DYNAMIC APERTURE AND RESONANCE CORRECTION FOR JPARC-RCS

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Abstract

The rapid cycling synchrotron (RCS) of the J-PARC project should provide the beam power of 1 MW at the final stage. One of the main issues for high-power proton machine is strict limitation of uncontrolled beam losses. The space-charge detuning effect of the high-intensity low-energy proton beam can lead to crossing different resonance lines and perturb the particle motion significantly, reducing the dynamic aperture of the machine. Main intrinsic field nonlinearities, which are common for this kind of synchrotrons, are the nonlinear field of the bending magnets, the fringing field of the magnets and the sextupole field nonlinearity, used for the chromaticity correction. To model the particle motion in the RCS bending magnets, the 3D (Tosca) field map has been taken into account. We discuss the nonlinear single particle dynamics for the RCS focusing structure, limitation of the machine dynamic aperture and the resonance correction technique.

INTRODUCTION

The rapid cycling synchrotron (RCS) of the J-PARC project should provide the beam power of 1 MW at the final stage. One of the main issues for high-power proton machine is strict limitation of uncontrolled beam losses. The space-charge detuning effect of the high-intensity low-energy proton beam can lead to crossing different resonance lines and perturb the particle motion significantly, reducing the dynamic aperture of the machine. According to the basic design of RCS, the incoherent tune shift of the low-energy proton beam at the injection energy of 181MeV is about (-0.15). As the result of the study of possible limitations of the beam survival for RCS [2], the 'bare' working point has been recommended in the area with the horizontal and vertical betatron tunes of 6.68 and 6.27, respectively. It was shown, that the strongest field nonlinearities for RCS are the sextupole field, used to correct the linear chromaticity of the machine, and the fringing field of the quadrupole magnets. These field nonlinearities will lead to excitation of the [-1,2] and [4,0] normal structure resonances, which are located near the design 'bare' working point. Additionally, the intrinsic field nonlinearity of the magnetic field of the bending magnets will lead to changing, first of all, the linear properties of the focusing structure of MR, and contribute to the resonance excitation. The magnetic field nonlinearity of the RCS bending magnet has been introduced for this study as the 3 dimensional field data, pre-simulated by TOSCA at the injection energy. In this report, we continue consideration the nonlinear single particle dynamics for the RCS focusing structure, in particular, limitation of the machine dynamic acceptance, caused by different structure resonances. The resonance correction technique for the normal sextupole resonance has been applied successfully.

SIMULATION APPROACHES

Two main tasks have been considered: (1) the single particle tracking through the ring with the 3D field presentation for the bending magnet to predict the beam survival for different betatron tunes around the 'bare' working point; (2) resonance analysis and possible correction.

For the first task, we used the 4th order Runge-Kutta integrator (non-symplectic), and for the second task we used the power of the normal form analysis, based on the 8th order truncated Taylor map for the bending magnet (which is symplectic up to the order of truncation). Both techniques are implemented in the extension of the MAD-X code [1]. To simulate the truncated Taylor map of the RCS bending magnet, the Gaussian wave-let 3D field representation has been utilized [3]. To introduce the fringing field of the RCS quadrupole magnets we used the model of the fringe field [4], which introduces the high-order effects without changing the linear properties of the machine's lattice. The intrinsic field nonlinearities of the magnets, in particular, the quadrupole fringe fields and the sextupole field for the chromaticity correction will lead to the amplitude dependent tune shift and to the non-linear resonance excitation [2]. In particular, the amplitude dependent tune shift is about 0.02 in both horizontal and vertical phase planes for the beam emittance of 340 π.mm.mrad at the injection energy 181MeV .

Field representation for RCS bending magnets

The effective length of the RCS bending magnet is 277.0cm, which provides the bending angle of 15 degrees for the particles with energy in the range from 181MeV upto 3GeV. To represent the 'real' field of the curved bending magnet with the parallel edges, we used the static 3D magnetic field $\{B_x,B_y,B_z\}$ on the mesh-grid, simulated

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by TOSCA for the basic design of the bending magnet. The mesh-grid with the step of 1cm in the {x,y,z}-directions has been chosen. The field data has been obtained in the 3D space with the maximum extension of [-30,15]cm , [-10,10]cm and [0, 400] cm in the horizontal, vertical and longitudinal directions respectively.

ANALYSIS OF THE LINEAR PROPERTIES OF RCS

Changing the linear properties of RCS with the 3D TOSCA bending magnets has been analysed. For that the bending magnet of MADX has been replaced by the magnet with the 3D_TOSCA field so that to keep the reference particle trajectory outside of the field mesh area, as it requires the basic lattice design. The path length of the reference particle in the middle plane of the 3D TOSCA field has been determined. The relative changing of the total path around the ring with the 'real' bending magnets is about $1.15 \cdot 10^{-4}$ in comparison with the path length in the 'ideal' MADX bending magnets.

The magnetic field of the 'real' bending magnet contains mainly the dipole, quadrupole and sextupole components [5]. It will lead to systematic changing the betatron tunes, the Twiss parameters and the linear chromaticity of RCS. In particular, the changing of the betatron tunes is about 1.5%, the changing of the beta-functions is up to 9% (at the entrance to the first 'real' bending magnet in the arc) and the natural linear chromaticity variation is about 3%.

NONLINEAR EFFECTS

The single particle tracking at the injection energy of 181MeV has been used to study possible limitation of the maximum beam size at the entrance of the bending magnet. For this study the direct integration of the equations of the particle motion in the 3D magnetic field has been utilized. The intrinsic field nonlinearities for this case are the realistic nonlinear field of the bending magnet, the fringe field of the quadrupole magnets and the sextupole field of the chromatic sextupole magnets. The limitation of the maximum beam size, which survives in the bending magnet as a function of the horizontal tune shows in Figure 1.

The first case represents the influence of the field nonlinearities of the bending magnets and the quadrupole fringe fields. The second case represents additional contribution of the sextupole field nonlinearity, used for the chromaticity correction. The vertical axis represents the initial particle coordinates in the horizontal and vertical phase planes with $x_0^{/} = y_0^{/} = 0$. The on-momentum particle motion has been observed during 1000 turns. The chromatic sextupole magnets introduce the dominant field nonlinearity for RCS, which could lead to the particle losses if the betatron tune of the particle is close to the normal sextupole resonance $-Q_x+2Q_y=6$ and to the normal octupole resonance $4Q_x=27$. Both resonances are the structure ones for RCS. Some shift of the minimum of the survival plot near the corresponding resonance lines is caused by the amplitude dependent tune shift, mentioned above.

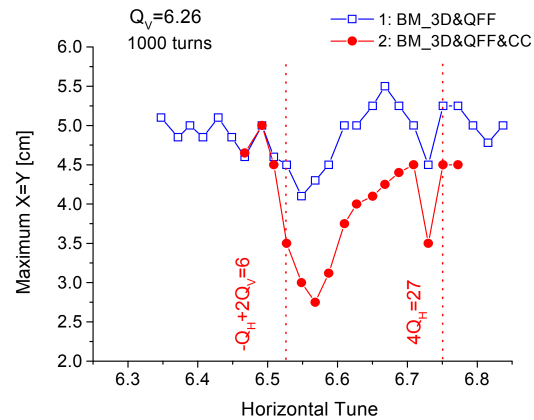

Figure 1: Particle survival in the RCS bending magnet for different working points.

The dynamic aperture for the worst case of the particle survival, in particular for $Q_x=6.56$ and $Q_y=6.26$, is shown in Figure 2. For this working point we analyzed two cases: intrinsic field nonlinearities of RCS without and with the chromatic sextupole magnets (CC).

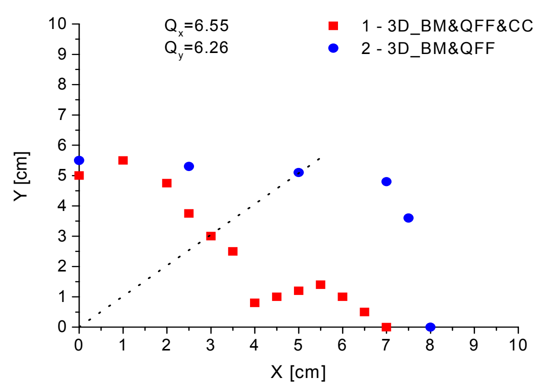

Figure 2: Dynamic aperture of the RCS bending magnet at the injection energy.

The coupling resonance $-Q_x+2Q_y=6$ leads to strong limitation of the dynamic aperture. Without the sextupole magnets for the chromaticity correction the dynamic acceptance of RCS at the injection energy at the entrance into the bending magnet is 384 π.mm.mrad and 333 π.mm.mrad for the horizontal and vertical phase plane, respectively. The 100%-emittance of the beam at the injection energy of 181MeV is about 340 π.mm.mrad. The limitation of the vertical dynamic acceptance is caused by strong nonlinearity of the 3D (TOSCA) magnetic field of the bending magnet for the off-middle plane points. For the working point near the [-1,2] resonance the chromatic sextupole field nonlinearity reduces the dynamic acceptance of the bending magnet at the injection energy up to 216 π.mm.mrad and 187 π.mm.mrad in the horizontal and vertical phase plane, respectively.

CORRECTION OF THE [-1,2] RESONANCE

The correction of the systematic normal sextupole resonance $-Q_x+2Q_y=6$ has been analyzed for RCS lattice including the sextupole magnets for the chromaticity correction. For the analysis of the resonance driving terms, the Gaussian wavelets has been used to represent the TOSCA field data for the RCS bending magnets and to provide the differentiation in s-direction. In this case, the normal form analysis can be utilized for this system. According to the basic ring strategy the [-1,2] resonance correction scheme is based on two independent families of the additional sextupole magnets, which are located at the beginning and the end of each dispersion-free straight sections [5]. In this case these sextupole magnets will not contribute to the chromaticity of the machine.

Analysis of the [-1,2] resonance driving terms

By using the normal form analysis the resonance [-1,2] driving terms have been determined for the working point $Q_x=6.56$, $Q_y=6.26$, for which the minimum acceptable initial particle coordinates has been observed (Figure 1). The Cosine and Sine parts of the resonance driving term for the case without the chromatic sextupole magnets are [0.0868, -0.1969]. The corresponding parts of the resonance driving term with the activated chromatic sextupole magnets become [-1.1589, 2.6490]. This estimation of the resonance driving terms proves that the chromatic sextupole magnets of RCS contribute the major systematic nonlinearity, which leads to excitation of the normal sextupole resonance.

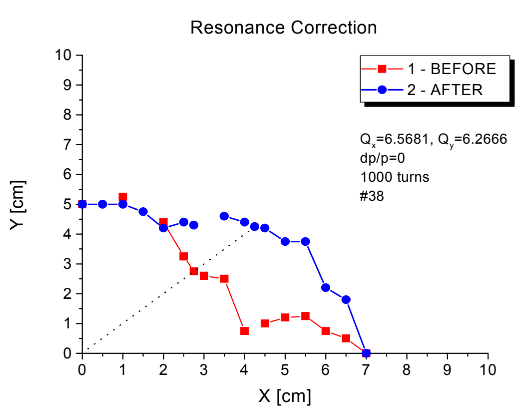

Figure 3: Dynamic aperture of the RCS bending magnet at the injection energy before (1) and after (2) correction of the systematic [-1,2] resonance.

By using two independent sextupole magnets for the resonance correction (the total number of the sextupole resonance correctors is 6), the resonance driving term for the required working point can be reduced to zero. The effective length of the sextupole correctors is 0.15m. The required integrated strength (by using the MAD definition) of the correctors are 0.112770 m^{-2} and 0.113920 m^{-2} (about 25% of the required strength of the chromatic sextupole magnets).

The estimation of the dynamic acceptance of the RCS bending magnet at the injection energy for the working point $Q_x=6.56$, $Q_y=6.27$ after the correction of the [-1,2] resonance improves significantly. The dynamic acceptance becomes 529 π.mm.mrad and 423 π.mm.mrad in the horizontal and vertical phase plane, respectively. For the off-momentum particle with the momentum spread of dp/p=±0.01 the dynamic acceptance of the RCS bending magnets after the resonance correction has been studied also. For the maximum momentum spread the horizontal and vertical dynamic acceptances are 410 π.mm.mrad and 300 π.mm.mrad, respectively. Then the momentum acceptance of the RCS at the injection energy has been estimated as $(dp/p)_{ACCEPT} = \pm 0.0085$.

CONCLUSION

The effects of the intrinsic field nonlinearities of bending and quadrupole magnets of RCS (JPARC) have been studied by using different simulation approaches. The magnetic field of the bending magnets as the 3D TOSCA field data has been used. Main intrinsic field nonlinearities are the nonlinear field of the bending magnets, the fringing field of the magnets and the sextupole field nonlinearity, used for the chromaticity correction. It was shown that the strongest field nonlinearity for RCS is the sextupole field of the chromatic sextupole magnets. After the correction of the systematic normal sextupole resonance the dynamic acceptance of the ring bending magnets becomes acceptable for the on- and off-momentum particles of the beam at the injection energy. The sextupole correctors with moderate strength should be used for that case.

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