ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS024

TUNE SHIFTS AND OPTICS MODULATIONS IN THE HIGH INTENSITY OPERATION AT J-PARC MR

T. Yasui*, The University of Tokyo, Tokyo, Japan
S. Igarashi, Y. Sato, K. Satou, K. Ohmi, T. Koseki[1], KEK, Tsukuba, Japan
[1]also at The University of Tokyo, Tokyo, Japan

Abstract

The space-charge effect to the tune shift was measured at the injection process of the Main Ring of Japan Proton Accelerator Research Complex. It was evaluated by measuring the quadrupole oscillations at the mismatched injection. The results were reproduced by the space-charge tracking simulations. The incoherent tune shift and the modulation of the betatron function by the space-charge were simulated for the benchmark of the simulator. The results were in good agreement with the analytical calculations. For the beam intensity of the neutrino user operation, the betatron function can be modulated 20% at low action.

INTRODUCTION

In the Main Ring (MR) of Japan Proton Accelerator Resserch Complex (J-PARC) [1], the high intensity proton beam is made for the neutrino experiments and the nuclear experiments. The proton beam is injected in MR with 3.3×10^{13} protons per bunch (ppb) [2]. It is extracted with 2.6×10^{14} protons per pulse (ppp) and about 1.5% of the beam loss is observed in the neutrino operation [2]. Efforts have been made for beam loss reduction. One of the reasons for the beam loss is the mismatch of the Twiss parameters at the injection.

In this paper, we aimed at understanding the space-charge effects for the injection matching parameters, in order to obtain optimized Twiss matched parameters. First, the coherent tune shifts were evaluated by measuring the quadrupole oscillations. The quadrupole oscillations reflect the space-charge effects and the dipole oscillations do not. The tune shifts were calculated by obtaining the differences of the tunes from the dipole oscillations and those of the quadrupole oscillations. The results were reproduced by the simulations. Second, the tunes and the Twiss parameters of the indivisual particles in the beam were evaluated by the simulations and by the analytical calculations. The tunes and the Twiss parameters of the individual particles depend on their actions because they feel the space-charge forces and the sextupole fields forces.

MEASUREMENT OF COHERENT TUNE SHIFT BY QUADRUPOLE-MODE OSCILLATIONS

Principles

The decimal parts of the betatron tune ν_{di} is same with the frequency of the dipole oscillation f_{di}. On the other hand,

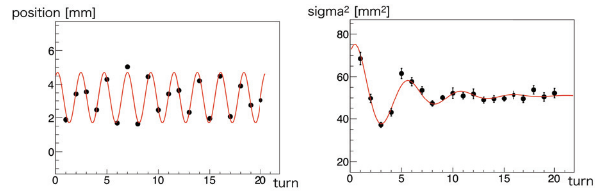

Figure 1: The beam center positions (left) and beam sizes (right) per turn. The plots are the data from the IPMs and the red lines are the fits for them.

the frequency of the quadrupole oscillation also depends on the betatron tune. The betatron tune can be written as $\nu_{quad} = (1 - f_{quad})/2$ by aliasing. It was observed that ν_{di} was slightly different from ν_{quad} in J-PARC MR. It is interpreted that ν_{quad} reflected the space-charge effects and ν_{di} did not, because the space-charge force was internal force. In this paper, the tune shift is defined as $\Delta\nu \equiv \nu_{di} - \nu_{quad}$.

Methods

The center positions and the sizes of the beams were measured every turn by the profile monitors. The profile monitors used in the experiments were Residual Gas Ionization Profile Monitors (IPMs) [3] and Multi-Ribbon Profile Monitor (MRPM) [4].

IPMs collect ions or electrons derived from ionization between beams and residual gas. In this measurements, ions were used. The signals from the collected ions were enhanced by the micro channel plate and the secondary electron current were measured to acquire the beam profiles. There are two IPMs in MR, for horizontal profiles and for vertical ones.

The MRPM in MR is made of thin ribbons lined up at equal intervals. It collects electrons emitted from the surfaces of ribbons when the beams hit them, and measures the secondary electron current. The ribbons for the horizontal profiles are graphite with 3.0 mm width and 3 μm thick. Those for the vertical profiles are titanium with 1.5 mm width and 1 μm thick. The pitches of ribbons are 4.5 mm in horizontal direction and 2.5 mm in vertical direction.

The measurements by IPMs and those by MRPM were performed individualy. The horizontal and vertical betatron tunes were $(\nu_x, \nu_y) = (21.35, 21.43)$ which were same with the neutrino user operation. The single bunch beams were used and their intensities were changed from 0.6×10^{12} ppb to 4.8×10^{12} ppb. The chromaticities were adjusted around -3 to -7 taking care of the beam instability.

The injection errors and the mismatch in Twiss parameters were intentionally made to measure the both oscilla-

* tyasui@post.j-parc.jp

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS024

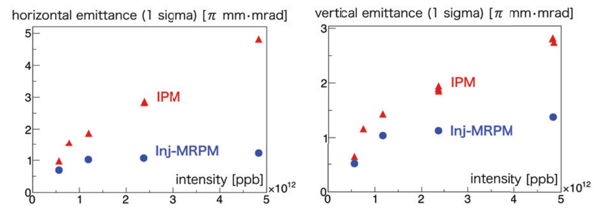

Figure 2: The horizontal (left) and vertical (right) emittances measured by the IPMs (red) and the MRPM (blue). The horizontal axises show beam intensity and the vertical axises show the emittances.

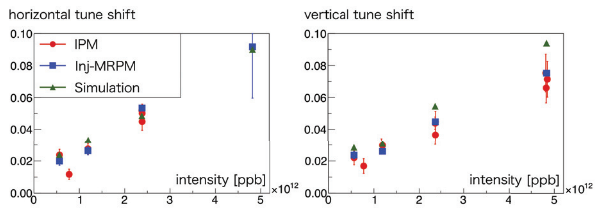

Figure 3: The horizontal (left) and vertical (right) tune shifts $\Delta\nu$ by the IPMs (red), by the MRPM (blue) and by SCTR (green). The horizontal axises show the beam intensity and the vertical axises show the tune shifts.

tions clearly. The center positions and the beam sizes were obtained by fitting the beam profiles with Gaussian distributions every turn. Figure 1 shows an example of dipole oscillations and quadrupole oscillations measured by the IPMs. The data were fitted by the function

$$g(x) = A\cos(2\pi f x + \phi)e^{-\eta x} + B \tag{1}$$

to get the frequencies.

Simulations were also performed by using Strategic Accelerator Design (SAD) [5] and Space-Charge TRacker (SCTR) [6]. SAD was used to obtain the basic optics settings and Twiss parameters. By SAD calculations, the beta functions at IPMs were estimated to be $\beta_{IPM,x}$ = 13.2 m, $\beta_{IPM,y}$ = 26.2 m, and those at MRPM were $\beta_{MRPM,x}$ = 17.0 m, $\beta_{MRPM,y}$ = 15.9 m.

SCTR is a tracking simulation code employing particle-in-cell algorithm taking the space-charge effect into account. The input beam distribution was set to Gaussian distribution in transverse direction and to parabola distribution in longitudinal direction. The initial conditions of the simulations were decided by the results of the MRPM. The initial longitudinal beam size was employed the data of Wall Current Monitors [7].

Results

Figure 2 shows the emittances measured by the IPMs and by the MRPM. It indicates that the differences of the emittances measured by the two profile monitors were larger as the beam intensity increased. IPMs overestimate the emittances because the distribution of collected ions spread by the space-charge effects before they reach the micro channel plate. Figure 3 shows the tune shifts by the IPMs, by the MRPM and by SCTR. The tune shift was larger at high intensity. The tune shifts by the IPMs and those by the MRPM matched in each intensity. The SCTR results also agreed with the experiments results. It confirms that the tune shifts came from the space-charge effects.

TUNE SHIFT AND OPTICS MODULATIONS

Motivations

The space-charge effect makes the modulations for Twiss parameters. The Twiss parameters may depend on the beam intensity for the injection optics matching. In case of Gaussian distribution, the space-charge force depends on the individual particle action. In this paper, the tunes and the beta functions were evaluated as the functions of the particle actions. The simulations were performed by SCTR. The results were confirmed by analytical calculations as the benchmarks of SCTR.

Methods

In the simulation, the input beams were set to Gaussian distribution in transverse direction and to parabola distribution in longitudinal direction. To minimize the effects of the synchrotron oscillation, test particles which had zero longitudinal amplitude were added and used to evaluate the tunes and the Twiss parameters. The tunes of test particles were obtained by calculating the phase advances in one turn. To obtain the Twiss parameters, 100 turns of the phase-space positions of each test particle were ploted, then fitted by

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = 2J. \tag{2}$$

For analytical calculations, the space-charge tune shift can be calculated by [8].

$$2\pi\Delta\nu_x = \frac{\lambda_p r_p}{\beta_{rel}^2\gamma_{rel}^3}\oint ds \frac{\beta_x}{\sigma_x^2}\int_0^\infty \frac{e^{-w_x-w_y}\,dt}{(2+t)^{3/2}(2r_{yx}+t)^{1/2}} \times [I_0(w_x) - I_1(w_x)]I_0(w_y), \tag{3}$$

where λ_p is line density of the beam, r_p is the classical radius of particles, σ_x, σ_y are the RMS beam size, $I_k(x)$ is the modified Bessel function, J_x, J_y are the actions of particles and

$$r_{yx} = \frac{\sigma_y^2}{\sigma_x^2}, \quad w_x = \frac{J_x\beta_x}{(2+t)\sigma_x^2}, \quad w_y = \frac{J_y\beta_y r_{yx}}{(2r_{yx}+t)\sigma_y^2}. \tag{4}$$

The beta functions were calculated analytically as follows. The transfer matrices of all the elements were obtained by SAD. The space-charge effect was appoximated as thin-lens. The transfer matrices of the space-charge effects were inserted in every element. Here the deforcusing forces of the space-charge transfer matrices were represented by the space-charge forces at zero action. The revolution transfer matrix was calculated and Twiss parameters were obtained. The space-charge matrices were updated based on the new Twiss parameters because the space-charge forces depend on the beam sizes. The process was iterated until they were converged.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS024

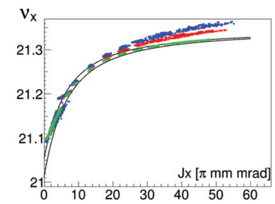

Figure 4: The tune as the function of the action. The colored plots show the simulation results: green plots are no sextupole, blue plots are 75% chromaticity correction and red plots were are chromaticity correction. The black lines are the results from analytical calculations. The difference of the two black lines is the bunching factor: the upper line is $B_f = 0.34$ and the lower line is $B_f = 0.31$.

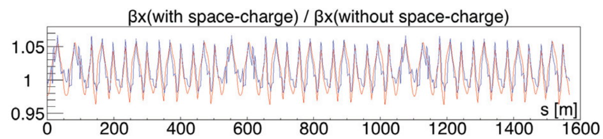

Figure 5: The ratio of the modulated beta functions to the SAD beta functions. The horizontal axis represented the direction along MR. The blue line is the result from SCTR and the red line is the result from analytical calculation.

Results

Figure 4 shows the tunes obtained by the simulations and by the analytical calculations. The horizontal and vertical tunes were set to $(\nu_x, \nu_y) = (21.35, 21.43)$. The intensity was 3.0×10^{13} ppb and initial emittances were $\varepsilon_x = 4.1\ \pi$ mm mrad, $\varepsilon_y = 4.4\ \pi$ mm mrad. The data from turn 3000 to turn 4000 were used for analysis. The bunching factor B_f, defined as the ratio of the average of the longitudinal signal height in a bucket to the peak signal height, was 0.31 at turn 3000 and was 0.34 at turn 4000. The simulations were preformed with three sextupoles strength: no sextupoles, 75% chromaticity corection and full chromaticity correction.

Sextupole fields were not taken into account in the analytical calculations. The analytical calculations were performed with two bunching factors: $B_f = 0.31$ and $B_f = 0.34$. The difference of the results of two bunching factors are considered to be the systematic error.

The simulations without sextupoles were in good agreement with the analitical results. SCTR was benchmarked with respect to the analytical calculations. From the results, the space-charge effect was dominant at small action. As the action became larger, the effect of sextupoles became larger.

Figure 5 shows the ratio of the modulated beta functions by the space-charge effect to the beta functions without the space-charge effect. The horizontal and vertical tunes were set to $(\nu_x, \nu_y) = (21.35, 21.40)$. The intensity was 5.0×10^{12} ppb. The emittances were $\varepsilon_x = \varepsilon_y = 2\ \pi$ mm mrad and the bunching factor $B_f = 0.22$. The chromaticity was fully corrected. The action of the particles was 0.2π mm mrad in the simulation and $0\ \pi$ mm mrad in the analytical calculation.

The result of the simulation was in good agreement with that of the analytical calculation. The beta functions were

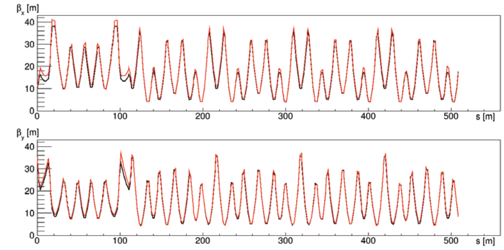

Figure 6: The horizontal (upper) and vertical (lower) betatron function as the function of distance. The black lines are the results of SAD. The red lines are the results of SCTR.

modulated in the region from -1% to +6%. The averaged beta functions were larger than the beta functions without consideration of the space-charge force. It is because the space-charge is deforcusing force.

Figure 6 shows the horizontal and vertical betatron functions. The black lines are the results of SAD, which excludes the space-charge effect. The red lines are the results of SCTR. The initial beam condition were same with the conditions in Figure 4. The sextupole strengths were set so that the chromaticity was corrected 75%. The action of the test particles was 1 π mm mrad. There are clear difference between two results. The difference comes from the space-charge effect. It shows that β_x modulated from -3% to +20% and β_y modulated from -7% to +15%.

The modulations of the betatron functions by the space-charge effect are small for the large action particles. On the other hand, the modulations by the sextupole effect are large for the large action. From the simulation that the action of the test particles is 50 π mm mrad, the β_x modulated at maximum +12% in the arc section.

CONCLUSIONS

The dipole oscillations and the quadrupole oscillations were measured by the IPMs and the MRPM. The coherent space-charge tune shifts were calculated by the frequencies of oscillations. The space-charge tune shift was larger as the beam intensity increased. The results were reproduced by the simulations. The incoherent tune shifts and the modulations of the betatron functions derived from the space-charge force were simulated by SCTR. The tune shifts of the simulation without sextupoles agreed with the analytical calculations. The simulation results of the betatron modulation were in good agreement with the analytical calculation in the low intensity and low action. From the simulation with the condition of the neutrino user operation, the betatron function can be modulated up to +20% at low action. At high action, the effect of sextupoles was dominant. The betatron function can be modulated up to +12% at high action.

ACKNOWLEDGEMENT

We thanks to the J-PARC MR groups for helping taking data. Especially, we are grateful to Y. Hashimoto for setting up the injection MRPM.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS024

REFERENCES

[1] T. Koseki *et al.*, "Beam commissioning and operation of the J-PARC main ring synchrotron", Prog. Theor. Exp. Phys., Volume 2012, Issue 1, 2012, 02B004.

[2] S. Igarashi, "High-Power Beam Operation at J-PARC", in *Proc. HB'18*, Daejeon, Korea, June 2018, TUA2WD02, pp. 147–152.

[3] K. Satou *et al.*, "Profile Measurement by the Ionization Profile Monitor with 0.2T Magnet System in J-PARC MR", in *Proc. IBIC'16*, Barcelona, Spain, Sep. 2016, WEPG69, pp 811–814.

[4] Y. Hashimoto *et al.*, "Multi-Ribbon Profile Monitor Using Carbon Graphite Foil for J-PARC", in *Proc. HB'10*, Morschach, Switzerland, Sep. 2010, WEO2A01, pp 429–433.

[5] http://acc-physics.kek.jp/SAD/

[6] K. Ohmi *et al.*, "Study of Halo Formation in J-PARC MR", in *Proc. PAC'07*, Albuquerque, NM, USA, June 2007, THPAN040, pp. 3318–3320.

[7] T. Toyama *et al.*, "Beam Diagnostics for the J-PARC Main Ring Synchrotron", in *Proc. PAC'05*, Knoxville, Tennessee, USA, May 2005, RPAT005.

[8] K. Ohmi and K. Sonnad, "Beta Function Measurement and Resonances Induced by Space Charge Force and Lattice Magnets", in *Proc. IPAC'16*, Busan, Korea, May 2016, paper MOPOR019.