SPACE CHARGE SIMULATION FOR J-PARC MAIN RING

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Abstract

The space charge effect in combination with the intrinsic field nonlinearity like the sextupole nonlinearity, used for the chromaticity correction, could lead to significant particle losses in a high beam intensity proton machine. For J-PARC Main Ring (MR) the total particle losses at the ring's collimator should be less than 1% from the expected maximum beam power of 45kW. To keep the particle losses during the injection process within the required limit it is necessary to optimize the beam parameters from the injector (J-PARC Rapid Cycling Synchrotron), the collimator aperture of the beam-line from RCS to MR and the collimator aperture of MR. Influence of the structure and non-structure high-order normal resonances for different working points is discussed. The budget of the beam losses for different commissioning scenario is presented.

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 ring arc consists of 8 identical modules with the phase advance of 0.75 per the module in transverse phase planes. This phase advance per module provides the zero-dispersion in the horizontal plane at the end of the arc. Moreover, 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. To provide the maximum MR beam power, RCS should be able to produce 1MW beam power for the 3GeV energy. According to the basic machine scenario, RCS will accelerate 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.

At the early stage of the machine commissioning the expected beam power from RCS is 0.3MW. This reduction of the RCS beam power is caused by small injection energy from LINAC into RCS. According to the 'Day-1' machine scenario, the maximum beam energy from the LINAC is just 181MeV. In that case, the expected power of the 50GeV beam of MR is about 237kW.

According to the basic scenario of the machine commissioning, which is based on the '8 bunches scheme', the injection process for MR should extend over 120msec (or about 21'500 turns).The total particle losses limit during the injection process is determined first of all by the capacity of the MR scraper, which is 450W. 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.

SPACE CHARGE AND FIELD NONLINEARITIES OF MR

The natural chromaticity of MR is about (-30) in both horizontal and vertical planes. 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 $\Delta Q_{xy}^{CH} \sim \pm 0.21$. 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. After the correction of the 'linear' chromaticity of the machine, the nonlinear chromatic tune shift becomes 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 $\Delta Q_{xy}^{AD} \sim + 0.025$ [3].

In addition, the sextupole field nonlinearity contribute to excitation of the 4^{th} order resonances, first of all to the structure resonance $4Q_x$=90 [3].

Additionally, each bending magnet of MR has the sextupole component. All bending magnets (the total number of the MR bending magnets is 97) have already manufactured and measured by using the rotating coil. The field measurement was performed for the current of 1000A to improve the measurement accuracy. The location of each bending magnets in the ring has already determined to minimize the closed orbit distortion, caused by the (BL)-errors. According to the results of the magnetic field measurements, performed for all magnets of the ring, at the injection energy the average integrated sextupole component is $<k_2L>\sim 5.2e\text{-}3[m^{-2}]$.

Also, the magnetic field measurement for the ring sextupole magnets has been performed. The total number of the sextupole magnets in MR is 72. Integrated sextupole field of the sextupole magnets was measured for the current of 200A. The location of each sextupole magnet is fixed according to the magnet index. According to the field measurement for the ring sextupole magnets, the relative deviation of the field sextupole component from the non-integrated 'ideal' strength of the sextupole magnets at the injection energy of 3GeV is $|\delta b_3| < 2.0e\text{-}3$.

Space charge tune shift & Resonances

The space charge tune shift depends on the beam power, the beam energy, the bunching factor and the beam environment. Estimation of the incoherent space charge tune shift including the beam environment shows that for the MR beam power of 1.8kW/bunch at the injection energy of 3GeV the incoherent tune space charge tune shift for the bunching factor B_f = 0.2 should be about ΔQ_{INC} ~ -0.14. This bunching factor at the injection energy can be provided by the 'single' harmonic RF cavity. 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.

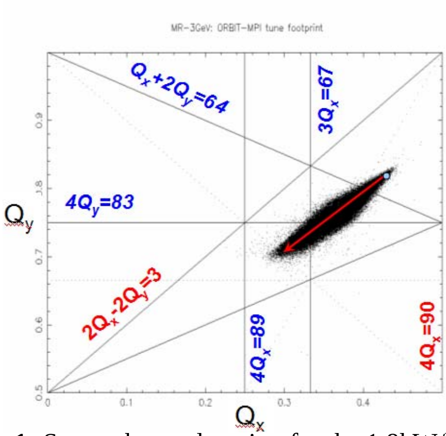

Figure 1: Space charge detuning for the 1.8kW/bunch beam power at the energy of 3GeV (B_f=0.2, the matched distribution in the longitudinal phase plane), including the beam environment with the rectangular chamber shape.

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 combined effect of the external field nonlinearities and the internal space charge of the beam should be studied to predict the particle losses for the basic scenario of the machine commissioning.

The space charge tune spread for the bunch 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. 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.

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 4^{th} 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 4^{th} order horizontal and vertical resonances ([4,0] and [0,4]) and to the 4^{th} order difference resonance ([2,-2]). Difference resonances are not usually regarded as dangerous to the operation of accelerators, if the beam has just the same transverse emittance for both phase planes. But if for some reason the transverse emittance in one phase plane will change, for example caused by the [4,0] resonance, then the high-order coupling will lead to increasing also the transverse emittance in the another phase plane.

In frame of this report we study the combined effect of the normal sextupole and the normal octupole resonances, which would lead to the transverse emittance growth and to the particle losses during the injection process. The 'lattice' normal sextupole resonances could be excited for MR only if the super-periodicity of the machine is broken. During the injection process the orbit of the circulating beam should be perturbed at the injection straight section. In addition, each bending and sextupole magnets of MR have the 'own' sextupole field component, which are also taken into the study.

SPACE CHARGE MODEL FOR MAIN RING

For intense low energy proton beams, space charge forces cannot be neglected, and the correct treatment of the space charge forces is required. The space charge forces are evaluated as self-consistent solution based on the Particle-In-Cell (PIC) model with the Fast Fourier Transformation (FFT). For this model the space charge forces are evaluated as nonlinear transverse kicks, distributed around the 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. Codes with the (2+1/2)D model are employing 2D FFT-Poisson solvers at the transverse kick nodes. However, the model is 3D in the sense that the space charge forces on a given macro-particle is scaled according to the longitudinal density at its position in the bunch, thus coupling the longitudinal motion into the transverse tune space [5]. This simplification of the space charge treatment is acceptable for the MR study, because the longitudinal bunch length is much longer than the transverse beam size and the synchrotron motion at the injection energy is about 500 turns.

At each transverse space-charge-kick node the space charge forces are evaluated as nonlinear kicks using a PIC model and FFT. Between the transverse space-charge-kick nodes the 'Teapot' like tracker can been used to provide the symplectic condition [5].

Convergence study

The study of space charge effects using the explicit second order PIC model involves three numerical parameters: N_K - the number of azimuthal integration steps; N_{MP} - the number of macro-particles; N_{FFT} - the spatial resolution (the grid parameters for the FFT algorithm). For the (2+1/2)D model an additional free parameter should be considered, in particular, N_{bin} the number of bin-points along the bunch to represent the longitudinal charge density of the beam.

For the convergence study we assumed the beam with the single bunch intensity of 2.475e13 ppb, which corresponds to the beam power of 3.5kW/bunch (or 0.6MW beam power from RCS). The binomial parabolic particle distribution in the transverse phase planes with the 100% emittance of 54 π·mm·mrad has been used to represent the beam. In this case the RMS beam emittance can be obtained by using the following relation $\varepsilon_{100\%} = 6\varepsilon_{RMS}$. In the longitudinal phase plane the beam has been represented by using the uniform particle distribution with the phase length of $\Delta\varphi = \pm 60$ degree (which corresponds to the initial bunching factor $B_f \sim 0.30$) and the momentum spread of $\Delta p/p = \pm 0.002$.

Results of the convergence study for the MR beam allow us to make some optimization of the 'free' parameters like the number of the grid-points (N_{FFT}), the number of the macro-particles (N_{MP}), the number of the longitudinal bin-points (N_{bin}) and the number of the transverse space charge kick points around the ring (N_{az}). The 99% emittance behavior in the horizontal and vertical phase planes has been studied for the 'bare' working point with the betatron tunes Q_x=22.428 and Q_y=20.82 also for different number of macro-particles. For both numbers of the macro-particles (10e4 and 20e4) the 99% emittance growth has been observed, which is caused by the space charge effect itself. For the case N_{MP}=10e4 the emittance growth is slightly over-estimated, but the required CPU time is about 2 times shorter, which makes this case more acceptable for study the injection process. The particle losses at the scraper for both cases are almost the same. Figure 2 represents the particle losses at the scraper acceptance of 60 π.mm.mrad during 1000 turns for the total number of the macro-particles of 20e4 and 10e4.

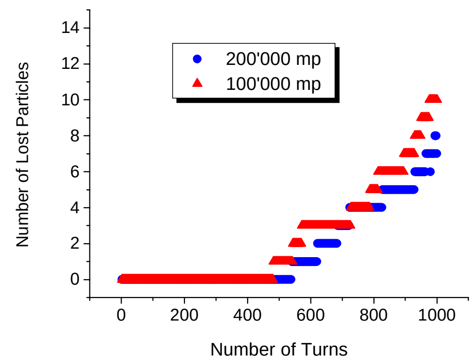

Figure 2: Particle losses for different number of macro-particles (10e4 and 20e4), represented the beam.

The particle losses at the scraper of MR have been slightly over-estimated in the case of 100'000 macro particles. Anyway, 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 transverse particles distribution at the injection energy represents the realistic beam, extracted from RCS. The beam passes through the beam-line collimator with the acceptance of 54 π mm.mrad. The total number of the beam's macro-particles after that is 91075 for the MR simulations. The matched particle distribution in the transverse phase planes at the MR scraper position is used as the initial transverse distribution with the following RMS emittance in the horizontal and vertical phase planes, respectively: 6.68 π mm.mrad and 7.85 π mm.mrad. The 99% emittance in the horizontal and vertical phase planes are 48.5 π mm.mrad and 50.2 π mm.mrad. The particle distribution in the longitudinal phase plane are generated to provide the matched distribution with the bunching factor of B_f=0.2 and the 99% longitudinal emittance about 4.3 eV.sec.

As was stressed above, all low-order resonances around the 'bare' working point are non-structure ones. For the case of 'ideal' super-periodicity (N_S = 3) only the 4th resonances will be excited. During the injection, the super-periodicity of the machine will be broken by creating the closed orbit shift in the injection straight section, so called 'injection dogleg'. To change the path for the circulating beam at the injection straight section, three bump magnets are used. Moreover, the circulating beam will have additional distortion, caused by the field of the opposite field magnetic septums, installed in the injection beam-line. To introduce the effect of the shifted orbit of the circulating beam, the bump magnets and the opposite field magnetic septums are represented as bending magnets with the edge focusing. In that case the effect of the edge focusing leads to the vertical beta-beating and excitation the normal sextupole resonances, mainly the coupling ones. The vertical beta beating around the ring, caused by the edge focusing effect of the bump magnets at the injection straight section, is less than 3%.

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 4^{th} 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.

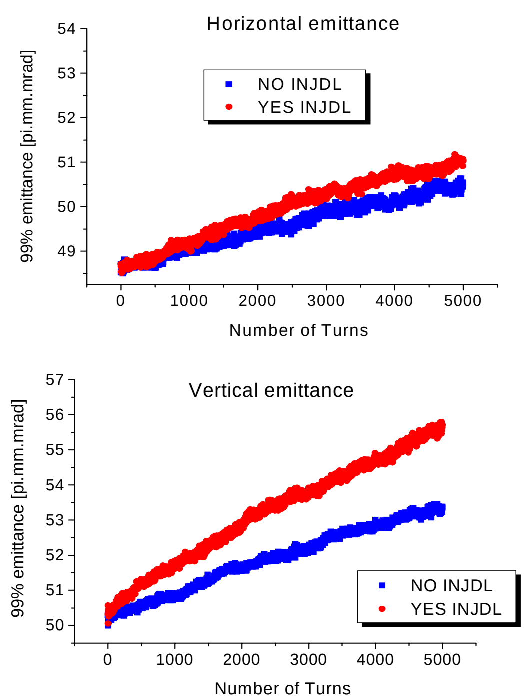

Figure 3: Emittance growth at the beginning of the injection process without and with Injection dogleg.

The explanation for the observed emittance growth is the following. The initial beam emittance in the transverse phase planes are almost the same. The difference resonance $2Q_x$-$2Q_y$=3 itself cannot produce the emittance growth in both transverse phase planes at the same time. The emittance growth is caused by excitation additional resonance. For the working point with the betatron tunes Q_x=22.43 and Q_y=20.82, 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 small amplitude particles, the 'core' particles, will be shifted from this resonance line by the space charge of the beam.

In the case of the broken super-periodicity by the 'injection dogleg' in the injection straight section of the ring, non-structure resonances will be excited. The main source for the normal sextupole resonances is the field nonlinearity of the chromatic sextupole magnets. 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. Additionally, the normal sextupole resonance Q_x+$2Q_y$=64 will be excited. 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 3).

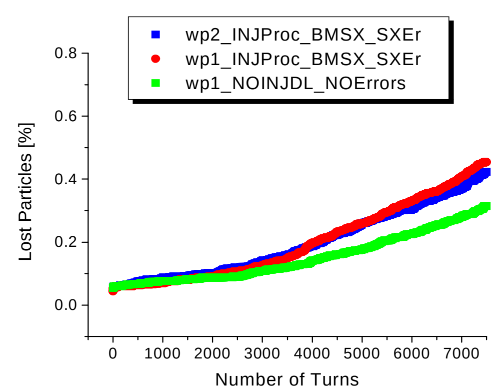

Figure 4: Particle losses at the MR scraper with acceptance of 70 π mm.mrad for different cases.

For real machine operation during the injection process, the opposite field magnetic septums will affect the circulating beam only during about 1msec (about 200 turns). During this time one batch (which will contain two bunches) from RCS will be injected to MR. Up to the next batch only the injection bumps will change the orbit of the circulating beam during about 7000 turns. For realistic estimation of the lost-beam power at the MR scraper, we implemented into the simulation this timing-process in addition to the measured sextupole field component of the ring bending and sextupole magnets. As was mentioned above, the location of each bending and sextupole magnets in the ring has been determined according to the magnet index.

Figure 4 represents the particle losses for one bunch during 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 elements of the 'injection dogleg' have the realistic timing. The difference in the particle losses at the MR scraper with the acceptance of 70 π.mm.mrad for two 'bare' working points in the case of the realistic timing of the injection 'dogleg' elements is small. As one can conclude from the obtained result, the particle losses in the case of the realistic timing of the MR injection dogleg for both working points is bigger, than the particle losses cased by only structure resonances. Non-structure resonances for MR lead to additional increasing the transverse emittances especially in the vertical phase plane.

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 particle losses for the whole injection time are shown in Figure 5 for two 'bare' working points. As one can see from this result, the difference in the particle losses for these working points is very small at least without excitation any skew resonances. 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 power dissipated in the MR scraper (A_{MR}=70 π.mm.mrad) is about 66.6W for the first batch (39.6W, 14.4W and 3.6W for the second, third and fourth batch respectively). The total power of the lost particles during the injection process for this case is just 124.2W.

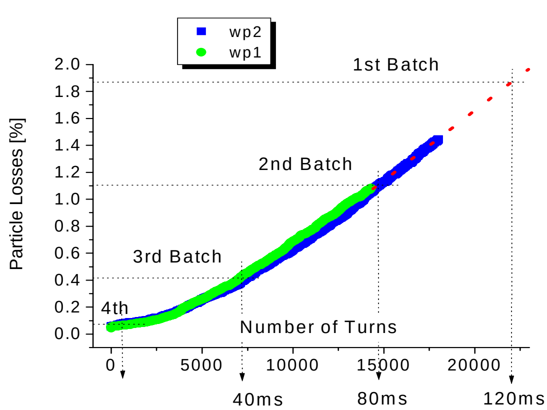

Figure 5: Particle losses for full injection time for different 'bare' working for the ring with the injection 'dogleg' including measured sextupole field component of the bending magnets and errors of the sextupole strength. Duration of the injection process for different batches of the beam is shown.

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 (which corresponds to 0.6MW beam power from RCS), 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. If the MR scraper acceptance is 60 π mm.mrad, the lost beam power becomes more than 660W, which is not acceptable for MR. If MR has just single harmonic RF system, the power of the lost beam becomes more than 600W even for the scraper acceptance of 70 π.mm.mrad.

For the MR beam power of 1.8kW/bunch, the particle losses at the beginning the acceleration process has been estimated. The acceleration process for MR is about 1.9sec, which is too long for the multi particle tracking study. After 120msec the particle losses for one bunch is about 5.7W. Then the total power of the lost particles of 8 bunches of MR at the beginning of the acceleration is about 45.6W. If we assume, that additional particle losses during long acceleration time is not more than 5W/bunch, then the total power of the lost beam for the 1.8kW/bunch operation during the injection and acceleration processes is less than 210W. For the 3.6kW/bunch operation the total power of the lost beam at the scraper should not exceed 310W, which is acceptable for MR.

CONCLUSION

For the realistic Main Ring parameters the space charge of the beam at the injection energy in combination with the intrinsic field nonlinearities leads to the transverse emittance blowing up, especially in the vertical phase plane. 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, which is 450W. For the bunch intensity 1.8kW/bunch and for 3.6kW/bunch, the total power of the lost beam is about 210W and 310W, respectively. Influence of the skew resonances should be studied.

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