DEVELOPMENT ACTIVITIES OF ACCELERATOR INSTRUMENTS FOR SACLA

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Abstract

The X-ray free-electron laser (XFEL), SACLA, is constantly operated for user experiments aimed at new science. However, experimental users demand further experimental abilities to XFEL facilities, such as many experiment chances by using multi-X-ray beamlines, much better repeatability of experimental conditions and further intense high-energy X-rays. To equip SACLA with these abilities in the future, we developed a 2π /3 quasi-constant gradient accelerating structure with an acceleration gradient of over 50 MV/m in order to adapt operation for generating the intense high-energy X-rays. A high-voltage power supply to charge the PFN of a klystron modulator, a klystron and an accelerating structure were also developed in order to upgrade a machine repletion cycle to 120 pps from the present 60 pps, since 120 pps is more suitable to increase the beam repetition to one of the multi-beamlines. To meet the further experimental repeatability realized by stable timing, such as a pump-probe experiment, an optical-fiber length control system in order to mitigate timing drift below 1 fs was developed. A highly precise cavity temperature control system in an injector cavity for below ± 2 mK (p-p) was also realized for the experimental repeatability. The performances of the above-mentioned instruments were experimentally tested to be sufficient for our demands of 50 MV/m, 120 pps, 1 fs and ± 2 mK (p-p).

INTRODUCTION

An X-ray Free-electron laser (XFEL) based on a linac, such as the SPring-8 angstrom compact laser, SACLA [1], is already operated for regular user experiments and almost single user machine; therefore it is a very expensive machine. Furthermore, experiment users usually demand intense and high-energy X-ray beams. To countermeasure the above-mentioned issue, X-ray multi-beamlines driven by one linac in order to accelerate a further high-energy electron beam are the solution. It is because that the high-energy electron beam allows us to increase X-ray flux and its energy in an undulator beamline, if the K value of the undulator is fixed to be a certain value. In the case of SACLA, we have plan to construct a new beamline of BL2 [2].

The next important issue is stability of the XFEL, because it guarantees repeatability of experimental results. Perturbation sources to the instability of the XFEL linac are mainly environmental condition changes, such as a temperature, humidity and vibration around accelerator instruments. In the case of SACLA, there is still X-ray laser intensity instability affected from the environmental condition changes. The perturbations, as which triggers the instability not satisfying a temporal stability demand of about 50 fs in rms, [3] mainly affect the rf phase and amplitude of injector cavities.

As solutions of the above-mentioned issues, we conducted development of a high-acceleration gradient and high rf-pulse repetition-rate linac for future XFELs [4]. Of course, our requirements to the acceleration gradient and the rf pulse repetition rate are as much as possible. However, there are empirically confirmed technical-limitations, such as the cooling capacity of instruments and a natural cavity surface breakdown limit in vacuum. Furthermore, we do not want to drastically change the present rf source conditions, such as an output rf power of 50 MW generated by the existing high-power pulse klystron, because the change demands much money and time consuming effort. Hence we set an acceleration gradient of 50 MV/m and an rf pulse rate of 120 pps, as our immediate targets, to overcome SACLA's performances of 40 MV/m and 60 pps. These targets should be attained by using the present rf source with minor modification.

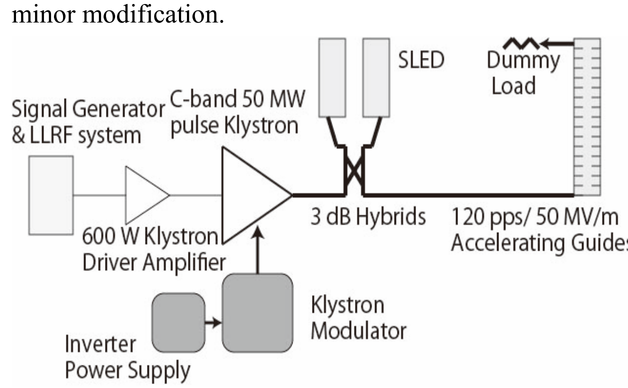

Figure 1: Experimental set-up of the 120 pps C-band acceleration unit.

Since the environmental condition perturbations mainly affect the rf phases of cavities along bunch compression process from the injector to three bunch compressors in SACLA, we developed a control system achieving highly stabilized a cooling water temperature of within several mK for an acceleration cavity and a 19 inch rack for a low-level rf (LLRF) system to reduce the effects from the perturbations [5]. Furthermore, an optical fiber length control to reduce effects from temperature and humidity changes to the low-level rf system of SACLA were also developed [6]. They were produced for

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the present SACLA linac. These developed systems are to realize the previously mentioned temporal stability. We proceeded with many instrument development items, but we do not have enough pages in this report. Hence, the status, such as the summaries and performances, of the above mentioned instruments are only described, as highlights.

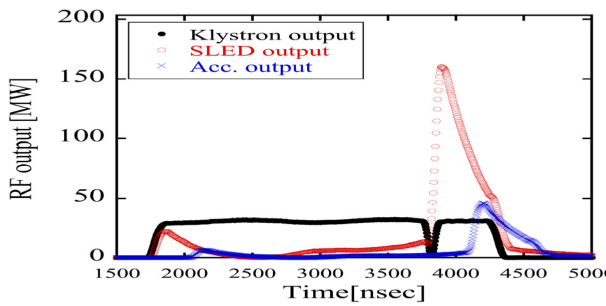

Figure 2: Rf power wave forms at 120 pps.

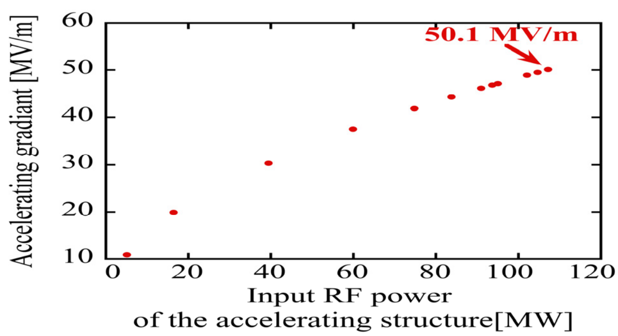

Figure 3: Acceleration gradients of the $2\pi/3$ CG accelerating structure, as a function of its input rf powers. These gradients are calculated by using a shunt impedance of 64 MΩ/m.

DEVELOPED INSTRUMENTS

120 pps High Gradient Accelerator

In order to realize the high repetition and high acceleration gradient linac, we constructed a test system for a high pulse-repetition rf source and an accelerating structure to generate an acceleration gradient of over 50 MV/m, as 1st step. Figure 1 shows an experimental set-up for our developed C-band (5712 MHz) high-power acceleration unit operated at a pulse repetition rate of 120 pps. This rf source mainly comprises an $2\pi/3$ quasi-constant gradient (CG) accelerating structure, an rf pulse compressor of SLAC energy doubler (SLED), a waveguide system, a 50 MW pulse klystron, a compact oil filled high-voltage klystron modulator, a high voltage-precision inverter power-supply and LLRF and control systems for them. The basic configuration of the test system is almost the same as that of SACLA. However, the average power capacity of the rf source is only improved from that of SACLA and, therefore, an rf pulse repetition cycle is increased from the present of 60 pps to 120 pps. We finally achieved 50 MV/m in a manufactured accelerating structure with a shunt impedance of 64 MΩ /m. Figure 2 shows rf power waveforms of an accelerating structure output, a SLED output and a klystron output, when the acceleration gradient reached 50 MV/m at 120 pps. The graph of the acceleration gradients, as a function of the input rf powers fed into the accelerating structure, is depicted in Fig. 3. As a result, we succeeded in operating the C-band acceleration unit with 50 MV/m at 120 pps for more than 8 hours without any serious rf breakdowns.

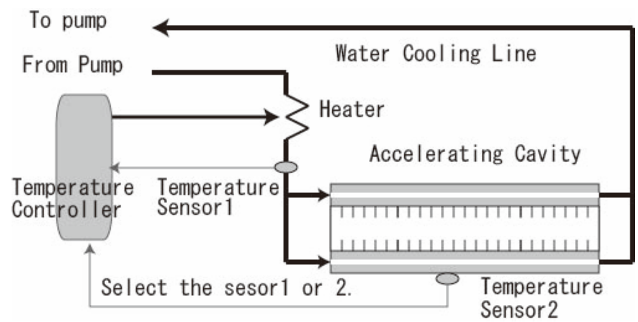

Figure 4: Highly precision cavity temperature controller.

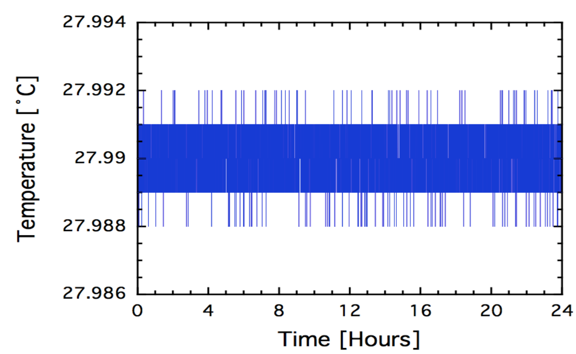

Figure 5: Temperature control performance of the 238 MHz sub-harmonic buncher. The temperature is regulated within +/- 2 mK (p-p).

High-Precision Temperature Controller

The individual rf instruments of SACLA were originally designed to satisfy a 50 fs temporal stability within a environmental temperature change of 0.1K (p-p). At this time, 50 fs is almost over the technical limit of temporal measurement accuracy. Since there are many rf instruments sequentially connected from a master oscillator to a cavity, some cavity did not satisfy the demanded temporal stability. Because the total temporal (rf phase) characteristic change is the sum of phase changes of all the sequentially connected instruments. For this reason, we developed a high-precision temperature controller for each acceleration cavity and the 19 inches rack for the LLRF system to obtain 10 times lower stability margin to the demanded temporal stability at each rf instrument. This stability margin is the immediate demanded target to verify stability after the improvement. Figure 4 shows configuration of the temperature controller for the 238 MHz sub-harmonic buncher of the injector, as an example, and its temperature control performance is shown in Fig.5. This controller can control

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the cavity temperature within +/- 2 mK (p-p). We also apply similar temperature control to the LLRF racks in the injector. This temperature control performance is sufficient to achieve the demanded temporal stability.

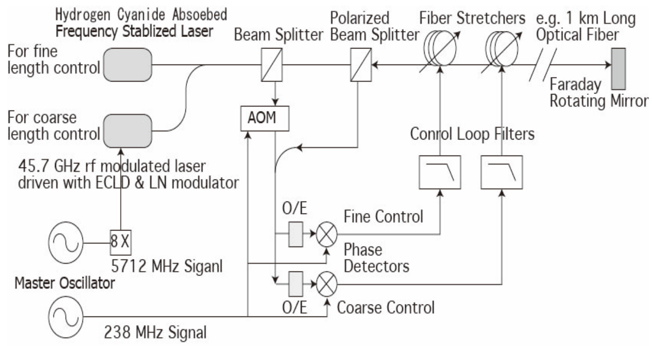

Figure 6: Optical-fiber length control system.

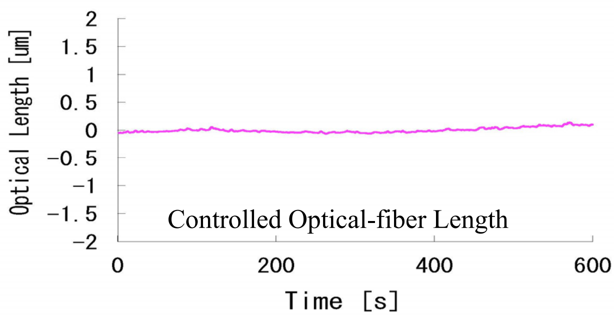

Figure 7: Control performance of the optical-fiber length control system. The fiber length is regulated within 1µm in the case of only the fine control.

Optical-Fiber Length Control

The perturbations from environmental temperature and humidity changes to driving optical fibers for SACLA were found out by operation experience in SACLA. [7] This driving optical fibers transmit continuous-wave (CW) reference rf-signals fed in to accelerator rf instruments and some parts of the LLRF instruments. These perturbations conduct X-ray intensity drift. To mitigate the effects from the perturbations, we developed an optical-fiber length control system, as shown in Fig. 6, to transmit an ultra-temporally stable 5712 MHz rf reference signal [6]. This signal is used for compensating the rf phase drift of the present LLRF system, just before rf pulse modulation for the klystron, with an inphase and quadrature (IQ) modulator. The compensation by using a phase comparator makes the minimum phase drift. Figure 7 shows performance of the optical fiber-length control system. The temporal resolution of the length control almost reached within 0.13 fs and the optical fiber length was apparently controlled within the resolution. However, we deduce a temporal stability performance of our LLRF system with the fiber length control is around 50 fs in rms by drift effects from rf and optical components outside of the optical-fiber length control loop. This 50 fs was measured by the phase comparison between the 5712 MHz reference rf signal fed into the driving optical fiber for the accelerator instrument and the ultra-stable 5712 MHz signal transmitted by the monitoring optical-fiber with its length control. Even thorough, we have the perturbations from the components outside of the length control loop; the 50 fs temporal control performance is sufficient for our demand.

SUMMARY

We mentioned our accelerator instruments development activities at SACLA, as the highlights mentioned above. One of the development items is a high-gradient C-band acceleration unit operated at a pulse repletion cycle of 120 pps. We confirmed the rf output form a developed klystron produced an acceleration gradient of 50 MV/m in a newly developed CG accelerating structure at 120 pps. To improve the present X-ray laser intensity-stability at SACLA, a high-precision temperature controller for the injector rf cavity was developed. The controller showed to have ability for controlling the cavity temperature within +/- 2 mK (p-p). An optical-fiber length control system was also developed. The system controls the temporal optical-fiber length change within 50 fs in rms. Both the temperature and fiber-length control system have almost sufficient performances to secure our demanded temporal stability of 50 fs in rms.

ACKNOWLEDGMENT

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