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STUDY FOR SPACE CHARGE EFFECT IN TUNE SPACE AT J-PARC MR

K. Ohmi, S. Igarashi, Y. Sato, KEK, 1-1 Oho, Tsukuba, 305-0801, Japan
H. Harada, JAEA, Muramatsu, Tokai, 319-1112, Japan

Abstract

J-PARC MR has been operated at tune operating point (ν_x, ν_y)=(22.40, 20.75). Tune spread due to space charge force makes overlap a sum resonance on linear x-y coupling $\nu_x+\nu_y=43$. Changing the operating point is one of possible measure to avoid the resonance. We study beam loss due to space charge force in various tune operating point.

INTRODUCTION

J-PARC MR has been injected proton beam $1.3\text{x}10^{13}$ ppb times 8 bunches (200 kW) [1] and is ready for high power beam more than $2\text{x}10^{13}$ ppb in June 2014 due to Linac upgrade. The design value is $4\text{x}10^{13}$ ppb (1 MW). MR has been operated at tune operating point (ν_x, ν_y)=(22.40, 20.75). Increasing space charge tune spread, a linear sum resonance $\nu_x+\nu_y=43$ becomes serious. An effort to suppress the resonance, in which 4 skew quadrupoles are installed, is achieving good results at the present beam intensity $1.3\text{x}10^{13}$ ppb [2]. However our final goal $4\text{x}10^{13}$ ppb is too far, therefore we have to prepare other options.

Changing the operating point far from the resonance is one of possible measure. Tune survey for the beam loss caused by space charge effects indicated three candidates of the new operating points. Characteristics of their tune operating points are discussed.

TUNE SURVEY

Beam loss simulation in transverse tune space has been performed using a code 'SCTR' [3]. The bunch population is $2.5\text{x}10^{13}$ ppb as a present target of MR operation. Beam distribution is assumed 40π µm parabolic in transverse and longitudinal bunching factor 0.2. The space charge tune shift is -0.62. Transverse aperture is set to 64 π µm, while maximum is around 80 π µm. Frozen model, in which the space charge potential is calculated once and stored every meter in the first turn, is used to complete simulations at many tune points. Tracking simulations are carried out 5,000 turns, while in real MR beam circulates 22,000 turns at the injection energy 3GeV and 90,000-260,000 turns during acceleration to 30 GeV. It is highest priority to find best/better operating point, but not accurate prediction of the beam loss.

Figure 1 shows simulated beam loss map in transverse tune space $20<\nu_x<23$, $20<\nu_y<22$. Green/red points indicate the beam loss <0.001%/0.5% in 5,000 turns. Magenta points indicate very high >10%. Tune adjust is performed using SAD. Tune adjust was failure in the light blue area. The present operating point (22.40, 20.75) is marked with blue point. Structure resonances up to 4-th order are drawn by thick lines, where MR has three super-periodicity. Non-structure resonances near present point are drawn by thin lines. Several candidates of operating points are found: areas of (0) the present tune (22.40, 20.75), (1) (21.40, 21.40) and (2) (20.90, 20.90). Third point (3) (22.4, 22.4) is discussed later. We study these operating points in detail in the rest of this paper.

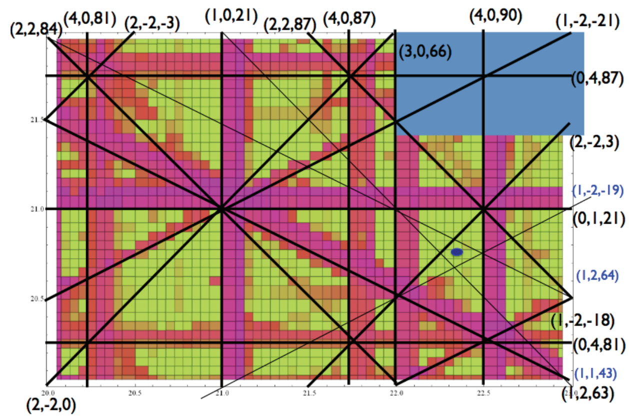

Figure 1: Simulated beam loss in tune space $20<\nu_x<23$, $20<\nu_y<22$.

LINEAR X-Y COUPLING CORRECTION

In a real accelerator, errors are indispensable. Misalignment and field strength errors make distortion of linear optics. Nonlinear dynamics of beam is characterized by integrals of nonlinear field strength and beta function/phase such as

$$K_{n-1}x^n \xrightarrow{yields} \oint K_{n-1}\beta_x^{n/2}\exp\left(-in\phi_x\right)ds$$

where $K_n = eB^{(n)}l/p_0$ for magnet with n-th order field derivative and the length l. Betatron phase error induces non-structured resonances. When x-y coupling exists, x is replaced by $x-r_4y+r_3p_y$, where $r_{1\text{-}4}$ is Twiss parameters characterize x-y coupling [4]. Skew resonance terms appear from $(x-r_4y+r_3p_y)^n$ such as x^2y. To suppress the skew resonances, x-y coupling at all sextupole magnets should be removed. Since it is too hard, people focus to suppress the coupling resonance driving terms,

$$S_\pm = \frac{1}{2}\int_s^{s+L} k_{sq}\sqrt{\beta_x\beta_y}\sin\phi_\pm\,ds$$

$$C_\pm = \frac{1}{2}\int_s^{s+L} k_{sq}\sqrt{\beta_x\beta_y}\cos\phi_\pm\,ds$$

where k_{sq} is strength of skew quadrupole component due to errors and $\phi_\pm = \phi_x \pm \phi_y$ is sum or difference of the horizontal and vertical betatron phases. The driving terms at s is related to Twiss parameters $r_{1\text{-}4}(s)$. They are compensated by skew quadrupole magnets. For example to compensate sum resonance, two skew quadrupoles

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$k_{sq}\sqrt{\beta_x\beta_y}$ =–$2C_+$, and $-2S_+$ installed at s and location with phase differences, $\Delta\phi_x = 0.25\times 2\pi$, $\Delta\phi_y = 2\pi$. Using 4 skew quadrupole magnets all driving terms at s can be deleted. This coupling correction does not mean x-y coupling is removed perfectly: that is, Twiss parameters $r_{1\text{-}4}$ at sextupole magnets are not zero. Twiss parameter $r_{1\text{-}4}$ contains variations with the frequency components $\phi_x \pm \phi_y$ along s. The amplitude of the frequency components is set to zero at s. This results suppression of $r_{1\text{-}4}$ in the whole ring generally. The suppression depends on location of error source and correction skew magnets.

In experiments, skew quadrupoles are set to minimize beam loss for a low intensity beam (~10^{12} ppb) near the resonance line [2].

CHARACTERISTICS OF TUNE OPERATING POINTS

(ν_x, ν_y)=(22.40, 20.75) Area

J-PARC MR has been operated in this tune area since start of operation. This area is one of best in the tune scan using ideal lattice as shown in Fig.1. The loss map changes, when alignment and strength/multipole errors in magnets are taken into account. Figure 2 shows beam loss map in this area taking into account errors. The errors are given by actual alignment of magnets in MR ring and field measurement of each magnet. Left and right pictures depict loss map with and without coupling correction, respectively. We can see that sum resonance of linear coupling ν_x+ ν_y=43 is serious for high intensity, and the coupling correction works reasonably, though not perfect.

The initial parabolic distribution is step function for J_x+J_y. The density is constant in the triangle area surrounded by $2J_x$+$2J_y$=40. The edge of the step distribution is broken due to space charge force repeating turns. Figure 3 shows beam distribution in J_x-J_y space after 5,000 turns for the case of no errors. Right picture is depicted with fine scale to focus hallo distribution. No particles arrive at the aperture limit $2J_{xy}$=64 yet.

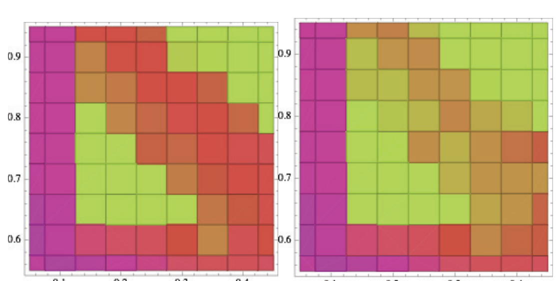

Figure 2: Beam loss map in (22.40, 20.75) area taking into account errors. Left and right pictures depict loss map with and without coupling correction, respectively.

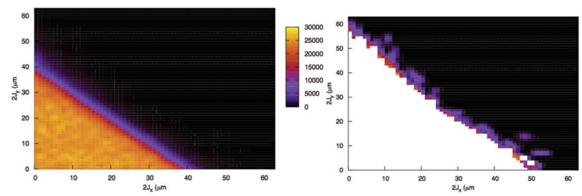

Figure 3: Beam distribution in J_x-J_y space after 5,000 turns for the case of no errors at (22.40, 20.75).

Figure 4 shows beam distribution in J_x-J_y space after 5,000 turns taking into account the errors. Clear hallo formation toward J_x~J_y direction is seen. In the fine scale, some particles are lost beyond the aperture limit $2J_{xy}$=64. Figure 5 shows beam distribution taking into account the errors and the coupling correction. The hallo seen in Fig.4 is reduced, but is not changed by the coupling correction qualitatively.

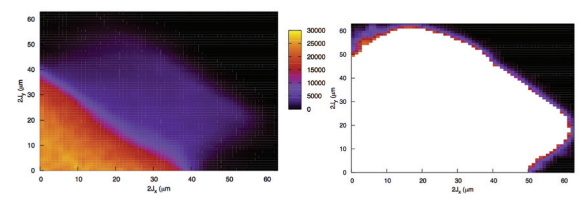

Figure 4: Beam distribution in J_x-J_y space after 5,000 turns taking into account the errors at (22.40, 20.75).

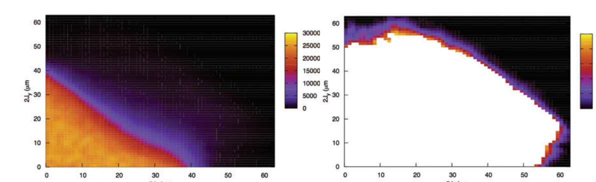

Figure 5: Beam distribution in J_x-J_y space after 5,000 turns taking into account the errors and the coupling correction at (22.40, 20.75).

(ν_x, ν_y)=(21.40, 21.40) Area

This area is a candidate of new operating point in J-PARC MR. Figure 6 shows beam loss map taking into account the errors and the coupling correction. A structure resonance ν_x-$2\nu_y$=21 is seen with/without the errors and correction. Other resonances do not appear in this area. Degradation due to errors is not strong compare with Fig.1. The performance is independent of the coupling correction. Figure 7 shows beam distribution in J_x-J_y space taking into account the errors. Hallo seen in Figs. 4 and 5 is not seen in this operating point.

We control tune by changing quadrupole magnets in straight section where collimators are installed. Reducing tune, increase of beta function limits the collimator acceptance <80π μm. Replacement of collimators is required to guarantee the acceptance 80π μm.

The same studies have been performed in (20.9, 20.9) area. The performance and beam distribution was similar. Smaller tune gave higher beta at collimators. Operation

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near integer may arise difficulties, for example close orbit control and management of the resistive wall instability.

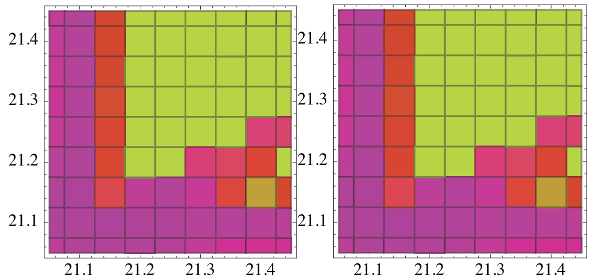

Figure 6: Beam loss map in (21.4, 21.4) area taking into account errors. Left and right pictures depict loss map with and without coupling correction, respectively.

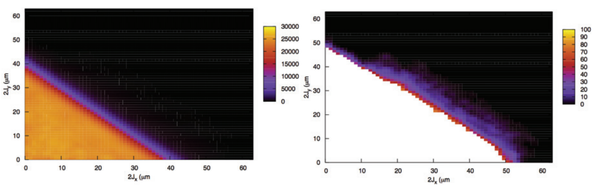
Figure 7: Beam distribution in J_x-J_y space after 5,000 turns taking into account the errors at (21.38, 21.40).

(ν_x, ν_y)=(22.40, 22.40) Area

The area becomes available refinement of tune adjust strategy. Figure 8 shows beam loss map without and with errors. Resonance line ν_x =22.2 is seen. The resonance is slightly enhanced by the errors.

Figure 9 shows beam distribution in J_x-J_y space taking into account the errors. Hallo is not seen in this operating point.

The horizontal tune is the same as the present operating point, while the vertical tune is higher. Beta functions at collimators are similar as those of the present operating point. Vertical beta function is squeezed compare than the present. The acceptance 80π μm is guaranteed. Since strength of quadrupoles at the straight section is stronger, power supply of magnets is severe near the top energy. The power supplies are required to be revised.

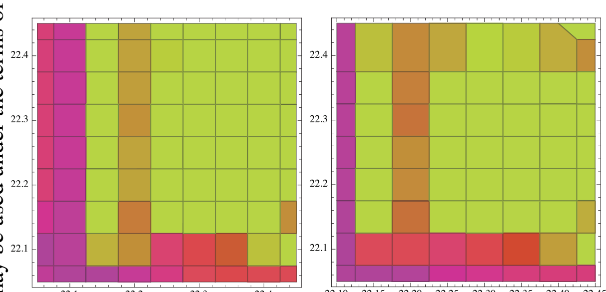
Figure 8: Beam loss map in (22.4, 22.4) area. Left and right pictures depict loss map without and with errors, respectively.

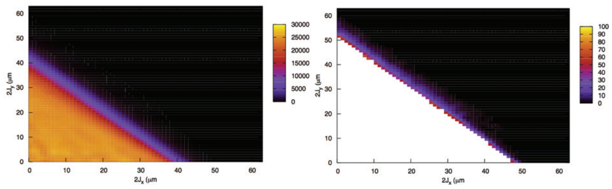
Figure 9: Beam distribution in J_x-J_y space after 5,000 turns taking into account the errors at (22.38, 22.40).

SUMMARY AND CONCLUSIONS

Space charge simulations using frozen model have been performed to search new operating point of J-PARC MR. The present operating point is one of the best. Correction of x-y coupling is key issue for higher intensity. Achievable performance depends on the source and correction scheme of the coupling.

Three candidates, (ν_x, ν_y)= (21.4,21.4), (20.9,20.9) and (22.4, 22.4), are proposed for new operating point. Beam loss due to space charge effect little depends on errors of magnet alignment at the operating points.

Collimator acceptance decreases for (21.4,21.4) and (20.9,20.9). For (22.4,22.4), the collimator acceptance is enough, but power supply should be revised. We decide which direction is the best, with experiences of beam operation and machine developments/studies.

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REFERENCES

[1] T. Kosei et al., PTEP 2012, 02B004 (2012).
[2] J. Takano et al., proceedings of 2012 annual meeting of Particle Accelerator Society of Japan (in Japanese). To be published in English.
[3] K. Ohmi et al., Proceedings of HB2012, THO1B03.
[4] K. Ohmi et al., Phys. Rev. E49, 751 (1994).