VARIOUS USAGES OF WALL CURRENT MONITORS FOR COMMISSIONING OF RF SYSTEMS IN J-PARC SYNCHROTRONS

Fumihiko Tamura*, Masanobu Yamamoto, Alexander Schnase, Masahito Yoshii, Chihiro Ohmori, Masahiro Nomura, Makoto Toda, Taihei Shimada, Keigo Hara, Katsushi Hasegawa
J-PARC Center, KEK & JAEA, Tokai-mura, Naka-gun, Ibaraki-ken, Japan

Abstract

Wall current monitors (WCM) for rf system commissioning are installed in the J-PARC synchrotrons, the RCS and the MR. The WCM signals are used as the input of the beam loading compensation system, and also used for diagnostics to adjust the rf system parameters. Since the rf and beam frequencies are in the range of a few MHz and several ten MHz, direct measurement of the WCM signals is possible. For the diagnosis, the WCM signals are taken by an oscilloscope with the revolution clock signal generated by the low level rf (LLRF) control system, and slices of the WCM waveform with lengths of the revolution periods are generated. By stacking the slices, one can get a mountain plot, which shows motions of bunches and variations of the bunch shapes. Also, time variations of the bunching factor, which are important for acceleration of high intensity proton beams, are obtained. The harmonic analysis is performed on the WCM signal and the cavity voltage monitor signal. By using complex amplitudes of them, one can calculate the impedance seen by the beam. We show examples of the analyzes described above. The rf parameters for high intensity beams have been successfully adjusted by using these analysis methods.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a multi-purpose high intensity proton accelerator facility, which consists of the linac, the rapid cycling synchrotron (RCS), and the main ring synchrotron (MR). At present, the maximum output beam power of the RCS and the MR is 300 kW and 200 kW, respectively.

In the RCS and the MR, wall current monitors (WCM) dedicated for rf system commissioning are installed [1, 2]. The WCMs are designed to have a high cut-off frequency more than a few 100 MHz, which is high enough compared to the beam frequency up to several ten MHz.

The low level rf (LLRF) control systems of the J-PARC RCS and MR are implemented by digital circuits to realize precise and reproducible rf control. The WCM signals are used as the input of the beam loading compensation [3], and used for diagnostics to adjust the rf parameters and patterns.

For the high power commissioning of the RCS and the MR, the information from the WCM is important and indispensable. The analysis of the WCM waveforms taken by a long memory oscilloscope is performed on a PC. In this paper, we show examples of the various analysis results of the WCM waveforms.

* fumihiko.tamura@j-parc.jp

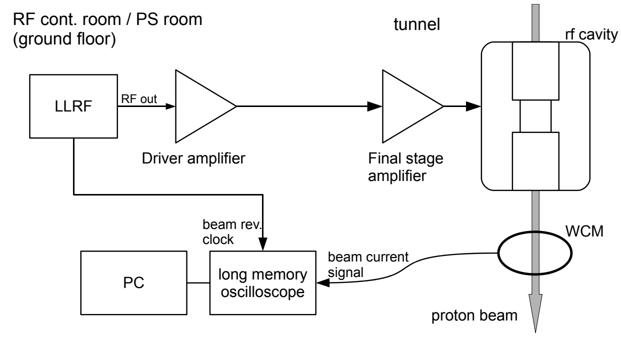

Figure 1: Measurement setup.

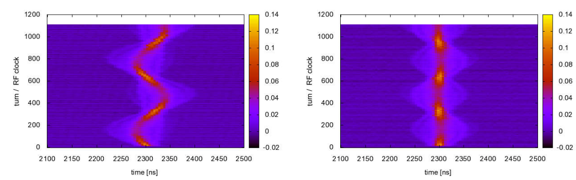

Figure 2: Mountain plots of the injected bunch. (Left) in case $f_{\rm rf} = 1.671650$ MHz, the momentum of the injected beam and the rf frequency are not matched. (Right) in case $f_{\rm rf} = 1.671750$ MHz, they are matched well.

BEAM CURRENT ANALYSIS USING WCM WAVEFORM SLICES

Since the beam frequencies are in the range up to several ten MHz, direct measurement of the WCM beam signal by using an oscilloscope is possible. As shown in Fig. 1, the WCM signal is taken together with the revolution clock signal, which is generated by the digital LLRF control system and precisely follows the accelerating frequency sweeps. The signals are recorded by a long memory oscilloscope and the waveforms are analyzed on a PC. Slices of the WCM waveform with lengths of the revolution period, which is calculated by using the revolution clock signal, are generated. Since the revolution clock signal follows the frequency pattern change, no additional information is necessary to generate the slices. By stacking the slices, one can obtain a mountain plot. Mountain plots are used to analyze the motions of bunches and variations of the bunch shapes. Figure 2 shows an example of the in-

ISBN 978-3-95450-119-9

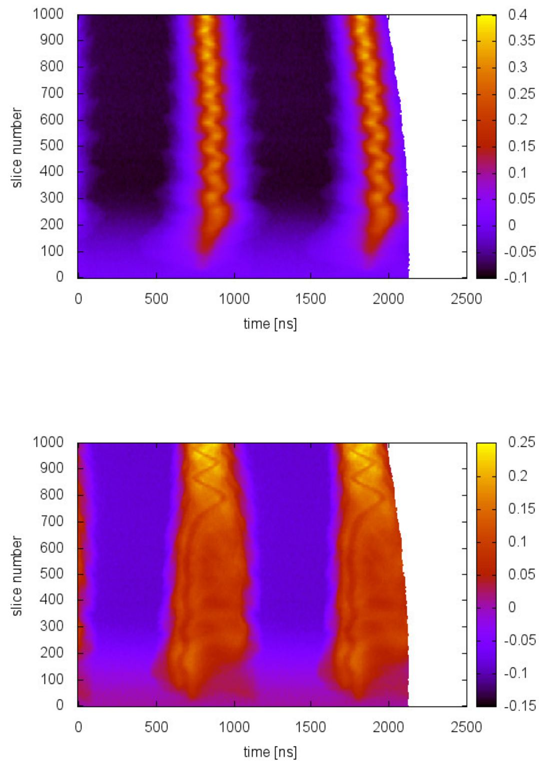

Figure 3: The mountain plots up to 1000 turns of the cases (top) without and (bottom) with the longitudinal painting.

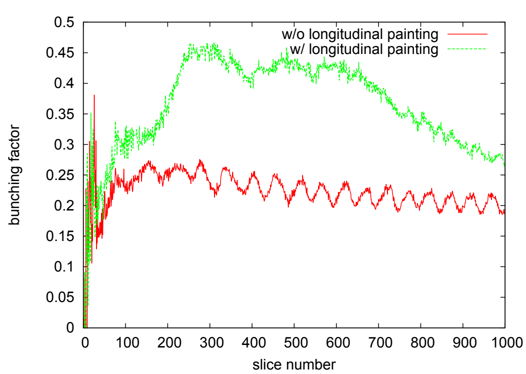

Figure 4: Comparison of the bunching factor up to 1000 turns of the cases without and with the longitudinal painting.

jection frequency correction in the MR using the mountain plots. If the injection rf frequency is not matched to the momentum of the injected bunch, dipole oscillations occur. In case of an rf frequency of $f_{\mathrm{rf}} = 1.671650$ MHz (Fig. 2 left), a dipole oscillation is observed and the amplitude corresponds to momentum mismatch of 0.1%. By using the slippage $\eta = -0.058$, the frequency is corrected, $f_{\mathrm{rf}} = 1.671750$ MHz (Fig. 2 right). The dipole oscillation disappears.

For high current acceleration in the RCS, the bunch shape control is a key to mitigate the space-charge tune shifts. The bunching factor (B_f), which is defined as the ratio,

$$B_f = (\text{average current})/(\text{peak current}), \tag{1}$$

is an important parameter. It is easy to calculate the bunching factor by using the slices of the WCM waveform.

To increase the bunching factor, the longitudinal painting scheme during the injection period is employed in the RCS. The longitudinal painting [4] is carried out by adjusting the RF system parameters and programs. We employ wide-band ($Q = 2$) magnetic-alloy (MA) loaded cavities so that the dual-harmonic operation is fully supported. In the dual-harmonic operation, each single cavity is driven by a superposition of the RF signals, the fundamental accelerating RF ($h = 2$) and the second harmonic RF ($h = 4$). Also, the momentum offset injection scheme and the second harmonic phase sweep are applied.

The mountain plots up to 1000 turns of the case with only fundamental rf and no momentum offset i.e. without the longitudinal painting, and the case with the 80 % second harmonic, the momentum offset of -0.2 % and the second harmonic phase sweep of 100 degrees are shown in Fig. 3. Also, the bunching factor plots without and with the longitudinal painting are shown in Fig. 4. The beam intensity is 2.5×10^{13} ppp, which corresponds to the beam power of 300 kW at the repetition of 25 Hz. In Fig. 3, one can clearly see that the bunch is widened with longitudinal painting. The bunching factor of more than 0.45 is achieved just after injection (at 250-th turn), while it was 0.25 in the case without longitudinal painting.

As described above, these analysis methods of the WCM waveform slices are very effective to adjust rf parameters.

HARMONIC ANALYSIS

The harmonic analysis of the beam current and the cavity voltage is important to investigate the beam loading and the impedance seen by the beam, because the wide-band MA cavity covers not only accelerating harmonic but also higher harmonics and the wake voltage in the cavity consists of these harmonics.

The harmonic analysis of the waveform is performed as follows. The full waveforms of the WCM and the cavity voltage monitor from the injection to the extraction are recorded together with the revolution clock signal. From revolution clock waveform, one can generate sine and cosine waveforms of the selected harmonics ($h = 2, 4, 6$ in case of the RCS) with unity amplitude on the PC. Then, the I/Q demodulation for the selected harmonic is performed by multiplying the sine and cosine waveforms with the monitor signal waveforms and applying a low-pass filter. The sine and cosine waveforms follow the accelerating frequency sweep, since they are generated from the revolution clock signal. By the I/Q demodulation, the complex amplitude of the selected harmonic is obtained.

ISBN 978-3-95450-119-9

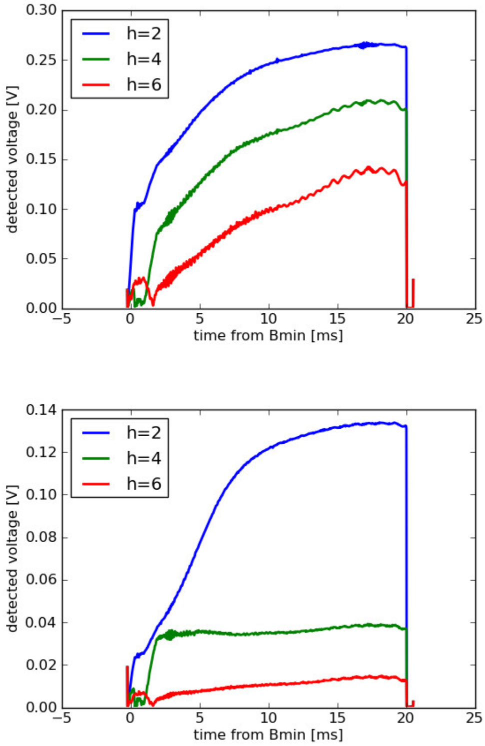

Figure 5: Typical harmonic components of (top) the WCM signal and (bottom) the cavity gap monitor.

By turning off the driving rf voltage of one of the cavities, it is possible to measure the wake voltage directly. The typical harmonic components of the WCM signal and the cavity gap monitor are plotted in Fig. 5. The beam intensity is 2.5×10^{13} ppp. Since the frequency sweep is slow compared to the wide frequency response of the MA cavity ($Q = 2$), a steady-state equation is a good approximation to calculate the time variation of the cavity gap impedance seen by the beam. Assuming steady state, the wake voltage in frequency domain is expressed as

$$V_{\rm cav}(\omega) = Z_{\rm cav}(\omega) \cdot I_{\rm beam}(\omega), \quad (2)$$

where ω is the angular frequency, $V_{\rm cav}(\omega)$ the gap voltage, $Z_{\rm cav}(\omega)$ the cavity gap impedance, and $I_{\rm beam}(\omega)$ the beam current. By using the equation and the conversions of the WCM and the cavity gap voltage monitor (beam current [A] = WCM voltage [V] / 0.05, gap voltage [V] = monitor voltage [V] $\cdot 3.35 \times 10^4$), the cavity gap impedance $Z_{\rm cav}(\omega)$ is obtained as a function of time. By using the frequency program, one can reconstruct the impedance curve in frequency domain. In Fig. 6, the reconstructed frequency response of the impedance seen by the beam is plotted. In the plot, the frequency response of the parallel circuit model ($R = 850\ \Omega$, $L = 50\ \mu$H, $C = 175$ pF) is also plotted. The measured impedance and the circuit model agree well.

Thus, the harmonic analysis of the WCM and cavity voltage monitor signal is very important for high power

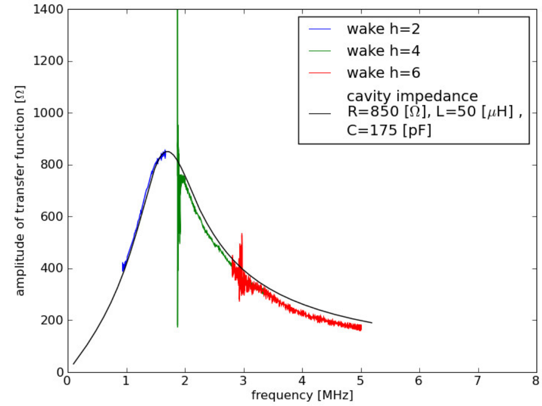

Figure 6: Translation to impedance. $Z(\omega) = V(\omega)/I(\omega)$.

beam commissioning. The analysis is applied to commissioning of the multiharmonic feedforward system for the beam loading compensation [3]. In the commissioning methodology described in the reference, the harmonic analysis is also used for the LLRF driving signal, so that the impedance seen by the beam with generating accelerating rf voltages and feedforward signals is analyzed. The feedforward system has been successfully commissioned and the impedance seen by the high power beam was reduced down to 1/30.

SUMMARY

In the RCS and the MR, WCMs dedicated for rf system commissioning are installed. As described above, various analysis methods on waveforms of the WCM are performed. The key is that the WCM waveform is captured with the revolution clock signal generated by the digital LLRF control system, which follows precisely the accelerating frequency sweeps. The analysis is performed on a PC. Commissioning of the rf system parameters using the analysis has been successfully performed for the high power operation in the RCS and the MR.

REFERENCES

[1] N. Hayashi, et al.: "Beam instrumentations for the J-PARC RCS commissioning", in Proceedings of EPAC08, Genoa, pp. 1125–1127, 2008.

[2] T. Toyama, et al.: "Beam diagnostics for the J-PARC main ring synchrotron", in Proceedings of Particle Accelerator Conference, Knoxville, Tennessee, pp. 958–960, 2005

[3] F. Tamura, et al.: "Multiharmonic rf feedforward system for beam loading compensation in wide-band cavities of a rapid cycling synchrotron", Phys. Rev. ST Accel. Beams, 14, 051004 (2011).

[4] F. Tamura, et al.: "Longitudinal painting with large amplitude second harmonic rf voltages in the rapid cycling synchrotron of the Japan Proton Accelerator Research Complex", Phys. Rev. ST Accel. Beams, 12, 041001 (2009).

ISBN 978-3-95450-119-9