Improvement of the longitudinal phase space tomography at the J-PARC synchrotrons

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Abstract. The longitudinal phase space tomography, which reconstructs the phase space distribution from the one-dimensional bunch profiles, is used in various accelerators to measure longitudinal beam parameters. At the J-PARC, an implementation of the phase space tomography based on the Convolution Back Projection method (CBP) has been used to measure the momentum spread of the injected beam. The method assumes that the beam distribution rotates without significant deformation during the synchrotron oscillation. Because of the nonlinearity of synchrotron motion with sinusoidal RF voltage, the method can be used only in limited situations such as small amplitude synchrotron oscillation. Algebraic Reconstruction Techniques (ART) in conjunction with particle tracking, which is implemented in the CERN's tomography code, allows accurate reconstructions even for nonlinear large amplitude synchrotron oscillations. We present the overview of the application of the CERN's tomography code to the J-PARC synchrotrons. The results of benchmarking are also reported.

1. INTRODUCTION

Japan Proton Accelerator Research Complex (J-PARC) has two high intensity proton synchrotrons: 3 GeV Rapid Cycling Synchrotron (RCS) and Main Ring (MR). The output beam power of the RCS and MR are 1 MW and 500 kW, respectively. In the J-PARC synchrotrons, the longitudinal phase space tomography, which reconstructs the phase space distribution from the one-dimensional bunch profiles, is performed to measure longitudinal beam parameters.

The tomography code[1] based on the Convolution Back Projection method (CBP)[2] has been used at the J-PARC. The CBP assumes that the beam distribution rotates without significant deformation during the synchrotron oscillation. The actual synchrotron motion with a sinusoidal RF voltage has the nonlinearity as shown in Fig. 1. Furthermore, where the longitudinal space charge effect (SC) affects the longitudinal beam motion, the behavior becomes more complicated. Therefore, the conventional tomography code can be used only in limited situations.

The hybrid algorithm which combines particle tracking with Algebraic Reconstruction Techniques (ART)[3], which is implemented in the CERN's tomography code[4], allows accurate reconstructions even under the condition that the nonlinearity and SC affect the longitudinal beam motion[5]. The introduction of the CERN's tomography enables us to make measurements under new conditions that are difficult to measure with the conventional code. This paper reports on the application of the CERN's tomography to the J-PARC synchrotrons and the results of benchmarking.

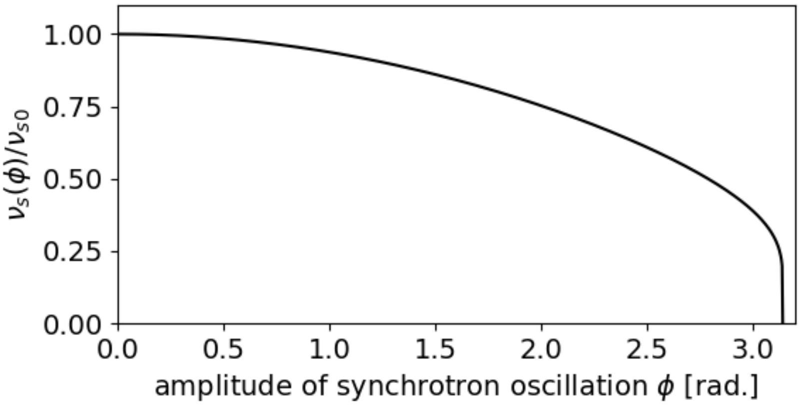

Figure 1. Amplitude dependence of synchrotron tune. ν_{s0} and ν_s are the synchrotron tunes where the amplitude of synchrotron oscillation are zero and ϕ, respectively.

2. Overview of the tomography at the J-PARC synchrotrons

In the J-PARC synchrotrons, the tomography is applied to measure the injection beam. The conditions of tomography measurements in the J-PARC synchrotrons are shown in Table 1.

For the RCS, in the injection process, multi-turn injection for 307 turns, is performed to accumulate 8.3E+13 protons per pulse (ppp) for the beam power of 1 MW. The harmonic number of the RCS is 2, therefore, 614 intermediate pulses are injected into the RCS. The intensity and length of a single intermediate pulse are 1.4E+11 ppb and 440 ns, respectively. The tomography measurement is perfomed at the single intermediate pulse injection. The strength of SC (V_{SC}) of the single intermediate pulse is very low compared to the driving RF voltage (V_{RF}) as shown in Table 1. Therefore, the SC does not affect the longitudinal beam motion. The bunch length corresponds to 50% of the RF bucket length, and the nonlinearity affects the longitudinal beam motion. Hence, the current tomography measurements are performed with the short bunch length (228 ns).

For the MR, the single-turn injection, which repeats four times to inject 8 bunches, is employed. The tomography is applied for a single bunch out of the 8 bunches and its intensity is 3.2E+13 ppb at 500 kW operation. The SC affects the longitudinal beam motion because the ratio of V_{SC}/V_{RF} is not so low of 20%. Therefore, the SC should be considered in the tomography for the MR. The bunch length corresponds to 30% of the RF bucket length. The nonlinearity of the synchrotron motion is not so large compared to the RCS.

3. Validation using the tracking simulation

We performed the longitudinal tracking simulation for each J-PARC synchrotron using the BLonD[6], a longitudinal beam tracking simulation code, and generate one-dimensional bunch profiles. Then, we reconstruct the initial phase space distribution using the CERN's tomography and compare it to the original distribution.

3.1. Validation for RCS

The initial phase space distribution used in the BLonD simulation for the RCS is shown in Fig. 2 (Left). The typical distribution of the injection beam of the RCS is uniform in the

Table 1. The conditions of tomography measurements in the J-PARC synchrotrons.

	RCS	**MR**
Proton Energy	400 MeV	3 GeV
Intensity	1.4E+11 ppb	3.2E+13 ppb
Length (Bunch/RF)	228(440)/815 ns	∼200/598 ns
Z_{SC}	∼270 Ω	∼50 Ω
V_{RF}	120 kV	155 kV
V_{SC}	∼0.4 kV	∼30 kV

longitudinal direction and gaussian in the momentum (dp/p) direction. The bunch length and standard deviation σ in the dp/p direction are set to 440 ns and 0.17 %, respectively.

Figure 2 (Right) shows the evolution of the simulated bunch profile of the RCS up to 90 turns, which corresponds to almost half cycle of the synchrotron oscillation. The interval between each bunch profile corresponds to 3 turns. The number of bins in a single bunch profile is 300 and the bin width corresponds to 2.7 ns.

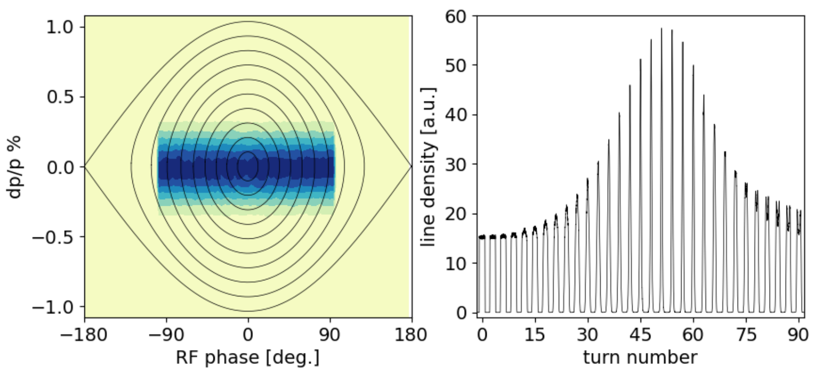

Figure 2. (Left) The initial phase space distribution used in the BLonD simulation for the RCS. (Right) Evolution of the simulated bunch profile of the RCS.

The results of the CERN's tomography using the simulated bunch profile are depicted in Fig. 3 (Left). Thanks to the hybrid algorithm, the reconstructed phase space distribution does not have significant distortion and well reproduces the original distribution. The comparison of the projection in dp/p direction is also depicted in Fig. 3 (Right). σ of the reconstructed dp/p distribution coincides with the original distribution. Thus, we confirm that the CERN's tomography can measure the 440 ns beams used in 1 MW operation of the RCS where the nonlinearity is not negligible.

3.2. Validation for MR

The initial phase space distribution used in the BLonD simulation for the MR is shown in Fig. 4 (Left). The injection beam of the MR can be expressed by the parabolic distribution. The width in the longitudinal and dp/p direction are set to 100 ns and 0.4 %, respectively. The intensity is set to 3.2E+13 ppb. The SC is taken into account in the BLonD simulation.

Figure 4 (Right) shows the evolution of the simulated bunch profile of the MR up to 600 turns, which corresponds to almost one cycle of the synchrotron oscillation. The interval between each

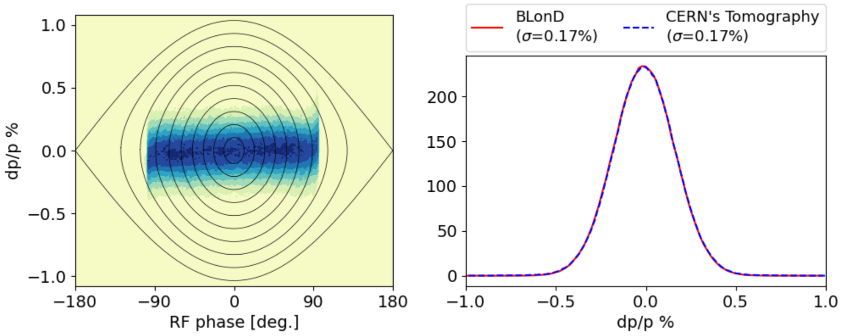

Figure 3. The results of the CERN's tomography for the RCS using the simulated bunch profile. (Left) Reconstructed initial phase space distribution. (Right) The projection in dp/p direction.

bunch profile corresponds to 10 turns. The number of bins in a single bunch profile is 300 and the bin width corresponds to 2.0 ns.

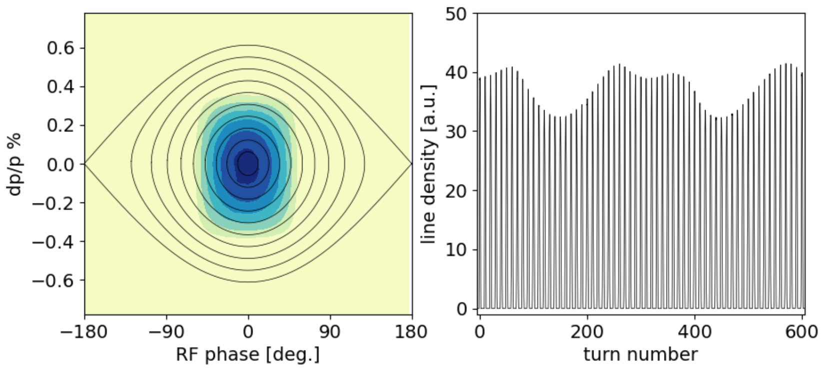

Figure 4. (Left) The initial phase space distribution of the BLonD simulation for the MR. (Right) Evolution of the simulated bunch profile of the MR including the SC.

The results of the CERN's tomography using the simulated bunch profile are depicted in Fig. 5. The tomography is performed in two cases: reconstruction with and without considering the SC. For the reconstruction without considering the SC, the reconstructed phase space distribution has a tilt and the RMS of dp/p distribution is 10% larger than the original distribution. Where V_{SC} can not be ignored, the effective RF voltage experienced by the beam becomes lower than V_{RF}. Hence, the accuracy deteriorates since the tomography is performed based on different bucket heights and synchrotron periods when the SC is not taken into account. The CERN's tomography considering the SC can reproduce the original distribution accurately. Thus, we confirm that the CERN's tomography can measure the high intensity beams used in 500 kW operation of the MR where the SC is not negligible.

4. Benchmarking measurement

The benchmarking of the CERN's tomography using the measured bunch profile data is performed. We compare the results of the CERN's tomography with the conventional code.

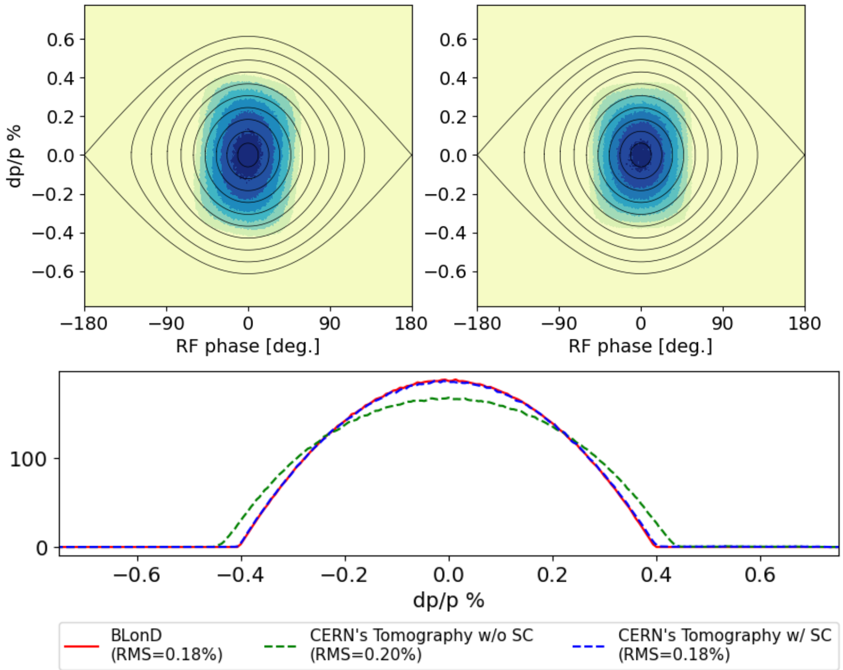

Figure 5. The results of the CERN's tomography using the simulated bunch profile of the MR. (Top left) Initial phase space distribution reconstructed without considering the SC. (Top right) Initial phase space distribution reconstructed considering the SC. (Bottom) The projection in dp/p direction.

4.1. Benchmarking for RCS

The results of tomography using the measured bunch profile of the RCS when the bunch length is 440 ns are shown in Fig. 7. The reconstructed phase space distribution of the conventional code has a distortion due to the nonlinearity. The CERN's tomography is able to reconstruct a proper phase space distribution that does not have distortions. σ of dp/p distribution are 0.15 % and 0.18 % for CERN's tomography and conventional code, respectively. The result of the CERN's tomography is consistent with that of the short pulse beam (228 ns), which has $\sigma = 0.15\%$.

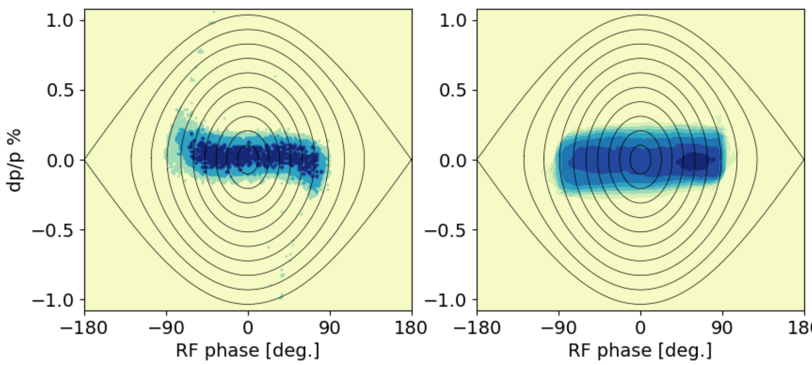

Figure 6. The comparison of the tomography using the measured bunch profile data of the RCS. (Left) Conventional code. (Right) CERN's tomography.

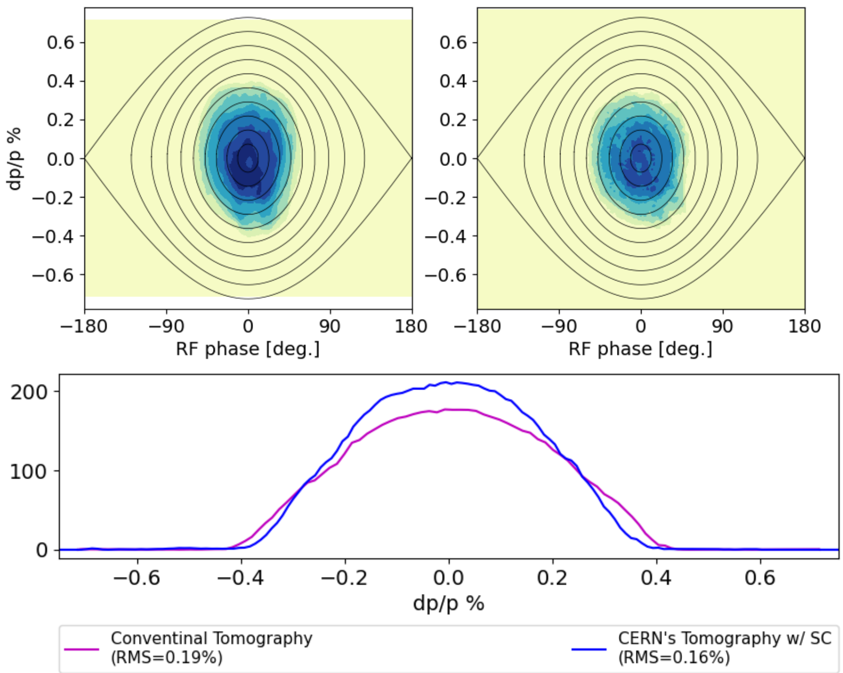

Figure 7. The comparison of the tomography using the measured bunch profile data of the MR 500 kW operation. (Top left) Conventional code. (Top right) CERN's tomography with SC reconstruction. (Bottom) The projection in dp/p direction.

4.2. Benchmarking for MR
The results of tomography using the measured bunch profile of the MR when the beam intensity is 3.2E+13 ppb are shown in Fig. 7. The result of the CERN's tomography has a 10% smaller RMS than conventional codes in dp/p distribution. Recent beam simulation studies have shown that a smaller dp/p distribution can better explain the beam behavior in the MR after the injection. The result of the CERN's tomography is consistent with the tendency.

5. Summary
The benchmarking of the application of CERN's tomography to the J-PARC synchrotrons is performed. The validation using the tracking simulation confirms that the CERN's tomography can accurately reconstruct the phase space distribution under the operating condition of the J-PARC synchrotrons, where the nonlinearity and SC affect the longitudinal beam motion. The results of the benchmarking measurement are reasonable. As an outlook, the tracking code[7] improved at the J-PARC will be implemented in the CERN's tomography to measure the longitudinal beam parameters during multi-harmonic acceleration of the J-PARC synchrotrons.

References
[1] M. Yoshimoto, N. Hayashi, M. Kawase, F. Tamura, M. Yamamoto, and M. Yoshii, "Longitudinal Phase Space Tomography at J-PARC RCS", in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper TH5PFP067, pp. 3358–3360.
[2] A. C. Kak, M. Slaney, *Principles of Computerized Tomographic Imaging*, IEEE Press, 1979.
[3] R. Gordon, "A tutorial on art (algebraic reconstruction techniques)", *IEEE Trans. Nucl. Sci.*, vol. 21, no. 3, pp. 78–93, Jun. 1974. `doi:10.1109/tns.1974.6499238`
[4] Longitudinal Phasespace Tomography `https://tomograp.web.cern.ch/`

[5] S. Hancock, M. Lindroos, and S. Koscielniak, “Longitudinal phase space tomography with space charge”, *Phys. Rev. Spec. Top. Accel Beams*, vol. 3, no. 12, Dec. 12, 2000. `doi:10.1103/physrevstab.3.124202`

[6] CERN Beam Longitudinal Dynamics code BLonD version 2.0.11 `https://blond.web.cern.ch`

[7] H. Okita *et al.*, “Improvement of longitudinal beam tracking simulation considering the frequency response of the cavity gap voltage monitor”, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1041. Elsevier BV, p. 167361, Oct. 2022. `doi: 10.1016/j.nima.2022.167361`