MAGNETIC FIELD MEASUREMENT AND RIPPLE REDUCTION OF QUADRUPOLE MAGNETS OF THE J-PARC MAIN RING

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Abstract

The magnetic field ripple of the quadrupole magnets of the J-PARC main ring has been measured to be the order of 10^{-4} of the normal magnetic field. It has been observed that the ripple frequency distribution of each magnet depends on where the magnet is in the magnet chain. The distribution can be explained with a transmission line model of the cable and magnets. The field ripple due to the common mode current ripple was reduced with changing the magnet cabling to be symmetrical with respect to the N and S poles of the quadrupole magnets. Ripples have been further reduced with bypass resisters.

MEASUREMENT TOOLS

Pickup Coil Production

Pick up coils have been produced to measure the magnetic field ripple of the quadrupole magnets due to the current ripple of the power supply [1]. The bobbin is a crystal cube of 15 mm×15 mm×15 mm. The crystal has a very small coefficient of expansion so that the effective cross sectional area is stable for the temperature change. A copper wire of 50 μm diameter was winded for 218 turns. The coil resistance has been measured to be 200 Ω (Fig. 1).

Figure 1: Pick up coils for the quadrupole magnet field ripple measurement.

The effective cross sectional area of the coil has been measured to be 0.04905 m^2 with a permanent magnet. The calibration system was built for the measurement of the cross sectional area. The magnetic field of the permanent magnet was measured precisely with a NMR magnetic field measurement system.

A wooden coil case was made to align the pickup coil on the mid plane of the quadrupole magnet. The shape of the case was designed to fit in the minimum gap (Fig. 2). Quick and accurate alignment was then achieved even though there were obstacles such as vacuum components.

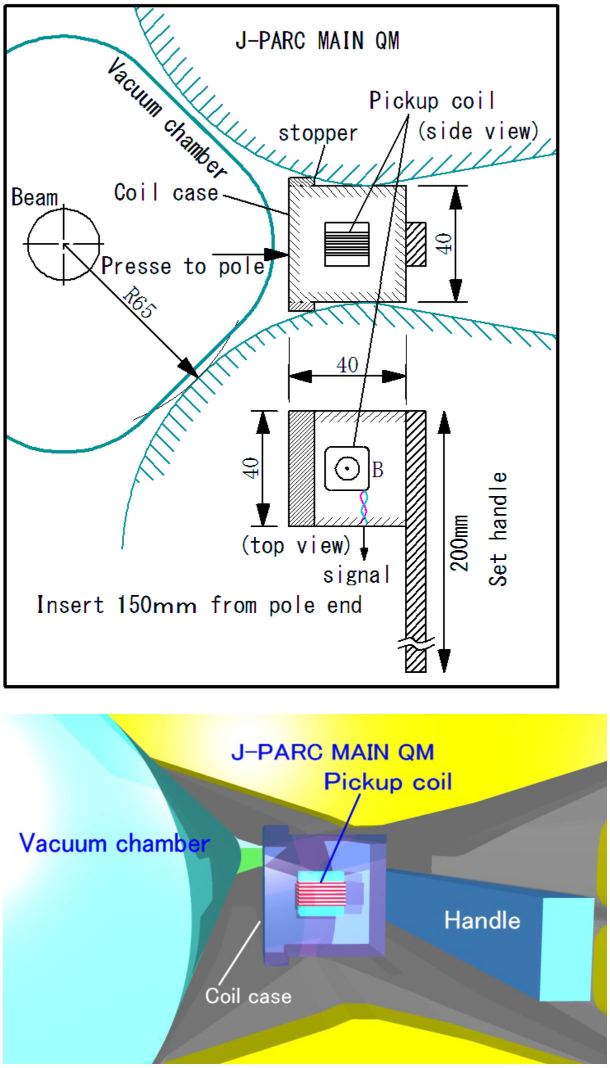

Figure 2: Wooden coil case design for the field measurement at the minimum gap of quadrupole magnets.

Data Acquisition

A FFT analyzer, ONOSOKKI CF-3600A, was used to acquire the signal data of the pickup coil. The coil output was taken with a high impedance termination and a 24-bit digitizer. The data were integrated to obtain the magnetic field flux. The typical sampling was 102.4 kHz. The data were transferred to other offline personal computers for further analysis.

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MEASUREMENT RESULTS

Ripple Distribution in the Frequency Domain

Measured magnetic field ripple is shown in Fig. 3 as a function of frequency. A relatively broad distribution was observed around 100 Hz. Shape peaks of the frequency of 150, 300, 600, 750, 900 and 1800 Hz were also observed.

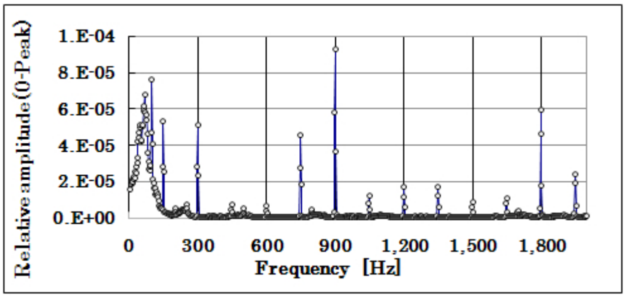

Figure 3: Relative magnetic field ripple of QFX164 as a function of frequency with respect to the normal field.

Ripple Distribution in the Magnet Chain

Magnetic field ripples have been measured for 24 out of 48 magnets of the QFX family. The ripple distribution of 150 Hz is shown in Fig. 4. The ripple amplitude is maximum at the magnet closest to the power supply and minimum at the midpoint of the magnet chain.

The ripple distributions of 300 Hz and 450 Hz are also shown in Fig.4. They have a node at the midpoint of the magnet chain. The ripple distribution of 600 Hz, however, has an antinode at the midpoint of the magnet chain. The wavelength is smaller for the ripple distribution of higher frequency.

Because the ripple of each magnet was measured independently, the phase information is unknown. We, however, infer that the ripple distributions of 150, 300 and 450 Hz are anti-symmetric and the common modes of the power supply current ripple are the cause. Meanwhile the distribution of 600 Hz is symmetric and the normal modes of the power supply current ripple are the cause.

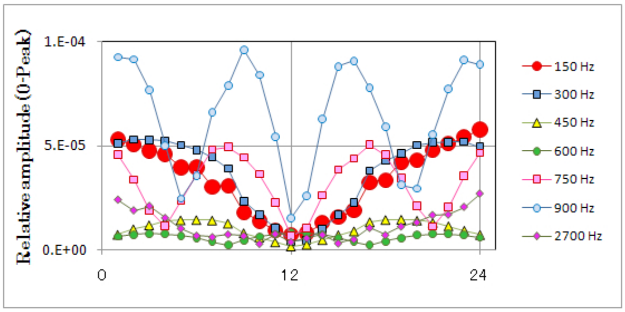

Figure 4: Ripple distribution of 150, 300, 450, 600, 750, 900 and 2700 Hz in the magnet chain. There are 48 magnets for the QFX family. Measurement was done for 24 out of 48 magnets.

TRANSMISSION LINE MODEL

Magnet Impedance and Cable Capacitance

The magnet chain can be expressed as a transmission line model with the magnet inductance, resistance and cable capacitance as shown in Fig. 5. The impedance of a QFX magnet has been measured for the frequency range of 20 Hz to 10 kHz. The resistance is 0.034 Ω at DC. It is measured to be larger for higher frequencies and 1020 Ω at 10 kHz. Most likely the eddy current loss and hysteresis loss of the iron sheet are the cause. The inductance component is less than the design value, 49.9 mH, by 10 % to 40 % for the frequency range of 20 Hz to 4 kHz. The capacitance of the cable is 3.1 μF for all the chain of 48 magnets.

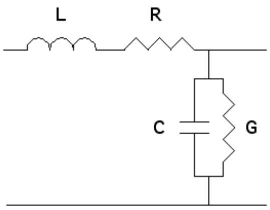

Figure 5: The inductance and resistance of a magnet and capacitance of cable for a transmission line model.

Transmission Line Parameters

The transmission line parameters are expressed as

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}.$$

The phase constant, β, has been calculated using the magnet impedance and the cable capacitance as shown as the red lines in Fig. 6. The measured values of the parameter from the magnetic field ripple distribution are shown as blue circles in Fig. 6.

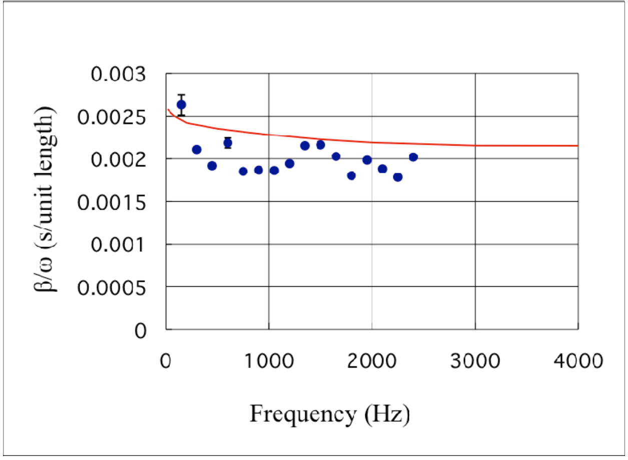

Figure 6: The measured values of the phase constant, β/ω, from the magnetic field ripple distribution for the frequency range of 150 Hz to 2400 Hz shown in blue circles and the calculated value from the transmission line model shown in red line.

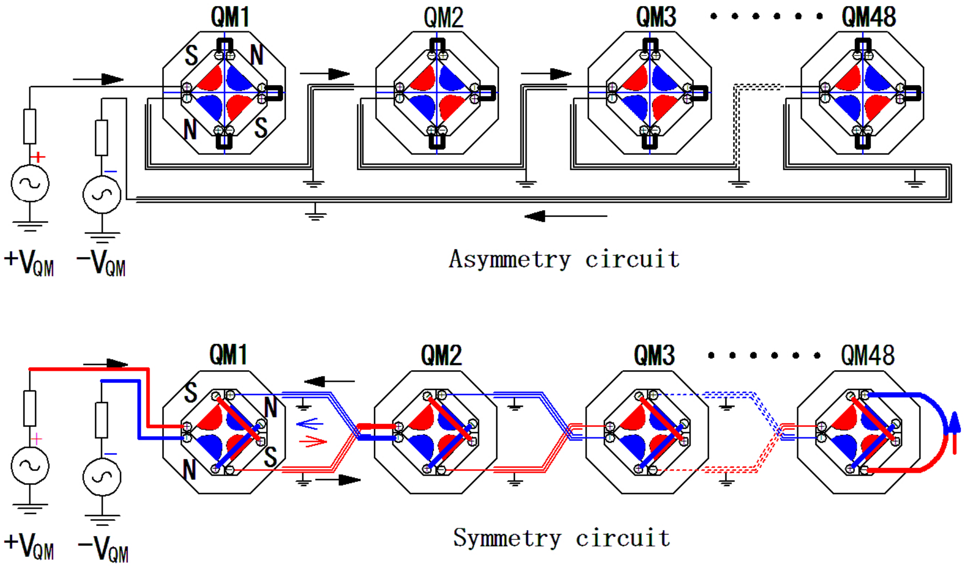

Figure 7: Asymmetrical cabling for common mode ripples (top). Symmetrical cabling for common mode ripples (bottom).

RIPPLE REDUCTION

Symmetrical Cabling

Magnetic field by common mode current ripples would be cancelled in the lowest order if the cabling is symmetrical with respect to the common mode current ripples of the power supply. The positive side of the power supply is connected to S poles of all the magnets and the negative side of the power supply is connected to N poles of all the magnets. The connection from the N pole cable to S pole cable is made at the end of the chain (see Fig. 7). Magnetic field by common mode current ripples, however, would not be cancelled if the cabling is asymmetric with respect to the common mode current ripples.

The cabling scheme for the bending, quadrupole and sextupole magnets has been changed in 2008 and 2009 to the symmetrical cabling. The magnetic field ripple has been measured after the cabling scheme change using the trim coils of the magnets [2]. Ripples of 150 Hz and the harmonics due to the common mode current ripples have been cancelled. Ripples of 600 Hz and the harmonics by the normal mode current ripples, however, have remained.

Bypass Resisters

Ripples of 600 Hz and higher frequency have been reduced with bypass resisters. A resister of 34 Ω was attached in parallel to each two poles of the quadrupole magnets. A part of current ripple would bypass to the resister and the field ripple would then be reduced. The measured distribution of the magnetic field ripples is shown in Fig. 8

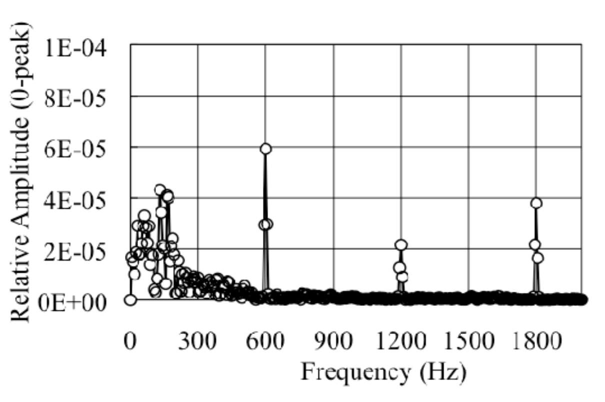

Figure 8: Magnetic field ripples of QFX141 in the frequeny domain with the symmetrical cabling and bypass resisters.

SUMMARY

Magnetic field ripples of the main magnets of the J-PARC main ring have been measured. Ripples of 150 Hz and the harmonics were observed up to the order of 10^{-4} of the normal field. The ripple distribution in the magnet chain can be explained with the transmission line model. Magnetic field ripples due to common mode current ripples have been cancelled by the symmetrical cabling. Ripples have been further reduced with bypass resisters.

REFERENCES

[1] S. Nakamura, "Issues and Countermeasures of the Magnet Power Supplies of the J-PARC MR", The 6th Accelerator Meeting in Japan, Ibaraki, Japan, Aug. 2009.

[2] S. Igarashi et. al., "Magnetic Field Ripple Reduction of Main Magnets of the J-PARC Main Ring using Trim Coils", IPAC10, Kyoto, Japan, May 2010, MOPEB011.