# PULSED BENDING MAGNET OF THE J-PARC MR

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## *Abstract*

Japan Proton Accelerator Research Complex (J-PARC) is under construction with a collaboration between Japan Atomic Energy Agency (JAEA) and High Energy Accelerator Research Organization (KEK). The J-PARC consists of a 180 MeV linac, a 3 GeV rapid-cycle synchrotron (RCS) and a 50 GeV synchrotron (MR). The bunch trains, which extracted from the RCS, is delivered both to the “Materials and Life Science Facility” and to the MR, two beam transport lines, 3-NBT and 3-50BT, are constructed. The switching of bunch trains is performed by a pulsed bending magnet. The field strength of 1.21 Tesla with rise and fall time of less than 40 msec is required. It was found that an effect induced by eddy current, which flows at thick end-plates, disturbs the flatness of the magnetic field. A simple compensation circuit has been adopted for a cure. A result from a field measurement, which shows a sufficient flatness, is presented.

## INTRODUCTION

In J-PARC [1], high intensity proton beams from a 3-GeV rapid cycle synchrotron (RCS) will be transported both to the “Materials and Life Science Facility” (MLF) and the main ring (MR). Only 8 bunches out of all will be transported to the MR at a repetition rate of about 0.3 Hz. A pulsed magnet is excited for the MR operation. A field rise/fall time of the pulsed magnet must be less than 40 msec due to a bunch spacing of the RCS beam.

## POWER SUPPLY & PULSED MAGNET

Main parameters of the pulsed magnet and its power supply are listed in Table.1 and 2, respectively. Magnetic core is assembled by the lamination with thickness of 0.5 mm. A power supply for the pulsed bending magnet consists of two types of power module, a GTO switch and an IGBT chopper, combined in series. The GTO switch is used by its higher output voltage, which is suitable for a ramping period to excite a large inductance of the magnet. The IGBT chopper is used to precisely stabilize an output current at flat-top period.

Table 1: Parameters of the pulsed magnet

| | |
|---|---|
| Max. magnetic flux density | 1.21 Tesla |
| Turns/pole | 32 |
| Inductance | 29 mH |
| Max. excitation current | 2180 A |
| Pole length | 1500 mm |
| Gap height | 142 mm |
| Field flatness | $< 5{*}10^{-4}$/650msec |

Table 2: Parameters of the power supply

| | |
|---|---|
| Max. output voltage | 4000 V |
| Max. output power | 8.7 MW |
| Pulse width | 100 to 650 msec |
| Current rise/fall time | 20 msec |
| Repetition rate | 0.3 to 1 Hz |

## FIELD MEASUREMENT

An integrated magnetic field (BL) was measured by a long pick-up coil. Induced voltage at the coil (length: 2.5 m, width: 20 mm, turn number: 20) was digitized by a precision ADC module (16bit, 1MS/s) and then integrated over time. Measured waveform is depicted in Fig.1.

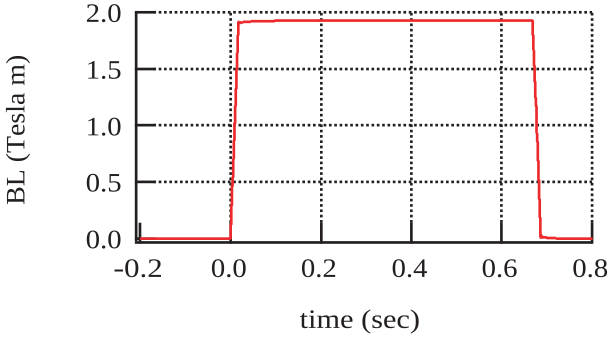

Figure 1: Measured BL waveform. A flat-top length was set to 650 msec for a test purpose.

Although an excitation current has an ideal rectangular shape with rise and fall time of about 20 msec, measured BL waveform has been somehow deteriorated at a flat-top region, as depicted in Fig.3.

A field flatness, which is defined by $\Delta BL \equiv (BL_{max} - BL_{min}) / BL_{max}$, is measured to be about $5{*}10^{-3}$. This is almost ten times larger than the acceptable

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value, which may result in an emittance blow-up of about 100%.

## EQUIVALENT CIRCUIT MODEL

It was found that the pulsed BL waveform is well expressed by a double-exponential equation as,

$$BL(t) = BL_0(1 - \alpha_1 Exp[-\frac{t}{\tau_1}] - \alpha_2 Exp[-\frac{t}{\tau_2}]). \quad .....(1)$$

Re-writing Eq. 1, an effective excitation current, which contributes only to induce dipole magnetic field, is expressed as,

$$I_{effective}(t) = I_0(1 - \frac{L_m}{L_{e1}+L_m} Exp[\frac{R_{e1}}{L_{e1}+L_m}] - \frac{L_m}{L_{e2}+L_m} Exp[\frac{R_{e2}}{L_{e2}+L_m}]) \quad , ......(2)$$

where $L_m$ is a inductance of the magnet, $Le_{1,2}$ and $Re_{1,2}$ are equivalent eddy-current inductance and resistance, respectively. Eq.2 is immediately translated to an equivalent circuit model, which is depicted in Fig.2.

A circuit simulation was performed with parameters summarized in Table.3. Those values are based on fitting results by Eq.1. The result is shown in Fig.3.

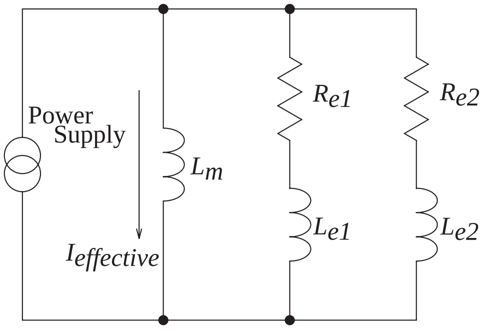

Figure 2: Equivalent circuit model of the pulsed magnet. The eddy current circuit is modelled by two LR circuits, which connected in parallel to the magnet.

Table 3: Lists of fitting parameters of an eddy-current circuit model

| | |
|---|---|
| $L_m$ | 29 mH |
| $R_{e1}$ | 48.176 ohm |
| $R_{e2}$ | 201.335 ohm |
| $L_{e1}$ | 4.9365 H |
| $L_{e2}$ | 3.777 H |

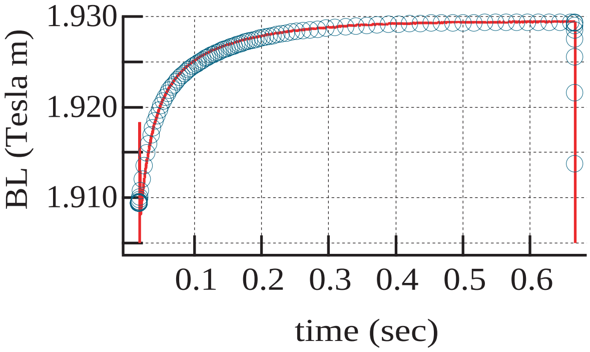

Figure 3: Comparison of the simulated BL waveform (circle) by the eddy-current circuit model with the measured one (solid-line).

The circuit simulation shows a good agreement with the measured BL waveform. The deviation of the simulated waveform from the measured value is less than $2*10^{-4}$.

## EDDY CURRENT COMPENSATOR

In the equivalent circuit, the eddy-current is treated as parallel circuits, which introduce a phase-delay in the magnetic field. Phase-advance circuits are adopted to compensate this effect as shown in Fig.4.

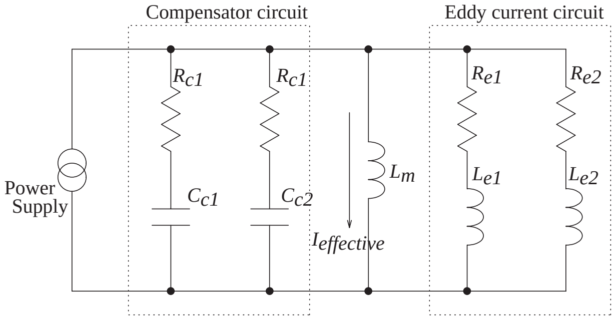

Figure 4: Circuit schematic of the eddy-current compensator.

At a rising period when a high voltage is applied to the magnet, the compensator capacitance, $C_{c1}$ and $C_{c2}$, are charged. When an excitation current reaches to a designed value, the applied voltage to the magnet goes to almost zero. The compensator starts to discharge the stored energy to the magnet. The compensator currents are expressed as,

$$I_{e1,2} = I_0\left(\sqrt{\frac{C_{c1,2}R_{c1,2}^{\ 2}}{C_{c1,2}R_{c1,2}^{\ 2} - 4L_m}} Sinh[\sqrt{\frac{C_{c1,2}R_{c1,2}^{\ 2} - 4L_m}{4C_{c1,2}L_m^{\ 2}}}] - Cosh[\sqrt{\frac{C_{c1,2}R_{c1,2}^{\ 2} - 4L_m}{4C_{c1,2}L_m^{\ 2}}}]\right) \times Exp[-\frac{R_{c1,2}}{2L_m}t], \quad .(3)$$

where $j\omega L_m \gg R_{e1,2} + j\omega L_{e1,2}$ is assumed. The field flatness is compensated if the waveform, expressed by Eq.3, has the same waveform as the eddy current (see Fig.5). Each parameters, $R_{c1,2}$ and $C_{c1,2}$, have been chosen to satisfy above condition and listed in Table.4.

Table 4: Parameters of the eddy current compensator

| | |
|---|---|
| $R_{c1}$ | 50 ohm |
| $C_{c1}$ | 2.1 mF |
| $R_{c2}$ | 200 ohm |
| $C_{c2}$ | 105 µF |

A measure BL waveform is shown in Fig.6. The pulse width was set to about 120 msec as in an actual MR operation case. The field flatness of less than $2*10^{-4}$ has been achieved in the operation.

## SUMMARY

A pulsed dipole magnet and its power supply has been developed. A field measurement by a pick-up coil method revealed that an eddy current at thick end-plates of the magnet seriously disturbs ramping of the BL waveform.

It was found that the measured BL waveform was well re-constructed by a double-exponential equation. This leads an equivalent circuit model of the pulsed magnet.

An adoption of a circuit, which has phase-advance components by capacitors, sufficiently compensates an effect by the eddy current. A field flatness of less than $2*10^{-4}$, which is well below the desired value, has been obtained.

## REFERENCES

[1] "Accelerator Technical Design Report for J-PARC", KEK Report 2002-13, (2003).

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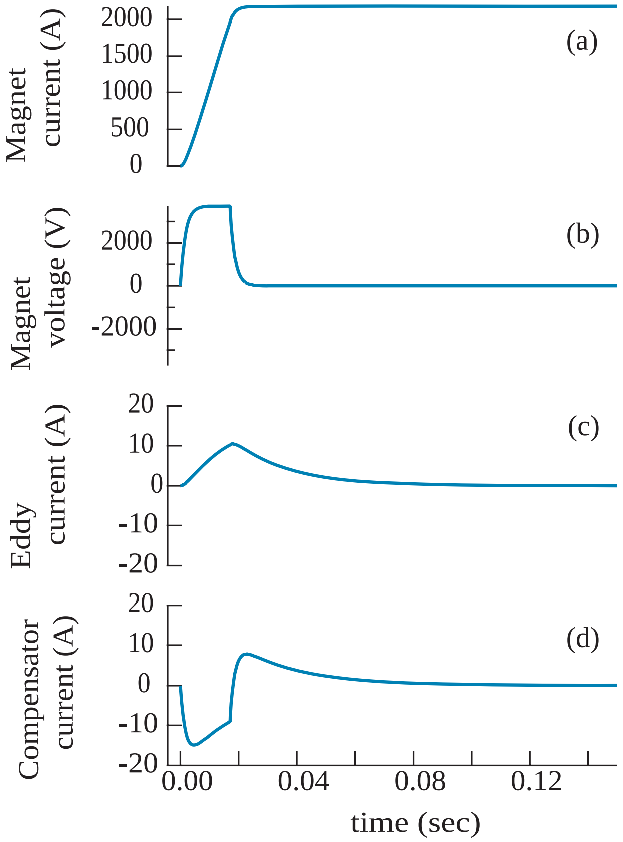

Figure 5: Comparison of various waveforms by a circuit simulation; magnet current (a), magnet voltage (b), eddy current (c) and compensator current (d).

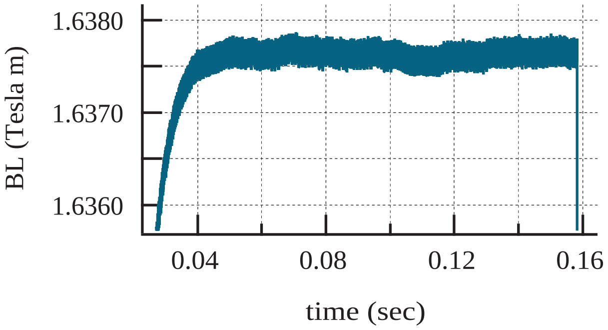

Figure 6: Measured BL waveform with the eddy current compensator. A field flatness of less than $2*10^{-4}$ was achieved. The excitation current was reduced to 1800 A for a test purpose.