高エネルギー加速器研究機構大型シミュレーション研究成果報告書（平成25年度）

(Brief report of the program)　　　　　　　　26　年01　月　21日

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受理番号 Proposal No.	12/13-25	研究課題名 Program title	Beam dynamics study for JPARC Main Ring: effects of the space charge and nonlinear fields

研究を終了しましたので、下記の通り報告します。

成果の概要
Abstract
（和文）

（英文）

(1) Further improvement of simulation tool (PTC-ORBIT code)

(2) High beam power operation scenario for JPARC Main Ring (beyond 1MW) for the neutrino experiments

(3) Modeling the ‘resonant’ slow extraction from JPARC Main Ring with ‘spill’ control to provide the required beam quality for the ‘hardon’ experiments

(4) Benchmark activity: understanding the results of beam measurements, performed during the machine study runs; comparison the measurements and simulations

研究成果を公開しているホームページアドレス

研究成果の公表	口頭研究発表件数	査読つきの学術論文数	プロシーディング論文数	その他（投稿中を含む）
	0	1	1	1

成果の公表リスト（それぞれの枠に番号をつけて記入願います。）

口頭研究発表
1. 2.
査読つきの学術論文(URL を記載)
1. T.Koseki et al, Beam commissioning and operation of the J-PARC main ring synchrotron, Prog. Theor. Exp. Phys. 2012, 02B004
プロシーディング論文(URL を記載)
1. A.Molodozhenstev, E.Forest, Further improvement of the PTC-ORBIT code to model realistic operation of high-beam power synchrotrons, IPAC13, Shanghai, May 2013.
その他（学位論文、紀要、投稿中の論文を含む）(URL を記載)
1. Beam dynamics study for JPARC Main Ring: Comprehensive study of the space charge and nonlinear field effects
特記（本研究に関係した、新聞記事・著作、受賞など）
1. 2.

Beam dynamics study for JPARC Main Ring: Comprehensive study of the space charge and nonlinear field effects

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Summary report

1. Motivation

J-PARC Main Ring should provide a proton beam with beam power more than 1MW. Strict limitation of particle losses for this kind of beam is required to avoid radiation damage. The particle losses are caused, first of all, by the combined effect of the machine resonances and the low energy space charge. To design and operate the high-beam-power proton rings, there is a need for comprehensive large-scale simulation program to study the injection, capture, acceleration, collimation and loss management in such rings, taking into consideration realistic machine imperfections. For this purpose the PIC code has been developed in collaboration between KEK and SNS (Oak Ridge, USA), which combines abilities of PTC (Polymorphic Tracking Code, KEK) and ORBIT-MPI (SNS). The code has been installed and compiled for the KEK Super Computer Systems and for the CERN multi-processor cluster.

The goals of this study are (1) better understanding the emittance growth mechanism at the injection energy for the J-PARC Main Ring to guarantee minimum particle losses around the machine, (2) optimization the machine performance for different scenario of the machine operation to provide ‘safe’ machine operation and (3) better understanding the spill control for the case of the slow resonant extraction of the accelerated beam. In addition (4) the benchmark of the simulations and performed measurements is required to demonstrate reliability of the simulation results for different cases.

Main achievements of 2013:

1. Further improvement of simulation tool (PTC-ORBIT code)
2. High beam power operation scenario of Main Ring
3. Modeling ‘resonant’ slow extraction from Main Ring
4. Benchmark activity

1. *Further improvement of simulation tool to model realistic operation of high-power synchrotrons*

The combined 'PTC-ORBIT' code has been developed to study the dynamics of the high intensity proton beams in synchrotrons, including the nonlinear machine resonances and the space charge effects in the self-consistent manner. In order to extend the code abilities the time variation of the main elements of the synchrotron has been introduced into the PTC module of the code. The 'dynamic' memory allocation, implemented in PTC, allows to use unlimited time tables for all elements (different kind of magnets and RF cavities) of the synchrotron. This feature opens the direct way to model the multi-turn injection process, acceleration process and the slow extraction process by using realistic machine description, in particular the dynamic variation of the betatron tunes, strength of the bump magnets, dynamic resonance correction or resonance excitation. To illustrate this ability the multi-turn injection process for the CERN PS Booster is presented below.

Figure 1 shows the required time variation of the chicane height, created by the combined action of four 'fast' kickers and four 'slow' bump magnets during the injection process for the CERN PS Booster. **Figure 2** represents the vertical RMS emittance evolution for two cases (1) without and (2) with the beta-beating dynamic compensation.

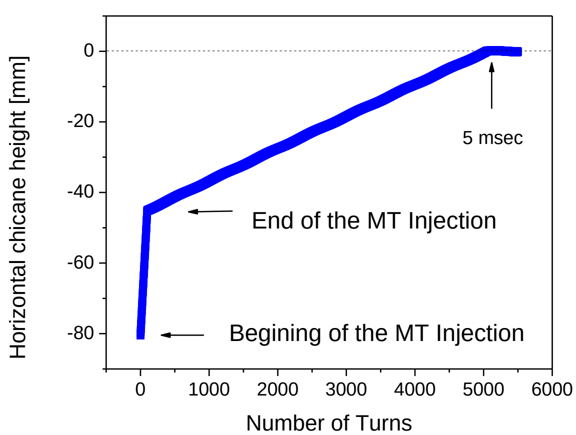

Figure 1: Chicane height variation during the multi-turn injection for the CERN PS Booster

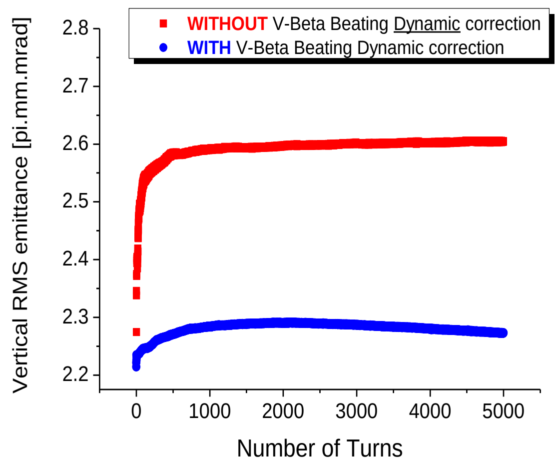

Figure 2: Vertical RMS emittance evolution without and with 'dynamic' [0,2,9] resonance compensation.

2. *High beam power operation scenario of Main Ring*

In the case of low-energy proton beam with significant space-charge detuning crossing different machine resonances becomes unavoidable. The low and high-order machine resonances are caused by the different kind of imperfections of the machine elements. **Figure 3** shows the space-charge detuning for the J-PARC MR at the injection energy of 3GeV in the case of the 500kW beam from RCS. The 2D color plot is used to observe the amount of the macro-particles in different places on the tune foot-print. The total number of the macro-particles is 200'000 for this case. The lattice ('bare') betatron tunes are 22.40 and 20.75 in the horizontal and vertical phase plane, respectively. The space-charge detuning effect depends on the transverse beam emittance and the longitudinal distribution of the beam. Parameters of the RF system should be determined to keep the bunch length constant during the injection process and at the beginning of the acceleration process. To meet this requirement the high harmonic RF system has to be used in combination with the fundamental harmonic RF system.

Crossing the low-order machine resonances will lead to significant emittance dilution. The effect of these resonances has to be simulated to avoid particle losses in the machine. For the basic 'bare' working point the 'sum' linear coupling resonance Qx+Qy=43 has been investigated experimentally by using the results of the simulations, including the resonance compensation scheme by utilizing 4 dedicated skew quadrupole magnets, installed in J-PARC MR during the summer shutdown period in 2012.

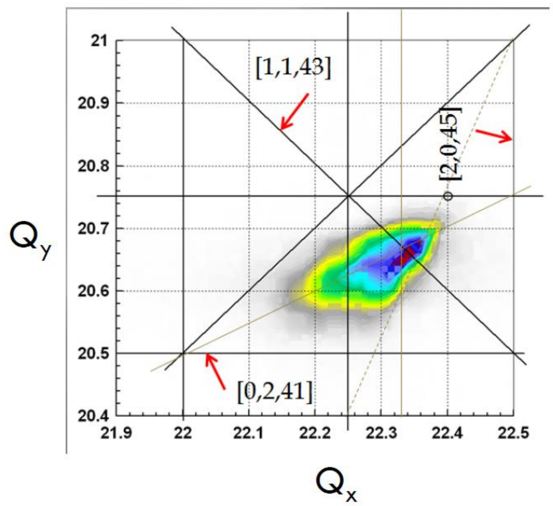

Figure 3: Space-charge detuning of the beam at the injection energy of 3GeV for J-PARC MR in the case of the 500kW beam from RCS.

During 2013 we continue our study to optimize the MR operational scenario to increase the beam power for the 'neutrino' experiments, in particular, the working point optimization at the injection energy of 3GeV for different beam power from RCS to minimize the transverse emittance dilution and particle losses. The emittance evolution ('core' RMS emittance and 'halo' 95% emittance) is shown on **Figure 4** (A and B, respectively) for different lattice tunes after the correction of the 'sum' linear coupling resonance [1,1,43]. After the 'lattice' working point optimization one can reduce the emittance dilution significantly including the 'halo' fraction of the beam emittance in the transverse phase-planes. The obtained results will be used for the MR operation, which will start from March 2014.

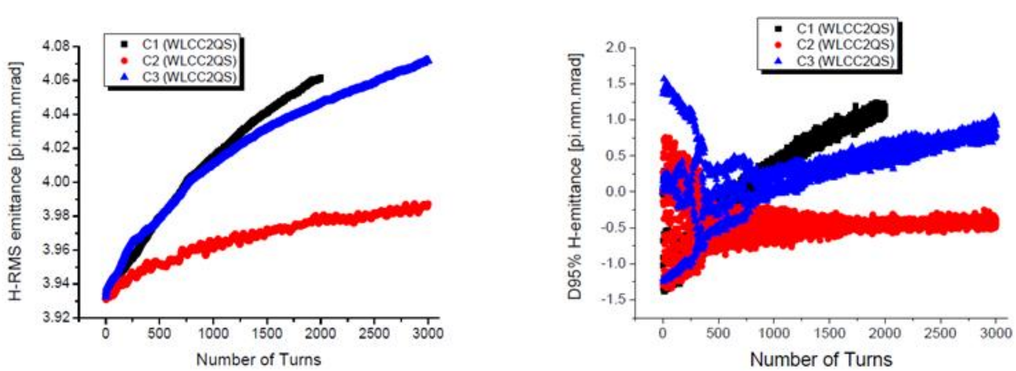

Figure 4: The emittance evolution ((A):'core' RMS and (B): 'halo' 95% emittance) for different 'lattice' tunes after the correction of the 'sum' linear coupling resonance.

3. *Modeling 'resonant' slow extraction from Main Ring*

J-PARC Main Ring, which should deliver the 30GeV proton beam to different nuclear physics experiments by using the 'resonant' slow extraction technique. The spill structure of the extracted particles should be uniform as much as possible. To realize this extraction technique it is necessary to change 'dynamically' during the extraction process: (1) height of the closed orbit distortion at the location of the electro-static septum, (2) strength of the quadrupole magnets to move the lattice tune into the [3,0,49] resonance area and (3) strength of the dedicated quadrupole magnets to modify the spill-structure of the beam during the extraction process. Moreover, it is necessary to compensate effects of the power supply 'ripple' of these quadrupole magnets for both low and high-frequency components. Finally, it is necessary to perform the transverse high-frequency 'shaking' of the beam particles during the slow-extraction process by using the transverse RF-knock out signal. All these dynamic variation of different MR magnets (low and high-frequency) can be introduced into the machine model by PTC for the multi-particle tracking. Below a few results are presented, which were obtained during 2013 for the 'slow' extraction J-PARC Main Ring operation at 30GeV energy by using the KEK Super Computer System.

Effect of the 'dynamic' bump ('dynamic' changing the horizontal closed orbit distortion at the location of the electrostatic septum) is presented in **Figure 5**. By using the appropriate time variation of the kick angle of four dedicated bump magnets in Main Ring the horizontal emittance of the extracted beam can be reduced from 2.5 till 1.0 π.mm.mrad. This result has been confirmed experimentally performed for Main Ring.

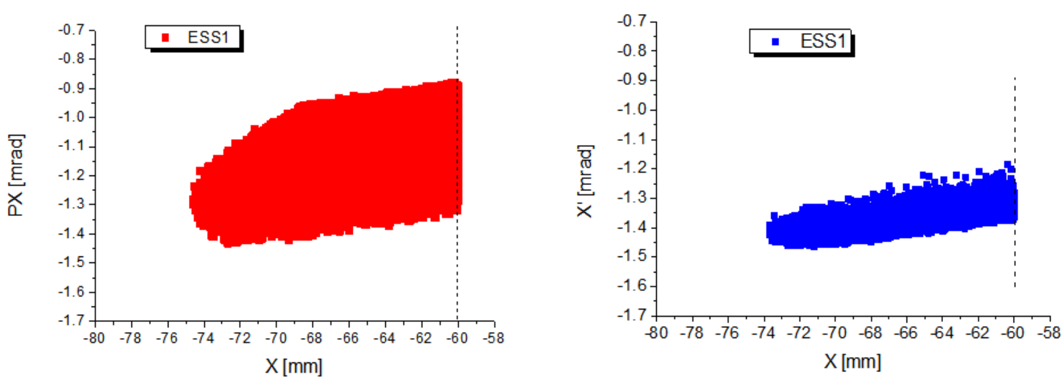

Figure 5: Effect of the 'dynamic' bump-strength variation during the slow extraction process.

Ripple of the power supply of the MR quadrupole magnets (especially the low-frequency ripple component) leads to significant distortion of the spill-structure in the case of the 'resonant' extraction. To simulate these effects the strength of the quadrupole magnets of J-PARC MR has been represented by the time table, which contains the information about the linear changing of the current and the ripple component of the power supply. The effect of the ripple of the current of the "QFN" quadrupole magnets is presented in **Figure 6**(A). For the tracking 10'000 macro-particles have been used to simulate the extraction process during 200msec (or 35'000 turns).

After applying the 'ripple' compensation technique the spill structure of the extracted beam has been improved significantly (**Figure 6**(B)). This 'ripple' suppression has been demonstrated experimentally for the J-PARC Main Ring.

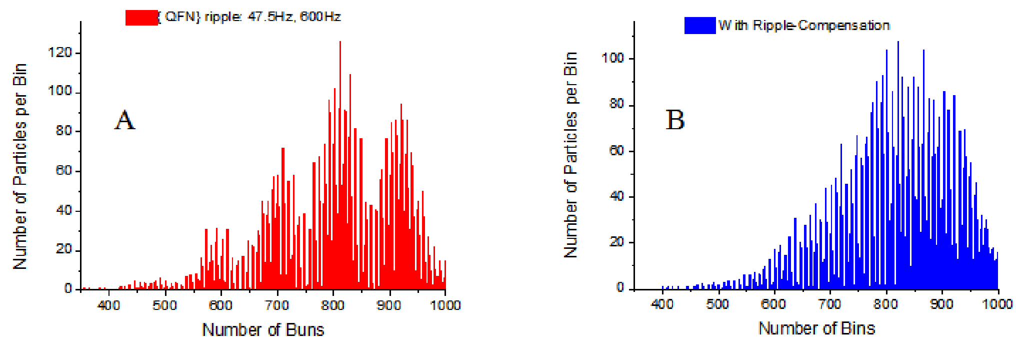

Figure 6: Effect of the 'ripple' compensation: (A) before and (B) after applying the anti-ripple low frequency signal.

The spill structure (or 'time' structure of the extracted beam) can be controlled by using dedicated quadrupole magnets with the appropriate variation of the quadrupole strength during the extraction period. To provide 'uniform' time structure the required time pattern for these dedicated quadrupole magnets has been optimized by using the PTC-ORBIT code. The improved 'uniform' spill structure and the 'natural' spill structure of the extracted beam are shown in **Figure 7** for the extraction period of 200ms.

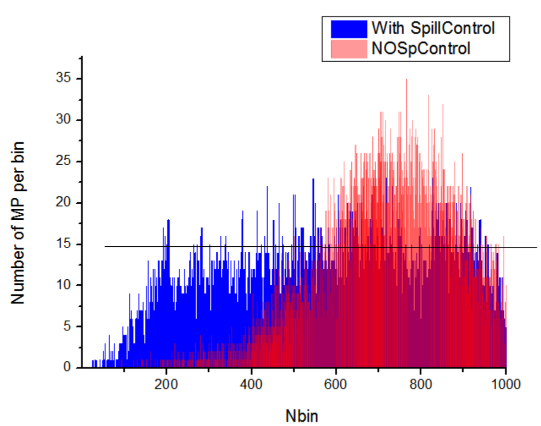

Figure 7: Modification the spill structure of the extracted beam.

4. Benchmark activity

Computer modeling the beam dynamics in synchrotron allows to simulate different processes to optimize the machine performance. By using results of measurements, obtained during the machine study, it is necessary to reproduce it by the simulations to check abilities of the computer modeling and to understand the observations. This benchmark activity is extremely important and should follow the machine study.

The results of measurements (the beam intensity) for the MR 'pencil' beam operation with small beam intensity are presented in **Figure 8**(A). The beam losses are caused by the effect of the 'sum' linear coupling resonance, which can be corrected for the normal machine operation by using an appropriate current set for dedicated skew quadrupole magnets, installed in J-PARC Main Ring. The corresponding computer modeling has been performed to reproduce the experimental result. On **Figure 8**(B) the comparison of the computer model and the 'RUN44' measurements are shown. The beam losses, observed during the machine study, have been reproduced by the multi-particle tracking based on the existing machine model.

Some difference between the results of measurements and modeling can be explained by limited number of the macro-particles to represent the beam. For this study 20'000 macro particles have been used. Large number of macro-particles is preferable in the sense of accuracy of the losses, but simulation time becomes very long even for the multi-processor computer.

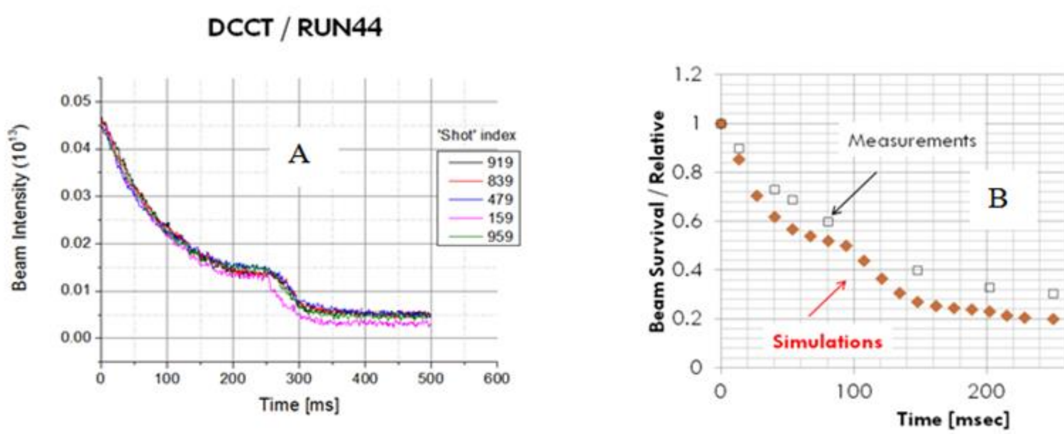

Figure 8: Beam losses, observed during RUN44 for J-PARC Main Ring (A) and the results of the computer modeling of RUN44 (B).

List of reports:

Published reports

1. T.Koseki et al, Beam commissioning and operation of the J-PARC main ring synchrotron, Prog. Theor. Exp. Phys. 2012, 02B004

2. A.Molodozhenstev, E.Forest, Further improvement of the PTC-ORBIT code to model realistic operation of high-beam power synchrotrons, IPAC13, Shanghai, May 2013.