EFFECTS OF THE FIELD LEAKAGE OF THE SLOW EXTRACTION SEPTUM MAGNETS OF THE J-PARC MAIN RING

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Abstract

During the early stage of the J-PARC Main Ring commissioning process the emittance growth at the injection energy, caused by the field leakage of the slow extraction septum magnets, has been observed. By using the measured field data, obtained for these magnets, we performed the analysis of the resonance excitation. The single particle dynamics in vicinity of the resonance lines has been studied by using the computational model of MR. The space charge effects of the low energy beam with the moderate beam power are taken into this analysis. Comparison between the results of the computational machine model and experimentally obtained particle losses for different 'bare' working points has been made. Some possible ways to reduce the transverse emittance dilution and the particle losses during the machine operation for the 'Nuclear and Particle Physics' experiments are 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. 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.

In frame of this report we concentrated on the effects of the field leakage of the slow extraction septum magnets at the injection energy for the proton beam with the moderate beam power of MR, which is determined by the beam power delivered by the J-PARC RCS (rapid cycling synchrotron). For the 'phase-1' of the JPARC operation the beam power of RCS at the energy of 3GeV is limited by 320kW. In this case the maximum beam power, delivered to the MR users is 145kW at the energy of 30GeV.

To minimize the particle losses in the case of the 'slow' extraction the 'bare' working point at the injection should be closed to the corresponding resonance line. To realize the 'slow' extraction process for the MR operation, large number of the septum magnets should be used. The field leakage of the slow extraction septum magnets will affect the circulating beam in the ring at the injection energy too. The performed field measurement indicates that this field leakage has strong non-linear field components. The particle losses at the injection energy for the MR 'slow extraction' scenario should be estimated carefully to find appropriate operation condition of MR and to keep the particle losses below the limit of the capacity of the MR collimation system.

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MEASURED FIELD DATA AND COMPUTATIONAL MODEL OF MR

The computational model of J-PARC MR has been developed by using all known field and alignment data for all MR magnets, including the field leakage of the slow extraction septum magnets [1]. This model of MR is based on the assumption that the ring magnets work in the 'safe' regime without any saturation effects. This model can be used to analyze single and multi particle dynamics in MR in the energy range from 3 till 30GeV.

The field components at the centre of the circulating beam for all septum magnets have been determined after the field measurements. The integrated normalized values at the energy of 3GeV are presented in Table 1. The field leakage of the septum magnets (SMS11 and SMS12) has strong sextupole and octupole components, which could contribute significantly to the excitation the MR machine resonances.

Table 1: Measured field components of the slow extraction septum magnets at the centre of the circulating beam at the injection energy of 3GeV

Index of septum magnets	Measured normalized field components of the 'slow extraction' septum magnets			
	K0L [-]	K1L [m^{-1}]	K2L [m^{-2}]	K3L [m^{-3}]
SMS11	3.71e-5	9.625e-4	**0.0535**	**1.7407**
SMS12	7.42e-5	0.001925	**0.1069**	**3.4814**
SMS21	-4.51e-6	-7.045e-4	-0.0157	-0.265
SMS22	-4.51e-6	-7.045e-4	-0.0157	-0.266
SMS23	-4.51e-6	-7.045e-4	-0.0157	-0.266
SMS24	-4.51e-6	-7.045e-4	-0.0157	-0.266
SMS31	-7.29e-5	-8.39e-4	-0.0049	-0.256
SMS32	-7.29e-5	-8.39e-4	-0.0049	-0.256
SMS33	-4.28e-5	-2.543e-4	-0.0067	-0.142
SMS34	0	0	0	0

For the 'real' machine operation the distortion of the super-periodicity during the injection process is caused by elements of the injection system, including the edge-focusing effect of the bump-magnets, by individual field errors (multi-pole field components) and misalignment errors of each MR magnets, by the field leakage of the septum magnets.

The computational model of the J-PARC MR has been created and tested by using the measured properties of the focusing structure of MR [1]. 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 physical aperture of the MR primary collimator has been set 60π for this study. The obtained 'global' view on the machine resonances, based on the realistic computational model of the J-PARC MR, is presented in Fig.1. The field leakage of the slow extraction septum magnets (Table 1) has been taken in to account for this study. The on-momentum single particle motion has been analyzed in frame of this study by using the PTC-ORBIT code [2].

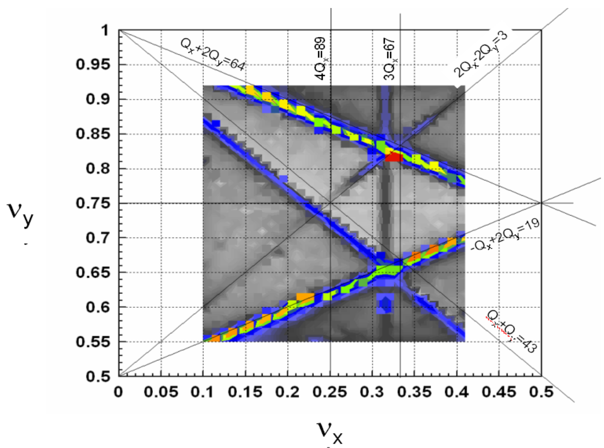

Figure 1: Beam survival and the machine resonances of MR, including the effects of the field leakage of the slow extraction septum magnets.

The observed shift of the resonance lines and the corresponding limitation of the beam survival is caused by the amplitude dependent tune shift, determined mainly by the second-order effect of the sextupole nonlinearity of MR. In comparison with the beam survival at the MR collimator, obtained without any field leakage of the slow extraction septum magnets (Fig.1, [3]) the depicted results (Fig.1) present clearly the effects of the field leakage of the slow extraction septum magnets at the injection energy of MR: all the normal sextupole resonances becomes stronger in addition to the 'sum' linear coupling resonance (compare with results, shown in Fig.1 of the report [1] with the same color-scale). By using this result one can conclude from the point of view of the single particle dynamics that the area around the betatron tunes (Qx=22.30, Qy=20.75) just near the [3,0,67] resonance line, used for the resonant beam extraction from MR, can be the candidate for the 'bare' working point to provide the MR operation with minimum particle losses during the injection and acceleration processes.

The normal sextupole resonances [3,0,67], [1,2,64] and [-1,2,19] would limit the MR performance, as the 'sum' linear coupling resonance [1,1,43] and the high-order coupling resonance [2,-2,3]. The estimated maximum beam emittance, which survives in MR at the position of the primary collimator (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 result, shown in Fig.2, demonstrates the effects of the field leakage of the slow extraction septum magnets (YES_SXSMFL)..

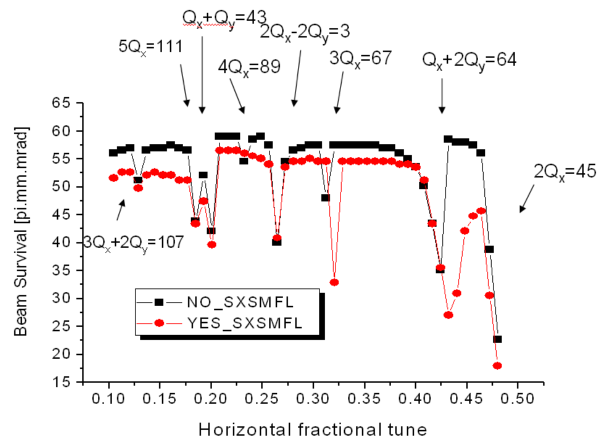

Figure 2: 'Beam survival' scan by using measured data of all known field and alignment errors of the MR magnets, including the field leakage of the slow extraction septum magnets (Table 1).

COMPARISON: SIMULATIONS AND MEASUREMENTS

The choice of the working point for small beam intensity depends only on the effects of the 'machine' resonances, presented in Fig.1 and Fig2. If we limit our analysis only by the region near the [3,0,67] resonance line, the best candidates for the working point position in the case of small beam intensity are the betatron tunes in the range Q_x~ (22.27÷22.30) and Q_y ~ (20.72÷20.78). For this area the particle losses at the MR collimator should be minimum one.

This predication, made on the basis of the realistic computational model of MR, has been checked experimentally for the case of small beam intensity (~2e11 protons per bunch or 4kW at 3GeV energy for the 6 bunches operation with the repetition time 3.5sec). The corresponding measurements have been done during RUN#30 (February, 2010). The 'tune scan' study has been performed for the fixed horizontal betatron tune of Qx=22.25 (Fig.3). The vertical tune has been changed in the range from Qy=20.73 up to Qy=20.81. No correction of the 'sum' linear coupling resonance has been done during that study.

The presented results of measurements (Fig.3), performed for the 'slow extraction' machine operation scenario, are in a good agreement (at least qualitatively) with the prediction, based on the corresponding simulations. The minimum particle losses have been obtained for the 'bare' working point with Q_{x0}=22.27 and Q_{y0}=20.76.

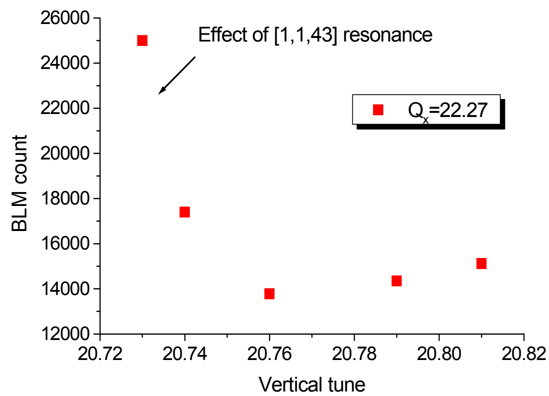

Figure 3: Measured count of the lost particles as a function of the vertical tunes (Qx=22.27 is fixed), obtained during the MR commissioning (RUN#30) for the 'slow extraction' machine scenario.

SPACE CHARGE EFFECTS AND MACHINE RESONANCES

The combined effects of the machine resonances and the low energy space charge effects have been studied by using the realistic MR operation scenario for the case of the moderate beam power. The 'bare' working point in frame of this study has been chosen near the 3rd order horizontal resonance line [3,0,67] (Q_{x0} = 22.30). The particle losses at the MR collimation system should be limited by 450W, which is the capacity limit of the collimation system. The tune scan along the [3,0,67] resonance line has been performed by changing the vertical tune in wide range from Q_{y0}=20.80 till Q_{y0}=20.625. This study has been carried out by using the PTC-ORBIT code [2], installed on the KEK super computer[1].

The 6D multi-particle tracking has been performed in the self-consistent manner. The tune variation has been made by using all MR quadrupole magnets to keep the required phase advance in the ARC and to provide minimum variation of the beta-functions for different working points. The similar fitting technique utilized for the routine manipulation of the MR lattice during the machine commissioning.

For this 'tune-scan' study we did not use any correction of the 'sum' linear coupling resonance [1,1,43]. As it was demonstrated during the MR commissioning runs [3], this correction can be performed by using the local vertical bump of the circulating beam at the locations of two sextupole magnets. Just below the [1,1,43] resonance line this correction is not needed, because the space charge of particles of the beam so that the effect of the 'sum' linear coupling resonance is vanished.

The particle losses at the injection energy have been studied by using the realistic computational model of MR. The particle losses at the MR collimator with the physical acceptance of 60π have been estimated. The 'short-term' tracking during a few synchrotron periods has been used for these simulations.

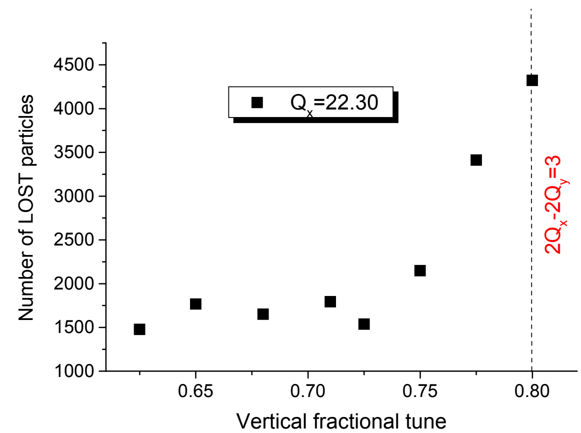

Figure 4: Predicted number of lost particles as a function of the vertical 'bare' betatron tunes (Qx0 = 22.30), obtained for the case of the 'slow extraction' MR operation scenario for the beam power 100kW at the maximum kinetic energy of 30GeV.

According to the obtained results (Fig.4) one can conclude that the area near the 4th order coupling resonance [2,-2,3] is not acceptable for the MR operation. The strong sextupole field nonlinearity of the sextupole magnets, used in MR for the natural chromaticity correction, and the space charge are the main sources for this resonance at the injection energy. The areas near the 'sum' linear coupling resonance [1,1,43], especially below, is a good candidate to operate the machine with small particle losses during the injection and acceleration in the case of the 'slow extraction' scenario of the MR operation with the moderate beam power of 100kW at the 30GeV. This prediction will be checked soon during next MR runs after the 'summer' shutdown.

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