

PERFORMANCE OF TRANSVERSE INTRA-BUNCH FEEDBACK SYSTEM AT J-PARC MR

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Abstract

A new broadband ($\sim 100\text{MHz}$) feedback system has been developed for suppression of intra-bunch oscillations and reduction of particle losses at the J-PARC Main Ring (MR). A new BPM has been designed and fabricated, based on Linnecar's exponential coupler stripline type, for a flatter and wider frequency response. The design and performance of the new BPM as well as preparation of a newly installed exciter and power amplifier is presented. We also report beam test results of suppression of horizontal intra-bunch oscillations at 3 GeV with the bunch length of 150-200 ns. Simple simulations results without wake fields and the space-charge effects qualitatively reproduce the experimental results of the intra-bunch FB 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 during the injection and at the onset of the acceleration. The present narrowband bunch-by-bunch feedback system (BxB FB) is effectively suppressing these transverse dipole oscillations, allowing to attaining the 230 kW beam power [1]. But the BxB feedback system can damp only the center of mass motions of the whole bunches. Even with the BxB feedback system on, internal bunch oscillations have been still observed, which is causing additional particle losses [2]. To suppress intra-bunch oscillations, a more wideband and elaborate feedback system (named the intra-bunch feedback system) has been developed [3].

INTRA-BUNCH FEEDBACK SYSTEM

Figure 1 shows the schematic of the new intra-bunch feedback system. It is composed mainly of three components: a BPM, a signal processing circuit (iGp12) and kickers. It divides each bucket to 64 slices and acts on each slice as if it is a small bunch (bunch-let) in a narrow band feedback system. The signal processing circuit detects betatron oscillation of each bunch slice using signals from the BPM and calculates feedback signals. These feedback signals are sent to the kickers through the power amplifiers. The new system and its set-up are similar to those of the current BxB feedback system. The main improvement is that each component now has a (64 times) wider frequency sensitivity than the one for the

BxB feedback system. The intra-bunch feedback system has been installed at the D3 building, while the current BxB feedback system is still operational at the D1 building.

Table 1: Main Parameters of J-PARC Main

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

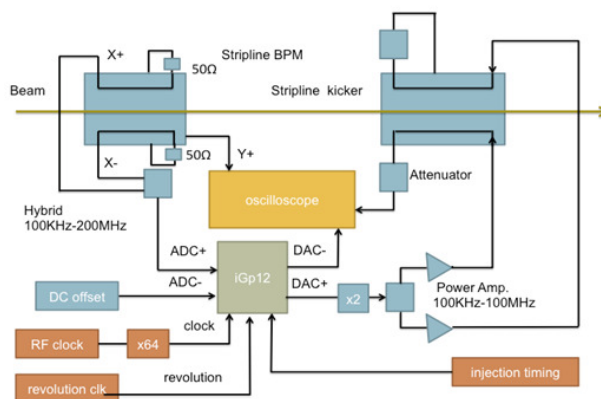


Figure 1: Schematic of the intra-bunch feedback system.

BPM

The new stripline BPM has been designed and fabricated based on Linnecar's electrode design [4] (see Fig. 2). It is equipped with the exponentially tapered electrodes which, in principle, allow a flatter and wider frequency response (the green line in Fig.3) than the conventional rectangular ones (the blue line in Fig.3). The diameter of the beam pipe is 147mm, and the length of the electrodes is 300mm. The electrodes are placed 67mm from the center of the beam pipe. The height of the electrodes from the chamber surface needs to be gradually reduced (proportional to its width) toward their tips for the impedance matching. The BPM characteristics were measured by the stretched wire method. The measured frequency response is shown by the red line in Fig. 3. It can be seen that the new BPM has a good frequency response up to 1GHz. The position sensitivity is also measured and it is found to be fluctuating around 0.027 by 0.002.

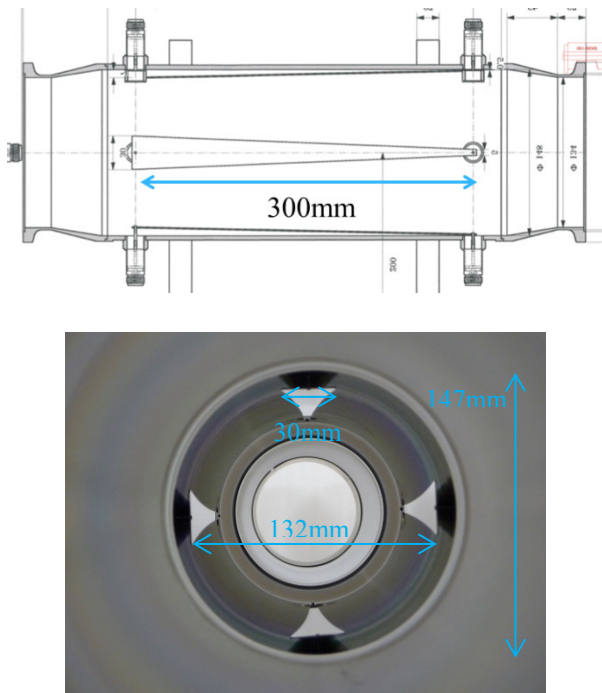


Figure 2: Side (top) and front (bottom) views of BPM.

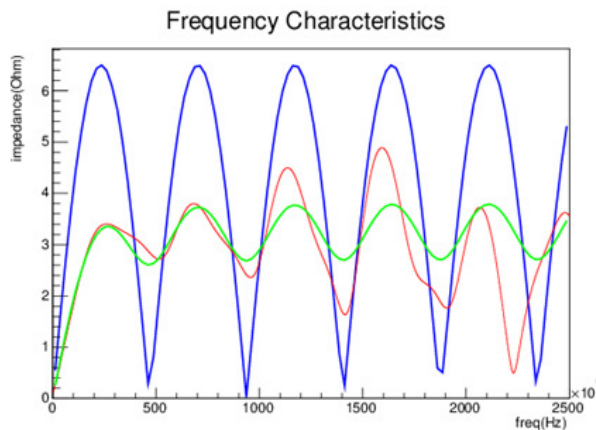


Figure 3: Theoretical and measured frequency responses of BPMs.

Stripline Kickers and Power Amplifiers

The new stripline kickers were also fabricated (see Fig. 4). The electrodes are 750mm long and they are put on the circle of the diameter 140mm. They are coated with the Diamond Like Carbon (DLC) to suppress the multipactoring effect, which may be serious when the kickers are used for slow extraction. The power amplifiers have 3kW capability. Their bandwidth is 100kHz-100MHz, which limits the bandwidth of the whole system now. The kick angle at 3 GeV when used with the two 3kW amplifiers is estimated to be 3.5 μ rad at DC.

Signal Processing by iGp12

We adopt the iGp12 signal processing module developed by Dimtel Inc. [5]. It samples BPM signals (through the hybrid coupler) at the rate of 64th harmonic

of the RF frequency (~100MHz). It divides each RF bucket into 64 bins (slices). It extracts betatron oscillation signals by using the n-tap FIR ($n \leq 16$, $n=8$ is used) filter on each slice, and feedbacks kick signals to each slice. As seen in Fig.3, the frequency characteristic of the BPM is approximately linear in the low frequency region (up to 200MHz). Thus, the beam position can be reconstructed by integrating the differentiated signals from the BPM.

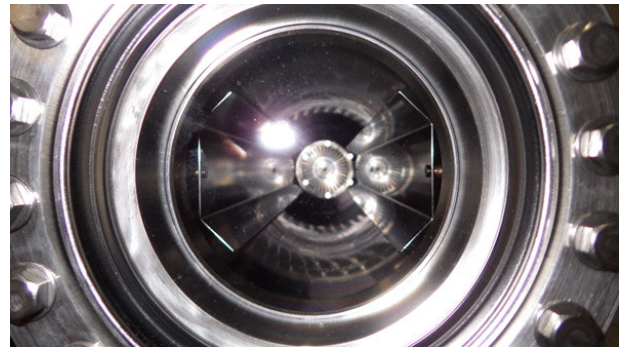


Figure 4: The front view of the horizontal stripline kicker.

BEAM TESTS AT 3 G V DC MODE

Beam Conditions

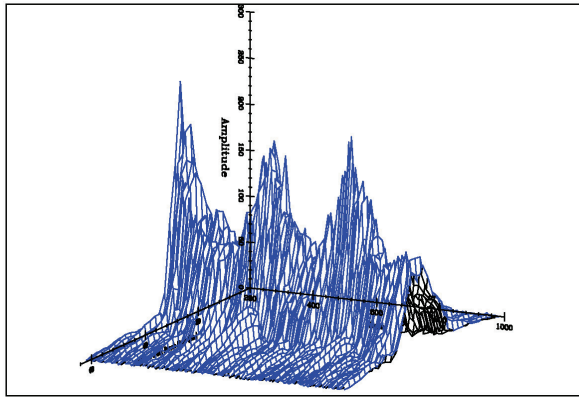
The first beam test was done in May 2014 with a single bunch of 2.7×10^{12} ppp at the energy of 3GeV. This beam intensity is 1/5 of the maximum intensity of MR at present. The main beam parameters are as follows: the bunch length is 150-200ns, the chromaticities are $\xi_x = +0.5$ and $\xi_y = +1.2$, and the synchrotron tune is $\nu_s = 1.7 \times 10^{-3}$. First, we applied the intra-bunch feedback system to the horizontal oscillations at the injection, while the vertical BxB FB system is always turned on (when it is tuned off, a large amount of particle losses prevents the testing).

Reduction of Horizontal Oscillations

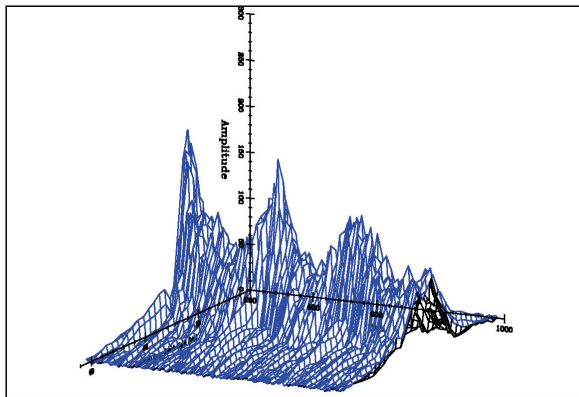
Figure 5 shows the 3-D view of the time evolutions of the oscillation amplitude of the horizontal dipole moment in the following three conditions: (top) both the intra-bunch and the BxB FB systems are off, (middle) only the BxB FB system is on, and (bottom) only the intra-bunch FB system is on. The X-and Y-axes show the oscillation amplitudes of the bunch-slices and the revolution turn, respectively. The large horizontal oscillations are excited around the 262th turn due to the mismatching field of the injection kicker magnets. The horizontal oscillation decays even without the feedback systems, indicating that it is not instability. It can be clearly seen that the intra-bunch FB system damps the horizontal oscillations much quicker than the BxB FB system.

The slow change of the dipole moment amplitude (300 turns) is due to the change in the longitudinal profile of the bunch, not the horizontal oscillation amplitude itself. A possible cause of this longitudinal profile change is a quadrupole oscillation of the bunch in the longitudinal phase space due to mismatching between the bunch and the bucket shapes.

Title: RUN54_2014-05-07-13-36-33 3GeV DC H:BxB Off IB Off, V:BxB On



Title: RUN54_2014-05-07-14-27-45 3GeV DC H:BxB On IB Off, V:BxB On



Title: RUN54_2014-05-07-14-10-10 3GeV DC H:BxB Off IB On, V:BxB On

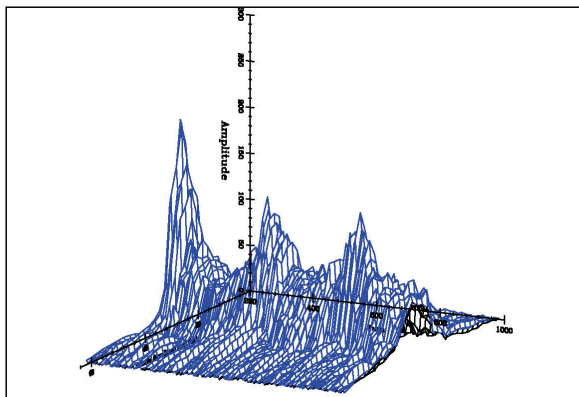


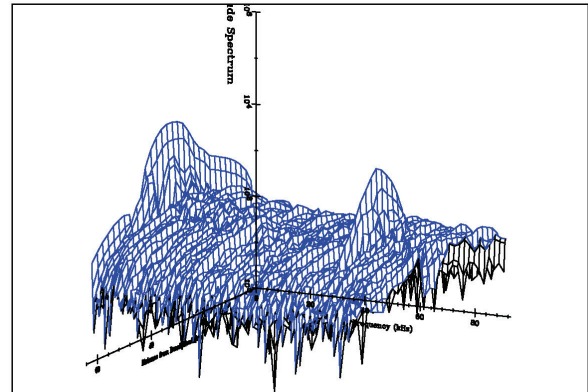
Figure 5: Time evolutions of the horizontal dipole moment after excited at 262th turn. (Top) Both the intra-bunch and BxB FB systems are off. (Middle) Only the BxB FB system is on. (Bottom) Only the intra-bunch FB system is on.

Figure 6 shows Fourier transforms of the horizontal oscillations of the bunch slices shown in Fig. 5: (top) all FB systems off, (middle) only BxB FB system on, and (bottom) the only intra-bunch FB system on. The Y-axis is the frequency. Even when the BxB FB system is on, the betatron sidebands are clearly visible at around 76kHz. But, they disappear when the intra-bunch FB system is turned on.

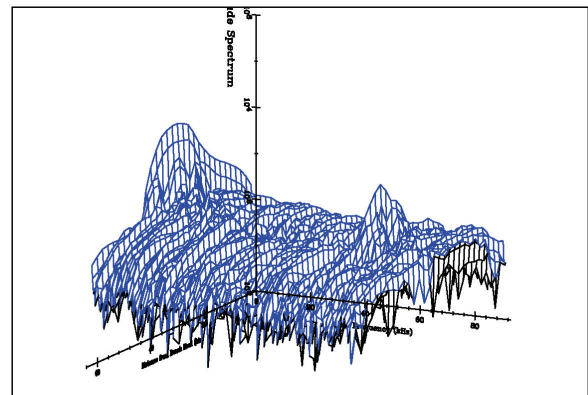
Figure 7 shows the evolution of the bunch signals at every 100 turns after the large perturbation at the 262th turn. In each plot, signals are superimposed on 10

consecutive turns. It can be seen in the bottom figure that the intra-bunch oscillations are almost completely damped by the intra-bunch FB system after the first 100 turns.

Title: RUN54_2014-05-07-13-36-33 3GeV DC H:BxB Off IB Off, V:BxB On



Title: RUN54_2014-05-07-14-27-45 3GeV DC H:BxB On IB Off, V:BxB On



Title: RUN54_2014-05-07-14-10-10 3GeV DC H:BxB Off IB On, V:BxB On

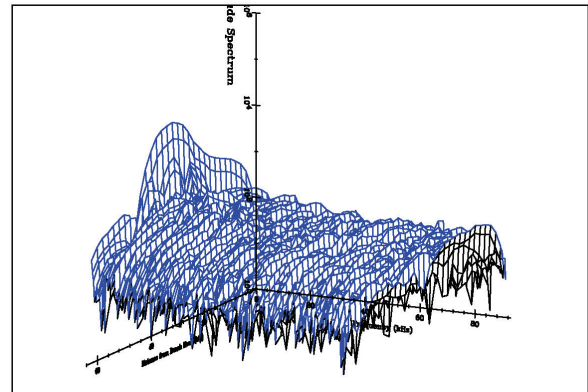


Figure 6: FFT of horizontal dipole moment amplitude.

SIMULATIONS

We made very simple simulations to see if they can qualitatively reproduce the experimental results of the intra-bunch FB system. Macro particles of 6400 are used. Wake fields, space charge effects and nonlinear effects are not included in these simulations. We plan to add more effects such as wake fields, the space charge and the multi-bunch effects for more accurate evaluations in future.

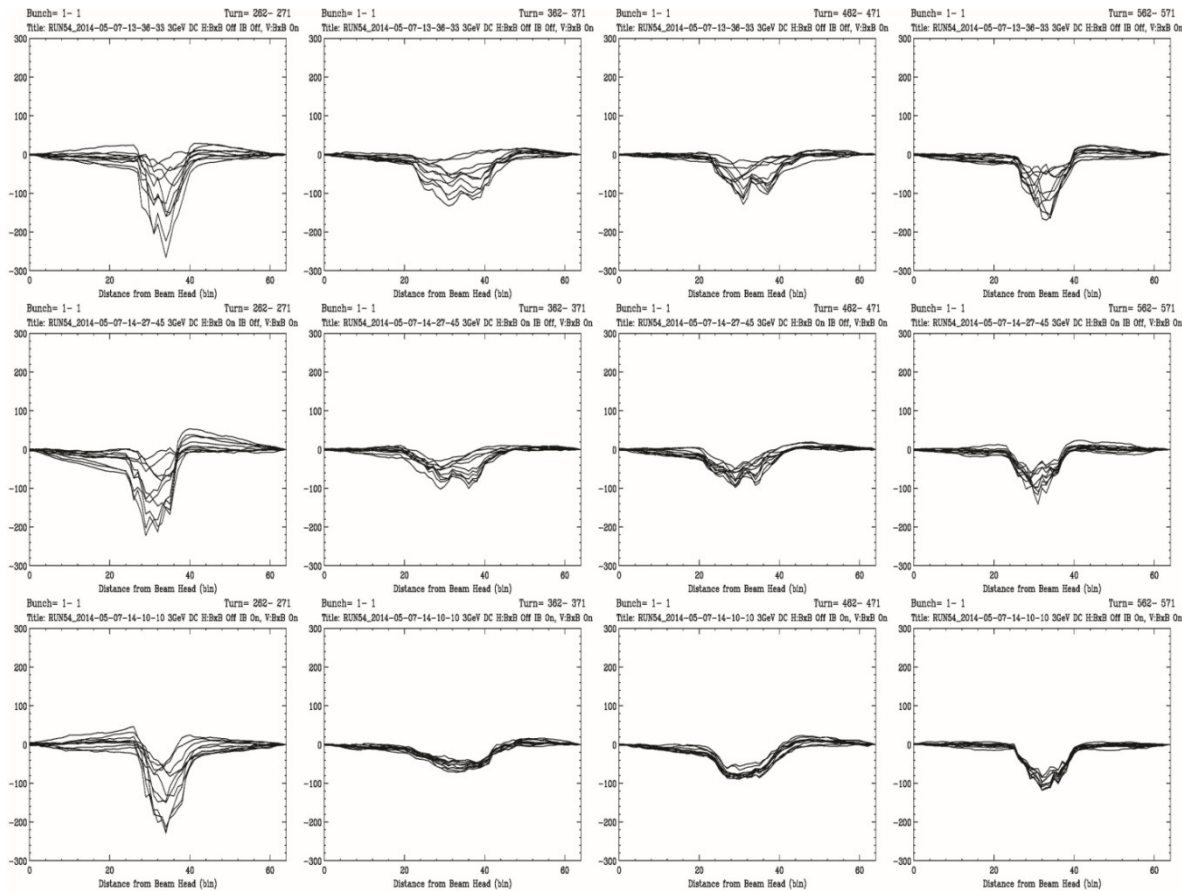


Figure 7: Time evolution of the bunch signals at every 100 turns after the large perturbation at the 262th turn. In each plot, signals are superimposed on 10 consecutive turns. (Top) Both the intra-bunch and the BxB FB systems are off. (Middle) Only the BxB FB system is on. (Bottom) Only the intra-bunch FB system is on. The 1st row corresponds to 262th turn, the 2nd row to 362th turn, the 3rd row to 462th turn, and the 4th row to 562th turn, respectively.

Figure 8 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. At the maximum gain configuration, the damping time is about 2000 turns and 40 turns when only the BxB FB is on and when only the intra-bunch FB is on, respectively. The experimental results when both the feedback systems are turned 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.

INTERNAL MOTIONS

In Fig. 9, the delta signal motions are plotted every 5 turns after the 200th turn from the perturbation kick. In simulations, arbitrary offsets are added to match with the initial perturbations of the experiment. Good qualitative agreements are seen between the simulations and the experiments.

CONCLUSIONS

The first beam test successfully demonstrates that the new intra-bunch FB system is quite effective to suppress intra-bunch oscillations. Simple simulation results without wake fields nor the space-charge effects qualitatively reproduce the experimental results of the intra-bunch FB system. However, the horizontal oscillations presented in this paper are merely incoherent oscillations caused by the kicker mismatching field. More serious instabilities and resulting particle losses are observed on the vertical plane during the injection and at the onset of acceleration (when $\xi_y = -0.3$). They can be, however, suppressed by setting the vertical chromaticity to $\xi_y = -3.2$, although a smaller (slightly negative) vertical chromaticity is preferable for operational purposes. Preliminary beam tests on the vertical instabilities suggest that the new intra-bunch feedback system helps in stabilizing the beam against occasional bursts of large particle losses. More testing and tuning of the system are under way. The intra-bunch FB system is now used in routine operation at J-PARC MR. The beam loss at the injection is reduced from 350W to 170W.

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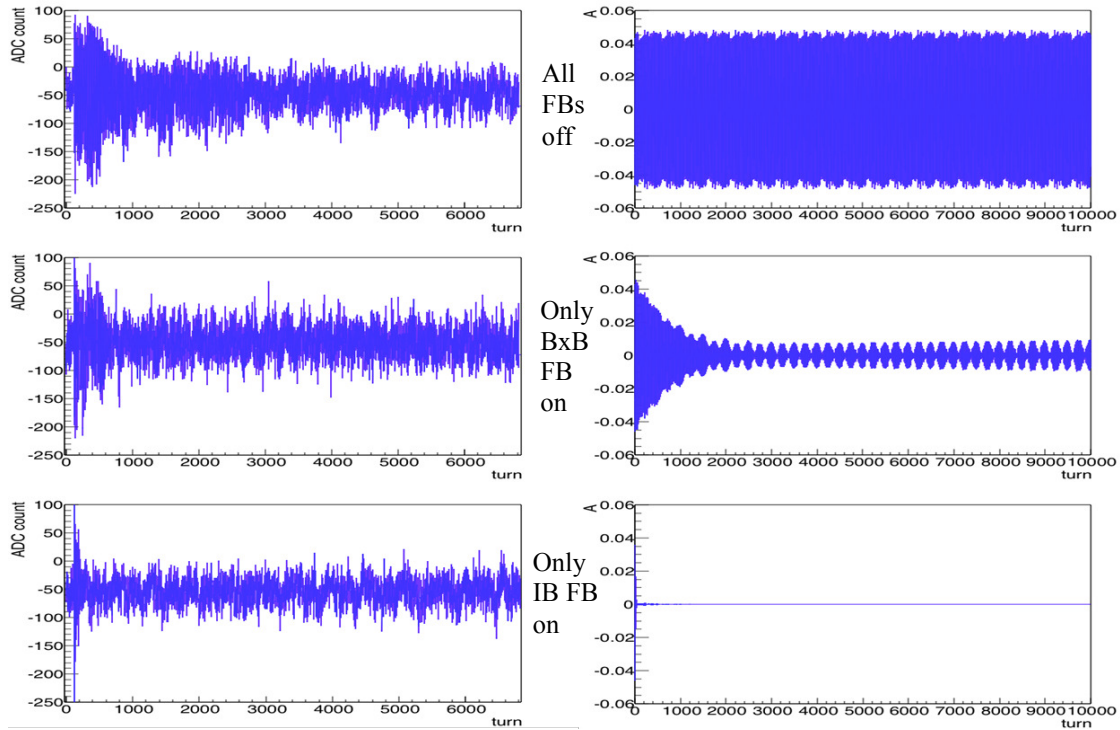


Figure 8: Time evolution of the center slice of the bunch (the 30th slice). The left figures are the experimental results (Top: all FBs off, Middle: only BxB FB on, Bottom: only intra-bunch FB on) and the right ones are the simulations (Top: all FBs off, Middle: only BxB FB on, Bottom: only intra-bunch FB on).

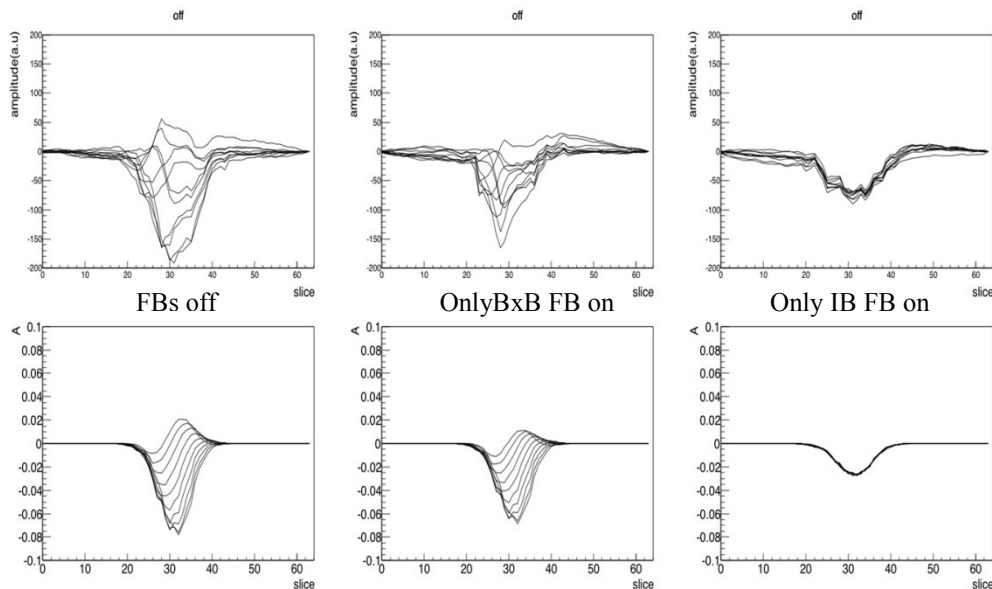


Figure 9: The delta signal motion around 250th turn after a perturbation kick. The top figures are for the experimental results (Left: all FBs off, Middle: only BxB FB on, Right: only intra-bunch FB on) and the bottom ones are for the simulations (Left: all FBs off, Middle: only BxB FB on, Right: only intra-bunch FB on).

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