MAGNETIC FIELD RIPPLE REDUCTION OF MAIN MAGNETS OF THE J-PARC MAIN RING USING TRIM COILS

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Abstract

Efforts have been made to reduce the magnetic field ripple of the bending, quadrupole and sextupole magnets of the main ring of the Japan Proton Accelerator Research Complex (J-PARC) using the trim coils of the magnets. The quadrupole magnet has 24 turn main coil and 11 turn trim coil per pole those can be considered as a primary winding and a secondary winding of a transformer. When the trim coil is shorted, the induced trim coil current cancels the magnetic field ripple. The field ripple of the quadrupole magnet was reduced by a factor of 6 by shorting the trim coil. The trim coil current, however, deforms the acceleration field pattern if the coil is shorted all the time of the current pattern of flat bottom, acceleration, flat top and recovery. MOSFET switches have been used to short the coil and to reduce the field ripple during the flat bottom and flat top. Modules were built for the quadrupole and sextupole magnets. The plan has been made to wind optimized trim coils for the bending magnets.

INTRODUCTION

The main ring of the Japan Proton Accelerator Research Complex (J-PARC) utilizes 96 bending magnets, 216 quadrupole magnets and 72 sextupole magnets to make the closed orbit. Efforts have been made to reduce the ripple by improving the power supplies [1]. The power supplies, however, generates undesirable current ripple of the order of 10^{-4} [2]. The effects have been observed to the beam orbit ripple, tune ripple and spill structure in the slow extraction. Further ripple reduction is necessary for better beam orbit.

The quadrupole magnet has 24 turn main coil and 11 turn trim coil per pole those can be considered as a primary winding and a secondary winding of a transformer (see Fig. 1). If the trim coil is shorted, the ripple current is bypassed to the trim coil and the magnetic field ripple should be improved. The trim coil current, however, deforms the acceleration field pattern if the coil is shorted all the time of the current pattern of flat bottom, acceleration, flat top and recovery. A switch is needed to short the trim coil and to reduce the field ripple only during the flat bottom and flat top.

The sextupole magnets also have trim coils originally for the beam optics correction. The bending magnets, however, do not have trim coils. The impedance and turn number of the trim coils to be winded can be optimized.

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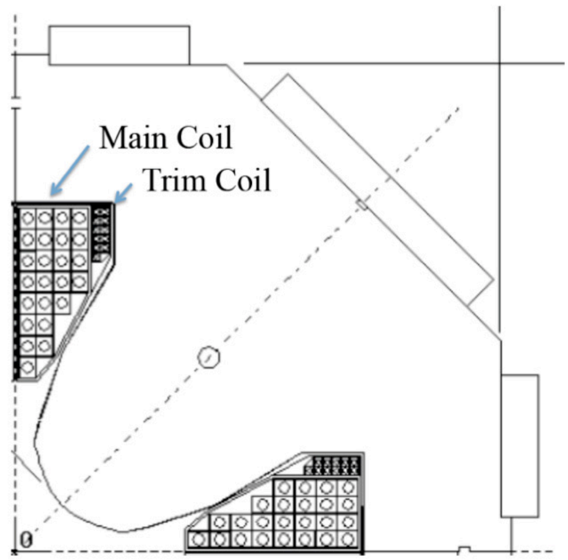

Figure 1: Cut view of the quadrupole magnet.

FIELD RIPPLE REDUCTION FACTOR

The field ripple reduction factor can be deduced using the transformar model of the main coil and trim coil. The field flux of the primary and secondary windings are expressed as

$$
\begin{aligned}
i\omega\Phi_1 &= i\omega L_1 I_1 + i\omega M I_2 \\
i\omega\Phi_2 &= i\omega M I_1 + i\omega L_2 I_2 = -R I_2
\end{aligned}
\quad (1)
$$

when the secondary winding is connected to a resistor as shown in Fig. 2.

Assuming the coupling is ideal, the ripple reduction factor is a function of the inductance and resistance of the secondary winding and the frequency of the ripple as the following form:

$$\Phi_2 = \frac{1}{1 + (i\omega L_2 / R)} M I_1 . \quad (2)$$

Better ripple reduction can be obtained when the resistance of the secondary circuit is low (see Fig. 3).

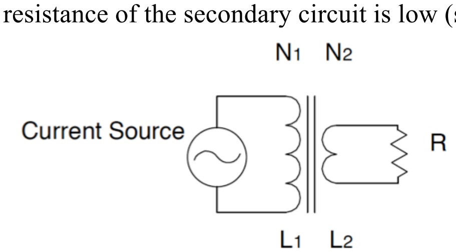

Figure 2: Transformer model of the primary and secondary windings of the magnet.

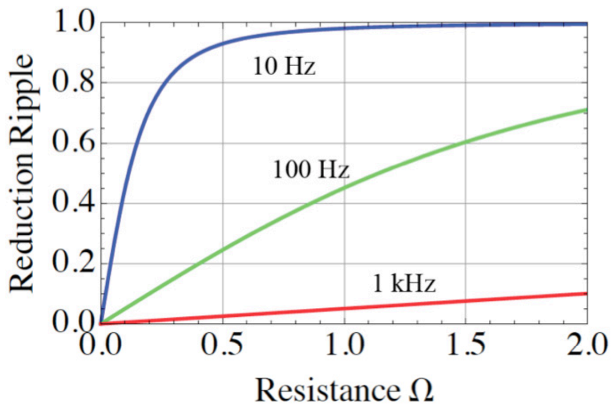

Figure 3: Ripple reduction factor as a function of the resistance of the secondary circuit for the frequency of 10 Hz (blue), 100 Hz (green) and 1 kHz (red).

The trim coils are connected to cables those go to one of the power supply buildings. Power supplies are planned to connect to the other end of the cable for the optics correction, beam based alignment or active ripple cancellation. The resistance of the trim coil and the cable is 0.3 ~ 0.7 Ω, depending on the length of the cable. If the cable end is shorted at the power supply building, the ripple reduction factor will be 1/6 ~ 1/3.

FIELD MEASUREMENT

The effect of the field ripple reduction was measured with one turn coil that is winded to some quadrupole magnets for the field measurement or test of active ripple cancellation. The output signal of the one turn coil is digitized using the FFT analyzer, ONOSOKKI CF-3600A, and integrated to obtain the field flux of the magnet.

The trim coil was shorted with the MOSFET relay, OMRON G3VM-61BR that is for small analogue signal switch. The resistance of the MOSFET relay is 0.065 Ω when the relay is on. The effect of the field ripple reduction is shown in Fig. 4 in the time domain and Fig. 5 in the frequency domain. The ripple reduction of 1/6 was achieved.

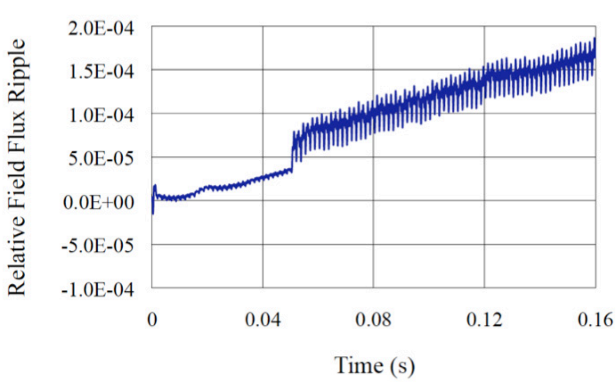

Figure 4: The effect of the field ripple reduction for QFN071 in the time domain during the flat top when the trim coil was shorted during the first 50 ms.

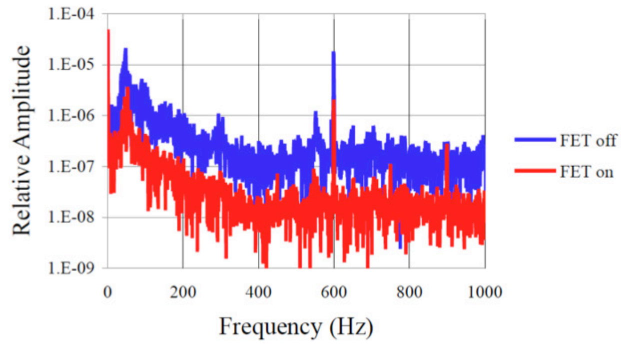

Figure 5: The effect of the field ripple reduction for QFN071 in the frequency domain during the flat top for the trim coil is shorted by the MOSFET (blue) and open (red).

POWER SUPPLY STABILITY

Modules have been produced using MOSFET relays to short the trim coils of all quadrupole and sextupole magnets during gated timings. The gate can be set to arbitrary timing using VME modules during the main magnet pattern. The MOSFET relay G3VM-61BR was observed to have little margin of voltage and current for our purpose. We plan to search for a switch with more margins.

The current deviation of the quadrupole magnets is found to be larger when the number of the magnets with shorted trim coils increases (see Fig. 6). The power supply becomes unstable when the trim coils of all the QFN magnets are shorted. When the trim coils are shorted, the impedance of the magnets becomes smaller and the current feedback of the power supply seems to be unstable. Feedback parameters of the power supply should be optimized for stable operation.

Meantime we have decided the number of magnets for the trim coils to be shorted by measuring the current deviation of the power supplies. The measurements have been done so far for six quadrupole families. The trim coils of 40 out of 48 magnets can be shorted for the QFN family with the stable power supply operation.

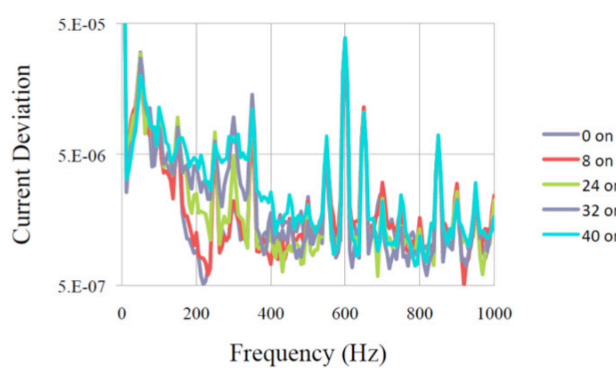

Figure 6: The current deviation of the QFN power supply at the flat top when the number of the magnets with shorted trim coils are 0, 8, 25, 32 and 40 out of 48 magnets.

EFFECT TO BETATRON TUNE RIPPLE

Effects to the beam have been measured by shorting the trim coils of six quadrupole magnet families. The number of shorted magnets was 133 out of total 216 quadrupole magnets. The trim coils were shorted during the flat top of the main magnet pattern.

Horizontal betatron tune was measured using the tune measurement system [3]. Betatron oscillation was excited with an exciter and the oscillation was measured with a beam position monitor. The tune was calculated from the side band in the frequency domain of the differential signal of the opposite electrodes of the beam position monitor.

When the trim coils were not shorted, the tune ripple was about 0.004 (p-p). It was improved to 0.002 (p-p) by shorting the trim coils (Fig. 7). The improvement of the 50Hz component was manifest in the frequency domain (Fig. 8).

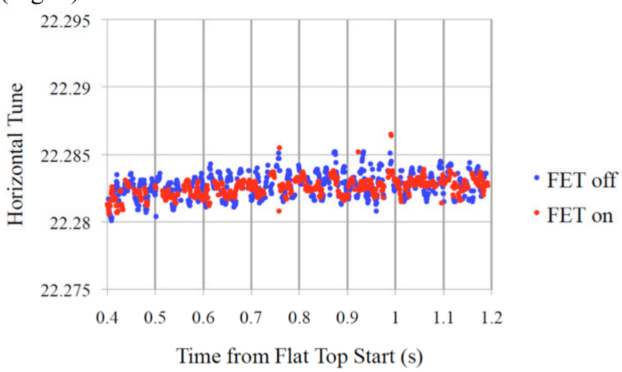

Figure 7: Horizontal tune ripple in the time domain.

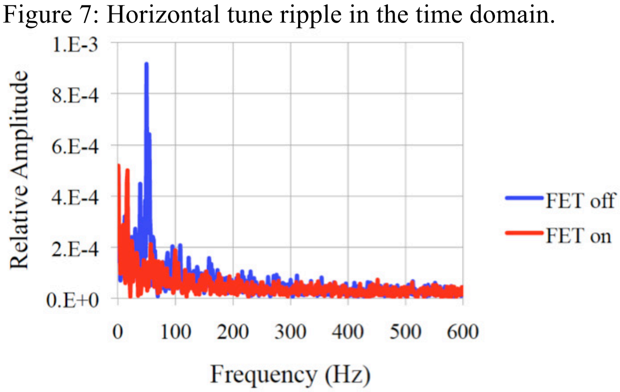

Figure 8: Horizontal tune ripple in the frequency domain.

PLAN FOR THE BENDING MAGNETS

The bending magnets do not have trim coils. A plan has been made to wind the secondary windings. The cross section and the turn number of the windings have been optimized to achieve the ripple reduction of about 1/6. The plan is to make 8 turns of the secondary winding per pole with a copper cable of 38 mm^2 cross section.

The ripple reduction effect was measured with a bending magnet in the power supply building originally for the magnetic field monitoring. The secondary winding was prepared as planned. The power amplifier was connected to the main coil to supply about 0.2 A of current for the frequency of 10 to 1000 Hz. A MOSFET relay circuit was connected to the secondary winding. The signal of a pick up coil was measured to observe the effect of the shorted secondary windings. The ripple reduction factor was measured to be 1/10 for the frequency range of 100 to 500 Hz (Fig. 9).

The MOSFET relay is planned to be placed at the bending magnet. Less impedance and better ripple reduction are then expected than the situation that the MOSFET relay is placed at the power supply building and connected to the secondary winding with long cables. The radiation hardness has been tested for the MOSFET relay. Total of 4 relays have been placed in the slow extraction section of the main ring tunnel where the radiation level was moderately high during the slow extraction operation. All relays have survived during three months of the beam operation.

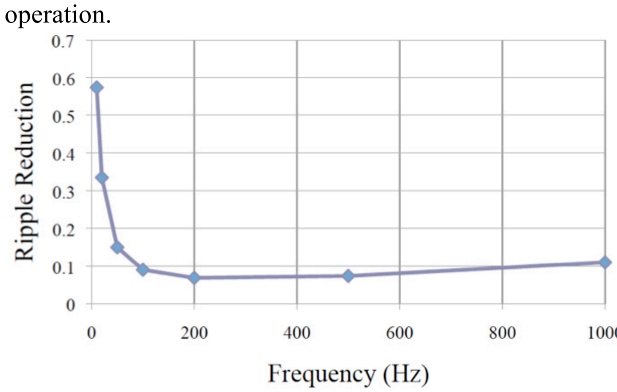

Figure 9: Ripple Reduction by shorting the secondary windings of the bending magnet.

SUMMARY

Magnetic field ripple has been reduced using the trim coils of the quadrupole magnets. When the trim coil is shorted with the MOSFET relay, the induced trim coil current cancels the magnetic field ripple. The impedance of the magnet is significantly smaller when the trim coil is shorted. The magnet power supply then becomes unstable when the trim coils of all the magnets are shorted. The feedback loop gain should be optimized to achieve stable operation. Optimized secondary windings have been planned and tested for the bending magnets.

REFERENCES

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