STABILITY PERFORMANCE OF THE INJECTOR FOR SACLA/XFEL AT SPRING-8

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Abstract

To realize stable lasing of an X-ray free electron laser, it is required to obtain more stability of more than one or two figures compared with a conventional accelerator technology. At SACLA, stabilities of 100 ppm and 50 fs in the amplitude and timing of the accelerating RF field, respectively, have been attained, resulting in an achievement of a beam energy stability of 0.02% (std.) or less at 8-GeV. However, two variations with different cycle periods were found in the laser power. One was a long-term variation over several hours, which was in agreement with the phase drift of a 238 MHz/SHB. The other was caused by a variation of the beam position in a 30-MeV injector section. A periodically changed beam position of 30 μm (std.) was found out at a cycle of 0.5 Hz by a fast Fourier transform method using BPM data. The temperatures of all the injector RF cavities are kept within 28±0.04˚C by controlling the cooling water temperature. The AC power supply of the controller to heat the cooling water is operated at 0.5 Hz by a pulse width modulation control with alternatively turning on and off. A strong correlation between the laser intensity fluctuation and the modulation frequency of the AC power supply was found out. We are planning to improve the RF cavity temperature variation to an order of less than 0.01 K by establishing a new temperature regulation system using a continuous level control with a DC power supply. This plan will reduce the XFEL power fluctuation.

INTRODUCTION

User experiment at SACLA started in March of this year after beam commissioning for one year [1]. Toward increasing laser intensity, an accurate beam adjustment of a linear accelerator was carried out during the beam commissioning. At the same time, we have conducted some research and analysis aiming at high-level laser stability.

In order to realize a stable X-ray Free Electron Laser (XFEL) at SACLA, the peak current of an electron beam, passing through a 90-m long undulator section, should reach 3 kA with a normalized emittance of 1π mm mrad or less. In addition, it is important to maintain this beam performance with a high-level stability. Because even a slight beam orbit variation of without 4μm (rms) in the accelerator end causes unstable laser oscillation, which measures decreasing half of the peak laser intensity, in the undulator, RF equipment has to be very carefully designed so as to minimize its variation in the RF amplitude and phase [2]. We took thorough stabilization countermeasures against all of the RF equipment, such as controlling a cooling water temperature for each RF cavity by using a precise temperature regulation system, employing a low-noise power supply and the suppressing of a mechanical vibration. As a results, stability performances of the RF cavities were improved to almost satisfy the target values, that is the RF amplitude and time jitter were <100 ppm and <50 fs, respectively. Accordingly, the beam energy stability of 0.02% (std.) or less has been achieved at the end of the 8-GeV accelerator because of the highly stabilized RF system.

However, it was observed that the laser power with an optimized lasing parameter decreased in a few hours. We were forced to spend about one hour in readjustment of the lasing parameter for recovering the laser power. To make the user experiment more efficient, it was urgent to investigate the cause of the laser power variation and fix it. The possible causes are as follows: (1) a variation of the beam arrival time with the velocity bunching process in the injector section, (2) RF phase drift due to a low level RF system of the injector section, which depends on the environment temperature, and (3) RF phase fluctuation of the cavities, which depends on the cooling water temperature. To clarify the causes, the correlations between each apparatus and surrounding factors were investigated. Consequently, the dominant factors were clarified, and a readjustment procedure for recovery of the laser power was established. The laser power is kept stable during user experiment at present, as shown in Fig. 1. This report presents details of the analysis of beam fluctuation and improvement of laser performance.

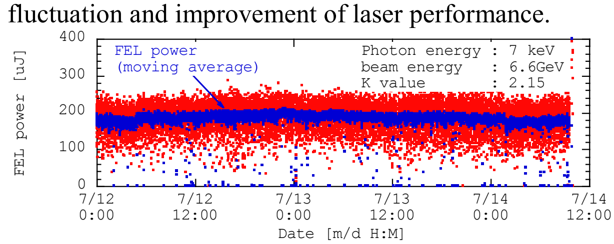

Figure 1: Stability of laser power in user experiment measured using photo detectors.

LONG-TERM VARIATION

Measurement of Laser Power Stability, Beam Arrival Time and Beam Energy

Accelerator operation was performed during three days to reveal which part of the accelerator caused beam variation. First, the condition of the lasing parameter was optimized for 10-keV photon energy at 7-GeV. The laser power immediately after the optimization reached 0.13 mJ.

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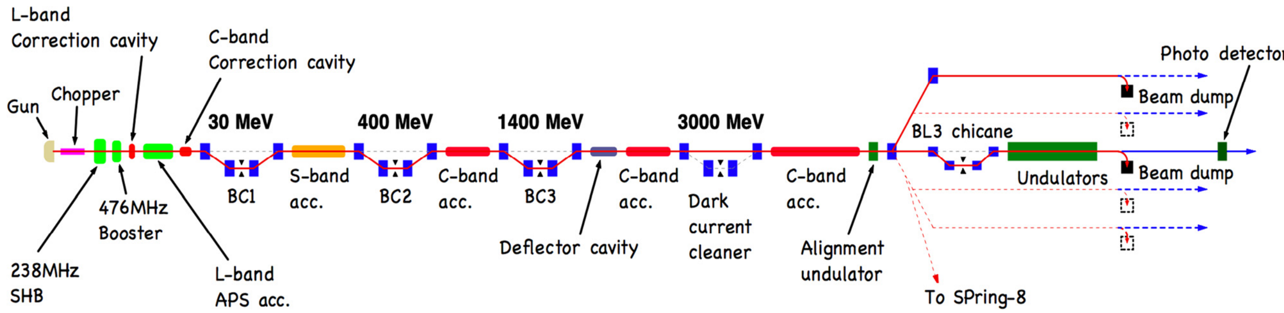

Figure 2: Schematic view of the linear accelerator and undulator section in SACLA.

The laser power was measured by using photo detectors located at the downstream of the undulators, as illustrated in Fig. 2. Figure 3 shows a trend of the laser power over three days. The operation setting points to control accelerator components, such as the RF phase of 238 MHz/SHB, were not changed, although the laser power decreased rapidly dozens of times because of occurring self-fire or firing miss on klystron modulator. Moreover, regardless of a control system failure in November 27th, all parameters were maintained under the same conditions before and after the failure.

To ascertain the cause of the laser power variation shown in Fig. 3, the beam position and the beam arrival time were also measured by using beam position monitors (BPMs), which were installed at intervals in the accelerator. In addition, the variation of the beam energy was measured by using a BPM with a multi stripline installed in each bunch compressor (BC1, BC2, BC3). Figure 4 (a) and (b) show trends of the beam arrival time after BC1 and the beam energy in BC2, respectively. Since a beam is fixed at off crest RF phase in BC, the beam energy is affected significantly by the slight variation of the beam arrival time. We find out that the laser power level decreases to less than 70% of the peak of 0.13 mJ (green line in Fig. 3) when the variation of beam phase shift at the BPM after BC1 exceeds a tolerance of 0.6 degree specified in Fig. 4 (a).

The RF phase drift of the cavity for velocity bunching process in the injector section was considered to be a primary cause for the variation in the beam arrival time. Figure 5 shows trends of the beam arrival time obtained from the phase information on beam-induced voltage in 238 MHz/SHB, 476 MHz/Booster and L-band correction cavity. As shown in Fig. 5, because the drifts of the beam phase after 476 MHz/Booster had similar tendency, the RF phase drift of 238 MHz/SHB was estimated to be a dominant factor of the long-term variation in the laser power.

Although low-level RF instruments for 238 MHz/SHB are stabilized by a thermally controlled 19” enclosure, the beam in the SHB is affected by a temperature variation of less than 0.1˚C [2]. It turned out that a band-pass filter of a reference signal of 238 MHz/SHB has a temperature dependence of -10.6 ps/K. Thus, we are planning to replace it with another band-pass filter with 2 ps/K and to improve the temperature stability of the 19” enclosure with a precision temperature control of ±0.002 K.

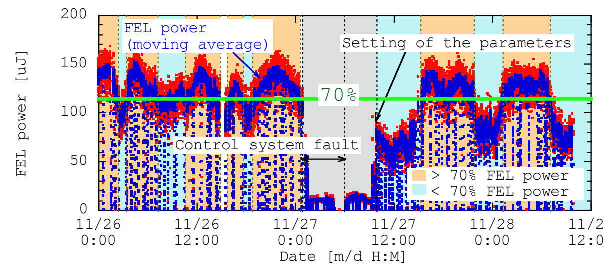

Figure 3: Measurement result for the laser power.

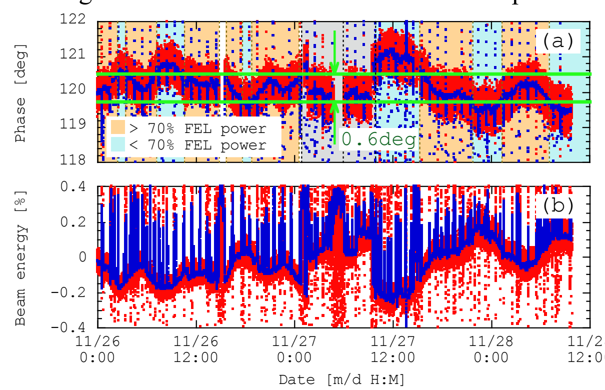

Figure 4: (a) Beam arrival time after BC1. The beam phase is equivalent to 0.58 ps/1 degree. (b) Beam energy in BC2, where the energy dispersion is η = -345mm.

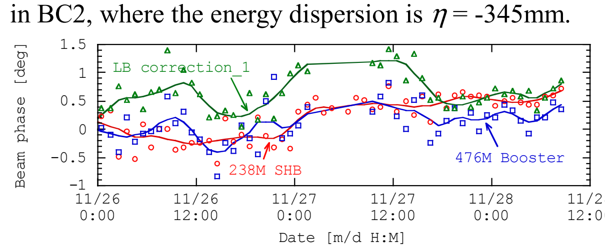

Figure 5: Beam arrival time obtained by an induced voltage from the beam in each RF cavity of the injector.

BEAM POSITION FLUCTUATION

To clarify a cause of the shot-by-shot laser power fluctuation, a correlation analysis and a frequency analysis of the fluctuation were carried out for the data measured simultaneously by using the BPMs. The beam parameters were optimized for 10-keV photon energy at a repetition rate and a beam energy of 10 Hz and 7-GeV, respectively. The beam orbit at the undulator section and the beam energy were corrected by using a slow feedback control (time constant of more the one second) during measurements.

ISBN 978-3-95450-122-9

Correlation Plots

The laser power and the position fluctuated significantly during beam commissioning. To trace an origin of the short-term fluctuation, the correlations between the beam position in each place of the accelerator and the laser power were investigated by using BPM data of 3000 shots for 5 minutes. The beam position fluctuation at the entrance of the undulator section was 10 μm (std.). A significant correlation between the beam position at the entrance of the undulator section and the laser power was recognized, as shown in Fig. 6 (a). Judging from Fig. 6 (b), the correlation between the beam positions after BC1 and at the entrance of the undulator section, the laser power fluctuation was obviously generated from a beam position jitter of 30 μm in the injector section.

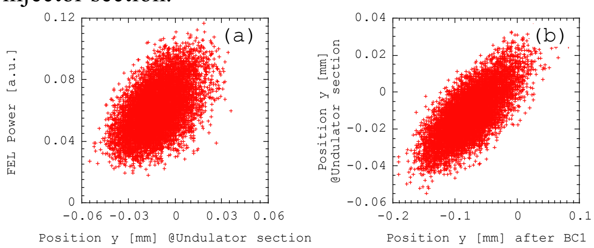

Figure 6: (a) Correlations between the beam position at the entrance of the undulator section and the laser power. (b) Correlations between the beam position after BC1 and at the entrance of the undulator section.

Fourier Transform Analysis

In order to analyze the frequency components of the beam position jitters in the injector section, a fast Fourier transform analysis was performed, as shown in Fig. 7. The highest peak was observed at a periodic cycle of 0.5 Hz, which coincided with an operating cycle of the temperature controller equipped with the precise temperature regulation system for RF cavities. In addition, it shifted to 2 Hz when the operating cycle of the temperature controller was changed from 0.5 Hz to 2 Hz, as shown in Fig. 7. It means that the beam position was affected by the operating cycle of temperature controller in RF cavities, although each temperature of RF cavity was regulated within 28±0.04˚C [3].

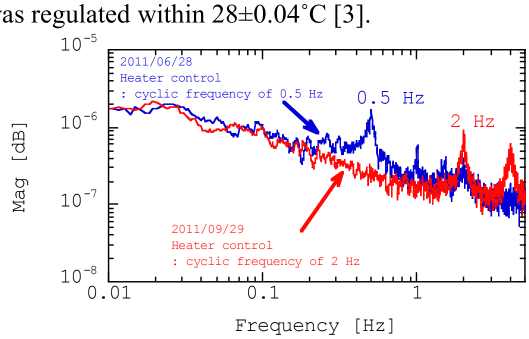

Figure 7: Results of a period analysis using the beam position jitters data after BC1. Blue and red lines are the spectra when the temperature controller of RF cavities was operated at a cycle of 0.5Hz and 2Hz for the heating regulation, respectively.

Moreover, different beam position jitters were observed to be synchronized with the operating cycle of the temperature controller for each RF cavity, as shown in Fig. 8. For example, the maximum magnitude at 1.1 Hz corresponds to the operating cycle of L-band APS accelerating structure. The slight variation in each RF cavity contributed to the beam position jitters in the injector section.

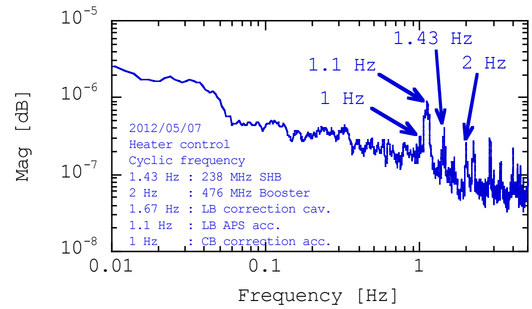

Figure 8: Spectrum of the beam position jitters after BC1 under different conditions of the operating cycle of the cooling water temperature controller in the RF cavity.

CONCLUSION

The 8-GeV accelerator of SACLA is required to continuously supply a stable beam with extreme high quality. Thus, we started to research the cause of instabilities in the accelerator during beam commissioning. It was clarified that the RF phase drift of 238 MHz/SHB might be dominant factor of the long-term variation in the laser power, judging from the phase information on beam-induced voltage. In the user experiment, the laser power can be recovered easily and promptly by tuning the RF phase of 238 MHz/SHB at the moment.

One possible factor for the laser power fluctuation was the influence of the switching frequency of temperature controller equipped with a precise temperature regulation system in the injector section. In order to reduce the laser power fluctuation, a new precise temperature regulation system by using a continuous level control with a DC power supply is installed in the injector section in August. In addition, a temperature measurement and control module with extremely high temperature resolution of 0.001 K has been adopted in place of a conventional less-accurate PLC temperature measurement module. The laser power can be expected to be more stable.

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