EFFECTS OF COHERENT RESONANCES FOR THE J-PARC MAIN RING AT THE MODERATE BEAM POWER

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Abstract

For the high beam power operation of the J-PARC Main Ring the particle losses has to be minimized. The combined effects of the machine resonances and the space charge should be taken into account in the self-consistent manner to simulate mechanism of the emittance growth during the injection and acceleration processes. In frame of this report we analyze different coherent modes of the space charge dominated beam at the injection energy for some basic operation scenario of the J-PARC MR with the moderate beam power, taken into account measured field components and alignment errors. This analysis allows to identify the most dangerous resonances and to understand the effect of the emittance dilution after the resonance correction for the realistic set of the machine parameters.

INTRODUCTION

In the case of proton machine with high beam power, crossing of the 'machine' resonance is unavoidable. The 'lattice' resonances in the real machine have many external sources: nonlinear fields, field errors of the individual magnets of the machine, multipole field components of different types of magnets in addition to misalignment errors and field leakage of the septum magnets, used to inject and extract the beam. The space charge of the low energy proton beam, depending on beam intensity, transverse and longitudinal beam size, beam energy and beam environment, depresses tunes of individual particles of the beams (the incoherent effect) so that the tune of the individual particles of the beam becomes quite different from the 'bare' tune (or the 'lattice' tune) in both transverse planes. The collective property of the beam (in particular, the coherent tunes), depending on the beam environment, will be changed too by the space charge of the beam. In addition to the detuning effect, the space charge potential itself introduces strong nonlinearities, which will contribute to excitation low and high-order resonances. The space charge resonance driving terms depend on the particle distribution in the 6D phase plane, which is far away from the static distribution. The particles will cross periodically the resonance stop-bands, determined by the combined effect of the lattice imperfection and the space charge of the low energy high intensity beam, leading to the transverse emittance dilution and the particle losses. The report is devoted to analysis of the coherent modes of the beam for the realistic imperfection of the J-PARC Main Ring. The combined effect of the machine resonances and the space charge has been studied for the case of the moderate beam power for the MR operation [1].

The tune-scanning simulations for the MR moderate beam power have been performed to define 'basic' working point for the machine operation. The 'sum' linear coupling resonance [1,1,43] has been recognized for the J-PARC MR as the most dangerous resonance, which can limit the performance of the machine. The biggest particle losses have been observed for the cases when the coherent tune of the beam was located close to the resonance stop-band. The resonance correction scheme has been applied successfully in the 'local' and 'global' sense to improve the MR performance. This scheme is based on the linear decoupling by using four independent skew-quadrupole magnets placed in the dispersion-free straight insertions of the ring. The analysis of the high-order coherent modes shows that the remained particle losses is cause by the high-order resonances, excited by the machine imperfections in combination with the space charge of the low energy beam. The best way to avoid these particle losses is optimization the 'bare' working point, considering the beam properties at each operational stage of the machine. In frame of this report we discuss combined effects of the machine resonances and the low energy space charge at the injection energy for the moderate beam intensity, determined for MR by the RCS beam power of 300kW at the 3GeV energy. According to the basic MR operation scenario the corresponding beam power at the injection energy is 2kW per bunch.

COHERENT MODE ANALYSIS

The combined PTC_ORBIT code [2] allows us to study single particle dynamics and collective effects of synchrotrons without any modification of the machine description, including the RF cavity, magnet misalignment, different kind of field errors and multipole field components of the magnets. The Normal Form analysis of the complicated magnet system, implemented in PTC, opens the way to develop the 'lattice' resonances correction procedures. The combined PTC_ORBIT code has been compiled successfully for the KEK supercomputers* (HITACHI SR11000 and IBM 'Blue Gene').

In frame of the code the transverse space charge forces are evaluated as nonlinear kicks using the explicit second order PIC model and FFT. The second order symplectic s-propagator has been used to track the macro-particles from one space-charge node to another. The nonlinear elements of the machine are considered as the symplectic thin lenses.

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The realistic machine conditions have been introduced step-by-step for the MR study to identify most dangerous resonances around the basic 'bare' working point, excited by different kind of machine imperfections including: the injection dog-leg with the edge-focusing effects of the bump-magnets, the measured field errors for all magnets, misalignment errors of the magnets and the field leakage of different kind of septum magnets, used at the injection and extraction beam lines.

As the result of the self-consistent multi-particle tracking study, low and high-order moments of the 4D particle distributions can be defined as a function of time. The Fourier transformation of these time-dependent moments gives us the frequency spectrum of the moments. Using this spectrum one can immediately check the coherent resonance condition of the corresponding resonance.

The space charge of the beam, depending on the beam properties, changes the frequency spectrum of the coherent modes. The spectrum analysis of the <x^3> coherent mode for the 'bare' working point with the betatron tunes (Q_x=22.318, Q_y=20.87) is presented in Fig.1 (A,B) to confirm that effect for the realistic set of the machine imperfection. The sextupole field nonlinearity for the MR chromaticity correction leads to the amplitude dependent tune shift, which is about (+0.02) for the tail particles of the beam (corresponding to the design beam emittance of 54π mm.mrad), so that some particles have the horizontal tune near the 3rd order horizontal resonance [3,0,67]. The coherent frequency spectrum of the <x^3> coherent mode without the space charge effects (Fig.1(A)) has two peaks.

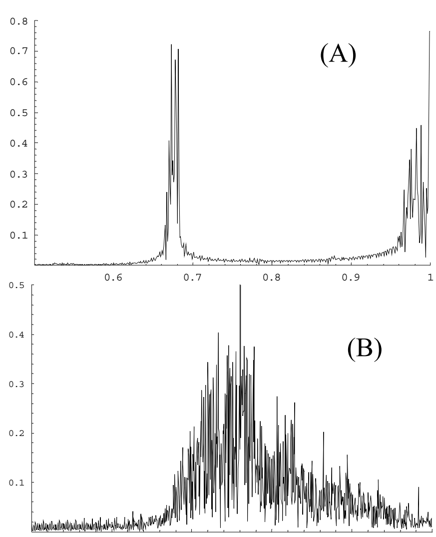

Figure 1: Spectrum analysis of the <x^3> coherent mode without (A) and with (B) the space charge detuning effect for the 'bare' working (Q_x=22.318, Q_y=20.80).

The first peak corresponds to the 'bare' lattice tune. The second peak represents the resonance condition for the [3,0,67] coherent resonance for 'tail' fraction of the beam. The space charge of the low energy beam changes the coherent properties of the beam (Fig.1(B)) by depressing the tunes and stabilizing the particle motion for this particular case. As the result, the 3rd order coherent resonance condition, observed in Fig.1(A), vanishes for this 'bare' working point.

The space charge detuning effect can lead to crossing the 'sum' linear coupling resonance [1,1,43] for the case of the moderate beam power of MR. The resonance strength is determined, first of all, by the lattice imperfection. The effect of this resonance on the particle motion depends on the location of the 'bare' working point and the coherent space charge detuning. The spectrum analysis of the <xy> coherent mode for the 'bare' working point (Q_x=22.318, Q_y=20.80) without and with the (LC) alignment errors for the MR magnets is presented in Fig.2 (A,B).

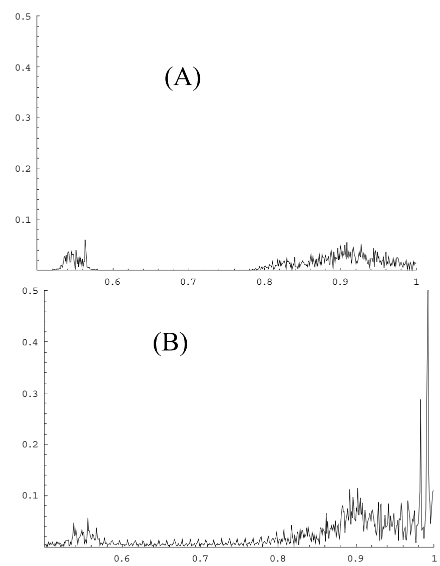

Figure 2: Spectrum analysis of the <xy> coherent mode for the basic MR operation scenario without any alignment errors (A) and with realistic alignment errors (B) of the magnets including the low energy space charge effects.

The estimated coherent space charge tune shift for the MR moderate beam power is about (-0.05). If the 'bare' working point is chosen above the [1,1,43] resonance line on the distance about 0.05, the effect of linear coupling resonance on the particle motion becomes quite strong, leading to dramatic particle losses at the MR collimator. In this case the coherent resonance condition has been satisfied $((\nu_{x,o}-\Delta\nu_{x,coh})+(\nu_{y,o}-\Delta\nu_{y,coh})=m)$. As the result, the maximum amplitude of the frequency spectrum for this case becomes much bigger than for another 'bare' working point. It is obvious that this area on the tune diagram should be avoided for the machine operation with high beam power.

EFFECTS OF HIGH-ORDER RESONANCES

The 'sum' linear coupling resonance of the J-PARC MR can be corrected by using the appropriate set of 4 independent skew quadrupole magnets, located in the dispersion-free straight sections of the ring [3]. It was found, that remained high-order coupling, caused by the combined effect of the machine sextupole nonlinearity, the machine imperfections and the space charge of the low energy proton beam with the moderate beam power, can lead to emittance dilution for the MR operation.

The spectrum analysis of the high-order coupling mode $<x^2y^2>$ before the correction of the 'sum' linear coupling resonance is presented in Fig.3 for the basic bare working point for two cases: without (A) and with (B) the realistic set of the alignment errors of the MR magnets. Similar effect has been observed for the coherent modes $<x^4>$ and $<y^4>$, which characterize the 4th order coherent resonance.

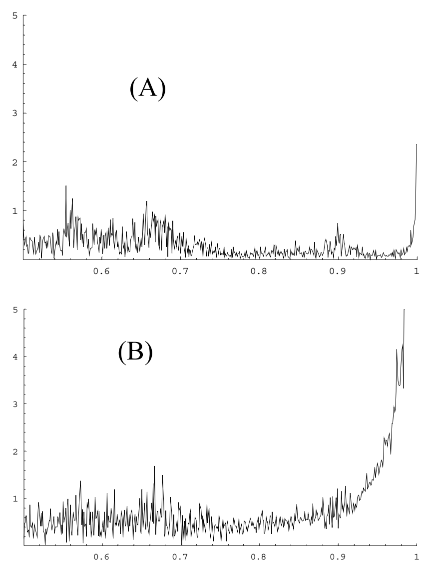

Figure 3: Spectrum analysis of the $<x^2y^2>$ coherent mode for the basic MR operation scenario including the low energy space charge effects without (A) and with (B) alignment errors of the MR magnets before the correction of the 'sum' linear coupling resonance.

The remained emittance dilution, which could lead the particle losses during the injection process, has been observed after the correction the 'sum' linear coupling resonance. The halo formation of the beam has been checked by looking at the 99% emittances as a function of time. The horizontal 99% emittance dilution before (red) and after (blue) the correction the 'sum' linear coupling resonance is presented in Fig.4.

To understand the mechanism of the emittance growth after the correction the linear coupling resonance, the high-order coherent mode analysis has been performed. The obtained result (Fig.5) indicates the existence of the high-order coherent resonances for the basic working point after the linear decoupling. The high-order coupling resonance [2,2,86] in combination with the 4th order resonances [4,0,89] and [0,4,83] is the source for the observed emittance growth after the linear coupling correction.

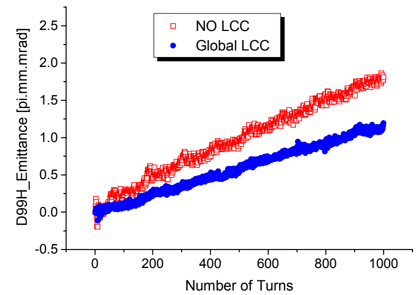

Figure 4: Dilution of the horizontal 99% emittance before (red) and after (blue) the correction of the 'sum' linear coupling resonance for the moderate MR beam power and the realistic alignment errors of the MR magnets.

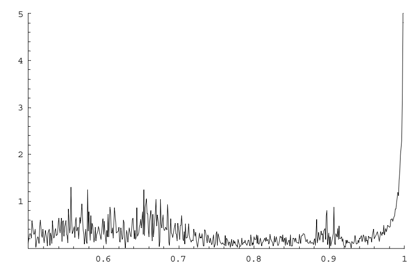

Figure 5: Spectrum analysis of the $<x^2y^2>$ coherent mode after the correction the 'sum' linear coupling resonance for the basic MR operation scenario including the low energy space charge effects and the alignment errors of the MR magnets.

CONCLUSIONS

For the basic operation scenario of the J-PARC MR the low-order coherent resonance [1,1,43] has been recognized as the most dangerous resonance, which can lead to limitation the MR beam power. The performed analysis of the coherent modes before and after the correction the 'sum' linear coupling resonance shows that after the successful correction of the linear resonance the remained emittance dilution is caused by the 4th order coupling resonance [2,2,86] in combination with the 4th order horizontal and vertical resonances. The self-consistent study has been performed for the case of the moderate beam power by using the PTC_ORBIT code.

REFERENCES

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[3] A.Molodozhentsev, E.Forest, "Simulation of Resonances and Beam Loss for the J-PARC Main Ring", ICFA-HB08 Workshop, August 25-29, 2008.