Design of the Injection Bump System of the 3-GeV RCS in J-PARC

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***Abstract*—The injection bump system of the 3-GeV RCS (Rapid Cycling Synchrotron) in J-PARC (Japan Proton Accelerator Research Complex) consists of the pulse bending magnets for the injection bump orbit, which are four horizontal bending magnets (shift bump), four horizontal painting magnets (h-paint bump) and two vertical painting magnets (v-paint bump). The shift bump magnets, which are connected in series in order to form a closed bump orbit. The injection bump system needs the power supplies with the high speed and flexible current pattern. Furthermore, the tracking error is required less than 1.0% for 1.0 μs pulse current. The power supplies with the IGBT (Insulated Gate Bipolar Transistor) chopper units, which are controlled by the switching frequency over 60 kHz, realize its performance. The decay time of the shift bump power supply is less than 200 microseconds.**

I. Introduction

J-PARC accelerator system consists of three accelerators: a linear accelerator (400-MeV Linac), a rapid cycling synchrotron (3-GeV RCS) [1]–[3] and a 50-GeV synchrotron ring. The incoming beam emittance of the 400-MeV linac is 4 π $\mathrm{mm-mrad}$ and the collimator acceptance in the 3-GeV RCS is 324 π $\mathrm{mm-mrad}$. The 3-GeV RCS is designed to provide beam power of 1 MW for a Material and Life Science Facility (MLF). Furthermore, it is used as a booster synchrotron for the 50-GeV synchrotron ring.

In the first stage, the energy of the injection beam and the extraction beam is 181 MeV and 3 GeV, respectively. And the extraction beam power is 0.6 MW at a repetition rate of 25 Hz. In the second stage, the injection beam energy and the extraction beam power are to be upgraded to 400 MeV and 1 MW, respectively.

The machine acceptance of the injection transport line is designed to be 30 π $\mathrm{mm-mrad}$, and that of 3-GeV RCS is 486 π $\mathrm{mm-mrad}$. It is very important to decrease a beam loss. Therefore, a wide aperture of the magnetic gap and a wide good field region of the magnetic field are required. Furthermore, the low tracking error of each power supply and the accuracy of the current waveform to the programmed pattern are needed.

II. Construction of the Injection Bump System

A. Design of the Injection Bump System

The injection system of the 3-GeV RCS in J-PARC is composed of eight horizontal bump magnets and two vertical painting magnets. The outline of the injection system is shown in Fig. 1. The horizontal bump magnets are divided into two types. One type named "shift bump magnet (BUHS)" produces a fixed main bump orbit to merge the injection beam into the circulating beam in the horizontal plane. They are realized with four magnets connected in series, which are located at the long straight section. The BUHS has a longitudinally split structure to insert a foil for H0 beam stripping (2nd Foil). Another type named "h-paint bump magnet (BUHP)" shifts the circulating beam horizontally for painting. They consist of four magnets, which are divided into two pairs. One pair is arranged upstream of the F quadrupole magnets, and another pair downstream of the D quadrupole magnets. Each magnet is excited individually.

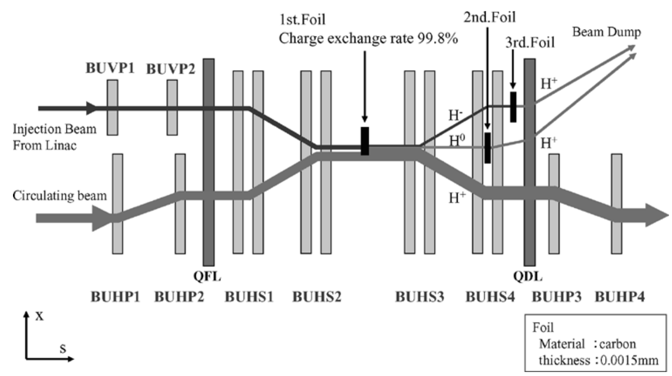

Fig. 1. Outline of the injection system (painting injection).

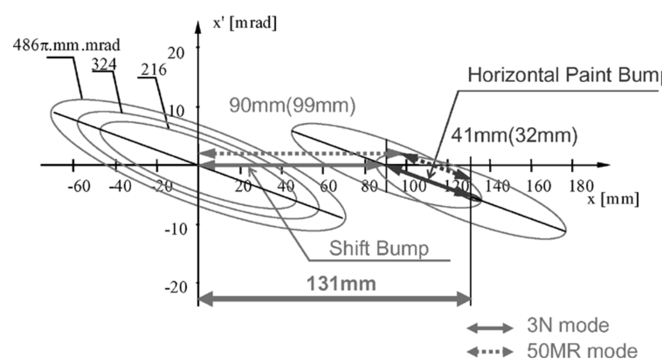

Fig. 2. Horizontal painting injection.

The vertical paint magnets named "v-paint magnet (BUVP)" vary the injection angle at the charge exchange foil (1st Foil). The BUVP1 is placed in the transport line at a betatron phase of π upstream of the foil.

B. Painting Injection

In case of the painting injection, the beam emittance is 216 π $\mathrm{mm-mrad}$ for MLF (3N-mode), and 144 π $\mathrm{mm-mrad}$ for 50-GeV ring injection (50MR-mode). As shown in Fig. 2,

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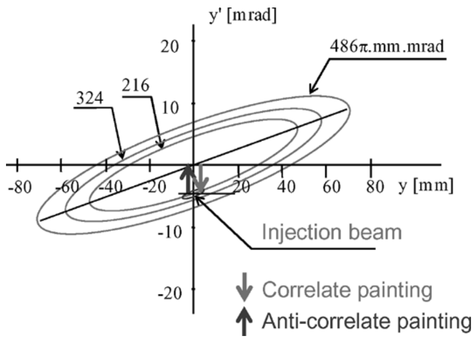

Fig. 3. Correlated and anti-correlated painting injections.

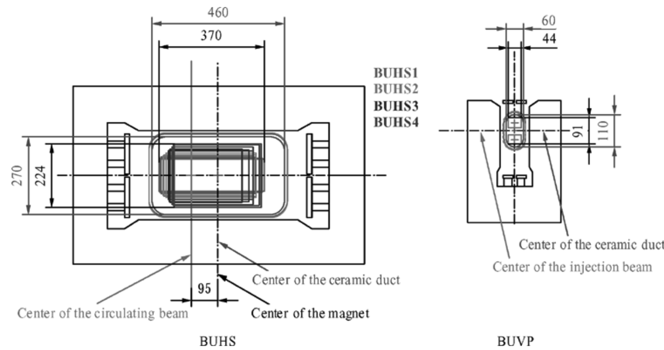

Fig. 4. Beam stays area of the shift bump magnet and the v-paint magnet.

TABLE I
PARAMETERS OF THE INJECTION BUMP MAGNETS

Title.	**BUHS**	**BUHP**	**BUVP**
Number of magnets	4	4	2
Structure	W- frame	C-type	C-type
Core Length [mm]	400 - 400	400	400
Maximum Field [T]	0.2611	0.2603	0.0855
Maximum Current [A]	32200	29000	3400
Turns per Coil	2	2	2
Gap Height [mm]	310	280	100
Coil Inside Distance [mm]	616	370	240
Beam Stay Area [mm] [Horizontal / Vertical]	370 / 224	257 / 250	44 / 91
Lamination thickness [mm]	0.15	0.1	0.1

the horizontal painting area is controlled by the BUHS and the BUHP by changing the excitation level in a pulse-to-pulse mode. Furthermore, RCS injection system is designed to facilitate painting in both correlated and anti-correlated painting injections, as is shown in Fig. 3. They are achieved by changing the excitation pattern of the BUVP. The painting injection by the BUHS, BUHP and BUVP control the uniformity and the shape of the beam profile.

III. DESIGN OF THE INJECTION BUMP MAGNETS

A. Magnet Parameters

The hardware of the injection pulsed magnets is designed to accept the 400 MeV injection beam. The parameters of the three type magnets (BUHS, BUHP and BUVP) are given in Table I. The aperture of the BUHS and the BUHP correspond to the full acceptance.

B. Beam Stay Area and the Ceramic Duct Size

The beam stay areas of the bump magnets are shown in Fig. 4 and Fig. 5. The beam stay area of each magnet includes the circulating and the injection beam for the various injection conditions. The BUHS is moved by 95 mm to accommodate the injection beam as well as the circulating beam with 486

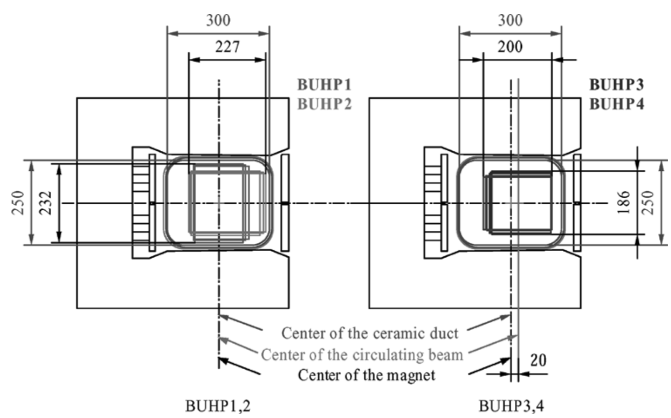

Fig. 5. Beam stays area of the h-paint bump magnets.

π mm−mrad, and the BUHP 3 and 4 are moved by 20 mm to avoid the interference with dump line modules. The beam stay area of the BUHP in the Table I shows the maximum outline of the BUHP from 1 to 4. The biggest inner size of the ceramic duct [4], which is the BUHS, is 460 mm in width and 270 mm in height. As seen in the figure, there is enough space between the beam and the duct allowing a low loss operation. All the injection bump magnets are set out of vacuum and the ceramic ducts are inserted between the gaps.

IV. DESIGN OF THE POWER SUPPLIES

A. Power Supply Parameters

The power supplies of the injection bump system require fast and flexible current patterns. Furthermore, to realize the high power operation with a tracking error less than 1%, the rectifiers and the choppers of the power supplies utilize many IGBT units in series and parallel.

In the first stage, the each power supply is manufactured by the specification of 181 MeV injection beam, and it can be upgraded to 400 MeV injection beam in the second stage. The specifications of the power supplies for 400 MeV operation are listed in Table II. The operation parameters of the beam deflection angle and the exciting current of 181 MeV and 400 MeV injection beam are given in Table III. The total beam displacement by the BUHS and the BUHP is 131 mm. In the case of the 3N-mode, the beam displacements by the BUHS and the BUHP

TABLE II
SPECIFICATION OF THE POWER SUPPLIES FOR 400 MEV OPERATIONS

	Current [kA]	Voltage [kV]	IGBT Rating	Rectifier		Chopper		
				Composition	Total number of arms	Composition	Total number of arms	Resultant switching frequency [kHz]
Shift	32.3	12	3300V 1200A	8 stages, 1 parallel 3 phase rectifiers	48	8 stages, 35 parallels 4-quadrant choppers	1120	64
H-Paint 1	29.0	1.2	1200V 300A	2 stages, 1 parallel 3 phase rectifiers	12	2 stages, 26 parallels 4-quadrant choppers	208	600
H-Paint 2	23.4	1.2	1200V 300A	2 stages, 1 parallel 3 phase rectifiers	12	2 stages, 20 parallels 4-quadrant choppers	160	600
H-Paint 3,4	21.0	1.2	1200V 300A	2 stages, 1 parallel 3 phase rectifiers	12	2 stages, 20 parallels 4-quadrant choppers	160	600
V-Paint 1,2	3.4	0.6	1200V 300A	1 stage, 1 parallel 3 phase rectifier	6	1 stage, 3 parallels 4-quadrant choppers	12	300

TABLE III
OPERATION PARAMETERS

		Beam Deflection Angle [mrad]	Current [A]	
			181MeV	400MeV
3N-mode	Shift	56.0	17580	27480
	H-Paint1	25.1	14230	22250
	H-Paint2	18.5	10490	16400
	H-Paint3	15.6	8850	13830
	H-Paint4	16.8	9530	14900
50MR-mode	Shift	61.4	19270	30130
	H-Paint1	19.6	11110	17380
	H-Paint2	14.5	8220	12860
	H-Paint3	12.3	6970	10910
	H-Paint4	13.2	7480	11700
	V-Paint1	8.0	1620	2530
	V-Paint2	6.0	1220	1900

are 90 mm and 41 mm, respectively. For 50 MR-mode, the displacements are 99 mm and 32 mm, respectively. The 3N-mode and 50 MR-mode can be switched to another in a pulse-to-pulse mode.

B. Decay Time of the Shift Bump Power Supply

The temperature of the 1st foil is dependent on the decay time of the shift bump power supply. The marginal temperature of the carbon foil, the thickness of which is 0.0015 mm and $290 \times 10^{-6}\ \mathrm{g/cm^2}$, is about 1000 K. When it exceeds 1000 K, the form of the carbon foil changes and the efficiency of charge exchange drops down.

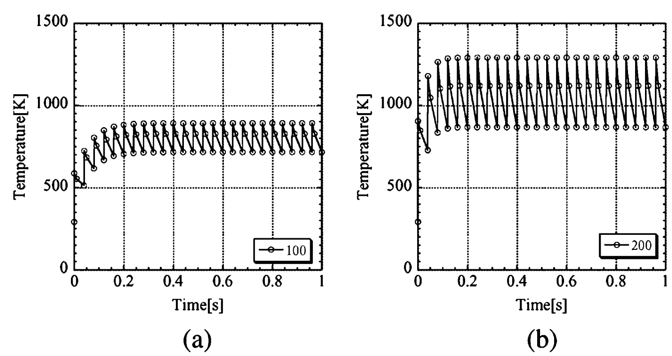

Fig. 6. Carbon foil temperature. (a) 100 microseconds decay time; (b) 200 microseconds decay time.

The simulation results of the carbon foil temperature with 100 microseconds and 200 microseconds decay time are shown in Fig. 6 [5]. The radiation emissivity is assumed to be 0.5 for the 400 MeV injection case. At 25 Hz repetition rate, it is equilibrated in several seconds. In the case of 200 microseconds decay time, the foil temperature is higher than 1000 K. In order to decrease the hit of the circulating beam at the foil, it is necessary to operate the shift bump power supply with decay time less than 200 microseconds.

C. Exciting Current

The current waveforms of each power supply are shown in Fig. 7. The decay time of the shift bump power supply is designed less than 150 microseconds. The formulas of the flexible current waveforms in the figures correspond to the correlated and the anti-correlated painting schemes, the latter of which realizes the uniform beam distribution in the real two dimensional space.

The tracking accuracy between each power supply of the h-paint bump and the v-paint magnet must be less than 1%. Furthermore, it has to make the flexible current waveform

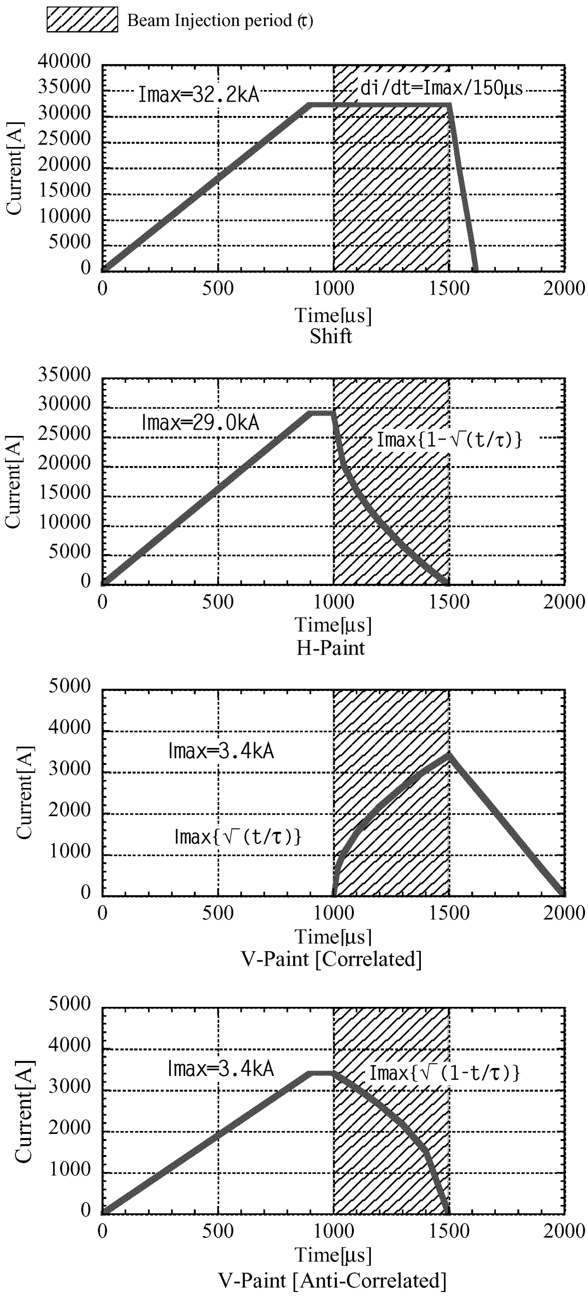

Fig. 7. Current waveforms of each magnet power supply. The formulas of the beam injection period show the required current waveforms for correlated and anti-correlated paintings.

less than 1% accuracy to the programmed pattern. The beam injection period is 500 microseconds.

D. Measurement Results

The measurement results of the exciting current waveforms, which are the shift bump and the h-paint bump, are shown in

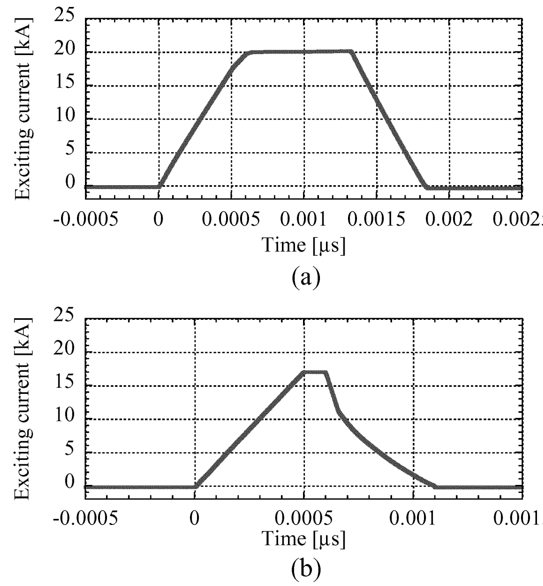

Fig. 8. First measurement results. (a) Shift bump waveform; (b) Paint bump waveform.

Fig. 8, respectively. The current waveform of the BUHS is excited by the power supply of the h-paint bump 1. The excited current is 20 kA that corresponds to 181 MeV beam injection at the beam physics run. The paint bump waveform is excited by using the dummy load which has the same inductance with the BUHP. The exciting current is measured by PEARSON CT (model 1423). The deviations of the current from the programmed value have been confirmed less than 1%. The various outputs of a flexible current pattern will be measured.

V. Summary

The design of the injection beam line has been made so as to have a sufficient acceptance for low-loss beam injection. The painting area is optimized for both the MFL users and the 50-GeV users in a pulse-to-pulse mode operation.

The power supplies are operated by the specification of 181 MeV with the first stage, but they are upgradeable to 400 MeV injection. The high power test of the shift bump magnet has been in progress.

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