MULTI-HARMONIC RF CONTROL SYSTEM FOR J-PARC RCS

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Abstract

The RF cavity of J-PARC Rapid Cycling Synchrotron (RCS) has a low Q value and a wide band which covers the frequency from the accelerating frequency to the second harmonic frequency. The cavity is driven by a composite signal of the fundamental RF and the second harmonic RF. The system acts as a bunch shaping system as well as an accelerating system. In this presentation, a multi-harmonic RF control system is studied. The signal processing is based on a combination of digital hardware like 16 bit multipliers, arithmetic units, and FPGAs with commercially available signal processors. The beam loading compensation is a critical issue because of the high beam-current in the ring. The RF feedforward compensation system is discussed. Also the stability is discussed under the beam feedback loops.

INTRODUCTION

Japan Proton Accelerator Research Complex (J-PARC) is a project of a high-intensity accelerator complex which consists of 400 MeV linac, 3 GeV rapid cycling synchrotron (RCS), and 50 GeV synchrotron (MR).

The RCS accelerates the beam from 180 MeV (will be 400MeV) to 3 GeV in 20 msec. The harmonic number of the RCS is 2, and the number of the bunches in the ring is 2 for RCS users and 1 for the MR injection. The fundamental accelerating frequency varies from 0.94 to 1.67 MHz. The maximum accelerating voltage is 435 KV by 12 RF cavities. The average circulating beam current is from 3.8 amperes at the injection and 6.7 amperes at the extraction.

Since the beam current is high, the bunching factor must be as large as possible to alleviation the space charge effects. We employ two techniques as following; (1) the momentum-offset multi-turn injection scheme and (2) making a wide potential well by superposing the second-harmonic ($h = 4$) RF voltage. At the injection, the second harmonic voltage is relatively high as $V_2/V_1 > 0.5$ where V_1 and V_2 are the fundamental and the second harmonic RF voltage respectively, to make the bunch shape flatten effectively (as shown in Figure 1). The fundamental and the second harmonic RF voltages are fed into the same cavity. We employ a magnetic-alloy (MA) loaded cavity without a tuning loop to realize a high accelerating voltage. Hence, the cavity must be wide-band and must have a low Q-value to cover the frequency range from the fundamental to the second harmonic frequencies. The Q-value of the RCS cavity is to be about 2.

The LLRF controls for this multi-harmonic system are discussed. Also, a scope of multi-harmonic beam loading is taken into account and the means of loading compensation are discussed.

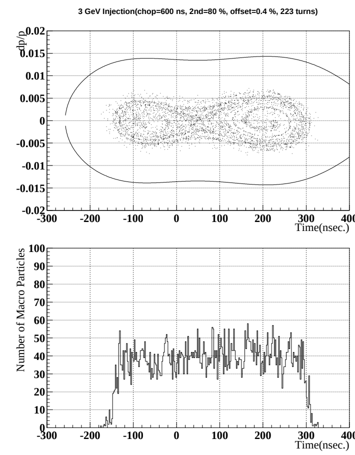

Figure 1: A simulated flat bunch generated by using the momentum-offset injection scheme and applying the second-harmonic voltage ($V_2/V_1 = 0.8$).

MULTI-HARMONIC LLRF SYSTEM

The LLRF block diagrams for the J-PARC ring RF are shown in Figure 2 and 3. The whole system is based on digital signal processing with digital hardwares like 16 bit multipliers, arithmetic units, and FPGAs with commercially available signal processors.

The core of the system is the Direct Digital Synthesis (DDS) technology. By using DDS, the multi-harmonic signals are directly generated without PLL, and the signals are easily synchronized. In the RCS LLRF system, the phase-counter block accumulates the phase by proper steps corresponding to the frequency pattern, and generates sawtooth (phase) waves of the harmonics of $h = 1, 2, 3, 4, 5$. The fundamental ($h = 2$) and the second-harmonic ($h = 4$) phases are used for the generation of accelerating signal, for the feedforward, and for the phase-loop. The other harmonics ($h = 1, 3, 5$) are used only for the feedforward. We discuss on the feedforward beam loading compensation in the later section.

The feedback loops are common one. The radial loop, the phase loop and the AVC (Auto Voltage Controller). Note that there is no cavity tuning loop since the cavity is an MA-loaded one without tuning. The radial loop controls the frequency and the phase loop gives the offset of the phase. In the second-harmonic phase loop, the phase offset

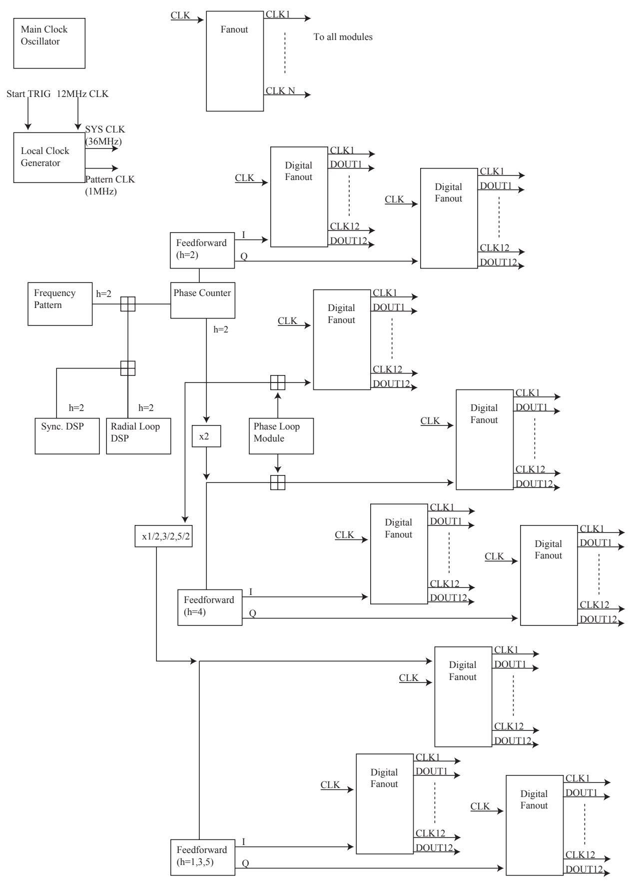

Figure 2: Block diagram of LLRF system.

is determined by the difference between the fundamental cavity RF phase and the beam phase, so that the fundamental and the second harmonic signals follow the beam with perfectly synchronized steps and the composite of the RF bucket keeps the sharpe.

Each of the 12 cavities has own phase pattern and the amplitude pattern to compensate the amplifier gain difference and cavity impedance, and also to realize the counter-phasing between each cavity.

BEAM LOADING COMPENSATION

The circulating beam current in the RCS is fairly high and the beam loading effects have to be carefully considered. In the RCS, the parameters are chosen so that relative loading factor Y is less than 1, except near the injection and the extraction[5], while the beam current is as same as the generator current during acceleration. Y is fairly higher than 1 at the extraction because the RF voltage is small to match the RF bucket with MR RF bucket. The phase of the fundamental accelerating voltage in the RF cavities goes far from the correct phase without compensation. The beam loading must be compensated for stable acceleration.

Furthermore, since the cavity has a low Q-value, the higher harmonic voltages are induced in the cavity. Figure 4 shows the Fourier components of the beam current. The

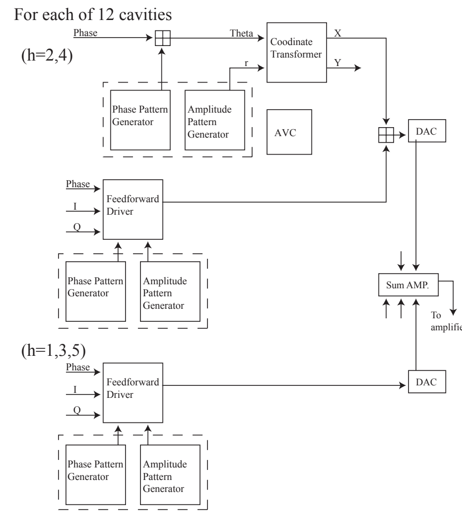

Figure 3: Block diagram of LLRF signal control unit for each cavity.

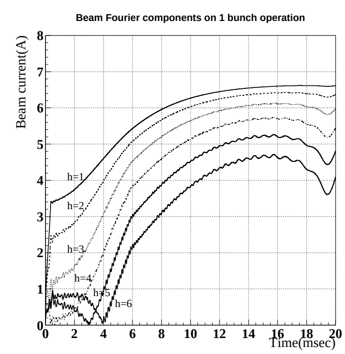

Figure 4: Fourier components of the beam current.

induced higher-harmonic voltages cause the bucket distortion. The distorted RF buckets during the acceleration and near the extraction are illustrated in Figure 5. The figure shows that the bucket distortion is not very crucial when the relative loading is not very high. However, one can see that the bucket is seriously distorted when Y is large. In order to suppress this bucket distortion, the beam loading compensation of higher harmonic component is necessary [6]. In the two-bunch acceleration case, $h = 2, 4...$ components must be compensated. Additionally, $h = 1, 3, 5...$ components also have to be cancelled when the ring accelerates the one-bunch beam for the MR injection. A particle tracking simulation result in the case of two-bunch acceleration is shown in Figure 6. The results show that the bucket distortion is not very serious and no strong emittance blow-up occurs, if up to the second harmonics ($h = 4$) are cancelled by a feedforward system.

A prototype feedforward module has been designed and built [7]. A test with real beam signals of KEK-PS MR has been performed in December 2002. We tried to pick up only the accelerating frequency (6.02 MHz) signal from the beam signal including revolution frequency components at

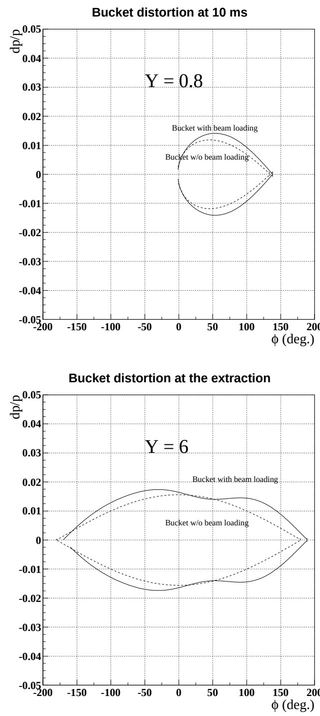

Figure 5: Distorted buckets during the acceleration and near the extraction (two-bunch operation case).

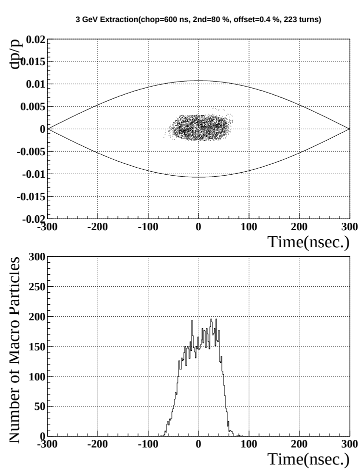

Figure 6: Particle tracking simulation results with $h = 2, 4$ feedforward, in the case of two-bunch acceleration.

the injection period. The results are shown in Figure 7. A 20 dB separation was achieved. Since 6 MHz is more than the second harmonic frequency of J-PARC RCS, the basic configulation of the module has a feasibility to the application for the real J-PARC RCS.

SUMMARY

We summarize the presentation as below.

- In the J-PARC RCS, an MA-loaded low-Q cavity is employed to realize the multi-harmonic drive. The system acts as a bunch shaping system as well as an accelerating system.
- The multi-harmonic LLRF system is based on the DDS technology.
- An RF feedforward system is to be employed to compensate the beam loading. In the case of the single-bunch operation, the components of $h = 1, 3, 5$ must also be cancelled as well as the cavity-drive components ($h = 2, 4$).

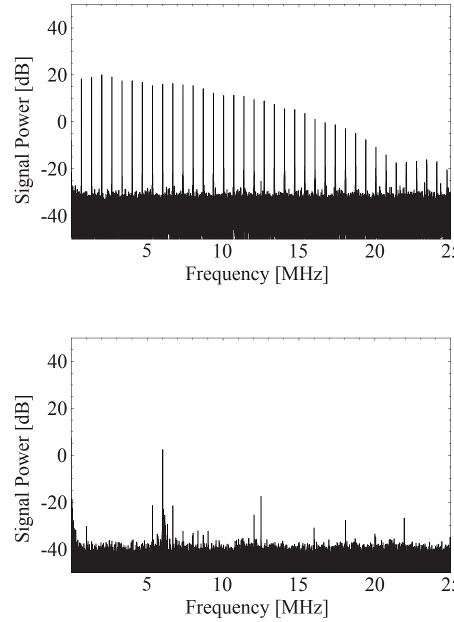

Figure 7: Spectrum of the beam signal at the injection (top) and the output of the feedforward module, center frequency is 6.02 MHz (bottom).

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