

# ORBIT BEAM SIMULATION PROGRESS IN THE 3-GeV RAPID CYCLING SYNCHROTRON OF J-PARC

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## Abstract

We have made a significant progress with ORBIT 3-D particle tracking code for numerous beam simulations in the 3-GeV Rapid Cycling Synchrotron (RCS) of Japan Proton Accelerator Research Complex. Namely, for a single particle dynamics, MAD lattice and the corresponding ORBIT TEAPOT model have been made to give exactly same results to that with SAD model used for the RCS beam commissioning. The time dependent lattice functions of the injection chicane bump magnets and similar other time dependent lattice imperfections, which are already found to cause significant beam losses in the real machine have been successfully introduced. Recently, time dependent transverse and longitudinal impedances of the extraction kicker magnets have also been introduced. As a result, the ORBIT code should proved to be much more matured for beam simulations in synchrotrons. Beam simulation results illustrating these new realistic features are presented.

## INTRODUCTION

Figure 1 shows a layout of the 3-GeV Rapid Cycling Synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC). The RCS has three-fold symmetric lattice with 3 arc and 3 long straight sections having a circumference of 348.333 m [1]. RCS is designed for a beam power of 1 MW by accelerating  $8.33 \times 10^{13}$  protons from 400 MeV to the 3 GeV at 25 Hz. The 3-GeV beam is simultaneously delivered to the downstream Material and Life Science Facility (MLF) and the Main Ring (MR). The injection energy is 181 MeV at present and will be upgraded to the 400 MeV later this year. RCS operates now with more than 300 kW and a maximum beam power of more than 500 kW has already demonstrated in a recent beam studies. Realistic numerical beam simulations by using 3-D space charge code SIMPSONS followed by systematic beam studies made it possible to achieve such a high power beam with optimizing beam loss to a minimum level even at this low injection energy of 181 MeV [2].

The ORBIT 3-D particle tracking code was developed at the Spallation Neutron Source (SNS) of Oak Ridge originally for high intensity accumulator rings but recently new capabilities has given for applications to synchrotrons [3, 4]. In the present study we are thus motivated to apply those capabilities for beam simulations in the RCS. It is

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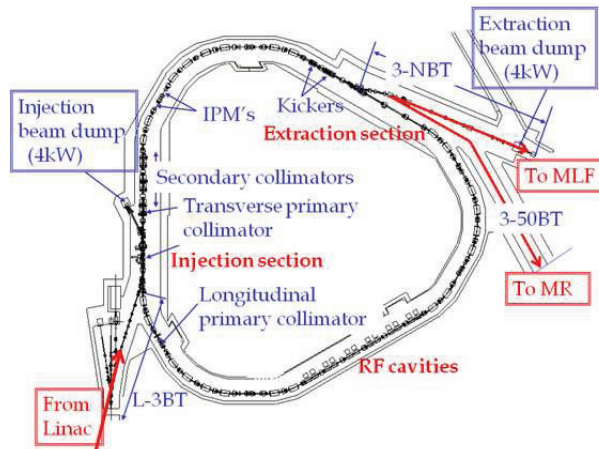


Figure 1: Layout of the J-PARC 3-GeV RCS.

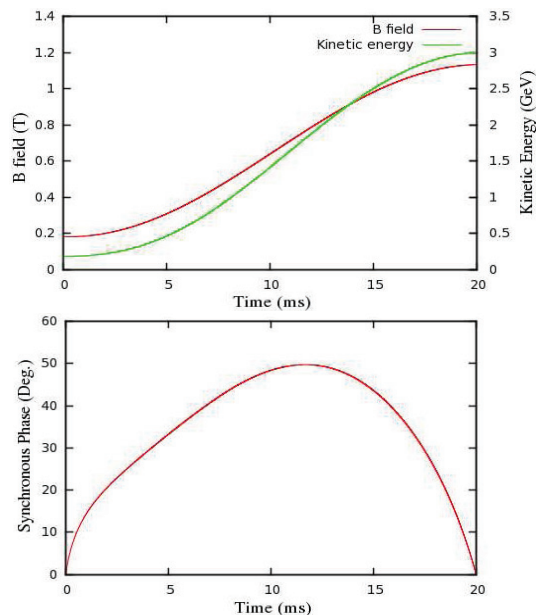


Figure 2: Sinusoidal ramping pattern of the B field of the bending magnets and the corresponding kinetic energy. The synchronous phase is shown in the bottom.

very interesting to have more than one completely independent simulation platforms applied to the same machine. A benchmark not only with an rms level of the beam behaviors but a detail an extensive comparison such as halo formation, beam loss mechanism as well as limitations of each code and accordingly further development can be done.

Figure 2 (top) shows the sinusoidal ramping B field of the bending magnets and corresponding kinetic energy in the course of 20 ms acceleration cycle at present with 181 MeV injection. A rapid change of the synchronous phase can be seen in the bottom figure. It is thus very interesting to apply ORBIT capabilities for such a rapid cycling synchrotron like RCS.

In order to apply ORBIT code for the RCS beam simulation, we had to construct a MAD lattice first from the original SAD lattice [5, 6]. Because, one needs MAD output in order to generate TEAPOT model used for ORBIT tracking [4]. We considered first a single particle dynamics. In RCS, measured lattice functions for a low intensity beam are optimized to those given by SAD model. SAD has fringe fields definition for all magnets, MAD partially has but in ORBIT no treatment of the fringe field and includes symplectic hard-edge fringe field formulation given in Ref [7]. The fringe fields of the RCS magnets are comparatively large and for a single particle dynamics the vertical betatron tune is calculated to be change nearly 0.03 with and without fringe fields of the bending magnets. In order to construct a MAD lattice, all bending and quadrupoles magnets are given with their effective length determined from the field measurement data. Then within SAD platform, the original lattice functions (with fringe fields on) such as beta and dispersion functions as well as betatron tunes are reproduced by varying all 7 families of the quadrupoles. The SAD lattice is then transformed to the MAD lattice, which gives exactly same results as given by SAD. As a result, TEAPOT is constructed by using the MAD output. Figure 3 shows the horizontal (top) and vertical (bottom) beta functions calculated by using ORBIT's statistical lattice function diagnostic (blue points), MAD (red points) and SAD (lines). It is clearly seen ORBIT's lattice functions agree well with those given by both MAD and SAD. The horizontal and vertical betatron tunes are set to be 6.45 and 6.42, respectively.

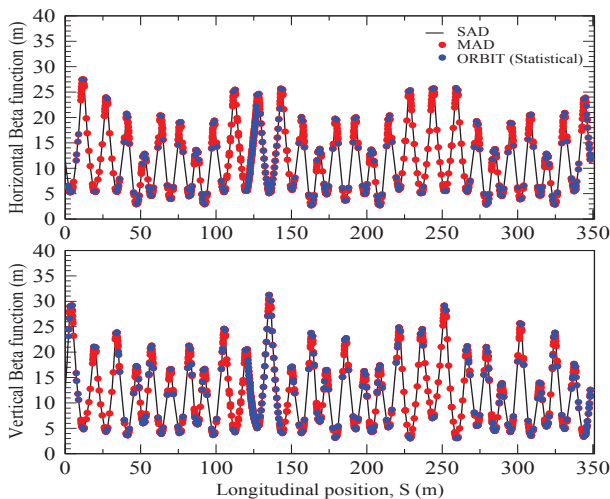


Figure 3: Comparison of the beta functions calculated by ORBIT's statistical lattice function diagnostic (blue points), MAD (red points) and SAD (lines).

## TIME DEPENDENT LATTICE FUNCTIONS

Recently, we have finished introducing almost all relevant time dependent parameters for which lattice functions are changed as a function of time. Namely, edge focusing effects of the chicane and painting bump magnets, extraction leakage field, chromatic correction sextupoles and also impedances of the extraction kicker magnets.

### Edge focusing effect of the Chicane magnets

In order to take into account the additive edge focusing effects of 4 horizontal injection DC chicane bump magnets (SB) as well as 4 horizontal painting bump magnets (PBH), we defined them as multipole elements in the TEAPOT. The effect of PBHs are comparatively much smaller as compared to SBs and thus we focused only for SBs here. Each SB has a bending angle of 58 mrad for producing a horizontal orbit bump offset of 93 mm. As a result, they induced a substantial vertical focusing perturbation resulting a considerable deviation of the vertical lattice functions from the design values. The vertical beta-beating at maximum is as high as nearly 30% making a vertical tune deviation by around 0.016. It is worth mentioning that not only SBs with full strength at-top during beam injection of 0.5 ms but it should be properly addressed during their linear ramping down to zero strength by the next 0.5 ms.

Figure 4 shows an orbit bump offset (top) of a single particle for a single turn injection plotted for 0.042 ms (20 turns) intervals. The SBs are programmed in order to give an appropriate kick at each turn so as the corresponding orbit bump offset in the middle of SBs is determined. A corresponding deviation of the tune and only for the vertical one is then found to be quite expected as shown in the bottom. Such a large beta-beating in the first order causes a significant aperture reduction resulting a beam loss for a larger transverse injection painting. In order to compensate this effect, 6 quadrupole correctors will be installed later this year [8].

### DC leakage field, Time dependent Sextupoles

The leakage field from the extraction DC magnets, which is also time dependent as the energy is ramped is also introduced as thin lenses. The horizontal and vertical tunes at the bottom energy change to -0.0026 and 0.0014, respectively. The chromatic corrector sextupoles are introduced with DC fields as applied to the real machine.

### Kicker Impedance

Extraction kicker impedances especially, the transverse impedance is considered to be the dominant source to cause beam instability in RCS [9]. Beam instability is observed when a full AC chromatic correction is done. The longitudinal impedance is compensated by the rf beam loading. Originally kicker impedances in ORBIT was already introduced for a DC ring [10]. But for synchrotrons that is not so straight forward as one has to cope with a change of

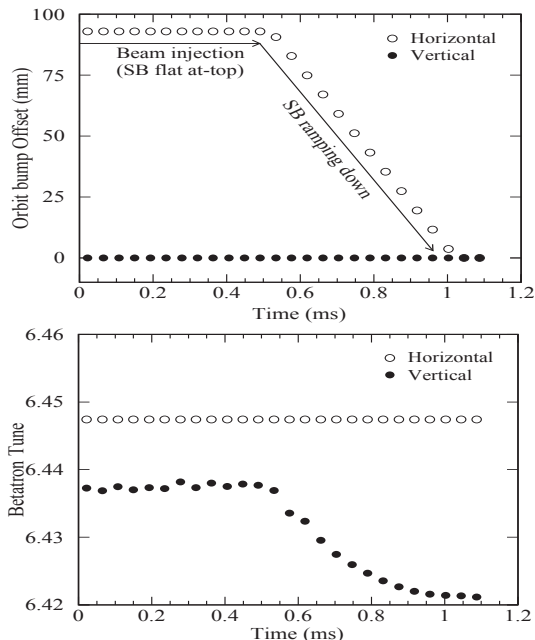


Figure 4: Time dependent edge focusing effect of the chicane bump (SB) successfully introduced in the ORBIT as results are found to expected.

the Lorentz  $\beta$  and also dependence of the impedance itself on  $\beta$ , practically for each turn. We have also succeeded introducing time dependent impedances of the extraction kicker magnets very recently. A systematic beam study has also been done recently with a maximum beam power of 500 kW and the corresponding numerical simulations are in progress.

### SPACE CHARGE SIMULATION

By introducing almost all realistic parameters as discussed above, the ORBIT code is now capable of doing 3-D space charge simulation for the RCS. The longitudinal beam behaviors on rf parameters, mesh size dependence on the number of macro particles have been studied extensively. As a first trial, the numerical simulation for a beam power of 420 kW ( $3.5 \times 10^{13}$  particles per pulse) has been done for the case of parameter ID 8 as defined in Ref. [2]. A correlated transverse painting of  $100\pi$  mm mrad with a full longitudinal painting were applied together. Namely, the second harmonic rf voltage ( $V_2$ ) with 80% to that of fundamental one ( $V_1$ ) and its phase sweep ( $\phi_2$ ) from -100 to 0 degrees were employed, while the momentum offset ( $\Delta p/p$ ) was set to be -0.2%. The second harmonic rf voltage is applied during injection up to 3 ms (see details in Ref. [2]). The number of macro particles were  $2 \times 10^6$  for a mesh size of  $128 \times 128 \times 128$  for the x, y and z directions.

Figure 5 shows a time dependent simulated beam survival (black line) in comparison to that with measurement (red line) by a DCCT (dc current transformer) installed in the ring. The beam survival is normalized to 1 just at the end of accumulation process of first 0.5 ms. The measured

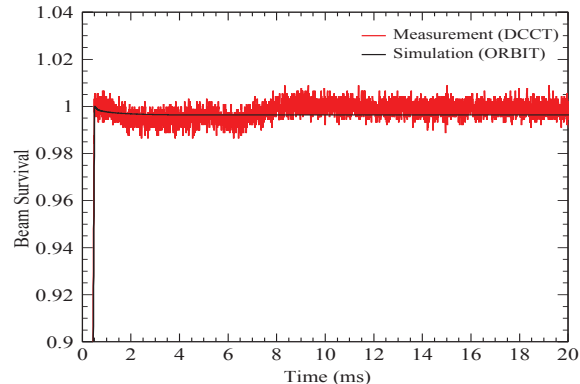


Figure 5: Comparison of the ORBIT beam simulation result with measurement. The simulation well reproduces the measured time dependent beam survival. Beam accumulation process corresponds to first 0.5 ms

data is found to be well reproduced by ORBIT simulation.

### SUMMARY

Significant progresses have been made with ORBIT 3-D particle tracking code by introducing all relevant time dependent parameters for realistic beam simulations in the RCS. An example of the numerical space charge simulation for a beam power of 420 kW is shown and it is found to well reproduce the experimental data. The ORBIT code capabilities are now proved to be much more enhanced for applications to synchrotrons.

### ACKNOWLEDGMENT

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