EFFECTS OF MAGNETIC FIELD TRACKING ERRORS ON BEAM DYNAMICS AT J-PARC RCS

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Abstract

In order to realize high intense operations in proton synchrotrons, a large ring acceptance is commonly required. In such a machine, intrinsic nonlinear magnetic fields play a significant role, and induced high-order resonances can strongly limit the betatron tunability. In such a situation, a clear understanding of a betatron tune change during the revolution, such as chromatic tune shift, space-charge incoherent tune shift and tune shift caused by magnetic field tracking errors, is a key issue. In this paper, we show results from space-charge simulations introducing magnetic field tracking errors and discuss the combined effects of various tune shifts on beam dynamics for the J-PARC 3-GeV rapid-cycling synchrotron.

INTRODUCTION

The 3-GeV rapid-cycling synchrotron (RCS) of J-PARC is designed to provide a 1-MW proton beam at a repetition rate of 25 Hz for the injection energy of 400 MeV [1]. The construction has been almost completed and its beam commissioning is to start in September, 2007. The injection energy is still 181 MeV at the initial phase, which is to be finally upgraded to 400 MeV. For the initial lower injection energy, we will aim at 0.3∼0.6 MW output, and then drive for the final goal of 1 MW output for the upgraded higher injection energy. The key issue in such a high intense operation is to control and localize the beam loss and decrease the uncontrolled beam loss. For this purpose, a large ring acceptance is required: in the RCS, a ring acceptance of 486π mm mrad is secured for a possible momentum spread of $\pm1\%$ to make a wide beam (216π mm mrad) by a multi-turn painting injection with the aim of suppressing the space charge, and to get an adequate ratio between physical and collimator (324π mm mrad) apertures for keeping a sufficient collimation efficiency (∼97%). Thus the RCS magnet has a large gap and consequently its aspect ratio (inner diameter over magnet length) is also large. In this kind of machines, intrinsic nonlinear magnetic fields, such as nonlinear behavior of a leakage field around the magnet edge, play a significant role, and the nonlinear motion of beam particles, especially with large amplitudes, is a common issue. Nonlinear magnetic fields excite different high-order transverse resonances, making a limitation of the betatron tunability.

In such a situation, a betatron tune change for the revolution is a key issue. In the RCS, the chromatic tune shift will be corrected with three families of sextupole magnets, while the sextupole fields itself also contribute to nonlinear resonances. Therefore the main sources of the tune change are the space-charge defocusing force and magnetic field tracking errors between dipole and quadrupole magnets. The space-charge tune shift depends on the beam distribution, and is large for particles with small betatron amplitudes in general. Thus it is an incoherent tune shift (in fact a tune spread). On the other hand, the tune shift due to magnetic field tracking errors is independent of betatron amplitudes, and is more easily correctable. In order to realize the requested beam current, it is essential to control the betatron tune spread and excursion in the limited tunable space during the revolution. For this concern, we have performed space-charge tracking simulations introducing possible magnetic field tracking errors, and investigated the combined effects of various tune shifts on beam dynamics.

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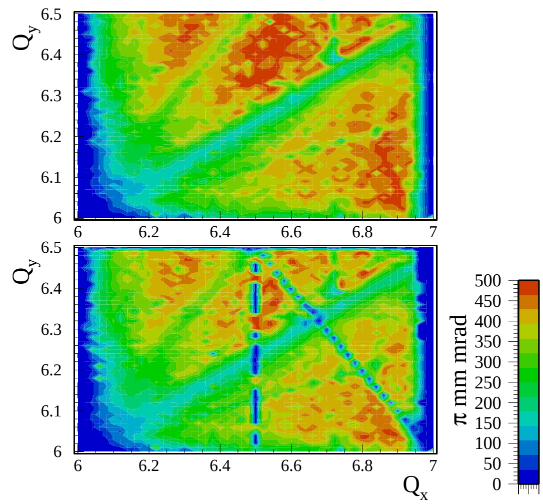

Figure 1: Dynamic acceptance maps as a function of Q_x and Q_y estimated for on-momentum particles near the nominal operating point, in which the upper one shows a map obtained without random field and alignment errors and the lower one is with the random errors.

BETATRON RESONANCES AT THE RCS

Fig. 1 shows dynamic acceptance maps obtained from single-particle tracking simulations [2] with a code called SAD [3]. In this simulation, possible intrinsic nonlinear fields in the RCS are included: chromatic correction sextupole fields, and multipole field components of dipole, quadrupole and sextupole magnets based on the measurements. As shown in the upper figure, several nonlinear structure resonances coming from the three-fold symmetric lattice of the RCS appear in the nominal operating region. The sextupole fields required for the chromatic correction and also the intrinsic sextupole field component in the dipole magnet strongly excite the $Q_x - 2Q_y$=−6 resonance. In addition, different higher-order resonances, such as $2Q_x - 2Q_y$=0 and $Q_x - 4Q_y$=−18, are induced directly by higher-order nonlinear field components or / and by the sextupole field component through the 2^{nd}-order perturbation expansion. The $4Q_x$=27 can also be excited by sextupole and octupole field components, while their contributions to the driving term seem to be compensated with each other in this condition. However this 4th-order resonance can be strongly driven also by the space-charge force.

The lower figure is a similar map in additionally including random field (|ΔBL/BL|<8×10^{-4} for dipoles, |ΔBL'/BL'|<1×10^{-3} for quadrupoles, and |ΔBL"/BL"|<7×10^{-4} for sextupoles, based on the measurements) and alignment (|Δx| and |Δy|<0.4 mm for displacement errors, and |Δθ|<0.8 mrad for rotation errors along the beam direction, assuming Gaussian distribution) errors. In this estimation, COD caused by the random errors was corrected with 52 sets of steering magnets assuming a realistic BPM position resolution of 0.25 mm. In this case, random linear resonances additionally appear: $Q_x + Q_y$=13 by skew quadrupole field errors, and $2Q_x$=13 by normal quadrupole field errors. In addition, there still exist anxious random resonances caused by the three-hold symmetry breaking: e.g. $3Q_x$=20 by normal sextupole field errors, and $2Q_x - Q_y$=7 by skew sextupole field errors. While such high-order random resonances are not strongly excited as for this estimation, they may be enhanced depending on different random alignment errors.

SPACE CHARGE SIMULATIONS

Fig. 2 shows beam survival ratios obtained in the same condition as the above single-particle tracking simulations (Fig. 1) assuming 0.3 MW and 0.6 MW output for the injection energy of 181 MeV using a fully 3D particle-in-cell code called SIMPSONS [4]. In terms of the space-charge effect, this situation is rather severe than that for 1 MW output with the injection energy of 400 MeV. In the simulations, 2×10^5 macro-particles, a transverse grid of 50 (r)×64 (θ) in the polar coordinate for the radius of the conducting boundary of 0.17 m and a longitudinal grid of 100 (z) were employed, and all the physical quantities were chosen according to the specifications in the design.

In the upper figure of Fig. 2, the black and blue curves are results for the 0.3 MW output case obtained without and with random field and alignment errors. In this case, the bare working point was chosen at (6.68, 6.27), which is just located in the stable region surrounded by $Q_x - 2Q_y$=−6, $4Q_x$=27, $Q_x + Q_y$=13, $2Q_x$=13 and Q_y=6. As for the 0.3 MW operation, the Laslett space-charge tune shift is around -0.2 at maximum, and the betatron tune spread of particles almost stays in the stable region during the revolution. Therefore there is no significant beam loss and no big difference between the two results in this case.

The lower figure of Fig. 2 shows similar results obtained for the 0.6 MW output case. In this case, the Laslett space-charge tune shift reaches to -0.4 at maximum, and thus the particles cannot avoid the anxious resonances. In the simulation, the bare working point was set at (6.72, 6.35) on trial, which is just above the sum resonance of $Q_x + Q_y$=13 that can be driven by skew quadrupole field errors. While the sum resonance is not excited in the simulation condition of the black curve, the blue curve suffers heavy beam losses by the resonance. Because most of the beam particles in the blue curve are far from the sum resonance for the injection through the early stage of the acceleration thanks to the large Laslett tune shift, there is no big difference between the blue and black curves in this period. However, as the tune shift gets smaller according to the acceleration, the beam particles approach the resonance, and thus in this case the beam loss increases accordingly at a great rate, as shown in the figure.

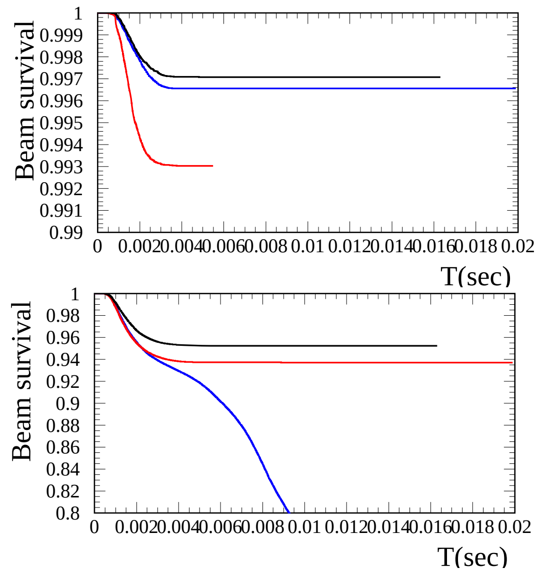

Figure 2: Beam survival ratios as a function of revolution obtained for the 0.3 MW (upper) and 0.6 MW (lower) output operations with the injection energy of 181 MeV. The black and blue curves show results obtained without and with random field and alignment errors. The red curve shows a similar result in additionally including magnetic field tracking errors.

EFFECTS OF MAGNETIC FIELD TRACKING ERRORS

In addition to the space-charge tune shift, another possible source of the betatron tune excursion is magnetic field tracking errors between dipole and quadrupole magnets. The RCS focusing structure consists of 24 dipole magnets and 60 quadrupole magnets, which are excited with a 25 Hz DC-based sinusoidal current pattern in 8 independent resonant networks. In order to assure a close tracking between them, the RCS dipole and quadrupole magnets are designed so that a saturation of the field gets small. In measurements, it is confirmed that the saturations of the fields are within 3% for the operating current. In the actual

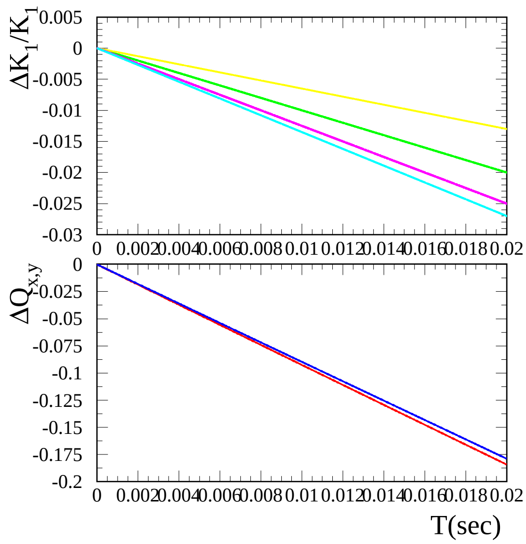

Figure 3: The upper one shows magnetic field tracking errors included in the space charge simulations, in which the 4 sets of errors correspond to tracking errors between the dipole magnet and the quadrupole magnets classified into 4 types. The lower one is betatron tune excursions caused by the tracking errors, in which the red and blue lines show those for horizontal and vertical tunes.

operations, we will adjust their trackings within 0.1% by compensating with higher frequency waves.

In the simulations, 3% tracking errors based on the saturation measurements were included preparing for the worst, as shown in the the upper figure of Fig. 3. The 4 sets of linear errors correspond to tracking errors between the dipole magnet and the quadrupole magnets classified into 4 types. While in fact the linear tracking errors are not realistic, we can see the essence of influences of tracking errors on the beam. The lower figure of Fig. 3 shows betatron tune excursions caused by the linear tracking errors, for which the tune deviation gets to -0.18 at the top energy.

The red curves in Fig. 2 show results from space-charge simulations in additionally including the magnetic field tracking errors. As for the 0.3 MW operation, there is no significant effect of tracking errors on the beam loss. The space-charge tune shift gets smaller according to the acceleration, while the tune shift caused by the assumed tracking errors gets larger in contrast. Therefore it can be interpreted that both tune shifts are well compensated and the core of beam particles stays in the stable region. On the other hand, the situation of the beam loss significantly changes for the 0.6 MW operation case. This is why the beam core successfully avoid the resonance crossing to $Q_x + Q_y$=13 by the tune shift caused by the tracking errors, as shown in Fig. 4. This simulation proposes a possible operation that effectively utilizes the limited tunable space due to the excited betatron resonances by coherently shifting the tune according to a decline of the incoherent space-charge tune shift. Such a operation can be realized by controlling the magnet power supply trackings and will be very useful for the reduction of the beam loss especially in high current beam operations involving a large incoherent tune shift.

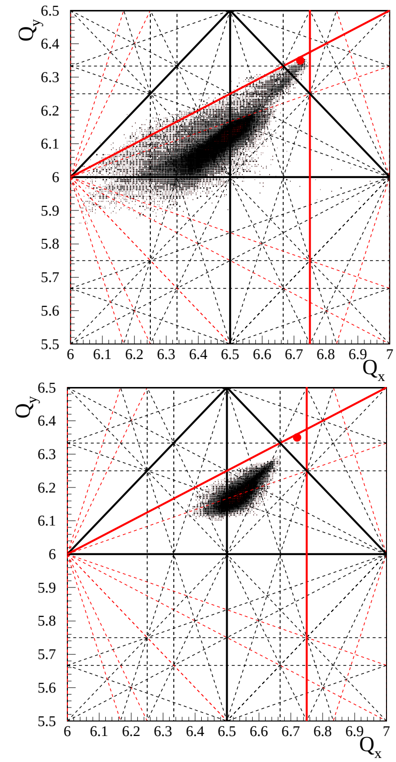

Figure 4: Space-charge tune spreads at 0.5 msec (upper) and 8 msec (lower) for the 0.6 MW operation obtained from simulations including magnetic field tracking errors.

SUMMARY

For the J-PARC 3-GeV RCS, we performed space-charge simulations introducing possible magnetic field tracking errors assuming 0.3 and 0.6 MW output operations for the injection energy of 181 MeV, and investigated the combined effects of various tune shifts on beam dynamics. The simulation results suggest we can make the most of the limited tunable space due to the induced betatron resonances by coherently shifting the tune according to a decline of the space-charge incoherent tune shift, namely a possibility of the reduction of the beam loss by controlling the magnet power supply trackings.

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