HEAD-TAIL INSTABILITIES OBSERVED AT J-PARC MR AND THEIR SUPPRESSION USING A FEEDBACK SYSTEM

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Abstract

This talk presents analysis of head-tail instabilities observed at the J-PARC MR (Main Ring) and their suppression using a feedback system. At the MR, we have been observing serious instabilities during the injection and at the onset of acceleration. Without the feed-back system on, nearly one third of particles are lost due to the instabilities at the beam power of 120kW. At the injection, the instabilities take place on the horizontal plane by injection errors resulting in a large displacement of injected bunches and due to collateral kicks of already injected bunches by the kicker fields. On the other hand, the instabilities at the onset of acceleration develop on the vertical plane from the noise level. Measurements of the horizontal oscillation initially suggested higher-order head-tail modes excited during the injection. However, the detailed analysis unveils that a simple dipole mode can have temporal appearance of higher-order head-tail modes due to a large chromaticity. The comparison between the measurements and the theoretical prediction shows that they have very similar behaviours.

INTRODUCTION

J-PARC consists of three proton accelerators: a 400 MeV linear accelerator (currently operating at 180 MeV), a 3 GeV Rapid-Cycling Synchrotron (RCS) and a 50 GeV (currently 30 GeV) Main Ring (MR). The main parameters of the MR are summarized in Table 1.

Table 1: Main parameters of the MR ring.

Circumference	1568 m
Injection Energy	3 GeV
Extraction Energy	30 GeV
Repetition Period	3 sec
RF Frequency	1.67-1.72 MHz
Number of bunches	8
Synchrotron tune	0.002-0.0001
Betatron tune	22.4, 20.77

In the normal operation mode, over 90% of the protons accelerated in the RCS are directed to the muon and neutron production targets in the Materials and Life Science Experimental Facility (MLF). The remaining protons are transported to the MR for further acceleration before being extracted via one of two (fast and slow) MR extraction ports.

The MR impedance is dominated by the transverse resistive-wall impedance of the stain-less steel chamber and the horizontal kicker impedance [1]. The kicker impedance has sharp peaks at about 1MHz and 10MHz. It is almost halved after four injection kickers were replaced by parasitic-impedance-free new models with HOM dampers (we still use five old-type kickers). The transverse resistive-wall impedance is exceptionally high, since the first betatron unstable line appears at around 40kHz on the vertical plane where the skin-depth is comparable to the wall thickness and the transverse impedance is proportional to the inverse of the frequency, not the square root of the frequency [2]. The beam instability evaluation before the commissioning of MR started predicted that beam instabilities would start to hurt beam operation from the beam power of 100-200kW. Although, the necessity of a damper system has been recognized, the actual development has been delayed due to financial constraints. After the commissioning of MR started, the careful inventory of the existing hardware revealed that we already have some key components necessary to compose the damper system: several unused Stripline Position Monitors (SPM) and the exciters for tune measurements that can be exploited as damper kickers. It was found that only remaining component to be developed is a signal processing circuit to filter and process SPM data and then to produce kick signals. The whole project costs only less that 100k USD.

Figure 2 sketches the transverse bunch by bunch feedback system. The beam position signals are sampled at an RF frequency times 64 rate (108.8MHz at 3GeV). The signal processing and digital filtering circuits consist of two LLRF4 boards with four 14-bit ADCs and two 14-bit DACs. They extract the betatron oscillation signals using 8-tap FIR filters. Its system integration and firmware development including EPICS interface was done by the Dimtel Inc. The kick signals are sent to the stripline damper kickers through the power amplifiers (two 500W/ 10kHz-250MHz ones for the horizontal plane and two 1kW/100kHz-8MHz ones for the vertical plane) to provide a single kick per bunch per passage for the both directions.

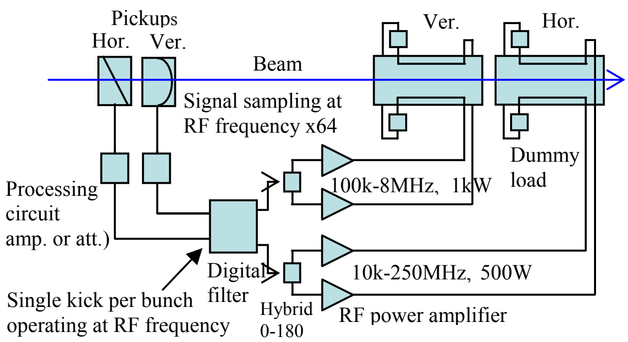

Figure 2: Schematic view of the transverse bunch-by-bunch feedback system.

Figures 3 (a) and (b) show the beam oscillation signals from the SPM recorded at a 500MHz sampling rate for the first 128ms period covering the injection of the last batch of bunches from RCS (K4) and the onset of acceleration (P2) where all instabilities take place. The top figure (a) shows the signals with the feedback (FB) off, while the bottom figure (b) shows one with the FB on. The strong vertical oscillations can be seen just after the onset of acceleration when the FB is off. The large horizontal oscillation can be also seen just after the injection of the last batch of bunches. They are basically gone when the FB is tuned on. The DCCT monitor shows that the particle losses at the injection and at the onset of acceleration are about 500W and 4,800W, respectively, far larger than the collimator tolerance of 400W. They are reduced to 100W and 25W, respectively, when the FB is on. The FB is now a must in daily operation of MR.

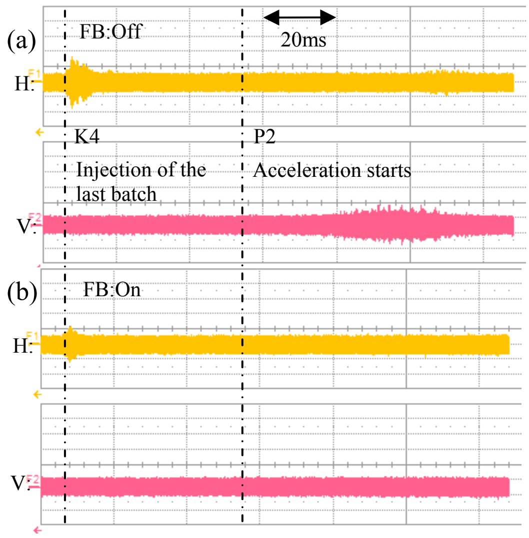

Figure 3: The beam oscillation signals from SPM for the first 128ms (a) when FB is off and (b) when FB is on.

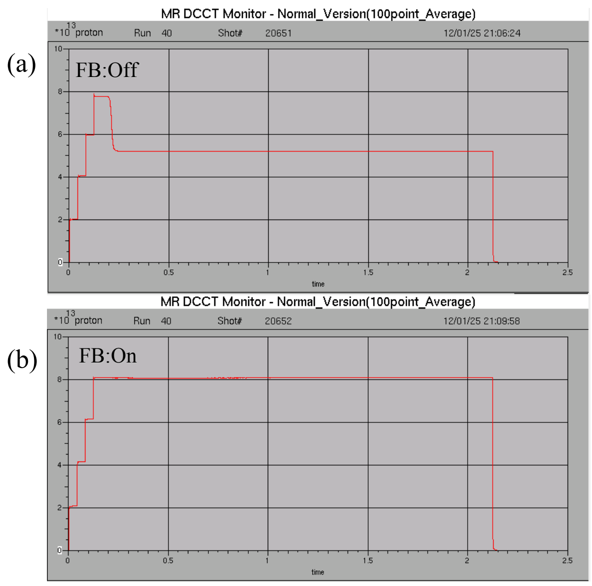

Figure 4: The beam intensity measured by the DCCT monitors (a) when FB is off and (b) when FB is on.

Figures 4 (a) and (b) show the beam intensity measured by the DCCT monitors without and with FB, respectively. It can be seen that the beam loses almost 30% of particles due to the beam instabilities when FB is off.

HEAD-TAIL INSTABILITY THEORY

Let us revisit the head-tail instability theory [3]. The chromaticity is defined by

$$\xi = \frac{d\omega_\beta}{\omega_\beta} / \delta \ , \tag{1}$$

where ω_β is the angular betatron frequency and $\delta = \Delta p / p$ is the relative momentum deviation. In other words, the betatron frequency depends on the momentum deviation as

$$\omega_\beta(\delta) = \omega_{\beta 0}(1 + \xi\delta) \ . \tag{2}$$

When a particle moves along the ring, the accumulated betatron phase advance is given by

$$\phi_\beta(s) = \int \omega_\beta(\delta) \frac{ds}{\beta c} = \omega_{\beta 0}\left(\frac{s}{\beta c} - \frac{\xi}{\eta}\tau\right) \ , \tag{3}$$

$$\equiv \omega_{\beta 0}\frac{s}{\beta c} - \omega_\xi \tau$$

where τ is the arrival time difference of the particle at the position s (positive toward the head of bunch), βc is the velocity of the particle, and η is the slippage factor. Thus, the betatron phase advance varies linearly along the bunch and attains its minimum (maximum) at the head (tail) of the bunch. Next, let us check how the difference of phase advance between the head and the tail of the bunch changes over one synchrotron oscillation period, using the four particle model in the synchrotron phase space as illustrated in Fig. 5. We assume that the arrival time is oscillating as

$$\tau = \hat{\tau}\cos(2\pi\nu_s k) \ , \tag{4}$$

where ν_s is the synchrotron oscillation tune and k is the revolution turn. We also assume that the chromaticity is negative and the ring is operated below the transition energy ($\eta < 0$). Thus particles move clockwise.

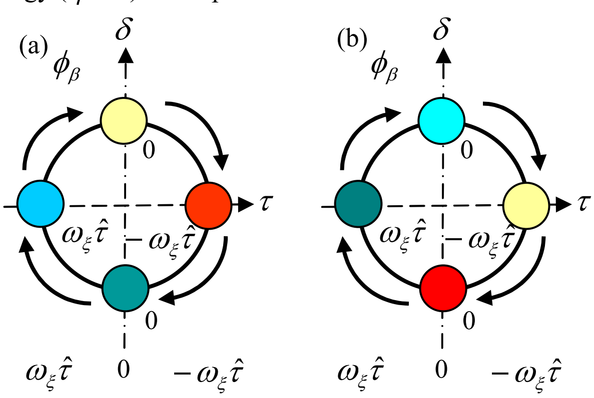

Figure 5: (a) The initial phase advance setting of the four particles. (b)The phase advance after a quarter period of the full synchrotron oscillation.

In principle, the betatron phase advance slows down (quickens up) by $\omega_\xi \hat{\tau}$ for every quarter period of synchrotron oscillation as the particle moves forward (backward) along the synchrotron orbit, respectively. As can be seen in Fig.5, the initial phase relationship along the bunch is preserved after the quarter period of synchrotron oscillation. One can quickly check that the phase pattern remains stationary over the full period of the synchrotron oscillation. In other words, the difference of the phase advance between the head and the tail of the bunch is constant, and we denote this constant as χ:

$$\chi = \phi_{\beta Tail} - \phi_{\beta Head} = 2\omega_\xi \hat{\tau} = 2\frac{\xi}{\eta}\omega_{\beta 0}\hat{\tau} = \text{constant} \qquad (5)$$

Let us assume that the dipole moment observed at a single point in the ring has the following standing wave pattern:

$$p_m(t) = \begin{cases} \cos(m+1)\pi \dfrac{t}{\tau_L} & m = 0,2,4,... \\ \sin(m+1)\pi \dfrac{t}{\tau_L} & m = 1,3,5,... \end{cases}, \qquad (6)$$

where $\tau_L = 2\hat{\tau}$ is the total bunch length. The transverse pick-up signal observed at that point on the k-th revolution turn is given by

$$I_m(t) \propto p_m(t)\exp(i\omega_\xi t + i2\pi k \nu_{\beta 0}), \qquad (7)$$

where $\nu_{\beta 0}$ is the betatron tune. The effect of the travelling-wave component over the standing-wave $p_m(t)$ is to shift the bunch spectrum by ω_ξ. Figure 6 shows an example with the transverse resistive-wall impedance and the narrow-band kicker impedance. The spectra are drawn for the head-tail modes 0 and 1 with positive phase difference χ. In this example, the mode 0 is stabilized, while the mode 1 becomes unstable by the transverse resistive-wall impedance at low frequency.

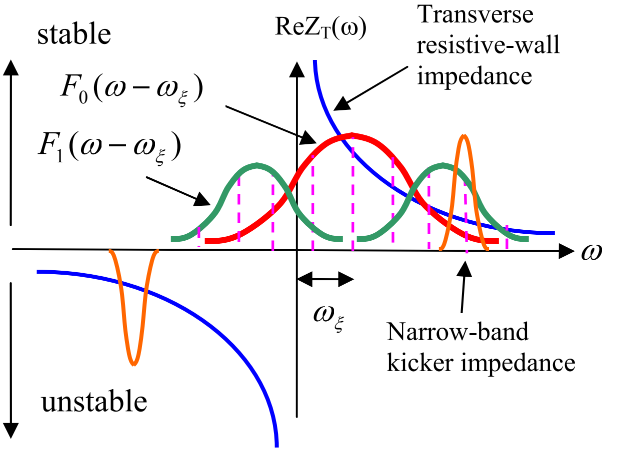

Figure 6: An example of the bunch spectrum shift by non-zero chromaticity.

The shift of the left peak of the bunch spectrum of the mode 1 means that a part of the mode now oscillates slowly. The head and the tail of the bunch will move almost in phase, not out of phase, to synchronize with the low frequency impedance. On the other hand, the shift of the right peak of the bunch spectrum of the mode 1 implies that this part of the mode now oscillates faster. In summary, the mode m=1 is degenerated at zero chromaticity, but are now split to slower and faster oscillating parts by non-zero chromaticity. These split modes are equally excited due to the standing-wave condition of head-tail modes, and thus have a node at the centre just like the m=1 mode at zero chromaticity.

BEAM SIGNAL MEASUREMENT AT MR

We have done several beam studies to investigate beam oscillation signals from the SPM in more depth. The studies were done with 8 bunches with the beam power of 120-140kW. The typical chromaticity pattern is shown in Fig. 7.

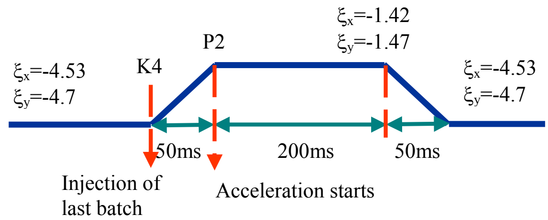

Figure 7: The typical chromaticity pattern.

Vertical Instability at the Onset of Acceleration

The vertical instability at the onset of acceleration (see Fig. 3(a)) is a text book case of the head-tail instability: noise with the right phase relationship as shown in Fig.5 is picked up and then grows. Let us count head-tail modes that could be excited at the onset of acceleration by the low frequency transverse resistive-wall impedance and the 10MHz kicker impedance. The phase difference χ for the chromaticity $\xi = -1.45$, the total bunch length of $\tau_L = 2\hat{\tau} = 150ns$ and the slippage factor of 0.058 is 4.4. That means that the low frequency impedance can excite the m=0 or m=1 mode. The 10MHz kicker impedance can produce $\chi = 13.8$ and thus the m=3 mode is likely to be excited. Figures 8 show the maximum amplitude of the vertical oscillation when the FB is turned off (left) and is turned on (right), respectively.

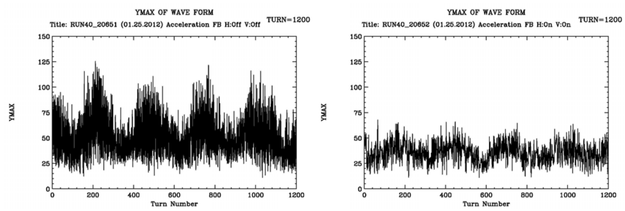

Figure 8: The time evolution of the maximum amplitude of vertical oscillation for the FB off (left) and on (right).

From these figures, the growth time can be estimated as about 1.2ms. The huge damping effect by the FB is recognizable in the right figure of Fig. 8. Figure 9 shows the vertical oscillation signals superimposed on 10 consecutive turns (when FB is off). There is no node visible, suggesting that the vertical oscillation is just a dipole mode. The BBU approach for the growth time estimate delivers the growth time of 1.5ms, in a reasonable agreement with the measurement of 1.2ms [4].

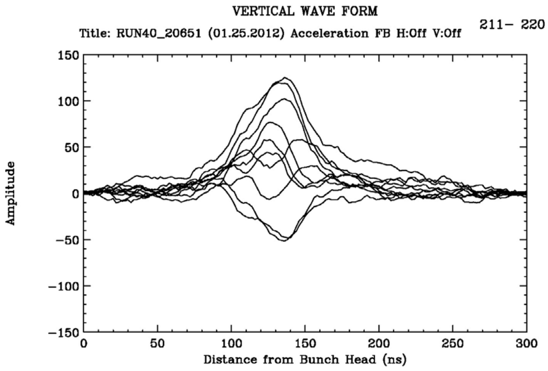

Figure 9: The vertical oscillation signals superimposed on 10 consecutive turns when FB is off.

Another interesting finding is the pulsational behaviour of the oscillation amplitude. At the onset of acceleration, instability develops from noise level and then the oscillation amplitude starts to grow. Eventually, some parts of the beam hit the wall and get lost. The instability then loses its mechanism of growth and starts to decay. After while, the instability picks up steam again and starts to grow. The above process is repeated until the beam loses enough particles that the instability ceases for good.

Horizontal Instability at the Injection

The horizontal instabilities during the injection have very different features. They start, not from noise, but from a large transverse displacement due to injection errors or ones by kicks by the mismatching field of the injection kicker magnets. There is no betatron phase difference along the bunch at the moment of the injection or the kicks by the mismatching field. Nevertheless, if we still apply the Sacherer's text book analysis to this case, the head count of head-tail modes that could be excited at 140kW is the m=3 mode by the low frequency resistive-wall impedance and the m=6 mode by the 10MHz kicker impedance. Figures 10 show the time evolution of the maximum amplitude of horizontal oscillation of the first bunch at the injection of the last batch when the FB is off (left) and is on (right), respectively. Figures 11 show the measured horizontal oscillations of the same bunch for the FB on (left) and FB off (right) at the 1st (top), 250-th (middle) and 501-th (bottom) turns, respectively.

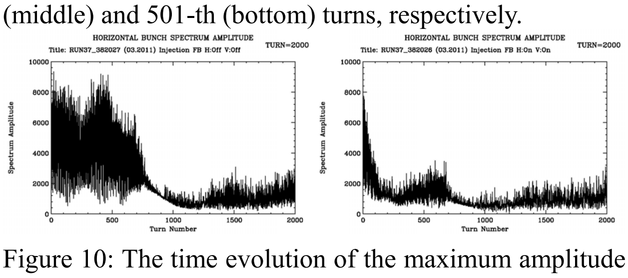

Figure 10: The time evolution of the maximum amplitude of horizontal oscillation of the first bunch at the injection of the last batch (K4) for the FB off (left) and on (right), respectively.

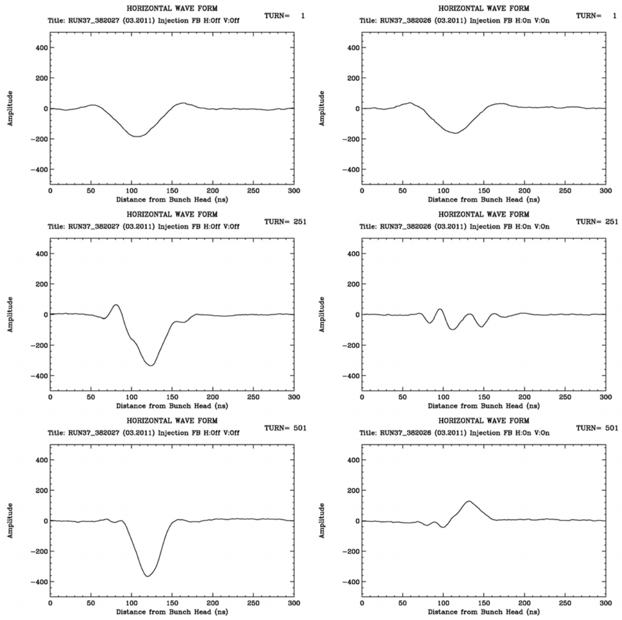

Figure 11: The measured horizontal oscillations of the first bunch at the injection of the last batch (K4) for the FB off (left) and FB on (right) at the 1st (top), 250-th (middle) and 501-th (bottom) turns, respectively.

One can see that main growing mode with the FB off is the dipole mode and it is very quickly and effectively damped by the FB system. However, the complicated intra-bunch oscillations occasionally emerge and then fade out. It looks like that a lower-order head-tail mode appears first and then it is converted to a higher-order mode (m=6 or 7), and then converted back to the lower-order mode again after one full synchrotron oscillation period (~500 turns). Although these seeming head-tail modes impose no harm on the MR operation at present, if they are really head-tail modes excited by the kicker impedance and will grow more rapidly at higher beam power, they may pose significant threat on the MR operation. For the present narrow-band FB system cannot damp intra-bunch oscillations. This possibility raised a significant concern over the future operation of MR. To defuse this threat, first we started to develop two types of intra-bunch feedback systems. At the same time, we made more in-depth investigation of the measured intra-bunch oscillations to find their true identity.

Figures 12 show the horizontal oscillation signals superimposed on 10 consecutive turns starting from 251-th turn. No clear node is visible.

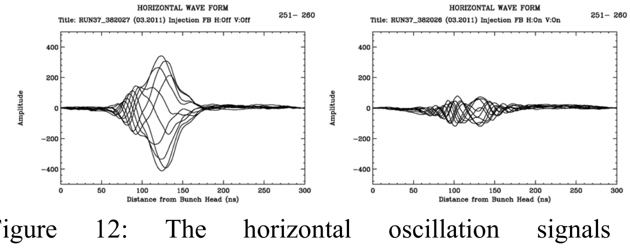

Figure 12: The horizontal oscillation signals superimposed on 10 consecutive turns starting 251-th turn for the FB off (left) and the FB on (right), respectively.

One possible explanation is that the kicker 10MHz impedance is not strong enough to sustain higher-order head-tail modes alive for long period of time by locking the phase synchronisation with them. Another possible explanation is that the simple application of Sacherer' text book analysis is not inadequate in the present case.

Let us re-investigate how the betatron phase difference between the head and the tail of a bunch evolves over a full synchrotron oscillation period using the four particle model (see Fig. 13). All the particles have the same betatron phase at the beginning. At every a quarter period of the full synchrotron oscillation, the phase difference between the head and the tail increases by $2\omega_\xi\hat{\tau}$ till the half of the synchrotron oscillation. Then, the phase difference starts to decrease and come back to zero at the full synchrotron oscillation (namely, the picture next to (d) comes back to (a)). More detailed analysis shows that the phase difference oscillates like

$$\chi = \phi_{\beta Tail} - \phi_{\beta Head} = \frac{\xi}{\eta}\omega_{\beta 0}\tau_L \cdot (1-\cos(2\pi\nu_s k)) \qquad (8)$$

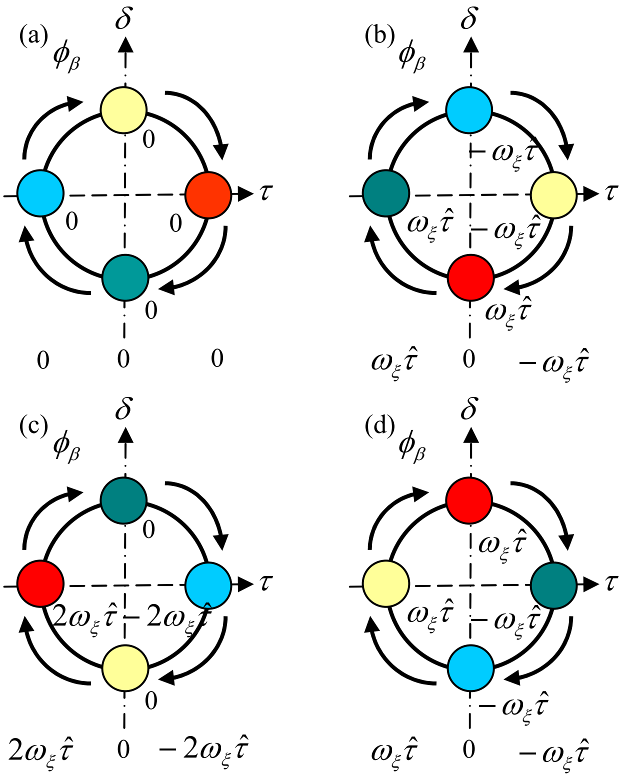

Figure 13: (a) The initial zero phase difference. (b-d) Change in phase advance after every quarter period of the full synchrotron oscillation. After (d), the phase difference comes back to (a).

Let us see how a simple dipole mode changes its oscillation appearance when the phase difference between the head and the tail oscillates as specified in Eq. (8). Figures 14 show the simulated horizontal oscillations and their superposition on 10 consecutive turns at the 1st (top), 251-th (middle) and 501-th (bottom) turns, respectively. They are strikingly similar to the right figures of Figs. 11 and Fig. 12. We also analysed the frequency spectra of the horizontal oscillation signals and found that the low frequency signal (lower than ~5MHz) is dominating and there is no clear peak at high frequency. This result also indicates that the simple dipole mode with the oscillating betatron phase difference between the head and the tail of the bunch can create temporal deceptive appearance as higher-order head-tail modes.

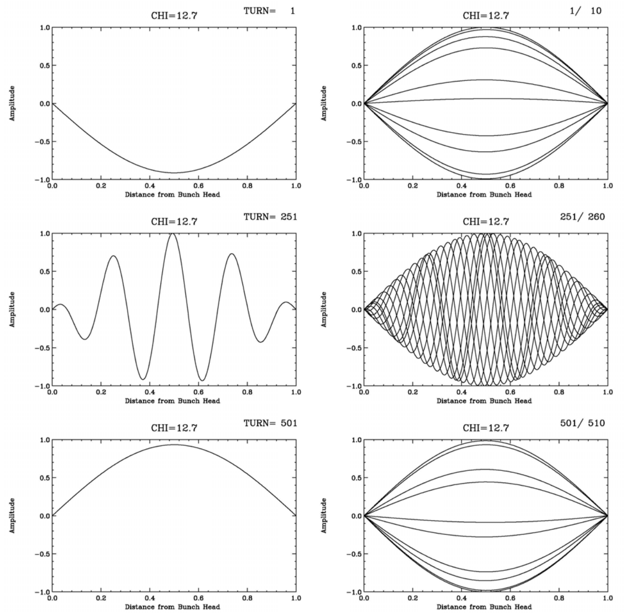

Figure 14: The simulated horizontal oscillations and their superposition on 10 consecutive turns at the 1st (top), 251-th (middle) and 501-th (bottom) turns, respectively.

SUMMARY

It has been demonstrated the present feedback system is quite effective to suppress beam instabilities at the MR. The initial analysis of the oscillation signals of the horizontal instabilities during the injection hinted excitation of higher-order head-tail modes and it raised a concern over the future operation of MR. However, the more detailed analysis revealed that the instabilities during the injection are, despite their appearance, merely the dipole oscillations with the oscillating betatron phase difference between the head and the tail of the bunch over a synchrotron period. The kicker impedance is now halved and the concern over higher-order head-tail instabilities proved unfounded at least up to ~300kW beam power.

REFERENCES

[1] Y.H. Chin et al., "Impedance and Beam Instability Issues at J-PARC Rings", HB2008, Nashville, August 2008, WGA01, p.40 (2008).

[2] A. Burov and V. Levedev., "Transverse Resistive-Wall Impedance for Multi-Layer Round Chambers," EPAC'02, Paris, June 2002, p. 1452 (2002).

[3] F.J Sacherer, "Transverse Bunched Beam Instabilities", CERN/PS/BR76-21 (1976).

[4] Y. Shobuda, private communications.