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COMPENSATIONS OF THIRD-ORDER RESONANCES IN J-PARC MR

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Abstract

This report presents the methods and the demonstrations for compensations of the third-order resonances in the main ring synchrotron of Japan Proton Accelerator Research Complex. The third-order structure resonance was compensated by applying the new beam optics, whose phase advances in the arc sections were adjusted to cancel the resonance driving terms. It was verified by the aperture survey simulations and the beam loss measurements. The third-order nonstructure resonances were compensated by using the trim coils of the sextupole magnets. The beam loss was clearly reduced by applying them.

INTRODUCTION

The main ring synchrotron (MR) of Japan Proton Accelerator Research Complex (J-PARC) [1] provides high-intensity proton beams for the neutrino and hadron experiments. In the fast extraction (FX) operation, the beams are injected with a kinetic energy of 3 GeV and an intensity of 3.3×10^{13} protons per bunch (ppb), and are accelerated to 30 GeV. The present beam power in FX operation is 515 kW. The MR launches the future plan to upgrade the beam power to 1.3 MW in FX operation [2, 3]. It is necessary to reduce the beam loss for realizing 1.3 MW. Most of the beam losses are observed in the low-energy ($\lesssim$ 5 GeV) region. It is because the space charge effects are strong. The beams are under the influences of various kinds of resonances because of their large tune spread distributions.

Figure 1 shows the result of the aperture survey simulation in the present FX operation [4], performed by using a particle-in-cell tracking code [5]. Magnet imperfections were included, and the space charge effects were not included in the simulation. The present operation tune is at $(\nu_x, \nu_y) = (21.35, 21.43)$ [6, 7]. It indicates that the third-order resonance $\nu_x - 2\nu_y = -21$ is strong. Since the MR has three-fold symmetry, it is a structure resonance induced by sextupole magnetic fields. Though they look weak, the third-order nonstructure resonances $3\nu_x = 64$ and $\nu_x + 2\nu_y = 64$ have significant effects on the beams in FX operation, because they are close to the operation tune [2]. In this report, compensation methods of both structure and nonstructure resonances are described.

STRUCTURE RESONANCES

Principle and Method of Compensation

A new method to compensate the third-order structure resonance was considered [4]. Note that we do not consider

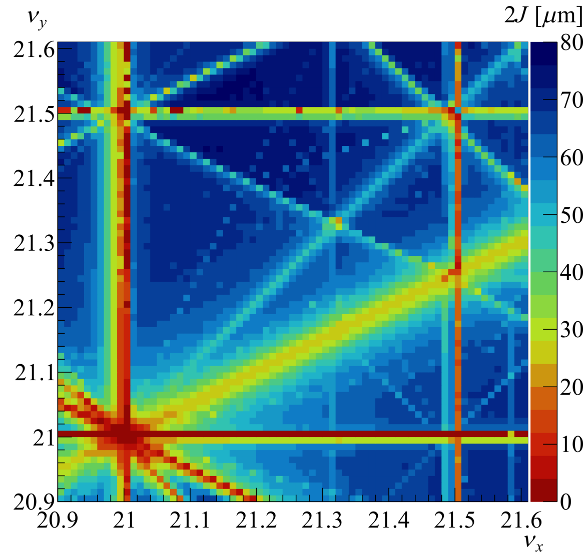

Figure 1: Aperture Survey in the present FX operation [4].

any field errors in this section because they do not cause structure resonances but nonstructure resonances. The compensation method makes use of the following features of the MR:

- The major sources of the sextupole magnetic fields are in the arc sections of the synchrotron.
- The arc section is made of several numbers of the same structure.
- The synchrotron has straight sections.

For the first feature, the main sources of the sextupole magnetic fields are the sextupole and bending magnets in the MR. All sextupole magnets are in the arc section because they are installed to correct the chromaticity by using the dispersion. For the second feature, we will call one structure as a module. Given that the module length along the reference orbit is L_{mod}, the second feature can be expressed as the following equations:

$$K_2(s + L_{\text{mod}}) = K_2(s), \quad \beta_u(s + L_{\text{mod}}) = \beta_u(s), \tag{1}$$

where K_2 is the sextupole magnetic field strength, $\beta_u(u = x, y)$ is the betatron function, and $[s, s + L_{\text{mod}}]$ is in the arc sections. The third feature is needed to adjust the tune by changing the beam optics in the straight sections.

From now on, we will focus on the compensation of the structure resonance $\nu_x - 2\nu_y = -21$. Since the MR has three-fold symmetry and $K_2 = 0$ in the straight sections, the

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resonance driving term $G_{1,-2,-21}$ [8] can be written as

$$G_{1,-2,-21} = \frac{\sqrt{2}}{8\pi} \oint \beta_x^{1/2} \beta_y K_2 e^{i[\psi_x - 2\psi_y]} ds \tag{2}$$

$$= 3\frac{\sqrt{2}}{8\pi} \int_{\text{one arc}} \beta_x^{1/2} \beta_y K_2 e^{i[\psi_x - 2\psi_y]} ds, \tag{3}$$

where ψ_u is the phase advance. Since one arc section is made of 8 modules in the MR, defining the phase advance in one module as

$$\Delta\psi_{\text{mod},u} \equiv \psi_u(s + L_{\text{mod}}) - \psi_u(s) \tag{4}$$

and using Eq. (1), $G_{1,-2,-21}$ becomes

$$G_{1,-2,-21} = 3\frac{\sqrt{2}}{8\pi} \int_s^{s+L_{\text{mod}}} \beta_x^{1/2} \beta_y K_2 e^{i[\psi_x - 2\psi_y]} ds \times \sum_{k=0}^{7} e^{ik[\Delta\psi_{\text{mod},x} - 2\Delta\psi_{\text{mod},y}]}. \tag{5}$$

This equation indicates that the resonance driving term $G_{1,-2,-21}$ can be canceled by setting

$$\Delta\psi_{\text{mod},x} - 2\Delta\psi_{\text{mod},y} = \frac{2\pi j}{8} \quad (j \in \mathbb{Z},\ j/8 \notin \mathbb{Z}). \tag{6}$$

We made a new optics with

$$(\Delta\psi_{\text{mod},x}, \Delta\psi_{\text{mod},y}) = 2\pi(\frac{3}{4}, \frac{11}{16}). \tag{7}$$

The horizontal phase advance was not changed to keep the arc section achromat.

Verifications of Compensation

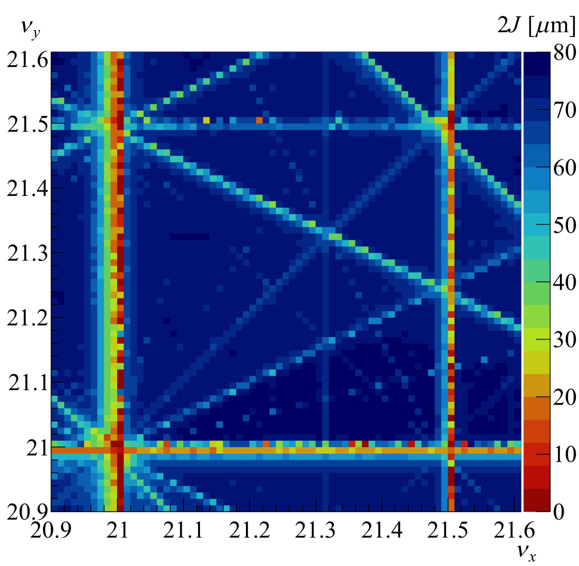

Figure 2: Aperture Survey with the new-arc optics [4].

Figure 2 shows the result of the aperture survey simulation with the new-arc optics. The tune was changed only with the quadrupole magnets in the straight section to maintain Eq. (7). It is clear that the third-order structure resonance $\nu_x - 2\nu_y = -21$ was well weakened. Although there can be seen residual effects of $\nu_x - 2\nu_y = -21$, they were derived from imperfections of magnets. The resonance $\nu_x - 2\nu_y = -21$ remained as a nonstructure resonance. The effect of $\nu_x - 2\nu_y = -21$ vanished in the simulation without errors.

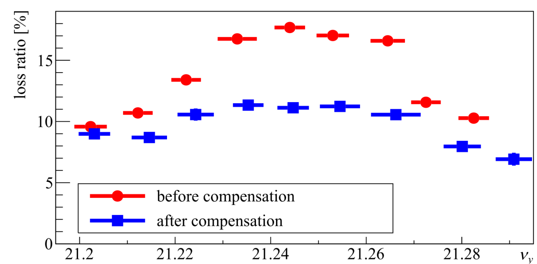

Figure 3: Measured beam loss ratio before (red) and after (blue) the compensation in each tune [4].

The compensation was also demonstrated with several experiments in [4]. Here we briefly introduce one of them. The beam loss scans were performed crossing the resonance $\nu_x - 2\nu_y = -21$ with present FX optics (before compensation) and with new-arc optics (after compensation). In both optics, the horizontal tune was set to $\nu_x = 21.44$, and the vertical tune was changed. The beam intensity was set to 2.3×10^{13} ppb, and the collimator aperture was set to 40π mm mrad both in horizontal and vertical planes. The beam circulated 130 msec in the MR, which corresponded to 24000 turns. The direct-current current transformer (DCCT) was used to evaluate the beam loss. We defined the beam loss ratio as the ratio of decreased current in 130 msec to the injection current.

Figure 3 shows the results of the beam loss scans. In the result before compensation, the beam loss took the maximum value at around $\nu_y = 21.24$. It indicated the effects of the resonance $\nu_x - 2\nu_y = -21$. On the other hand, in the result after compensation, the peak was well suppressed. It indicated the resonance $\nu_x - 2\nu_y = -21$ was weakened with the new-arc optics.

NONSTRUCTURE RESONANCES

Compensation of Nonstructure Resonances

In FX operation, the third-order nonstructure resonances $3\nu_x = 64$ and $\nu_x + 2\nu_y = 64$ have significant effects on the beam. In the MR, four trim coils of the sextupole magnets are installed to compensate them simultaneously [2].

Principle Since the resonance driving term is a complex number, it can be canceled by applying two free parameters in principle. For example, when the resonance driving term $G_{3,0,64}$ is canceled by two trim coils at $s = s_A, s_B$, the condition can be written as follow:

$$\frac{\sqrt{2}}{24\pi} \sum_{j=AB} \beta_{x,j}^{3/2} \Delta(K_2 L)_j e^{i3\psi_{x,j}} + G_{3,0,64} = 0, \tag{8}$$

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where $\beta_{u,j}$ is the betatron function at $s = s_j$, $\Delta(K_2L)_j$ denotes the sextupole magnetic field strength by the trim coils, and $\psi_{u,j}$ is the phase advance. In this equation, we removed the integration by approximating $L \ll 1$.

To compensate two nonstructure resonances $3\nu_x = 64$ and $\nu_x + 2\nu_y = 64$ at the same time, four trim coils at $s = s_A, s_B, s_C, s_D$ should meet the following conditions:

$$\frac{\sqrt{2}}{24\pi}\sum_{j=ABCD}\beta_{x,j}^{3/2}\Delta(K_2L)_j e^{i3\psi_{x,j}} + G_{3,0,64} = 0, \tag{9}$$

$$\frac{\sqrt{2}}{8\pi}\sum_{j=ABCD}\beta_{x,j}^{1/2}\beta_{y,j}\Delta(K_2L)_j e^{i(\psi_{x,j}+2\psi_{y,j})} + G_{1,2,64} = 0. \tag{10}$$

These equations can be solved as

$$\begin{pmatrix}\Delta(K_2L)_A\\ \Delta(K_2L)_B\\ \Delta(K_2L)_C\\ \Delta(K_2L)_D\end{pmatrix} = -\frac{8\pi}{\sqrt{2}}(\vec{V}_A,\vec{V}_B,\vec{V}_C,\vec{V}_D)^{-1}\begin{pmatrix}3\mathrm{Re}[G_{3,0,64}]\\ 3\mathrm{Im}[G_{3,0,64}]\\ \mathrm{Re}[G_{1,2,64}]\\ \mathrm{Im}[G_{1,2,64}]\end{pmatrix}, \tag{11}$$

$$\vec{V}_j = \begin{pmatrix}\beta_{x,j}^{3/2}\cos(3\psi_{x,j})\\ \beta_{x,j}^{3/2}\sin(3\psi_{x,j})\\ \beta_{x,j}^{1/2}\beta_{y,j}\cos(\psi_{x,j}+2\psi_{y,j})\\ \beta_{x,j}^{1/2}\beta_{y,j}\sin(\psi_{x,j}+2\psi_{y,j})\end{pmatrix}. \tag{12}$$

The matrix $(\vec{V}_A,\vec{V}_B,\vec{V}_C,\vec{V}_D)$ should be regular.

Experiments First, the tune scans were performed to search for the on-resonance conditions. We set the tune where the beam loss took the maximum value. Although the bare tune was not on each resonance, we expect that the tune including the space charge effects was on each resonance. Second, the currents of two trim coils were scanned to minimize the beam loss. The resonance driving term $G_{3,0,64}$ was calculated by Eq. (8), and $G_{1,2,64}$ was also obtained by the same method. Then, using Eqs. (11) and (12), the trim coils were set to compensate the resonances simultaneously.

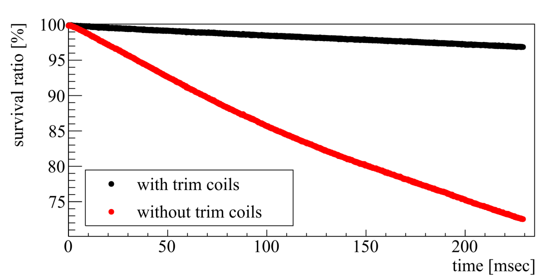

Figure 4: Beam survival ratio as a function of circulating time with and without the trim coils.

It is true that the beam loss is reduced by applying the values from Eqs. (11) and (12), however, they are not the best values in many cases. One reason is that there might be some systematic errors in measuring $G_{3,0,64}$. The beam might be affected not only by $3\nu_x = 64$ but also by $\nu_x + 2\nu_y = 64$ because of its large space charge tune spread. Therefore, all trim coils were scanned and optimized to minimize the beam loss.

Figure 4 shows the beam survival ratio with and without trim coils. The beam survival was clearly recovered by applying the trim coils.

Sources of Nonstructure Resonances

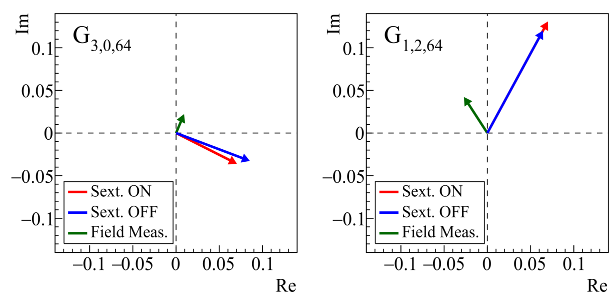

Figure 5: Resonance driving terms $G_{3,0,64}$ and $G_{1,2,64}$.

The field strengths of all bending, quadrupole, and sextupole magnets in the MR were measured [9]. The resonance driving terms $G_{3,0,64}, G_{1,2,64}$ calculated by the measured field strengths are shown as green arrows in Fig. 5. However, resonance driving terms calculated by optimized currents of the trim coils, shown as red arrows, are different. It suggests that there are other sources for the nonstructure resonances.

To evaluate the contributions of the sextupole magnets to the resonances, the resonance driving terms were also measured with turning off the sextupole magnets by scanning the trim coils. The results are shown as blue arrows in Fig. 5. Compared with the red arrows, it indicates that the contributions of the sextupole magnets to the nonstructure resonances are relatively small. Further study is needed to specify the main sources of the nonstructure resonances.

CONCLUSIONS

Compensations of the resonances have been studied in the J-PARC MR. The third-order structure resonance $\nu_x - 2\nu_y = -21$ was compensated using the new-arc optics. It was demonstrated by the aperture survey simulations and by the beam loss measurements. The influences of the new-arc optics on other resonances are under studying. The third-order nonstructure resonances $3\nu_x = 64$ and $\nu_x + 2\nu_y = 64$ were compensated simultaneously by using trim coils of the sextupole magnets. The beam survival was recovered by the compensations. By measuring the resonance driving terms with turning on/off the sextupole magnets, it was found that the contributions of the sextupole magnets to the resonances were relatively small.

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