

# STATUS REPORT ON THE COMMISSIONING OF THE JAPANESE XFEL AT SPRING-8

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## Abstract

The X-ray free electron laser (XFEL) facility, which has been constructed since 2006 in the SPring-8 campus next to the storage ring as a five-year project, was completed as shown in Fig.1 on schedule in March 2011. The facility is named SACLA (SPring-8 Angstrom Compact free-electron LAsEr) by its features. In the final construction stage high power aging of all the RF components was performed in parallel with the construction aiming at smooth beam commissioning. Owing to this preparation the beam tuning could be started on 21<sup>st</sup> February and three months later, on 7<sup>th</sup> June XFEL lasing was successfully observed at a wavelength of 1.2 Angstrom. Beam tuning efforts have been continued towards achieving the target laser performance. This paper reports the operation status of SACLA focusing especially on the achieved accelerator and laser performances.

## INTRODUCTION

SACLA is the world's first compact XFEL facility based on a SPring-8 Compact SASE Source (SCSS) concept [1], which aims at achieving simultaneously a small scale, laser stability, operation reliability and extensibility. The construction of SACLA was started in 2006 towards the completion in March 2011. Although an operation reliability problem of modulator power supplies delayed the preparation of high power RF aging, the RF aging was started from the completed components in October 2010. As a result, SACLA beam tuning began from 21<sup>st</sup> February ahead of the schedule.

At the end of March full energy acceleration of 7.8 GeV was achieved and spontaneous radiation was first observed at a wavelength of 0.8 Angstrom. From the beginning of April the beam tuning towards SASE lasing



Figure 1: Aerial photo of SACLA.

was started. Although we took certain time for tune-up of the beam diagnostic system and encountered various unpredicted troubles, the first lasing was achieved on 7<sup>th</sup> June at a wavelength of 1.2 Angstrom. After facility inspection, we continued the beam tuning to improve the laser intensity and stability until the summer shutdown. The present tuning was carried out with a short pulse mode and we obtained the following performance, a maximum laser power of 4 GW and a wavelength range from 0.8 to 1.6 Angstrom. Figure 2 and Table 1 show the system configuration and main design parameters, respectively.

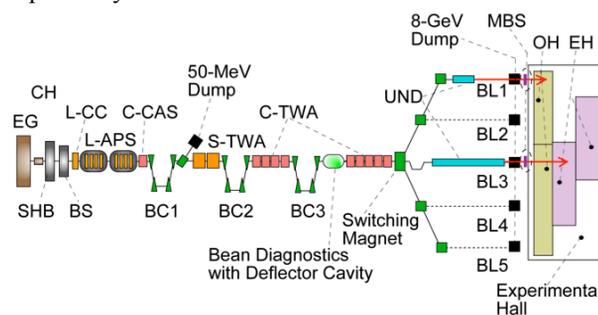


Figure 2: Schematic configuration of SACLA. EG, 500-kV electron gun; CH, chopper with collimator; SHB, 238-MHz sub-harmonic-buncher; BS, 476-MHz booster; L-APS, L-band alternating periodic structure (APS) typed standing-wave cavity; S(C)-TWA, S(C)-band travelling-wave acceleration tube; BC: bunch compressor; UND, undulator; BL, beam line; MBS, main beam shutter; OH, optical hatch; EH, experimental hatch.

Table 1 Main Design Parameters

Parameter	Target Value
Beam energy (GeV)	4~8
Bunch compression ratio	> 3000
Peak current (kA)	3~4
Repetition rate (Hz)	Max. 60
Normalized slice emittance ( $\pi \mu\text{mrad}$ )	< 1
Shortest SASE laser wavelength (Angstrom)	0.6
Laser power (GW)	20~30
K-value setting range	1.1~2.2
Undulator period length (mm)	18
Number of undulator periods	277
Number of undulator segments	18

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## PRESENT ACCELERATOR PERFORMANCE

The design modifications and achieved performances for the accelerator sub-systems are described in this section.

### Injector

The injector of SACLA [2] is basically the same as that of the SCSS test accelerator [3-5]. Figure 3 shows a picture of the injector section from the electron gun side. The major design changes are as follows:

- Change of the APS RF frequency from S- to L-band to enlarge the transverse and longitudinal acceptances.
- Installation of two kinds of correction cavities to linearize the beam energy chirp.
- Installation of earth field compensation coils to suppress a twist of the electron beam along the running direction.

The electron beam emittance extracted from the pulsed thermionic gun was measured with a slit scan method. The measured horizontal phase space distribution is shown in Fig. 4. The emittance is estimated to be  $1.1 \pi \mu\text{mrad}$ , which agrees well with the design value, suggests that the electron gun system works properly. The steering strengths over the injector section are much reduced compared with those of the test accelerator due to the earth field compensation.



Figure 3: Picture of the SACLA injector section.

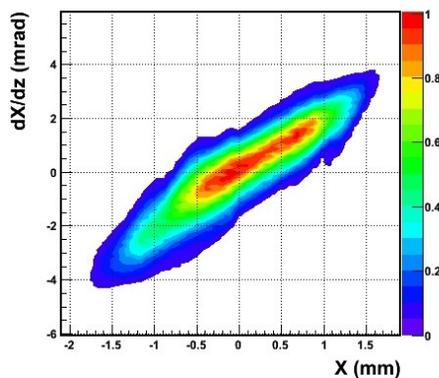


Figure 4: Horizontal phase space distribution of the 1 ns beam after the chopper.

### Magnet System

The major design changes of the magnet system [6] from the test accelerator are as follows:

- Change of a yoke shape and an end-shim design to reduce multi-pole components in the bunch compressors.
- Installation of a quadrupole pair at the dispersion peak of each chicane to correct the dispersion leakage.
- Adoption of pattern excitation procedures to avoid hysteresis of the important magnets.
- Installation of bypass lines for the 2<sup>nd</sup> and 3<sup>rd</sup> bunch compressor magnet chicanes to measure the compression performance of each compressor.

Since the measured dispersion leakage at each chicane was quite small due to the design improvement, the correction quadrupole pairs are presently not excited. The accuracy of magnetic field reproducibility is good enough to switch the undulator beam lines and to select the chicane or its bypass line. The installation of the bypass lines turned out to be effective to optimize the multi-stage bunch compression system.

### RF System

Figure 5 shows the C-band acceleration tubes, waveguides and pulse compressors installed in the tunnel. The major design changes of the RF system [7] are as follows:

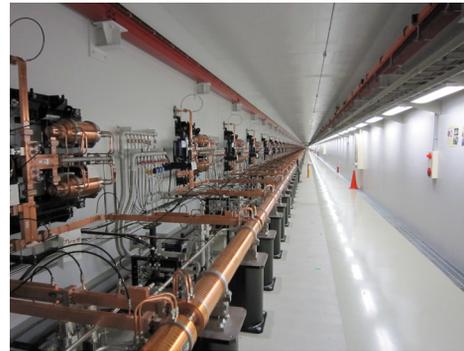


Figure 5: C-band acceleration system in the tunnel.

- Change of an S-band acceleration tube type (constant gradient to dumped structure) to suppress higher order modes in the optional multi-bunch operation.
- Adoption of a pulse compressor in each S-band unit and change of the S-band acceleration tube length from 2 to 3 m to increase the acceleration efficiency.
- Unification of the klystron and modulator oil tanks for higher operation reliability.
- Design change of the Pulse Forming Network (PFN) charger circuits for high charging stability and operation reliability.
- Adoption of 16-bit ADC/DAC to the IQ modulator/demodulator system for improving the resolution of RF phase and amplitude control.
- Environmental temperature stabilization by a water-cooled rack for LLRF electric circuits.

- Introduction of precise timing signal generation and transmission over a distance of 700 m.

Owing to the significant changes described above both the manufacture and installation of the high-power RF equipment were behind the schedule. We decided to increase the beam energy step by step by using the preparation-completed units, while continuing the aging. A target acceleration gradient of 35 MV/m has been achieved for the acceleration units with RF aging fully performed. Currently the beam energy used for the FEL operation is 7 GeV, lower than a design goal of 8 GeV. The averaged fault interval of the high-power RF equipment is about 30 min. under this operation condition [8].

The stable SASE operation needs the extremely high RF stability for the injector and the bunch compression system. To surpass the design target it is unavoidable to stabilize the PFN charging voltage within 100 ppm in full width. The developed charger enables highly precise charging with a variation of 10 ppm in standard deviation (STD). As a result of all the developments involving stabilization of the PFN charging voltage, the precise timing system, the high-resolution Low Level RF (LLRF) system, etc, we have achieved the target RF stability. For example, phase variations of 0.007 deg. (design target ~0.01 deg.) and 0.032 deg. (design target ~0.1 deg.) in STD are routinely obtained for SHB and the first C-band acceleration tube, respectively [9]. Figure 6 shows the measured SHB phase stability over 12 hrs. This RF stability has realized sufficiently stable bunch compression.

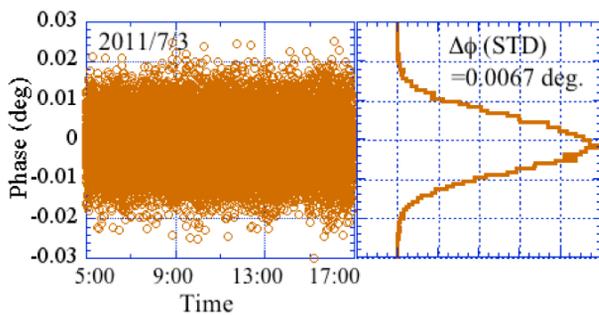


Figure 6: SHB phase stability over 12 hrs. Each data point represents an average of 10 shots.

Dark current from the high gradient C-band accelerating structures has never been a serious problem for the beam tuning since the beginning of the commissioning. Under the present operation condition, the dark current is quite low, 2 pC/pulse at the end of the accelerator. The beam halo monitor [10], which was installed at the entrance of the undulator beam line, clarified that no beam halo exists +/- 2 mm apart vertically from the beam centre. The small chicane was installed in the accelerator section at which the beam energy is about 3 GeV in order to remove the high-energy dark current. The systematic dark current measurement, however, shows that this dark current remover is presently not necessary for the reliable operation. We are

therefore planning to install additional accelerator units here instead of the chicane to increase the beam energy.

### Beam Diagnostic System

The major design changes of the beam diagnostic system [11] are as follows:

- Change of a Beam Position Monitor (BPM) type from the cavity to strip-line type for BPMs installed in the dispersive arc of the magnetic chicane to reduce a measurement error.
- Installation of Time Of Flight (TOF) monitors in the injector section to keep TOF constant over the injector.
- Installation of an RF deflector downstream of the final bunch compressor to measure a temporal profile of the compressed bunch.
- Installation of Coherent Synchrotron Radiation (CSR) monitors at three magnetic bunch compressors to detect a drift of the bunching condition.

Signal gains of the installed BPMs were larger compared with those in the test accelerator. We thus added external attenuators to enlarge a dynamic range of the measurement. After this treatment the BPM resolution has reached a level of sub-micron under the constant beam condition [12]. In practical beam tuning, where for example, the beam energy is widely changed by adjusting the RF acceleration phases, we found that the BPM readouts have rather large systematic errors. This reason is so far not clear. This large systematic error is one of the serious obstacles for the beam tuning, especially the beam based alignment that requires a highly precise orbit measurement.

C-band RF deflector has been working with the designed streak performance [13] since the early commissioning stage. The RF deflector provides the beam temporal profile information with a resolution of a few tens of fs. We could thus optimize effectively machine parameters of the multi-stage bunch compressor on the basis of the temporal profile information. On the other hand, Optical Transition Radiation (OTR) monitor [14] could not observe a two-dimensional profile of the fully compressed bunch, because strong Coherent OTR (COTR) appears downstream of the 3<sup>rd</sup> bunch compressor. To solve this problem, we replaced an OTR screen made of stainless steel by a Ce:YAG screen with the mask inserted in front of the lens. The mask covers the narrow angular divergence of COTR and stops it. Since the fluorescence having the beam profile information has wider angular divergence, it passes the outside of the mask and forms the profile image through the lens on the Charge Coupled Device (CCD) detector. By this improvement, we can measure the beam profile of the full compressed bunch. We presently change the screens of two locations, the diagnostic section just after the 3<sup>rd</sup> bunch compressor and the end of the C-band accelerator. Figure 7 shows the vertically streaked profile of the fully compressed bunch. In this measurement the pulse duration is about 30 fs including a natural beam size.

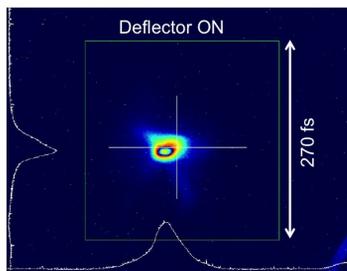


Figure 7: Vertically streaked profile of the fully compressed bunch.

### Control System

To stabilize the laser amplification, cross correlation between laser (or electron beam) properties and machine parameters is investigated by using single-shot data. And then, the machine parameters are optimized so as to obtain the stable laser performance. For this correlation analysis we need Synchronized Data Acquisition System (SDAS) to acquire monitor signals and RF parameters synchronized with the laser shot. To this end, the synchronized trigger pulses are delivered to the many distributed CPUs along the accelerator. In this system, a consecutive tag number is given to each laser shot and also to various measured data of the accelerator [15]. At present the developed SDAS is working stably under the routine operation with 10 Hz and the acquired data is beneficial for the beam tuning.

### PRESENT LASER PERFORMANCE

We achieved the first laser amplification of SASE XFEL by tuning the system with the following steps [16]; (1) tuning of a bunch compression system [17], (2) optics tuning and emittance measurement, (3) matching of beam transverse envelop to a focusing potential of an undulator beam line, (4) alignment of an undulator beam line, (5) fine tuning of undulator K-values, (6) tuning of phase shifters, and (7) K-value tapering for energy loss by a wake-field. The laser amplification was verified by measuring the X-ray spectrum with a small spatial aperture. Figure 8 shows an example of the measured SASE spectrum together with the spontaneous radiation

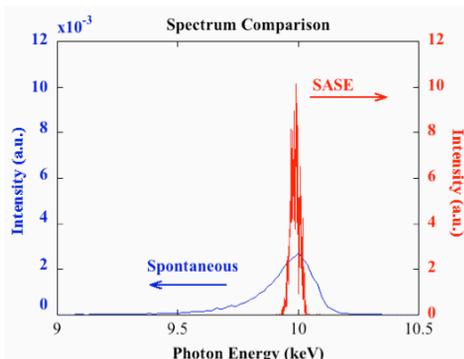


Figure 8: SASE laser spectrum at 10 keV.

one. The laser intensity increases by more than three orders of magnitude compared with that of the spontaneous radiation.

Since the first lasing obtained on 7<sup>th</sup> June, we have been making following efforts; (1) expansion of a lasing wavelength range, (2) increase in the laser power, (3) stabilization of the laser amplification, and (4) improvement of the laser reproducibility. The outline of the above efforts is described below.

### Expansion of Lasing Wavelength Range

The maximum K-value of the undulators installed in SACLA is 2.2 and it is adjustable by changing the magnetic gap between 40 to 3.5 mm. A practical K-value range is from 1.1 to 2.2 in SASE FEL operation from the viewpoint of an effective amplification gain. In combination with the beam energy change, a wide wavelength range can be covered with a high resolution. The laser operation has been presently performed in the beam energy ranging from 7.0 to 7.4 GeV with the K-values between 1.3 and 2.2. Although the FEL amplification is currently achieved between 0.8 and 1.6 Angstrom, the laser wavelength can be further shortened by increasing the beam energy up to 8.0 GeV.

### Increase in Laser Power

The beam tuning is being performed with what we call a short pulse mode where about 100 pC charges are compressed into a pulse-duration of 30 fs in FWHM. Assuming that the laser pulse duration is one half of the beam duration due to the narrowing, the laser power is estimated to be 4 GW at a wavelength of 1.2 Angstrom under the condition where the K-value and beam energy are set to 1.8 and 7 GeV, respectively. The estimated laser power is smaller by a several factor than the expected value by a simulation code, SIMPLEX [18]. The laser power can be potentially increased by properly improving the operation condition. We presently consider the following causes for the lower laser power; (1) insufficient optimization of the multi-stage bunch compression, (2) misalignment of the undulator beam line, and (3) insufficient optimization of the undulator parameters. We aim at achieving sub-mJ laser power as soon as possible by clarifying the causes of the above problem.

### Stabilization of Laser Amplification

It is critically important for efficient and precise tuning of undulator parameters to stabilize the laser amplification. We therefore focused on stabilization of the accelerator for two weeks just after the first lasing. The systematic correlation study showed that timing control of the beam chopper and unstable temperature control of the L-band APS cause the serious peak current variation. Owing to this information we could solved these control-relating issues. The serious remaining issue is a vertical beam orbit fluctuation of about 20  $\mu\text{m}$  in STD. This is caused by AC heater on/off procedures for a precise temperature control of the cavities and

acceleration structures in the injector section. We are investigating the two approaches, increasing in on/off cyclic frequency and replacing the AC heaters by DC ones.

To suppress the laser intensity drift we have currently introduced the following slow feedbacks in the usual laser operation; (1) TOF correction over the injector, (2) beam orbit correction at the entrance of the undulator beam line, (3) beam energy corrections at the 2<sup>nd</sup> and 3<sup>rd</sup> bunch compressors, and (4) beam energy correction at the exit of the accelerator. Figure 9 shows the laser power variation over 1 hr at a wavelength of 1.6 Angstrom. The variation is 18% in STD and the large intensity drops are due to the vertical orbit fluctuation originating from the accelerator instability.

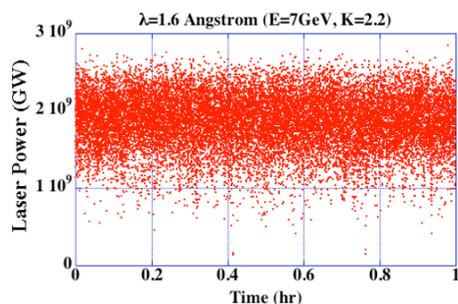


Figure 9: Laser power stability over 1 hr.

### Improvement of Laser Reproducibility

Presently 24 hrs operation of SACLA has been performed since the beginning of the beam commissioning. After finishing the beam operation, the electron beam from the gun is just stopped at the beam chopper until the next operation. The regular beam operation is started after finishing the daily operation meeting starting at 9:00 AM. It takes about 1 hr for providing the laser through the routine procedure comprising of loading the accelerator parameters, checking the beam and laser conditions and optimizing the laser power using several knobs. By this simple procedure, the laser intensity which is 60~70% compared with the peak performance is routinely obtained. The presently used knobs are (1) electron gun high voltage, (2) phase of the L-band correction cavity, (3) phase of the C-band correction acceleration tube, and (4) beam orbit injected to the undulator beam line.

### NEAR TERM SCHEDULE

We will start at least test use of SASE in November this year and also start the user operation in March next year. Toward these events we are tackling with the laser performance improvement such as further stabilization and increase of the laser power, etc.

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