ANALYSIS OF TRANSVERSE INSTABILITIES OBSERVED AT J-PARC MR AND THEIR SUPPRESSION USING FEEDBACK SYSTEMS

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Abstract

This paper presents an analysis of head-tail instabilities observed at the J-PARC MR (Main Ring) and their suppression using feedback systems. Instabilities were mainly observed at low energies. About 30% of particles are lost due to the instabilities if the feed-back system is turned off at the beam power of 120kW. Both horizontal and vertical instabilities were observed. Measurements of the horizontal oscillations initially suggested the excitation of higher-order head-tail modes during the injection. An analysis unveils that a dipole mode has a temporal appearance of higher-order head-tail modes if the chromaticity is sufficiently large. The development of instabilities in the presence of a large chromaticity should be considered for conditions beyond the Sacherer's text book case.

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 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, 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 1 sketches the transverse (narrow-band) 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.

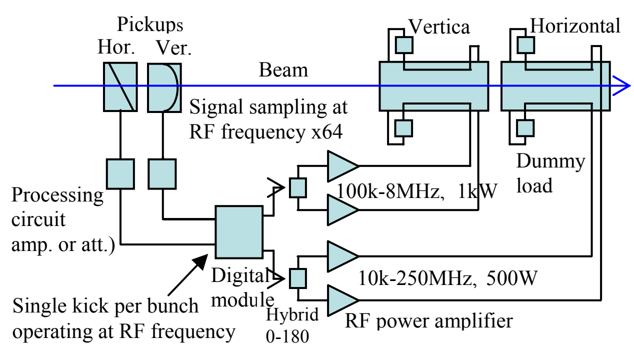

Figure 1: Schematic view of the transverse bunch-by-bunch feedback system (narrow-band).

Figures 2 (a) and (b) show the beam oscillation signals from the SPM recorded at a 500MHz sampling rate for the first 128ms period that covers 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.

ISBN 978-3-95450-138-0

The strong vertical oscillations are visible just after the onset of acceleration when the FB is turned off. The large horizontal oscillation can be also seen just after the injection of the last batch of bunches. They are strongly damped 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, which are far larger than the collimator tolerance (400W). They are reduced to 100W and 25W, respectively, when the FB is turned on. Figures 3 (a) and (b) show the beam intensity measured by the DCCT monitors without and with FB, respectively. It can be seen that almost 30% of particles are lost due to the beam instabilities when FB is turned off. The FB is now indispensable in daily operation of MR.

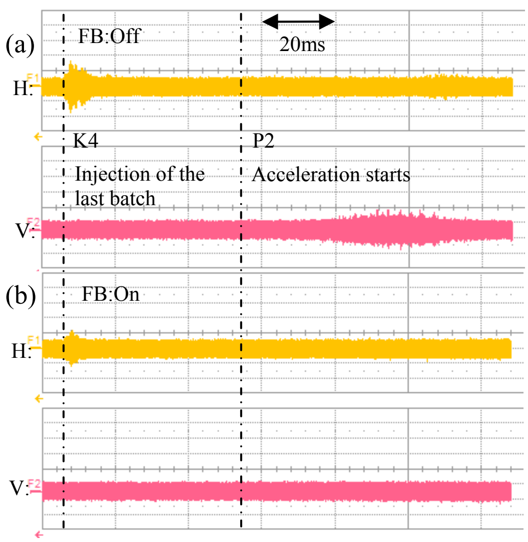

Figure 2: The beam oscillation signals from SPM for the first 128ms (a) when FB is turned off and (b) when FB is turned on.

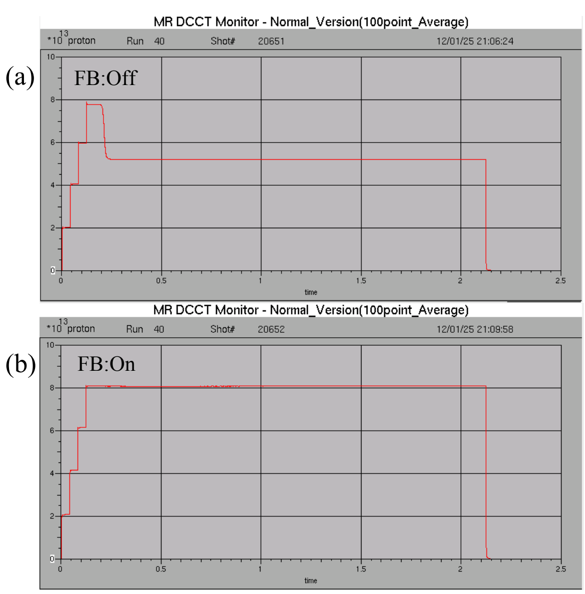

Figure 3: The beam intensity measured by the DCCT monitors (a) when FB is turned off and (b) when FB is turned on.

HEAD-TAIL INSTABILITY THEORY

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

$$\xi = \frac{d\omega_\beta}{\omega_\beta} / \delta \, , \quad (1)$$

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

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

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

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

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.

To investigate how the difference of phase advance between the head and the tail of the bunch varies over one synchrotron oscillation period, we have developed the four particle model in the synchrotron phase space, as illustrated in Fig. 4. We assume that the arrival time is oscillating as

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

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 in synchrotron phase space.

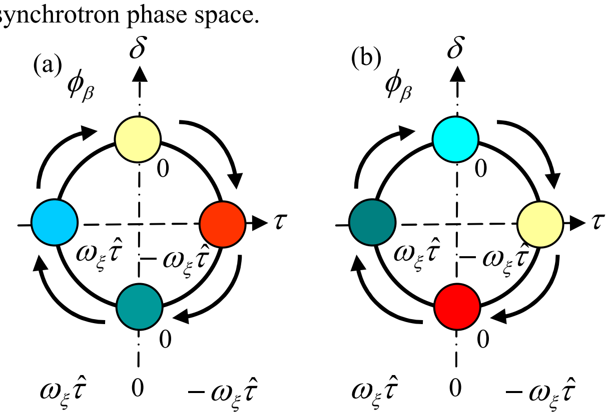

Figure 4: (a) The initial phase advance setting of the four particles. (b)The phase advance after a quarter period of the full synchrotron oscillation.

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.4, 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:

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

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

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

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

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

where $\nu_{\beta 0}$ is the betatron tune. The effect of the travelling-wave component $\exp(i\omega_\xi t + i2\pi k\nu_{\beta 0})$ over the standing-wave dipole moment $p_m(t)$ is to shift the bunch spectrum by ω_ξ. Figure 5 shows an example where the transverse resistive-wall impedance and the narrow-band kicker impedance are shown as impedance examples. 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.

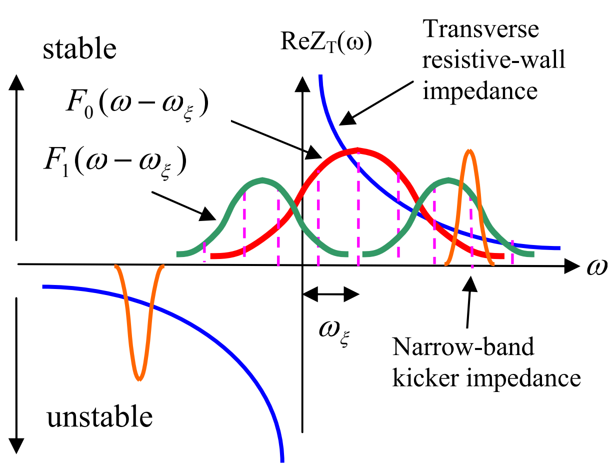

Figure 5: An example of the bunch spectrum shift by non-zero chromaticity.

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 mode 1 bunch spectrum implies that this part of the mode now oscillates faster. In summary, the mode m=1 is degenerated at zero chromaticity, but it now splits 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 they always have a node at the centre just like the m=1 mode at zero chromaticity.

BEAM SIGNAL MEASUREMENT AT MR

We have made 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. 6.

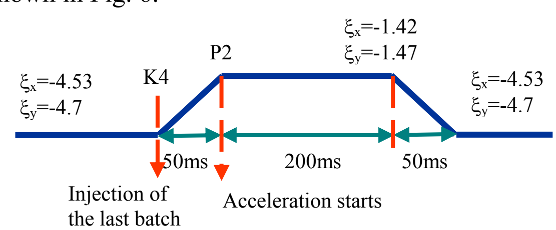

Figure 6: The typical chromaticity pattern.

Vertical Instability at the Onset of Acceleration

The vertical instability at the onset of acceleration (see Fig. 2(a)) is a text book case of the head-tail instability: it starts with a noise with the right phase relationship as shown in Fig.4 and then grows. Let us estimate head-tail modes that could be excited at the onset of acceleration by the MR transverse impedances. The phase difference χ is 4.4 for the chromaticity $\xi = -1.45$, the total bunch length of $\tau_L = 2\hat{\tau} = 150ns$ and the slippage factor of 0.058. That leads to the excitation of the m=0 or m=1 mode by the low frequency transverse resistive-wall impedance. The 10MHz kicker impedance can produce $\chi = 13.8$ and thus the m=3 mode is likely to be excited. Figures 7 show the maximum amplitude of the vertical oscillation when the FB is turned off (left) and is turned on (right), respectively.

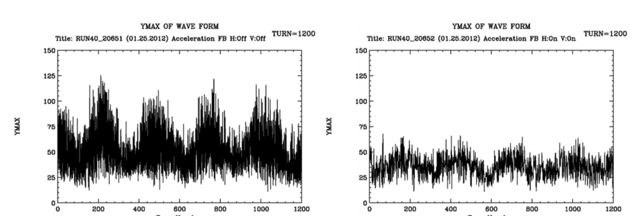

Figure 7: The time evolution of the maximum amplitude of vertical oscillation for the FB off (left) and on (right).

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. 7. Figure 8 shows the vertical oscillation signals superimposed on 10 consecutive turns (when FB is tuned off). No node is visible, suggesting that the vertical oscillation is just a

ISBN 978-3-95450-138-0

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].

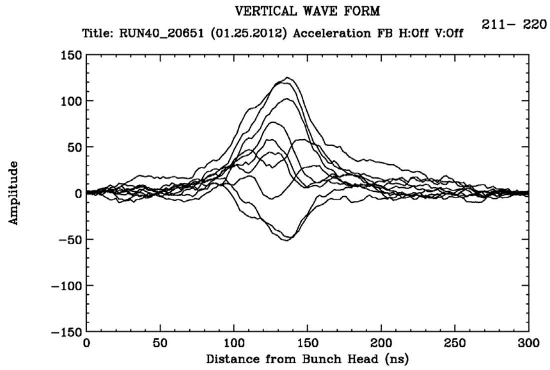

Figure 8: The vertical oscillation signals superimposed on 10 consecutive turns when FB is turned off.

Horizontal Instability at the Injection

The horizontal instabilities during the injection evolve from very different initial conditions compared to conventional head-tail instabilities. 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 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 9 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 turned off (left) and on (right), respectively. Figures 10 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.

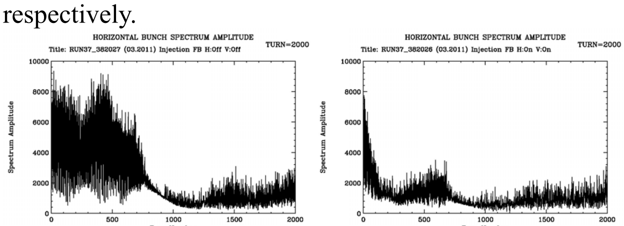

Figure 9: The time evolution of the maximum amplitude of horizontal oscillation of the first bunch at the injection of the last batch (K4) for the FB off (left) and on (right), respectively.

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, complex intra-bunch oscillations occasionally emerge and fade out. It looks like that a lower-order head-tail mode appears first and then it is transmuted into higher-order modes (m=6 or 7), and then transmuted back to the lower-order mode again after one full synchrotron oscillation period (~500 turns). No large particle loss has been observed associated with these intra-bunch oscillations at present. However, if they are indeed head-tail modes excited by the 10MHz kicker impedance, it is likely that they will impose a significant limit on the beam power in future, since the present narrow-band FB system is ineffective to damp such intra-bunch oscillations. To defuse such possibility, first we started to develop a broadband intra-bunch feedback system based on the iGp12 module [5]. At the same time, we made more in-depth investigation of the measured intra-bunch oscillations to find their true identity.

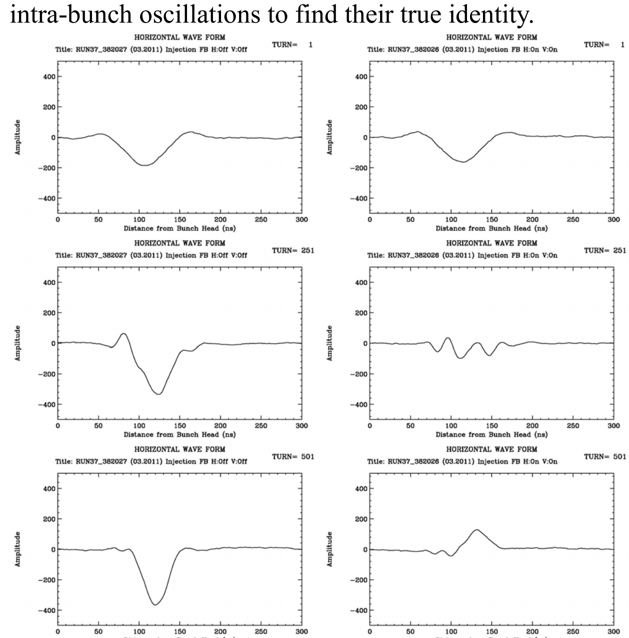

Figure 10: The measured horizontal oscillations of the first bunch at the injection of the last batch (K4) for the FB off (left) and FB on (right) at the 1st (top), 250-th (middle) and 501-th (bottom) turns, respectively.

The iGp12 digital signal processing module is widely used in electron rings. It is operated at the rate of RF frequency times 64 and replaces the present narrowband digital module shown in Fig. 1, which is operating at just the RF frequency. It divides each RF bucket into 64 segments (bins) and acts on each bin as if it is a small bunch (bunch-let) in a narrowband mode.

Let us take a closer look at the horizontal oscillations signals to see if they are forming envelops, one of signatures of head-tail modes. Figures 11 show the horizontal oscillation signals superimposed on 10 consecutive turns starting from 251-th turn. No clear node is visible in the both cases with and without active FB.

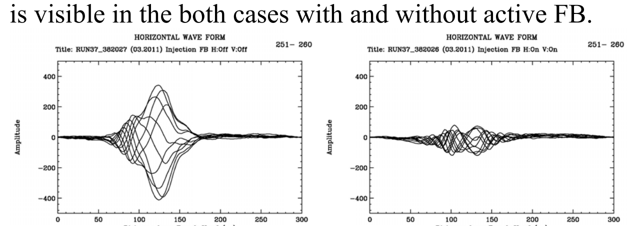

Figure 11: The horizontal oscillation signals superimposed on 10 consecutive turns starting 251-th turn for the FB off (left) and the FB on (right), respectively.

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. Another possible explanation is that the simple application of Sacherer' text book analysis is 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 again (see Fig. 12). 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

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

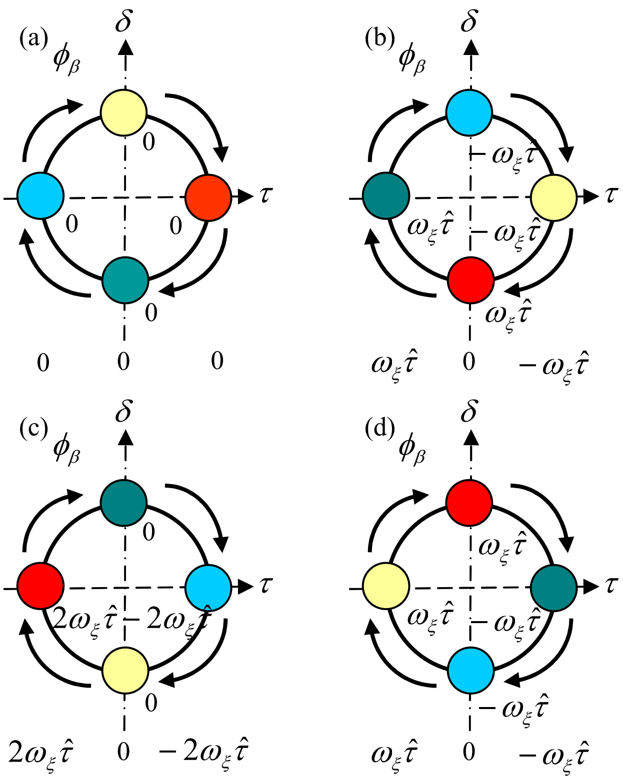

Figure 12: (a) The initial zero phase difference. (b-d) Change in phase advance after every quarter period of the full synchrotron oscillation. After (d), the phase difference comes back to (a).

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 13 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. 10 and Figs. 11. We also analysed the frequency spectra of the horizontal oscillation signals and found that the low frequency signal (lower than ~5MHz) is dominant and there is no clear peak at higher frequency. These results demonstrate that a simple dipole mode can create a temporal deceptive appearance of higher-order head-tail modes, when the betatron phase difference between the head and the tail of the bunch is oscillating as in Eq. (8).

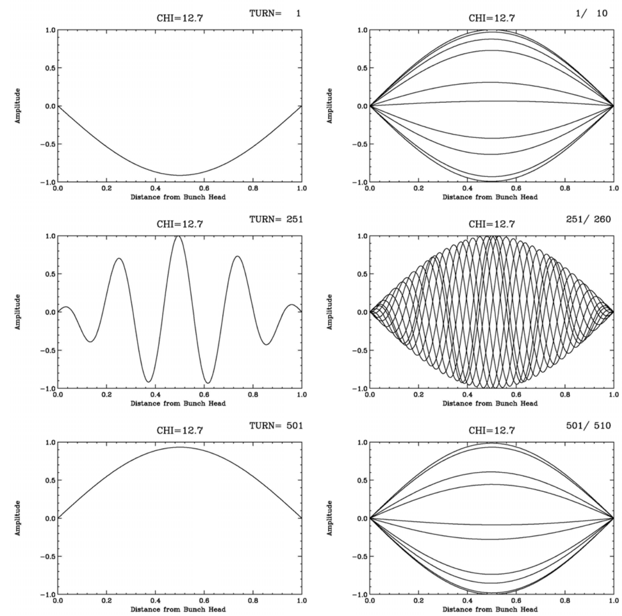

Figure 13: The simulated horizontal oscillations and their superposition on 10 consecutive turns at the 1st (top), 251-th (middle) and 501-th (bottom) turns, respectively.

SUMMARY

The present (narrowband) bunch-by-bunch feedback system is found to be quite effective to suppress transverse beam instabilities at MR, allowing the beam power to reach 230kW with only particle losses of 400W. The initial analysis of the horizontal instabilities during the injection raised concern over the excitation of higher-order head-tail modes. However, the detailed analysis revealed that a simple dipole oscillation can be deceived as higher-order head-tail modes, when a bunch starts to oscillate from a large transverse displacement. The new broadband intra-bunch feedback system is under testing.

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ISBN 978-3-95450-138-0