DEVELOPMENT OF THE FEEDFORWARD SYSTEM FOR BEAM LOADING COMPENSATION IN THE J-PARC RCS

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Abstract

In the J-PARC Rapid Cycling Synchrotron (RCS), the heavy beam loading effects due to the high intensity proton beam must be compensated for stable acceleration. The beam feedforward technique is used to compensate the beam loading in the RCS. We present the development of the feedforward system. We designed and built the full-digital system with modern FPGAs to realize high accuracy, stability and predictability of the compensation. Because of the low Q value of each accelerating cavity, the wake voltage consists of not only the accelerating harmonic component but also higher harmonics. Thus, the system is designed to compensate the beam loading at several harmonics. The system has two parts. In the first part, vector components of the selected harmonic are detected from the beam signal picked up by a wall current monitor. The compensation RF signal is generated from the vector components with proper gain and phase in the latter part. The gain and phase are set individually for each harmonic and each of the twelve cavities. We also present the preliminary test results of the newly developed modules.

INTRODUCTION

J-PARC [1, 2] is a high-intensity proton accelerator complex project. The complex is composed of 181 MeV linac, 3-GeV Rapid cycling synchrotron (RCS), and 50-GeV synchrotron (MR). The beam power in the RCS is to be in the order of 1MW. The beam current is very high and the beam loading effects must be investigated well [3] and the beam loading compensation system is necessary.

The RF parameters of the RCS are shown in Table 1. Magnetic Alloy (MA) loaded cavities are employed to realize high accelerating voltages. The Q-value of the RCS cavity is chosen as 2. No tuning loops are necessary to cover the accelerating frequency sweeps. Also, a single cavity is driven by the superposition of multi-harmonic RF signals. The fundamental ($h = 2$) signal is for the acceleration of the beam and the second harmonic ($h = 4$) is to modify the RF bucket for the bunch shape control.

In the RCS, the beam feedforward method is employed to compensate the heavy beam loading [4, 5]. The wake voltage in the RF cavity consists of not only the fundamental accelerating RF component ($h = 2$), but also the other harmonics ($h = 4, 6$). Thus, the multi-harmonic compensating signals are generated from the beam signal picked up by the wall current monitor (WCM). The compensating signal is generated so that the final amplifier generates a current which cancels the wake voltage. Each harmonic component of the compensating signal is adjusted in amplitude and phase because of the frequency response of the RF system.

The LLRF system of the RCS including the beam loading compensation system is now under construction[6, 7]. The full-digital system is based on direct digital synthesis (DDS). In this presentation, we discuss the implementation details of the compensation system. We also present the preliminary test results of the compensation modules.

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IMPLEMENTATION DETAILS

The block diagram of the beam loading compensation system is shown in Figure 1 and Figure 2. The details of the blocks are described in the following sections. We are building these modules with modern FPGAs. The high-performance arithmetic functions of FPGA is necessary for the realization of FIR filter in the I/Q signal detection blocks.

BCA (Beam Current Analysis) module

In the BCA (Beam Current Analysis) module, the vector components of the selected harmonic are detected from the beam signal picked up by a WCM. The beam signal from the WCM is digitized by the AD converter with the sample frequency of 36 MHz. The signal is led into the I/Q signal detection blocks for the $h = 2, 4, 6$ harmonics. In each block, the beam signal is multiplied by cosine and sine signals, which have unity amplitude. After the low-pass filters (LPF), the I/Q vector signals contain the information of the selected harmonics. The bandwidth of the low-pass filter

Table 1: Parameters of the RCS RF.

circumference	348.3 m
energy	0.181–3 GeV
Accel. freq.	0.94–1.67 MHz
harmonic number	2
max RF-voltage	450 kV
repetition period	40 msec
duty (power)	30%
No. of cavities	12
Q-value	2
average power	120 kW/cavity

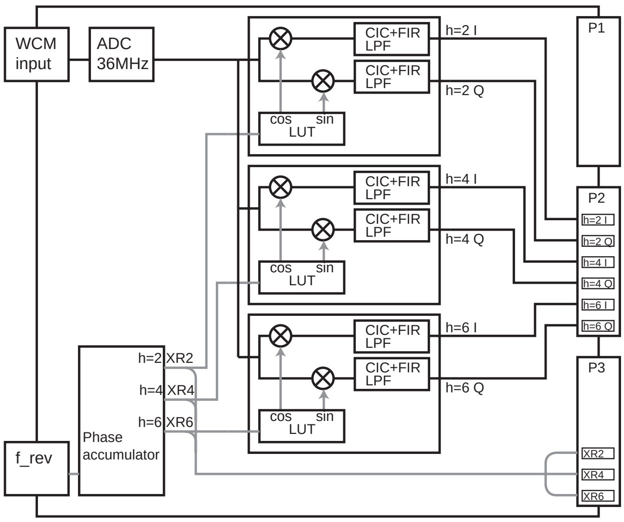

Figure 1: BCA (Beam Current Analysis) module, main part.

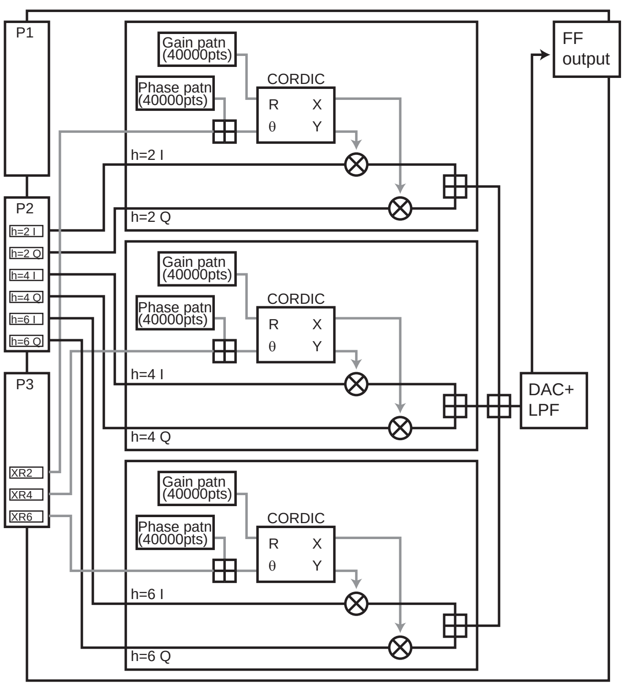

Figure 2: FFC (Feedforward Controller) module, main part.

is designed as 200 kHz to reject all the other harmonics. The minimum frequency difference to the next harmonic is 470 kHz at the injection time.

The cosine and sine signals are generated by a lookup table with the XR2, XR4 and XR6 phase reference signal. The phase accumulator generates these phase reference signals by using the frequency information from the module "Sweep Pattern Generator (SPG)"[6]. By basic arithmetic operation, higher harmonic phase signals are generated without phase-locked loops (PLL), so that the XR2 and the higher harmonic phase reference signals are perfectly synchronized.

Finally, the I/Q vectors of the $h = 2, 4, 6$ harmonics are distributed to the FFC (Feedforward Controller) modules via the backplane. The phase reference signals (XR2, XR4 and XR6) are distributed as well.

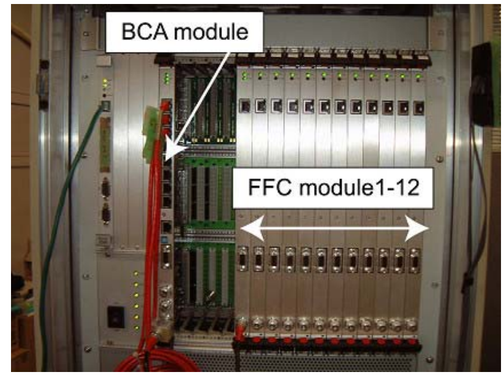

Figure 3: BCA and FFC modules in the 9U VME chassis.

FFC (Feedforward Controller) module

Each of the twelve RF cavities has its own FFC (Feedforward Controller) module. The I/Q vector of each harmonic ($h = 2, 4, 6$) is input from the backplane. The I/Q vector (I_h, Q_h) of the harmonic h is represented as

$$I_h = A_h \sin(\phi_h) \tag{1}$$
$$Q_h = A_h \cos(\phi_h), \tag{2}$$

where A_h and ϕ_h are the amplitude and the phase of the harmonic component, respectively. The vector is multiplied with a vector (X_h, Y_h),

$$X_h = G_h \cos(\omega_h t + \psi_h) \tag{3}$$
$$Y_h = G_h \sin(\omega_h t + \psi_h), \tag{4}$$

where ω_h is the frequency of the harmonic, G_h and ψ_h are the gain and the phase chosen to generate the proper cavity voltage which cancels the wake voltage. The block outputs the RF signal as follows,

$$G_h \cdot A_h[\cos(\omega_h t + \psi_h)\sin(\phi_h) + \sin(\omega_h t + \psi_h) A_h \cos(\phi_h)] = G_h \cdot A_h \sin(\omega_h t + \phi_h + \psi_h). \tag{5}$$

According to the frequency sweep the characteristics of the RF cavities change, thus, the gain and the phase are implemented as patterns. The $h = 2, 4, 6$ compensation signals are summed up and converted to the analog signal. After the analog LPF (removing aliasing) the signal is output. The output signal is summed with the RF driving signal and sent to the amplifiers.

The function of the combination of the BCA and the FFC is essentially a band-pass filter which has passbands around the frequency of the harmonics $h = 2, 4, 6$. The passbands follow the accelerating frequency sweep.

A picture of the BCA and the FFC in the 9U VME chassis is shown in Figure 3.

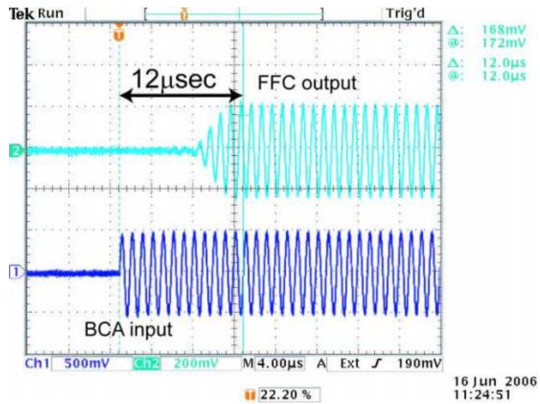

Figure 4: Group delay of the compensation system.

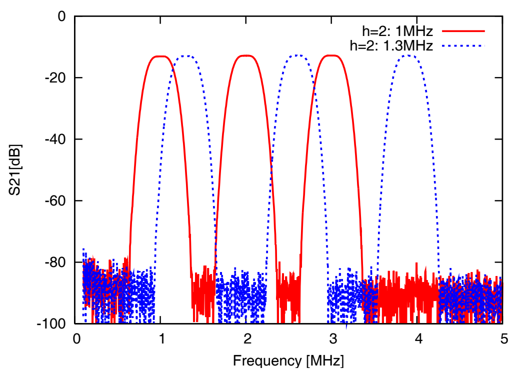

Figure 5: Frequency responses for the different accelerating frequencies.

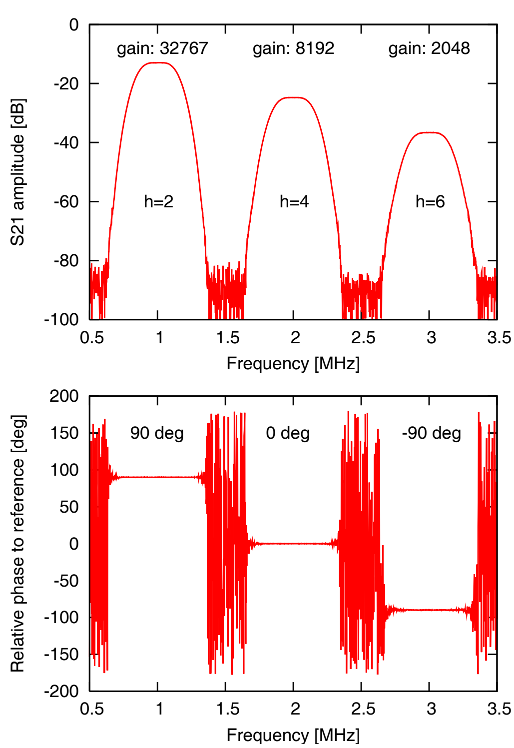

Figure 6: The gain and the phase of each harmonic is set individually.

PRELIMINARY TEST RESULTS

Preliminary tests have been performed. The group delay from the "WCM in" of the BCA to the FFC output is about 12 μsec (see Figure 4). The FIR filters in the I/Q signal detection part is the main source of this delay. The frequency response of the system is measured by network analyzer (8753E). Figure 5 shows the responses at two different accelerating frequencies. The solid line and dashed line correspond the accelerating frequencies of 1 MHz and 1.3 MHz, respectively. In the measurement, the gain of the each harmonic is set to 32767 (maximum). The rejection of the stopband is around -75 dB. The -3 dB bandwidth of the passband is 141 kHz.

It is demonstrated that the gain and the phase of each harmonic can be defined individually in Figure 6. In the figure the arbitrary gain and phase are set. The gain of the harmonics $h = 2$, $h = 4$ and $h = 6$ are 32767 (maximum), 8192, and 2048, respectively. Also, the phase of the harmonics are set to 90, 0, -90 degrees respectively. The amplitude and relative phase responses of the harmonics are as expected.

SUMMARY

We summarize the presentation as follows.

- MA-loaded RF cavities are employed in the RF systems of the J-PARC RCS. A beam loading compensation system is necessary for stable acceleration.
- The beam feedforward method is employed for compensating the heavy beam loading.
- Preliminary tests of the beam loading compensation system have been performed.

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