SPACE CHARGE EFFECTS FOR JPARC MAIN RING

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Abstract

J-PARC Main Ring (MR) should provide the beam power up to 0.8MW at the maximum energy of 50GeV. The total beam intensity in this case should be 3.3e14. According to the basic machine parameters the harmonic number of MR is 9, the number of bunches around the ring is 8. The power of the bunch is about 6 kW at the injection energy of 3GeV. At the beginning of the high power operation we expected to get about 2 kW per bunch. Limitation the uncontrolled particle losses for the high-intensity beam accelerators is one of the most serious issue. The MR collimator should cut the tail particles during the injection process and at the beginning of the acceleration. Acceptable power of the lost beam at the scraper is about 500W, which is about 1% from the beam power at the injection energy. In frame of this report we analyze the combined effect of the low-energy space charge and the 'lattice' resonances, caused by the machine imperfection for different machine operation scenario including the collimation system of the 3-50BT beam line between RCS and MR and the MR collimator system. The measured field data for main magnets of MR has been used for this study. The budget of the particle losses during the injection and acceleration processes for the MR operation have been established.

INTRODUCTION

Limitation the uncontrolled particle losses is one of the most serious issue for high-intensity beam accelerators. For this kind of accelerators the combined effect of the low energy space charge and the resonances, excited by the external field nonlinearities should be studied to keep the particle losses below some acceptable level during the injection and acceleration process. According to the basic scenario of the J-PARC Main Ring operation, the injection time is about 120 msec (or about 25'000 turns) and the acceleration process is about 2 sec (or about 400'000 turns). The particle losses at the MR collimator should be kept below 500W. If it is necessary, the acceptance of the collimator can be changed from 54π to 81π in both horizontal and vertical planes. In addition, to control the particle losses in MR the collimator of the 3-50BT beam line between MR and RCS with changeable acceptance. The design capacity of the 3-50BT collimator is about 500W. In principal, by using these two 'knobs' one can keep the particle losses below the acceptable limit. Detailed study of the low energy space charge effects in combination with the non-linear resonances, caused by the machine imperfection, should be done for a basic machine operation scenario.

MAIN RING PARAMETERS

The expected power of the injected beam for MR at the beginning of the high power operation is about 2kW/bunch or 1.25e13 ppb. The corresponding beam power of the extracted beam from RCS should be about 300kW at the 3GeV energy. Two bunches should be accelerated into RCS and 8 bunches in MR. For the final energy of the accelerated beam of 30GeV, the maximum power of the extracted beam for MR will be about 145kW.

The MR RF system will be based on the fundamental RF cavities (h=9). The longitudinal emittance of the injected beam for MR should be about 3 eV.sec with the bunching factor about 0.2. In this case the incoherent space charge tune shift, including the rectangular beam pipe with size ± 70 mm, is about 0.17. The initial particle distribution in the longitudinal phase plane has been generated so that to provide the matched condition for the particle distribution with the required longitudinal emittance and bunching factor.

The transverse particle distribution for MR at the injection energy has been obtained assuming the 'linear' transformation of the particle distributions in both transverse phase planes after the 3-50BT collimator to the observation/injection point. The transverse particle distribution has been obtained after the 6D tracking for RCS including the injection (without painting process) and acceleration processes.

The particle losses at the 3-50BT collimator have been studied by using the STRUCT code for different beam power from RCS and different acceptance of the 3-50BT collimation. In the case of the total beam power of 16 kW at the 3GeV energy delivered from RCS to MR, the total power of the lost beam at the 3-50BT collimator is about 135W for the collimator acceptance of 54 π mm.mrad, which much smaller than maximum acceptable.

Main intrinsic nonlinear field for MR is the sextupole field nonlinearity, used to correct the linear chromaticity. The MR lattice has been designed so that without distortion of the ring super periodicity this nonlinearity will not lead to excitation the normal sextupole resonances [1]. The injection dogleg changes the super periodicity of MR so that both structure and non structure resonances can be excited. The following measured field data have been taken into account: the normal and skew sextupole field components of the MR bending magnets; the quadrupole field error of the MR quadrupole magnets at the injection energy; the sextupole field error of the MR sextupole magnets used for the chromaticity correction. The location of each MR magnet has been fixed according to the results of the shuffling procedure [2] to minimize the effects of these field errors at the leading order. Moreover, to excite the skew quadrupole

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and sextupole resonances the corresponding misalignments of the MR quadrupole and sextupole magnets have been assumed. The transverse tilt of these magnets has been generated to provide the uniform distribution of the misalignment errors with the maximum value of 0.5 mrad.

Additionally, measured field data of the opposite field magnet septum [3] and the bump magnets have been introduced into the injection dog leg of the ring. Analysis of the field measurement for the opposite field magnet septum shows that this septum will have the field leakage with strong sextupole field component. The integrated strength of the sextupole component of the field leakage of this septum is about a half of the required integrated strength for the chromaticity correction for the magnetic field of the septum of 0.56T. In combination with distortion of the ring super periodicity this strong sextupole component will lead to excitation the normal sextupole resonances, first of all, $3Q_x=67$. The opposite field magnet septum will be powered only for 1 msec (or 200 turns) to inject one batch (two bunches) from RCS. The realistic timing of the injection process has been taken into the account to build the realistic computation model of MR to get reliable estimation of the particle losses.

COMPUTATIONAL MODEL

To build the realistic computational model for MR we used ORBIT [4]. The transverse beam size for MR is much smaller than the longitudinal length of the bunch, then the space charge model one can utilize the 2&1/2 model with the beam environment, implemented into the code. For this model the transverse mesh with 128x128 mesh points at the center of the bunch has been utilized for the FFT Poisson solver. To scale the space charge along the bunch the 512 longitudinal bin points have been used. The number of macro particles about 200’000 has been used for the beam representation. The number of the transverse space charge nodes around the ring is 1100 with distance between the nearest nodes about 1.5 m The convergence study shows that the accuracy of the obtained particle losses for this computation model of the MR low energy beam is about 3%. This value could be improved by increasing the number of macro particles, but the CPU time will be unacceptable big. To perform the full time tracking during the injection period (~ 25’000 turns) we used the multi processor computer DELL PowerEdge68000 and the HITACHI SR11000 super computer, which is a part of the KEK super computer.

EFFECT OF THE SPACE CHARGE AND THE FIELD LEAKAGE

This work is based on the study of main sources of the emittance growth for J-PARC MR, performed before [5]. Now after field measurements of all MR magnets [6] we can analyze influence of the following resonances on the low energy particle motion: normal quadrupole, sextupole and octupole resonances; skew quadrupole and sextupole resonances. The effect of these resonances for the fixed beam intensity depends on the ‘bare’ working point. According to the basic MR design, the ‘bare’ working point should be located near the $3Q_x$ resonance, which will be used for the slow extraction of the accelerated beam. After the analysis of the MR single particle dynamics two basic ‘bare’ working points have been determined: (WP1) Q_x=22.42, Q_y=20.82; (WP2) Q_x=22.30, Q_y=20.92. In the case of the strong sextupole component of the field leakage of the opposite field septum of the injection beam line, this resonance could lead to unacceptable particle losses, if the ‘bare’ working point with $Q_x > 22.333$ is chosen.

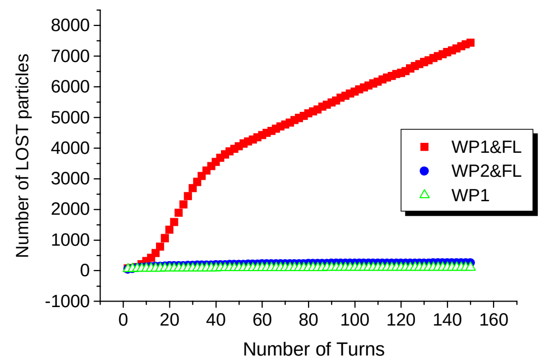

Figure 1: Particle losses as a function of turn number for different ‘bare’ working points in the case of the field leakage of the opposite field septum.

In the case of WP1 the space charge will change the particle tunes so that some part of the beam will cross the $3Q_x$ resonance, leading to the emittance growth and the particle losses. The particle losses as a function of the turn number are presented in Fig.1 for both ‘bare’ working points during 150 turns. For this case the MR collimator acceptance of 60 π mm.mrad has been assumed. Without the field leakage of the opposite field magnetic septum the particle losses for the ‘bare’ working point WP1 is almost zero (the ‘open’ triangle marks in Fig.1). For the ‘bare’ working point WP2 the sextupole field component of the field leakage of the opposite field magnetic septum will not lead to significant particle losses.

EFFECT OF THE SPACE CHARGE AND FIELD ERRORS

Main parameters of the machine should be optimized to keep the particle losses below the acceptable level. The physical rectangular aperture of the MR collimation system can be change in the range from 54 π up to 81 π mm.mrad. The upper value of the collimator aperture is equal to the physical aperture of the chamber around the ring. From the collimation efficiency point of view the acceptance of the collimator should be close to the minimum value. The particle losses during the injection and acceleration process have been simulated for different values of the MR collimator, the 'bare' working points and different initial particle distribution.

Particle losses during the injection process

The computational model of the MR operation with the realistic timing of main elements of the injection dog-leg has been used during full injection time. According to the basic MR operation scenario, the time interval between batches in MR is about 40msec, so that first two bunches (the first batch from RCS) should be kept at the injection energy during about 120msec. The opposite field magnetic septum will be power only for 1msec to inject the batch into MR. After simulation of the particle losses for the first batch one can estimate the particle losses for another batches to get the total particle losses.

Figure 2 represents the simulated power of the lost beam during 120msec for the bunch of the first batch for the MR operation. The total RF voltage of all RF cavities of MR for this case is 40kV with the fundamental harmonic h=9. The jaw of the 3-50BT beam line collimator is 54 π mm.mrad. The transverse particle distribution for MR is matched at the observation point, which is the MR collimator. The beam power is 2kW/bunch. The 'bare' working point WP2 has been chosen for this simulation to eliminate the emittance growth, caused by the $3Q_x$ resonance. The physical acceptance of the MR collimator is 54 π mm.mrad. According to the obtained result, the power of the lost beam for the first bunch during the full time of the injection process for MR is about 85W. The total power of the lost beam of the initially matched beam in the transverse and longitudinal planes for four batches during the injection process for these machine parameters is about 400W.

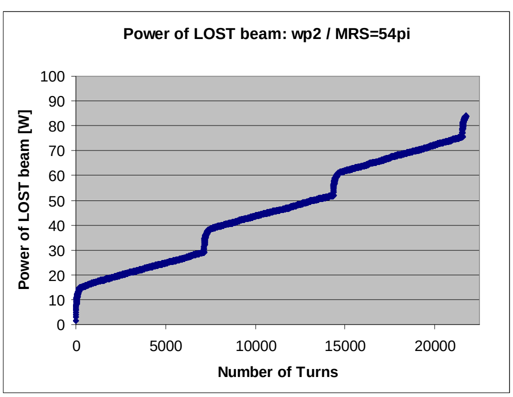

Figure 2: Power of the lost beam of the 2kW/bunch beam power at the MR collimator with the physical acceptance of 54 π mm.mrad and for the 'bare' working point Q_x=22.30, Q_y=20.92 during the 'full-time' injection process.

The particle losses for the initial mismatched particle distribution have been checked. To keep the particle losses at the MR collimator below the acceptable level, the initial 'beta' mismatching should be less than 10%. In this case for the MR collimator aperture of 60π and the 'bare' working point WP2 the total power of the lost beam (for 8 bunches) is about 440W.

Particle losses during the acceleration process

The realistic time pattern for the B-field of the MR bending magnets and for the parameters the RF system has been used to simulate the acceleration process for MR. The RF voltage for this pattern was changed from the initial value of 40kV to 280kV during 13msec at the beginning of the acceleration process. The magnetic field was changed by using the parabolic function during 100msec and after that the linear function up to the maximum value. For this time pattern the significant variation of the bunching factor was observed, which leads to increasing the space charge tune shift and crossing additional 'lattice' resonances. According to the obtained results (for the MR collimator aperture of 60π and the 'bare' working point WP2), the particle losses at the beginning of the acceleration process should be observed (during about 120msec) with the total power of the lost beam about 120W. The acceleration process for the MR operation has been simulated up to 250msec from the beginning of the acceleration.

CONCLUSION

For different basic 'bare' working points for MR and for the beam power of 16kW at the injection energy of 3GeV the power of the lost beam at the MR collimator has been estimated. By using two collimation systems, installed in the 3-50BT beam line and in MR, one can keep the power of the lost beam below the acceptable level. The operation scenario for the high power beam at the injection energy (> 20kW) should be studied next.

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REFERENCES

[1] "Accelerator Technical Design Report for JPARC", KEK Report 2002-13.
[2] M.Tomizawa et al., "Position Shuffling of the J-PARC Main Ring Magnets", EPAC06, Edinburgh, Scotland, 2006, p.1984.
[3] I.Sakai et al., " Operation of the Opposite-Field Septum Magnet for the J-PARC Main Ring Injection", EPAC'06, Scotland, 2006, p.1750.
[4] J.Galambos et al., PAC'99, New York, 1999, p.314.
[5] A.Molodozhentsev et al., "Study of Particle Losses mechanism for J-PARC Main Ring", EPAC06, Edinburgh, Scotland, 2006, p.2811.
[6] K.Niki et al., "Results of Field Measurements for JPARC Main Ring Magnets", EPAC06, Edinburgh, Scotland, 2006, p.2547.