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 25-26 年度）

(Brief report of the program)　　　　　　　　　H26 年　11　月　25　日

研究責任者名 Name	MOLODOZHENTSEV Alexander	所属機関 Affiliation	KEK (Accelerator Division 1)
受理番号 Proposal No.	大型 13/14-05	研究課題名 Program title	Beam dynamics study for JPARC synchrotrons

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) benchmark the beam measurements and machine modeling at the moderate beam power and optimization the high beam power operation of J-PARC Main Ring;

(2) simulations of the slow-extraction process from JPARC Main Ring;

(3) off-line modeling of the beam dynamics for the J-PARC Main Ring to support the beam power up-grade process for Main Ring;

(4) further development and optimization the codes to study the beam dynamics in the ‘space-charge’ dominated synchrotrons

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	0	3	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　Presentations at scientific meetings concerning the program

1. International Particle Accelerator Conference, IPAC14, Dresden, June 15-20, 2014
2. International Workshop (ICFA HB14), Michigan, November 9-14, 2014

査読つきの学術論文(雑誌名等には 巻、頁、発表年を記載)（＊）不足する場合には追加願います。

Refereed Journal Articles (name of journal, volume, page, year)

1	著者名 Author	
	タイトル title	
	雑誌名 name of journal	
	URL	
2	著者名	
	タイトル	
	雑誌名等	
	URL	

プロシーディング論文(雑誌名等には 巻、頁、発表年を記載)（＊）不足する場合には追加願います。
International Conference Proceedings (name of journal, volume, page, year)

1.	著者名 Author	A.Molodozhentsev, S.Igarashi, Y.Sato, J.Takano
	タイトル title	Study linear coupling resonance for J-PARC Main Ring: observations and simulations
	雑誌名等	Proceeding of IPAC Conference (IPAC14), Dresden, June 15-20, 2014
	URL	http://accelconf.web.cern.ch/AccelConf/IPAC2014/papers/tupro052.pdf
2.	著者名	A.Molodozhentsev
	タイトル	Modeling slow extraction process for J-PARC Main Ring
	雑誌名等	Proceeding of IPAC Conference (IPAC14), Dresden, June 15-20, 2014
	URL	http://accelconf.web.cern.ch/AccelConf/IPAC2014/papers/thpro067.pdf
3.	著者名	A.Molodozhetsev, Y.Shirakabe, Y.Muto
	タイトル	Numerical study of intrinsic ripples in J-PARC Main Ring magnets
	雑誌名等	Proceeding of IPAC Conference (IPAC14), Dresden, June 15-20, 2014
	URL	http://accelconf.web.cern.ch/AccelConf/IPAC2014/papers/tupro093.pdf
4.	著者名	
	タイトル	
	雑誌名等	
	URL	

その他（学位論文、紀要、投稿中の論文を含む）（著者、タイトル、論文種別、URL を記載）
Others (thesis for a degree, bulletin, papers to be published, etc.)

1. A.Molodozhentsev, S.Igarashi, Y.Sato, J.Takano,
Beam dynamics study for J-PARC Main Ring by using the ‘pencil’ and space-charge dominated beam: measurements and simulations,
in Proceedings of the ICFA HB workshop, Michigan, Nov.9-14, 2014

特記（本研究に関係した、新聞記事・著作、受賞など）（過去に遡っても構いません。）
Special Notes (newspaper article, literary works, awards, etc.)

1.
2.

Beam dynamics study for JPARC synchrotrons:

study the space charge and nonlinear field effects

<u>'SCSCS' Research group:</u>

A.Molodozhentsev, S.Igarashi, T.Koseki, Y.Sato, M.Tomizawa,

KEK, Accelerator Division 1

Summary report

<u>Motivation</u>

J-PARC Main Ring should deliver to users a proton beam with beam power more than 1MW. Strict limitation of particle losses during the operation with 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 in a 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 PTC-ORBIT combined code has been installed and compiled for the KEK Super Computer Systems.

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

The emittance growth and particle losses during the injection and beginning of the acceleration processes are caused by the combined effects of the space charge of the low-energy high-beam intensity proton beam (internal nonlinearities) and the intrinsic field nonlinearities of the ring magnets (external nonlinearities). The optimum machine parameters should be determined to avoid emittance dilution and uncontrolled particle losses. This optimization process includes the operational working point on the betatron tune diagram for different beam intensity, as well as the optimum beam parameters, produced by the injector (RCS). Appropriate correction of the machine resonances should be applied to reach the high-beam power with limited particle losses. Optimum machine parameters have to guarantee the acceptable level of the particle losses in the ring and maintain the stable machine operation.

Main achievements during 2013-2014:

1. Benchmark activity for both ‘pencil’ and space-charge dominated beams
2. High beam power operation scenario of Main Ring

1. Benchmark activity for both ‘pencil’ and space-charge dominated beams

‘Pencil’ beam

Effects of the machine resonances, caused by imperfections of magnets of MR, are studied experimentally by using a low intensity ‘pencil’ beam. The beam dynamics study for J-PARC Main Ring has been performed by using the KEK Hitachi Super Computer. An appropriate scheme to compensate the ‘sum’ linear coupling resonance has been proposed, tested and implemented successfully for J-PARC MR [1]. Information about the beam losses and the transverse beam profiles have been collected for different working points on the betatron tune diagram during the machine study by using the ‘pencil’ beam setting for the MR operation. The accumulated data have been used to benchmark the results of the computer modelling of the low-intensity beam dynamics for MR with experimental observations. This benchmark activity is required to improve and check the machine model, which should be used to study the Main Ring operation scenario in the case of the space-charge dominated regime.

Effects of the isolated resonance Qx+Qy=43 (or [1,1,43]) were studied experimentally and modeled successfully during the machine study, performed in the period of 2012-2013 for the ‘bare’ working point with the betatron tunes of 22.2875 and 20.6975 in the horizontal and vertical phase planes, respectively. It was demonstrated that after the compensation the [1,1,43] resonance with optimized time pattern for the skew quadrupole strength the ‘pencil’ beam had been injected and accelerated without losses. Without the resonance compensation the significant losses (more than 90%) were observed experimentally and reproduced by modeling.

For the ‘bare’ working point with the betatron tunes of 22.195 and 20.795 in the horizontal and vertical phase planes respectively, the combined effect of different ‘machine’ resonances was observed experimentally (Runs 46, 2013) and reproduced successfully by using the computational Main Ring model.

From the computer modeling of the beam dynamics it becomes clear that for the lattice working point with the betatron tunes of 22.195 and 20.795 in the horizontal and vertical phase plane, respectively, a combined effect of the linear coupling [1,1,43] and the high order [5,0,111] resonances has been observed. It was demonstrated experimentally and by modeling that compensation the [1,1,43] resonance prevents trapping the particles into the high-order resonant islands, created by the 5th order horizontal resonance.

The simulated beam profile for this working point without activating the compensation of the [1,1,43] resonance is presented in Fig.1. To obtain reasonable agreement with the experimental results, it is necessary to have appropriate number of macro-particles of in the 6D distribution and high-order field errors of the MR magnets have to be added into the model of the machine. As the result, the simulated horizontal 1σ beam size after 120ms from the injection become 13.8mm. The measured one was 15.4mm (see Fig.2). The measured (RUN46) and simulated particle losses are shown in Figure 3.

The particle losses during the injection have been simulated for the realistic setting of the Main Ring RF system and the collimator acceptance of 70 π mm.mr. The simulated particle losses (see Fig.3) also are in good agreement with the experimental observation for this 'bare' working point.

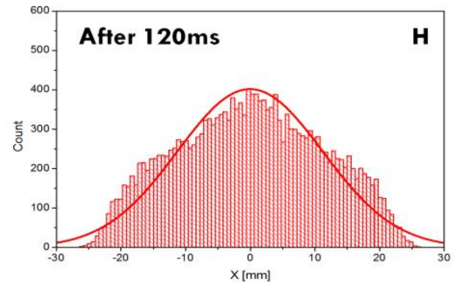


Figure 1: Simulated horizontal beam profile after 120ms for the 'bare' working point Qx=22.195 and Qy=20.795 without the [1,1,43] resonance compensation.

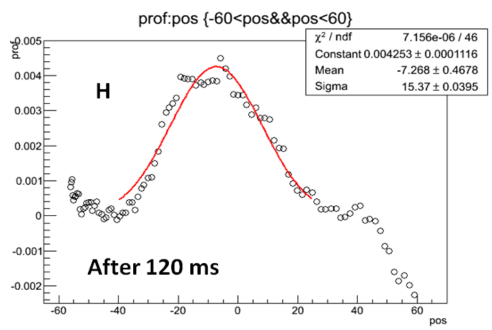


Figure 2: Horizontal beam profile measurement performed after 120ms from injection for the 'bare' working point Qx=22.20 and Qy=20.80 without the [1,1,43] resonance compensation.

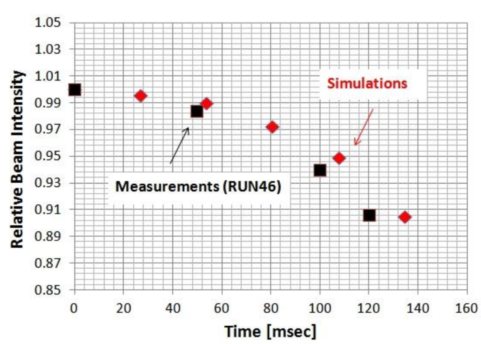


Figure 3: Reproduction the measured (RUN46) particle losses for the case of the combined resonances injection for the 'bare' working point Qx=22.20 and Qy=20.80 without the [1,1,43] resonance compensation.

'*Space-charge' dominated beam*

Dedicated measurements (RUN54-RUN55/2014) and simulations were performed for the 'low-energy' 'space charge dominated' case to check the ability of the computational model to reproduce the experimental observations.

The RCS beam power at 3GeV was fixed to keep it on the level of 315kW (Ion Souce: 25mA / "chopping time": 460ns / LINAC: 400MeV). Different painting areas were used to accumulate in RCS the required beam power at the injection energy of 400MeV: 100π and 50π.

Different machine conditions with different beam parameters (for the fixed beam intensity) were studied experimentally and used for the extensive simulations to reproduce beam survival in MR for different parameters of the RF system; transverse beam emittance evolution for different initial beam parameters, for different levels of the chromaticity compensation and effect of the [1,1,43] resonance compensation for the space-charge dominated beam. All these studies are extremely useful for better understanding the MR peculiarities for the 'high-beam power' operation.

The performed modeling of the beam dynamic is based on the pre-simulated 6D distribution of the beam, accelerated by RCS from 400MeV up to 3GeV. The total number of macro-particles in this distribution is 498'622. Different conditions for the multi-turn 'painting' injection in RCS has been used to prepare the initial particle distribution for the MR study to be in agreement with the experimental study.

The incoherent space charge detuning in the case of the low-energy high-power beam for MR depends on the MR RF setting, the bunch length of the beam extracted from RCS (200ns for the present RCS extraction kicker) and the 'painting' area for the RCS injection. The beam intensity was 2.75e13/2 ppb (2 bunches per pulse). The performed simulations show that after 1200 turns (a few synchrotron periods for MR at 3GeV) the maximum space charge detuning is about (-0.15) for the '100π' RCS painting area and about (-0.35) for the '50π' RCS painting area, respectively. The simulated incoherent space charge detuning at the injection energy of 3GeV after 1200 turns for different RCS painting area is shown in Figure 4. The 'basic' lattice tunes (Q_x=22.40, Q_y=20.75) and V_{rf}=160kV (h=9) have been used for these simulations.

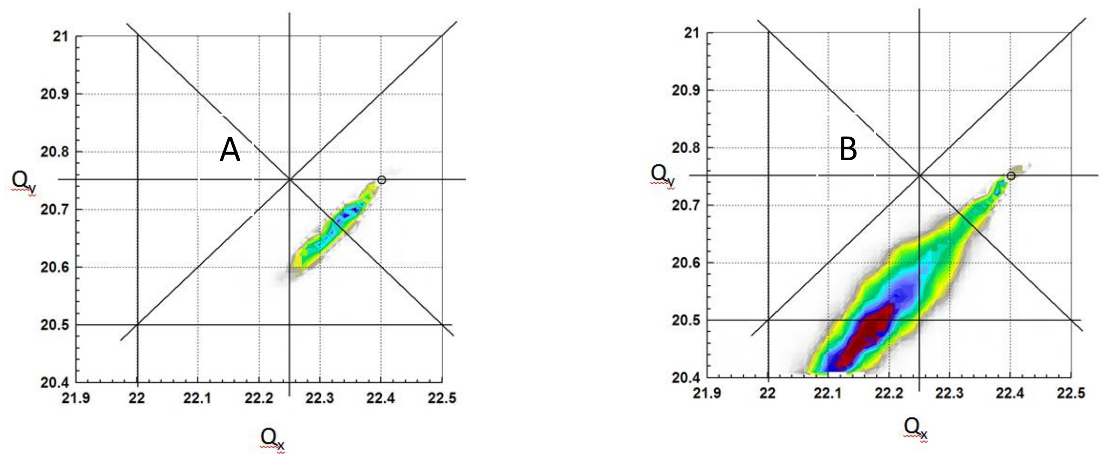


Figure 4: 2D histogram of the incoherent space charge detuning (3GeV with the intensity of 1.375e13 ppb) in MR for the RCS 'paint' emittance at 400MeV: (A) '100π' and (B) '50π'.

Modeling the beam survival in MR at the injection energy of 3GeV was performed for different RF parameters to compare it with the results of measurements, performed during RUN54 (Fig.7). For the multi-particle tracking the following parameters have been used: MR collimator acceptance of 70π, partial 'linear' chromaticity correction (85%) and the RF voltage of 160kV and 200kV for the case of the fundamental RF system (h=9).

The obtained simulated results for the beam survival (Fig.5-A) are in a qualitative agreement with the experimental observation (Fig.5-B). Some discrepancy between the observations and simulations can be explained by different definitions for the MR collimator aperture, which was not defined clearly during RUN54. The 'basic' lattice tunes (Q_x=22.40, Q_y=20.75) were used for this study.

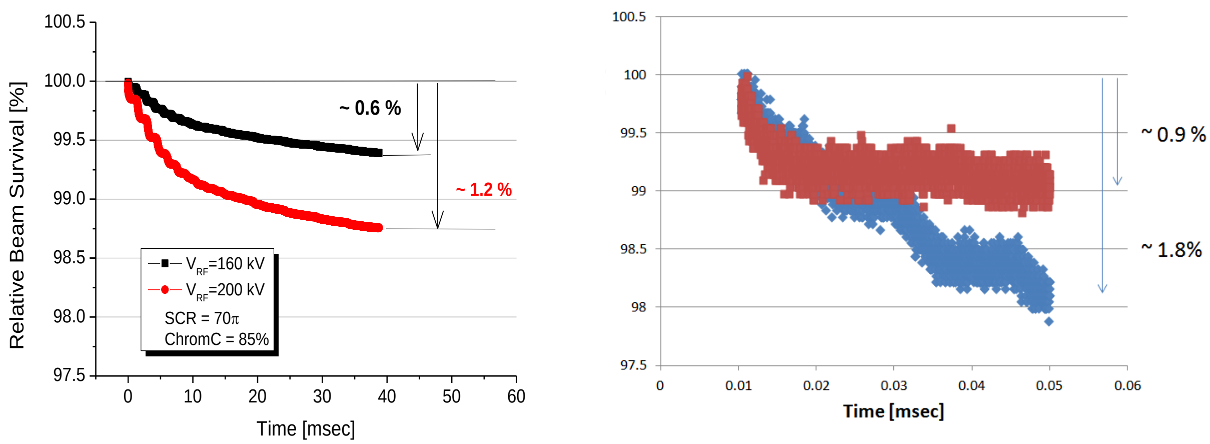


Figure 5: Beam survival in the MR collimator for different RF voltages (160kV and 200kV) for the basic 'bare' working point: (A) simulated (collimator acceptance of 70π); (B) measured (collimator acceptance > 60π).

Comparison between the performed simulations and measurements for different beam emittance from RCS (with the intensity of 1.375e13ppb) is presented in Figure 8 for the '100π' case and the 'basic' lattice tunes (Q_x=22.40, Q_y=20.75). The 'black' dots with the 'error'-bar represent the results of the measurements. The 'blue' and 'green' lines show the simulated RMS emittance evolution before and after the [1,1,43] compensation, respectively.

The agreement between the measured RMS emittance and the simulated one for the case of the '100π' paint RCS emittance is quite reasonable (Fig.6). Similar agreement has been demonstrated and for the case of the '50π' paining RCS area. Some discrepancy can be explained by the effect of the initial beam mismatching, which becomes important for the case of 'strong' space-charge.

After the [1,1,43] resonance compensation the particle losses at the MR collimator were reduced significantly. The simulated losses for this case are presented in Figure 10 for the case of the 93% partial chromaticity correction and for the 'paint' RCS emittance of 50π and 100π. The particle losses in MR for the '100π' case during 55msec becomes 110W. For the case of the '50π' paint RCS emittance at 400MeV and for the 93% chromaticity correction the particle losses at the MR collimator (with the acceptance of 65π) the particle losses during 55msec after the injection can be estimated as 44W. The 'fast' losses, observed at the beginning of the injection process, are caused by the initial beam mismatching in the transverse and longitudinal planes.

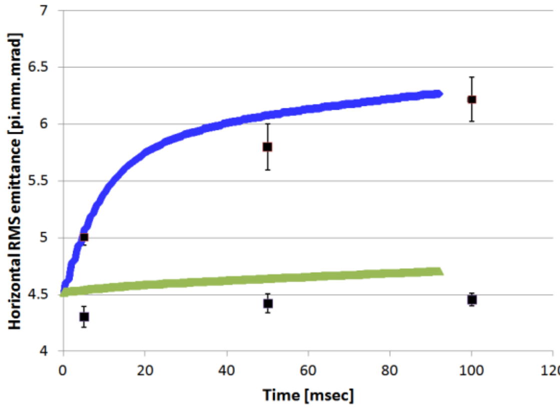


Figure 6: Horizontal RMS emittance evolution (measured and simulated) for the ‘100π’ paint RCS beam.

The particle losses, observed experimentally for the same settings of the main parameters of the injected beam and MR, are in agreement with the simulated results. The total losses in MR for the case of the ‘50π’ paint RCS emittance at 400MeV and for the 93% chromaticity correction, obtained experimentally after the compensation the [1,1,43] resonance, was about 120W totally including losses during the injection and acceleration processes.

The effects, observed for the ‘basic’ working point in the case of the ‘pencil’ beam and the ‘space-charge dominated’ beam, are reproduced by using the developed computational model of the machine. As the result, the low-loss MR operation has been achieved for the beam power of 315kW from RCS. Improvement of the machine model should be continued to be able to suppress effects of the high-order resonances and optimize the MR performance in the case of the ‘Mega-Watt’ operation.

2. High beam power operation scenario of Main Ring

High power MR operation scenario has been simulated by using the developed (and tested for the moderate beam power) computational model of J-PARC Main Ring. The MR operation scenario is based on 8 bunches with the repetition time of 2.4sec. The performed modeling is based on the initial 6D particle distribution, pre-simulated for the RCS operation with 500kW and 1MW beam at the energy of 3GeV. The bunch length of the beam, extracted from RCS, is limited by the power supply of the RCS extraction kicker. The current bunch length cannot be bigger than 200ns, which is much smaller than the design parameters (300ns). The short bunch with the high beam intensity (4.17e13 proton per bunch, which corresponds to the ‘1MW’ RCS operation) will lead to significant space-charge detuning at the beginning of the ‘injection’ process for the MR operation. This effect of the ‘short’ bunch, injected into MR from RCS, can lead to significant particle losses in the 3-50BT beam collimation system and the MR collimation system. Appropriate balance between the acceptances for these collimators was set by using the developed computation model of the machine. The tune-scan study was performed for the ‘high-power’ MR operation (for the pre-simulated RCS beam) to minimize the particle losses in Main Ring.

The incoherent space-charge detuning for the beam intensity of 4.17e13ppb (RCS 1MW beam) is presented in Figure 8 for the ‘basic’ bare working point. The double harmonic RF system was used for this study (100kV(h=9) and 70kV(h=18)). The detuning was simulated after 1500 turns from the injection of the bunch into MR.

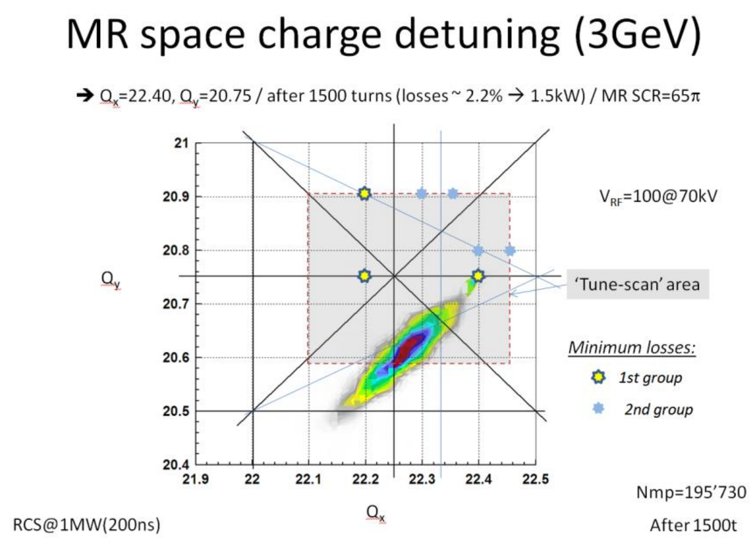


Figure 8: Incoherent space charge detuning for the MR beam intensity of 4.17e13ppb (at 3GeV). The 'yellow' starts represent the 'bare' working point with minimum particle losses at the MR collimator (65π)

Tune-scan was performed for the beam intensity of 4.17e13 ppb at 3GeV to define potential 'bare' working points for the high-power MR operation.

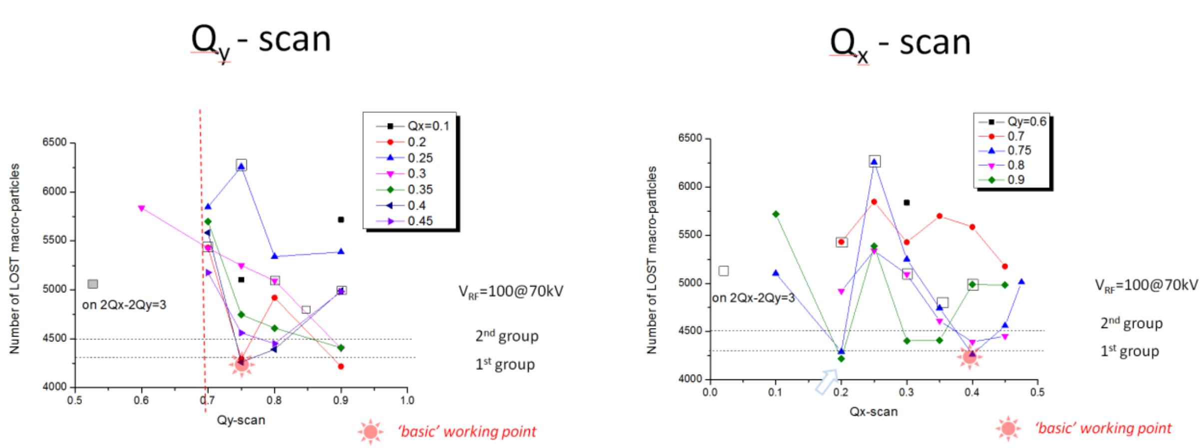
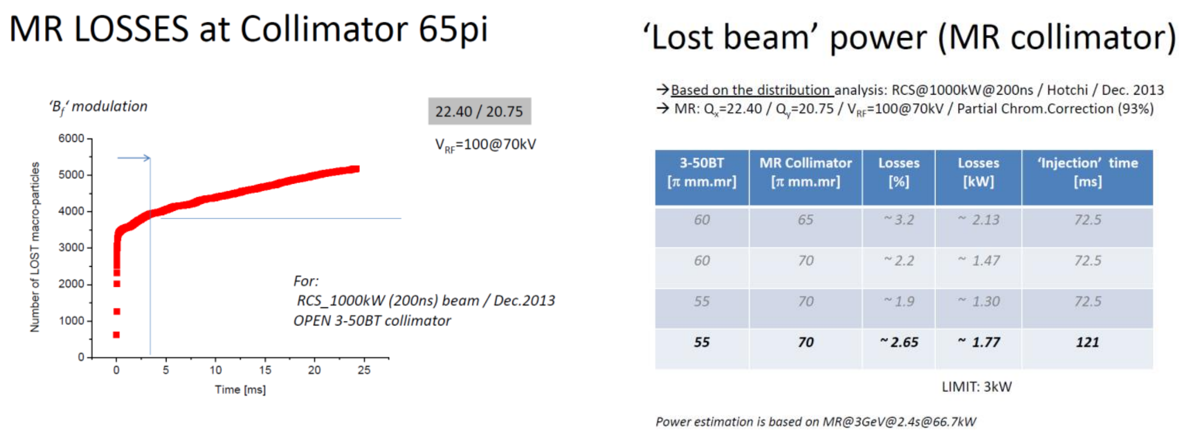


Figure 9: Particle losses for different 'bare' working points for the beam intensity of 4.17e13 ppb at 3GeV (MR collimator acceptance=65π)

After the compensation the [1,1,43] resonance by using the dedicated skew quadrupole magnets, the current 'basic' working point (Qx=22.40, Qy=20.75) allows to keep the beam with small particle losses. As the result of the tune-scan a few additional working points were defined with similar losses at the injection energy of 3GeV. These 'bare' working points are shown in Figure 8.



3-50BT [π mm.mr]	MR Collimator [π mm.mr]	Losses [%]	Losses [kW]	'Injection' time [ms]
60	65	~ 3.2	~ 2.13	72.5
60	70	~ 2.2	~ 1.47	72.5
55	70	~ 1.9	~ 1.30	72.5
55	**70**	**~ 2.65**	**~ 1.77**	**121**

Figure 10: Particle losses and estimation of the total lost beam power for the 'basic' working point.

The particle losses at the MR collimator (acceptance=65π) during 25msec after the injection and the total power of the lost beam at 3GeV are shown in Figure 10. The lost beam power has been studied for different acceptance of the 3-50BT collimator and the MR collimator to find some optimum balance between these two collimators.

List of reports:

1. A.Molodozhentsev, S.Igarashi, Y.Sato, J.Takano, Study linear coupling resonance for J-PARC Main Ring: observations and simulations, in Proceedings of IPAC'14 Conference, Dresden, June 15-20, 2014

2. A.Molodozhentsev, Modeling slow extraction process for J-PARC Main Ring, in Proceedings of IPAC'14 Conference, Dresden, June 15-20, 2014

3. A.Molodozhetsev, Y.Shirakabe, Y.Muto, Numerical study of intrinsic ripples in J-PARC Main Ring magnets, in Proceedings of IPAC'14 Conference, Dresden, June 15-20, 2014

4. A.Molodozhentsev, S.Igarashi, Y.Sato, J.Takano, Beam dynamics study for J-PARC Main Ring by using the 'pencil' and space-charge dominated beam: measurements and simulations, in Proceedings of the ICFA HB14 workshop, Michigan, Nov.9-14, 2014.