BEAM DYNAMICS AND LOW LOSS OPERATION OF THE J-PARC MAIN RING

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Abstract

Operation with low particle losses during the injection and acceleration processes is crucial for the J-PARC Main Ring. To avoid the radiation damage of the machine it is necessary to identify and correct most dangerous machine resonances, which should be done in combination with the collective effects, in particular the low energy space charge effects. In frame of this report we present the status of the Main Ring commissioning process and compare main experimental data with the simulation results, corresponding to this stage. For the operation of the Main Ring with the moderate beam power we review the status of the simulation work and discuss the budget of the beam losses.

INTRODUCTION

According to the design specification [1], Main Ring (MR) of the Japanese Particle Accelerator Research Center (J-PARC) should provide the proton beam with the beam power of 800kW at the extraction energy of 50GeV. The accelerated beam will be extracted from MR by using both ‘slow’ and ‘fast’ extraction procedures to deliver the proton beam to the Nuclear and Particle Physics Experimental Hall and to the neutrino production target of the Neutrino Experimental Hall, respectively.

One of the most essential issues for such high intensity proton synchrotrons is minimizing the particle losses during the machine operation to avoid radiation problems. The particle losses have to be localized at the MR injection area, at the collimator location, at the fast and slow extraction areas. The design capacity of the radiation shielding at these places are 135W, 450W, 1.1kW and 7.5kW respectively. The particle losses around the MR should be below the 0.5W/m limit, which should guarantee the dose rate on the surface of the MR shielding less than 0.03μSv/h. Main particle losses will occur at the injection energy, so that the MR performance should be optimized to keep the particle losses during the injection process below the design limit, which is about 2.4% of the total beam intensity at the 3GeV energy. The particle losses at the MR collimator area should be below 1% and around the ring less than 1.4% of the total beam intensity at the 3GeV energy.

DESIGN PECULIARITIES OF J-PARC MR

The MR beam power depends on the beam power delivered by the rapid cycling synchrotron (RCS), performance of which is determined by the linear accelerator. For the ‘phase-1’ operation of J-PARC the kinetic energy of LINAC is limited by 181MeV. In this case the maximum expected beam power from RCS at the 3GeV energy is 300kW. At the beginning of the MR operation the maximum output energy is 30GeV instead of 50GeV and total number of bunches is 6 instead of 8. These factors will determine the MR performance. The expected beam power from MR to users at this stage (2009) will be about 100kW. Table 1 contains basic information about the design performance of RCS and MR of J-PARC for different operational stages.

Table 1: Expected Beam Power for Different Operational Stages of J-PARC RCS and MR

RCS (3GeV) **F_{REP} = 25 Hz**			**MR (h = 9, Nb = 6 / 8)** **F_{REP} = 0.3 Hz**		
kW		p. pulse (pulse=2b)	kW	GeV	p.p. bunch
#1	300	2.5e13	10.9 /14.55	3	1.25e13
			109 /145.5	30	
#2	600	5e13	29	3	2.50e13
			484.8	50	
#3	1000	8.33e13	48.5 808.1	3 50	4.17e13

According to the power upgrade plan, the beam power of MR should be increased at least 5 times with strict limitation of the particle losses. The space charge effects become one of the most serious issues for the MR operation especially during the injection process. These effects should be studied in combination with the lattice resonances in the self-consistent manner.

The design ‘bare’ working point [2] has been chosen so that to avoid influence of any structure resonances of the ‘ideal’ focusing structure of the machine. For a high beam power scenario of the MR operation the ‘bare’ betatron tunes have to be optimized to provide acceptable particle losses.

SIMULATION TOOLS AND MODEL

Many numerical simulation codes, based on self-consistent treatment of the space charge effects by using the particle-in-cell (PIC) space charge model, have been constructed to model the multi-particle dynamics in the space-charge dominated machines. To be able to study the combined effects of the machine resonances and the space charge we combined abilities of two codes: Polymorphic Tracking Code (PTC) [3], and ORBIT_MPI [4].

The PTC_ORBIT code [2] allows us to study single particle dynamics and collective effects of the 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').

The transverse space charge forces are evaluated as nonlinear kicks using the explicit second order PIC model and FFT [4]. For J-PARC MR the transverse size of the beam is much smaller than the longitudinal one, so that to study the space charge effects we adopted the "2+1/2D" model, implemented to the 'ORBIT' code. The second order symplectic s-propagator, implemented into PTC [3], 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. For the PTC tracking we used the small bending angle approximation, which is acceptable for the J-PARC MR study. The integration length or the distance between the space charge nodes is the 'free' parameters of the propagator [2].

SINGLE PARTICLE DYNAMICS: SIMULATIONS AND OBSERVATIONS

For the single particle dynamics study the realistic machine conditions have been introduced step-by-step to identify most dangerous resonances around the suggested 'bare' working point, excited by different kind of machine imperfections: the injection dog-leg with the edge-focusing effects of the bump-magnets, the measured field errors for the MR magnets, misalignment errors of the magnets and the field leakage of different kind of septum magnets, used at the injection and extraction beam lines. The single particle motion for the on- and off-momentum cases has been investigated by using the PTC code.

Resonance driving terms of low-order resonances, excited by the field errors of the MR magnets, have been minimized by using the mixing ('shuffling') procedure, performed after the corresponding field measurements for each type of the machine magnets [5]. The MR sextupole magnets for the chromaticity correction introduce into the lattice the strongest nonlinear field will contribute to the low-order ([1,1,43]) and high-order (mainly [3,0,67], [2,-2,3], [1,2,64], [-1,2,19], [4,0,90], [2,2,86]) resonances for the non-ideal focusing structure of the synchrotron.

The performed study of the single particle dynamics consists of two parts: dynamic aperture and beam survival at the MR collimator. The simulated dynamic aperture of the machine with the realistic field and misalignment errors is more than 200π mm.mrad for the wide range of the betatron tunes. The dynamic aperture analysis shows that the low-order and high-order resonances, observed for MR, can produce smearing of the particle trajectories in the transverse phase planes even if the particle motion is stable. This effect will lead to the particle losses if the physical limit of the machine aperture is introduced. In this case the beam survival study provides us information about maximum beam size (or emittance) at the observation point which can survive in the ring. The beam survival at the MR collimator for different tunes has been simulated by using the short-term tracking (a few synchrotron periods). The physical acceptance of the MR collimator has been assumed as 81π mm.mrad, which is the case of the 'open' collimator for the real machine operation. The linear chromaticity of the machine has been corrected to zero. This study has been performed without consideration the effects of the closed orbit distortion. The linear coupling has been introduced by artificial misalignment of the MR quadrupole and sextupole magnets, assuming the Gaussian distribution of the errors: $\sigma_{TILT} = 2.5\times10^{-4}$ rad, $\sigma_{SHIFT} = 5.0\times10^{-4}$ m (cut=2σ) [7].

The beam survival at the collimator presented in Fig.1, indicates clearly that the linear coupling resonance [1,1,43] is the potential source for the particle losses and can limit the machine performance. The amplitude dependent tune shift, caused by mainly the MR sextupole field nonlinearity, leads to the shift of the beam survival minimum from the resonance line. The obtained results predict the particle losses in the vicinity of the linear sum-coupling resonance at the 81π collimator, if the beam emittance is more than 23 π mm.mrad.

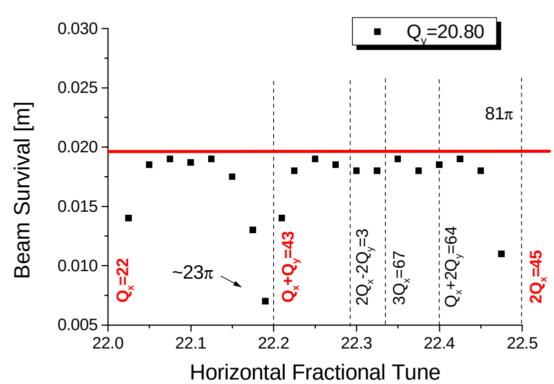

Figure 1: Simulated 'Beam Survival' at the MR collimator with the acceptance of 81π mm.mrad as function of the horizontal betatron tune (Qy=20.80 fixed).

The J-PARC Main Ring commissioning process has been started from May 2008. Many items have been performed during first 5 'Runs' including: (1) tuning of the injection process; (2) RF capture and acceleration up to 30GeV; (3) tuning the fast and slow extraction processes; (4) improvement of the power supply stability of the MR magnets; (5) measurement of the MR lattice parameters; (6) COD measurement and correction and so on [Kobayashi, PAC09]. The machine tuning has been

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performed so far by using the RCS ‘single-shot’ with the ‘zero-beam’ intensity of 4×10^{11} p per bunch (just 1% of the design goal). After suppressing the power supply ripple of the MR magnets the tune stability has been improved by one order till (±0.005), which makes possible study of the main machine resonances. The achieved accuracy of the tune measurement, based on the ‘turn-by-turn’ analysis, is quite acceptable (±0.0005). The tune scanning for the MR operation with the ‘zero-beam’ intensity has been performed successfully during “RUN20” of the machine commissioning in December 2008.

Rough estimation of the beam survival rate (the beam transmission, obtained thought the DCCT output) in MR has been used to analysis of the obtained results. The measurements have been made by using the ‘single-shot’ operation, keeping the beam at the injection energy of 3GeV during 1sec without the acceleration. After that the beam has been extracted to the injection dump. The sextupole magnets were powered to provide the required chromaticity correction. The closed orbit distortion has been corrected partially with the remained maximum COD about ±(3÷4) mm in both horizontal and vertical planes.

The results, obtained experimentally (Fig.2) and simulated ones (Fig.1), indicate clearly that the linear coupling sum resonance [1,1,43] is the strongest potential source for the particle losses during the MR operation. The measured transverse emittance of the beam, injected to MR, has been estimated as 20π mm.mrad.

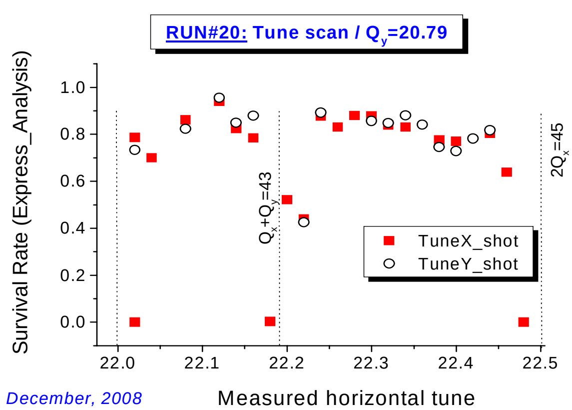

Figure 2: ‘Survival Rate’ of the beam at the injection energy for different values of the horizontal betatron tunes, obtained during the MR commissioning RUN#20 in December 2008.

The survival rate, estimated for the tunes near the [1,1,43] resonance, looks smaller than the simulated beam survival at the same bare working point. This difference can be explained by the fact, that the closed orbit distortion for the real machine operation is bigger. The effect of this resonance on the beam can be minimized by keeping, first of all, the vertical closed orbit distortion less than (±1mm) at the location of the sextupole magnets.

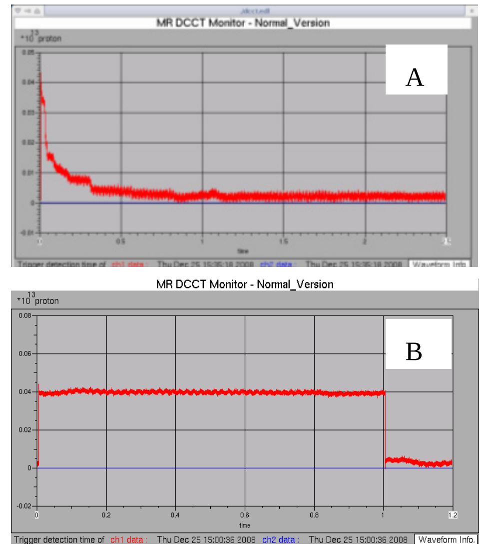

Figure 3 (A,B): The measured changing the beam intensity during the injection process for the MR operation (RUN20) for different ‘bare’ working points: on the [1,1,43] resonance (A) and away from the [1,1,43] resonance (B).

Changing of the beam intensity during the injection process for two different ‘bare’ tunes for the MR operation (RUN20) is presented in Fig.3(A,B). For the case when the betatron tunes are located near the sum linear coupling resonance [1,1,43] (Fig.3A) the significant particle losses have been observed experimentally. If the betatron tunes are chosen to avoid influence of this resonance (Fig.3B) the beam intensity remained constant during the observation time.

The performed analysis of the single particle dynamics and the obtained measured data shows that the 3rd order resonances, like [3,0,67] and [1,2,64], can also lead to significant emittance growth and the particle losses in MR during the injection process. After the ‘shuffling’ procedure [5] the additional contribution to the sextupole resonances comes from the non-linear components of the field leakage of injection and slow extraction septum magnets. At the early stage of the machine operation Main Ring does not have any elements for the resonance correction. Only one possible way can be used to reduce the particle losses: the optimization of the working point of the machine should be performed.

Resonance Correction

To suppress the most dangerous resonances for the MR operation, appropriate correction schemes have been investigated in frame of the single particle dynamics study. The harmonic analysis of the beta-beating caused by the quadrupole errors has been analyzed. The corresponding half-integer resonance correction scheme based on minimization the required harmonics by using the trim coils of the MR quadrupole magnets has been applied for MR [6]. It was shown that to reduce the effect of the quadrupole errors one can use at least 10 independent trim coils (with strength just about 5% from the nominal value), placed in the quadrupole magnets of MR at the dispersion-free straight sections.

The linear coupling resonance can be corrected by using appropriate set of four skew quadrupole magnets [6, 7], placed in the dispersion-free straight sections of MR. It was demonstrated that the linear decoupling can be performed both locally (at the location of the MR collimator) and globally, minimizing the linear coupling around the ring. The simulated results, indicated the beam survival at the MR collimator before and after the correction of the linear coupling resonance [1,1,43], is presented in Fig.4.

The normal sextupole resonances like [3,0,67], [1,2,64] and [-1,2,19] also can be corrected by using two additional sextupole magnets to suppress each resonance, placed at the dispersion-free straight sections of the ring [6]. All these study have been performed for 'idealized' focusing structure of the machine to demonstrate the abilities of the proposed correction schemes for the MR operation. If these machine resonances will limit the performance of the 'real' machine, the correction schemes should be analyzed in combination with the space charge effects.

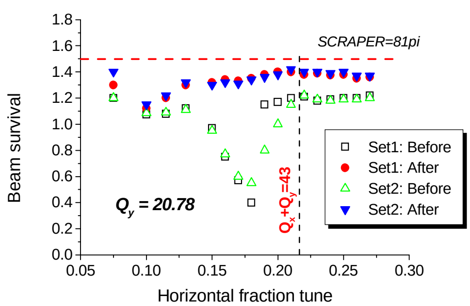

Figure 4: Simulated 'beam survival' at the MR collimator with the physical aperture of 81 π.mm.mrad for different horizontal betatron tunes (Qy=20.78) before and after the correction of the linear coupling resonance.

MACHINE RESONANCES AND SPACE CHARGE EFFECTS

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. In the case the beam power for the 8 bunches operation of MR is about 14.5kW at the injection energy of 3GeV and 145/242kW at the output energy of 30/50GeV, respectively. According to the basic scenario of the machine operation for this beam power, the MR RF system is based on the fundamental harmonic RF cavities (h=9) with the total RF voltage of 210kV. These parameters of the RF system have been chosen to provide the machine with the longitudinal emittance of 3eV.sec and the bunching factor of B_f=0.16. As the 'back-up' scenario we considered also other parameters of the RF system. The emittance growth and the particle losses have been simulated for the fundamental harmonic RF cavity with the RF voltage of 40kV (h=9). In this case keeping the case longitudinal beam emittance one can obtain bigger bunching factor (B_f ~ 0.4) so that the for the fixed beam intensity the incoherent space charge detuning becomes smaller.

As was stressed above, the influence of the machine resonances on the MR performance in the case of the 'zero' beam intensity can be minimized by appropriate tuning of the machine. The space charge of the low energy beam will change the incoherent and coherent properties of the beam, which leads to crossing the low- and high-order machine resonances. Moreover, the space charge itself contributes to the resonance excitation, which depends on transverse particle distribution, beam environment, the bunch length and the energy of the beam. Optimization of the working point for different MR beam power and different parameters of the RF system for the realistic set of the machine imperfections, obtained after the field measurements and the MR magnet alignment, should be done to avoid significant emittance dilution and particle losses.

The performed tune scanning [7] for the case of the moderate beam power by using the idealized MR lattice indicates clearly that the 'bare' working point for the MR operation should evade the area near the linear coupling resonance [1,1,43]. The initial particle distribution, used for this study, corresponds to the expected 6D distribution from RCS at the 3GeV energy. The effect of the collimators in the beam line between RCS and MR has been considered. The expected transverse emittances in the horizontal and vertical planes at the injection point of MR are not exactly the same. As the result of that the emittance growth and particle losses along the high-order coupling resonance [2,-2,3] have been observed too. For the performed tune scanning the closed orbit distortion, observed in the real machine, have not been considered. The linear coupling has been introduced into the lattice by the transverse tilt of the quadrupole magnets only. The performed analysis of the single particle dynamics shows that the main source for the linear coupling for the MR operation is the sextupole field nonlinearity of the chromaticity correction sextupole magnets.

The emittance growth in MR at the injection energy, caused by the linear coupling resonance [1,1,43], has the coherent nature changing the distribution of the core particles of the beam. The distance between the resonance line and the line on the betatron tune diagram, representing the location of the 'bare' working points for the cases with the biggest particle losses, is about (-0.06), which is in agreement with the expected coherent space charge detuning at the moderate beam power. The performed spectrum analysis of the <XY> coherent mode for the basic 'bare' working point above the [1,1,43] resonance line (Q_x=22.32, Q_y=20.87) indicates the coherent feature of this resonance [7].

The correction scheme to suppress the linear coupling resonance [1,1,43] in combination with the space charge effects has been applied for MR in the case of the basic working point with the betatron tunes 22.31 and 20.87 in the horizontal and vertical planes respectively. By using four independent skew quadrupole magnets the decoupling can be performed locally at the location of the MR collimator or globally, minimizing around the ring the linear coupling remained after the correction. The correction procedures have been performed by using the decoupling algorithm implemented to the PTC code. It was demonstrated that this resonance can be corrected by using the skew quadrupole components with the strength less than 5% of the maximum nominal value of the MR quadrupole magnets. The resulting beta-beating around the ring, caused by the skew quadrupole field components, is less than 6%.

The RMS emittance growth, after applying the correction the [1,1,43] resonance, becomes significantly small in comparison with the case without any resonance correction procedure [7] for the case of the moderate beam power and the basic 'bare' working point. The spectrum analysis of the linear coupling coherent mode indicates no <XY> coherent mode after the correction. Nevertheless, the analysis of the 99% emittance after the successful correction the [1,1,43] resonance shows the remained emittance dilution. This effect has been investigated by using the spectrum analysis of the high order coupling coherent mode, in particular, the $<X^2Y^2>$ mode, which is excited by the sextupole field nonlinearity in combination with the space charge. In addition, the high order coherent modes like $<X^4>$ and $<Y^4>$ have been observed for the basic working point [8].

BUDGET OF BEAM LOSSES

According to the design specification, the maximum power of the lost beam at the 3-50 beam-line and at the MR collimators should be about 500Watt. Additionally, the particle losses around the ring should be less than 0.5Watt/meter. The machine performance should be optimized to keep the particle losses during the MR operation below this level. For this study the 'realistic' particle distribution in the transverse phase planes has been used. This 4D distribution was based on the particle distribution obtained from RCS for the moderate beam power of 300kW at the maximum energy of 3GeV. For this case the particle losses at the 3-50 beam-line collimator has been estimated about 135Watt, if the jaw of the collimator has acceptance of 54 π.mm.mrad. By using the particle distribution, obtained after the beam passes through the beam-line collimator, the particle losses in MR have been estimated for the basic 'bare' working point without using any resonance correction schemes.

The budget of the beam losses for the MR operation depends on the longitudinal particle distribution at the injection energy, which determines by the time pattern of the RF system. Different scenario for the RF operation has been studied for the moderate beam power. The MR operation is based on the constant RF voltage during the injection and acceleration processes, which is equal to 210kV (h=9). The budget of the beam losses has been established for the current operation scenario of MR with 6 bunches. In the case of the physical acceptance of the MR collimation system 60π mm.mrad, the total power of the lost beam during the injection process has been estimated as 132Watt. During the acceleration process the power of the lost beam has been estimated about 11Watt/bunch. The resulting total power of the lost beam at the MR collimator system for the basic MR operation scenario can be kept below the acceptable limit even for the mismatched beam. If it is necessary, one can use the dynamic collimation system [9] to cut the beam halo during the acceleration process. As the 'back-up' scenario, the case with bigger bunching factor has been considered too.

FUTURE PLANS

The beam power upgrade plan [10] is based on the following steps. The RCS beam power at the 3GeV energy has to reach 600kW. The capacity of the collimation system of the 3-50 beam-line and MR should be increased up at least up to 4kW. The number of bunches in MR should be increased to the design value (N_{bunch}=8). The MR repetition rate has to reach 0.33Hz. In this case the expected beam power for the MR operation with the maximum energy of 30GeV is about 320kW. To reach this goal it is necessary to control the space charge effects at the injection energy by using the second harmonic RF cavity. In addition to that, the correction of the linear coupling resonance [1,1,43] should be utilized for the MR operation.

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