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MODELING SLOW EXTRACTION PROCESS FOR J-PARC MAIN RING

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Abstract

Resonant extraction of accelerated particles from synchrotrons is used widely nowadays. This extraction technique is based on excitation a high-order resonance. Extracted beam quality control is one of the most serious issues for this extraction method. Computational model of a synchrotron with the resonant extraction should be based on a realistic machine with proper implementation different kind of imperfections (field and misalignment errors) of magnets. To simulate the slow extraction process the time variation of different kind of magnets has to be used to optimize the spill quality of the extracted beam. The multi-particle tracking procedure has to be based on the symplectic integrator to avoid any artificial effects. For high intensity proton synchrotrons the collective effects should be taken into consideration, especially if experiments require low energy particles. In frame of this report we present the computational model of J-PARC Main Ring, developed to study the slow extraction with proper control of the spill quality. This model will be used to optimize the machine performance for different nuclear physics experiments in J-PARC.

INTRODUCTION

Main Ring (MR) of the Japanese Proton Accelerator Research Center (J-PARC) should deliver proton beams for ‘Neutrino’ and ‘Nuclear Physics’ experiments. For the second case the ‘slow’ extraction technique should be utilized with very precise control of the time structure (spill) of the extracted beam. If for the first case very high average beam power is requested (about 1MW at the final energy and more), for the second case the beam intensity is quite moderate but not negligible especially for the ‘bunched’ beam operation scenario. The Main Ring has been designed to provide the imaginary gamma-transition. The natural chromaticity of the machine is about (-30), which should be corrected almost to zero by using 72 sextupole magnets. The machine has three super-periods with three straight sections. The arcs of the machine have been design to provide the zero dispersion for the straight sections and cancellation the sextupole nonlinearity of the bending magnets.

The slow extraction of the accelerated beam for J-PARC is realized by using the 3^{rd} order horizontal resonance 3Qx=67, excited by eight dedicated sextupole magnets. The extraction process is controlled by changing the horizontal betatron tune of the machine, moving the particles into the resonance stop-band from the lower tunes.

In the case of the slow extraction with typical extraction period more than 1 sec the effect of power supply imperfection of the quadrupole magnets is critical. Proper correction of the power supply ripple has been performed for the MR operation by using dedicated quadrupole magnets to avoid significant modulation of the beam intensity during the extraction process.

To minimize the horizontal emittance of the extracted beam a dynamic bump has been employed successfully for the MR operation, which keeps minimized the angular distribution of the extracted particles. This technique is realized by using four dedicated bump magnets with a proper variation of the kick angle during the extraction process.

Additionally, the RF knockout system has been designed and implemented for the MR operation for finite correction the spill structure of the extracted beam.

To model the slow extraction process it is necessary to prepare a realistic machine description, which should be based on measured imperfections of different magnets including high-order field components and different alignment errors. In addition, the field leakage of the slow extraction septum magnets has to be taken into consideration.

For the multi-particle tracking a symplectic propagator should be used to avoid any artificial effects. Each element of the machine should have individual table, which define time variation of the fields, optimized to different operation scenario of the machine. The developed MR model has been used to study the beam dynamics and optimize the machine performance during the slow extraction providing the required beam quality.

COMPUTATIONAL MODEL OF J-PARC MAIN RING

The computational model of J-PARC Main Ring for different scenario of the machine operation, including the slow extraction has been developed and tested. For the machine description MADX with the PTC interface has been used. This option of the MADX is available for all MADX users. PTC is the Polymorphic Tracking Code, developed in KEK.

To prepare final lattice file (so called, flat file) for the PTC tracking it is necessary to define a few parameters, which will set the symplectic integration procedure, implemented into PTC [1]. Additionally different time tables for the Main Ring elements have been prepared to be able to change the machine properties dynamically during injecton, acceleration and extraction processes.

The basic computational model of J-PARC Main Ring contains measured data for all MR magnets, taken into consideration the measured field leakage of different septum magnets, used to inject (and extract) the beam. The parameters of all MR elements can be changed dynamically by using the time tables. The fringe field effects of different magnets have been taken into account by using the hard-edge approximation. The RF system of the machine can be represented as the multi-harmonic RF

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cavities with individual time table to control the voltage and phase during the acceleration process.

To model the slow extraction process for J-PARC Main Ring, the sextupole magnets for the resonance excitation have been powered-on with the constant strength. The dynamic bump of the closed orbit near the electrostatic septum has been introduced by the proper time tables to represent the measured position of the beam's center of mass during the extraction process. The edge focusing effects are taken into account by the definition of the bumps as the rectangular bending magnets.

The control of the time structure of the extracted beam has been implemented by using dedicated quadrupole magnets with the optimized time pattern of the quadrupole strength during the extraction process. For additional control of the spill quality the transverse RF knockout signal can be used.

Significant modulation of the spill of the beam during the slow extraction process has been observed experimentally for J-PARC Main Ring. This effect has been observed experimentally and simulated by using the developed computation model of the machine with the power-supply ripple of the Main Ring quadrupole magnets. The high frequency ripple changes the betatron tunes near the resonance stop-band. Dedicated quadrupole magnets with optimized high-frequency time modulation of the current during the extraction process have been installed to compensate this effect for the MR operation [2].

By using the PTC-ORBIT(MPI) code [1], developed in collaboration between KEK and SNS, the multi-particle tracking can be performed to study the slow extraction process utilizing the realistic model of the machine with programmed time variation of the MR elements. The code has been installed and compiled for the KEK super computer system.* Collective effects (space charge effects and impedance effects) can be simulated by using the machine model, depending on the experiment. For the COMET experiment [3] the space charge effects of the bunched beam have to be simulated to avoid uncontrolled emittance dilution during the injection and acceleration.

MODELING THE RESONANT EXTRACTION FOR J-PARC MR

The multi-particle tracking has been performed to model the slow extraction. The control of the time structure of the extracted beam has been utilized to provide uniform spill of the during the extraction process. The beam quality has been analyzed at the entrance of the electrostatic septum. The initial 6D macro-particle distribution (10'000 macro-particles) has been generated to represent the beam at the energy 30GeV. For this energy the space charge effects are negligible.

As was stressed above, during the extraction period the strength of the 'QFN' family (48 magnets) should be changed linearly to move the beam slowly into the resonant stop-band. For this model the total time of the extraction process has been limited by 0.2sec.

Ripple Effect and Compensation

It was demonstrated that the ripple of the power supply of the {QFN} magnets leads to significant distortion of the spill structure of the beam during the slow extraction process [2]. The low-frequency and high-frequency ripple of the power supply system should be compensated by using the dedicated quadrupole magnets with controllable amplitude of the 'anti-ripple' current.

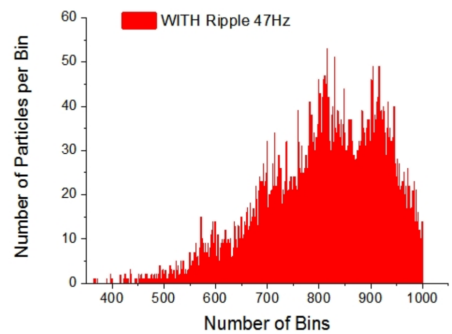

Figure 1: Time structure for the extracted beam at the entrance of ESS1 with the low-frequency ripple effect of the {QFN} magnets (47Hz).

Effect of the ripple of the current of the quadrupole magnets on the spill quality is presented in Fig.1 (before the compensation) and Fig.2 (after the compensation). This technique has been implemented into the MR operation.

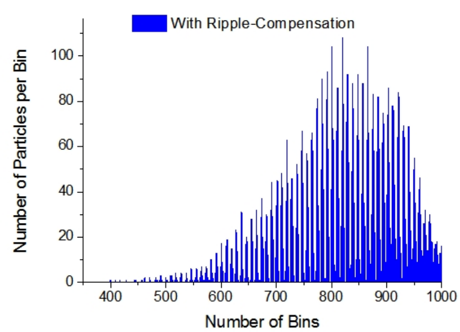

Figure 2: Time structure for the extracted beam at the entrance of ESS1 with compensation the low-frequency ripple effect of the {QFN} magnets.

Dynamic Bump

In order to minimize the extracted beam emittance in the horizontal plane at the electrostatic septum (ESS1) the 'Dynamic Bump' approach has been utilized for MR. This approach is based on the control of the beam position near ESS1 by using four dedicated bump magnets with the proper control the kick angle during the extraction process. To model this process the bump magnets are considered as the rectangular bending magnets, taking into consideration the 'dynamic' edge focusing effects and the fringe field effects. The result of

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the modelling the slow extraction with the 'Dynamic Bump' approach for the case of the coasting beam and full linear chromaticity correction is presented in Fig.3. By using this technique the horizontal RMS beam emittance at ESS1 has been reduced significantly from 0.25 (red) till 0.1 π mm.mr (blue) (see Fig.3). This result has been confirmed experimentally.

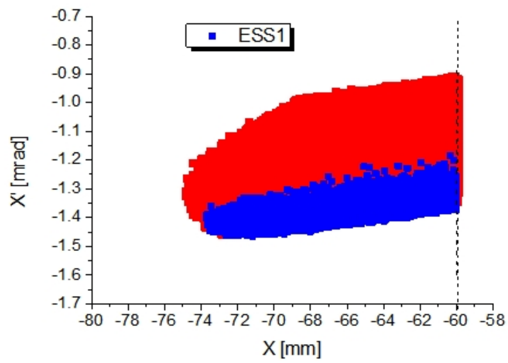

Figure 3: Particle distribution at ESS1 for the slow extraction from MR at the energy of 30GeV without (red) and with (blue) 'Dynamic Bump' technique.

Spill Control

The control of the time structure of the extracted beam for the MR operation is performed by using a dedicated quadrupole magnet with a proper time variation of the strength during the slow extraction process. By using this approach the semi-uniform spill has been obtained experimentally. The performed modelling the extraction process for MR is in agreement with the experimental results. The simulated spill control over the slow extraction process is presented in Fig.4 (blue). Additional control of the time structure of the extracted beam can be performed by utilizing the RF knockout technique, which also can be simulated in frame of the developed computational model of MR.

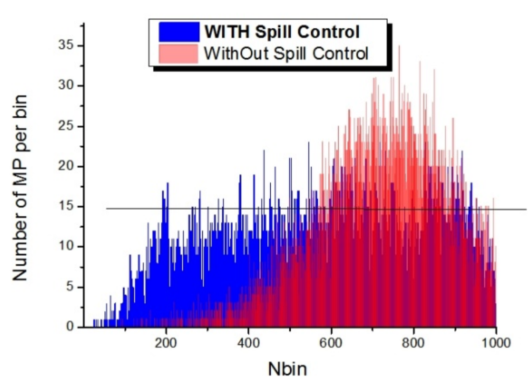

Figure 4: Spill control (blue) by using a dedicated quadrupole magnet with a proper time pattern during the slow extraction process.

Chromaticity Control

Full chromaticity correction is required to avoid significant emittance growth, caused by the chromatic detuning of the particles in the case of the coasting beam (see Fig. 5). If the bunched beam should be used for the slow extraction the periodical crossing the resonance stop-band by the off-momentum particles could lead to the emittance growth.

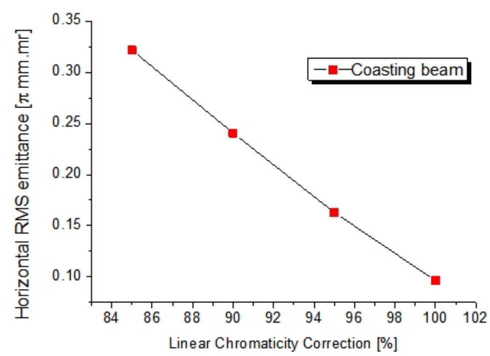

Figure 5: Control the horizontal RMS emittance of the extracted beam at ESS1 by chromaticity of MR with the activated 'Dynamic Bump'.

CONCLUSION

The developed computational model of J-PARC Main Ring has been improved to simulate the slow extraction process as it is realized for the MR operation. The obtained results, discussed in the report, are in agreement with the measurements. By request, this model of the machine can be used in combination with the collective effects (space charge effects and impedance effects), implemented into the PTC-ORBIT code [2]. The developed model of the MR slow extraction process will be used to provide the beam for the COMET [3] experiment.

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