NONLINEAR FIELD EFFECTS IN THE JPARC MAIN RING

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Abstract

The 'bare' working point has been optimized to avoid the particle losses during the injection process. The particle losses can be caused by smearing of the particle trajectories at the scraper location, determined by the high-order resonances even if the particle motion remains stable. The influence of main linear and high-order resonances around the optimized working point has been studied. Parameters of the extracted beam have been analyzed for different 'bare' working points. The correction schemes to suppress the normal sextupole resonances have been applied.

INTRODUCTION

Main Ring (MR) of the Japanese Particle Accelerator Research Complex (JPARC) should provide acceleration of the high-intensity proton beam from the energy of 3GeV to 50 GeV. The particles will be injected into MR from the rapid cycling synchrotron (RCS) during about 160 msec using just about 5% of the total beam intensity, accelerated by RCS. The expected beam intensity is 3.3e14 ppp and the repetition rate is about 0.3 Hz. The ration between the physical acceptance of the primary collimator of MR and the full beam emittance at the injection energy is 1.5. The incoherent space charge tune shift about (-0.2) is expected at the injection energy for the MR parameters. In this case it is not possible to avoid crossing the low- and high-order (up to 4^{th} order) resonances for the design beam intensity. These resonances can be excited by the space charge of the beam, intrinsic field nonlinearities, magnetic field errors and misalignment errors of MR. Optimization of the 'bare' working point should be performed to limit or avoid particles losses caused by these resonances. Moreover, appropriate correction schemes for these resonances should be considered. The high-order resonances which can be exited the space charge of the beam are not considered in this study.

INTRINSIC FIELD NONLINEARITIES

Main intrinsic field nonlinearities of MR are the sextupole field nonlinearity of 72 sextupole magnets, which should be used to correct the linear chromaticity of the machine, plus the fringing fields of the ring magnets. Additionally, according to the field measurement the magnetic field of the MR bending magnets has the sextupole component. The eddy current effect in the bending magnets will change this component during the acceleration cycle.

The imaginary transition lattice of the ring was adopted for MR, which has the natural linear chromaticity about (-30) for both transverse phase planes [1]. For the expected momentum spread of the captured beam, the chromatic tune shift at the injection energy can be close to the incoherent tune shift caused by the space-charge of the full intensity beam at the low energy. To eliminate the linear chromatic tune shift, two independent families of the chromatic sextupole magnets are planned to be used.

The chromatic sextupole field nonlinearity and the fringe field of the MR quadrupole magnets will lead to the amplitude dependent tune. The intrinsic amplitude dependent tune shift for the beam at the injection energy with the 100%-beam emittance of 54 π·mm·mrad is about $\Delta Q_{xz}^{LA} \sim +0.020$. This amplitude dependent tune shift for MR is determined mainly by the chromatic sextupole field nonlinearity [1].

The measured transverse field distribution in the MR bending magnet predicts the sextupole field component of the field at the injection energy in the good field region. The systematic integrated sextupole field component $b_2=(B^{//}L/B\rho)$ is estimated to be 0.0039 m^{-2}. The eddy current effect will increase the sextupole component of the bending magnets at the beginning of the acceleration cycle. The systematic integrated sextupole component in this case has been estimated to be about 0.0196 m^{-2}. The changing of the linear chromaticity for that field of the MR bending magnets becomes about 0.83 and 0.64 in the horizontal and vertical planes respectively.

OPTIMIZATION OF THE WORKING POINT

For optimization the 'bare' working point at the injection the beam survival at the scraper location has been studied. The MR dynamic aperture study [2] has shown that the dynamic aperture of the machine is bigger than the physical acceptance at the scraper location for wide range of the vertical betatron tunes from 19.28 up to 22.28. The beam survival at the MR primary scraper for different vertical betatron tunes has been analyzed. The high-order coupling of the particle trajectory, excited by the intrinsic field-nonlinearities, could lead to the particle losses even if the particle motion remains stable. Moreover, the misalignment errors have been introduced to excite also the linear coupling mechanism.

The performed study of the beam survival defined the vertical betatron tune around 20.78 as the 'bare' working point for MR at the injection energy. The horizontal betatron tune should be located close to the horizontal resonance $3Q_x=67$, used for the slow extraction of the accelerated particles.

The beam survival study is based on the 2 dimensional tracking by using the 9^{th} order Taylor map of the nonlinear elements of the ring [3]. Variation of the horizontal betatron tune has been performed by using the ring quadrupole magnets keeping the moderate values of the beta-functions.

The beam survival for this particular value of the vertical betatron tune can be limited by the skew sextupole resonance $2Q_x–Q_z=24$ and the horizontal half-integer resonance $2Q_x=45$ (Fig.1). To excite these resonances, the reasonable tilt of the chromatic sextupole magnets and the random errors of the strength of the quadrupole magnets have been introduced in to the study.

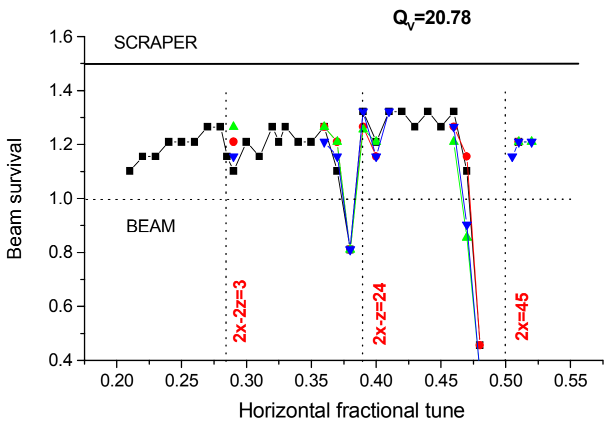

Figure 1: Beam survival at the scraper location for different horizontal tunes.

Beam behaviour during the slow extraction

The slow extraction based on the 3rd order horizontal resonance excitation has been analyzed during the optimization of the 'bare' working point position. For this study both types of the sextupole magnets (chromatic and extraction ones) have been introduced into the simulation including the distortion of the closed orbit, which should be used to move the beam to the electrostatic septum. Additionally, the misalignment errors have been considered to excite the linear coupling resonance. This study has been performed by using the symplectic tracking code PTC [4].

The initial particle coordinates in the horizontal and vertical phase planes are correspond to the beam edge at the extraction energy of 50 GeV.

Fig.2 (A,B) presents the particle motion near the separatrix for different vertical betatron tunes without any misalignment errors including the closed orbit distortion by the extraction bump-magnets. All other parameters are kept the same for both cases.

The high-order coupling developed by the sextupole nonlinearities of the chromatic sextupole magnets was observed for the first case (A: Q_x=22.31, Q_z=22.28) because the working point has been located close to the 0th harmonic resonance $2Q_x$-$2Q_z$=0. In the case of the optimized working point (B: Q_x=22.31, Q_z=20.78) the smearing of the particle trajectory near the separatrix is almost suppressed. Some smearing of the single particle trajectory near the separatrix for the optimized working point has been determined by the high-order coupling caused by the quadrupole fringe field and the sextupole nonlinearities.

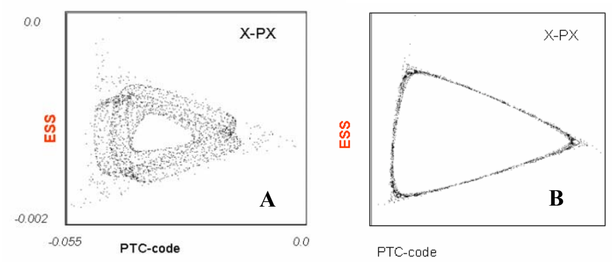

Figure 2: Particle motion near the separatrix for different values of Q_z: (A) - Q_z=22.28; (B) -Q_z=20.78. The horizontal tune is fixed Q_x=22.31

NORMAL SEXTUPOLE RESONANCES

The space charge effect changes the particle betatron tunes so that the particle can be push to some resonances excited by the intrinsic field nonlinearities in combination with the field and misalignment errors. For the optimized 'bare' working point with the betatron tunes Q_x=22.38 and Q_z=20.78, the beam survival at the injection energy can be limited by the normal sextupole resonances $2Q_z$-Q_x=19, $3Q_x$=67 and Q_x+2Q_z=64. All these resonances are not the structure ones for the ideal MR focusing lattice, but the resonance driving terms become nonzero in the case of the real machine with the injection chicane.

Fig.3 depicts the normal sextupole resonance driving term (NRS-NORM), in particular, for the resonance $2Q_z$-Q_x=19 in the case of the fixed value of the vertical tune Q_z=20.62 and different values of the horizontal tunes in the range from 22.23 up to 22.27 at the injection energy (dash line). For this case the injection chicane has been introduced additionally to the intrinsic sextupole field nonlinearities. Moreover, the random error of the sextupole field component of the MR bending magnets has been assumed for this study. The NRS-norm has sharp peak in the vicinity of the horizontal betatron tune Q_x = 22.24, which meets the resonance condition for the fixed vertical betatron tune of Q_z=20.62. Similar analysis of the resonance norm has been performed for other normal sextupole resonances around the optimized 'bare' working point including different error-seeds.

For the worst cases with the biggest resonance norm the beam survival at the MR scraper position has been simulated during 1000 turns. The corresponding beam survival around the [-1, 2] resonance for different horizontal tunes is presented on Fig.3 (solid line). The particles with the transverse emittance ($\varepsilon_x=\varepsilon_z$) more than 40 π·mm·mrad will be lost at the scraper. The observed shift of the minimum of the beam survival function from the resonance value of the horizontal tune is determined by the amplitude dependent tune shift caused by the intrinsic field nonlinearities. The on- and off-momentum particle motion has been studied.

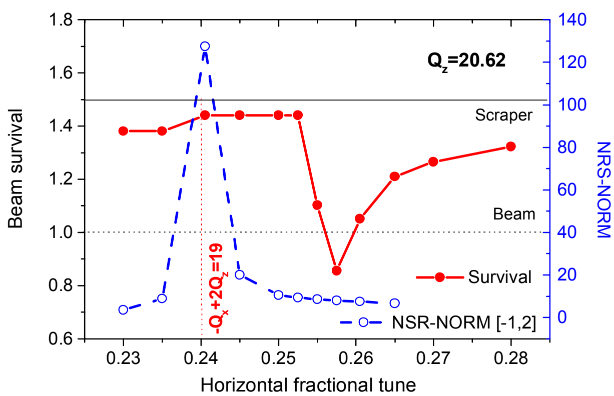

Figure 3: The resonance norm [-1,2] and the beam survival in vicinity of the normal sextupole resonance $2Q_z$-Q_x=19.

Similar studies have been performed for other normal sextupole resonances around the optimized 'bare' working point. The correction scheme should be considered to avoid the particle losses caused by these resonances.

Isolated resonance correction scheme

Each isolated normal sextupole resonance which is located around the optimized 'bare' working point can be corrected by the appropriate set of two independent sextupole correctors placed at the MR dispersion-free straight section, in particular, at the beginning and at the end of the RF straight section. The required strength of the sextupole correctors has been determined to make zero the corresponding resonance norm.

The required strength of the sextupole correctors for each resonance has been simulated for different error-seeds of the random sextupole field component of the MR bending magnets. After the correction the high-order coupling has been suppressed completely.

During the analysis of this correction scheme it was shown that the maximum required integrated strength of the sextupole correctors at the injection energy is $(k_{CS}L)$~0.06 m^{-2} to correct one of the normal sextupole resonances. The off-momentum particle tracking predicts that after the correction of one of the normal sextupole resonances the momentum acceptance at the injection energy will be determined only by the maximum height of the RF bucket for both fundamental harmonic numbers h=9 or h=18.

Multi-resonances correction scheme

The space charge of the low-energy beam with the design intensity changes the betatron tune of the beam particles so that the betatron tune foot print of the beam particles crosses at least two normal sextupole resonance lines at the same time. In this case the correction just only one separated resonance could lead to increasing the resonance driving terms of the remain normal sextupole resonances. In the case of full beam intensity, all the normal sextupole resonances should be corrected simultaneously by using the additional coils of the chromatic sextupole magnets of the ring.

To reduce the required strength of the sextupole correctors and to minimize changing of the chromaticity of the machine, selection of the correctors has been performed. The resonance driving terms have been suppressed for all three normal sextupole resonances located around the optimized 'bare' working point. The maximum number of the correctors is 12, combining in two independent families.

The maximum required strength of the correctors for all cases is limited by ±6% from the main strength of the chromatic sextupole magnets. Fig.5 presents the relative strength of the sextupole correctors for different error-seeds of the random sextupole component of the bending magnet field including the eddy current effect.

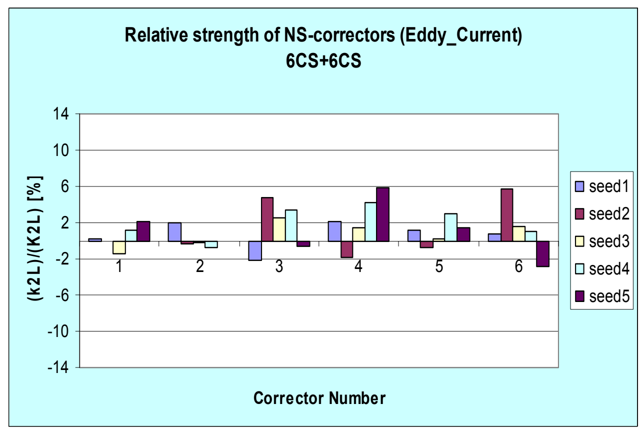

Figure 4: The relative strength of the sextupole correctors for different error-seeds.

The comprehensive analysis of the resonance excitation in combination with the space charge effects should be done including the resonance correction to eliminate the particle losses at the low energy level.

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