BEAM DYNAMICS STUDY FOR J-PARC MAIN RING BY USING THE 'PENCIL' AND SPACE-CHARGE DOMINATED BEAM: MEASUREMENTS AND SIMULATIONS

A.Molodozhentsev, S.Igarashi, Y.Sato, J.Takano, KEK, Tsukuba, Oho 1-1, 305-0801, Japan

Abstract

In frame of this report we discuss existing experimental results and compare it with simulations, performed extensively for different machine operation scenario, including the 'pencil' low intensity beam and the 'space-charge dominated' beam. The obtained results demonstrate agreement between simulations and measurements for emittance evolution and losses for different cases. The modelling of the beam dynamics has been performed by using the 'PTC-ORBIT' combined code, installed on the KEK supercomputer * [1,2]. The developed MR computational model will be used to optimize the machine performance for the 'Mega-Watt' MR operation scenario with limited losses.

INTRODUCTION

J-PARC Main Ring (MR) study has been performed during 2012-2014 to optimize the machine performance. As the result of this activity the '200 kW' proton beam has been delivered successfully to the 'Neutrino' beamline for the 'Super-Kamiokande' experiment. Total particle losses, localized at the MR collimation section, have been estimated as 120 W. The 'low-losses' MR operation has been achieved after optimization the injection process, stabilizing the power supply ripple, after searching the optimized setting for the MR RF system, dynamic control of the chromaticity, optimization of the 'bare' working point and compensation the linear coupling resonance.

Effects of the machine resonances, caused by imperfections of different kind of the MR magnets, have been studied experimentally by using a low intensity 'pencil' beam. The 'space-charge dominated' beam has been used to observed the effects of the machine resonances in combination with the space-charge effects, like the space charge detuning and space-charge resonances.

The appropriate scheme to compensate the 'sum' linear coupling resonance $Q_x+Q_y=43$ has been proposed, tested and implemented successfully for J-PARC MR [3,4] for the 'basic' working point. The benchmark activity was initiated to improve the machine model, which should be used to study the Main Ring operation scenario in the case of the 'Mega-Watt' machine operation.

'PENCIL' BEAM

During the J-PARC Main Ring study (RUN44, Nov.2012) the low intensity proton beam with small transverse emittance was used to study the [1,1,43] resonance and its compensation. The resonance correction approach now is based on dedicated four skew quadrupole magnets, installed in two straight sections of MR [4,5]. The single bunch injection into MR from RCS was performed to provide small beam intensity of 4e11 proton per bunch. The 2σ horizontal beam emittance of the 'pencil' beam, injected into MR, was just 3π mm.mrad. The beam profile measurements were performed by using the 'Flying Wire' monitor, installed in the dispersion-free straight section of MR

The PTC code was used to prepare the MR description taking into account measured imperfections of the machine magnets and realistic alignment of the elements. By using this machine description one can perform single or multi-particle tracking by the PTC-ORBIT code to study the beam dynamics for different scenario of the machine operation, including different time pattern for machine magnets and RF system. The ripple of the power supply can be also introduced into the machine mode. The KEK Super Computer system was used to simulate the injection and acceleration processes for J-PARC MR.

Effect of Isolated Resonance

To model the effect of the 'isolated' [1,1,43] resonance for MR, the resonance was excited by using the negative strength of the skew quads, defined experimentally to compensate the resonance (RUN44).

The study, based on single particle tracking, shows that the periodical crossing the [1,1,43] resonance stop-band by the off-momentum particles in the case of the realistic parameters for the RF system leads to significant limitation of the maximum beam emittance, which can survive if the 'bare' working point is close to the corresponding resonance line [5].

The performed multi-particle tracking was based on the 6D particle distribution, which represented the 3GeV 'pencil' beam, injection into MR from RCS. To make the long-term multi-particle tracking during 60'000 turns (corresponds to 320 ms at the energy of 3GeV) and to compare it with the observations we used 20'000 macro-particles in order to represent the 6D particle distribution in the single bunch.

The benchmark between the simulations and measurements (RUN44) was performed without any resonance correction for the 'bare' working point near the resonance line ($Q_x=22.2875$, $Q_y=20.6975$). The particle losses during the injection and beginning of acceleration were simulated for the realistic time pattern of the MR RF

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system and for the collimator acceptance of 70 π mm.mr. The simulated losses are in agreement with the results of the measurements [5] for the 'bare' working point Q_x=22.2875 and Q_y=20.6975 (Fig.1).

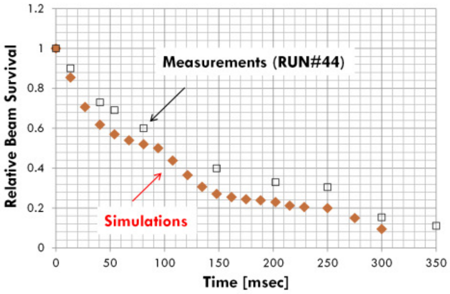

Figure 1: Reproduction the measured particle losses during the injection and acceleration processes for the case of the isolated linear coupling resonance.

Effect of Combined Resonances

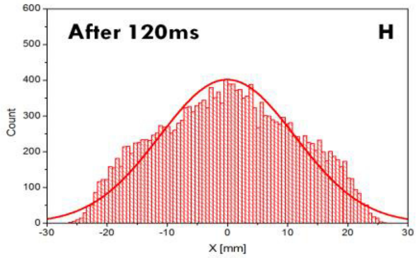

Figure 2: Simulated horizontal beam profile at the end of the tracking for the 'bare' working point Q_x=22.195 and Q_y=20.795.

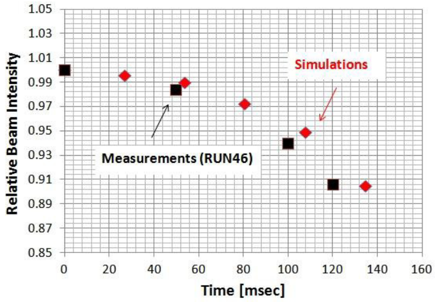

Figure 3: Reproduction the measured particle losses for the case of the combined resonances.

By using the developed computational model of MR it was demonstrated successfully [5] that the correction of the 'sum' linear coupling resonance [1,1,43] for the 'bare' working point (Q_x=22.195 and Q_y=20.795) prevents the trapping the large amplitude particles by the high-order horizontal resonance $5Q_x$=111.

To obtain a reasonable agreement with the experimental results, it is necessary to have appropriate number of macro-particles of in the 6D distribution and high-order field errors of the MR magnets have to be added into the model of the machine. The simulated (120ms after the injection) beam profile is presented in Figure 2. The simulated horizontal 1σ beam size after 120ms from the injection becomes 13.8mm. The measured one was 15.4mm, which shows good agreement between the simulations and measurements for this case. The simulated losses are in agreement with the measurements too (Fig.3).

SPACE CHARGE DOMINATED BEAM

Dedicated measurements (RUN54-RUN55/2014) and simulations were performed for the 'low-energy' 'space charge dominated' case to check the ability of the computational model to reproduce the experimental observations.

The RCS beam power at 3GeV was fixed to keep it on the level of 315kW (Ion Souce: 25mA / Chopping Time: 460ns / LINAC: 400MeV). Different painting areas were used to accumulate in RCS the required beam power at the injection energy of 400MeV: 100π and 50π.

Different machine conditions with different beam parameters (for the fixed beam intensity) were studied experimentally and used for the extensive simulations to reproduce beam survival in MR for different parameters of the RF system; transverse beam emittance evolution for different initial beam parameters and for different levels of the chromaticity compensation and effect of the [1,1,43] resonance compensation for the space-charge dominated beam. All these studies are extremely useful for better understanding the MR peculiarities for the 'high-beam power' operation.

Observation: 'RF' Effects

The particle losses at the injection energy of 3GeV for different sets of the MR RF system were studied experimentally. The 'painting' area for the RCS injection was set as 100π. The 'basic' lattice working point (Q_{xo}=22.40, Q_{yo}=20.75) with the partial 'linear' chromaticity correction (~85%) was used during RUN54. The fundamental RF system (h=9) of MR was used with different RF voltages: 160kV and 200kV.

The compensation of the linear coupling resonance [1,1,43] was not activated to check the effect of this resonance at the injection energy. Different RF voltage at the DC mode in the 'mismatched' case leads to changing the longitudinal particle distribution in the bunch (the bunching factor variation) so that the effect of the periodical crossing the [1,1,43] resonance can be observed.

The measured beam survival at the MR injection energy of 3GeV (DC mode) is presented in Figure 4 for the RF voltage of 160kV and 200kV. The beam intensity was 2.75e13 ppp (2 bunches per pulse). The collimator in the 3-50BT beam line between RCS and MR was opened during this study. The aperture of the MR collimator was not optimized, so that the horizontal acceptance was in the range (60÷80)π and the vertical collimator was opened. The observed particle losses were localized in the

MR collimator section. The losses observed for the 160kV RF voltage are about twice smaller than for the case of 200kV for the 'basic' working point.

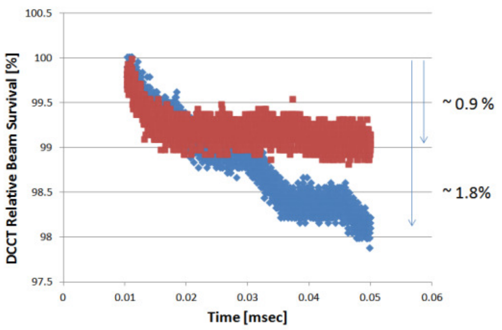

Figure 4: Measured beam survival at 3GeV (DC mode) in MR for different sets of the RF system (h=9): 160kV (brown) and 200 kV (blue).

Observation: [1,1,43] Resonance Effects

The beam profile measurements were performed for different beam conditions, injected into MR from RCS to observe the effect of the 'sum' linear coupling resonance [1,1,43] in the case of the 'basic' MR operation (V_{RF}=160kV(h=9) and Q_{xo}=22.40,Q_{yo}=20.75). The beam profile in the horizontal plane has been measured by using the flying-wire profile monitor.

The beam with different 'painting' area during the multi-turn injection into RCS has been used for this study, in particular, the '50π' and '100π' cases.

During this study the dedicated skew-quadrupole magnets were activated to observe the effect of the [1,1,43] resonance compensation for the different beams from RCS. The set for the skew-quads was optimized for the case of the MR operation with the 'pencil' beam (4e11 ppb) with the lattice tunes close to the resonance line Q_x+Q_y=43. The optimization of the current pattern for the skew-quads was performed for both injection and acceleration regions to minimize the losses.

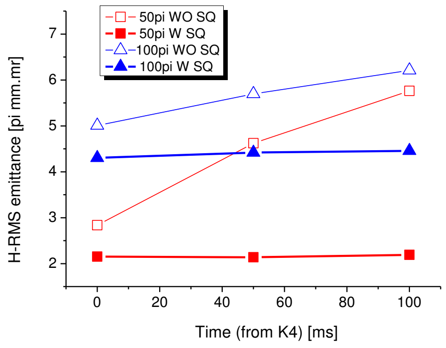

Figure 5: Measured horizontal RMS emittance at the 3GeV energy (MR 'DC' mode) for different beam parameters and machine setting.

The measured horizontal RMS emittance at the 3GeV ('DC' mode) in MR is presented in Figure 5 for the cases without ('WO') and with ('W') dedicated skew-quadrupoles for different beam conditions, injected into MR from RCS. After activation the skew-quads the RMS emittance growth in the horizontal plane has been eliminated for both cases: '50π' and '100π'.

The obtained experimental results have been used to compare it with the results of the modelling the beam dynamics in the case of the space-charge dominated regime.

SPACE-CHARGE DOMINATED BEAM: SIMULATIONS

The 'low-energy' space charge dominated regime of the MR operation was simulated extensively by using different beam and machine conditions, as it was made experimentally during the MR study (RUN54 and RUN55 during the 2014 machine study).

The MR model is based on the lattice representation, which takes into consideration measured imperfections of the MR magnets including field and alignment errors [3]. The space charge effects in combination with the lattice resonances, caused by the machine imperfections, were studied by using the combined PTC-ORBIT code [1,2]. In this combination, the ORBIT part of the code can be used to simulate collective effects ('PIC' type of code) in 'space-charge' nodes. The PTC in this combination is the 'symplectic' integrator, which integrates the particle motion between the 'space-charge' nodes. The integration method, used by PTC for MR study, was optimized to minimize the multi-particle tracking time. The 'ORBIT' parameters, to simulate the space-charge kicks, were optimized for the MR simulations during the convergence study [3]. It was shown that for the MR case one can use the 2.5D space charge model, implemented into the 'ORBIT' code, in particular, the 'fixed grid' method (128x128 mesh) with the distance between the space charge nodes not more than 1.5m.

The performed modelling of the beam dynamic is based on the pre-simulated 6D distribution of the beam, accelerated by RCS from 400MeV up to 3GeV. The total number of macro-particles in this distribution is 498'622. Different conditions for the multi-turn 'painting' injection in RCS has been used to prepare the initial particle distribution for the MR study to be in agreement with the experimental study.

Incoherent Space Charge Detuning

The incoherent space charge detuning in the case of the low-energy high-power beam for MR depends on the MR RF setting, the bunch length of the beam extracted from RCS (200ns for the present RCS extraction kicker) and the 'painting' area for the RCS injection. The beam intensity was 2.75e13/2 ppb (2 bunches per pulse). The performed simulations show that after 1200 turns (a few synchrotron periods for MR at 3GeV) the maximum space charge detuning is about (-0.15) for the '100π' RCS painting area and about (-0.35) for the '50π' RCS painting area, respectively. The simulated incoherent space charge detuning at the injection energy of 3GeV after 1200 turns for different RCS painting area is shown in Figure 6. The 'basic' lattice tunes (Q_x=22.40, Q_y=20.75) and V_{rf}=160kV (h=9) have been used for these simulations.

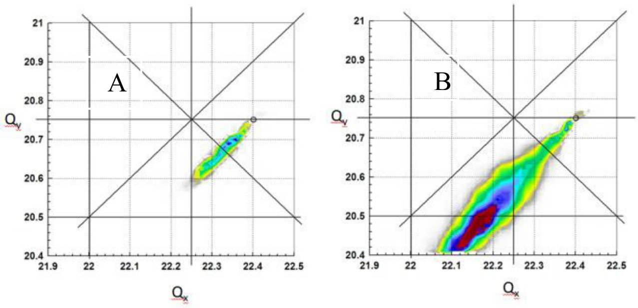

Figure 6: 2D histogram of the incoherent space charge detuning (3GeV with the intensity of 1.375e13 ppb) in MR for the RCS 'paint' emittance at 400MeV: (A) '100π' and (B) '50π'.

Modelling the 'RF' Effect at Injection

Modelling the beam survival in MR at the injection energy of 3GeV was performed for different RF parameters to compare it with the results of measurements, performed during RUN54 (Fig.7). For the multi-particle tracking the following parameters have been used: MR collimator acceptance of 70π, partial 'linear' chromaticity correction (85%) and the RF voltage of 160kV and 200kV for the case of the fundamental RF system (h=9).

The obtained results of the beam survival (Fig.7) are in a qualitative agreement with the experimental observation (Fig.4). Some discrepancy between the observations and simulations can be explained by different definitions for the MR collimator aperture, which was not defined clearly during RUN54. The 'basic' lattice tunes (Q_x=22.40, Q_y=20.75) were used for this study.

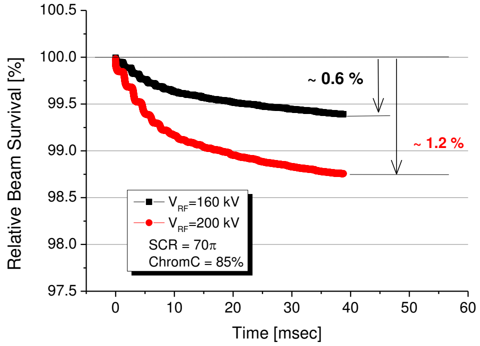

Figure 7: Simulated beam survival in the MR collimator for different RF voltages.

Modelling the [1,1,43] Resonance Effect

The effect of the [1,1,43] resonance by using the computational MR model has been simulated by using a simplified MR model.

Comparison between the performed simulations and measurements for different beam emittance from RCS (with the intensity of 1.375e13ppb) is presented in Figure 8 for the '100π' case and the 'basic' lattice tunes (Q_x=22.40, Q_y=20.75). The 'black' dots with the 'error'-bar represent the results of the measurements. The 'blue' and 'green' lines show the simulated RMS emittance evolution before and after the [1,1,43] compensation, respectively.

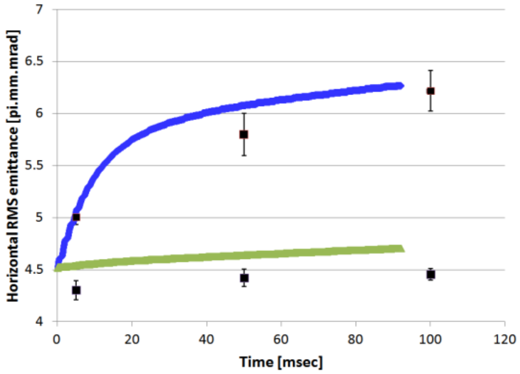

Figure 8: Horizontal RMS emittance evolution (measured and simulated) for the '100π' paint RCS beam.

The agreement between the measured RMS emittance and the simulated one for the case of the '100π' paint RCS emittance is quite reasonable (Fig.8). Similar agreement has been demonstrated and for the case of the '50π' paining RCS area. Some discrepancy can be explained by the effect of the initial beam mismatching, which becomes important for the case of 'strong' space-charge.

Losses at the MR collimator were analyzed during the multi-particle tracking for the case of the physical acceptance of the MR primary collimator of 65π for different levels of the 'linear' chromaticity compensation. The simulated particle losses at the MR collimator before and after the [1,1,43] resonance compensation are shown in Figure 9 and Figure 10, respectively. The effect of the partial chromaticity correction at the injection energy was observed experimentally and reproduced by using the MR computational model.

The particle losses for the case of the 93% chromaticity correction are smaller, which is in agreement with the experimental observation. Before the [1,1,43] resonance compensation the minimum simulated particle losses (during 55msec), observed for the case of the '50π' paint RCS emittance at 400MeV and for the 93% chromaticity correction (the 'red' line, Fig.9) can be estimated as 330W for the initial beam intensity of 1.375e13ppb (which corresponds to the MR beam power of 22kW at 3GeV).

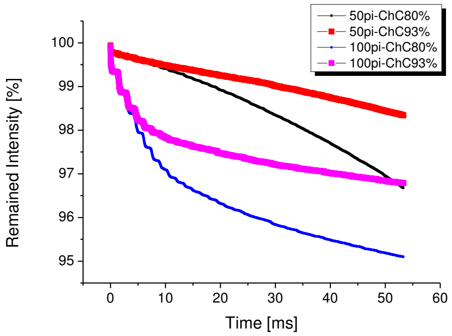

Figure 9: Particle losses at the MR collimator at 3GeV for different partial chromaticity correction and different initial RCS beam.

After the [1,1,43] resonance compensation the particle losses at the MR collimator were reduced significantly. The simulated losses for this case are presented in Figure 10 for the case of the 93% partial chromaticity correction and for the ‘paint’ RCS emittance of 50π and 100π. The particle losses in MR for the ‘100π’ case during 55msec becomes 110W. For the case of the ‘50π’ paint RCS emittance at 400MeV and for the 93% chromaticity correction the particle losses at the MR collimator (with the acceptance of 65π) the particle losses during 55msec after the injection can be estimated as 44W. The ‘fast’ losses, observed at the beginning of the injection process, are caused by the initial beam mismatching in the transverse and longitudinal planes.

The particle losses, observed experimentally for the same settings of the main parameters of the injected beam and MR, are in agreement with the simulated results. The total losses in MR for the case of the ‘50π’ paint RCS emittance at 400MeV and for the 93% chromaticity correction, obtained experimentally after the compensation the [1,1,43] resonance, was about 120W totally including losses during the injection and acceleration processes.

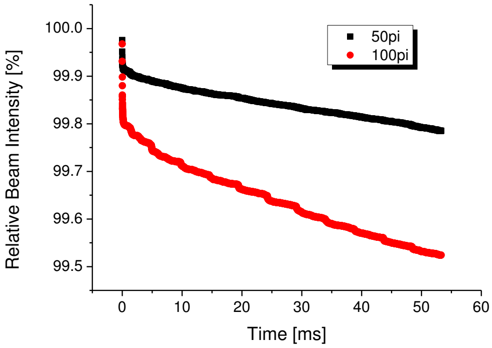

Figure 10: Simulated particle losses in MR at 3GeV after the compensation of the [1,1,43] resonance.

The ‘fast’ losses of the beam (Fig.10) just after the injection can be reduced by optimizing the initial beam conditions and the ‘RF’ matching by using the second harmonic RF system for the MR operation. The observed losses after the [1,1,43] compensation (Fig.10) can be explained by effects of other remained high order resonances, which caused by the combined effect of the machine imperfections and the space charge nonlinear effects. This subject requires further dedicated machine study and modelling using the computational MR model with the low-energy space charge effects.

CONCLUSION

The benchmark has been performed for the ‘pencil’ beam J-PARC MR operation by using the developed computational model of the machine. Acceptable agreement between the results of measurements and simulations is demonstrated for both losses and emittance evolution for different ‘bare’ working points. The observed effects of the isolated and combined resonances are explained and reproduced by using the computational model of J-PARC Man Ring.

The effects, observed for the ‘basic’ working point in the case of the ‘space-charge dominated’ beam, are reproduced by using the developed computational model of the machine. As the result, the low-loss MR operation has been achieved for the beam power of 315kW from RCS.

Improvement of the machine model should be continued to be able to suppress effects of the high-order resonances and optimize the MR performance in the case of the ‘Mega-Watt’ operation.

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