STABILITY IMPROVEMENTS OF SACLA

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Abstract

For stable user operation of SACLA, an XFEL intensity is demanded to be sufficiently stable within 10% level for a long-term drift. In the early period of XFEL lasing at SACLA, however, the XFEL intensity significantly decreased in a few hours, if we did not adjust the accelerator condition. We found that the rf phase of an injector part had significant fluctuation, which could be a major source of the XFEL intensity degradation. Therefore, we improved the temperature stability of the acceleration cavity in the injector from 0.08 K pk-pk to less than 0.01 K pk-pk by using a further precise temperature regulation system. As a result, the long term XFEL intensity drift was reduced to 10% pk-pk level, if operators sometimes finely adjusted rf parameters of the injector. At this moment, some more improvements for the XFEL intensity stabilization, such as the reduction of the temperature coefficient of low-level rf electronics, the construction of the fiber length control system for a reference rf transmission system etc. are ongoing. After these improvements, the XFEL intensity is expected to be sufficiently stable without any adjustments by operators.

INTRODUCTION

In order to utilize an x-ray free electron laser (XFEL) for physics experiments and biological sciences, the stability of XFEL intensity is important. For the effective use of XFEL, a long-term intensity drift of less than 10% pk-pk and a short-term jitter of less than 10% rms are demanded. In the early period of the commissioning of SACLA [1,2], however, the stability of the XFEL intensity was not sufficiently stable for user experiments. The XFEL intensity was degraded within a few hours if we did not tune the injector part of the accelerator, as shown in Fig. 1. In addition, a short-term jitter was more than 10% rms, which was larger than the intrinsic fluctuation of a SASE-FEL (a little less than 10% rms).

One of the causes of XFEL intensity variation is the peak-current fluctuation of an electron beam. In SACLA, we use velocity bunching in the injector part and three bunch compressors (BC) in the upstream part of the accelerator, as illustrated in Fig. 2, in order to obtain a required peak current of 3 kA. If a bunch compression ratio at each compression stage is changed, the peak current of the electron beam is degraded and the XFEL intensity is also decreased. In the bunch compression stage, an electron beam is accellerated at an off-crest phase of an acceleration rf field. Therefore, the small rf phase drift of the accelerator can affect the bunch compression ratio and the XFEL intensity can be degraded. The requirements for the rf phase stability in SACLA are 50 fs rms short-term jitter and a few 100 fs pk-pk long-term drift in the time-equivalent value of the rf phase [3].

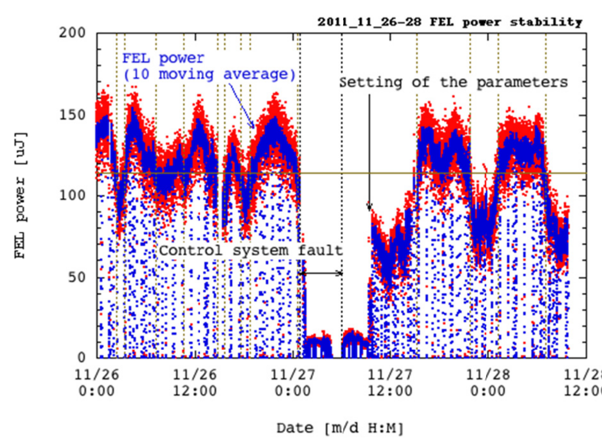

Figure 1: XFEL power trend graph in the early period of x-ray lasing at SACLA. Red points are shot-by-shot intensities and blue ones are 10-shot moving average. Although there was no FEL output in the middle of the measurement, this was not the stability issue but a machine trouble. In this data acquisition period, only the feedback control of each rf phase and the beam orbit in the undulator were performed.

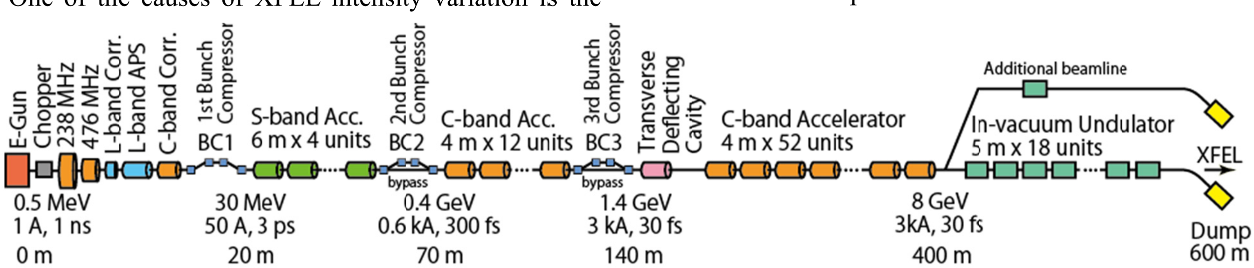

Figure 2: Schematic layout of SACLA.

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In order to achieve the demanded rf phase stability, we designed and constructed a high-precision and high-stability rf system for the SACLA accelerator [3]. For example, a high-voltage charger for the high-voltage pulse modulator of a klystron has a voltage stability of 1×10^{-5} rms [4]. For a low-level rf (LLRF) system, the rf phase can be measured within 0.3 degree pk-pk precision for a C-band accelerator, corresponding to 150 fs pk-pk [5]. Furthermore, the temperatures of acceleration structures [6] and LLRF electronics are regulated within 0.08 K pk-pk and 0.2 K pk-pk, respectively. Even though each component was designed to be sufficiently stable, the XFEL intensity degradation, as shown in Fig. 1, was still remained. Therefore, we studied the cause of the XFEL intensity fluctuation and improved the stability of the accelerator.

STRATEGY OF STABILIZATION

In order to achieve the required peak current, the bunch compression ratio of each bunch compression stage should be sufficiently stable. Otherwise, a variation of the bunch compression ratio at an upstream part would affect the downstream part and the peak current fluctuation would be accumulated. Therefore, the rf phase of every acceleration cavity in the bunch compression part should be sufficiently regulated.

One may consider the feedback control of the rf phase will improve the performance by using a beam energy monitor and a bunch length monitor in a bunch compressor. However, for the upstream part of BC1, there are five acceleration cavities with different rf frequencies and each of them has two degrees of freedom (rf phase and intensity). In this case, ten parameters, which have a complicated correlation, should be determined by a feedback control. Nevertheless, we do not have enough beam monitors due to technological issues, limited detector space and cost problems.

Consequently, we decided to improve the stability of the accelerator cavities upstream of BC1, as the first priority. In particular, the temperature drift of the accelerator cavity was reduced and the temperature coefficient of the LLRF system was improved.

STABILITY IMPROVEMENTS

At first, the frequency analysis was performed for the XFEL intensity variation to find causes of the instability. The result of the analysis is plotted in Fig. 3. From this figure, a sharp peak at 0.5 Hz was found and this could be a cause of short-term instability. For a long-term drift, the spectrum gradually increases as the frequency decreases. In the subsequent sub-sections, we consider the cause of the variation and describe the improvement of each fluctuation component.

Short-term Stability

The short-term jitter of 0.5 Hz was found to be correlated with a beam position jitter at BC1. The beam position at BC1 had almost the same spectrum as Fig. 3,

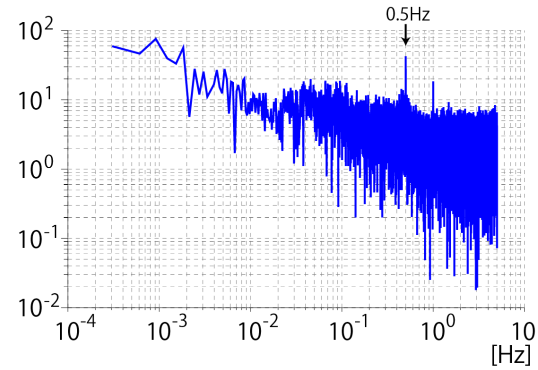

Figure 3: Spectrum of the XFEL intensity fluctuation.

which showed a peak at 0.5 Hz. This position data also indicated a correlation with the XFEL intensity, as plotted in Fig. 4. The fluctuation of the beam position was thought to be caused by a 0.5 Hz variation of the rf phase of an accelerator cavity upstream of BC1. The beam position fluctuation gives rise to an orbit distortion in the undulator section and the FEL interaction between the electron beam and its radiated x-rays is reduced. Furthermore, such an rf phase fluctuation also causes peak current degradation. The XFEL intensity instability was thought to be induced from these reasons.

This 0.5 Hz modulation was synchronized with the pulse-width modulation (PWM) of an AC heater for a precise temperature regulation system (PTRS) [6]. The PTRS consists of an about 5 kW heater with about an 10 l/min flow of cooling water and a PWM heater controller. In this case, a cooling water temperature was modulated with a 0.5 Hz frequency and the amplitude of water temperature swing was about 1 K. This temperature modulation affected the acceleration cavity temperature and the resonant frequency is slightly shifted periodically. This caused the rf phase modulation of the accelerator. Moreover, magnetic field leakage from a heater cable would slightly kick the beam. In order to remove this 0.5 Hz fluctuation of the beam, the heater of the PTRS should be driven by a DC current without PWM control. In this summer, we replace the PWM AC heater of the PTRS with a continuous DC heater [7].

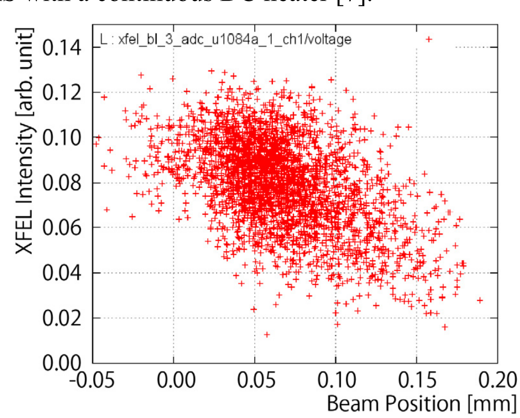

Figure 4: Scatter plot of the XFEL intensity (vertical axis) vs. the beam position downstream of BC1 (horizontal axis).

Long-term Stability of Accelerator Cavity Temperature

As described in the introduction, the accelerator cavity temperature was regulated within 0.08 K pk-pk by using the PTRS. However, an rf phase shift that came from the cavity temperature drift was observed. We found that this temperature drift was caused by an internal drift of the thermometer module of the PTRS. In order to test the stability of the thermometer module, a precise resister with a low temperature coefficient of 1 ppm was connected instead of a Pt 100 temperature detector and the output of the temperature module should be constant. The trend graph of the result is shown in Fig. 5. Even though the variation of the temperature module output was within 0.08 K, there was a cyclic modulation with a period of a few hours. This fake signal would make the variation of the cavity temperature. Thus, this thermometer module was not sufficient for the long-term stability of the XFEL intensity and a more precise thermometer module was required.

As a more precise thermometer module, we tested REX-F9000 developed by RKC Instrument Inc. [7]. This module was confirmed to have a 0.001 K resolution and a 0.004 K pk-pk stability, as shown in Fig. 6. By using this module, the temperature stability of the acceleration cavity was improved by ten times smaller than the previous system, and the rf phase drift was considerably reduced. Figure 7 shows the trend graphs of the phase of the acceleration rf field in the second L-band APS cavity before and after the thermometer module upgrade. L-band APS accelerator consists of two APS cavities and the rf phase of the first cavity is regulated by a PID feedback control of the LLRF system, but the phase of the second cavity is not regulated. Therefore, the rf phase before the PTRS upgrade had a large drift. After the PTRS upgrade, the rf phase stability was significantly improved.

Long-term Stability of the LLRF System

Another reason for the XFEL intensity drift was thought to be instability of the LLRF system. In SACLA, the master rf clock was distributed by an optical transmission system. Since the optical fiber is used for the signal distribution, fiber length expansion due to a temperature variation can be a cause of an rf phase shift. In addition, temperature drifts of the LLRF electronics, such as electric-to-optical (E/O) and optical-to-electrical (O/E) converters, in-phase and quadrature (IQ) modulators / demodulators can also affect the rf phase. Since the master rf clock signal is the reference of an acceleration field, a drift of the master rf clock is hard to recognize.

In order to check the stability of the reference signal, we monitored the beam arrival timing at each accelerator cavity upstream of BC1. The arrival timing was measured by using a beam-induced field method [8]. In this measurement, the acceleration rf power of the cavity was turned off and the beam-induced rf phase was detected. This rf phase represents the beam arrival timing with respect to the reference rf signal. The trend graph of the

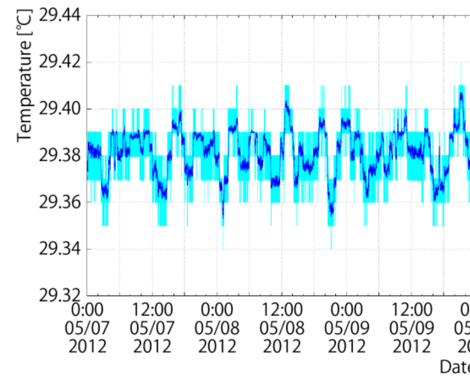

Figure 5: Trend graph of the old thermometer module connected with a precise resistor. The cyan line shows raw data and the blue line shows a moving average.

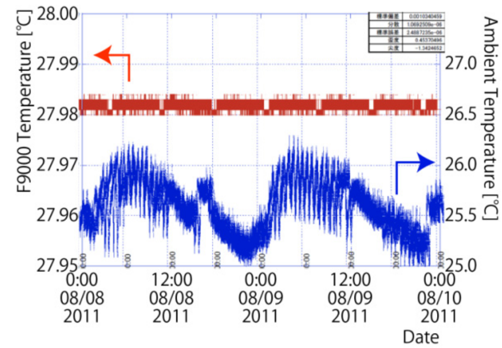

Figure 6: Trend graph of the new thermometer module, F9000, with a precise resistor (red line). Blue line shows an ambient temperature of the module.

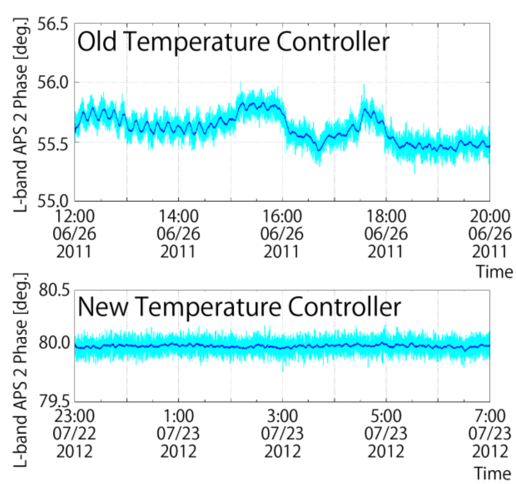

Figure 7: Trend graphs of the rf phase of the L-band second APS cavity with an old thermometer module (upper) and a new module (lower). Cyan lines show 10-shot average data and blue lines show 1000-shot average.

arrival timing for 2 days is shown in Fig. 8. The drift of the rf phase was 1 degree at each cavity, corresponding to approximately 10 ps at the 238 MHz cavity, for example. This phase drift was confirmed to be synchronized to the XFEL intensity degradation. Further investigation showed that the 238 MHz cavity phase had a larger correlation to the XFEL intensity.

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One of the reasons for the 238 MHz phase drift was found to be the temperature coefficient of a band-pass filter in an O/E converter module, which was 10 ps/K. Therefore, the band-pass filter will be replaced with better one with a thermal coefficient of less than 2 ps/K. In addition, the temperature of the LLRF electronics will be improved from 0.1 K pk-pk to 0.01 K pk-pk by using a precise temperature regulation system, which is similar to the system used for the accelerator cavity. After these improvements, the temperature drift of the LLRF electronics is expected to be 100 fs pk-pk.

Another reason can be come from the thermal expansion of the optical fiber. We employed a phase-stabilized optical fiber with the temperature coefficient of 2 ppm/K. In addition, the temperature of the fiber cable duct was kept within 0.1 K pk-pk by using cooling water. Even for this stable system, the fiber length can be changed by 100 fs for a 100 m cable. Since this drift is not negligible, we are constructing a fiber length regulation system by using a Michelson interferometer for the length measurement and a fiber stretcher for the length control [9]. By using the fiber length control system, less than 100 fs pk-pk stability of the acceleration rf phase is expected to be achieved.

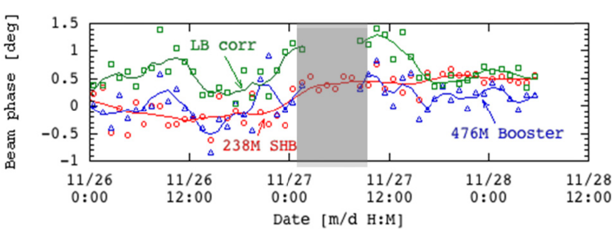

Figure 8: Beam arrival timing at each of 238 MHz, 476 MHz, and L-band correction cavities measured by using beam-induced field method. The vertical axis shows the rf phase. Time equivalent values of the phase are 11.7 ps/degree for 238 MHz, 5.8 ps/degree for 476 MHz, and 1.9 ps/degree for L-band (1428 MHz).

Stability of the XFEL Intensity for the Present System and Future Prospects

At this moment, some hardware improvements are still underway and only the PTRS was temporarily upgraded. Furthermore, beam feedback control for each bunch compressor has not been applied. Nevertheless, the XFEL intensity is sufficiently stabilized for user experiments, as shown in Fig. 9. The short-term intensity jitter is about 10% rms and the long-term drift is approximately 10% pk-pk for a few days. However, this stability was maintained by hourly fine adjustments performed by operating staffs.

After the completion of ongoing improvements, such as the more precise temperature regulation system with a DC heater and the fiber length control system, the XFEL stability will be further improved. When the peak current stability is sufficiently stable at BC1, we will consider introducing a bunch length feedback loop for BC2 and BC3. After these upgrades, the required stability is expected to be achieved without any adjustments by the operating staffs.

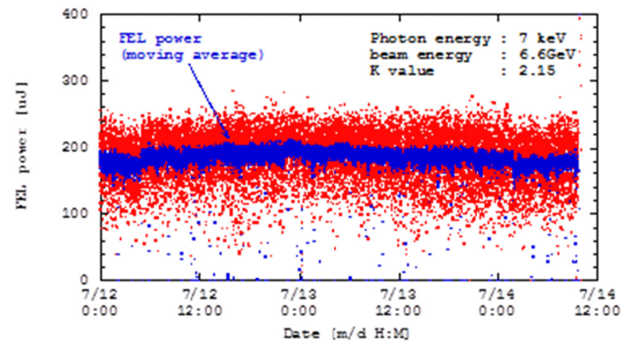

Figure 9: Trend graph of the XFEL intensity after stability improvements. Red dots are shot-by-shot intensity and blue dots are 10-point moving average.

SUMMARY

An XFEL intensity in SACLA was degraded to half within a few hours in the early period of commissioning, which was not sufficient for user experiments. Therefore, we studied the cause of the intensity degradation and improved the stability of an accelerator, especially for an injector part (upstream of BC1). For the short-term jitter, a 0.5 Hz PWM of the AC heater of a PTRS affected to an rf phase and a beam position. For long-term drift, the drift of a thermometer module and the temperature drift of LLRF electronics etc. were found. After improvements to reduce effects from these instability sources, the XFEL intensity was stabilized to about 10% rms for a short-term jitter and approximately 10% pk-pk for a long-term drift with fine tuning by operating staffs. After the completion of ongoing improvements, the required stability will be achieved without any adjustments by operating staffs.

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