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DESIGN OF BEAM FOCUSING SYSTEM WITH PERMANENT MAGNET FOR J-PARC LINAC MEBT1*

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Abstract

MEBT1 (Medium Energy Beam Transport 1) of the J-PARC LINAC is a 3 MeV beam transport system located between the RFQ (Radio Frequency Quadrupole) and DTL (Drift Tube Linac). In the MEBT1, the beam-optical matching for injection into DLT and chopping for injection into acceleration phase of 3 GeV synchrotron, located downstream to the LINAC, are performed. The characteristics of MEBT1 are an important factor in determining the beam quality in the J-PARC accelerator facility. To achieve beam power of 1 MW and beyond, improving the stability and reliability of MEBT1 is an important development issue. The application of permanent magnets to the beam focusing system to the MEBT1 is under consideration to achieve improved stability and reliability. In this presentation, we report the design of focusing magnets using permanent magnet material and the results of the lattice study of MEBT1 with permanent magnets.

INTRODUCTION

J-PARC (Japan Proton Accelerator Research Complex) is an experimental facility with a nominal proton beam output power of 1 MW [1,2]. The J-PARC accelerator has been gradually increasing its beam power since it started operation in 2006. As of 2022, steady operation is being conducted with a beam output power of 850 kW, and continuous operation with 1 MW is planned in a few years.

J-PARC LINAC is a 400 MeV negative hydrogen beam injector of the J-PARC accelerator facility [3]. For the J-PARC LINAC to achieve output power of 1 MW, the one of the important issues is to reduce the degradation of beam quality due to the space charge effect. Since the beam degradations such as emittance growth and formation of beam fragmentation cause beam loss and radioactivation of accelerator components. In the future, it is also planned to enhance the accelerated beam current of the LINAC from current nominal value of 50 mA to 60 mA. For the stable long-term operation with higher beam power, it is necessary to understand emittance growth mechanism and to reduce beam loss.

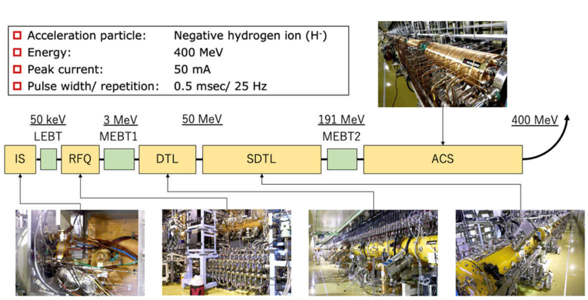

Figure 1: Configuration of J-PARC LINAC.

J-PARC LINAC MEBT1

The space charge effect is especially severe in the low energy part of the LINAC. MEBT1 (Medium Energy Beam Transport 1) is a beam transport section, where 3-MeV negative hydrogen beam is transported between RFQ (Radio Frequency Quadrupole) and DTL (Drift Tube Linac) (see Fig. 1). The MEBT1 consists of eight focusing magnets used for transverse matching of the beam for injection into the DTL, and two buncher cavities and two chopper cavities used for longitudinal matching for injection acceptance of the DTL and acceleration RF phase of the RCS (Rapid Cycling Synchrotron) at a later stage of the LINAC. The configurations of the devices are shown in Fig. 2.

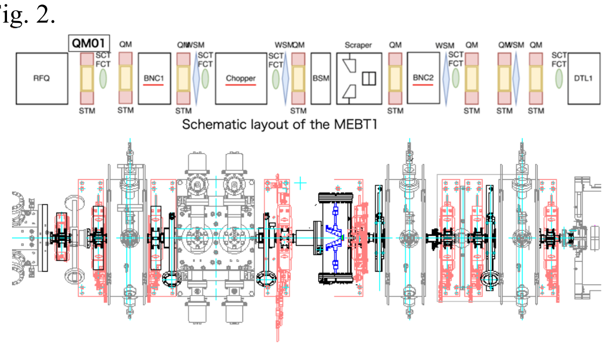

Figure 2: Layout of MEBT1.

Emittance Growth Mitigation with Octupole Focusing Field

In the current MEBT1, the formation of the beam fragmentation and beam emittance growth occurs due to the space charge effect [4]. From theoretical consideration, it is estimated that the emittance of MEBT1 is increased because the phase advance is lowered due to the space charge effect at the point where the transverse width of the beam is large [5].

To mitigate the emittance growth in MEBT1, a compensation technique which apply higher order focusing field is proposed [5]. Since the repulsive force due to the space charge effect has a higher-order nonlinear component, the emittance growth can be reduced by externally applying a focusing force to cancel the component. From the symmetry of the beam distribution, the divergence force due to space charge has an odd-order component, and the most influential component of the nonlinear term is the lowest third-order term. The octupole magnetic field component has a third-order focusing force. Therefore, externally applied octupole magnetic field can cancel the space charge effect. To verify the effectiveness of this method, we are investigating combined function magnet to apply external high-order magnetic field.

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COMBINED FUNCTION MAGNET WITH PERMANENT MAGNET FOR MEBT1

To achieve the compensation of emittance growth due to space charge effect, we have designed and fabricated combined function focusing magnet which can produce quadrupole magnetic field and octupole field components. The magnetic circuit design of the prototype magnets is shown in Fig. 3. In this design, permanent magnets are used to generate magnetic field. Detailed design is described in the Ref. [6]. The longitudinal magnet length is set as 50 mm and the beam bore diameter is 42 mm. In this magnet, quadrupole field component is produced by outer magnet group (blue trapezoidal magnets) configuring Halbach-type [7,8] quadrupole. Octupole field is produced by inner cylindrical magnets (shown yellow in the figure). The produced magnetic fields by each magnet group are shown in the Fig. 4. As the assembled magnetic circuit, these magnets can produce 30 T/m quadrupole and octupole magnetic field with its strength of 0 to 17,000 T/m^3, simultaneously.

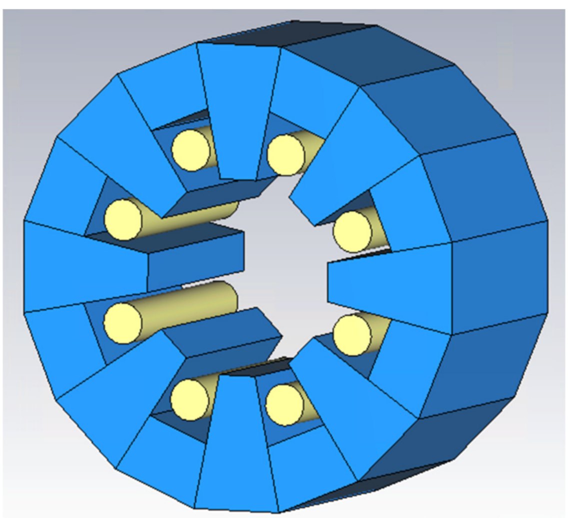

Figure 3: Designed configuration of permanent magnets for combined function focusing magnet.

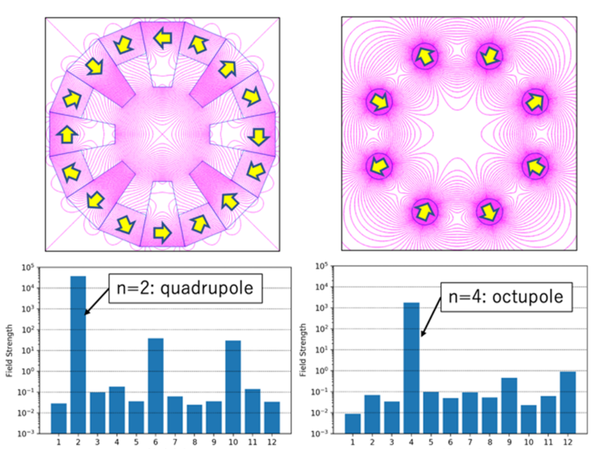

Figure 4: Produced quadrupole and octupole field in the prototype combined function magnet. The field was calculated with PANDIRA in Poisson/Superfish [9].

Based on the magnetic circuit design shown in Figs. 3 and 4, a prototype combined function magnet model was fabricated (Fig. 5). In this model, SmCo magnets were used to configure magnetic circuits. As the prototype, octupole modulation function is equipped manual mechanism to confirm how the rotating angle error affect the magnetic field quality. After the confirmation the required resolution of the rotating angle of the magnets to achieve sufficient field quality, automatic modulation mechanism with motors and gears will be installed. A preliminary measurement of the generated magnetic field in the beam bore of the prototype was performed. The magnetic field was measured with a high precision hole probe. The results are shown in Fig. 6. By adjusting the angles of the cylindrical magnets, octupole field strength can be successfully modulated. In order to install this magnet to the MEBT1 beam line, more precise evaluation on generated higher-order components not only the octupole field but also other parasitic component is required. We are planning measurements with harmonic coil for higher order analysis.

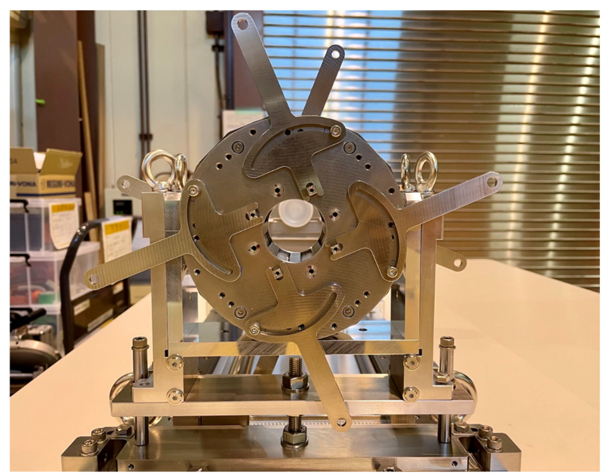

Figure 5: Fabricated prototype of combined function magnet.

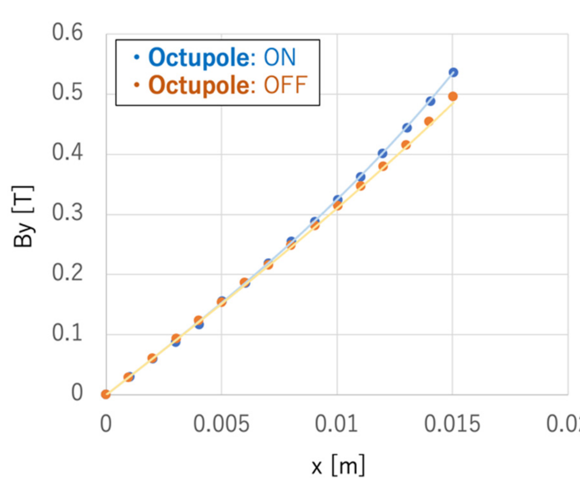

Figure 6: Generate magnetic field is the prototype combined function magnet. Octupole field component strength

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can be modulated by rotating cylindrical parts of the magnet.

SIMULATION STUDY FOR SPACE CHARGE COMPENSATION

In order to demonstrate the space charge effect compensation with developed combined function magnet, simulation studies were performed. In order to reduce the computational complexity and to clarify the effect of the octupole component, the calculation was carried out in the two-dimensional system of the transverse direction. Lattice structure for the simulation is shown in Fig. 7. Since the effect of acceleration is not included in the simulation, the focusing system of RFQ and DTL is modeled by installing FODO lattice with equal spacing. The lattice of current MEBT1 was arranged between the lattice of RFQ and DTL. Since the newly manufactured RFQ for J-PARC [10] is about 50 cm shorter than the current one, a new focusing system can be added to the space. As a new additional focusing system, the focusing magnet described in the previous chapter is placed. The WARP [11] code was used for the beam simulation. The magnitude of vertical emittance growth through transport in the lattice was used to evaluate the simulation results. The incident emittance at the injection point was set to 1.039 mm mrad, which is close to the current value of MEBT 1.

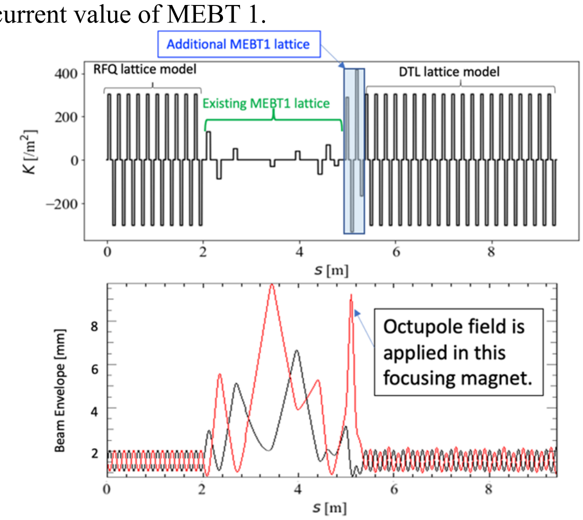

Figure 7: Simulation model of simplified 2D lattice structure.

Figure 8 shows the simulation results. When the octupole component is not applied (for 0 T/m^3 case), the emittance increases to 1.056 mm mrad and beam fragmentation was formed. When the applied amount of the octupole component is increased, the emittance increase is minimized (1.042 mm mrad) at 5000 T/m^3 octupole strength. The phase space distribution of the beam shows that the beam fragmentation is suppressed. Increasing the octupole strength further increases the emittance growth again. From the phase space distribution in the case of 9000 T/m^3, it can be seen that the direction of the arm of the beam fragmentation is reversed, and a focusing force seems to overcome the space charge effect.

In the future, the availability of the combined function magnet will be verified by more detailed simulations including three-dimensional calculations.

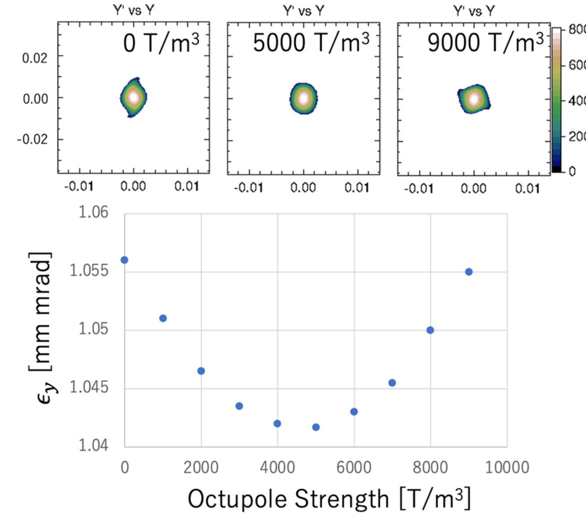

Figure 8: Results of the simulation. Upper figures show phase space distribution in vertical (y) axis of the extracted position. Lower figure shows the effect of octupole field strength on

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