STUDY OF THE J-PARC MR BEAM ORBIT BASED ON THE MAGNETIC FILED MEASUREMENTS

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Abstract

The beam orbit of the J-PARC main ring has been studied based on the magnetic field measurements of the bending, quadrupole and sextupole magnets. Measured variations of the main field components and multipole components were compiled in the particle tracking simulation program SAD. Position displacements and rolls of the magnets were also simulated with assumption of the alignment errors. The closed orbit distortion was estimated to be 12 mm for the horizontal direction and 15 mm for the vertical direction at the nominal tune of (22.4, 20.8). The steering magnets were capable of correcting the distortion. The modulation of the betatron amplitude function has been estimated. Available aperture reductions due to resonances have been studied with the single particle tracking for the horizontal tune range of 22.04~22.46 and the vertical tune range of 20.54~20.96.

1. Introduction

The main ring (MR) of the J-PARC is being constructed as a proton synchrotron with a circumference of 1567.5 m and the orbit should be closed with 96 bending magnets, 216 quadrupole magnets and 72 sextupole magnets. Magnetic fields of all magnets have been measured[1] [2]. The standard deviation of the main component variation of the bending magnets was 6×10^{-4} for 50 GeV. The variation distorts the close orbit. The distortion, however, can be minimized with the installation position shuffling of the bending magnets [3]. The magnet shufflings were also performed for the quadrupole magnets to minimize the betatron amplitude function (β) modulation and for the sextupole magnets to minimize a third order resonance strength [3].

Amplitude variations of the main field components, undesired multipole components and alignment errors of magnets affect the beam orbit. The closed orbit distortion (COD), β modulation and available aperture reduction due to resonances are concerned and to be studied using the measured field data and some assumption of alignment errors. The study has been performed using the particle tracking program SAD.

2. Multipole components of the bending magnets

The horizontal distribution of the bending magnet fields has been measured using a long flip coil. The coil radius was 19.09 mm and the length was 7 m. The coil was placed at five horizontal positions of -30mm, -15mm, 0 mm, 15 mm and 30 mm. Figure 1 shows the results of 12 magnets for the currents of (a) 200 A, (b) 1600 A, (c) 2200 A and (d) 3015 A. They correspond to the energies of 3 GeV, 30 GeV, 40 GeV and 50 GeV. The 3 GeV data suffered likely from noises and the obtained multipole data was not relatively reliable. The 30 GeV data, however, were more reliable and the field integral distributions were uniform within $\pm5\times10^{-4}$. The slope was a quadrupole component due to the sector geometry of the magnets. Small sextupole components were observed in the 40 GeV data. The sextupole components were larger in the 50 GeV data. Amplitude variations were larger for the higher energy. Effects of the magnet saturation were observed for 40 and 50 GeV.

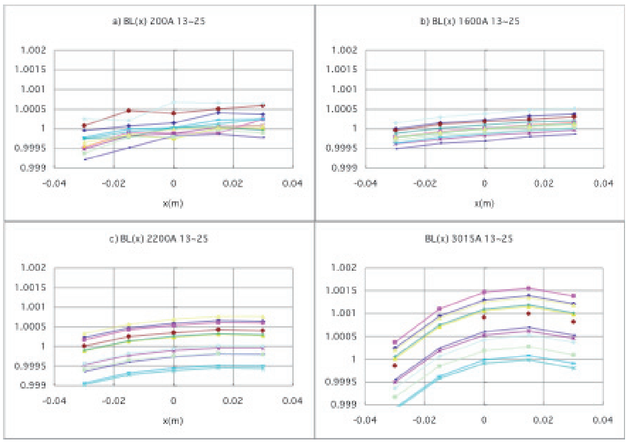

Figure1: Relative field integral as a function of the horizontal coordinate of 12 bending magnets for the corresponding energies of (a) 3GeV, (b) 30 GeV, (c) 40 GeV and (d) 50 GeV.

The data was fit with a 2nd order polynomial function. The fitted results of the dipole, quadrupole and sextupole components were transformed to be input files for the

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SAD simulations. The shuffled installation order of magnets was taken into account for the input files. The long flip coil data were available for 85 magnets out of total 97 magnets. The data for the rest of 12 magnets were created with Gaussian random numbers based on the standard deviation of the results of 85 magnets.

3. Multipole components of the quadrupole magnets and sextupole magnets

The multipole components of quadrupole and sextupole magnets have been measured using two harmonic coils. One of them was a radial coil with the radius of 59.5 mm and the length of 2 m and another was a tangential coil with the radius of 59.8 mm and the length of 3 m. All the sextupole magnets and the quadrupole magnets of the length of 1.46 m or less have been measured using the radial coil and the quadrupole magnets of the length of 1.56 m or more have been measured using the tangential coil. Figure 3 shows the amplitude (left) and phase (right) of the multipole field expansion of a reference quadrupole magnet for 30 GeV. The seven lines in the figure indicate results of seven time measurements for the same magnet. All of the higher multipole components were less than 1×10^{-3} and close to the noise level. The signal should be stable for measurements of seven times for both the amplitude and phase. The meaningful signal turned out to be only the 12-pole component. The amplitude was 3×10^{-4} for 30GeV. Main and 12-pole component amplitudes were compiled for all quadrupole magnets for the energies of 3, 10, 20, 30, 40 and 50 GeV. The results have been made to be input files for the SAD simulation. The accuracy of the measurement was better for the higher energy. The standard deviation of the main component amplitude is $1.1\sim3.8\times10^{-4}$ depending on the quadrupole magnet type for 30 GeV.

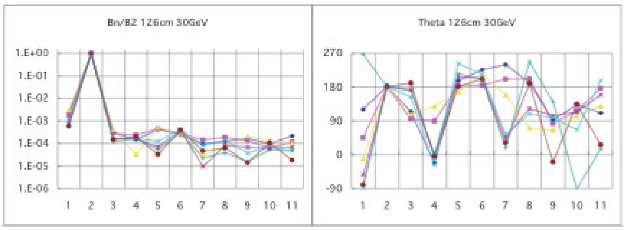

Figure3: The left figure shows seven time measurements of the relative amplitude of the multipole components of the reference quadrupole magnet for 30 GeV. The right figure shows seven time measurements of the phase of the multipole components of the reference quadrupole magnet.

The same analysis was repeated for the sextupole magnets. Only the 18-pole component turned out to be signal and the relative amplitude was 2×10^{-3} for 30 GeV. The standard deviation of the main component amplitude was $0.8\sim1.8\times10^{-3}$ depending on the energy. Main and 18-pole component amplitudes were compiled for all sextupole magnets and the input files were made for SAD.

4. COD and β modulation

The COD at the injection energy of 3 GeV has been studied using the SAD simulations with the input files of the multipole components of magnets for 30 GeV and assumptions for alignment and roll errors of the magnets. The 30 GeV data with a scaling factor of the momentum rigidity were chosen to study the beam orbit at the injection energy because the data quality was better and both the main component variation and the multipole component amplitude seemed unchanged largely when the magnet was not saturated. The alignment errors were assumed to be a Gaussian distribution of $\sigma = 0.3$ mm with a truncation of 2σ. The roll errors were assumed to be a Gaussian distribution of $\sigma = 0.3$ mrad with a 2σ truncation. The strength of the steering magnets was proven to be enough for the COD correction using the simulation even at the highest energy of 50 GeV. Figure 4 shows the horizontal COD for one-third of the ring for the horizontal tunes of 22.04~22.46 (top figure) and the vertical COD for the vertical tunes of 20.56~20.96 (bottom figure). The maximum COD was 30 mm when the tune was close to the integer. The COD was less than 1 mm after the correction using the steering magnets.

The COD was measured for the tune of (22.4, 20.8) for 20 samples of different random seeds for the alignment files. The rms of the maximum CODs of the samples was 12 mm for the horizontal direction and 15 mm for the vertical direction.

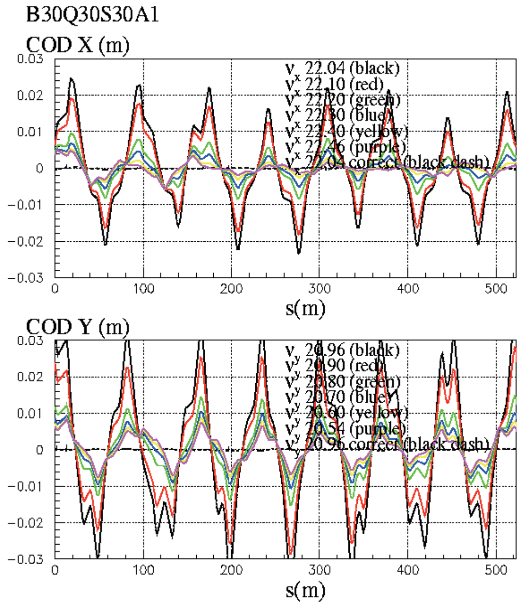

Figure4: The horizontal COD as a function of the longitudinal distance in one-third of the ring for $\nu x = 22.04 \sim 22.46$ and $\nu y = 20.8$ (top figure) and the vertical COD for $\nu y = 20.54 \sim 20.96$ and $\nu x = 22.4$ (bottom figure).

The β modulation has also been studied for the same magnet multipole files and alignment assumption.

Figure5 shows the horizontal β modulation for the horizontal tune of 22.04~22.56 and the vertical tune of 20.8 (top figure) and the vertical β modulation for the vertical tune of 20.54~20.96 and the horizontal tune of 22.4 (bottom figure). The reference was the β for the tune of (22.4, 20.8). The β modulation was reasonably small and at most 5 % at the same tune from the effect of the magnet errors. The modulation, however, was large and at most 30 % when the tune was close to a half integer.

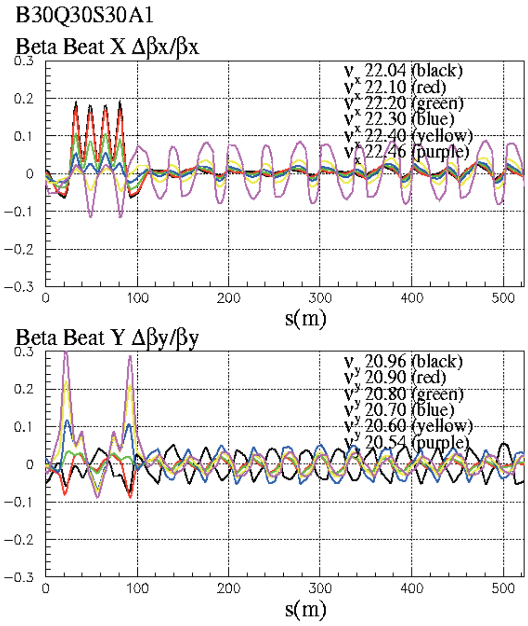

Figure5: The horizontal β modulation as a function of the longitudinal distance in one-third of the ring for νx = 22.04~22.46 and νy = 20.8 (top figure) and the vertical β modulation for νy = 20.54~20.96 and νx = 22.4 (bottom figure).

5. Aperture reduction due to resonances

Available aperture reductions due to resonances have been studied for the same assumption of the magnet errors. Ten particles were tracked using SAD for 1000 turns. The initial Courant-Snyder invariants of the particles were set to 8.1 π, 16.2 π, 24.3 π, 32.4 π, 40.5 π, 48.6 π, 56.7 π, 64.8 π, 72.9 π and 81 π mmmrad for both x and y. The Courant-Snyder invariants of each particle were checked at every turn and marked as a lost particle if the invariant was more than 81 π mmmrad. The tracking was performed for the horizontal tune range of 22.04~22.46 and the vertical tune range of 20.54~20.96.

A serious linear coupling resonance was observed at $\nu x + \nu y=43$. Random rolls of the quadrupole magnets were the main cause. Skew quadrupole magnets, those would not be available on Day 1, were effective for the correction and the equipment should be considered. A correction scheme using the vertical orbit at the sextupole magnets has been considered meanwhile. Third order resonances were observed. The correction using the extra coils of the sextupole magnets has been studied.

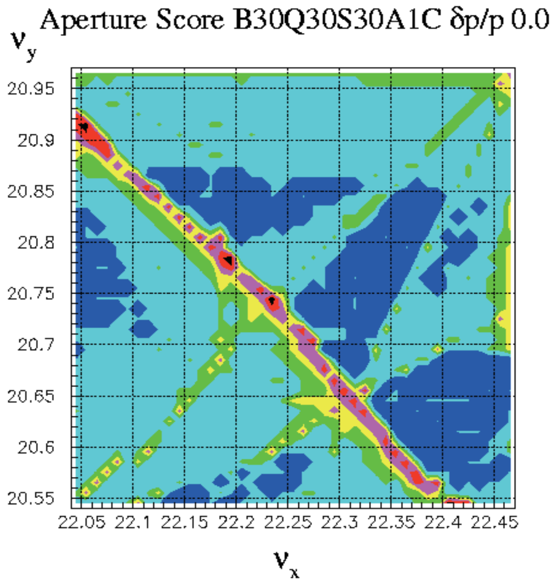

Figure6: Available apertures are shown in each color for the horizontal tune of 22.04~22.46 and the vertical tune of 20.54~20.96. The color of the tune area is blue if a particle with the Courant-Snyder invariant of 72.9 π mmmrad is survived. The color of sky blue is for 64.8 π, green for 56.7 π, yellow for 48.6 π, pink for 40.5 π, red for 32.4 π and black for 24.3 π or less.

6. Summary

Amplitude variations of the main field components and multipole components and alignment errors of the bending, quadrupole and sextupole magnets cause the COD, β modulation and resonances in the J-PARC MR. The steering magnets were capable of the COD correction. The β modulation was reasonably small and at most 5 % at the nominal tune of (22.4, 20.8). A serious linear coupling mostly due to random rolls of the quadrupole magnets was observed at $\nu x + \nu y=43$. Third order resonances were also observed. The correction schemes have been studied.

References

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