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TRACKING ERROR ANALYSIS ON THE POWER SUPPLY CURRENTS OF J-PARC MAIN RING MAIN MAGNETS

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Abstract

The power supply system for the main magnets in the J-PARC Main Ring (MR) has been upgraded to increase the average beam power by shortening the repetition cycle. A significant tracking error for the output electric current has been observed in the high repetition pattern with a short rise/fall time. An equivalent circuit analysis for the power supply output network has been conducted to examine the tracking error mechanism. Effects on longitudinal and transverse beams have been observed in the beam operation. Present and proposed manipulations to improve the tracking error effects are reported.

INTRODUCTION

A power supply system for the bending, quadrupole, and sextupole magnets in the J-PARC Main Ring (MR) has been upgraded to increase the average beam power of the fast extraction (FX) operation for the neutrino oscillation experiment and of the slow extraction (SX) operation for the experiments in the hadron facility. The repetition cycle times have been changed from 2.48 to 1.36 s for the FX operation, and from 5.2 to 4.24 s for the SX operation [1] (see Fig. 1). A well-known 'current ripple' originating from the power supply produces the magnetic field error in the magnets. As a different type of field error source, we have paid attention to the 'tracking error' we call in this paper. The tracking error can be generated at the beginning of the acceleration or at the end of the fall pattern with a high dI/dt in the cycle pattern. A significant tracking error has been observed in the high repetition pattern with a short rise/fall time. An equivalent circuit analysis for the output load based on the previous work [2,3] has been conducted to examine the tracking errors in the present operating pattern. Effects on the longitudinal and transverse beams have been observed during the beam operation. Present and proposed manipulations to improve the tracking error effects are reported.

OBSERVED TRACKING ERRORS

The tracking error $\Delta I/I \equiv (I - I_0)/I_0$ is obtained from the ideal current I_0 and the output current I. The output current I is derived from two DC current transducers (DCCTs), which were installed at both output terminals of the power supply to compensate for common mode noise [4]. Figure 2 shows the $\Delta I/I$ for the bending (BM4), quadrupole (QFN), and quadrupole (QDN) power supply families at a 5.2 s cycle slow extraction pattern. The 10 kHz sampling

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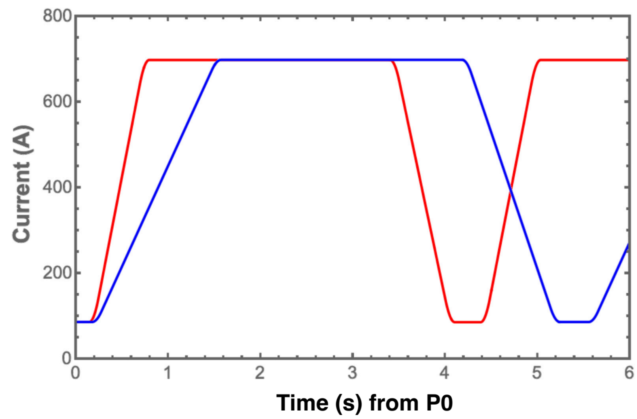

Figure 1: 5.2 s (blue) and 4.24 s (red) cycle slow extraction current patterns of QFN.

data are low-pass filtered at 100 Hz and averaged over 10 cycles. The current ripple generated from the power supply can be eliminated by these processings, and the tracking errors of interest can be clearly seen. The tracking errors are large at the beginning of the acceleration (from 0.14 s to 0.4 s in Fig. 2), which are ± 0.0003 and ± 0.0005 for BM4 and QFN/QDN, respectively. The tracking error can be seen at the end of the acceleration, however it is rather small.

Figure 3 shows the tracking error for the 4.24 s slow extraction cycle. The BM average shows the tracking error averaged over 6 BM families. The BM average $\Delta I/I$ has a very similar pattern to that of BM4. This means that each BM $\Delta I/I$ has a similar error pattern. The tracking errors are roughly double or more than those of the 5.2 s cycle. The plotted horizontal and vertical tune deviations (ΔQ_x and

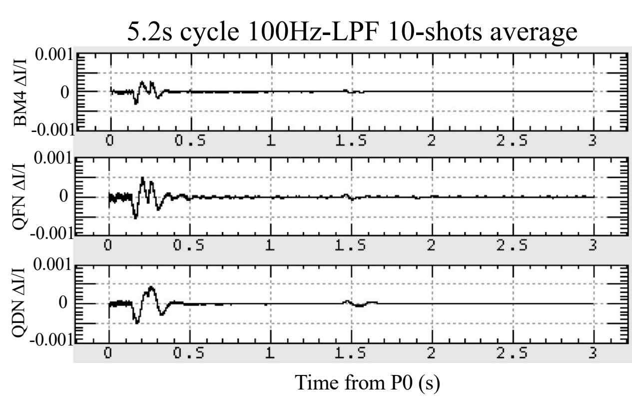

Figure 2: Tracking errors of 5.2 s cycle slow extraction current patterns.

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ΔQ_y) are calculated by the SAD code [5] from the tracking errors of the all BMs (BM1-6) and all quadrupole families (QFN, QDN, QFX1-2,QDX1-2, QFP,QFR, QDR, QFS1-2, QDS1-2, QFT1-2,QDT). The BM tracking errors can contributes to ΔQ_x and ΔQ_y through the chromaticity sextupole strength. The ΔQ_x and ΔQ_y by the tracking errors at the 4.24 s cycle are ~ ± 0.02, which limit the operating tune range for allowable beam loss.

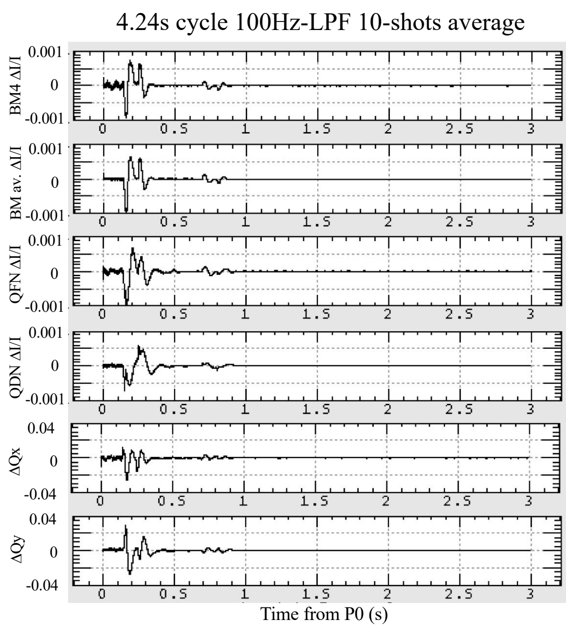

Figure 3: Tracking errors and tune deviations for 4.24 s cycle slow extraction current patterns.

TRACKING ERROR ANALYSIS

The previous works analyzed the tracking errors generated by the current ramping-up/down pattern for the J-PARC MR magnets [2, 3]. We briefly summarize the previous works. The power supply output is represented as a network consisting of cables and magnets with inductance, capacitance, and resistance (LCR). Figure 4 shows an equivalent circuit model for the QFN family. The 48 QFN magnets and their cables are grouped into 6 cells to simplify the simulation. Each cell has 8 magnets and going and returning paths reflecting the actual wiring [4]. The damping resisters (rA1-6 and rB1-6) were installed parallel to the magnet current paths to damp oscillations by the power supply ripple (each resistance is 1125 $\Omega \times 8$ in this model). The simulation by SPICE showed the tracking error can be generated by a ramping up/down pattern and a faster ramping generates a larger tracking error.

The QFN circuit simulation for operating 5.2 s and 4.2s cycle patterns was newly conducted. The circuit was analyzed by solving a simultaneous equation by Mathematica. The same circuit model as Fig. 4 and electric parameters as the reference [3] were used. Figure 5 shows the tracking error comparison between the 4.24 s and 5.2 s cycles. The tracking errors for the 4.2 s cycle are double those of the 5.2s cycle, which is consistent with the observed data. The

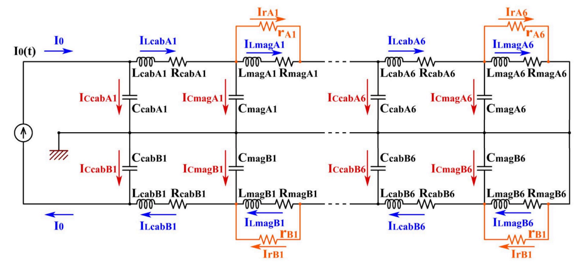

Figure 4: Simplified equivalent circuit model for the QFN family (referred from [3]).

tracking errors at the end cell (ILmagA6) is larger than that at the first cell (ILmagA1). The current oscillation with a higher frequency can be seen also for the end cell.

To reduce the tracking error, the idea of adding modulated current in the ideal current pattern was examined by the simulation. Figure 6 b) shows a demonstrated modulation current pattern, which was produced from the error pattern in the end cell through a 20 Hz LPF. Figure 6 c) and d) show the resultant tracking errors for the first and the end cell, respectively. These plots show the tracking errors for the 4.24 s cycle can be improved to a similar level as those of the 5.2 s cycle by adding the modulation current pattern. However, the tracking errors in each cell can not be perfectly compensated in this way.

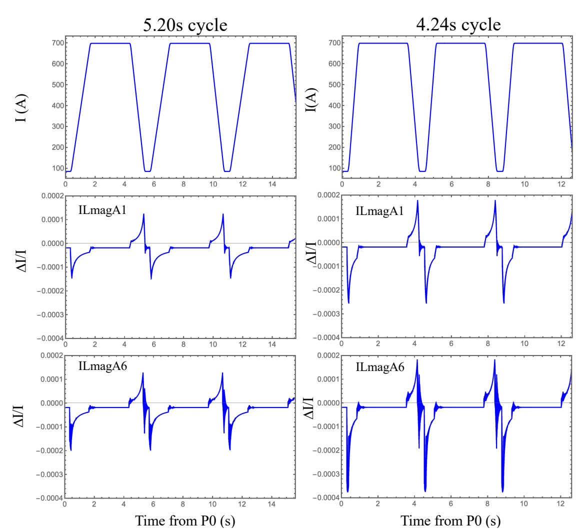

Figure 5: Comparison of QFN tracking errors simulations for 4.24 s and 5.2 s cycles.

CORRECTIONS OF TRACKING ERROR EFFECTS

The BM tracking error causes the beam momentum deviation from an ideal momentum pattern and produces an orbit distortion at the locations with finite dispersions. Figure 7 a) is the tracking error derived from the DCCTs signals, b) is the momentum deviation derived from the beam positions at the selected beam position monitors (BPMs) which have large dispersions in the arc sections. The DCCT and mo-

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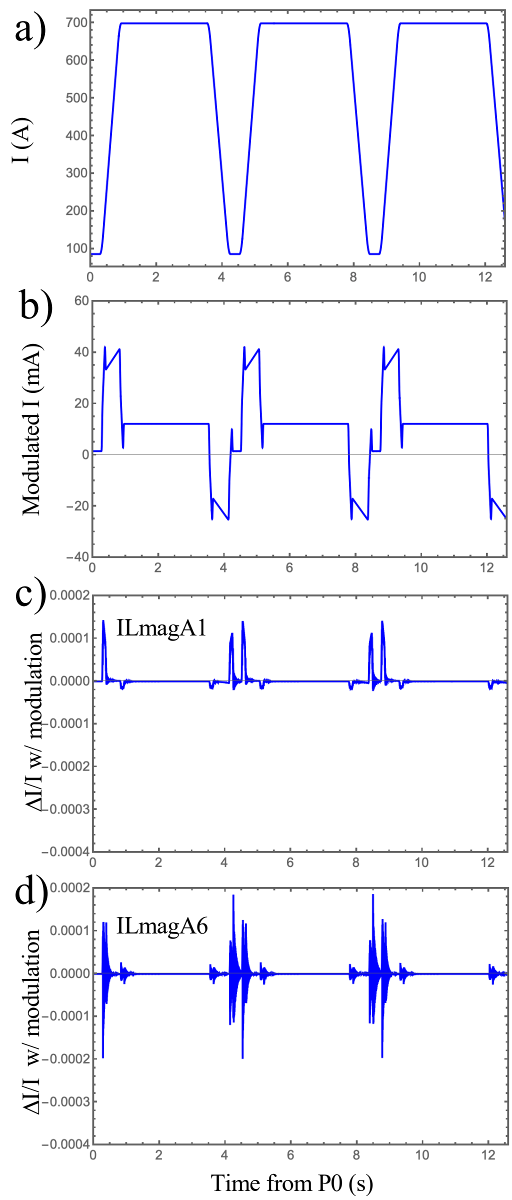

Figure 6: Demonstrated modulation current pattern for the QFN family and tracking errors for the first and the end cells (4.24 s cycle).

mentum patterns are similar but not exactly the same. In the current beam operation, the RF frequency pattern is corrected to compensate for the momentum deviation. Figure 7 c) shows the momentum deviation after the RF frequency correction. The momentum deviation has been successfully improved by the RF frequency correction. Then, the field gradient errors for all quadrupole families have been corrected by measuring the response matrices, which can be derived from the BPM positions under the selected horizontal or vertical corrector excitation through the injection to the acceleration [6] and at the flat top [7]. Significant horizontal or vertical tune deviations mainly by the quadrupole tracking errors have been improved by the field gradient error correction [8]. In this scheme, the beam momentum pattern can fluctuate from the ideal pattern due to the BM tracking errors. The momentum fluctuation could be suppressed by the BM current modulation corresponding to the measured momentum deviation pattern w/o RF frequency correction (Fig. 7 b)). Then the quadrupole field gradient error could be corrected.

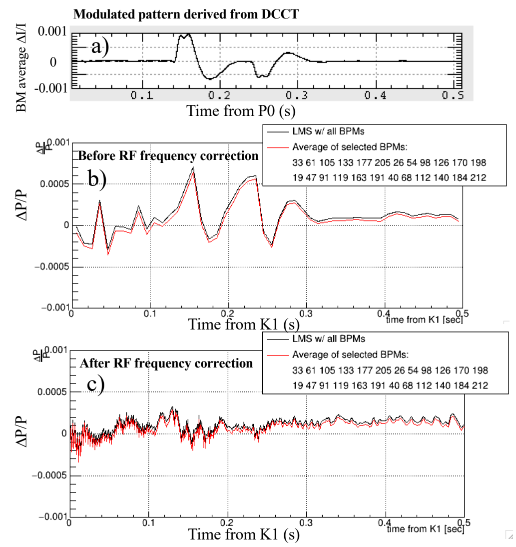

Figure 7: Measured BM tracking error average, momentum deviations w/o and w/ RF frequency correction.

CONCLUSIONS

The repetition cycle times of the J-PARC MR have been changed from 2.48 s to 1.36 s for the FX operation, and from 5.2 s to 4.24 s for the SX operation. A significant tracking error has been observed in a high repetition pattern with a short rise/fall time. An equivalent circuit simulation shows that the observed tracking errors are caused by a rapid sweep of the magnet currents, which supports the previous work's prediction. The simulation shows that modulating the ideal current pattern can improve the tracking error. The orbit distortion and tune deviation by the bending and quadrupole tracking errors have been improved by the RF frequency correction and then by the quadrupole field gradient correction based on the response matrix measurement in the present operation. The beam reference momentum still deviates from the ideal pattern according to the BM tracking errors in the present manipulation. To avoid it, we have proposed a scheme that modulates the BM current pattern corresponding to the momentum deviation pattern w/o the RF frequency correction and then corrects the quadrupole field gradients.

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