STUDY OF PARTICLE LOSSES MECHANISM FOR J-PARC MAIN RING

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Abstract

Detailed understanding as well as confidence in simulation modeling of long-term effects (~ 100'000 turns) of high intensity proton beam is crucial for Main Ring (MR) of the J-PARC project, where it is necessary to hold the high-intensity beam over typically ~ 2 sec with a loss level less than 1%. The major focus of such study is the combined effect of space charge and nonlinear resonances and its impact on halo formation and/or beam loss. In frame of this report, the tracking results for the injection process including realistic representation of the ring's focusing structure are discussed. Optimization of the working point during the injection process is presented. The halo formation and particle losses during the injection process for MR have been estimated for realistic magnetic field and misalignment errors.

INTRODUCTION

Main Ring (MR) of the Japanese Particle Accelerator Research Complex (J-PARC) should provide acceleration of high-intensity proton beam from the energy of 3GeV up to 50GeV, so that the maximum average beam power should reach 800kW. The repetition rate of the machine is 0.3Hz then the required beam intensity should be 3.3e14ppp. The incoherent space charge tune shift including the beam environment at the injection energy is about (-0.2). From this point of view, MR is not a space charge limit machine in an ordinary sense. But the stringent beam loss criteria need us to look at the particle losses, caused by the combined effect of the space charge itself and the nonlinear resonances, excited by intrinsic field nonlinearities and magnetic field errors. The total power of the particles lost at the MR scraper should be less than 450W [1].

The MR lattice is based on the missing bending magnet focusing structure of the arcs and consists of 3 super periods with the dispersion-free straight sections. The ring lattice provides the imaginary transition energy to avoid crossing the transition energy during acceleration. The natural chromaticity of the machine is about (-30) in both transverse planes. The MR lattice has been designed so that all driving terms of the third-order resonances excited by the chromatic sextupole magnets and by the average sextupole components of the bending magnets are canceled [2]. To extract the accelerated beam, both 'fast' and 'slow' extraction techniques will be used in MR. The 'slow' extraction technique is based on excitation of the 3rd order horizontal resonance, in particular, $3Q_x=67$. It determines the operational horizontal betatron tune. The vertical betatron tune is chosen around $Q_y = 20.80$ [3].

The MR beam power depends on the beam power from RCS, which is the injector for MR. At the early stage of the machine commissioning the expected beam power from RCS is 0.3MW. According to the basic machine scenario, RCS will accelerate at the same time 2 bunches with the repetition rate of 25Hz. During the injection period MR will accumulate 8 bunches (in the case of the fundamental harmonic h=9). Total beam power of MR at the injection energy should be about 4.75% from the RCS beam power. The expected power of the 50GeV beam of MR is about 237kW for that case. After increasing the injection energy to RCS, the expected beam power at the maximum energy should be about 1 MW for RCS and 0.8MW for MR.

The total particle losses limit during the injection process is determined first of all by the capacity of the MR scraper. Other areas around MR can accept the lost beam power about 0.5W/m. To meet this strict limit for the particle losses for MR we study the beam dynamics at the injection energy using the realistic machine parameters including the injection dogleg.

FIELD NONLINEARITIES AND SPACE CHARGE EFFECTS FOR MR

Without any chromaticity correction, the chromatic tune shift of the off-momentum particles with the momentum deviation of $\Delta p/p \sim \pm 0.007$ will be about $\Delta Q_{xy}^{CH} \sim \pm 0.21$, which is comparable to the space charge tune shift. To correct the 'linear' chromaticity we plan to use two independent families of the sextupole magnets, placed in each module of the ring's arcs.

Effects of the Sextupole Field Nonlinearity

After the correction of the 'linear' chromaticity of the machine, the nonlinear chromatic tune shift for the momentum spread of $\Delta p/p \sim \pm 0.007$ becomes $\Delta Q_{xy}^{CH} \sim \pm 0.008$. These sextupole magnets create strong intrinsic external nonlinear field for MR. As the result of that, the particles will have the amplitude dependent tune shift. At the injection energy the maximum beam emittance should be about 54 π.mm.mrad. For that emittance the MR amplitude dependent tune shift, caused by the sextupole field nonlinearity, has been estimated as $\Delta Q_{xy}^{AD} \sim +0.025$. The sextupole field nonlinearity contribute to excitation of the 4th order resonances, first of all to the structure resonance $4Q_x=90$ [3]. The off-momentum beta-beating after the chromaticity correction is about ±10% for the momentum spread of ±0.67%. The variation of the beam centroid position around MR in the horizontal plane after the chromaticity correction for the on- and off-momentum particles with $\Delta p/p=0.4\%$ and for the 'water-bag' particle distribution in the transverse phase planes has been observed after the linear chromaticity correction. The maximum horizontal shift of the beam centroid about 2mm has been observed in the MR arcs.

Space Charge Tune Shift & Resonances

The space charge tune spread for the intensity of 1.8kW/bunch at the injection energy of 3GeV is presented in Figure 1. The bunching factor for this case is $B_f = 0.2$. For the high beam energy (β~1) the contribution from the magnetic image in magnet poles should be taken into account. The beam pipe has the rectangular shape with the sizes ±70mm in the horizontal and vertical directions. The 'bare' lattice betatron tunes are Q_x=22.43, Q_y=20.82. The maximum space charge tune shift is (-0.15). The 'red' arrow represents the predicted incoherent tune shift including the effect of the beam environment. To keep the incoherent space charge tune shift at the same level for bigger beam power, the bunching factor should be increased up to B_f = 0.3. This bunching factor can be obtained by using the 'dual' harmonic RF cavity.

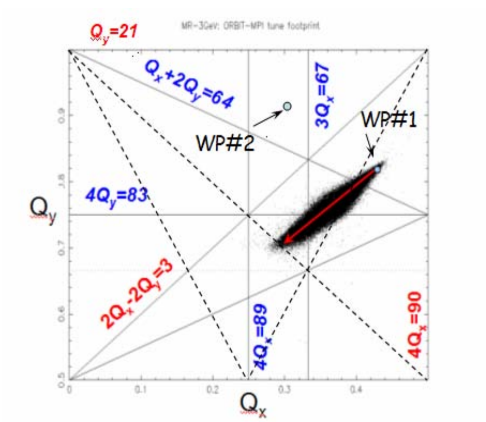

Figure 1: Space charge detuning for the 1.8kW/bunch beam power at the energy of 3GeV (B_f=0.2, the matched distribution in the longitudinal phase plane), including the beam environment with the rectangular chamber shape.

Two candidates for the 'bare' working point are shown in Figure 1. According to the previous studies, the working point wp#2 is more suitable for the slow extraction procedure. The space charge detuning will change the particle's tunes. In this case, even if the 'bare' tune is chosen far from some low-order resonances, the space charge effect could lead to crossing these resonances and, as the result, to increasing the transverse emittances.

The space charge potential could have both the even and the odd terms, if the beam has the asymmetric non-uniform particle distributions in the transverse phase planes. However, we expect that the MR beam at the injection energy should be close to the symmetric one. In that case the even terms of the space charge potential will be dominant. As the result, the 4th order resonances like [4,0] and [0,4] associated with the fourth-order even-mode potential terms are significantly more excited than the [3,0] and [0,3] resonances, associated with the third order odd-mode term [4].

The space charge of the MR beam will contribute, first of all, to excitation the 4th order horizontal and vertical resonances ([4,0] and [0,4]) and to the 4th order difference resonance ([2,-2]).

The normal sextupole resonances around the beam footprint are not structure ones ('solid' lines on Figure 2) then these resonances can be excited only if the super-periodicity of the machine is broken. Misalignment errors, in particular the transverse tilt of the ring quadrupole and sextupole magnets, lead to excitation 'skew' resonances ('dash' lines on Figure 2).

During the injection process the orbit of the circulating beam should be perturbed at the injection straight section. In addition, according to the results of the magnetic field measurements, performed for all magnets of the ring, the relative deviation of the field sextupole component from the non-integrated 'ideal' strength of the sextupole magnets at the injection energy is $|\delta b_3|$ < 2.0e-3 and the average integrated sextupole component of the ring bending magnets is $\langle k_2L\rangle$~5.2e-3[m^{-2}]. The location of each bending magnets has been fixed after the 'shuffling' procedure to reduce the closed orbit distortion.

Space Charge Model for Main Ring

In the case of MR to reduce the required CPU time for the space charge simulation we can use so called (2+1/2)D model instead of the 3D model. To study the injection process for MR the number of macro particles is chosen to be 100'000 and the main other parameters for the space charge simulation are the following: N_{FFT}=100x100, N_{az}=1100, N_{bin}=512.

TRANSVERSE EMITTANCE GROWTH AND PARTICLE LOSSES

For the space charge simulations the following machine parameters have been used. The RF voltage is chosen 210kV for the harmonic number 9. In this case MR will keep 8 bunches around the ring circumference. The beam power is 1.8kW/bunch at the injection energy of 3GeV, which corresponds to the 0.3MW beam power for RCS. The bunching factor B_f is equal to 0.2 for the RF cavity operation with only the fundamental harmonic. The matched particle distribution in the transverse and longitudinal phase planes at the MR scraper position is used as the initial transverse distribution.

At the beginning we studied the effect of the 99% emittance increasing for the ideal ring lattice without the injection 'dogleg' and without any errors for the ring magnets. For that case only the 4th order structure resonances should be excited by the space charge in combination with the sextupole field nonlinearity. The beam power at the injection energy of 3GeV for this study is equal to 1.8kW/bunch. The 'bare' working points are chosen with the betatron tunes Q_x=22.43/22.30.

For this working point the large amplitude particles, the 'tail' particles, can be trapped by the horizontal structure resonance, 4Q_x=90. This resonance will be excited by the sextupole field nonlinearity, used for the chromaticity correction. The space charge of the beam will also contribute to this resonance, because we expect the effect of the even terms of the space charge potential [4]. The 99% emittance behaviour is presented in Figure 2 (NO INJDL).

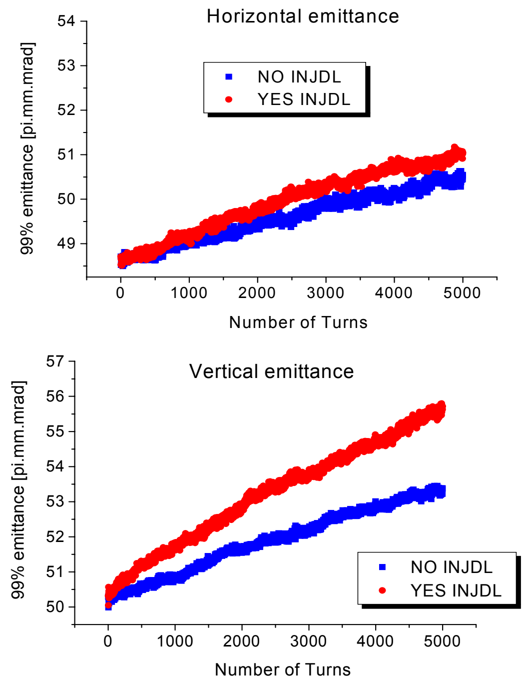

Figure 2: Emittance growth at the beginning of the injection process without and with Injection dogleg.

In the case of the broken super-periodicity by the 'injection dogleg' the non-structure resonances will be excited additionally. Assuming the symmetric beam, the contribution from the odd mode terms of the space charge potential should be small. The space charge potential itself will not have significant contribution to the 3rd order resonances. For the working point with the tunes of Qx=22.43, Qy=20.80, the 'core' particles will cross the resonance line 4Qy=83. Moreover, the normal sextupole resonance $Q_x+2Q_y=64$ will be excited also. For this coupling resonance, variation of the vertical emittance is two times bigger than the horizontal one. As the result, the vertical emittance growth becomes more significant, than the horizontal emittance growth (Figure 2).

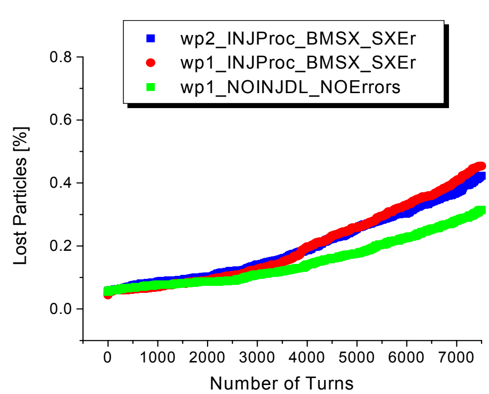

Figure 3: Particle losses at the MR scraper with acceptance of 70 π mm.mrad for different cases.

For estimation of the lost-beam power at the MR scraper, we implemented into the simulation the realistic timing for all elements of the 'injection dogleg' in addition to the measured sextupole field component of the ring bending and sextupole magnets

Figure 3 represents the particle losses for one bunch during (1/3)-rd of the injection process for two 'bare' working points ($Q_{x,y,1}$=22.43/20.80; $Q_{x,y,2}$=22.30/20.90). The non-structure resonances for MR lead to additional increasing the transverse emittances especially in the vertical phase plane, and as the result, increasing the particle losses at the MR scraper.

Skew Resonances

Preliminary tracking results indicate that the misalignment errors, in particular the transverse tilt of the ring quadrupole and sextupole magnets, will not lead to significant increasing of the particle losses.

Estimation of the Lost Beam Power for Different Commissioning Scenario

The beam losses during the realistic injection process for the '4 batch' operation scenario has been obtained. The first batch should circulate around MR during at least 120msec (or about 23'000 turns). In the case of the beam power of 1.8kW/bunch (or 0.3MW from RCS) and the bunching factor B_f=0.2 the total beam power dissipated in the MR scraper (A_{MR}=70 π.mm.mrad) is 124.2W.

The particle losses in the MR scraper for the high beam power from RCS (0.6MW) have been studied also. To keep the particle losses at the acceptable level, the bunching factor for the high beam power should be increased up to B_f=0.3 by using the dual harmonic RF cavity. For the MR beam power 3.6kW/bunch the total power of the lost particles for 4 batches at the MR scraper with the acceptance of 70 π.mm.mrad has been estimated as 216W.

CONCLUSION

Main reason for the particle losses during the injection process in MR is excitation structure and non-structure resonances. Nevertheless, the proper choice of the beam parameters, mainly the bunching factor, and the MR scraper acceptance allows us to keep total lost-beam power at the scraper of MR below the acceptable level for both low beam power and high beam power cases.

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