POSITION SHUFFLING OF MAGNETS AT THE J-PARC RCS

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Abstract

The J-PARC 3-GeV rapid-cycling synchrotron (RCS), which is now constructed at the JAEA site, has 24 dipole magnets, 60 quadrupole magnets with 7 families, 18 sextupole magnets with 3 families and 52 steering magnets. The magnetic field measurements for all the dipole and quadrupole magnets have been completed and their installations into the tunnel are in progress. While field deviations of dipole and quadrupole magnets cause closed-orbit and betatron-amplitude distortions, they can be reduced by arranging magnets considering their field deviations and betatron phases (position shuffling). In this paper, we present our scheme for the position shuffling of the RCS magnets and show some results of related optics calculations.

INTRODUCTION

The J-PARC 3-GeV rapid-cycling synchrotron (RCS) is designed to accelerate 8.3×10^{13} protons per pulse at a repetition rate of 25 Hz for an injection energy of 400 MeV. The injection energy is 181 MeV at the 1st stage, which will be finally upgraded to 400 MeV. The construction of the RCS is in progress at the JAEA site and its beam commissioning is to start in September, 2007. As shown in Fig. 1, the RCS has a three-fold symmetric lattice for its circumference of 348.333 m [1]. Each superperiod consists of two 3-DOFO arc modules and a 3-DOFO insertion. Each arc module has a missing-bend cell, where the horizontal dispersion has a maximum value. Three families of sextupole magnets are prepared at each missing-bend cell and utilized for the chromatic correction. The insertions are designed to be dispersion free. The injection and collimation systems occupy one of the three insertions; the injection system uses the first one and a half cells and the collimator system takes the rest. The extraction and RF systems are each allocated in the other two insertions.

Fig. 2 shows a layout of the RCS lattice for one superperiod. The RCS focusing structure consists of 24 dipole magnets (BM), 60 quadrupole magnets with 7 families (QFL, QDL, QFM, QFN, QDN, QFX and QDX), 18 sextupole magnets with 3 families and 52 steering magnets. The magnetic field measurements for all the dipole and quadrupole magnets were carried out and their variations in dipole and quadrupole lengths were evaluated. Field deviations of dipole and quadrupole magnets cause linear betatron perturbations such as closed-orbit distortion (COD) and betatron-amplitude distortion, and also the COD can be a secondary source of nonlinearity by coupling with in-

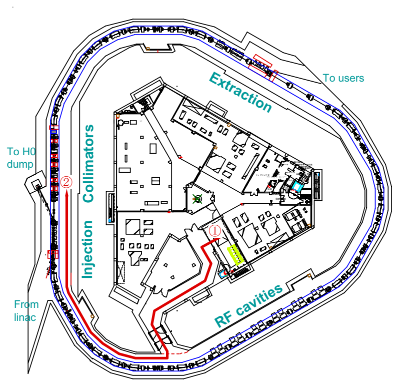

Figure 1: Schematic view of the J-PARC RCS.

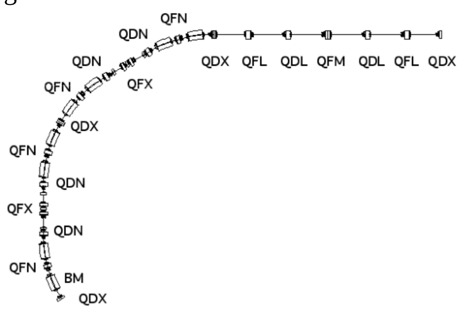

Figure 2: Layout of the RCS lattice for one superperiod.

trinsic nonlinear fields. However, such distortions can be reduced by arranging magnets considering their field deviations and betatron phases (position shuffling). Although COD can be well-corrected in the RCS with steering magnets installed as the companion to each quadrupole magnet, the shuffling of the dipole magnets is valuable in terms of saving the limited performance of the steering magnets, as there can be other sources of COD such as alignment errors. On the other hand, the shuffling of the quadrupole magnets is essential in the RCS, because we do not have any correction knobs for focusing field errors at present. In this paper, we present our scheme for the position shuffling of the RCS magnets and show some results of related optics calculations.

SHUFFLING OF DIPOLE MAGNETS

The integrated magnetic field ($BL=\int B_y ds$) for the dipole magnets was measured using a long flip-flop coil with a 25 Hz DC-based sinusoidal current pattern. In the measurement, the AC component was the most precisely obtained with an accuracy of 5×10^{-5}. The accuracy for the absolute value of the integrated field, such as those at the injection (181 MeV) and extraction (3GeV) energies, was 10 times worse due to a large measurement error for the DC component. Therefore, we decided to discuss the position shuffling of the dipole magnets with the AC com-

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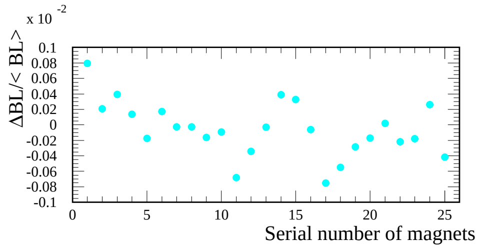

Figure 3: Deviations for the amplitude of the AC component of the integrated magnetic field, measured for 25 dipole magnets.

ponent data. Fig. 3 shows deviations for the amplitude of the AC component measured for 24+1 dipole magnets (one of them for the reference magnet). The position shuffling of the dipole magnets was optimized so as to minimize COD caused by those deviations.

The COD at position s caused by distributed dipole field errors of ΔB is expressed as,

$$x_{co}(s) = \frac{\sqrt{\beta(s)}}{2sin\pi\nu}\int_s^{s+C}\sqrt{\beta(t)}\frac{\Delta B(t)}{B\rho} \times cos(\pi\nu + \psi(s) - \psi(t))\,dt, \quad (1)$$

where β and ν are beta function and betatron tune, ψ is betatron phase, and $B\rho$ is momentum rigidity. According to Eq. 1, by choosing a pair of magnets with a similar deviation and assigning it to where its horizontal phase difference is close to (2n+1)π, the contribution to COD of this pair can be canceled out with each other, where n is integer. In the RCS, the phase advance between two DOFO arc modules on both sides of each missing-bend cell is $\sim\pi$, and thus we optimized the shuffling making use of this optical configuration. Fig. 4 shows horizontal COD distributions at the reference tune of (6.68, 6.27) calculated with a code called SAD [2]. In the figure, the blue curve corresponds to COD obtained for the arrangement in the order of the serial number without any position shuffling, while the red one is after the shuffling. The COD is drastically reduced (7 mm to 1 mm) by the shuffling. Fig. 5 shows a horizontal betatron tune dependence of COD after the shuffling. The COD maintains a small value over the nominal operating region except for integer resonance lines. Since effects of the dipole field errors are compensated at betatron phases close with each other, the change of COD is insensitive for that of the betatron tune.

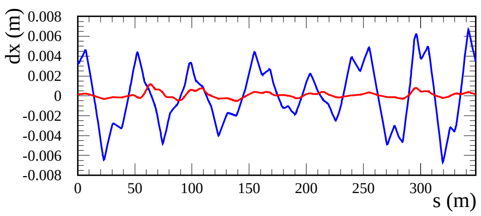

Figure 4: Calculated horizontal COD distributions caused by the field deviations of the dipole magnets; the blue and red curves correspond to COD before and after the shuffling of the dipole magnets.

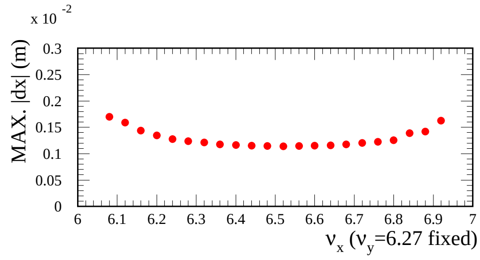

Figure 5: Horizontal tune dependence of COD after the shuffling of the dipole magnets.

SHUFFLING OF QUADRUPOLE MAGNETS

Fig. 6 shows deviations for the integrated field gradient (GL=$\int B_y' ds$) measured for 12 quadrupole magnets of the QFX family using a harmonic coil with a similar current pattern as that for the dipole magnet. As shown in the figure, there is no correlation between those at 181 MeV and 3GeV. The deviations for the other families also have a similar tendency. For a period from the injection through the early stage of the acceleration, the space-charge effect is the strongest, bringing emittance growth, large incoherent tune shift, etc. Therefore the impact of the focusing field errors, such as beta modulation and half-integer stopband, on beam particles is the severest for this period. Therefore we focused on the injection period and discussed the position shuffling of the quadrupole magnets so as to minimize betatron-amplitude distortion at the injection energy.

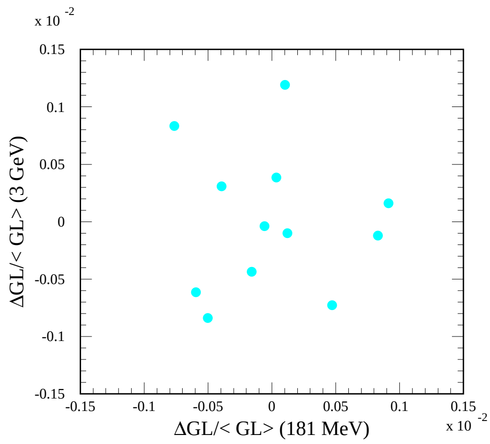

Figure 6: Deviations for the integrated field gradient, measured at 181 MeV and 3 GeV for 12 quadrupole magnets of the QFX family.

The betatron-amplitude distortion caused by distributed quadrupole field errors of ΔG is expressed as,

$$\frac{\Delta\beta(s)}{\beta(s)} = -\frac{1}{2sin2\pi\nu}\int_s^{s+C}\beta(t)\frac{\Delta G(t)}{B\rho} \times cos2(\pi\nu + \psi(s) - \psi(t))\,dt, \quad (2)$$

which can be reduced in a way similar to the closed-orbit analysis. According to Eq. 2, by assigning a pair of magnets with a similar deviation to where its betatron phase difference is close to (2n+1)π/2 or by allocating that of

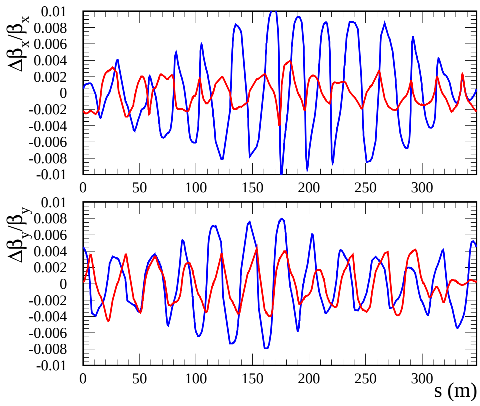

Figure 7: Betatron-amplitude distortions caused by the field deviations of the quadrupole magnets calculated at 181 MeV; the blue and red curves show those before and after the shuffling of the quadrupole magnets.

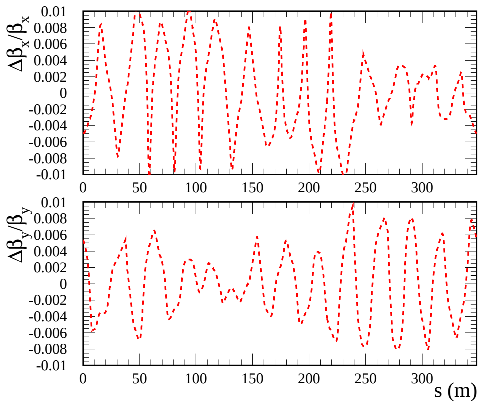

Figure 8: Betatron-amplitude distortions calculated at 3 GeV with the shuffling of the quadrupole magnets optimized at 181 MeV.

the opposite sign to the where of around $2n\pi/2$, the contribution to betatron-amplitude distortion of this pair can be canceled out with each other. On the basis of this manner, we optimized the position shuffling of the RCS quadrupole magnets for the injection energy. Fig. 7 shows betatron-amplitude distortions at the reference tune of (6.68, 6.27) calculated with SAD for the injection energy, in which the blue and red curves show those before and after the shuffling. The beta modulations for both horizontal and vertical are significantly reduced (1% to 0.4%) by the shuffling. Fig. 8 shows similar distortions calculated at the extraction energy for the shuffling optimized at the injection energy. Since there is no correlation between the field deviations at 181 MeV and 3 GeV, there remains 1% of the modulation at 3 GeV. Fig. 9 plots betatron tune dependences of betatron-amplitude distortion after the shuffling. While the beta modulation increases exponentially in approaching half-integer lines, it is kept at around 0.5% for 181 MeV and 1% for 3 GeV over the possible operating region shown by arrows in the figure. In this connection, half-integer stopbands were estimated for $2\nu_x$=13 and $2\nu_y$=13 lying near the nominal operating region. The width of the pth harmonic half-integer stopband caused by distributed focusing field errors of ΔG is expressed as,

$$\Delta\nu = |\frac{1}{2\pi}\oint \beta(s)\frac{\Delta G(s)}{B\rho}e^{-jp\frac{\psi(s)}{\nu}}ds|,$$

inside which the focusing field errors generate coherent additive phase-space kicks every revolution and consequently stable betatron motions will cease to exist. The stopband widths were obtained to be 0.0007 for $2\nu_x$=13 and 0.0004 for $2\nu_y$=13 at 181 MeV, and 0.0020 and 0.0013 at 3 GeV. Due to the shuffling optimized at 181 MeV, the widths at 181 MeV are still narrower than those at 3 GeV.

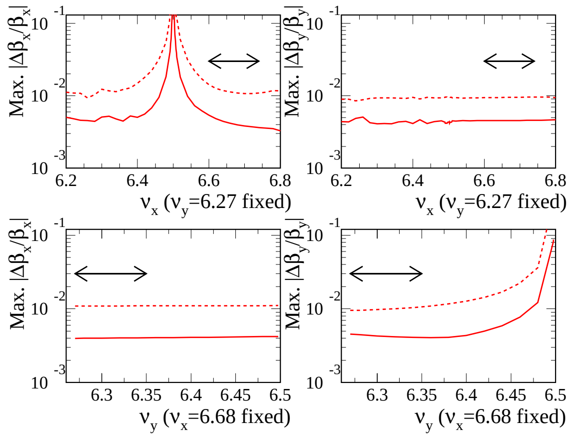

Figure 9: Betatron tune dependences of betatron-amplitude distortion after the shuffling of the quadrupole magnets; the solid and dotted curves are those at 181 MeV and 3 GeV.

SUMMARY

On the basis of the results of the magnetic field measurements, we carried out the position shuffling for the dipole and quadrupole magnets of the J-PARC RCS so as to minimize COD and betatron-amplitude distortion considering their field deviations and betatron phases.

The COD caused by the field deviations of the dipole magnets of $\pm 8\times 10^{-4}$ was reduced by their shuffling from 7 mm to 1 mm.

As for the shuffling of the quadrupole magnets, we focused on the injection period where the impact of focusing field errors on beam particles is the severest. The betatron-amplitude distortion caused by the field deviations of the quadrupole magnets of $\pm 1\times 10^{-3}$ was reduced by the shuffling from 1% to 0.4% at the injection energy, while there remained 1% of the modulation at the extraction energy for the shuffling optimized at the injection energy, because of no correlation between the field deviations at the injection and extraction energies.

REFERENCES

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[2] "Strategic Accelerator Design (SAD)", http://acc-physics.kek.jp/SAD/sad.html.