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MEASUREMENT OF THE LONGITUDINAL COUPLED BUNCH INSTABILITIES IN THE J-PARC MAIN RING

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Abstract

The J-PARC Main Ring (MR) is a high intensity proton synchrotron, which accelerates protons from 3 GeV to 30 GeV. Its beam power for the fast extraction reached 470 kW, which corresponds to 2.4×10^{14} protons per pulse, in February 2017, and the studies to reach higher beam intensities are in progress. We observed the longitudinal dipole coupled bunch instabilities in the MR for the beam power beyond 470 kW. To investigate the source of the instabilities and to mitigate them, we analyzed the beam signals throughout the acceleration cycle to obtain the oscillation modes and their growth by using two methods. One focuses the motion of the bunch centers and the other used the frequency spectrum of the beam signal. We describe the methods and the measurement results of the longitudinal coupled bunch instabilities in the J-PARC MR.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a high intensity proton accelerator facility, which consists of the 400 MeV linac, the 3 GeV Rapid Cycling Synchrotron (RCS), and the 30 GeV Main Ring (MR). The MR delivers the proton beams to the neutrino experiment by the fast extraction (FX), and to the hadron experiments by the slow extraction (SX). The operation parameters of the J-PARC MR and the RF system for the fast extraction are shown in Table 1.

Table 1: Operation Parameters of the J-PARC MR and the RF System for the Fast Extraction

energy	3–30 GeV
repetition period	2.48 s
accelerating period	1.4 s
accelerating frequency f_{RF}	1.67–1.72 MHz
revolution frequency f_{rev}	185–191 kHz
harmonic number h_{RF}	9
number of bunches N_b	8
maximum rf voltage	300 kV
fundamental harmonic cavities	7
second harmonic cavities	2
Q-value of rf cavity	22

The MR delivers 2.4×10^{14} protons per pulse, which corresponds to the beam power of 470 kW, to the neutrino experiment as of February 2017, and studies toward higher beam intensity are in progress. During studies, the longitudinal bunch oscillation appeared to be an issue to achieve higher beam intensities than 500 kW.

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LONGITUDINAL BUNCH OSCILLATION IN THE J-PARC MR

The beam signal from an Wall Current Monitor (WCM) [1] is recorded by an oscilloscope, LeCroy WP715Zi, with the sampling frequency of 500 MHz.

Figure 1 shows the typical mountain plot of the beam signal at the beam power of 480 kW for the fast extraction during the studies. The bunches start the dipole oscillations from the middle of the acceleration and their amplitudes keep increasing until the extraction. One can notice that the amplitudes and the phases of the oscillations of the bunches are different.

This kind of the oscillations is called the coupled bunch (CB) oscillation, and the instability caused by the CB oscillation is called the CB instability (CBI). The identification of the CB oscillation mode is necessary to find the source of the CBI.

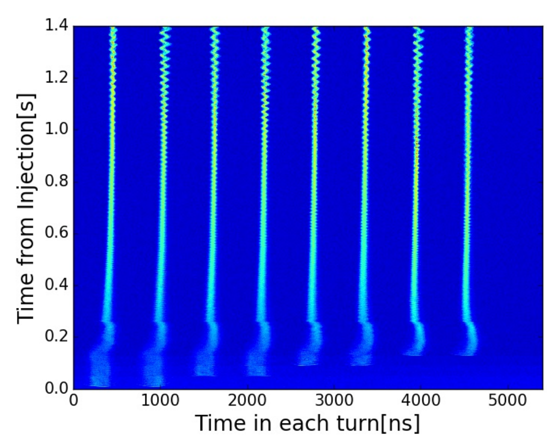

Figure 1: The mountain plot for the fast extraction in the J-PARC MR with the beam power of 480 kW during the studies.

COUPLED BUNCH OSCILLATION

For M bunches, there are M modes of the CB oscillation with the mode number $n = 0...M-1$. The phase difference of the synchrotron oscillation between adjacent bunches is $2\pi n/M$. For each mode, all bunches oscillate with the same frequency and the amplitude but with different phases.

The CB modes can also be seen in the spectrum of the beam signal as sidebands of the harmonic components [2].

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The frequency of the CB mode n can be expressed as follows:

$$f_{p,m,n} = |(pM + n)f_{\text{rev}} + mf_s|, (-\infty < p < \infty), \quad (1)$$

where f_{rev} is the revolution frequency, f_s the synchrotron frequency, and m the type of the synchrotron motion. The case with $m = 1$ corresponds to the dipole oscillation. The CB modes appear as the Upper Side Bands (USBs) and the Lower Side Bands (LSBs) in the cases of $p \geq 0$ and $p < 0$, respectively. Below the accelerating frequency, the USB and the LSB with the CB mode n can be expressed as follows:

$$f_n^{\text{USB}} = nf_{\text{rev}} + mf_s \quad (2)$$
$$f_n^{\text{LSB}} = (M - n)f_{\text{rev}} - mf_s. \quad (3)$$

There are 9 CB modes for the J-PARC MR since the harmonic number of the J-PARC MR is 9. The spectra of the CB modes in the MR up to the harmonic $h = 11$ are illustrated in Figure 2.

There are two sidebands with different CB modes in each harmonic component.

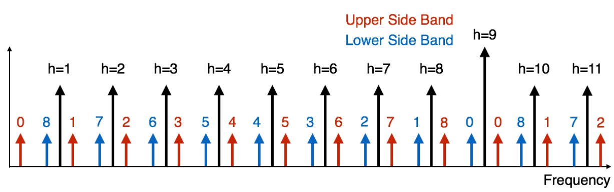

Figure 2: The coupled bunch oscillation mode for the J-PARC MR.

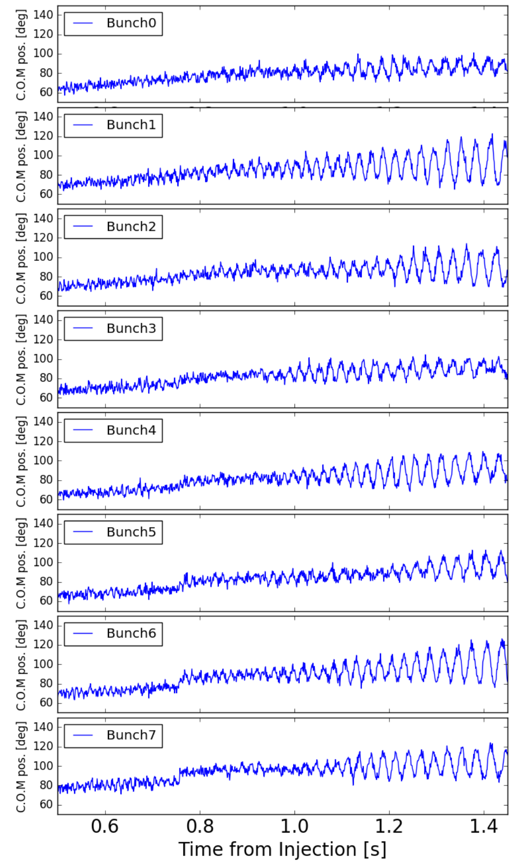

Figure 3: The tracks of the bunch centers.

COUPLED-BUNCH OSCILLATION ANALYSIS

We use two different methods to analyze the CB oscillation. We apply these method to the measured beam signal and compare the results.

Bunch Center Motion Analysis

The CB modes can be identified by analyzing the phase difference of the synchrotron oscillation between bunches [3].

The phases of the synchrotron oscillations for the bunchs are obtained by analyzing the motion of bunch centers. The bunch centers are calculated from the the center of mass of the WCM signal for each bunch. Figure 3 shows the track of the bunch centers obtained from the WCM signal shown in Figure 1. The differences of the amplitude and the phase between bunches can be clearly seen in Figure 3 .

The phase and the amplitude of the synchrotron motion are obtained by fitting the track of the bunch center for each bunch with a sinusoidal function as:

$$y_i = a_i \sin(2\pi f_s t + \theta_i) + C_i, \quad (4)$$

where y_i is the track of the center of mass of $i-$th bunch, a_i and θ_i are the amplitude and the phase of the synchrotron oscillation for $i-$th bunch, respectively. The fit range is determined to cover two cycles of the synchrotron oscillation estimated by the operation parameters.

The amplitudes and the phases of the CB modes are obtained by applying the DFT according to

$$A_n e^{-i\Theta_n} = \frac{1}{M}\sum_k a_k e^{-i\theta_k} e^{2\pi ikn/M}, \quad (5)$$

where A_n and Θ_n are the amplitude and the phase of the CB mode n. Figure 4 shows the time variation of the amplitudes of the CB modes during the acceleration for the WCM signal shown in Figure 1. The CB mode $n = 8$ has the largest amplitude for the most of time during the acceleration. In addition to the CB mode $n = 8$, the amplitude of the CB modes with $n = 4, 6, 7$ are increasing until the extraction.

Frequency Spectrum Analysis

To identify the CB modes from the beam spectrum, the LSBs and USBs of the harmonic components must be extracted from the beam signal. We apply the single side band filtering [4] to obtain the LSBs and USBs.

Figure 5 shows the procedure of the single side band filtering. In the offline analysis, the single side band filtering is applied to the recorded waveform of the beam signal from WCM.

The harmonic components of the beam signal are detected by the quadrature detection [5]. If we assume the beam

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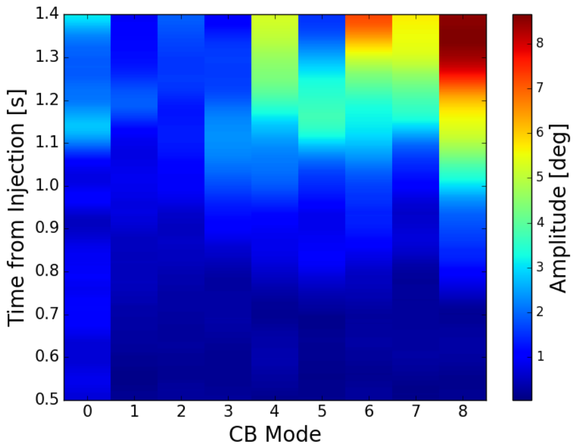

Figure 4: The amplitudes of the CB oscillation modes.

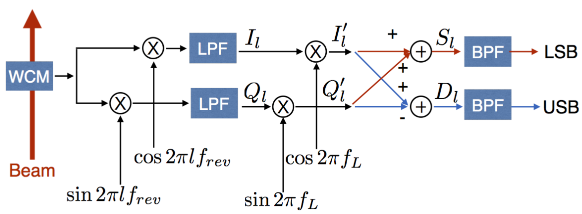

Figure 5: Procedure of the single side band filtering.

spectrum as

$$y = \sum_l A_l(t)\sin(2\pi l f_{\rm rev} + \phi_l(t)), \tag{6}$$

the IQ signal for the harmonic component ($h = l$) after the quadrature detection are expressed as

$$I_l = \frac{A_l(t)}{2}\sin\phi_l(t) \tag{7}$$

$$Q_l = \frac{A_l(t)}{2}\cos\phi_l(t) \tag{8}$$

Figure 6 and 7 show the spectrograms for I_8 and Q_8, respectively. There is a strong sideband with decreasing frequency in both figures. The frequency of the sideband is consistent with the estimated synchrotron frequency shown as red dotted line the figure.

Since the frequency of the sidebands in IQ components agree with the estimation, the sidebands can be extracted by the single sideband filtering using the estimated frequency. The I and Q signals are multiplied by the unity signals, $\cos 2\pi f_L t$, $\sin 2\pi f_L t$, respectively, to obtain the I_l', Q_l', where f_L is the frequency satisfying $f_L = f_s + f_c$, and f_c is the carrier frequency which can be chosen freely.

$$\begin{aligned} I_l' &= I_l \cos 2\pi f_L t \\ &= \frac{A_l(t)}{4}(\sin(\phi_l(t) + 2\pi f_L t) \\ &\quad + \sin(\phi_l(t) - 2\pi f_L t)) \end{aligned} \tag{9}$$

$$\begin{aligned} Q_l' &= Q_l \sin 2\pi f_L t \\ &= \frac{A_l(t)}{4}(\sin(\phi_l(t) + 2\pi f_L t) \\ &\quad - \sin(\phi_l(t) - 2\pi f_L t)) \end{aligned} \tag{10}$$

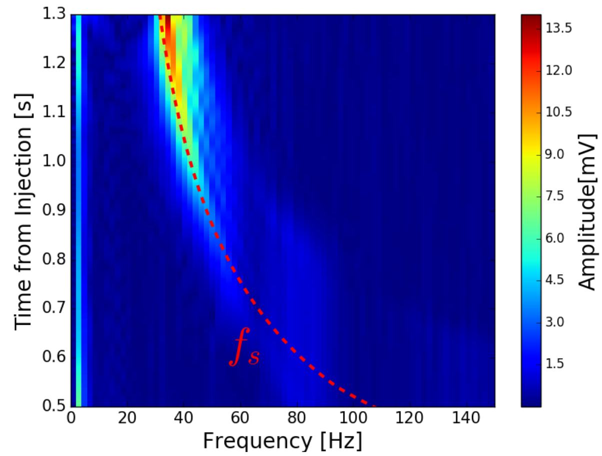

Figure 6: Spectrogram for the I component h=8 (I_8). Red dotted line represents the estimated synchrotron frequency.

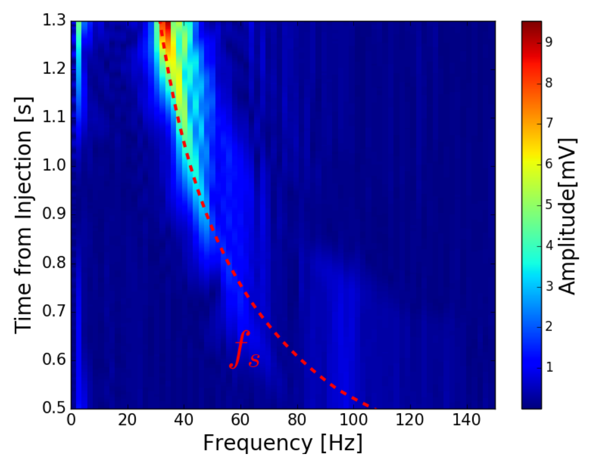

Figure 7: Spectrogram for the Q component h=8 (Q_8). Red dotted line represents the estimated synchrotron frequency.

The sum and the difference of I_l', Q_l' are calculated to obtain S_l, D_l, respectively.

$$S_l = \frac{A_l(t)}{2}\sin(\phi_l(t) + 2\pi f_L t) \tag{11}$$

$$D_l = \frac{A_l(t)}{2}\sin(\phi_l(t) - 2\pi f_L t) \tag{12}$$

The D_l oscillates with the carrier frequency f_c in the case of the USB ($\phi_l(t) = 2\pi f_s t$), and the S_l oscillates with f_c in the case of the LSB ($\phi_l(t) = -2\pi f_s t$). The LSB and the USB of the harmonic component with $h = l$ are obtained by applying the BPF with the pass band around f_c to S_l and D_l.

Figure 8 and Figure 9 show the time variation of the amplitudes of the LSB and the USB of the harmonic components for the WCM signal shown in Figure 1. The sidebands with the largest amplitude are the USB of the harmonic component $h = 8$ and the LSB of the harmonic component $h = 10$.

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Both sidebands correspond to the CB mode $n = 8$. In addition to the sidebands for the CB mode $n = 8$, the amplitudes of the sidebands corresponding to the CB mode $n = 2, 4, 6, 7$ are increasing until the extraction.

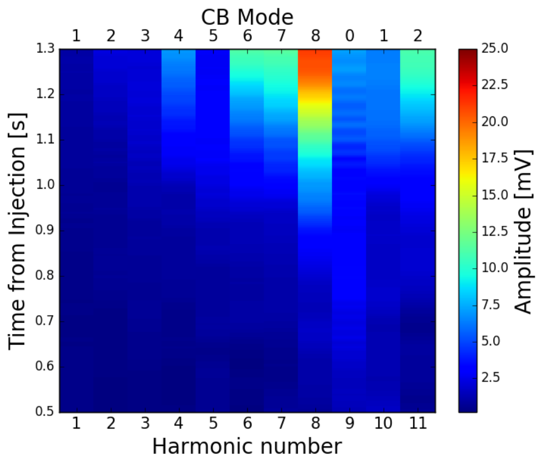

Figure 8: The time variation of the amplitudes of the USBs of the harmonic components.

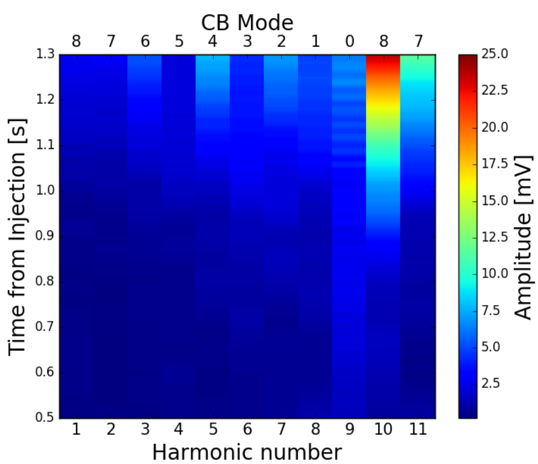

Figure 9: The time variation of the amplitudes of the LSBs of the harmonic components.

DISCUSSION

The results from both methods show that the CB mode $n = 8$ has the largest amplitude. Figure 10 shows the comparison of the time variation of the amplitudes of the CB mode $n = 8$ between the results of the bunch center motion analysis and the beam spectrum analysis. Both results show similar trend of growth. Thus, it is convincing that both methods are observing the same CB mode. The relation between the observables of two methods is left for the future study.

The strongest CB mode is found in the sidebands of the neighbor harmonics of the acceleration harmonic $h = 9$. The RF cavities have relatively large impedances in the neighbor

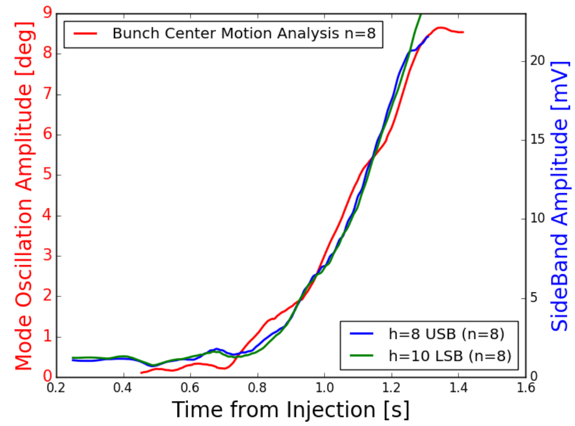

Figure 10: Comparison between the bunch center motion analysis (Red) and the frequency spectrum analysis (Blue for the USB of $h = 8$, Green for the LSB of $h = 10$).

harmonics and these impedance are compensated by the RF feedforward system [5]. The remaining impedances in the neighbor harmonics due to imperfection of the compensation is considered to be the possible source of the CBI in the MR.

Many CB modes with noticeable amplitudes other than $n = 8$ are observed in the results of both methods. The uneven bunch filling pattern of the J-PARC MR, in which 8 out of 9 buckets are filled by the bunches, is a possible source of of the excitation in the multiple CB modes.

SUMMARY

The coupled bunch instability is an issue to achieve the beam intensities beyond 500 kW in the J-PARC MR. To mitigate the CBI, we apply two methods to identify the CB modes. One method uses the motion of bunch centers, and the other uses the frequency spectrum. Both methods show a consistent result that the CB mode $n = 8$ had the largest amplitude. Both methods show similar trend of growth for the CB mode $n = 8$. Thus, we consider that the CBI of the same CB mode is observed by two methods with different aspects. Since the strongest CB mode is found in the sidebands of the neighbor harmonics of the acceleration harmonic $h = 9$, the remaining impedances of the RF cavities in the neighbor harmonics due to imperfection of the compensation is considered to be the possible source of the CBI in the MR.

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