OPERATION OF THE J-PARC MAIN RING WITH THE MODERATE BEAM POWER: PREDICTIONS AND OBSERVATIONS

A.Molodozhentsev, KEK, Tsukuba, Japan

Abstract

The routine operation of J-PARC Main Ring for the Neutrino experiments has begun from April 2010, providing the moderate beam power at the maximum energy of 30GeV. The obtained beam power, extracted from the machine at this stage for the '6 bunches' operation with the repetition time of 3.3 sec, is about 110kW. Total power of the lost beam is just 100Watt, localized at the MR collimation system, which is in good agreement with predictions. After the summer shutdown 2010 the number of bunches, accelerated in the J-PARC Main Ring, will be increased up to 8. The expected beam power for the 'Neutrino' experiments will reach 140kW, which is the basis for the continuous routine operation of MR during 2010.

To optimize the machine performance, providing minimum particle losses during the injection and acceleration processes, the computational model of the J-PARC Main Ring has been established. The combined effects of the machine resonances and the space charge of the beam at the injection energy have been studied for different scenarios of the machine operations with the moderate beam power.

In frame of this report the comparison between predictions, based on the corresponding simulations, and measured beam losses is analyzed for different 'bare' tunes. The linear decoupling 'proof-of-principal' correction scheme and the obtained experimental results are discussed for the case of the moderate beam power of the J-PARC Main Ring. The predicted and obtained budget of the beam losses for the machine operation with the moderate beam power is presented. Finally, the basic scenario for the high beam power operation is discussed shortly.

INTRODUCTION

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 is 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 is produced 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 is used by MR. The beam, extracted from RCS, is injected to MR by using the single-turn injection technique. The total beam power in MR at the injection energy of 3GeV for the case of the '8-bunches' operation 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 140kW.

The MR performance for the low-beam intensity case, predicted by the computational MR model [1], has been compared with the measured characteristics of the MR including the beam survival at the injection energy for different betatron tunes. The obtained results, which represent the effects of the machine resonances, will be discussed in this report.

For the MR operation the significant contribution of the 'sum' linear coupling resonance $Q_x+Q_y=43$ to the particle losses has been predicted and observed at the early stage of the machine commissioning. The correction approach, based on the local vertical bump of the circulating orbit at the location of the sextupole magnets, has been proposed and tested successfully for J-PARC Main Ring.

The tune scanning analysis has been performed for different operation scenario of the machine with the maximum equivalent beam power of 100kW at the extraction energy of 30GeV. This analysis has been made for both the computational MR model and for the real machine operation. The obtained results will be also discussed in this report. Finally, the optimum machine performance has been established providing minimum particle losses, localized at the Main Ring collimation system. The observed power of the lost beam during the injection and acceleration processes is about 100Watt, which is much below the capacity limit of the MR collimation system. The obtained experimental result agrees with the predictions, based on the MR computational model for the moderate beam power.

MAIN RING OPERATION WITH 'ZERO' BEAM INTENSITY

The J-PARC Main Ring commissioning process was started in 2008 from 'zero' beam intensity, which is just about 1% from the design intensity. The 'direct' injection scheme without bump-magnets, which change the circulating orbit in the injection straight section of the ring, has been used to inject the beam into MR. The lattice properties have been studied and compared with the results of the computational model of the machine [2].

The Main Ring computational model has been developed, representing the synchrotron with the realistic machine imperfections including measured field data and measured alignment error for each magnet. The measured properties of the MR focusing structure are in reasonable agreement with the simulated values, in particular the closed orbit distortion, the beta functions in the horizontal and vertical directions, linear chromaticity of the machine before and after the correction by using 72 sextupole magnets and so on.

Big efforts, connected to optimization the MR performance, have been made by the commissioning group [3] providing the good agreement between the simulated and measured basic properties of the focusing structure of the machine: minimization the injection errors; closed-orbit correction and RF tuning; improvement the power supplies of the dipole and quadrupole magnets and other items. After improvement of the power supply system of the quadrupole magnets the variation of the betatron tunes $(\Delta Q_{x,y})_{max}$ is in the range ±0.0015 for the time period more than 1sec. The tune scanning has been performed at different stages of the machine commissioning to check the predictions, based on the computational model of the machine, and to find a 'safe' area for the basic 'bare' working point, which provides minimum particle losses during the injection and acceleration processes.

By using the computational model of J-PARC MR [2] the tune scan study has been performed, first of all, by analyzing the single particle dynamics. The dynamic aperture of the machine and the beam survival at the MR collimator have been studied taken into consideration realistic machine imperfections for both on- and off-momentum particles [4]. During that study it was found that 'smearing' of the particle trajectory, caused by low- and high-order resonances (mainly the coupling resonances), could lead to the particle losses at the MR collimation system.

The simulated beam survival at the MR collimator with the acceptance of 60π is presented in Fig. 1. The machine operation scenario corresponds to the case of the 'fast' extraction of the beam to the 'Neutrino' beam-line. In the case of the 'slow' extraction operation scenario of J-PARC MR it is necessary to take into account the effect of the field leakage of the extraction septum magnets, which disturb the beam also at the injection energy.

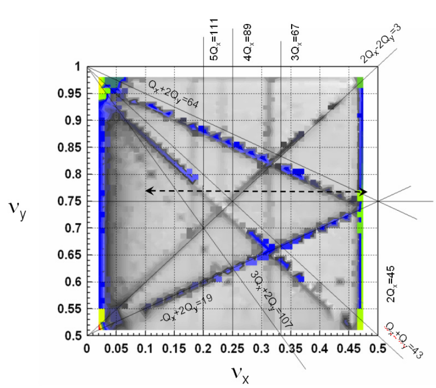

Figure 1: Beam survival study and the MR machine resonances, observed for the on-momentum particle for the 'fast' extraction operation scenario of J-PARC MR.

The short-term single particle tracking procedure during 4'000 turns (~ 21msec at 3GeV) has been used for that tune-scan, taken into account the synchrotron oscillation of the off-momentum single particles. This number of turns corresponds to a few synchrotron periods, which is determined by parameters of the RF system. 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. The 'light grey' color represents the 'bare' working points with minimum emittance dilution and minimum particle losses at the MR collimator.

The obtained results demonstrate clearly that in addition to the integer and half-integer resonances the 'sum' linear coupling resonance [1,1,43] , the normal sextupole resonances [3,0,67], [1,2,64] and [-1,2,19], as well as the high-order coupling resonance [2,-2,3] would limit the MR performance.

The tune scanning with 'zero' beam intensity of the MR beam has been performed to check the predicted effects of the lattice resonances, caused by the machine imperfections (RUN#27/2009 and RUN#28/2009).

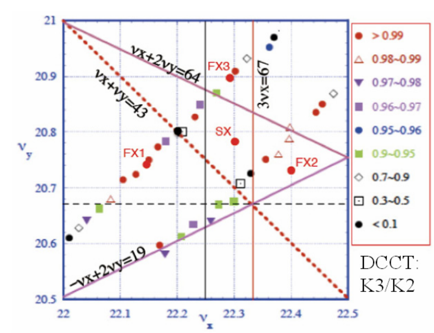

Figure 2: Measured beam survival for different 'bare' working points for the single bunch operation with the intensity of 4×10^{11} proton per bunch (RUN27&28/2009).

The single bunch operation without acceleration (the capture time of 2sec) has been set with the 'direct' injection of the bunch into MR. The survival of the beam has been observed during 40msec, which corresponds to the capture time of the batch in MR in the case of the RCS repetition frequency of 25Hz. The horizontal and vertical closed orbit distortion of MR has been corrected at the injection energy so that to keep is in the range (±2mm) and (±1mm) in the horizontal and vertical planes respectively. The linear chromaticity of the machine has been fully corrected.

The collimation system of the 3-50 beam line between RCS and MR was not used, so that the 100% transverse emittance of the injected beam was expected to be equal about 80π. The 'fast extraction' scenario of the MR operation has been used for this study. The injection errors have been minimized to avoid unexpected particle losses at the beginning of the injection (capture) process. The measured beam survival rate for different lattice tunes is presented in Fig. 2.

The obtained experimental results are in agreement with the predictions, made by using the computational MR model for the single particle dynamics (Fig. 1). Significant particle losses have been observed experimentally near the low-order lattice resonances, including the 'sum' linear coupling resonance [1,1,43], and near the 3rd order horizontal resonance [3,0,67]. For the lattice betatron tunes, indicated as 'FX1', 'FX2' and 'FX3' on Fig. 2, the experimentally observed particle losses were less than 1% for the 'zero' beam intensity (4×10^{11} proton per bunch).

'Sum' Linear Coupling Resonance Correction: Proof-of-Principal

The correction approach, which can be used to suppress the effect of the 'sum' linear coupling resonance, has been proposed and tested for J-PARC MR by using the computational model of the machine [1]. It was demonstrated that the linear decoupling can be performed globally or locally at the MR collimation system.

The correction procedures for the both decoupling algorithms have been implemented to the 'PTC' code. The 'local decoupling' method is the method based on the matrix decoupling at the point of observation (at the position of the MR collimator). To perform the 'global' linear decoupling we minimized a 'Ripken' lattice function summed around the ring [2].

By using the computational MR model it was shown that the 'global' approach of the linear decoupling can be realized by two independent families of the skew-quadrupole magnets. In this case the required maximum quadrupole components of the skew quadrupole magnets are less than 5% of the nominal value of the MR normal quadrupole magnets. The beta-beating around the ring, cause by the skew quadrupole components, is less than 6%.

At this stage of the MR commissioning process the machine does not have any dedicated resonance correction magnets. It was decided to use artificial vertical distortion of the circulating orbit at the location of two appropriate sextupole magnets. These two sextupole magnets from 72 magnets, installed in the MR arc sections, are used primary to correct the linear chromaticity of the machine. This practical approach of minimizing the linear coupling 'globally' around the machine has been checked by using the computational model of MR and applied successfully to MR during the machine study.

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 frame of the computational model of MR the global linear decoupling has been performed by using the localized vertical bump of the circulating orbit at the position of two appropriate sextupole magnets (SDA019 and SDB028). The required local bump of the closed orbit in the vertical plane is (3÷4) mm.

This prediction has been confirmed experimentally, first of all, for the case of the 'zero' beam intensity (4×10^{11} proton per bunch). The 'lattice' tunes were set near the [1,1,43] resonance line (Q_x=22.20, Q_y=20.80). The required vertical bumps of the closed orbit at the location of SDA019 and SDB028 sextupole magnets are (+4mm) and (-5mm), respectively. The maximum vertical closed orbit distortion around the machine was kept in the range (±1mm). The DCCT output before and after the linear decoupling for the DC operation mode of J-PARC MR is presented in Fig. 3 (A) and (B) respectively.

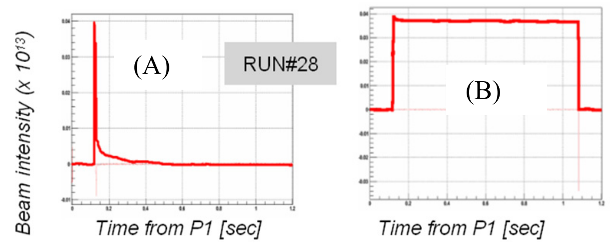

Figure 3: Beam intensity (DCCT output) during the capture process (T_{CAP} ~ 1sec) at the injection energy (no acceleration) before (A) and after (B) the [1,1,43] resonance correction by using the local vertical bump of the orbit at the position of two sextupole magnets (SDA019 and SDB028).

MAIN RING OPERATION WITH THE 'MODERATE' BEAM POWER

After the basic machine tuning with the 'zero' beam intensity, the machine study has been performed by using the 'moderate' beam power from RCS. The goal of this study was the safe operation of J-PARC Main Ring with 6 bunches, providing the 100kW beam power at the extraction energy of 30GeV to the 'Neutrino' experiments.

The particle losses should be localized at the MR collimation system, which has the lost beam power capacity about 450W. The particle losses around the ring should be not more than 0.5W/m to avoid the radiation damage of the J-PARC environment. Low-loss operation scenario has been studied by using the Main Ring computational model (PTC-ORBIT code) and realistic 6D particle distribution, expected from J-PARC Rapid Cycling Synchrotron [1].

Optimum Beam Parameters from RCS

J-PARC MR operation at this stage was based on the fundamental harmonic RF system, which contains 4 RF cavities with total maximum RF voltage of 180kV. The RF voltage during the injection process (in the case of 6 bunches operation this process is about 80msec) should be optimized taken into consideration the longitudinal parameters of the injected beam from RCS. In the case of the space charge dominated beam the bunch length and the particle distribution in the longitudinal phase plane is one of the critical parameters, which should be optimized to minimize the particle losses.

The measurement of the bunching factor has been performed after successful general tuning of the MR RF system. The observed oscillation (±15%) of the bunching factor of the beam just after the injection into MR is unavoidable ($< B_f >$ ~ 0.2). To get this bunching factor, the second harmonic RF voltage should be used in RCS at the top energy. Depending on the location of the 'bare' working point it could lead to crossing the lattice resonances and, as the result, to the transverse emittance growth and to the particle losses. The optimum RF voltage during the injection process for the MR operation with the moderate beam power has been defined in the range (70÷80) kV.

MR Operation: Predictions and Observations

The optimization of the MR operation has been performed for the following injection processes at the early stage of the machine study: (1) 1 bunch operation by using the 'direct' injection; (2) 1 batch operation by using the realistic injection procedure including effects of the bump magnets and field leakage of the injection septum magnets; (3) the 'multi-batches' operation with 6 bunches. Using the computational model of J-PARC Main Ring we performed required simulations for the '1 bunch' injection process including the effects of the bump magnets (with edge focusing effects) and the measured field leakage of the injection septum magnets (including the 'eddy current' septum magnet).

For the case of the MR operation with the moderate beam power (1.8kW/bunch at 3GeV) all predictions are based on the 'short-term' self-consistent tracking study by using the realistic 6D particle distribution at the injection energy. According to the observed experimental results in the case of the moderate beam power for the MR operation, the particle losses can be estimated (and predicted qualitatively) by using the 'short-term' tracking simulations during a few synchrotron periods (~ 4000 turns). After the performed optimization of the injection process by using the 'short-term' tracking the particle losses for a long period have be checked.

MR Tune Scanning

The tune scanning analysis has been performed for MR to find an appropriate 'bare' working point, which could provide minimum particle losses during the injection process. The beam intensity corresponds to the 100kW beam power at the 30GeV energy for the MR operation scenario with 6 bunches. As was stressed above, the realistic 6D particle distribution of the beam from RCS has been used, including the effect of the 3-50 beam line collimation system. The parameters of the MR RF system have been fixed so that to produce the matching between the longitudinal particle distribution and the RF separatrix, keeping the bunching factor almost constant ($B_f \sim 0.2$).

The realistic MR computational model has been utilized to simulate and predict the effects of the coherent resonances leading to the transverse emittance dilution. The correction of the 'sum' linear coupling resonance has been performed by using the local vertical bump of the circulating orbit at the locations of two sextupole magnets. The effects of this correction approach has been discussed above for the 'zero' beam intensity for both simulation and measurement.

'Q_y=20.75' Scan

The predicted and observed particle losses at the MR collimator for the horizontal tune scan with the fixed vertical 'bare' tune (Q_y=20.75) are presented in Fig. 6 (A) and (B), respectively. The coherent 'sum' linear coupling resonance [1,1,43] has been corrected for each 'bare' working point of this tune scan. For this tune scan the coherent resonances [2,0,45], [3,0,67] and [2,-2,3] have been observed by analyzing the FFT spectrum of the correspondent moments of the transverse particle distributions. As the result, for the 'bare' tunes around these resonance lines the particle losses occur. According to the prediction, based on the 'short-term' tracking study, the minimum particle losses should be obtained for the horizontal 'bare' tune near Q_x=22.40 (Fig. 4(A)).

The minimum particle losses have been obtained experimentally for the horizontal 'bare' tune of Q_x=22.40 (Fig. 4(B)), which is in good agreement with the prediction, made for the fixed vertical 'bare' tune of Q_y=20.75.

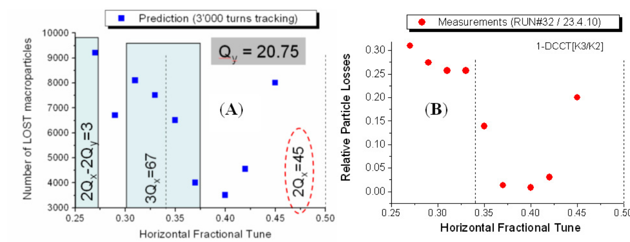

Figure 4: The predicted (A) and observed (B) particle losses at the MR collimator for the horizontal tune scan with the fixed vertical 'bare' tune (Q_y=20.75).

'Q_x=22.30' Scan

The tune-scan analysis for the fixed horizontal 'bare' tune of Q_x=22.30 has been performed for the case of the J-PARC MR operation with the moderate beam power at the injection energy (Fig. 5). The 'fast extraction' scenario was simulated for this case by using the realistic computational model of the machine.

The horizontal tune (Q_x=22.30) is chosen near the 3rd order horizontal resonance, so that without the space charge detuning effect this resonance could lead to significant particle losses. The space charge will depress the incoherent and coherent betatron tunes, keeping the tunes away the resonance stop band. The 'sum' linear coupling resonance [1,1,43] can be corrected by using the correction approach, discussed above. The predicted and measured particle losses before and after the linear coupling resonance correction indicate that for the vertical 'bare' tunes above the [1,1,43] resonance line the particle losses after the correction reduce significantly. Increasing the particle losses for the vertical tunes above Q_y=20.80 is determined by the effects of the [2,-2,3] and [1,2,64] resonances.

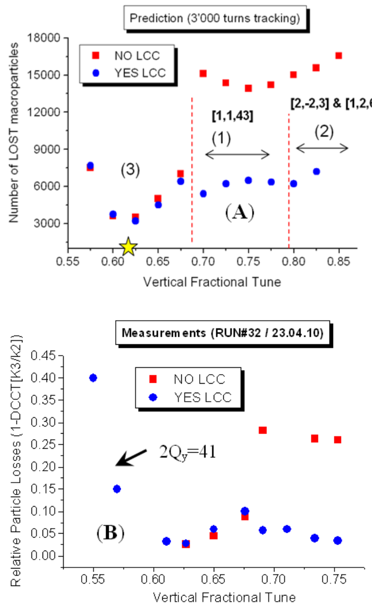

Figure 5: The predicted (A) and observed (B) particle losses at the MR collimator for the horizontal tune scan with the fixed horizontal 'bare' tune (Q_x=22.30).

Minimum particle losses for the vertical tune Q_y=20.625 has been observed for both predictions and measurements (Fig. 5(A),(B)). For the vertical 'bare' tunes below Q_y=20.575 significant particle losses are determined by the half-integer resonance $2Q_y$=41, caused by the machine imperfections and the space charge of the low energy beam itself. The effect of this resonance on the particle losses in this area depends on the bunching factor of the beam.

'Q_x=22.20' Scan

The vertical tune scanning has been performed also for the fixed horizontal tune Q_x=22.20 for the case of the moderate beam power for J-PARC MR, including the 'sum' linear coupling resonance. Minimum particle losses have been obtained just below the [1,1,43] resonance line (Q_y=20.77). The range of the 'bare' working points for this case is limited by the effects of the high-order coupling [2,-2,3] and normal sextupole [1,2,64] resonances. These results have been confirmed experimentally including the injection and acceleration processes.

Current Status of the MR Operation

The best result for the J-PARC MR operation with the beam power of 100kW at the extraction energy of 30GeV has been obtained for the proposed 'bare' working point (Q_x=22.40, Q_y=20.75 presented in Fig. 4). The total power of the lost beam during the injection and acceleration processes for this case is just 100Watt for the 'six-bunches' operation scenario. The particle losses are localized at the collimation system of MR and occur mainly at the beginning of the injection process. The obtained experimental result is in agreement with the predicted lost beam power for this case. This level of the beam losses is below the capacity of the MR collimation system, so that these losses are acceptable for the J-PARC MR operation with the moderate beam power.

BEAM POWER UP-GRADE SCENARIO OF J-PARC MAIN RING

Next 'mile-stone' of the beam power upgrade for the J-PARC Main Ring is the continuous operation with the beam power about 4.8kW/bunch. In this case the maximum energy of LINAC is 181MeV. The expected beam power from RCS at the 3GeV energy should be 600kW. The repetition time for the J-PARC MR should be reduced up to 2.47sec. The number of bunches, accelerated in MR, should be increased from 6 to 8. In this case the expected beam power from MR, delivered to the 'Neutrino' experiments, should be about 390kW at the extraction energy of 30GeV.

To reach this goal during next two years it is necessary to increase the capacity of the 3-50 beam line collimator from 450W till 2kW and the capacity of the MR collimator from 450W till 2kW. The MR operation scenario should be based on usage the second harmonic RF system to modify the shape of the longitudinal separatrix. Extensive simulations now are in progress to establish the low losses operation scenario for both J-PARC synchrotrons, for RCS and MR.

CONCLUSION

The low loss operation of J-PARC Main Ring has been established successfully for the machine operation with the moderate beam power. The predicted beam behaviour and beam losses for different 'bare' working points are in reasonable agreement with the experimental observations. By using the computational model of J-PARC Main Ring the optimization of the machine performance for the high beam power operation should be performed, as well as the optimization of the RCS performance.

REFERENCES

[1] A.Molodozhentsev and E.Forest, "Beam Dynamics and Low Loss Operation of the J-PARC Main Ring", KEK Preprint 2009-29, November 2009.

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

[3] H.Kobayashi, "J-PARC Main Ring", in Proc. of PAC'09 Conference, Vancouver, Canada, May 2009.

[4] A.Molodozhentsev et al, "Study of the Beam Dynamics for the 'fast extraction' Operation Scenario for J-PARC Main Ring", in Proc. of IPAC'10 Conference, Kyoto, Japan, May 2010.