Measurement of the Paint Magnets for the Beam Painting Injection System in the J-PARC 3-GeV RCS

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***Abstract*—The beam painting injection system of the 3-GeV RCS in J-PARC, which realizes the uniform beam distributions in the ring, consists of four horizontal paint bump magnets and two vertical paint magnets. The power supply of the paint bump magnet is required to excite the current with high accuracy that varies from 17.6 kA to zero during 0.5 ms. The IGBT chopper units, a switching frequency of which is 50 kHz each, are multiply-connected to achieve the effective carrier frequency of 600 kHz. Accordingly, the output accuracy of the exciting current has been achieved to be less than 1.0%. The measurements of the magnetic field with the actual current waveform were performed and the good performance was confirmed.**

***Index Terms*—IGBT, measurement of the magnetic field and exciting current, paint bump, 3-GeV RCS in J-PARC.**

I. Introduction

J-PARC (Japan Proton Accelerator Research Complex) accelerator consist of three accelerators, a linear accelerator (Linac), a rapid cycling synchrotron (3-GeV RCS) and a main ring (50-GeV MR). The beam injection system of the 3-GeV RCS is composed of four shift bump magnets (BUHS), four horizontal paint bump magnets (BUHP) and two vertical paint magnets (BUVP) [1]–[3].

The horizontal paint bump magnet shifts the circulating beam horizontally according to the current waveform during the painting injection time at 0.5 ms. Two horizontal paint bump magnets (BUHP01 and 02) are arranged in the upstream of the QFL magnet and other two horizontal paint magnets (BUHP03 and 04) are arranged in the downstream of the QDL magnet. The vertical paint magnet varies the injection beam angle at the charge exchange foil (FOIL01). Two vertical paint magnets (BUVP01 and 02) are arranged in the transport line from the LINAC at a betatron phase of π upstream of the foil. The arrangement of the BUHP01-04 and the BUVP01 and 02 is shown in Fig. 1.

For the modeling of the beam painting injection system with good accuracy, the accurate data of the magnetic field is required. Moreover, in order to produce the high intensity beam without distortion and beam loss, the exciting current of the power supply is required to perform the high speed controllable and the flexible current pattern with less than 1.0% accuracy.

The magnetic field of the horizontal paint bump magnet and the vertical paint magnet was measured. Furthermore, the measurement of the power supply that has the IGBT (Insulated Gate Bipolar Transistor) chopper units with 600 kHz switching frequency was performed.

II. Design of the Magnets

A. Horizontal Paint Bump Magnet

The core size of the horizontal paint bump magnet is the same for all. The length of the iron core is 400 mm and the lamination sheet is 0.1 mm thickness [4]. The coil is two turns and it is water-cooled. But the coil shape of each magnet is different because of the spatial condition. The maximum magnetic field is 0.16 T with 17.6 kA exciting current.

The BUHP01 and 04 have the same shape of the coil that is spread horizontally (TYPE-1), and the BUHP02 and 03 have no horizontal spread (TYPE-2). The uniform field region with less than $\pm 1.0\%$ inhomogeneity is required for each type magnet; the TYPE-1 is 209 mm in width and the TYPE-2 is 227 mm in width. These field regions satisfy the acceptance of the painting injection with the 486 $\pi\ \mathrm{mm}-\mathrm{mrad}$ beam [1]. The schematic view of the TYPE-1 and the TYPE-2 is shown in Figs. 2 and 3, respectively.

B. Vertical Paint Magnet

The lamination sheet of the BUVP is the same thickness and material as the BUHP. The coil is two turns, but it is no water-cooled. The maximum magnetic field is 0.053 T with 2.1 kA exciting current. The schematic view of the BUVP is shown in Fig. 4.

It is required that the uniform field region with less than $\pm 1.0\%$ inhomogeneity is 91 mm in width. This area satisfies the acceptance of 30 $\pi\ \mathrm{mm}-\mathrm{mrad}$ beam [1].

III. Design of the Power Supply

A. Basic Composition

The paint bump power supply is composed of the indirect conversion device by a rectifier and a chopper that used the IGBT units to exciting the current in arbitrary waveforms. Fig. 5 shows the schematic view of the basic composition of the power supply circuit and the block diagram of the control.

In order to realize the high-speed and the highly precise control in the nonlinear area, the repeated control has been implemented by the feed forward control with the ACR (Automatic Current Regulation control), the m-AVR (minor loop Automatic Voltage Regulation control) and the PWM (Pulse Width Modulation control).

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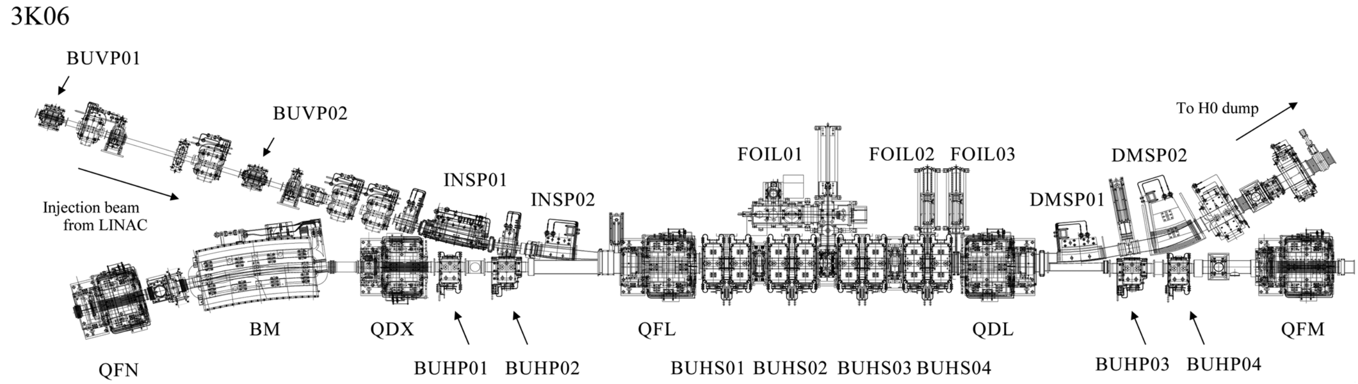

Fig. 1. Schematic view of the injection area. Four horizontal paint bump magnets (BUHP01-04) and two vertical paint magnets (BUVP01 and 02) are arranged in the injection area of the 3-GeV RCS.

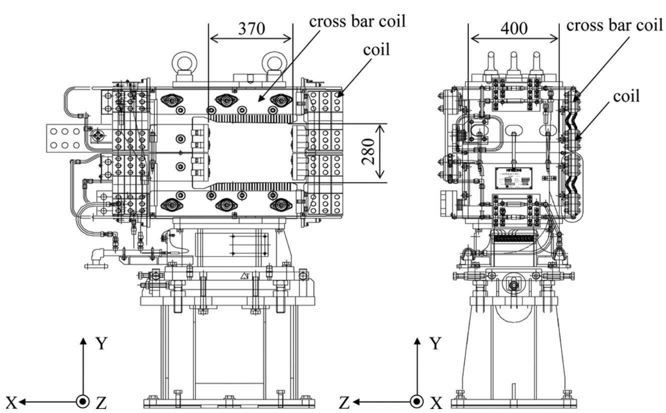

Fig. 2. Schematic view of the TYPE-1 (BUHP01 and 04).

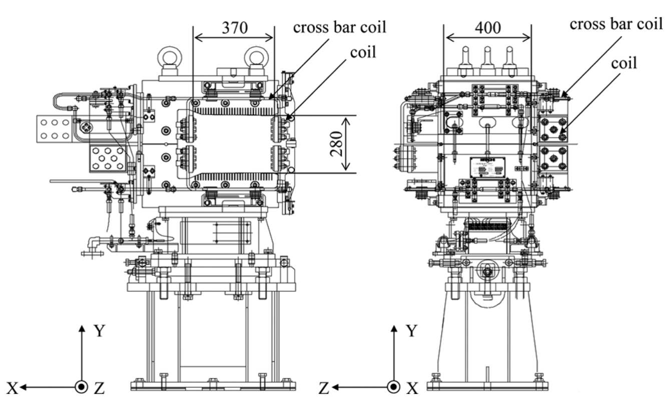

Fig. 3. Schematic view of the TYPE-2 (BUHP02 and 03).

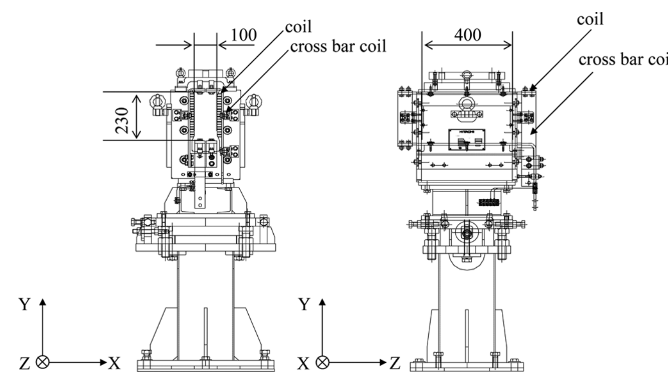

Fig. 4. Schematic view of the BUVP01 and 02.

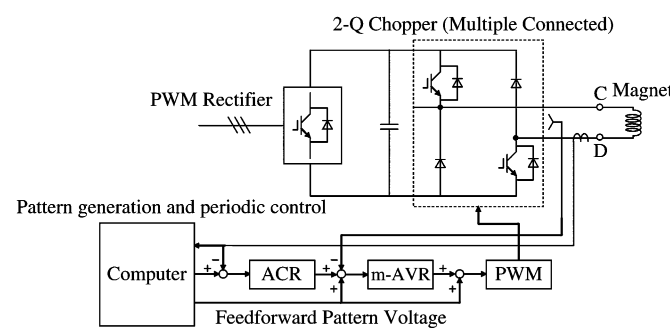

Fig. 5. Schematic view of the basic composition of the power supply circuit and the block diagram of the control.

B. Parameter of the Power Supply

The circuit of the IGBT chopper units is two quadrants and each assembly is consisted of 5 parallels with the 1200 V-300 A IGBT. The whole of the circuits, each assembly of a plus current terminal C and a minus current terminal D is composed of 18 parallels, respectably. A signal carrier of the pulse width control is assumed as the same every 3 parallels, and so that is considered as 6 multiples. The phase of the signal carrier is shifted on the plus current terminal C and the minus current terminal D and so that becomes 12 multiples as a whole.

An elementary frequency of the IGBT switching is 50 kHz and the composition frequency becomes 600 kHz. The paint bump power supply with the IGBT chopper units has the capacity to perform the current pattern with highly speeds and flexibility less than 1.0% tracking error for 1.0 μs pulse current.

Furthermore, the IGBT chopper units have four quadrants composition because of the performance for the current reversal. However, the four quadrants chopper will decrease the output voltage because of the dead time with changing over the control. Therefore, the operation of the power supply is performed with two quadrants chopper units by switching the chopper units each of the positive current side and the negative current side, respectively.

IV. Experimental Results of the Magnetic Field

A. Horizontal Paint Bump Magnet of the TYPE-1

The design of the iron core and the coil has been computed by TOSCA [4]. In each coil type, to achieve a good magnetic

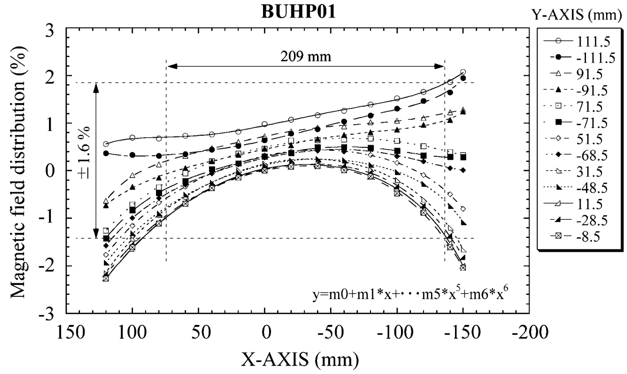

Fig. 6. Measurement result of the integrated magnetic field distribution of the BUHP01. $-135\ \mathrm{mm} < \mathrm{x} < 74\ \mathrm{mm}$ is requirement area.

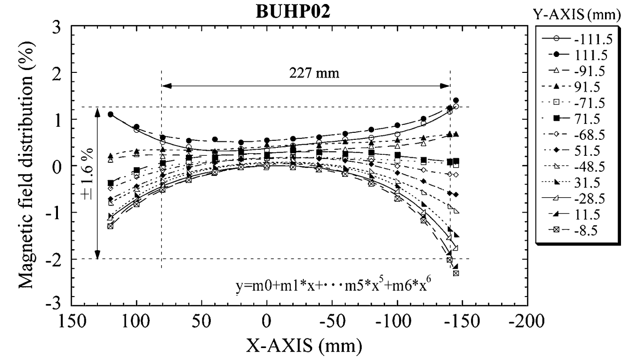

Fig. 8. Measurement result of the integrated magnetic field distribution of the BUHP02. $-139\ \mathrm{mm} < \mathrm{x} < 88\ \mathrm{mm}$ is requirement area.

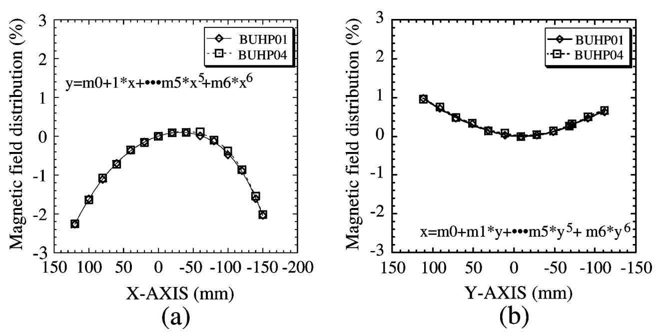

Fig. 7. Difference of the integrated magnetic field distributions of each TYPE-1. (a) Distribution of x-axis and $\mathrm{y} = 0$. (b) Distribution of y-axis and $\mathrm{x} = 0$.

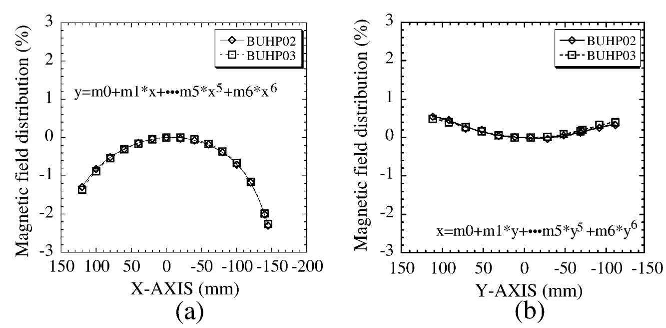

Fig. 9. Difference of the integrated magnetic field distributions of each TYPE-2. (a) Distribution of x-axis and $\mathrm{y} = 0$. (b) Distribution of y-axis and $\mathrm{x} = 0$.

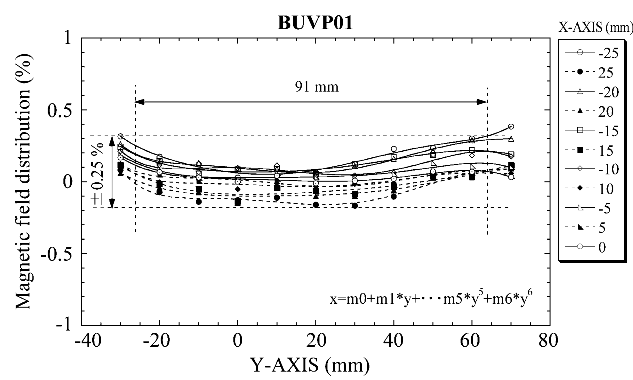

Fig. 10. Measurement result of the integrated magnetic field distribution of the BUVP01. $-26.5\ \mathrm{mm} < \mathrm{y} < 64.5\ \mathrm{mm}$ is requirement area.

field region, the shape and the position of the cross bar coil have been changed [2]. The relative magnetic field of the TYPE-1 was measured using the long search coil. The long search coil that is three turns with an enameled wire of 0.1 mm is 6 mm in width and 2500 mm in length. The measurement result of the integrated magnetic field distribution of the BUHP01 is shown in Fig. 6. The distribution is based on the center of the gap, and the ratio is computed with $(BL_x - BL_0)/BL_0 * 100$. BL_x is the integrated magnetic field at each measurement position (x-axis), and BL_0 is the integrated magnetic field based on the center of the gap ($\mathrm{x} = 0$, $\mathrm{y} = 0$).

As a result, the uniform field region with less than $\pm 1.6\%$ inhomogeneity was 209 mm in width. This result satisfies the acceptance of the requirement for the $216\pi\ \mathrm{mm} - \mathrm{mrad}$ beam.

The difference of the integrated magnetic field distribution of each TYPE-1 magnet is compared, as shown in Fig. 7. The good agreement was obtained within a range of 0.05%.

B. *Horizontal Paint Bump Magnet of the TYPE-2*

The method of designing the TYPE-2 magnet is the same as the TYPE-1. The integrated magnetic field distribution of the BUHP02 was measured, and the result is shown in Fig. 8. The distribution of the ratio is the same expression as the TYPE-1. The uniformed field region with less than $\pm 1.6\%$ inhomogeneity was 227 mm in width. This result satisfies the acceptance of the requirement for the $216\ \pi\ \mathrm{mm} - \mathrm{mrad}$ beam.

The difference of the integrated magnetic field distribution in each TYPE-2 is compared, as shown in Fig. 9. The good agreement was obtained within a range of 0.05%.

C. *Vertical Paint Magnet*

The vertical paint magnet has been designed at the same as the method of the BUHP. The magnetic field of the vertical paint magnet was measured using the short search coil. The short search coil that is ten turns with an enameled wire of 0.1 mm is 6 mm diameter. The integrated magnetic field from the mapping data is shown in Fig. 10. The computation of the ratio is the same expression as the BUHP. The uniform field with less than $\pm 0.25\%$ inhomogeneity is 91 mm in width. This result satisfies the injection beam acceptance of the $30\ \pi\ \mathrm{mm} - \mathrm{mrad}$ beam.

The difference of the integrated magnetic field distribution of each BUVP is compared, as shown in Fig. 11. The good agreement was obtained within a range of 0.05%.

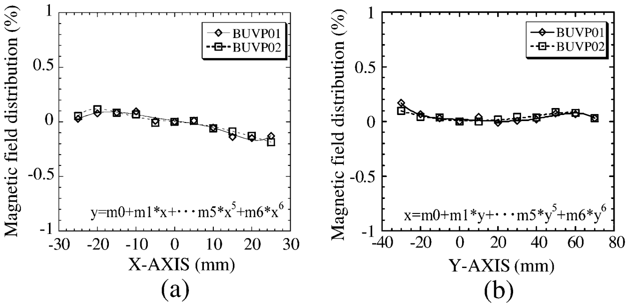

Fig. 11. Difference of the integrated magnetic field distributions of each BUVP: (a) Distribution of x-axis and $y = 0$. (b) Distribution of y-axis and $x = 0$.

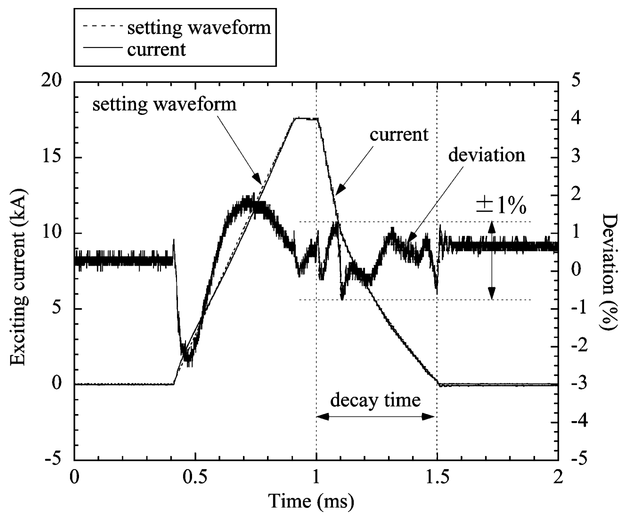

Fig. 12. Exciting current waveform of the BUHP01.

V. Experimental Results of the Power Supply

A. Horizontal Paint Bump Waveform

The exciting current waveform of the BUHP01 was measured by PEARSON CT (model 1423), as shown in Fig. 12. The deviation of the current from programmed value has been confirmed less than $\pm 1.0\%$ during 0.1 ms flattop and 0.5 ms decay area. Furthermore, the various current patterns of the flexible waveform have been performed. Fig. 13 shows another painting waveform of the BUHP01. After painting at the decay time 0.5 ms, the exciting current was reversed. This reversed current waveform assists the avoidance of the hit on the foil with circulating beam when the decay time of the shift bump power supply is to be long and the foil temperature exceeds 1000 K [1].

B. Vertical Paint Waveform

The beam painting injection system of the 3-GeV RCS in J-PARC is designed to facilitate the painting injection both of the correlated painting and the anti-correlated painting. They have been achieved by changing the excitation pattern of the vertical paint power supply. Fig. 14 shows the correlated painting injection waveform of the BUVP01. The exciting current was measured by PEARSON CT (model 1423). The deviation of the current from the programmed value has been confirmed less than $\pm 1.0\%$ at the rise time 0.5 ms.

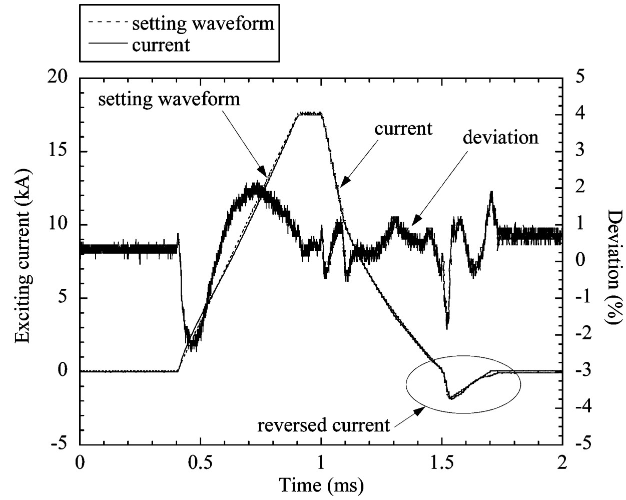

Fig. 13. Painting waveform of the assistance for the shift bump magnet power supply.

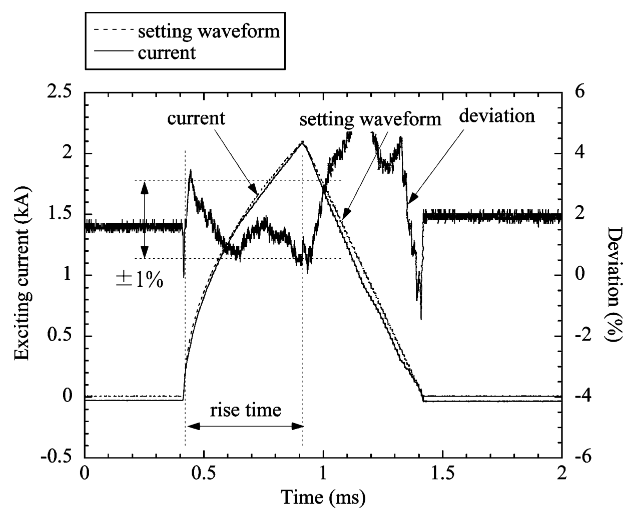

Fig. 14. Exciting current waveform of the BUVP01.

VI. Summary

The distributions of the integrated magnetic field both the horizontal paint bump magnet and the vertical paint magnet were measured. These results show that the required accuracy has been fulfilled. Furthermore, the tracking error less than 1.0% for 1.0 μs pulse current has been satisfied with the multiply connected IGBT chopper units.

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