STABILIZATION OF BEAM PERFORMANCE DUE TO IMPROVEMENT OF THE PRECISE TEMPERATURE REGULATION SYSTEM OF THE SACLA INJECTOR

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Abstract

The acceleration field of the rf cavities of an injector in SACLA have to be precisely controlled in order to generate a stable electron beam for x-ray free-electron laser (XFEL) users. To maintain the rf voltage and the phase in each cavity, the temperatures of all cavities were kept within 28±0.04˚C by a precise temperature regulation system, which was equipped with the pulse-width modulation (PWM) AC heater with the on-off control. The beam position in the injector was affected by slight leakage magnetic fields from the AC heater elements and those cables. We replaced the existing (PWM-AC-type) precise temperature regulation system with a new system (DC-type) for each rf cavity in the injector in order to remove the leakage magnetic field of the heater current. Additionally, a thermometer module with the high resolution of 0.001˚C was installed into the new system. Consequently, the temperature variation of the rf cavities was maintained within 28±0.004˚C. The beam position jitter in an undulator was reduced to less than one-third, and the laser position variation was suppressed to within 20 μm.

INTRODUCTION

Toward increasing and stabilizing the x-ray laser intensity of SACLA to efficiency progress user experiments, we have made numerous improvements in the 8-GeV linear accelerator since beam commissioning [1]. It is also important to improve the pointing stability, which is nearly one-tenth of the beam size. The stability of laser intensity of less than 10% (rms) is required from our design [2]. The stability of the laser intensity, however, was not sufficiently stable to adopt the design value for user experiment in the period of the beam commissioning [3].

At that time, the laser intensity became low within a few hours without the tuning of the linear accelerator. One of the causes of the laser intensity drift was the peak current drift of an electron beam. Furthermore, a fluctuation of the laser intensity for the short-term had a strong correlation with the beam position jitters.

The exact locations of the causes of those beam intensity drift and fluctuation were investigated by the measurements of a beam energy and a beam position in the individual sections (injector, magnetic bunch compressor: BC1, BC2 and BC3) of the 8-GeV linear accelerator, as shown in Fig. 1. By the investigation, it was found that the causes of the beam characteristics variations were in the injector. The causes of the variations were described as the following [4].

- The beam energy drift after the injector was caused by the slight phase drifts of the rf cavies in the injector, as a velocity bunching section.
- The beam position after the injector had a periodic variation of 2 Hz in a short-term.

To mitigate these beam variations in the injector, we determined the root causes of these variations, and carried out the countermeasures, as described below.

The rf phase drift was caused by the temperature change of the rf cavity although the temperature of the rf cavities were maintained within 28±0.04˚C by a precise temperature regulation system (PTRS). The temperature stability was not sufficiently. Therefore, we replaced the conventional thermometer module with a high-resolution thermometer module in the PTRS.

The beam position jitters in the short-term, at which was a periodic fluctuation of 2 Hz, was synchronized with the current period of the pulse width modulation (PWM) for the AC heater of the PTRS. We thought, a periodic tiny leakage magnetic field from the AC heater element or its cable could make a periodic fluctuation of the beam position. Therefore, we upgrade the existing PTRS to a new PTRS system without any periodical on-off control of the heater current. Continuous current control for the heater by using a DC power supply to be installed in the new PTRS stabilized the temperatures of individual rf cavities in the injector.

In this paper, the performances of the existing PTRS and the new system are shown first. Mitigation of the beam position jitters with the new PTRS system is also described.

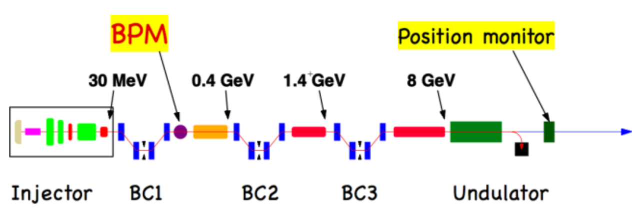

Figure 1: Schematic view of the 8-GeV linear accelerator and undulator section in SACLA.

IMPROVEMENT OF THE PRICISE TEMPERATURE-REGULATION SYSTEM

Existing Precise Temperature-regulation System

The existing PTRS was designed to maintain a temperature variation of the rf cavity within 28±0.1˚C.

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The PTRS consists of a controller, a thermometer, an AC power supply and a 5 kW heater element for a cooling water flow of about 20 l/min, as shown in Fig. 2. The heater control with the PTRS was carried out by the PWM control with a periodical on-off current of 2 Hz [5]. The controller equips with a programmable logic controller (PLC) a thermometer module (F3CU04-0S, Yokogawa Electric Co., Ltd.) which the proportional, integrate and differential (PID) feedback-control is installed. The cooling-water temperature at the inlet of each rf cavity is measured by using a mineral-insulated platinum resistance thermometer (Pt100Ω, three-wire method). This measured temperature signal is fed in to the thermometer module.

The existing PTRS feedback-control, for example, randomly shook the temperature of a 238-MHz sub-harmonic buncher (SHB) within 28±0.02˚C since the thermometer module generated an unexpected tiny-fake signal like instability, as shown in Fig. 3.

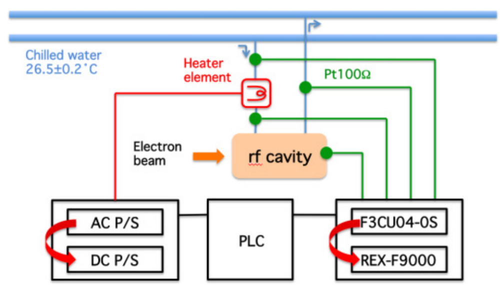

Figure 2: Schematic drawing of the PTRS used to heat the cooling water for rf cavities.

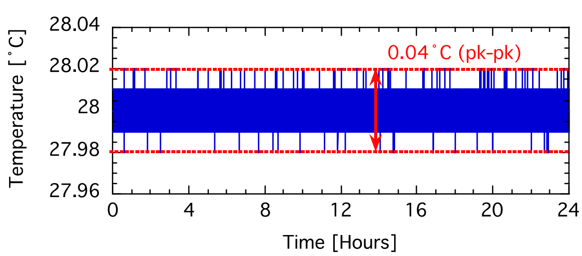

Figure 3: Temperature variation within 28±0.02˚C of the 238-MHz SHB in the conventional PTRS.

Upgrade of the Existing Precise Temperature-Regulation System

As described in the introduction, in order to realize further temperature stability of the rf cavity, the new upgraded PTRS uses a precise thermometer module (REX-F9000, RKC Instrument Inc.) with a high temperature-measurement resolution of 0.001 K. The REX-F9000 is in place of the F3CU04-0S. We tested this module to confirm its temperature measurement resolution and stability. The module shows stability of 0.004 K (pk-pk) for a day [6].

To reduce the periodical magnetic leakage field from the heater and its cable, a DC power supply (200 V / 35 A) was employed instead of an AC power supply for the PWM, as shown in Fig. 2. The DC power supply continuously control current fed in to the heater element.

Consequently, the temperature variation of the 238-MHz SHB reduced from the present 0.04 K (pk-pk) to 0.008 K (pk-pk) by the REX-F9000 without the unexpected random fake-signal, as shown in Fig. 4.

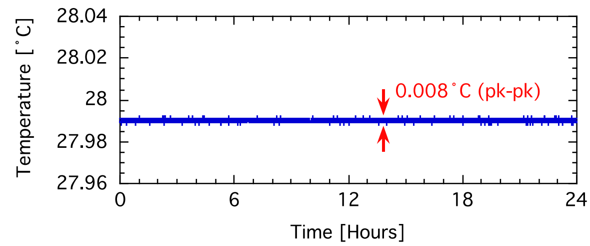

Figure 4: The temperature stability of the 238-MHz SHB was improved by the REX-F9000.

PHASE STABILITY OF RF CAVITY

In addition to phase control by the temperature regulation within 0.04 K in the 238-MHz SHB with the existing PTRS, the rf phase was regulated by a PID feedback control of a low-level rf system (LLRF) with the changes in temperature, as shown in Fig. 5 [7]. The controlled rf phase was frequently disturbed since the F3CU04-0S made the fake temperature-measurement signal. The amount of unexpected phase correction of the feedback control by the fake signal was 0.05 deg (pk-pk) during three minutes.

This is why the precise thermometer module (REX-F9000) is needed. The rf phase disturbance of the 238-MHz SHB due to the temperature fake signal was considerably reduced after upgrading the PTRS, as shown in Fig. 6, because of the fake signal was not almost fed in to the feedback control loop of the LLRF. Consequently, the variation of the beam energy after the injector due to the rf phase drift caused within 0.04 K and the fake signal was considerably reduced.

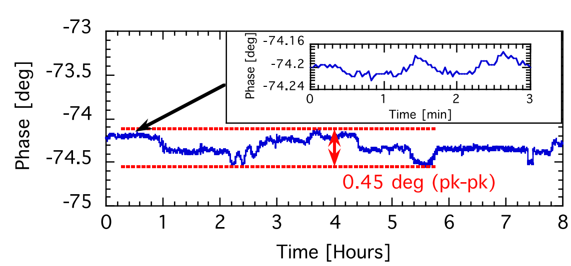

Figure 5: The rf phase drift of the 238-MHz SHB before the upgrade of the PTRS.

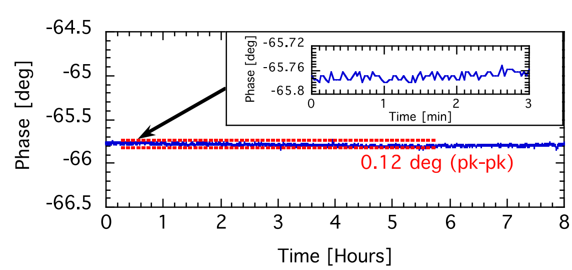

Figure 6: The rf phase drift of the 238-MHz SHB after the upgrade of the PTRS.

STABILIZATION OF BEAM POSITION JITTERS

Spectral Analysis on Beam Position Jitters in the Injector

In order to analyze the frequency components of the beam position jitters in the injector, a fast Fourier-transform analysis was performed. The beam position was measured by using a beam position monitor (BPM) after the 1st magnetic bunch compressor (BC1), as shown in Fig. 1. Figure 7 (a) shows the spectrum of the beam position jitters before the upgrade of the PTRS. The peak was observed at a periodic cycle of 2 Hz, which coincided with the operating periodic PWM current of the existing PTRS. To check the influence of the magnetic field generated by the current of the AC heater and its cable, we changed the current operating-cycle of the heater controller. And then, the frequency component of the beam position jitters changed immediately in response to the current operating-cycle change. This means that a leakage magnetic field generated by the periodic current from the AC heater and those cables kicked the low-energy beam in the injector.

The beam position jitter of 2 Hz was removed after the upgrade of the PTRS, as shown in Fig. 7 (b). In addition, the variation of beam position jitters at the periodic cycles of several second or more was reduced because the REX-F9000 could drive without any long-term drift.

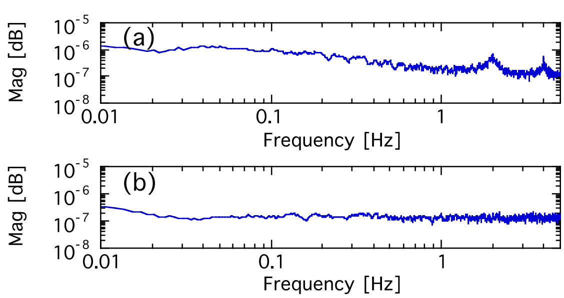

Figure 7: Result of a spectral analysis of the beam position data after BC1. The frequency of the beam position jitters in the vertical was observed at 2 Hz before (a) the upgrade of the PTRS, and its fluctuation was removed after (b) the upgrade of the PTRS.

Improvement of Laser Pointing Stability

The reduction of the beam variation in the injector as presented above had a remarkable effect on improving laser pointing stability. The laser position fluctuation was observed at a place of 80 m downstream of the undulator exit, before and after the improvement, as shown in Fig. 8. The laser position was measured with using a laser position monitor (4 quadrant intensity monitor) at the laser diagnostic section (Optical hutch), as illustrated in Fig. 1. The fluctuations of the laser position in the horizontal and vertical direction, which were 52.4 μm and 40.2 μm, respectively, were reduced to one-half and one-fifth, respectively, after the upgrade of the PTRS, and were sufficiently smaller than the laser spot size.

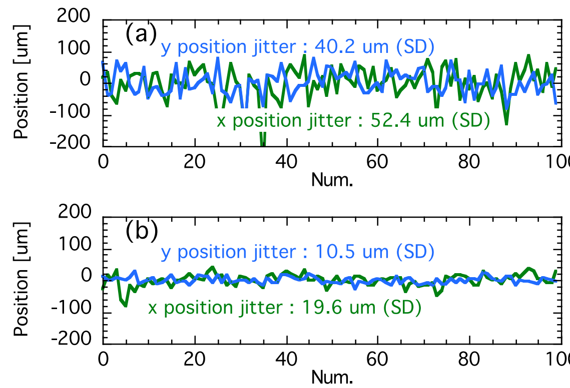

Figure 8: Laser position stability observed at a place of 80 m downstream of the undulator exit, before (a) and after (b) the improvement.

SUMMARY

The long-term temperature stability of the rf cavity was kept within 0.008˚C by a heater controller of REX-F9000, which the upgrade of the PTRS was equipped. Furthermore, in order to suppress the leakage magnetic field, a DC heater power supply, which manipulates continuous heater-current level control, replaced an AC heater PWM power supply.

The variation of the beam energy and position in the injector were considerably reduced after the replacement. Especially, beam position jitters in the undulator beam line were sufficiently reduced to a value less than the beam size. Therefore, the user experiments became more efficient since a focused x-ray laser beam was extremely stabilized. In addition, the long-term stabilized electron beam has made a contribution to increasing the laser intensity to facilitate longer-stable precise measurements of the beam performances, because of the replacement of the heater controller. The laser with the stability of about 10% has been supplied to the user experiments.

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