OCTUPOLE MAGNETS FOR THE INSTABILITY DAMPING AT THE J-PARC MAIN RING

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Abstract

Octupole magnets have been installed for the instability damping at the main ring of the Japan Proton Accelerator Research Complex. The transverse instability was observed during the injection and acceleration periods and caused the beam losses. The chromaticity tuning and bunch-by-bunch feedback system have been applied to suppress the instability. Octupole fields were observed to be effective for the instability damping. The beam loss, however, was observed because of the dynamic aperture reduction. A plan to install more octupole magnets has been made to recover the dynamic aperture.

INTRODUCTION

The main ring of the Japan Proton Accelerator Research Complex (J-PARC) has been providing high intensity proton beams to the nuclear and elementary particle physics experiments such as the T2K neutrino oscillation experiment. Eight proton bunches of the kinetic energy of 3 GeV are injected during the injection period of 0.17 s and accelerated to 30 GeV in 1.4 s. The high intensity operation of 1.1×10^{13} protons per bunch (ppb) has been achieved for the fast extraction operation.

One of the obstacles to achieve the high intensity is the transverse instability [1]. It is observed during the injection and acceleration periods and causes the beam losses. The transverse instability occurs with the beam intensity of 0.5×10^{13} ppp or more with the condition of full chromaticity correction. It has been suppressed with the chromaticity tuning. The chromaticity is set to typically about –4 during the injection for both horizontal and vertical tunes. It is optimized to be about –2 for 0.1 s at the beginning of the acceleration, because the chromatic tune spread seems to cause the beam loss if the chromaticity is not corrected well. The chromaticity is set to typically about –4 during the rest of the acceleration period to suppress the transverse instability.

The bunch-by-bunch feedback system with the strip line kickers has also been applied to suppress the instability [2]. It effectively damps the transverse instability and improves the beam loss. It has been indispensable for the high intensity operation.

The non-linear magnetic field of the octupole magnets creates a tune shift that depends on the amplitude of the betatron oscillation. The instability should then be suppressed with the Landau damping effect. The side effect of the dynamic aperture reduction is, however, anticipated. Three octupole magnets were installed during the summer shutdown of 2011. We will describe the beam test results and the proposal of installation of more octupole magnets to recover the dynamic aperture.

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AMPLITUDE DEPENDENT TUNE SHIFT

The tune shift that is necessary to suppress the instability is expressed as

$$\Delta\nu \gg \frac{1}{2\pi n} \approx \frac{1}{2\pi 190} = 0.001, \qquad (1)$$

if the growth rate is 1 ms (~190 turn). The magnetic field gradient of the octupole magnet is related with the tune shift as

$$\Delta\nu_x = \frac{1}{2\pi}\frac{1}{16}\frac{1}{(B\rho)}\frac{\partial^3 B}{\partial x^3}\{\beta_x^2\varepsilon_x - 2\beta_x\beta_y\varepsilon_y\}\Delta s, \qquad (2)$$

$$\Delta\nu_y = \frac{1}{2\pi}\frac{1}{16}\frac{1}{(B\rho)}\frac{\partial^3 B}{\partial x^3}\{\beta_y^2\varepsilon_y - 2\beta_x\beta_y\varepsilon_x\}\Delta s. \qquad (3)$$

The available installation places were decided for the octupole magnets at each one of the three straight sections (Fig. 1). We considered that the places with zero dispersion were preferable and three-fold symmetry of the main ring should be maintained. The betatron amplitude functions are βx=12.06 m and βy=23.51 m. When the horizontal amplitude εx=54π mmrad, the vertical amplitude εy=0π mmrad, the magnetic field gradient of the octupole magnet is $\partial^3B/\partial x^3$=1000 T/m^3 and the magnet length Δs=0.2m, three octupole magnets make the tune shift of Δνx= 0.0036. This satisfies the condition of Eq. 1 and these parameters of the field gradient and magnet length are then required for the octupole magnets.

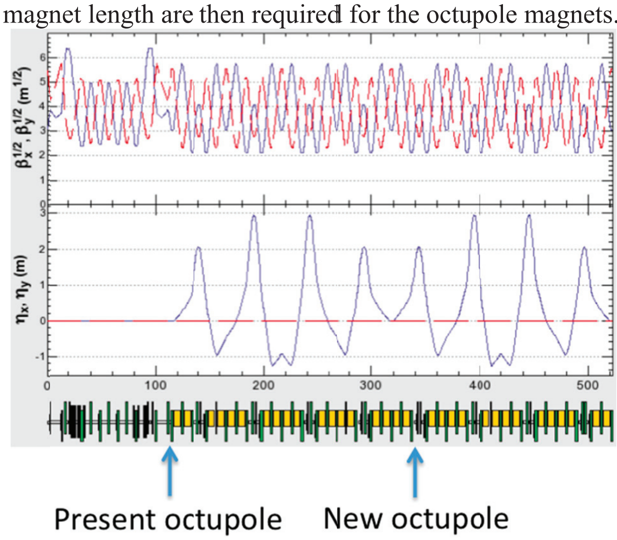

Figure 1: The betatron amplitude function and dispersion function of one super period (one-third) of the main ring and the present installation place for the octupole magnet and new installation place that will be mentioned in the later section.

The tune shift was also calculated with a particle tracking program, SAD. Ten particles with the horizontal betatron amplitude of εx=8.1π ~ 81π mmmrad and

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vertical amplitude of εy=0π mmmrad, the x-px phase space distribution were calculated for 100 turns at the reference point in the main ring. The amplitude dependent tune shift was calculated for each particle from the phase space distribution.

There are 72 sextupole magnets for the chromaticity correction in the main ring. The sextupole fields will not contribute to the amplitude dependent tune shift in linear approximation. The second order effect [3], however, makes the amplitude dependent tune shift as shown as the red symbols in Fig. 2. The tune shift with both the sextupole magnets and octupole magnets was calculated as shown as the blue symbols in Fig. 2. The calculation results for the tune shift with the SAD calculation are in good agreement with the results from Eq. 2.

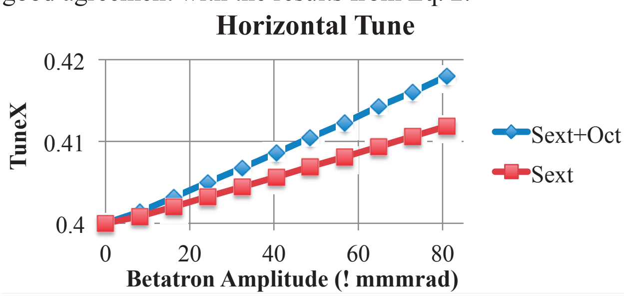

Figure 2: Amplitude dependent tune shift with the sextupole magnets (red symbols) and with both sextupole and octupole magnets (blue symbols).

OCTUPOLE MAGNETS

For J-PARC we reuse octupole magnets those have been used at KEK-PS for their head-tail instability damping. Because they were manufactured 35 years ago, we have tested the magnets including the magnetic field measurements. The bore diameter is 140 mm and the length is 0.2 m. The core is made of solid iron.

The magnetic fields of the all three octupole magnets were measured with a hall probe and x-y movable stage. The field gradient $\partial^3 B / \partial x^3$ was measured to be 973 T/m^3 when the current was 1 A. From the measurement the coil was probably winded about 700 turn per pole with 2mm^2 copper wire. The resistance was 18 Ω. The field uniformity is within 1 % for the x range of –60 mm to +60 mm. The allowed multipole of 24-pole was observed within 0.7 % of the main octupole component. The measurement was performed with a rotationally movable stage as shown in Fig. 3.

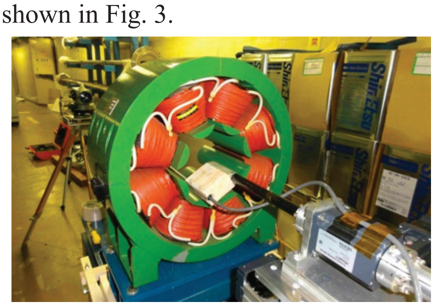

Figure 3: The octupole magnet and magnetic field measurement devices.

We have installed the three octupole magnets in the main ring in the summer of 2011. They were aligned within the position accuracy of 0.1 mm and the rotation accuracy of 0.2 mrad.

BEAM TEST RESULTS

The instability damping with the octupole magnets has been demonstrated at the beginning of acceleration with eight-bunch beam of 1.2×10^{13} ppb. We observed vertical instability when the chromaticity was fully corrected form the beginning of acceleration (P2) to P2 + 0.1 s. Fig. 4 shows the difference of the right and left beam position monitor (BPM) signals for the horizontal differential signal and the difference of the top and bottom BPM signals for the vertical difference signal with the octupole magnet current of 1 ~ 3 A. Vertical coherent oscillation is observed the octupole manget current of 1 A. The oscillation is smaller when the current is 2 A. The instability is not observable with the current of 3 A. During the injection period, the chromaticity was being set to –4 and the instability was then suppressed.

The beam loss, however, was observed with the octupole magnets. The reduction of the dynamic aperture with the octupole field is the cause of the beam loss.

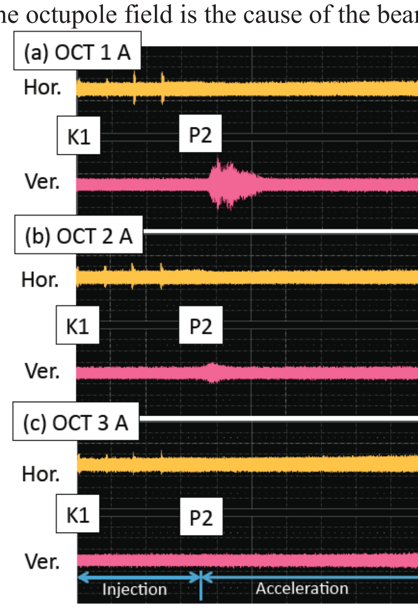

Figure 4: The difference of the right and left beam position monitor (BPM) signals for the horizontal differential signal (yellow) and the difference of the top and bottom BPM signals for the vertical difference signal (red) as a function of time (50 ms per div.) with the octupole magnet current of 1 A (a), 2 A (b) and 3 A (c).

DYNAMIC APERTURE

Nonlinear field of the octupole magnet reduces the dynamic aperture. We have studied the aperture with the particle tracking program, SAD. Ten particles with both the horizontal and vertical Courant-Synder invariant εx = εy = 8.1 ~ 81π mmmrad were tracked with the consideration of the magnet errors of multipole components and alignment errors with the SAD model of

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the main ring. The multipole components were based on the magnetic field measurements. The alignment errors in this model were assumed to be random numbers with Gaussian distributions of the standard distribution of 0.1 mm. The score was counted for the number of survival particle out of the initial ten particles after 1000 turns with the acceptance cut of 81π mmmrad at the reference point. Figure 5 shows the aperture score without octupole magnets. The sextupole magnets for the chromaticity correction were included in the model. Linear coupling resonances and third order resonances are visible. They have been observed with the tune scan of the beam survival measurement.

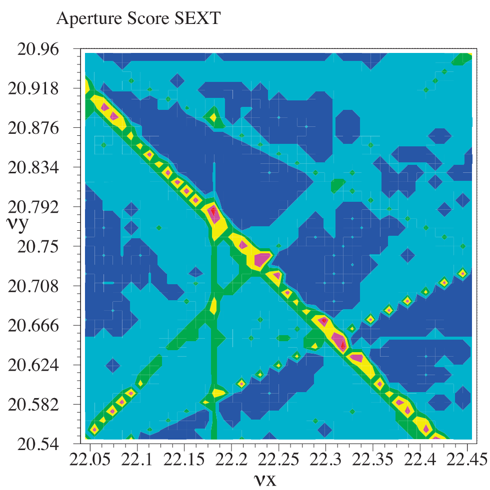

Figure 5: Available apertures without octupole magnets are shown in each color for the horizontal tune of 22.04~22.46 and the vertical tune of 20.54~20.96. Ten particles with the Courant-Snyder invariant of εx = εy = 8.1 ~ 81π mmmrad were tracked for 1000 turns. The aperture score is the number of survived particles with the cut of 81π mmmrad. The color of the tune area is blue if the score is 9. The color of sky blue is for 8, green for 7, yellow for 6, pink for 5, red for 4 and black for 3 or less.

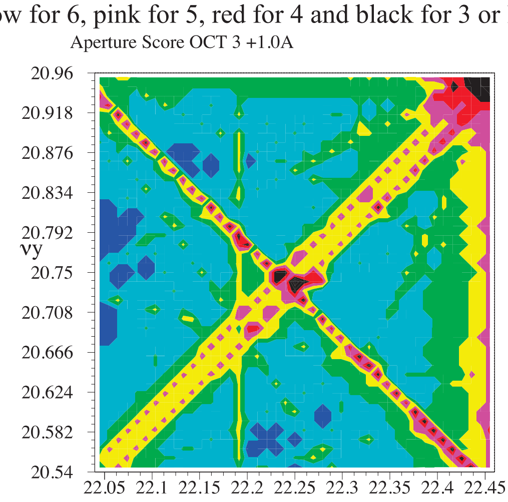

Figure 6: Available apertures with three octupole magnets.

Figure 6 shows the aperture score with three octupole magnets. The structure resonances of 2νx – 2νy = 3 and 4νx = 90 is created with the octupole field even with the three fold symmetry of the main ring.

Installation of three more octupole magnets has been proposed to cancel the structure resonances. The new installation place in each super period has been chosen to be in one of the missing bend cells (Fig. 1) with the consideration of the phase advances of both 2ϕx − 2ϕy and 4ϕx between the present octupole magnet and new magnet. The field gradient of the new magnet should be twice of the present magnet for the resonance cancellation. The amplitude dependent tune shift in the new scheme with the present magnets of 0.5 A and the additional magnets of 1 A is same as that in the present scheme with 1 A. Figure 7 shows the aperture score with the new scheme. The improvement is observed on the structure resonance lines and the vicinity.

The effect of non-zero dispersion for the additional magnets was studied with the SAD tracking of off-momentum particles of δp/p = 0.5%. The aperture near the operation tune turned out to be maintained.

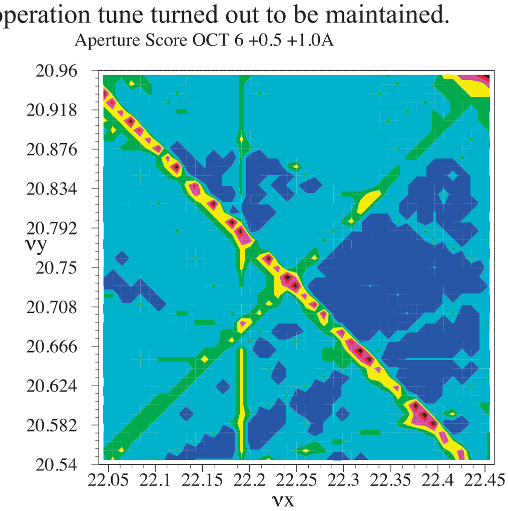

Figure 7: Available apertures with six octupole magnets.

SUMMARY

Octupole fields were observed to be effective for damping of the transverse instability that emerged during the injection and acceleration period at the main ring of the J-PARC. The beam loss, however, was observed because the nonlinear field reduced the dynamic aperture. A plan to install more octupole magnets has been proposed to recover the dynamic aperture.

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