

# PERFORMANCE EVALUATION OF THE INTRA-BUNCH FEEDBACK SYSTEM AT J-PARC MAIN RING

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## Abstract

An intra-bunch feedback system has been developed at J-PARC (Japan Proton Accelerator Complex) Main Ring (MR) for suppression of head-tail motions and reduction of particle losses. This system consists mainly of a BPM, a signal processing circuit (iGp12), power amplifiers, and stripline kickers. These components were fabricated and installed to MR in April of 2014. This system successfully suppressed internal bunch motion caused by injection kicker errors in the 3GeV constant-energy operation. It also achieved a shorter damping time than that by the bunch-by-bunch feedback system, which is currently used in the routine operation. Comparisons with simulations confirm that internal motion is actually suppressed by intra-bunch feedback system.

## INTRODUCTION

The J-PARC is composed of three proton accelerators: the 400MeV linear accelerator (LINAC), the 3 GeV Rapid Cycling Synchrotron (RCS), and the Main Ring (MR) Synchrotron. The main parameters are listed in Table 1. At the J-PARC MR, transverse instabilities have been observed at the injection and during the acceleration. The present narrowband bunch-by-bunch feedback system (BxB FB) is effectively suppressing these transverse dipole oscillations [1]. But the BxB feedback system can damp only the whole bunches, and internal bunch oscillations have been still observed, which is causing additional particle losses [2]. To suppress intra-bunch oscillations, a more wideband and advanced feedback system (named the intra-bunch feedback system) has been developed.

Table 1: Main Parameters of J-PARC Main Ring

Circumference	1568m
Injection Energy	3GeV
Extraction Energy	30GeV
Repetition Period	2.48s
RF Frequency	1.67-1.72 MHz
Number of Bunches	8
Synchrotron Tune	0.002-0.0001
Betatron Tune (Hor./Ver.)	22.41/20.75

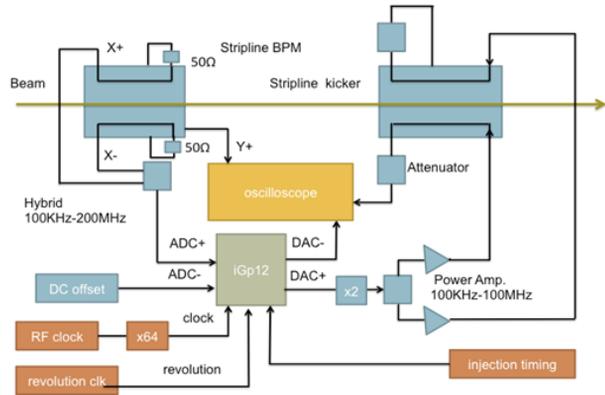


Figure 1: Schematic of the intra-bunch feedback system.

## INTRA-BUNCH FEEDBACK SYSTEM

Figure 1 shows the schematic of the intra-bunch feedback system. It is composed mainly of three components: a BPM (Fig. 2), a signal processing circuit (iGp-12) and kickers (Fig. 3). The signal processing circuit detects betatron oscillation of bunches using signals from the BPM and calculates feedback signals. These feedback signals are sent to the kickers through the power amplifiers.

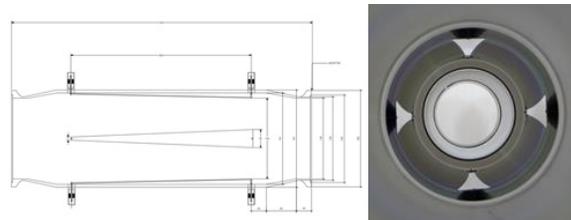


Figure 2: Side (left) and front (right) views of BPM.

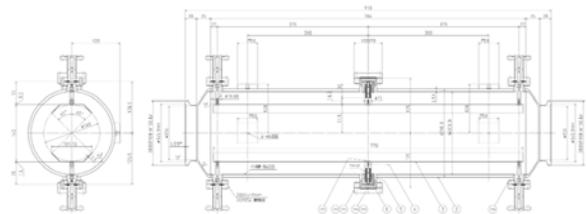


Figure 3: Kicker design.

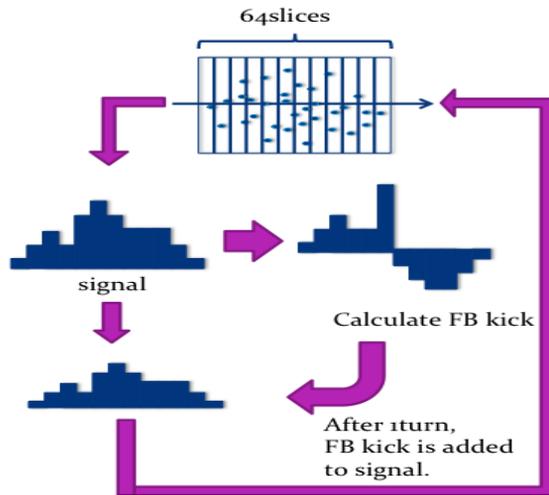


Figure 4: Schematic view of simulation.

## PERFORMANCE TESTS WITH 3 GeV BEAM

We tested the performance of the new feedback system with 3GeV beams. The beam parameters are listed in Table. 2. The results are shown in Figs. 6, 7 and 8. We found that the intra-bunch feedback can damp betatron oscillations faster than the BxB FB system and is quite effective to suppress internal bunch motions [3]. To assess the performance of the feedback system further, we developed a macro particle simulation code and compare its results with measurements.

Table 2: Parameters at the Beam Test

Beam intensity(/pulse)	$2.7 \times 10^{13}$
Number of bunches	1
Bunch width	150ns
chromaticity	+0.5
Twiss parameter : alpha	-0.45896
Twiss parameter : beta	15.5835
Horizontal offset x/x'	0.001/0.0
Initial longitudinal distribution tau/delta	Gaussian/Gaussian

## SIMULATION METHOD

Macro particles of 6400 are used in this simulation. Each RF bucket is divided into 64 slices. Particle positions are calculated turn by turn and put into each slice to make a dipole current signal. From this signal, FB kicks are calculated through the n tap FIR filter (n=4 or 8), and after 1 turn, the kicks are added to the signal (Fig. 4). The equation of motion is given in Eq. (1) - (4). Wake fields, space charge effects and nonlinear effects are not included. The filter coefficients are given in Eq. (5) and (6). In case of BxB FB system, only the peak of BPM signal is used. On the other hand, the intra-bunch FB filters each slice. Here we note that the BxB FB system

uses BPM signal directly, and the peak of “differentiated” signal is used. But in the intra-bunch feedback system, the signal process module integrates the BPM signals before filtering. The same parameters are used as for the beam test.

$$\tau_{n+1} = \tau_n - \frac{\eta}{\beta c} \Delta s \delta_n \quad (1)$$

$$\delta_{n+1} = \delta_n + \frac{\beta c}{\eta} \left( \frac{v_{s0}}{R} \right)^2 \Delta s \tau_{n+1} \quad (2)$$

$$\begin{pmatrix} x_n \\ x'_n \end{pmatrix} = \begin{pmatrix} \cos \mu + \alpha \sin \mu & \beta \sin \mu \\ -\gamma \sin \mu & \cos \mu - \alpha \sin \mu \end{pmatrix} \begin{pmatrix} x_n \\ x'_n \end{pmatrix} \quad (3)$$

$$\mu = 2\pi(v\beta_x + \xi\delta_n) \quad (4)$$

$$b[n] = \sin((n-1)\omega T_s + \Delta\phi) - \Delta \quad (5)$$

$$\Delta = \frac{1}{N_{tap}} \sum_{n=0}^{N_{tap}-1} \sin(n\omega T_s + \Delta\phi) \quad (6)$$

## THE CALACTERISTICS OF FEEDBACK SYTEMS

Figure 5 shows the signals and the mean positions of each slice. Signals are superimposed every turn from the 250th turn. In both the BxB FB and the intra-bunch FB systems, feedback signals are calculated from the dipole moment. Thus, the intra-bunch FB system cannot kick slices at the exterior of the bunch effectively, and as a result, the mean positions at the bunch exterior have larger amplitudes than those at the bunch center.

## OSCILLATION AMPLITUDE

Figure 6 shows the time revolution of center slice of the bunch. The left figures are for experimental results and the right ones are for simulations. It can be clearly seen that the intra-bunch FB system damps oscillations faster than the BxB FB system. This tendency qualitatively agrees with the experiments. The damping time in the simulation is about 100 turns. This also agrees with the experiments. The experimental results when the feedback is off shows damping of signals, indicating the existence of additional damping mechanisms, such as non-linear effects or wake fields. More elaborate simulation models are needed for accurate evaluations. Figure 7 shows the spectrograms of the oscillation amplitudes. They also show good agreements with the experiments.

## INTERNAL MOTIONS

In Fig. 8, the delta signal motions are plotted every 5 turns after the 200th turn from the perturbation kick. In simulations, an artificial offset is added to match with the experiment. Good agreements are seen between the simulations and the experiments. Figure 9 is the waterfall plot of this motion. The delta signals are FFTed for 200 turns and only the amplitudes of betatron frequency (~75kHz) are plotted here for each slice.

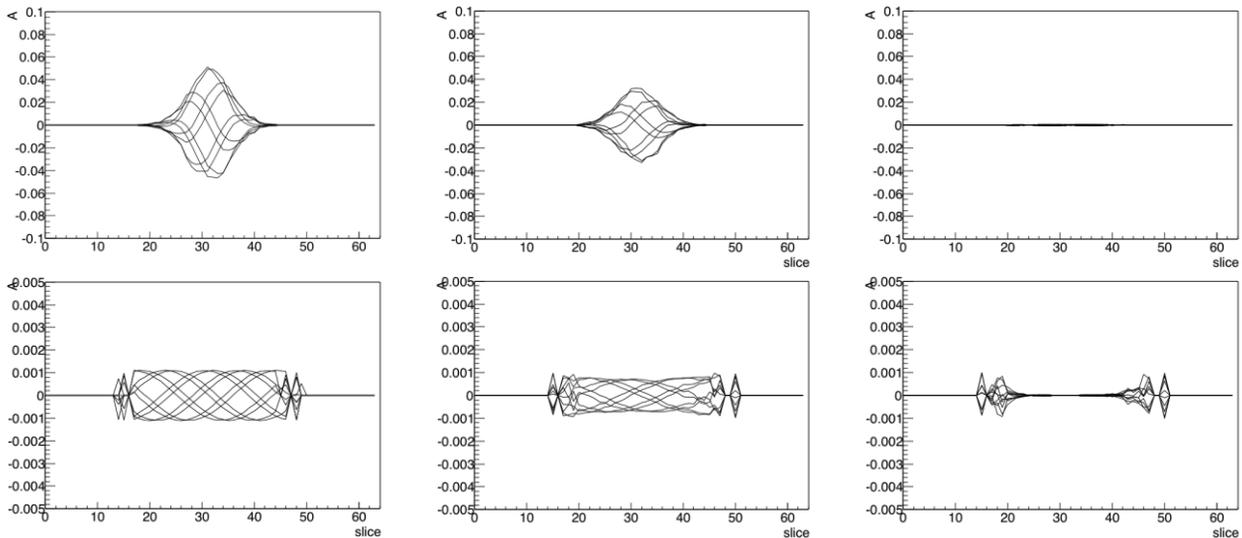


Figure 5: The delta signal motion and the mean position around at the 250th turn. The top figures are for the delta motion (Left: FBs off, Middle: BxB FB on, Right: intra-bunch FB on) and the bottom ones are for the mean positions (Left: FBs off, Middle: BxB FB on, Right: intra-bunch FB on).

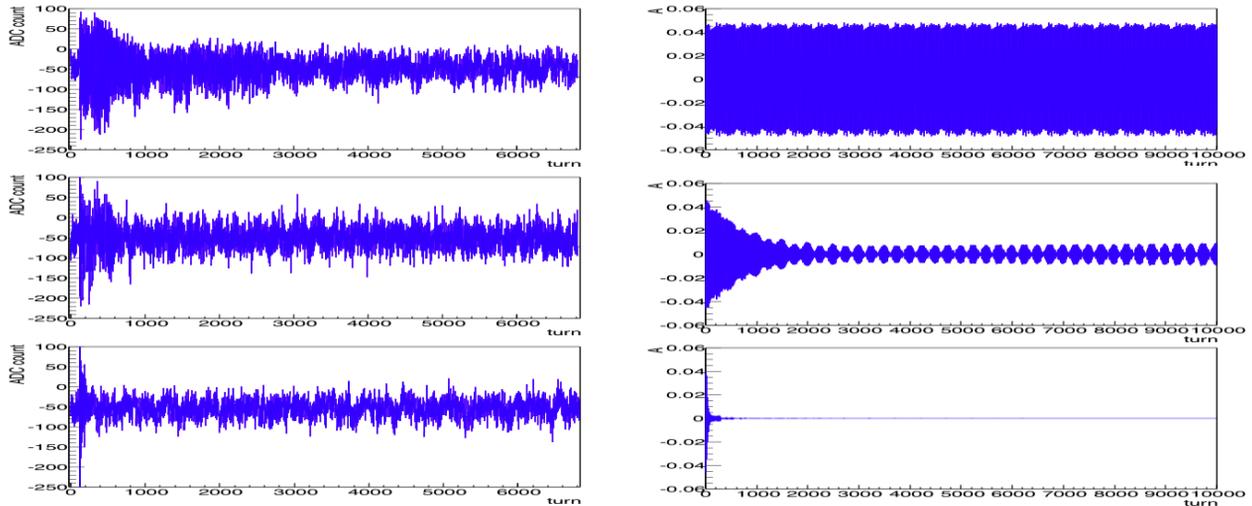


Figure 6: Time evolution of the center slice of the bunch (the 30<sup>th</sup> slice). The left figures are the experimental results (Top: FBs off, Middle: BxB FB on, Bottom: intra-bunch FB on) and the right ones are the simulations (Top: FBs off, Middle: BxB FB on, Bottom: intra-bunch FB on).

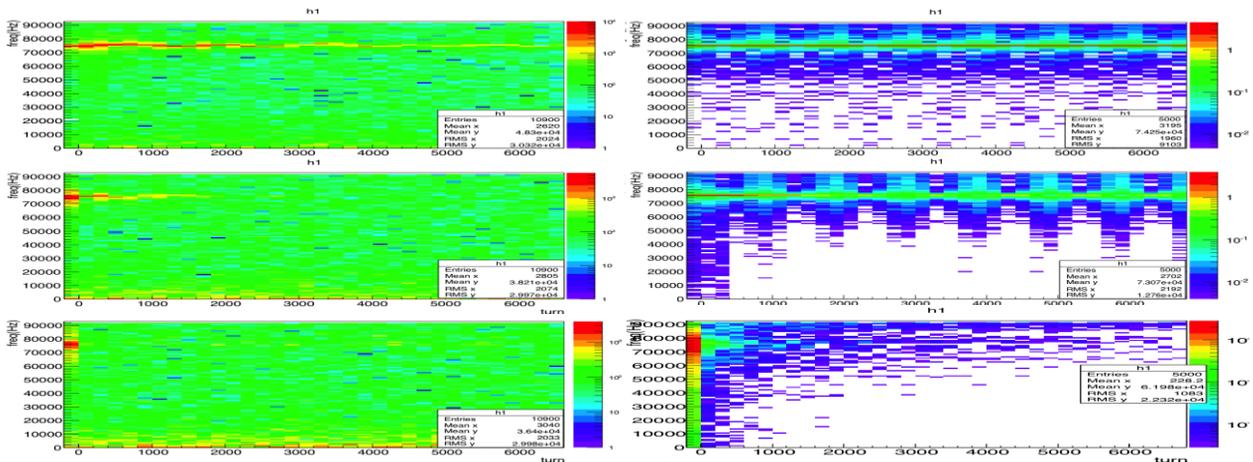


Figure 7 Spectrograms of the center slice of the bunch (the 30<sup>th</sup> slice). The left figures are the experimental results (Top: FBs off, Middle: BxB FB on, Bottom: intra-bunch FB on) and the right ones are the simulations (Top: FBs off, Middle: BxB FB on, Bottom: intra-bunch FB on).

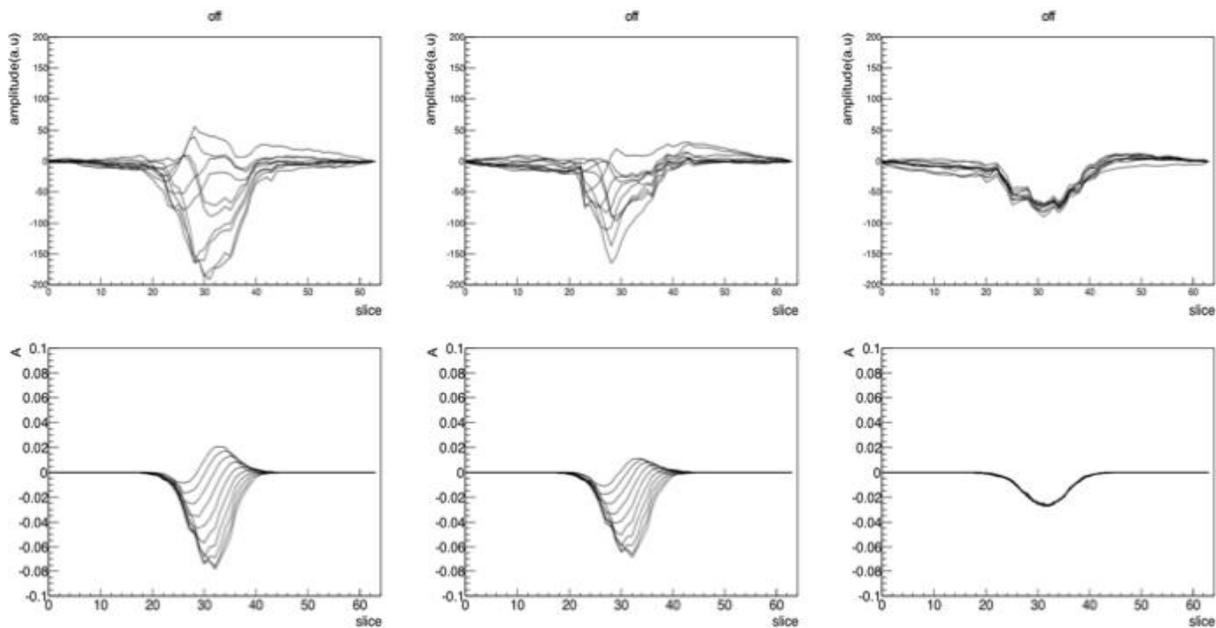


Figure 8: The delta signal motion around 250th turn after a perturbation kick. The top figures are for the experimental results (Left: FBs off, Middle: BxB FB on, Right: intra-bunch FB on) and the bottom ones are for the simulations (Left: FBs off, Middle: BxB FB on, Right: intra-bunch FB on).

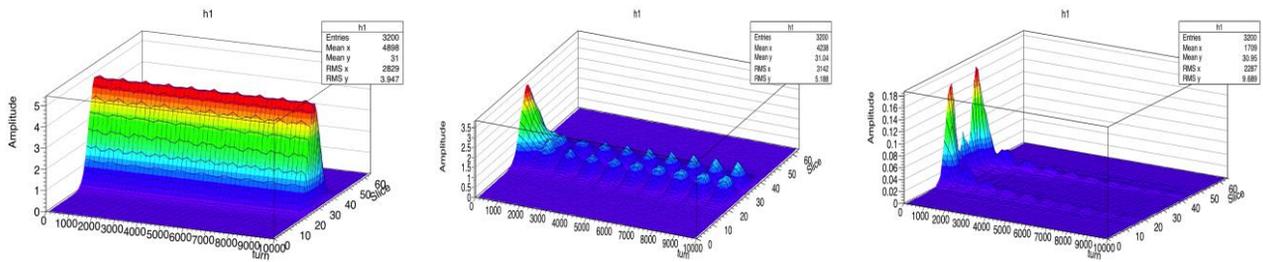


Figure 9: The waterfall plot of simulations (Left: FBs off, Middle: BxB FB on, Right: intra-bunch FB on).

### GAIN AND DAMPING TIME

We tried to search for the maximal gain to damp betatron oscillations. The gain  $2.0 \times 10^{-4}$  is the maximum for the intra-bunch FB system and the gain  $3.125 \times 10^{-6}$  is for the BxB FB system. At those values, the damping time is about 40 turns and 2000 turns for these system respectively for them. Even a larger feedback gain might be available with the intra-bunch FB system.

### SUMMARY

We made very simple simulations, and confirmed that they qualitatively reproduce the experimental results of the intra-bunch FB system. We plan to add more effects

such as wake fields, the space charge and the multi-bunch effects for more accurate evaluations.

### REFERENCES

- [1] Y. Kurimoto, *et al.*, “Bunch by bunch feedback system in J-PARC MR”, DIPAC2011, Hamburg, May 2011, p482, (2011).
- [2] Y. H. Chin, *et al.*, “Analysis of transverse instabilities observed at J-PARC MR and their suppression using feedback systems“ NA-PAC2013, Pasadena, September-October 2013, p.27, (2013).
- [3] K. Nakamura, *et al.*, “Intra-bunch feedback system in The J-PARC Main Ring”, IPAC2014, Germany, June,(2014).