BEAM ACCELERATION WITH FULL-DIGITAL LLRF CONTROL SYSTEM IN THE J-PARC RCS

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Abstract

In the J-PARC RCS (Rapid Cycling Synchrotron) we employ a full-digital LLRF control system to accelerate an ultra-high intensity proton beam. The key feature is the multi-harmonic RF signal generation by using direct digital synthesis (DDS) technology. By the system, highly accurate, stable and reproducible RF voltages are generated in the wide-band RF cavities loaded by magnetic alloy (MA) cores. The beam commissioning of the J-PARC RCS has been started in October 2007. The accelerators, the linac and the RCS, show good stability. The beam orbit and the longitudinal bunch shape are reproducible from cycle to cycle especially thanks to the stability of the linac energy, the RCS bending field and the frequency and voltage of the RCS RF. This reproducibility makes the beam commissioning efficient. We present the examples of the beam orbit and the beam signals. Also, we discuss the performance of the beam control and future plans.

INTRODUCTION

The beam commissioning of the J-PARC RCS (rapid cycling synchrotron) has been started in October 2007. Acceleration of 1×10^{13} protons per pulse (two bunches) was successfully performed in February 2008. We employ wide-band ($Q = 2$) RF cavities loaded by magnetic alloy (MA) cores to achieve the high accelerating voltage, which is necessary to accelerate the high intensity proton beam. Each cavity is driven by the superposition of the dual-harmonic RF signals for both of the acceleration and the bunch-shape control.

The beam commissioning of the RCS relating to the RF system has two modes, the 181 MeV "storage-ring" mode and the 3 GeV accelerating mode. In this paper we present the beam commissioning results in both modes.

FULL-DIGITAL LLRF SYSTEM

We employ a full-digital LLRF control system. The details of the system are described in [1]. The key feature is the multi-harmonic RF signal generation by using direct digital synthesis (DDS) technology. Each cavity is driven by the superposition of the fundamental and the second-harmonic RF signals. In the system we use common feedback loops as follows. 1) AVC (auto voltage control), for each of the cavities, 2) phase feedback, which compares the beam phase and the phase of the vector-sum of the cavity voltage, 3) radial feedback, the RF frequency is modulated by using the beam orbit. As of June 2008, we have not closed the phase and radial feedback loops in normal beam operation because the beam is stable without them. The digital monitor outputs of the orbit and phase signals from the feedback modules are only used for beam monitoring.

We generate the beam-revolution clock signal by the LLRF system. With the clock, the beam signals from the WCM (wall current monitor) are recorded by an oscilloscope (Lecroy WP950) at the sample rate of 200 Msamples/s for 20 ms, which corresponds to the duration from injection to extraction, to analyze the turn-by-turn bunch shape and to generate for example mountain plots.

BEAM COMMISSIONING

181 MeV "storage-ring" mode

In the "storage-ring mode", the RF frequency is constant. For the data shown here, it was 0.9388 MHz.

We measured the synchrotron frequencies (f_s) as the function of accelerating voltages by analyzing the WCM signals with a real-time spectrum analyzer. By measuring f_s, we can check the actual voltages felt by the beam. The measured and calculated frequencies are plotted in Figure 1. In the plot the x-axis is the square root of the voltage normalized by the harmonic number. The measured f_s are about 3.5 % higher than the calculations.

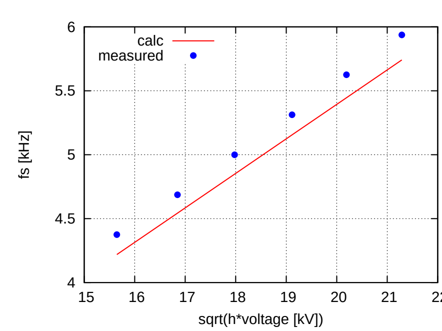

Figure 1: measurement and calculation of f_s.

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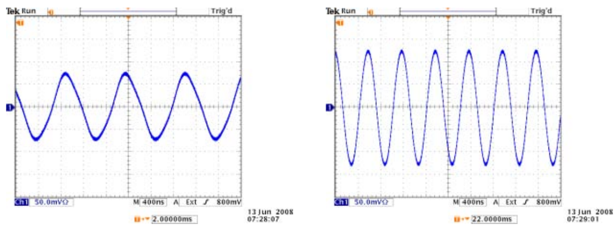

Figure 2: Gap voltage monitor signal. Left: 0.938 MHz (near injection), right: 1.67 MHz (near extraction).

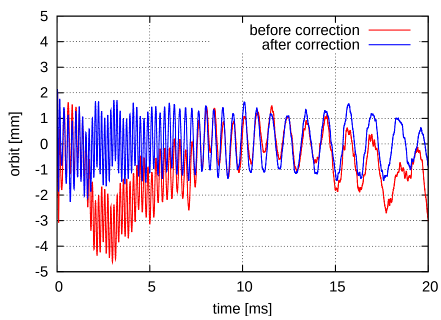

Figure 3: Orbit before (red) and after (blue) correction.

At the injection frequency, the distortion of the accelerating voltage due to the class-AB operation is relatively large as shown in Figure 2. The amplitude of the third-harmonic component is nearly 10% of the fundamental RF. We consider that this distortion causes the deviation of f_s.

3 GeV acceleration mode

Since the cycle-to-cycle fluctuation of the bending magnet field is quite small after the warming-up, we adjust the accelerating frequency pattern without the online radial feedback loop. We take an orbit signal of a full accelerating cycle and correct the frequency pattern using the following formula,

$$\Delta f_{\text{correction}} = f_{\text{rf}} \times \eta \times \frac{\Delta R}{(\text{dispersion})}. \quad (1)$$

After several iterations the orbit comes close to the center. In Figure 3, the orbit before and after correction are shown. Before correction, the deviations of the dipole oscillation center were -3.5 mm near 2 ms after the injection and -2 mm near the extraction. The orbit was within ± 1 mm after correction.

The beam current signal from the WCM is recorded for the turn-by-turn analysis. A typical beam current analysis is shown in Figure 4. In the figure, the average current per bunch, peak current and bunching factor (b_f) are plotted. We employ the chopped beam injection. One can see that the beam current increases during the 220 turn injection period. Then the bunch is accelerated with showing quadrupole oscillations. Also the mountain plot of the full 20 ms acceleration is shown in Figure 5.

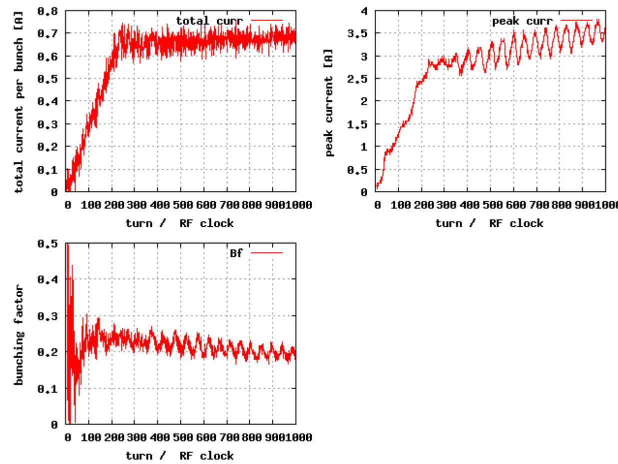

Figure 4: Beam current analysis up to 1000-th turn. Average current per bunch (upper left), peak current (upper right), bunching factor (lower).

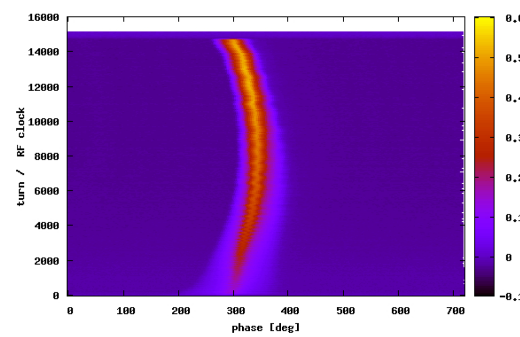

Figure 5: Mountain plot of a full acceleration cycle.

Effect of the third-harmonic on synchronous phase

The synchronous phase (ϕ_s) is obtained by subtracting the beam phase from the phase of the vector-sum cavity voltage. A typical ϕ_s with the voltage pattern with maximum voltage of 348 kV is plotted in Figure 6. In the figure, the expected ϕ_s is also plotted. The calculation and the measurement results agree in most parts of the accelerating cycle. This means that the accelerating voltage is very close to the expected value; therefore the AVC works properly. However, one can notice a small deviation from 1 ms to 7 ms.

We considered that this deviation is because of the voltage distortion by the third-harmonic shown in Figure 2, and performed a test of the cancellation of the third-harmonic.

We set the phase of the cavities as follows. The phases of a half of the cavities are set $+30$ degrees from the normal operation, and for the other half of cavities -30 degrees

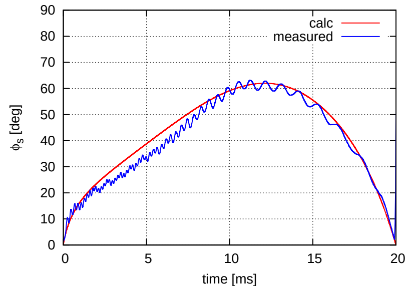

Figure 6: Measured and calculated synchronous phase. Maximum voltage is 348 kV.

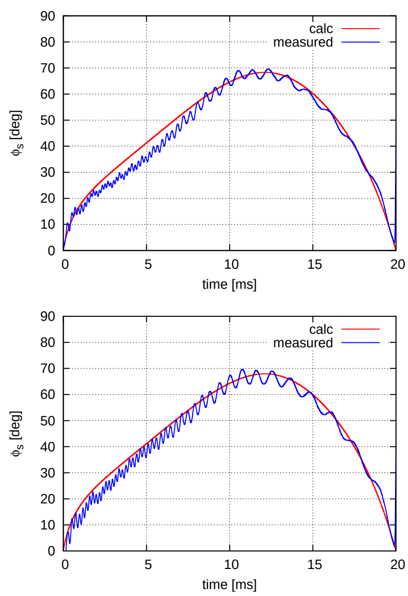

Figure 7: ϕ_s without (upper) and with (lower) third-harmonic cancellation. Maximum voltage is 333 kV.

are set. By this phase setting, the phase of the fundamental component is unchanged and the amplitude is scaled by $\sqrt{3}/2$ compared to the normal phase setting. On the other hand, the phases of the third-harmonic of the odd- and even-number cavities are $+90$ and -90 degrees, respectively. Therefore the third-harmonic component is canceled.

The comparison without and with this cancellation is shown in Figure 7. The maximum vector-sum voltages are set to 333 kV in both cases. In case of the third-harmonic cancellation, the voltage is set taking the reduction by the phase setting into account. Much smaller deviation from the calculation was observed in the case with the third-harmonic cancellation.

Thus, we confirmed that the deviation of ϕ_s is because of the cavity voltage distortion by the third-harmonic component. Since the deviation is not large and the direction of the deviation is to the safe side, we operate with the voltage distortion as is.

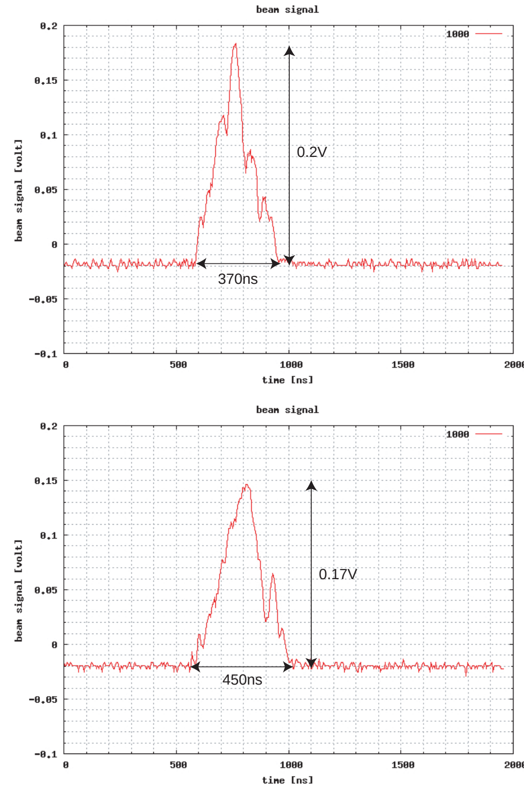

Figure 8: Bunch signals from WCM at 1000-th turn (2 ms) without (upper) and with (lower) the second-harmonic RF (max 50% amplitude of the fundamental).

Acceleration with second-harmonic RF

A preliminary beam test with the second-harmonic RF [2] was performed in February 2008. In the test, the beam was injected for only 100 μs (500 μs is the designed value). Bunch signals at the 1000-th turn after the injection without and with the second-harmonic RF are shown in Figure 8. The maximum amplitude of the second-harmonic is 50% of the fundamental RF. One can see that the bunch is lengthened and the peak current is reduced with the second harmonic, while there are filaments due to the short injection time.

OUTLOOK

The beam test for the longitudinal painting with the second-harmonic RF and the designed macro-pulse width (500 μs) will be performed in the end of June 2008.

REFERENCES

[1] F. Tamura et al., "Low Level RF Control System of J-PARC Synchrotrons" in the proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee, p. 3624–3626

[2] F. Tamura et al., "Dual-harmonic AVC for J-PARC RCS", to be published in PRST-AB