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BEAM INSTABILITY ISSUE AND TRANSVERSE FEEDBACK SYSTEM IN THE MR OF J-PARC*

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Abstract

In the J-PARC MR, according to the beam power upgrade over 100 kW, beam losses due to transverse collective beam instabilities had started to appear. We had introduced "bunch-by-bunch feedback" system in 2010. Continuing beam power upgrade over 250 kW again caused the transverse instabilities. We introduced "intra-bunch feedback" system in 2014. This has been suppressing those instabilities very effectively. But further beam power upgrade over 500 kW (2.6E+14 ppp, 8 bunches) needs upgrade of "intra-bunch feedback" system. The current understanding of the transverse instabilities in the MR and the effect of the feedback system are presented from the view points of simplified simulation without the space charge effect and measurements. We are upgrading the system in two steps. The first step is "time-interleaved sampling and kicking" with two feedback systems. The second step is getting the sampling rate twice as much as the current rate, ~110 MHz. Details are explained using simulation.

INTRODUCTION

Figure 1 is the layout of the accelerators in J-PARC. The Main Ring (MR) accelerates 8 proton bunches from 3 GeV to 30 GeV [1]. Figure 2 shows beam power history from January 2010 to April 2021. We have two acceleration modes, a slow extraction mode and a fast extraction mode. In the slow extraction mode (Fig. 3, [2]), the beam power is about 64 kW, the beam intensity is 7E+13 protons in a current MR cycling time 5.2 seconds. In the fast extraction mode (Fig. 4), the beam power is about 500 kW, the beam intensity is 2.6E+14 protons in a current MR cycling time 2.48 seconds.

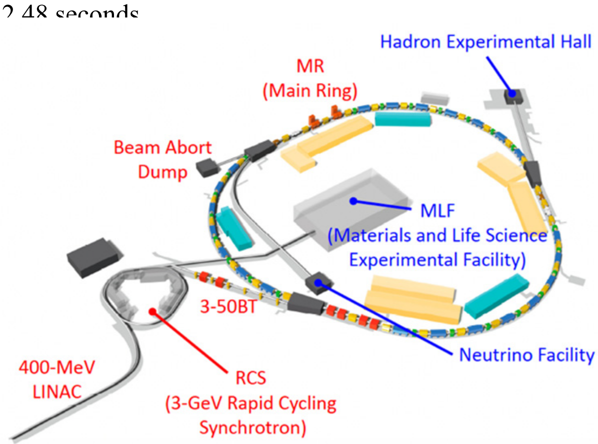

Figure 1: Schematic layout of J-PARC accelerators and experimental facilities.

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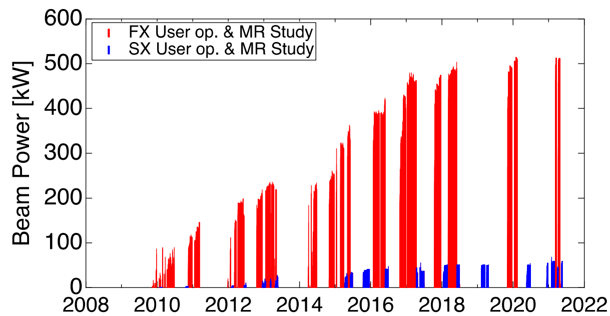

Figure 2: Beam power history of the MR.

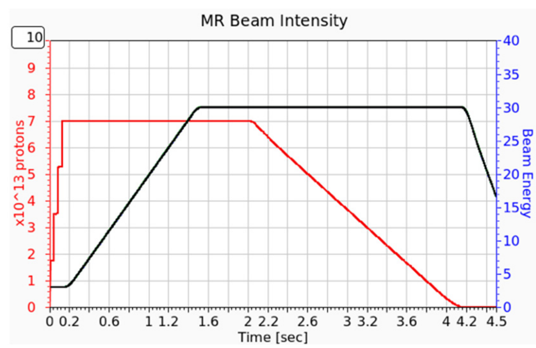

Figure 3: Slow extraction.

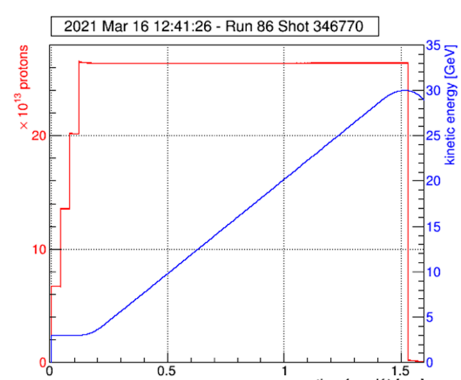

Figure 4: Fast extraction.

PRESENT OBSERVATIONS IN THE MR

SX Mode

In the SX mode, a bunch-by-bunch feedback system is sufficient to suppress instabilities. Limiting factor to increase the SX beam power is the beam instabilities in debunching process at the 30 GeV flat top [2]. In debunching process at the 30 GeV flat top, longitudinal microwave instability occurs, then electron cloud build-up, transverse

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instability, vacuum pressure-rise and beam loss occur at the same time.

The example of an electron cloud event and related topics are also presented by Tomizawa [2] in this workshop. Causality of the phenomena, i.e. the electron cloud build-up and transverse instability, are not yet clear because there are a few events without electron cloud signal. The beam power is set as high as possible with several countermeasure, such as RF manipulations. Current operation is a result of compromise between user requirement for higher beam power and effectiveness of the countermeasure.

FX Mode

In the FX mode, transverse (horizontal/vertical) intra-bunch feedback system is an essential ingredient. Another essential ingredient is horizontal and vertical chromaticities. Figure 5 shows the operating point and estimated incoherent tune spread [1].

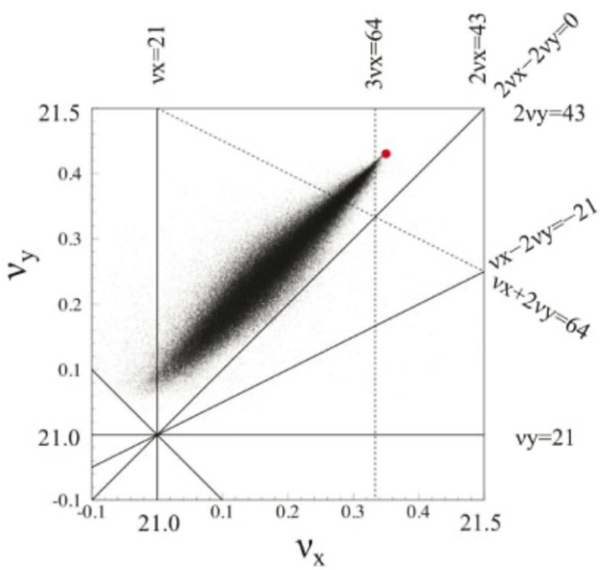

Figure 5: Incoherent tune spread in the MR.

TRANSVERSE INTRA-BUNCH FEEDBACK

Figure 6 is the block diagram of the intra-bunch feedback system in the J-PARC MR [3]. The signal detected with the stripline BPM is fed to the iGp12H [4], a processing circuit, then amplified and fed to the kicker. The system bandwidth is determined by the processing clock of 64 multiple of the RF frequency, that is, 107 – 110 MHz. Simplified signal flow is shown in Fig. 7. Beam bunch is coloured with black. The intra-bunch position is sampled with the processing clock, filtered with FPGA, amplified, then fed to the corresponding position in the bunch, but one-turns later. The four-turns signals are processed at each feedback cycle.

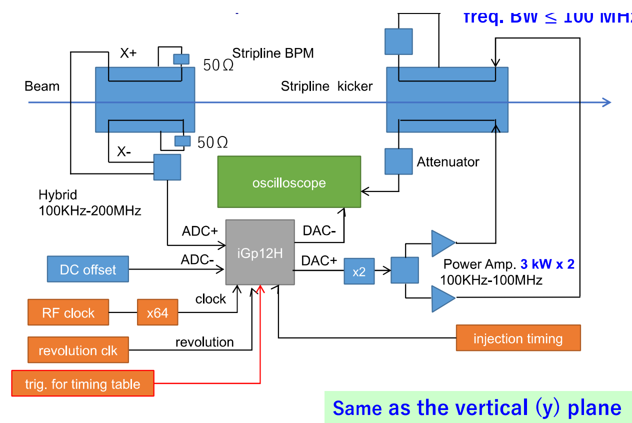

Figure 6: Block diagram of the transverse intra-bunch feedback system in the J-PARC MR.

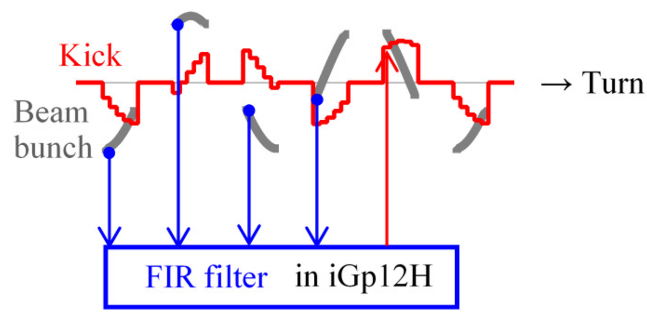

Figure 7: Simplified signal flow. Signal flow from blue dots to a red arrow tip is one feedback loop. This kind of process is performed in each bunch slice.

STABILITY OF THE MR BEAM

Using this feedback system, several dedicated beam experiments were performed. We can store the bunches with the transverse intra-bunch feedback on and keep them stable without instabilities. When we switched off the feedback of a desired plane at a desired timing, the beam becomes unstable.

Vertical Instability

Examples are shown as spectrograms of transverse oscillation in Figs. 8 and 9. Single bunch case is in Figs. 8 and 3 bunches case in Fig. 9. Chromaticities are nearly zero. Precise values are $\nu_x = \Delta\nu_x / (\Delta p/p) = 0.56$ and $\nu_y = -0.37$. The feedback is switched off at the timing indicated by dashed lines in the figures. First unstable motion occurred in the vertical plane.

We examined the effect of space charge with changing the bunching factor from 0.3 to 0.17. The results (Figs. 10 and 11) are that a beam with smaller bunching factor, i.e. larger peak current case, is more stable.

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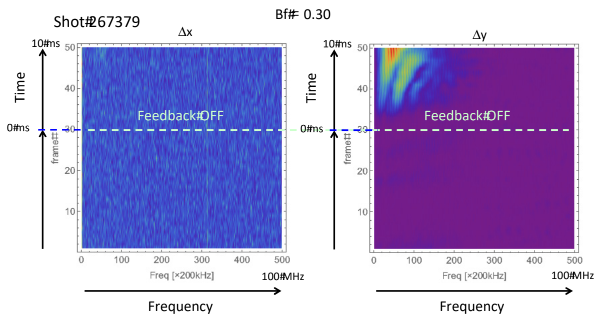

Figure 8: Stability of the single bunch with the number of protons, 7e+12.

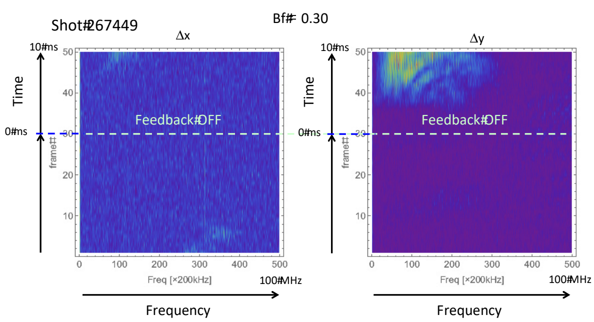

Figure 9: Stability of the three bunches stored symmetrically in the MR with the total number of protons, 2.8e+13.

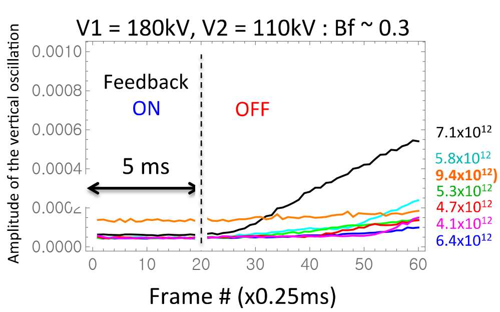

Figure 10: Vertical instability with single bunch, $B_f \sim 0.3$.

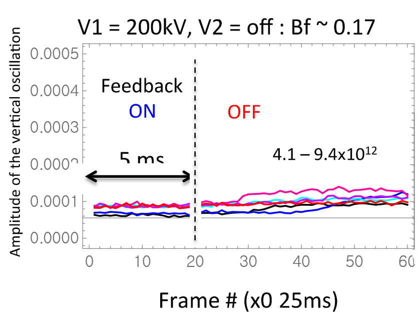

Figure 11: Vertical instability with single bunch, $B_f \sim 0.17$.

Closer look into the intra-bunch motion shows at the larger bunching factor 0.3, the mode seems 1, and growing steadily (Fig. 12). On the other hand, at the smaller bunching factor 0.17, the mode seems higher, and the instability grows and damps (Fig. 13).

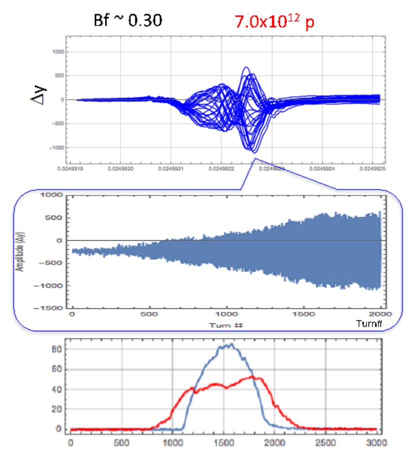

Figure 12: Intra-bunch motion with $B_f \sim 0.3$. Top plot shows an overlap of vertical intra-bunch position signals. Middle plot shows the growth of the maximum amplitude timing. Bottom plot shows longitudinal bunch profiles at injection (indigo line) and equilibrium (red line).

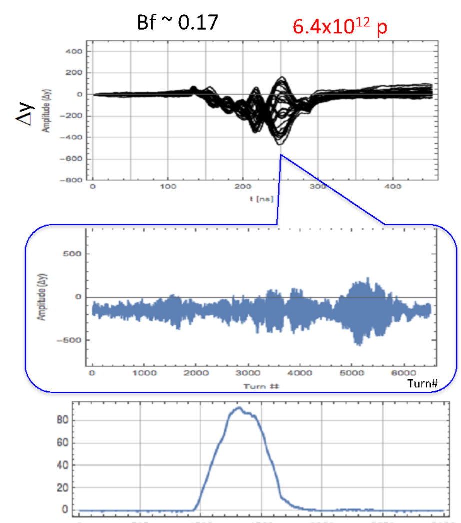

Figure 13: Intra-bunch motion with $B_f \sim 0.17$. The meaning of the plots is the same as Fig. 12.

With three bunches stored symmetrically in the ring, same tendency was observed. The growth rate with $B_f \sim 0.3$ increases as the bunch intensity gets larger as shown in Fig. 14. When $B_f \sim 0.17$, the beam is stable even at the highest intensity in the case of $B_f \sim 0.3$ (Fig. 15).

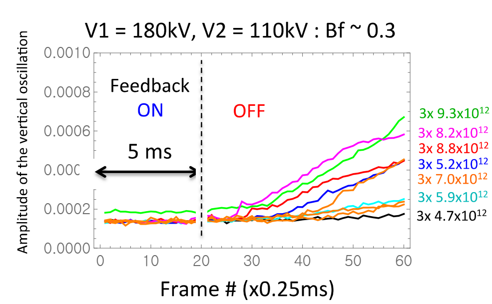

Figure 14: Vertical instability with 3 bunches, $B_f \sim 0.3$.

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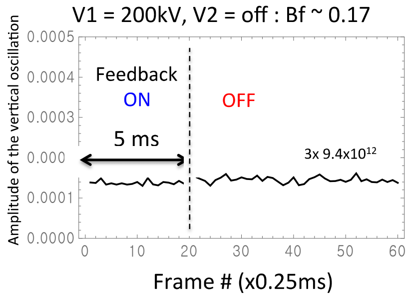

Figure 15: Vertical instability with 3 bunches, $B_f \sim 0.17$.

Chromaticity effects is summarized in [5]. The internal oscillation mode is 0 in a slightly positive chromaticity, while in a slightly negative chromaticity, the mode is more than 1, as the theory predicts. In a positive chromaticity clear coupled bunch oscillation was observed.

Horizontal Instability

With the parameters of a routine operation of 500 kW beam power, we measured growth rates at several intensities, with switching only the horizontal feedback off after 8 bunches were stored in the MR. After feedback is switched off, the horizontal instability occurs (Fig. 16), then the beam touches the vacuum chamber, and beam loss occurs (Fig. 17). The aim was rather getting practical information for the operation.

The result is plotted in Fig. 18 with blue dots and dashed line. The maximum growth rate in the case of nearly full corrected chromaticity is indicated with red dushed line. The growth rate scatters even at the same intensity. The reason is not yet clear. The present operation is at almost a limit of feedback ability, that is, with any optimization attempts almost no stable operation has been achieved at higher beam power. Damping ability should be strengthened almost 50 % more to reach the beam power of 1.3 MW.

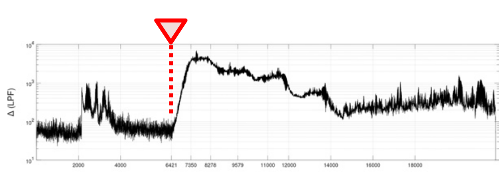

Figure 16: Example of the growth rate. Indicated with the red dashed line.

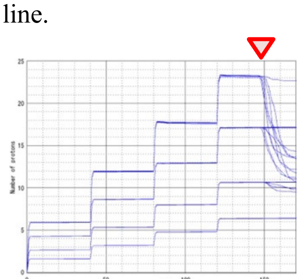

Figure 17: Beam intensity variation. Several shots are overlapped. At the timing indicated with the red triangle beam losses start. Growth rates are estimated using data before this loss timing.

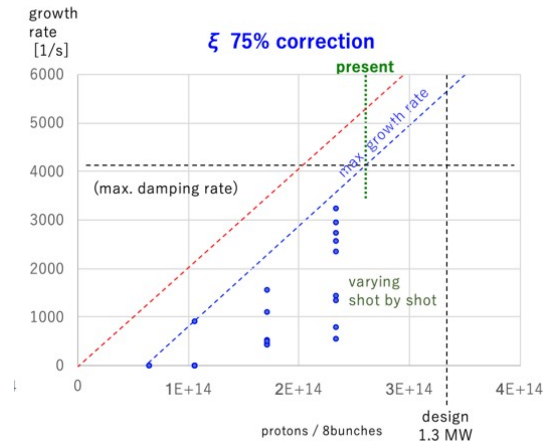

Figure 18: Growth rates with 8 bunches. A red dashed line indicates maximum growth rates with about ten shots in the case of 95% chromaticity correction. Blue dots and dashed lines indicate in the case of 75% chromaticity correction.

SIMULATION

We simulated the instability discretizing with a triangular distribution [6]. Plots in Fig. 19 are wake potentials of the resistive wall (a left plot) and the FX kickers (a right plot). Main purpose of this simulation is examining the stability of the feedback system.

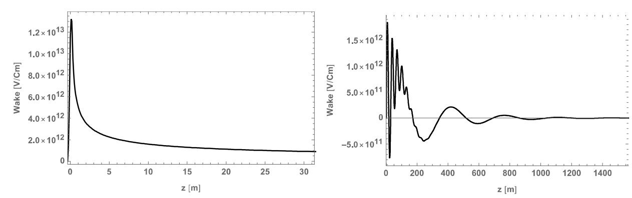

Figure 19: Wake potentials used in the simulation.

Figure 20 is an example of the simulation at the chromaticity -1. The simulation starts with uniform dipole injection error. This mode is stabilized, then mode 1 intra-bunch motion occurs.

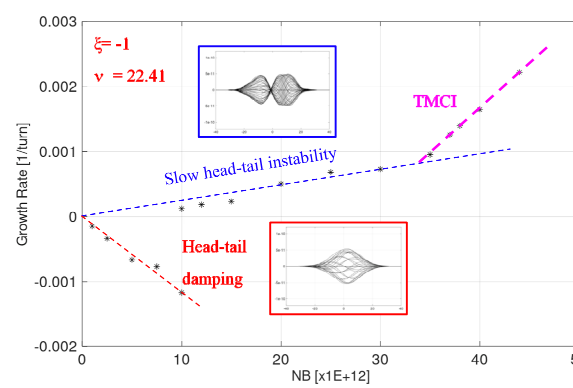

Figure 20: Simulated instability.

With several rates of processing clock, beam stabilities are calculated with the intra-bunch feedback. In this case the chromaticity was set to zero. Raising the rates of the processing clock makes the beam more stable (Fig. 21). This direction is the goal of upgrade plans.

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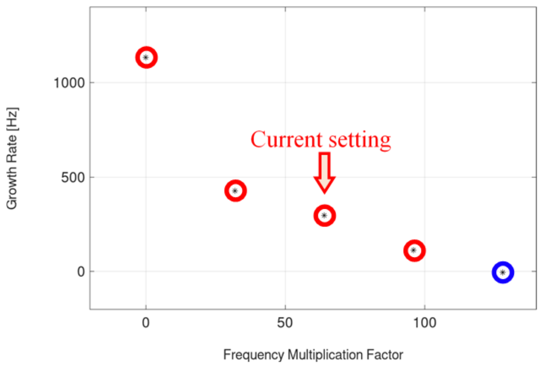

Figure 21: Growth rate variation with various processing clock rates. Clock rate is a multiplication factor times f_{RF}, 1.67 – 1.72 MHz.

Examining the intra-bunch oscillation, stabilizing occurs at certain positions and in other positions bunch becomes unstable (Fig. 22). This is because the optimum feedback is only possible at the sampling time and motion at the other timing is not optimum. In a measurement, similar signals are obtained (Fig. 23).

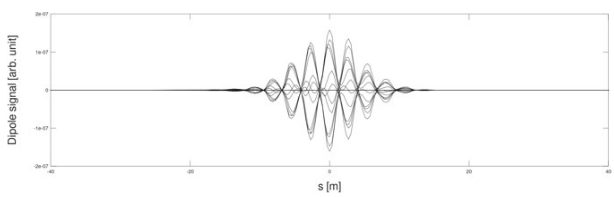

Figure 22: Simulated dipole signals, overlap of 13 turns with the processing clock of 64 multiple of f_{RF}.

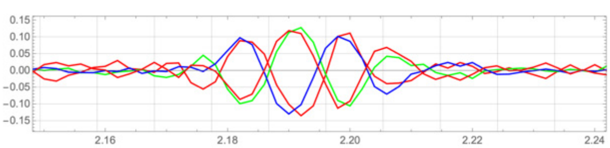

Figure 23: Measured dipole signals, overlap of 3 turns, suggesting stable and unstable points along the bunch caused by the processing clock.

Then we came up with the following idea. Fortunately, we have two feedback systems (Fig. 24) due to a historical reason. Shifting the processing clock by a half clock each other (Fig. 25), we call it "time interleaved sampling and kicking", the stability may get better. The result of the simulation (Fig. 26) supports this possibility. This is an intermediate plan of the feedback improvement for beam power upgrade.

SUMMARY

Present knowledge on the transverse instabilities in the J-PARC MR is reviewed: (1) vertical plane is more unstable than the horizontal, which is reasonable considering vacuum duct geometry, (2) resistive wall seems dominant source, then kickers, more precisely under study, (3) space charge instability suppression is observed.

The intra-bunch feedback system works well up to the beam power ~ 500 kW. Above 500 kW some improvements of the feedback are necessary: (1) time interleaved sampling and kicking with the current processing frequency, 64 x f_{RF} (or slightly higher 96 x f_{RF}), (2) doubling the processing clock frequency from 64 x f_{RF} to 128 x f_{RF}.

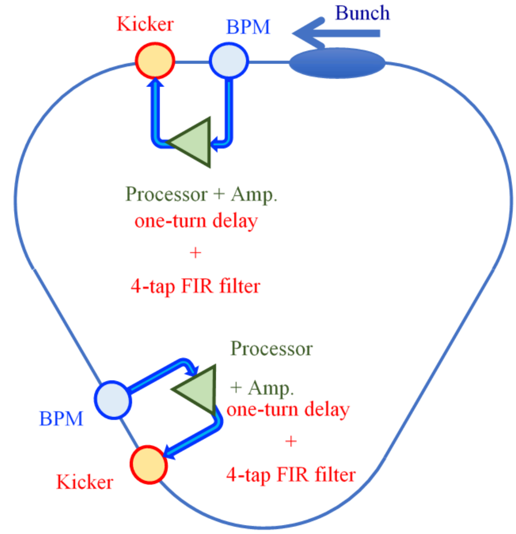

Figure 24: Two feedback systems in the MR.

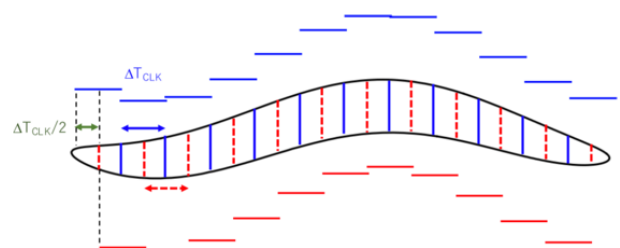

Figure 25: Sampling timings of the two systems, shifted by $\Delta T_{CLK}/2$.

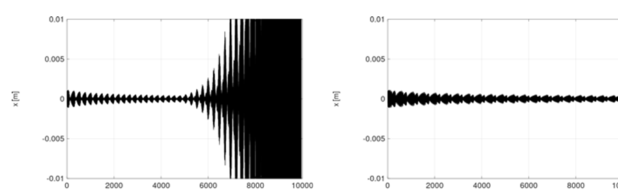

Figure 26: Simulated results w/o and with the time interleaved sampling and kicking by two feedback system. Left: the same timing Right: interleaved sampling and kicking with $\Delta T_{CLK}/2$ shift.

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