PRECISE RF CONTROL SYSTEM OF THE SCSS TEST ACCELERATOR

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Abstract

We present the development and performance of the low-level rf control system of the SCSS test accelerator. The rf phase and amplitude of the acceleration field are precisely controlled by a low-level rf system comprised of IQ modulators / demodulators and VME waveform generators / digitizers. Recent improvements established high-resolution phase and amplitude setting capabilities of 0.01 degree and 0.01%, respectively. In addition, the phase disturbance due to the temperature drift of an acceleration cavity was reduced by tuning a precise temperature regulation system. The temperature fluctuation was improved to be 0.01 K rms. As a result, the rf phase and amplitude stabilities of sub-harmonic buncher cavities were achieved to be 0.02 degree rms and 0.03% rms, respectively. The saturated FEL radiation in the wavelength region of 50–60 nm is stably generated.

INTRODUCTION

The X-ray free electron laser (XFEL) facility at SPring-8 is under construction. The test accelerator for XFEL, called SCSS test accelerator, is in operation and stably supplies VUV-FEL beams to users [1]. In general, a short wavelength (< 100 nm) FEL requires a high peak current (a few kA) and low-emittance (~1 π mm mrad) beam. To obtain such a high-quality beam, we designed a precise beam injector system comprising a thermionic electron gun, sub-harmonic buncher cavities and bunch compressors. To compress the bunch length without the growth of emittance, the phase and amplitude of the acceleration cavities should be precisely controlled. In the XFEL case, the timing fluctuation of the acceleration rf field must be less than 100 fs, which corresponds to an rf phase of 0.2 degree in the C-band main accelerator (5712 MHz) and 0.01 degree in the 238 MHz sub-harmonic buncher cavity. Since this requirement was too difficult to realize during the construction phase of the test accelerator, timing precision of the low-level rf system of the test accelerator was originally designed to be as low as sub-picosecond [2]. However, we found that the precision was not sufficient for the saturation of FEL radiation, even in the VUV-FEL case. Therefore, we improved the resolution and stability of the rf system. In addition, the cooling water system of the acceleration cavities was also optimized to stabilize the resonant frequency further. In this paper, we present recent improvements and performances of the low-level rf control system of the SCSS test accelerator. Especially, we focus on the rf stability of the 238 MHz and 476 MHz sub-harmonic buncher cavities.

RF CONTROL SYSTEM

A block diagram of the low-level rf control system is given in Fig. 1. Reference rf signals are distributed from a master oscillator, which is manufactured to be very low-phase noise (i.e. low timing jitter). To generate a pulsed rf signal with appropriate phase and amplitude, the reference signal is processed by an IQ (in-phase and quadrature-phase) modulator [2]. The waveform of a baseband signal is generated by a VME high-speed D/A converter board [3]. The pulsed rf signal modulated with the IQ modulator is amplified by a high-power amplifier, such as a solid-state amplifier or a klystron, and fed into an acceleration cavity. A tiny part of an rf power in the accelerator cavity is picked up and detected with an IQ demodulator [2]. The waveforms of the detected baseband signals are recorded by a VME high-speed A/D converter board [3]. To stabilize the acceleration rf field in the cavity, the cavity temperature is kept constant by a precise temperature regulation system [4]. The rf phase and amplitude are also controlled by a PID (Proportional-Integral-Derivative) feedback control program. The details of each component are described below.

IQ Modulator and Demodulator

The IQ modulator is a vector rf modulator. The output of the IQ modulator, $V(t)$, is

$$V(t) = I(t)\cos(\omega t) + Q(t)\sin(\omega t), \qquad (1)$$

where ω is the angular frequency of a carrier wave and $I(t)$ and $Q(t)$ are input baseband signals of in-phase and quadrature, respectively. The IQ modulator can generate any rf signal with arbitrary phase and amplitude waveforms. Conversely, the IQ demodulator receives an rf signal, and reproduces the phase and amplitude baseband waveforms. This function is realized by a microwave IC including two mixers and a quadrature phase splitter. The phase error was measured to be 0.5 degree and the amplitude error was a few % [2]. To reduce the temperature drift, rf circuits are mounted on a heated plate and the temperature is regulated within 0.1 K.

VME High-speed D/A and A/D Converters

Phase and amplitude waveforms for the IQ modulator are generated with a VME high-speed D/A converter board, and those of the IQ demodulator are recorded by a VME high-speed A/D converter board [3]. Both D/A and A/D boards have 12-bit resolution. The corresponding phase and amplitude resolutions are 0.03 degree and 0.05 %, respectively. The sampling rate is 238 MHz, which is a sub-harmonic of the main accelerator frequency, 5712 MHz. For the D/A board, the D/A

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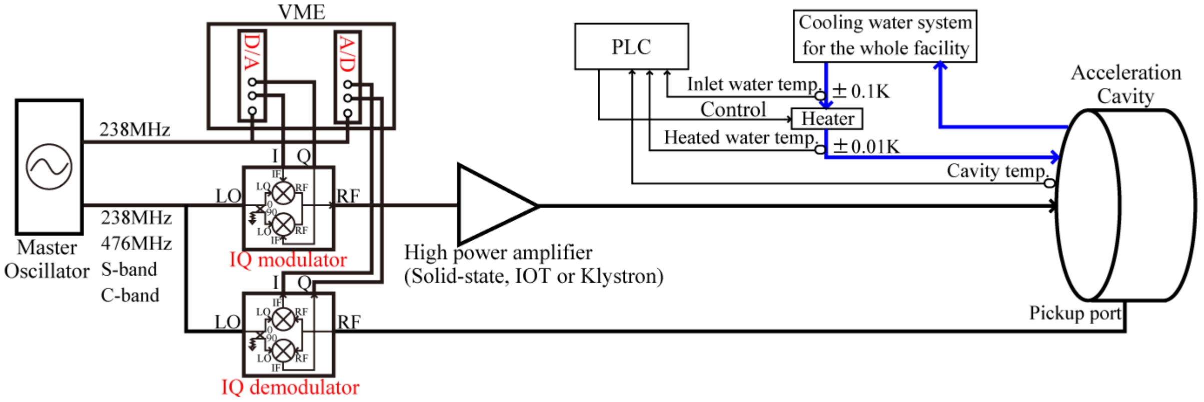

Figure 1: Block diagram of the low-level rf system and the precise temperature regulation system.

converter IC, itself, has 14-bit resolution. However, the resolution is rounded off to 12 bits by the firmware of FPGA on the D/A board to match the A/D converter resolution.

Temperature Regulation System

To prevent drift of the resonant frequency of the acceleration cavity, the cavity temperature is demanded to be kept constant. Suppose that the resonant frequency varies from f_0 to $f_0 + \Delta f$, the phase of the rf field in the cavity may change as

$$\Delta\varphi = 2Q_L \cdot \frac{\Delta f}{f_0}\ \text{[rad.]}, \tag{2}$$

where Q_L is the loaded Q value of the cavity, typically 10000. In general, $\Delta f / f_0$ is 17 ppm/K, which comes from the thermal-expansion constant of cupper. Therefore, the rf phase shift is on the order of 10 degrees/K. To reduce the rf phase fluctuation down to 0.1 degree, the temperature drift must be less than 0.01 K. Since the temperature stability of a cooling water system for the whole facility is not sufficient ($\pm$ 0.1 K), a precise temperature regulation system [4] is equipped. A block diagram of the system is shown in Fig. 1. This system has an electric heater between the water inlet of the cavity and the cavity water jacket to control the water temperature. The temperatures of the water and cavity are measured and the heater power is controlled in order that the cavity temperature is kept within a few 0.01 K. This function is implemented by a programmable logic controller (PLC).

IMPROVEMENTS AND PERFORMANCE

At the beginning of machine tuning, the stability of the rf phase and the amplitude was sufficient to observe the FEL amplification. However, it was not sufficient for the FEL saturation. To stabilize the acceleration rf field further, some of the components were improved. We tuned the temperature regulation system, introduced a PID feedback control program and enhanced the resolution of the VME D/A board.

Tuning of the Temperature Regulation System

At first, although the cavity temperature was stabilized within 0.1 K, a slow fluctuation of the rf phase was still observed. We found that the fluctuation was caused by hunting of the cavity temperature. The reason for the hunting was a phase delay due to the large heat capacity of the cavity. Therefore, we changed the temperature observation point from a cavity body surface to a heated water inlet. We also adjusted the control parameters and implemented a digital low-pass filter to the thermometer module. Although the cavity temperature, itself, is out of the control loop, the cavity temperature is sufficiently regulated because any temperature disturbances, such as room-temperature drift, are moderated by the large heat capacity and because absorbed heat is removed by the cooling water before a temperature fluctuation. The performance of the temperature-regulation system is shown in Fig. 2. While the temperature drift of the incoming water is about 0.2 K, the cavity temperature is stabilized within $\pm$ 0.02 K by the regulation system. Since the resolution of the thermometer is 0.01 K, this performance is close to the measurement limit.

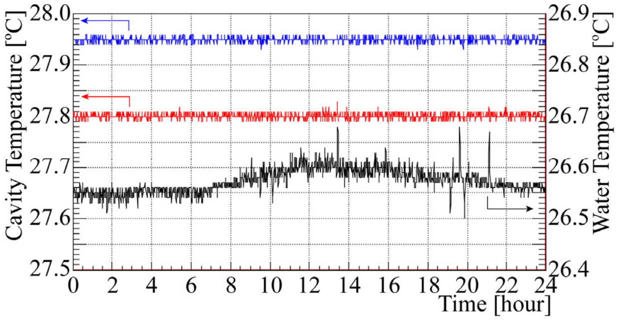

Figure 2: Trend graphs of the temperatures of the 238MHz cavity (red), the 476MHz cavity (blue) and water from the facility (black).

PID Feedback Program

The acceleration rf phase and the amplitude are stabilized by PID feedback software. The phase and the amplitude manipulated with the IQ modulator are adjusted by the software using measured signals of the cavity pickup with the IQ demodulator. The refresh rate is 1 Hz, while the repetition rate of the accelerator is 60 Hz, maximum. Therefore, the fluctuation frequency of less than 0.1 Hz is regulated. The feedback program worked well and the stability was almost equal to the resolution limit (12 bits) of the D/A and A/D boards. However, we still observed a correlation between the FEL intensity and the rf phase set to the D/A board. Only one digit change of the phase value seriously affected the FEL intensity. Therefore, some resolution enhancements of the D/A and A/D boards were demanded.

Enhancement of resolution

Since the D/A board originally has 14-bit resolution D/A converter chips, one possibility is to upgrade the firmware of the board. However, we started to improve the software because a firmware modification takes a long time and requires great effort. The firmware upgrade had been postponed when the effect of the software improvement was confirmed. The software improvement was implemented by applying a dither [5] to the flat part of a waveform amplitude. To represent 1/4 of the least-significant bit (LSB), for example, LSBs are set to be high in 25% of the total clocks, and the others (75%) are set to be low. Although the dithering process produces high-frequency noise, it is eliminated by a low pass filter on the board and a narrow bandwidth of the cavity resonance. We confirmed that at least 2 bits were enhanced and a phase resolution of 0.01 degree and an amplitude resolution of 0.01% were achieved. Recently, a firmware upgrade has just been completed and the same performance was confirmed.

An enhancement of the A/D board resolution was also achieved by software. Since the feedback program uses only one data point in one second, we implemented an averaging routine to the data-acquisition program. The number of averaging points is 10, because the accelerator repetition rate is 10 Hz at this moment. The random noise is reduced to be $1/\sqrt{10}$, corresponding to a resolution enhancement of 1.7 bits.

Trend graphs of the phase and amplitude of the 238MHz sub-harmonic buncher cavity are shown in Fig. 3 as an example. The amplitude stability is 0.03% rms and the phase stability is 0.02 degree rms.

FEL Performance

After the improvements of the rf and cooling system, accelerator tuning was efficiently achieved and the FEL intensity reached saturation in the fall of 2007 [1]. A trend graph of the FEL intensity is shown in Fig. 4. The fluctuation is approximately 10%, which is consistent with the FEL saturation. The FEL intensity is stably maintained for over 10 hours, which is sufficient for user experiments.

SUMMARY

The SASE-FEL accelerator requires a very precise and stable rf system. To realize such a high-quality rf system, an IQ modulation and demodulation system with VME high-speed D/A and A/D boards was developed and improved. The acceleration cavity temperature is also regulated within ± 0.02 K by a special water system. As a result, the rf field in the acceleration cavity is precisely controlled with the stability of 0.02 degree rms in phase and 0.03 % rms in amplitude. This performance helped the accelerator tuning very well and a saturated FEL light was observed.

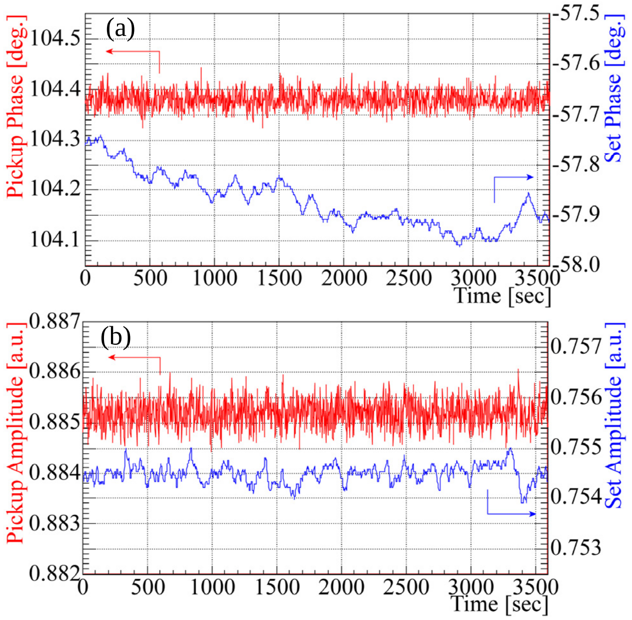

Figure 3: Trend graphs of the rf phase (a) and the amplitude (b) of the 238 MHz cavity. The red lines show values detected with the IQ demodulator and the blue lines show set values to the IQ modulator.

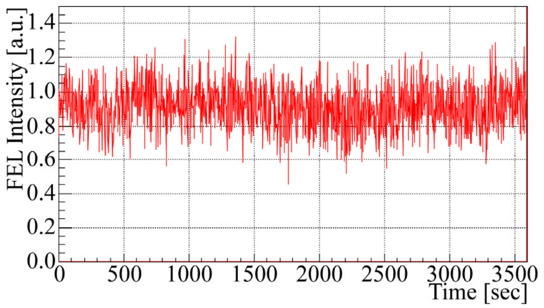

Figure 4: Trend graph of the FEL intensity monitored with a PIN photo-diode.

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