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STUDY LINEAR COUPLING RESONANCE FOR J-PARC MAIN RING: OBSERVATIONS AND SIMULATIONS

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Abstract

J-PARC Main Ring (MR) should deliver a high-power beam to neutrino experiments with limited particle losses. The low-order machine resonances have to be compensated to achieve the required beam parameters. In frame of this report the beam dynamics for the case of the low-intensity 'pencil' beam is discussed to understand the results of measurements, performed during RUN44 and RUN46 (2012-2013). The obtained experimental results are used to benchmark the computer modelling the 'sum' linear coupling resonance, as well as the combined effect of the 'sum' linear coupling and high-order resonances.

INTRODUCTION

Effects of the machine resonances, caused by imperfections of different kind of magnets of MR, are studied experimentally by using a low intensity 'pencil' beam. The beam dynamics study for J-PARC Main Ring has been performed by using the KEK Hitachi Super Computer*. An appropriate scheme to compensate the 'sum' linear coupling resonance has been proposed, tested and implemented successfully for J-PARC MR [1]. Information about the beam losses and the transverse beam profiles have been collected for different working points on the betatron tune diagram during the machine study by using the 'pencil' beam setting for the MR operation. The accumulated data have been used to benchmark the results of the computer modelling the low-intensity beam dynamics for MR with experimental observations. This benchmark activity is required to improve and check the machine model, which should be used to study the Main Ring operation scenario in the case of the space-charge dominated regime.

RESONANCE OBSERVATIONS

During J-PARC Main Ring study (RUN44, Nov.2012) the low intensity proton beam with small transverse emittance had been used to study the [1,1,43] resonance and its compensation. The resonance correction approach is based on dedicated four skew quadrupole magnets, installed in two straight sections of MR. The single bunch injection into MR from RCS had been performed to provide small beam intensity of 4e11 proton per bunch. The 2σ horizontal beam emittance of the 'pencil' beam, injected into MR, is 3π mm.mrad. The measurement had been performed by using the Flying Wire Monitor, installed in the dispersion-free straight section of MR. The 'acceleration' mode for the MR operation had been activated with a proper pattern for the skew quadrupoles during this study so that the beam was injected, captured at the energy of 3GeV and accelerated up to the energy of 30GeV.

Effect of Isolated Resonance

For this study the bare working point was set close to the [1,1,43] resonance line. The 'set' values of the betatron tunes in horizontal and vertical phase planes were 22.275 and 20.685, respectively.

The MR RF system for this study was based on the single harmonic operation (h=9) with the initial RF voltage of 90kV during 80ms. After that the RF voltage had been increased linearly up to 280kV during next 50ms without acceleration of the beam. The acceleration started 130ms after the beam was injected by changing the RF phase smoothly (parabolic) from zero till 0.4rad during next 100ms.

The linear chromaticity of MR had been corrected partially with the remained chromaticity of $\xi_{xy} = -6$. The collimator acceptance was set 70π mm.mrad in the horizontal and vertical phase planes.

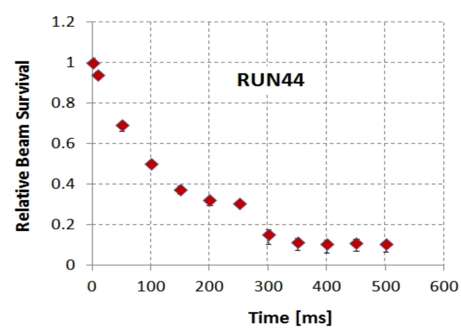

Figure 1: Beam intensity measurement for the 'pencil' beam operation without the [1,1,43] resonance compensation ('set' tunes: Qx=22.275, Qy=20.685).

The particle losses, observed experimentally for the 'pencil beam MR operation (see Fig.1) without the resonance correction, indicate significant effect of the 'sum' linear coupling resonance on the beam during the injection and acceleration processes. All losses had been localized at the MR collimator area. After an appropriate compensation the [1,1,43] resonance with optimized time pattern for the skew quadrupole strength the beam had been injected and accelerated without losses.

Effect of Combined Resonances

During the MR study (RUN46, Feb.2013), the beam profile and beam losses had been studied at the injection

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energy of 3GeV for the low intensity ‘pencil’ beam with the same initial beam parameter as for RUN44. The ‘set’ values for the horizontal and vertical betatron tunes were 22.20 and 20.80, respectively. The MR operated in the ‘injection’ mode during 120msec. The linear chromaticity of the machine was fully corrected. The voltage of the MR RF system was constant during the capture process and equal to 90kV (h=9). The collimator acceptance was 70π mm.mrad (as for RUN44).

For these machine conditions only small particle losses (about 9% during 120ms) had been observed without any correction the [1,1,43] resonance (see Fig.2).

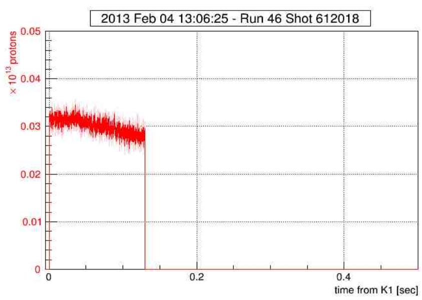

Figure 2: Beam intensity measurement for the ‘pencil’ beam operation without resonance compensation (‘set’ tunes are Qx=22.20, Qy=20.80).

The horizontal beam profile measurements have been performed to get information about the emittance dilution of the ‘pencil’ beam for this working point

The horizontal beam profile measurement, performed after 120ms from K1 without any resonance compensation, is shown in Figure 3. The measured 2σ beam emittance is 60.8π mm.mrad. The observed significant emittance blow up in the horizontal plane did not lead to significant beam losses as for RUN44 (see Fig.1), which can be explained by the ‘trapping’ mechanism into high-order resonance islands.

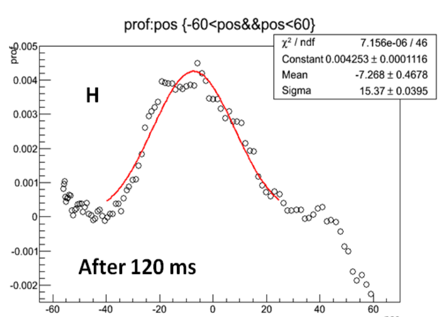

Figure 3: Horizontal beam profile measurement performed after 120ms from injection for the ‘bare’ working point Qx=22.20 and Qy=20.80.

The [1,1,43] resonance compensation, applied for this ‘bare’ working point, improved the horizontal beam profile significantly (see Fig.4). It shows that the correction of the ‘sum’ linear coupling resonance prevents large amplitude particles to be trapped by the high-order resonance. This mechanism has been checked by the single and multi-particle tracking at the injection energy for this particular betatron tunes.

The accumulated experimental data has been used to model the beam dynamics in the case of the low-intensity ‘pencil’ beam and explain the observations. In addition, benchmark between the measurements and results of the computer modelling has been performed to prepare the appropriate model of the machine for modelling the space charge dominated cases.

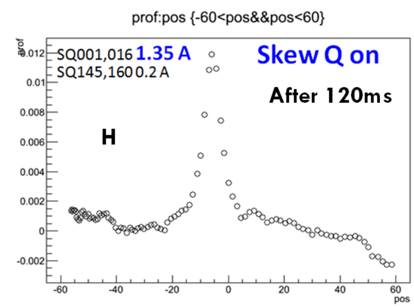

Figure 4: Horizontal beam profile measurement performed with activated resonance compensation scheme (after 120ms from injection for the ‘set’ tunes: Qx=22.20 and Qy=20.80).

SIMULATIONS AND BENCHMARK

The existing computational model of MR should be able to reproduce these effects. In the case of the low intensity ‘pencil’ beam the collective effects can be neglected.

The MADX(PTC) code allows us to prepare the MR description by using 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 [2] to study the beam dynamics for different scenario of the machine operation, including different time pattern for machine magnets and RF system. The PTC part of this combined code is used mainly as the tracker (or symplectic integrator), which propagates the particle through different elements of the machine. The KEK Super Computer system was used to perform the simulations for the injection and acceleration processes, based on the multi-particles tracking.

Effect of Isolated Resonance

The linear coupling resonance has been excited in the MR model by using the negative strength of the skew quads, required to compensate the resonance for the MR operation (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

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survive if the 'bare' working point is 22.2875 and 20.6975 in the horizontal and vertical phase planes respectively.

The performed multi-particle tracking is based on the 6D particle distribution, which represents 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 compare with the observations we used 20'000 macro-particles to represent the 6D particle distribution in the single bunch.

Benchmark of simulations and measurements (RUN44) has been performed for the without any resonance correction. The particle losses during the injection and beginning of acceleration have been simulated for the realistic time pattern for the Main Ring RF system and the collimator acceptance of 70 π mm.mr. The simulated losses are in agreement with the results of the measurements (see Fig. 5). The particle losses are caused by the periodical crossing the [1,1,43] resonance by the particles of the beam.

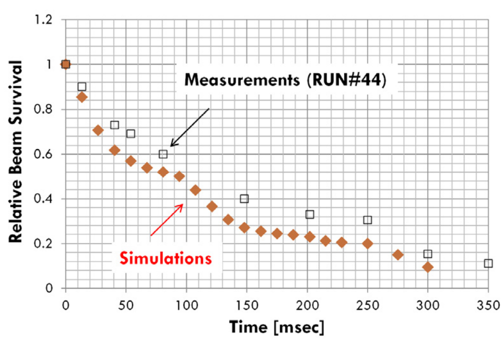

Figure 5: Reproduction the measured particle losses during the injection and acceleration processes for the case of the isolated linear coupling resonance.

Effect of Combined Resonances

From the results of the single particle tracking it is clear that for the lattice working point with the betatron tunes of 22.195 and 20.795 in the horizontal and vertical phase plane respectively we have a combined effect of the linear coupling [1,1,43] and the high order [5,0,111] resonances. Compensation the [1,1,43] resonance prevents trapping the particles into the high-order resonant islands.

The simulated beam profile for this working point is presented in Fig.6. To obtain 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. As the result, the simulated horizontal 1σ beam size after 120ms from the injection become 13.8mm. The measured one was 15.4mm (see Fig.3).

The simulated particle losses (see Fig.7) are in good agreement with the experimental observation for this 'bare' working point.

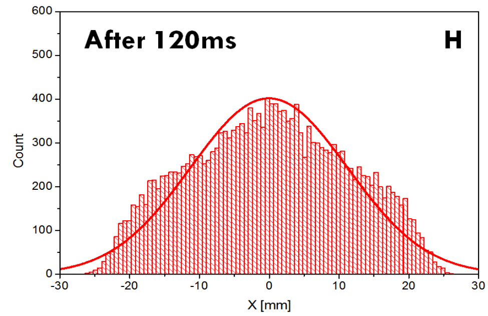

Figure 6: Simulated horizontal beam profile at the end of the tracking for the 'bare' working point Qx=22.195 and Qy=20.795

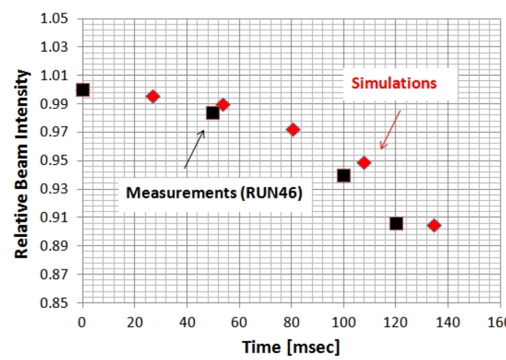

Figure 7: Reproduction the measured particle losses for the case of the combined resonances.

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 has been demonstrated for both losses and emittance evolution for different 'bare' working points. The observed effects of the isolated and combined resonances have been explained by using the computational model of J-PARC Man Ring.

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