STUDY OF THE BEAM DYNAMICS FOR THE 'FAST EXTRACTION' OPERATION SCENARIO OF THE J-PARC MAIN RING

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Abstract

During the early J-PARC Main Ring commissioning and the machine operation with the moderate beam power the 'fast extraction' bare working point has been studied to provide the machine operation in the safe regime. We discuss main experimental results obtained so far and compare with the results of the computational model of the machine, including the first experimental approach to minimize the effect of the 'sum' linear coupling resonance. The strategy to increase the beam power by keeping the moderate space-charge detuning is presented shortly. The advantage of the second harmonic MR RF cavity, including the estimation of the beam losses during the injection and acceleration processes, is discussed.

INTRODUCTION

The J-PARC Main Ring (MR) should provide acceleration of the proton beam from the injection energy of 3GeV up to the maximum extraction energy of 50GeV. At the early operation stage of MR the maximum energy is limited by 30GeV. The accelerated proton beam will be delivered to the 'Neutrino Experiment' and to the 'Nuclear and Particle Physics Experiments' by using the 'fast' and 'slow' extraction techniques, respectively. For the 'phase-1'operation of the J-PARC Complex the 300kW beam power will be delivered to users by the rapid cycling synchrotron (RCS), which accelerates the proton beam from 181MeV up to 3GeV with the repetition rate of 25Hz providing 2 bunches per pulse. According to the design specification of the J-PARC Complex, only about 5% of the average RCS beam power will be injected to MR by using the single-turn injection technique. The total beam power of 8 bunches in MR at the injection energy of 3GeV in this case will be 14.5kW (1.25e13 protons per bunch). At the energy of 30GeV the maximum expected beam power for the 'phase-1' of the MR operation is 145kW.

Emittance growth caused, first of all, by the combined effects of the machine imperfection resonances ('external' sources) and collective effects of the low energy high intensity proton beam ('internal' sources), could lead to significant particle losses during the injection and acceleration process. To provide the safe operation of the machine the particle losses for the 'phase-1' stage of the MR operation can not exceed the capacity of the MR collimation system, which is 450W. The particle losses around the machine have to be limited by 0.5W/m to meet the strict requirements on the radiation safety of the machine. The MR performance should be optimized to keep the particle losses during the injection and acceleration processes below the design limit.

MAIN RING IMPERFECTIONS AND MACHINE MODEL

The computational model of the MR focusing structure has been developed by using all known data of the field measurements of each individual magnet of MR [1]. The position of each magnet in the ring has been determined to minimize the low-order effects, including the closed orbit distortion, the beta-beating around the ring and the driving term of the 3rd order horizontal resonance. Analysis of the measured basic properties of the focusing structure of the real machine and the corresponding properties of the computational model of the machine demonstrates the agreement [1] and allows using this computational model of the J-PARC MR for the comprehensive study of the machine resonances.

The following high-order field components have been introduced in to the MR model to provide the realistic description of the machine: up to the sextupole components in each bending magnet; up to the 5^{th} order components in each quadrupole magnet and up to the 8^{th} order in each sextupole magnet. The edge focusing effect has been introduced into the representation of the injection bump magnets. The fringe field effect of the MR quadrupole magnets has been also introduced into the model to take into consideration the 'octupole-like' effect of this field nonlinearity. The alignment errors of each MR magnets have been used for the realistic description of the machine.

The computational model of MR has been created and analyzed by using the PTC-ORBIT code [2]. For the correct representation of the single particle dynamics for the J-PARC MR the horizontal and vertical closed orbit distortions have been set to keep these distortions around the machine below ±3mm and ±1.5mm in the horizontal and vertical planes, respectively. These values have been set also for the real MR operation after the correction of the closed orbit distortion by using the MR steering magnets.

The tune scan of wide area on the betatron tune diagram around the basic 'bare' working point has been performed to analyze the beam survival at the MR primary collimator. The beam survival at the MR primary collimator with the physical aperture of 60π is presented in Fig.1. The on-momentum single particle motion has been analyzed in frame of this study. The single particle tracking has been performed by PTC during a few synchrotron periods. The fitting procedure for each working point was based on variation of all quadrupole magnets of the machine, to obtain the required phase advance in the arc modules and to minimize changing the beta-functions around the machine.

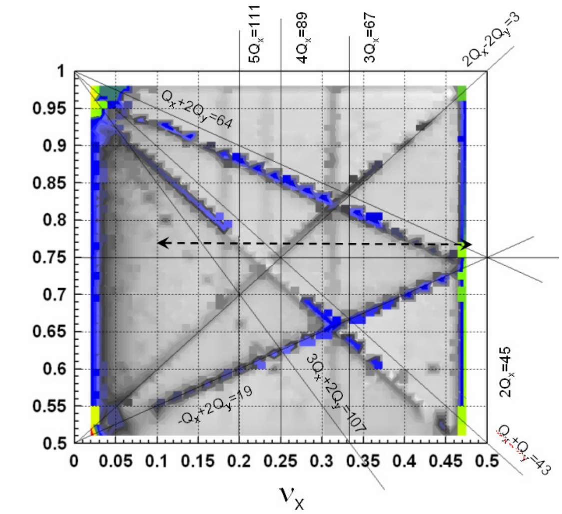

Figure 1: Beam survival study and the MR machine resonances, observed for the on-momentum particle.

The beam survival in the 'color' scale and the corresponding lattice resonances are shown in Fig.1 to identify the observed resonances and their effects, leading to limitation the maximum emittance of the beam, which could survive in the vicinity of the 'machine' resonances. The linear coupling resonance [1,1,43], caused by the 'skew' quadrupole field components of MR, is one of the lattice resonance, which should be avoided or corrected to provide the safe operation of the machine even in the case of the moderate beam power. This resonance has been observed during the early MR commissioning process [1]. The obtained results demonstrate clearly that the normal sextupole resonances [3,0,67], [1,2,64] and [-1,2,19] will limit the MR performance too, as well as the high-order coupling resonance [2,-2,3].

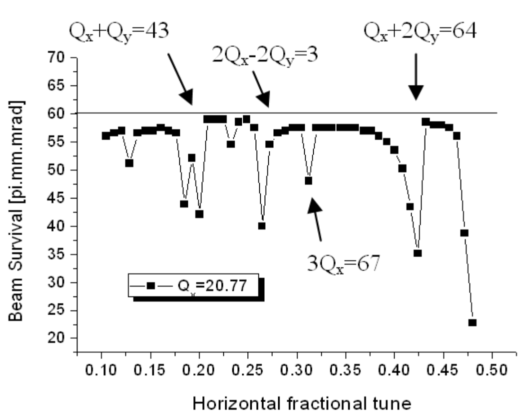

Figure 2: Beam survival study and the MR machine resonances, observed for the on-momentum particle.

The estimated maximum beam emittance, which survives in MR at the position of the primary collimator with the physical acceptance of 60π for the on-momentum particle is presented in Fig.2. For this case the vertical betatron tune has been fixed (Q_y=20.77) and the horizontal betatron tune has been changed (the 'dot' line on Fig.1). The betatron tunes near the integer [1,0,22] and half-integer [2,0,45] horizontal resonances should be avoided. The maximum beam emittance at the injection energy is limited by $(35\div40)\pi$, if the 'bare' working point is chosen near the MR resonances.

PARTICLE LOSSES: PREDICTIONS AND OBSERVATIONS

The particle losses during the injection and acceleration process for the MR operation has been estimated for different operation scenario by using the computational model of MR. For the moderate beam power from RCS only the fundamental harmonic RF system of MR has been used. It was predicted that for the RF voltage of 80kV the bunching factor of the injected beam can be kept not less than 0.18. The initial 6D particle distribution for this study was obtained from the RCS group. The beam in RCS has been prepared for the MR injection by using the second harmonic voltage just before the extraction. The effect of the collimation system of the 3-50 Beam Transport (BT) line between RCS and MR has been taken into consideration to get the realistic 6D particle distribution in the single bunch at the injection energy for MR.

'Sum' linear coupling resonance [1,1,43]

To minimize the effect of the linear coupling at the injection energy without using special skew quadrupole magnets, we decided to utilize the local vertical bump at the locations of two sextupole magnets, used for the chromaticity correction. This correction approach can be used temporary for the MR operation with moderate beam power to demonstrate the correction ability. This correction approach is limited by the BPM's resolution and the accuracy of the steering magnets setting.

To realize this correction scheme the phase advance $(\Delta\mu_x+\Delta\mu_y)$ between two appropriate sextupole magnets should be close to 90 degrees. In this case one can make the global decoupling of the particle motion around the machine. By using the computational model of MR it was predicted that the vertical local bump at the location of the sextupole magnets SDA019 and SDB028 should be in the range $(3\div5)$mm. To minimize the particle losses, caused by the [1,1,43] resonance for the MR high beam power operation, it is necessary to use the dedicated 'skew' quadrupole magnets, placed in the dispersion-free straight sections [3].

Tune scan for the moderate beam power

During the early stage of the MR commissioning the optimization of the MR performance has been performed successfully: COD correction, RF manipulation to keep the required bunching factor, minimization of the injection errors and mismatching in the transverse and longitudinal planes, betatron tune stabilization during injection and acceleration processes and so on. To provide the safe machine operation with high beam power, the systematic tune scan has been performed at the moderate beam power from RCS. The beam power delivered to the user at the maximum energy of 30GeV is about 100kW.

The prediction of the particle losses for different 'bare' working points has been made using the computational MR model and the 'short'-term self-consistent multi-particles tracking, including the machine resonances and the space charge effects of the high-intensity low energy beam. This study has been performed by using the PTC-ORBIT code [2], installed on the KEK super computer*. This prediction has been confirmed successfully during the machine study (RUN#32, April 2010).

Effect of the 'sum' linear coupling resonance correction is presented in Fig.3 for the MR operation scenario with the moderate beam power. The linear decoupling has been done 'globally' by using two skew quadrupole magnets in the MR computational model. This correction approach would 'de-couple' the lattice and reduce the particle losses significantly for the 'bare' working points above the [1,1,43] resonance line for the 'space charge dominated' beam. The minimum particle losses have been obtained just below the normal sextupole resonance [-1,2,19] for both cases: without and with the linear coupling correction.

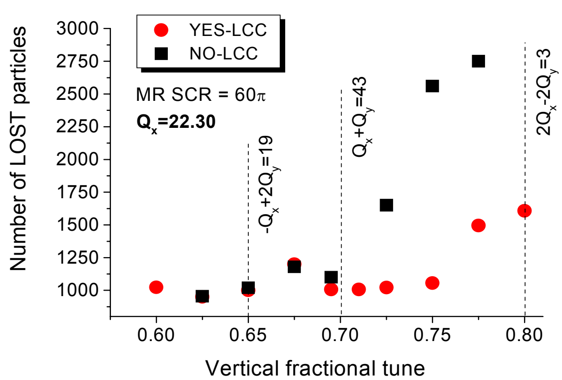

Figure 3: Predicted particle losses in MR for the moderate beam power for different vertical 'bare' tunes (Q_x-fixed) before and after the correction of the 'sum' linear coupling resonance [1,1,43].

The measured particle losses during the injection process for the same machine parameters are presented in Fig.4 without and with the correction of the 'sum' linear coupling resonance (RUN#32). From the obtained experimental results one can see clearly that for the fixed horizontal betatron tune Q_x=22.30 the best vertical betatron tune, which allows to get minimum particle losses around the machine, is just below the normal sextupole resonance [-1,2,19]. By using the working point with the measured tunes of (Qx=22.31, Qy=20.64), the minimum power of the lost beam has been obtained, which is the minimum record so far: 272W for the case of the 6 bunch operation (100kW@30GeV).The particle losses are localized at the MR collimation system.

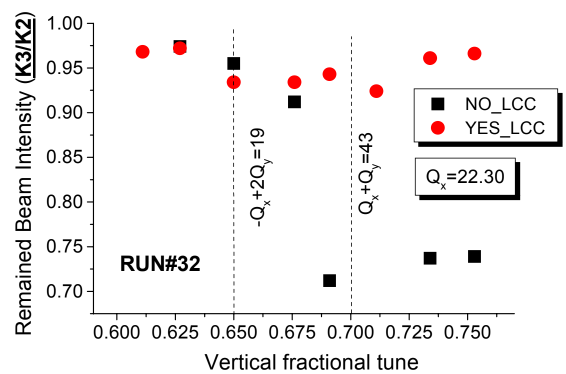

Figure 4: Measured particle losses during the injection process for the moderate beam power from RCS for different vertical 'bare' tunes (Q_x-fixed) before and after the correction of the 'sum' linear coupling resonance [1,1,43].

UP-GRADE FOR J-PARC MR

The MR beam power up-grade scenario is based a few key points. First of all, it is necessary to increase the capacity of the beam collimation systems in the 3-50 beam transport line, delivered the beam from RCS to MR, and the MR collimation system. The capacity of the 3-50BT collimation system will be improved from 450W till at least 2kW during the summer shot-down 2010. The MR collimator capacity will be increased from 450W till 2 kW at the same time. The second harmonic RF cavity will be available for the MR operation after the summer shot-down this year. After changing the existing 'fast extraction' kicker, the number of bunches accelerating in MR will be 8 instead of 6.

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