT entrance, and “Strong (Weak)” is the emittances at MEBT end with longitudinal strong (weak). The numbers in a parenthesis is the variation of the emittances at the MEBT injection.

	Horizontal (mm-mrad)	Vertical	Longitudinal (MeV-deg)
Entrance	0.22	0.21	0.11
Strong	0.27 (+26%)	0.29 (+33%)	0.11(+6%)
Weak	0.24 (+14%)	0.28 (+29%)	0.11 (-2%)

efficient aperture of the cavity. To achieve the transmission over 99 %, we need a new chopper cavity of which aperture is sufficiently wide. We estimate the necessary aperture size from the simulation. Based on the simulation, we are developing a new chopper cavity at present.

Table 3 shows the longitudinal and transverse emittances of the MEBT entrance and the MEBT exit with “Strong” or “Weak” parameter sets. The numbers in a parenthesis are the growth rate at the MEBT exit. As the growth rate of “Weak” is about two-thirds of “Strong”, we can mitigate the emittance growth if we choose “Weak”. On the other hand, the longitudinal beam width of “Weak” at the chopper center is 12 deg and it is near twice of the width of “Strong” (7 deg) as shown in Fig 2(a) and 2(b). The longitudinal beam width in the present lattice is estimated to be about 6 deg from a simulation, and we observed large tail of which full width is over 100 deg [6]. Assuming the beam tail is spread in proportional to the core part, the beam tail of “Weak” distributes over 200 deg. The RF chopper system is impossible to eliminate the this broad tail in principle. Therefore “Strong” is the only solution. Even if we adopt “Strong”, the chopper electric field of 2.5 MV/m is required to achieve the sufficient beam extinction. Since 2.5 MV/m is over the available range of the current RF source, we consider the upgrade of the RF source.

The “Strong” requires the buncher RF sources to supply the E_0TL of 0.21 MV to BNCH01 and 0.18 MV to BNCH02. However, whereas the maximum E_0TL of present BNCHs is limited to 0.17 MV due to the limitation of the RF power source. Therefore we consider the upgrade of the buncher RF sources.

SUMMARY

Toward to the intensity upgrade of the J-PARC linac, we successfully have conducted the transverse and longitudinal matching of MEBT with 3D particle-in-cell simulation. Based on the obtained lattice, we check the requirements to every elements in MEBT, and find that we need the upgrade of the bunchers and the RF chopper system. We will continue the investigation of MEBT elements.

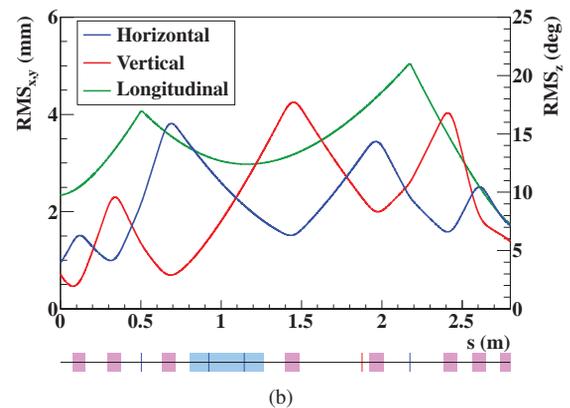
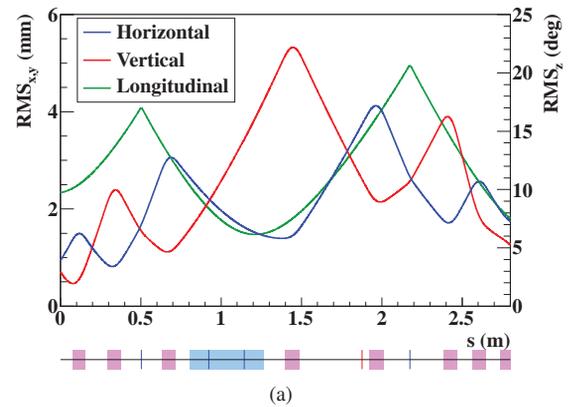


Figure 2: Beam profile along MEBT. The bottom figures of each histogram shows the element positions; pink boxes are the quadrupole magnets, the blue box is the chopper cavity and blue lines around 0.5 and 2.2 m are bunched cavities, respectively. (a) Beam profile of weak longitudinal focus. (b) Beam profile of strong longitudinal focus.

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