LOW LEVL RF AND TIMING SYSTEM FOR XFEL/SPRING-8

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Abstract

The construction of XFEL/SPring-8 is progressing. In this accelerator, it is needed to obtain stabilities of 50 fs and 1E-4 in time and amplitude of the acceleration voltage. To satisfy these requirements, rf components, such as a reference rf oscillator with low phase noise, IQ modulators and so on, were developed. These modules were installed to an SCSS test accelerator. Their performance was confirmed by monitoring the beam arrival timing compared with the reference rf signal. The measured time jitter of the arrival timing was 46 fs, which implies that the rf modules have a potential to control the timing of the accelerator within several 10 fs. Using these modules, the SCSS test accelerator is operated stably and offers EUV light to user experiments. The compression factor of the XFEL is about 10-times larger than that of the test accelerator. Thus special care is taken for the XFEL to keep the temperature of rf modules constant. For delivery of the reference rf signals, an optical system is adopted instead of coaxial cables, because signal transmission loss with coaxial cable is not allowed for the long distance for the XFEL..

INTRODUCTION

Construction of the XFEL/SPring-8, Japan is in progress. Fig. 1 shows a schematic view of the rf components of the XFEL. An electron beam with an energy of 500 keV and a current of 1A is extracted from a thermionic gun. Velocity bunching is done by using 238 MHz, 476 MHz, and 1428 MHz (L-band) sub harmonic cavities, which increase the beam energy and compress the bunch length. Then, the beam is passed through cavities with frequencies of 2856 MHz (S-band) and 5712 MHz (C-band) and three magnetic bunch compressors (BC 1 ~ 3). Two correction cavities are used to compensate for the non-linearity of the sine wave, and to give a linear energy chirp to the beam. The peak current is increased very carefully as the beam energy is increased.

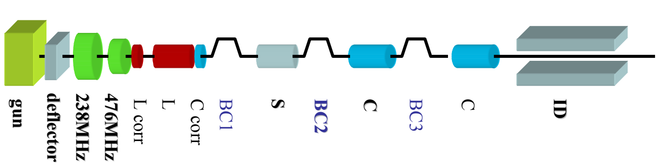

Figure 1: Schematic view of the rf components in the XFEL.

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This is because the beam emittance is easily blown up by a strong space charge force. Thus the allowable amplitude and phase fluctuations of the accelerating cavity voltages at the bunch compressor section are very severer: 50 fs and 1E-4 [1]. At the crest acceleration section the requirement to the rf phase stability is relaxed: 240 fs because dV/dt is nearly zero. Finally, the expected peak current at the insertion device is 3 kA with a beam energy of 8 GeV. To obtain saturated self-amplified spontaneous emission (SASE) light, it is important to maintain a very high peak current, i.e., a very high bunch compression ratio. The phases and amplitudes of the rf cavities should be stable within their tolerances, as mentioned above.

To satisfy these requirements, the rf components, such as a reference rf oscillator with low phase noise and an IQ (In-phase and Quadrature) modulator / demodulator have been developed [2]. Their performances measured at a test accelerator, issues concerning temperature stabilization of the rf modules, and the delivery system of the reference signal for the XFEL are shown in the following.

PERFORMANCE OF THE LLRF SYSTEM AT THE SCSS TEST ACCELERATOR

The SCSS test accelerator was constructed in 2005. Its beam energy is 250 MeV. The machine length is about 70 m. Components shown in Fig.1 with bold face are installed in the test accelerator. To drive all of the high power rf sources of the test accelerator, and to realize stable SASE generation, a low-noise reference signal oscillator was developed. The phase noise of 5712 MHz signal is -140dBc/Hz at an offset frequency of 1 MHz to the carrier signal. The sub-harmonic signals for velocity bunching are generated by dividing the 5712MHz signal. The reference signals are transmitted to 19" racks located along the klystron gallery of the test accelerator through coaxial cables. There, the reference signal is modulated by an IQ modulator controlled by a high-speed 14-bits DAC, and fed to a high-power klystron. It excites the accelerating cavity. The phase and the amplitude of the accelerating voltages are monitored by an IQ demodulator and high-speed 12-bits ADCs.

As described in the previous section, the phase and amplitude of the 238MHz sub-harmonic cavity voltage are sensitive to the lasing stability. Thus, a feedback process to stabilize the rf phase and amplitude of the cavity voltage is introduced. Fig. 2 shows the set and measured values of (a) the phase and (b) the amplitude of the pickup signal of the 238MHz cavity. The setting

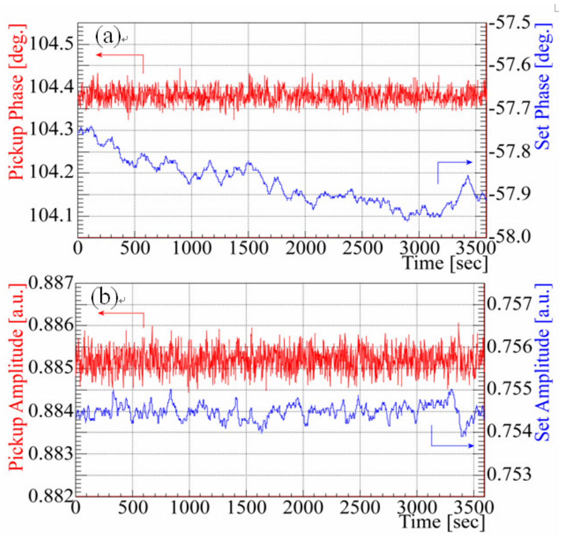

Figure 2: Set and measured value of (a) the phase and (b) the amplitude of the 238 MHz cavity pickup signal at the test accelerator.

resolutions are 0.01 degree and 1E-4 in phase and amplitude. Fluctuations of the phase and amplitude are 0.02 degree and 3E-4 in r.m.s. [3].

To evaluate the total performance of the rf system of the test accelerator, the beam arrival time to a reference rf signal was measured. The signal from the cavity of an RF BPM located after a C-band accelerating structure has a frequency component of 4760 MHz. The phase difference between this signal and the 4760 MHz reference rf signal was measured. The r.m.s. value of the phase fluctuation was 0.08 degree, which corresponds to 46 fs in time. This implies that our rf control systems, including the master oscillator, the delivery system of the reference rf signals, and the cavity phase and amplitude controls with the IQ modulators and demodulators, have a potential to achieve a time jitter of less than several 10 fs. Fig. 3 shows trend of the arrival time for one week during a user run. There is a small drift of the arrival time each day. It has a strong correlation to the beam energy measured at a dispersive section of the BC of the test accelerator. This implies that a change of the beam energy leads to an arrival time change through the R56 parameter of the BC. The main source of this drift may be caused by a temperature change due to a daily machine operation cycle: starting in the morning and stopping in the night. This thermal cycle may cause a voltage change in the high-voltage power supply of the electron gun, a length change of the cavity pickup cables used for rf monitoring, the gain or offset change of detection in the IQ demodulator modules and so on. Although there are still small drifts in the arrival timing, the laser intensity is almost constant, as shown in Fig. 3. The r.m.s. value of the fluctuation of the laser intensity is about 10%. The test accelerator is operated stably, and provides stable EUV light to experimental users [4, 5].

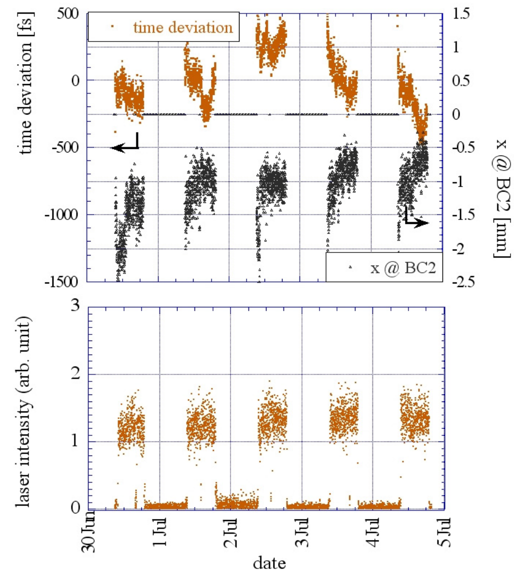

Figure 3: Trend of the arrival time (top), horizontal beam position measured at a dispersive section of the BC (middle) and the observed EUV laser intensity (down) for one week.

IMPROVEMENTS OF THE LLRF SYSTEM FOR THE XFEL

Here, two topics describing improvements in the low-level rf system of the test accelerator to extend to the XFEL/SPring-8 are shown. One is a temperature-control issue to overcome the drift problem described in the previous section. The other is a delivery issue of the reference rf signals to adapt for the long machine length of the XFEL.

Temperature-Control Issue

Because the bunch compression factor of the XFEL is about 10-times larger than that of the test accelerator, the temperature drift allowed in the test accelerator may not be sufficient at the XFEL. Special care should be taken for the temperature control in the low-level rf system for the XFEL. A water-cooled 19” rack was developed to stabilize the temperature around rf modules, such as a receiver module for the reference rf signal, an IQ modulator, an IQ demodulator, a preamplifier for driving a klystron and so on. The rack has a heat exchanger and blowers to stabilize the temperature inside the rack. The heat exchanger is cooled by water whose temperature is kept constant within +/- 0.2 degree. The performance test of this cooling rack with a constant heat load of 1 kW was carried out. A step change of 4 K to the ambient temperature was applied at the test. This is because the temperature stability of the large klystron gallery of the XFEL is designed to be within +/- 2K in a specification of the air conditioner. The temperature stability inside the rack was within 0.4 degree at this test.

A software feedback control process is used to stabilize the rf phases and the amplitude of all the accelerating cavities (238, 476, 2856, 5712 MHz cavities) along the test accelerator. This feedback works with preconditions, which include that the low-level rf system has a stable rf reference and a minimum drift of the rf phase and amplitude detection. Thus the lengths of a reference signal line and a pickup cable from the rf cavity to the rf detector included in the rack should be stabilized. For this purpose, the reference cable and the pickup cables of the XFEL will be equipped with thermal insulation and water cooling.

Delivery of Reference rf Signals and the Trigger Signal

Because of the long delivery length, we use an optical-fiber link to distribute reference rf signals and a trigger signal at the XFEL [6]. Fig. 4 shows a schematic diagram of a system used to deliver the signals. We have the reference signals of the several sub-harmonic frequencies, and the trigger signal, as mentioned previously. To reduce the number of fiber cables for delivering signals, we apply a wavelength division multiplexing (WDM) for the system. Prototype modules of an optical transmitter and a receiver for a 5712 MHz signal transmission were fabricated. The phase noise of the signal before and after optical transmission was checked in a test. A slight increase of the phase noise of a 5712 MHz signal was observed above an offset frequency of 1 MHz. However the value of the phase noise integrated along the region was small, and corresponds to about 7 fs, which is an allowable level for the XFEL requirement.

We use a phase-stabilized optical fiber with a thermal-expansion coefficient of 5 ps/km/K to prevent rf phase drift in the reference signals. Even if we use this stabilized fiber, the time delay could be as much as 500 fs with conditions of 1km length and a temperature change of 0.1 K. This change of the delay time is not allowable for the XFEL, and thus a feedback control circuit is prepared to stabilize the optical length of the fiber. This circuit is based on a Michelson interferometer. A preliminary test of the circuit was carried out by using an existing 2 km optical fiber cable placed along the circumference of the SPring-8 ring accelerator. The test result showed that the stability of the optical length controlled by the circuit was within 2 μm in a frequency range below 100 Hz.

SUMMARY

We have developed low-level rf components for XFEL. The basic components are used in the SCSS test accelerator. A phase jitter of 0.02 degree and an amplitude fluctuation of 3E-4 in r.m.s at a 238 MHz cavity were obtained with these components. The total performance of the low level rf system was confirmed by measuring the beam arrival time, whose jitter was less than 46 fs in r.m.s, For temperature stabilization of the rf components, a water-cooled 19" rack was developed. For distributing of the reference signal of the XFEL, an optical transmission system with WDM and an optical length control system for the fiber cable were developed. Their test results show that an increase of the phase noise in the transmission system was suppressed down to 7 fs, and the optical length of a fiber cable was controlled to within 2 μm for a 2 km fiber. The total performance satisfies the requirements for the XFEL.

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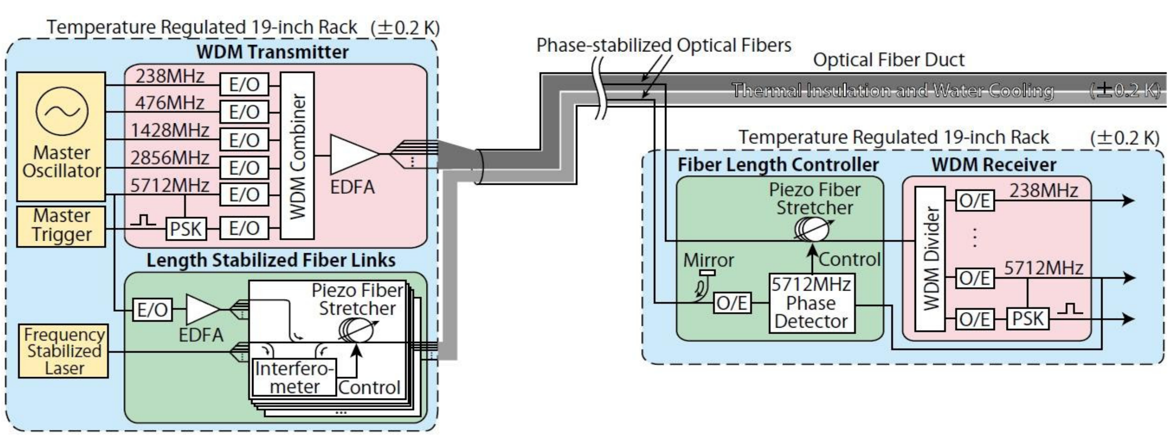

Figure 4: Schematic view of reference rf signals and the trigger-signal delivery system.