SIMULATION OF RESONANCES AND BEAM LOSS FOR THE J-PARC MAIN RING

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Abstract

The J-PARC Main Ring [1] should provide to users a proton beam with high beam power. Strict limitation of particle losses during the operation is required to avoid radiation damage. The particle losses are caused first of all by the combined effect of the machine imperfections and the low energy space charge. Beam dynamics studies have been performed at the moderate beam power of 14.5kW of the low energy beam to optimize the MR performance. The effect of the low and high order resonances on the particle losses at the injection energy has been studied for different 'bare' working points. The sum linear coupling resonance [1,1,43] has been identified as the most serious resonance for the MR operation, which leads to significant particle losses during the injection process. To minimize the effect of this resonance the appropriate correction procedure has been applied successfully. After correction of the low order coupling resonance the particle losses are caused mainly by the high-order resonances, excited by the low energy space charge and the machine imperfections. The particle losses for different machine operation scenarios have been estimated, including the injection and acceleration processes. The study of the combined effect of the MR imperfections and the space charge of the beam with moderate beam power has been performed by using the PTC_ORBIT code [2], installed on the KEK super computer HITACHI SR11000.

INTRODUCTION

Space charge effects of the low energy high intensity proton beams are recognized as one of the most significant problems for modern accelerators, which lead to emittance dilution and limit the total number of particles in the beam. This subject becomes extremely important for proton synchrotrons with beam power of hundreds of kilowatts, which are used as proton drivers for spallation neutron sources. For such high intensity proton synchrotrons one of the most essential issues is minimizing the particle losses during the machine operation to avoid radiation damage. It is extremely significant to understand the emittance evolution and perform optimization of the machine performance.

The space charge of the proton beam, depending on beam intensity, transverse and longitudinal beam size, beam energy and beam environment, depresses the tunes of individual particles so that the incoherent tune of the 'core' particles 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) will be changed too by the space charge of the beam. Moreover, the space charge of the high intensity low energy proton beam itself introduces internal nonlinear fields, which can be quite destructive even for an ideal machine.

In a real synchrotron there are many external sources that excite low-order and high-order resonances. These include nonlinear fields, field errors and multipole field components of different types of magnets in addition to misalignment errors. These 'machine' resonances can be characterized by the resonance stop-bands inside of which the particle motion is disturbed, leading to emittance dilution and to particle losses in the machine chamber.

In the case of a proton machine with the high beam intensity, crossing of the 'machine' resonance is unavoidable. Moreover, the space charge potential itself introduces strong nonlinearities, which will excite 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 a static distribution. The goal of the design of such synchrotrons is the optimization of the machine performance which should be based on a comprehensive analysis of the combined effects of time dependent space charge forces in addition to imperfection errors.

MR LATTICE AND RESONANCE

The natural chromaticity of the machine is about (-30) in both transverse planes, which lead to significant chromatic detuning. To correct it 72 sextupole magnets, placed into the MR arcs, are used introducing the main nonlinear field of the machine. The focusing structure of the MR arcs has been designed to provide cancellation of the nonlinearity of the chromatic sextupole magnets, so that the normal sextupole resonances should not be excited [1]. Nevertheless, this field nonlinearity of MR will lead to excitation the 4th order resonances.

The design 'bare' working point has been chosen so as to avoid influence of any structure resonance and to meet the requirements of the slow extraction process, based on the 3rd order horizontal resonance. The only one structure resonance, which cross the area near the operational point, is the so-called 'Montague' resonance [2,-2,3]. In the case of a low beam power this resonance will be excited by the chromatic sextupole magnets, which have an 'octupole-like' effect on the particle motion. The strong nonlinearity of the potential of the space charge dominated beam also contributes to the 4th order coupling resonance.

This resonance can lead to the emittance exchange and to the significant particle losses if only the transverse emittances of the low energy beam for some reasons are quite different.

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During the MR injection process the distortion of the super-periodicity is caused by elements of the injection system (three bump magnets to create the injection 'dog-leg', including the field leakage from the injection septum magnets), individual field errors (multipole field components) and misalignment errors.

After 'shuffling' procedure, performed for the MR magnets by using the measured field data, the distortion of the focusing structure has been minimized by keeping a minimal COD, beta beating and $3Q_x$ resonance driving term [3]. In our study of the single particle dynamics and the collective effects, we used the fixed location of the MR magnets with the measured field errors. The random misalignment errors of the MR magnets have been included too.

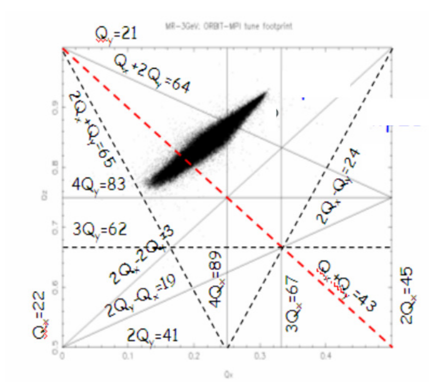

Figure 1: Foot print of the betatron tunes of the proton beam with beam power of 14.5kW at the injection energy of 3GeV.

The space charge detuning (depressing) effect leads to crossing different resonances depending on the beam environment and beam parameters. At the injection energy of 3GeV the incoherent tune shift should be estimated including the image fields. For this estimation we assumed that the MR beam pipe has a rectangular shape with transverse size ±70mm. In the case of the parabolic transverse particle distribution with 100% emittance of 54πmm.mrad, a moderate beam intensity and a bunching factor B_f=0.16 the estimated value of the Laslett incoherent tune shift for MR is about (-0.16) for both transverse planes. The foot-print of the betatron tunes of the proton beam at the injection energy with a moderate beam power of 14.5kW is presented in Fig.1 including the main resonances for this area. The coherent detuning, caused by the low energy space charge at the injection energy, can be estimated as (-0.036) in the horizontal plane and (-0.068) in the vertical plane.

The low and high-order resonances are excited by the combined effect of the space charge of the high-intensity proton beam and the 'lattice' resonances. Depending on the 'bare' working point on the betatron tune diagram, the space charge detuning effect will lead to crossing different resonances. Optimization of the working point for the basic machine parameters should be performed to avoid significant emittance dilution and particle losses for our realistic set of the machine imperfections.

Tune scanning

For a realistic 6D initial particle distribution at the injection point of MR a tune scan has been performed for a moderate beam power at the injection energy by using the HITACHI SR11000 system of the KEK super computer. For each 'bare' working points the particle losses at the MR collimator with tan acceptance of 60π have been estimated for 4000 turns. From the obtained results the potentially dangerous resonances have been identified, which could limit machine performance.

From the tune scanning study one can make the following conclusions. For the analyzed region the most dangerous resonances, which lead to significant particle losses, are the linear coupling sum resonance [1,1,43], the 4th order difference coupling resonance [2,-2,3] (so called 'Montague' resonance), the half-integer resonance [2,0,45], the fourth order integer resonance [4,0,90] and the linear resonance [0,1,21].

The 'bare' working point with betatron tunes Q_x=22.32 and Q_y=20.87 has been chosen as the 'basic' working point for the MR operation with the moderate beam power and the bunching factor B_f=0.16. For this working point the 'lattice' linear coupling resonance [1,1,43] is the most dangerous resonance for the MR operation with the moderate beam power. It should be corrected. The main source for this linear coupling resonance is the vertical shift of the optical axis of the MR sextupole magnets, caused by the alignment errors and the vertical closed orbit distortion (Fig.2).

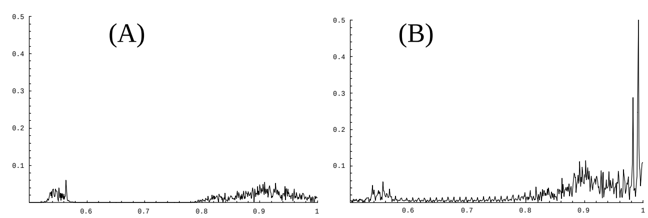

Figure 2: Spectrum analysis of the <XY> coherent mode for the 'basic' working point including the low energy space-charge effect without (A) and with (B) the vertical shift of the optical axis of the MR sextupole magnets

LINEAR COUPLING RESONANCE CORRECTION

For the MR operation we chose a linear coupling correction scheme, based on four independent skew-quadrupole magnets, placed at the edge of the 'INJ' and 'RF' straight sections of the ring. By using these skew-quadrupole magnets one can make a 'global' or a 'local' correction of the linear coupling resonance. The 'global' correction of the linear coupling resonance allows minimization of the remained coupling after the correction around the whole ring. In the case of the 'local' correction of the linear coupling resonance, linear decoupling has been performed at the location of the MR collimation system. The correction procedures for the both decoupling algorithms have been implemented with the ‘PTC’ code.

Global reduction of Coupling

To perform the ‘global’ linear decoupling we minimized a ‘Ripken’ lattice function summed around the ring. We can define a function denoted β_{yx} at any point around the lattice as:

$$< y^2 > \;=\; \beta_{yy} < I_y > + \beta_{yx} < I_x > . \tag{1}$$

We then sum this lattice function around the ring:

$$F = \oint_C \beta_{yx}(s)ds \;. \tag{2}$$

Again, using a Newton search, we minimize:

$$\frac{dF}{dk_n} = \oint_C \frac{d\beta_{yx}(s)}{dk_n} ds = \sum_{i=magnets} \frac{d\beta_{yx}(i)}{dk_n} L_i \;. \tag{3}$$

This Newton search is done ‘slowly’ to avoid divergence. At the end, we obtain a local extremum of the function *F*.

The ‘global’ linear decoupling procedure has been used for MR successfully (Fig.3). It was shown that by using a set of the skew quadrupole magnets one can minimize the linear coupling around the ring. Maximum quadrupole components of the skew quadrupole magnets are less than 5% of the maximum nominal value of the MR normal quadrupole magnets. The beta-beating around the ring, cause by the skew quadrupole components, is less than 6%.

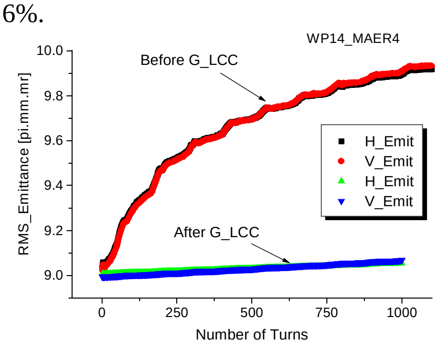

Figure 3: RMS emittance evolution in the horizontal and vertical phase planes before and after the linear coupling correction.

The performed FFT analysis of the <XY> coherent mode after the linear decoupling procedure shows that the linear decoupling has been performed successfully. The emittance growth after the ‘global’ decoupling has been studied for the ‘basic’ working point of the moderated beam power at the injection energy. The RMS emittance evolution in the horizontal and vertical phase planes before and after the ‘global’ linear coupling correction is presented in Fig.3. The transverse RMS emittance growth has been reduced. The remained emittance growth is caused by the high-order resonances, first in importance the 4th order resonances, excited by the space charge itself.

The spectrum analysis of the 4th order coherent modes like <X^4>, <Y^4> and <X^2Y^2> has been performed after the ‘linear’ decoupling for the ‘basic’ working point of the moderate beam power.

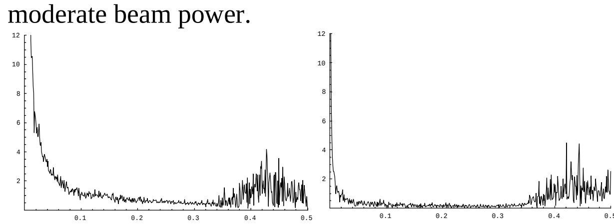

Figure 4: Spectrum analysis of the <X^4> coherent mode for the ‘basic’ working point before and after the linear coupling correction.

The spectrum analysis of the <X^4> coherent mode for the ‘basic’ working point before and after the ‘global’ linear coupling correction is presented in Fig. 4. The peak, corresponding to the 4th order coherent resonance, after the linear coupling correction becomes narrow and the resonance effect on the emittance growth becomes smaller. Nevertheless, the remained effects of the 4th order coherent resonances lead to a transverse emittance growth for both transverse phase planes after the linear coupling correction. The performed analysis shows that this emittance growth can be suppressed without any high-order resonance correction schemes by reducing the vertical closed orbit distortion at the location of the MR sextupole magnets.

ESTIMATION OF THE BEAM-LOSS BUDGET FOR THE MR OPERATION

The particle losses for the ‘basic’ working point (Q_x=22.318, Q_y=20.870) and for the moderate beam power of the JPARC Main Ring of 14.5kW has been estimated for different parameters such as the physical aperture of the MR collimation system and the maximum voltage of the RF system of MR.

The budget of the lost beam power has been established for the case of the RF voltage with V_{RF}=210kV operating on the fundamental harmonic (h=9). The performed study predicts that the total power of the lost beam during the injection and acceleration processes at the MR collimator (with aperture of 60π) can be kept below 330W for the initially mismatched beam (with the 10% beta-mismatching), if the maximum vertical shift of the sextupole axis from the center of the circulating beam is less than 0.6mm. The designed capacity of the total amount of the lost beam power for the MR collimation system is 450W [1].

REFERENCES

[1] “Accelerator Technical Design Report for JPARC”, KEK Report 2002-13.

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