

# THE SPRING-8 ANGSTROM COMPACT FREE ELECTRON LASER (SACLA)

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## Abstract

Commissioning of the world's first compact X-ray FEL (XFEL) facility named SPring-8 Angstrom Compact free electron LASER (SACLA) began in the spring of 2011 and soon demonstrated lasing at a wavelength of 1.2 Angstrom. The laser intensity did not reach a sub-mJ level before the summer shutdown. Owing to elaborate efforts on improving the beam tuning procedures together with the beam diagnostic system, the laser power saturation was achieved at around or longer than 1 Angstrom in the autumn of 2011. Finally, the laser pulse energy has been beyond a sub-mJ level in the wavelengths ranging from 1 to 3 Angstrom. The official user operation has been started since March 2012 showing laser availability higher than 90% constantly. Towards higher laser performance and efficient use R&D activities on X-ray self-seeding and beamline fast switching are now under way.

## INTRODUCTION

SACLA is the world's first compact XFEL facility based on a SPring-8 Compact SASE Source (SCSS) concept [1], which aims at a "general purpose" machine spread widely. The beam commissioning of SACLA was started on 21<sup>st</sup> February 2011.

Although the first lasing was achieved on 7<sup>th</sup> June at a wavelength of 1.2 Angstrom [2], it was not easy to increase the laser intensity up to a sub-mJ level. We thought that a main cause of this lower laser intensity is the non-optimized accelerator operating condition being far from the design one. As a result of improving the beam tuning procedure we finally succeeded in operating the system under nearly design condition and then achieved SASE XFEL saturation. A target pulse energy value of a sub-mJ has been attained over the wide wavelength range.

In this report we first describe key improvements in the beam tuning process for achieving the design target. We next show the achieved laser and operational performances of SACLA. We at last outline our future upgrade plan.

## KEY IMPROVEMENTS IN THE BEAM TUNING

Three key improvements are described in this section, which played important roles to overcome the difficulties and to attain the design target.

### Reliable Projected Emittance Measurement

Projected emittance of the electron beam is measured with a conventional Q-scan method [3] using a beam

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profile monitor [4] comprising a screen, an optical system and a CCD detector. The beam profile measurement after full bunch compression utilizes optical transition radiation (OTR) from a stainless steel screen. Even though we successfully suppressed coherent OTR (COTR) illumination on the CCD detector [2] by inserting a spatial mask to stop COTR, we still had a strong dependence of the evaluated emittance values on the measurement conditions before the summer shutdown in 2011. We therefore could not efficiently utilize the transverse emittance information in our beam tuning process. Figure 1 shows the correlation between an evaluated emittance value and a focal length of a Q-scan system at the exit of the third bunch compressor (BC3) before and after the improvement. It is clear that the Q-scan data had non-negligibly systematic errors in the measured beam profiles before the improvement. In order to reduce the systematic errors we performed:

- Optimization of the spatial mask parameter such as a location, shape and size for removing COTR on the detector.
- Fine tuning of focusing on the screen.

After the above improvement we have been able to make a reliable and reproducible projected emittance measurement and to obtained reasonable emittance values at around  $1\pi$  mmmrad constantly as shown by the blue circles in Fig. 1 having no correlation with the focal length.

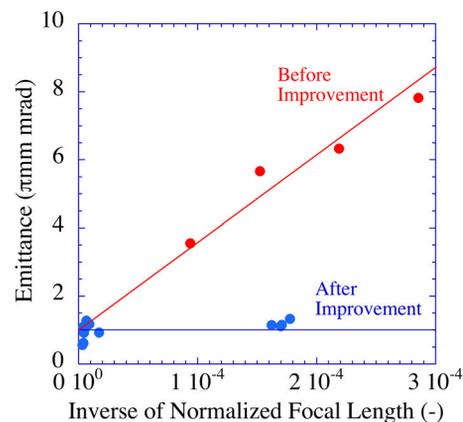


Figure 1: Correlation between an evaluated emittance value and a focal length of a Q-scan system at the exit of BC3 before and after the improvement.

### Optimization of Three-stage Bunch Compressor

The three-stage bunch compressor at SACLA has two kinds of nonlinear chirp correctors [5]. One is a L-band correction cavity (L-CC) to control an initial condition of the beam injected to the compressor, in other words, to compensate nonlinear chirp in a velocity-bunching

process. The other is a C-band correction accelerating structure (C-CS) to sufficiently linearize the bunch compression process at BC3 [6,7]. The both locate at the most upstream section of the three-stage compressor. These two correctors are usually operated at around an acceleration phase of -180 degree (deceleration phase) to mainly cancel the second order nonlinearity out as shown by the black solid line in Fig. 2 [6,7]. However, the setting phase of C-CS was far from the design value, nearly -145 degree due to some mistake happened in the early tuning stage. This unusual phase apparently makes the optimization on a bunching process complicated by tightly linking the linear energy chirp to the second order one. A linear-compressive part of the bunch resultantly becomes narrow and decreases the number of electrons contributing to the lasing as schematically shown in Fig. 2. We therefore tried to adjust this phase set incorrectly, but failed in the correction before the summer shutdown. Since C-CS locates at the most upstream section of the system, we have to change the major focusing parameter over the accelerator to keep the transverse beam envelope in changing the phase of C-CS. After establishing the reliable projected emittance measurement we tuned the focusing parameter and electron beam orbit finely step-by-step from BC1 towards BC3 by keeping the emittance value at around  $1\pi$  mmmrad. By this procedure we first reached a laser intensity of sub-mJ/pulse with the nominal accelerator parameter used in the computer simulation [8].

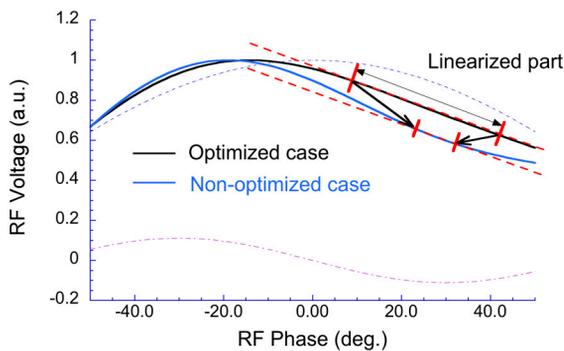


Figure 2: Schematic view of non-optimized linearization.

The charge of the accelerated electron beam was about 100 pC before the summer shutdown. This small transmission was due to the C-CS phase set incorrectly. After the tuning described above, we can keep the emittance value at around  $1\pi$  mmmrad after full bunch compression with an energy slit at BC1 opened widely. The beam charge resultantly increased up to 250 pC, nearly the design value.

### Adequate Treatment of Electron Beam Orbit through Undulator Beamline

At SACLA the electron beam orbit through the undulator beamline is set by overlapping the spontaneous radiation from each undulator on the target locating far

downstream from the exit of the undulator beamline. In this procedure the electron beam energy and K-value are kept constant, usually at 7 GeV and 1.8, respectively. Once the reference orbit is determined, we then refine the correction steering table for different conditions so as to correct the deviation from the reference. Before summer shutdown this procedure was applied to the operation with different beam energy and as a result we did not achieve the sufficient laser intensity, especially in a longer wavelength region where a laser amplification gain is relatively high. To solve this problem we investigated the dependence of the laser intensity on the beam orbit by changing the beam energy little by little from the reference energy. We found that the correction of the orbit deviation from the reference actually reduces the laser intensity. This result means that the readout by the RF-BPM does not represent the real orbit deviation when we change the beam energy. After this study we changed the orbit setting routine to only refine the correction table for different K-values keeping the energy same as that used in the orbit setting process. The steering magnet parameter in the undulator beamline has not been dependent on the beam energy but only on the K-value. This change much contributed for increasing the laser intensity over the wide wavelength region.

## LASER PERFORMANCE

The present SASE XFEL performance is summarized in Table 1.

Table 1: Achieved Laser Performance

Parameter	Achieved Value
Pulse energy (mJ)	0.1 ~ 0.5
Peak power (GW)	> 10
Intensity fluctuation (%)	10 ~ 20
Lasing wavelength (Angstrom)	0.6 ~ 3
Spatial coherence	nearly full
Repetition rate (Hz)	10

### Pulse Energy

Pulse energy of XFEL is measured by a single-shot non-destructive intensity monitor using backscattered X-rays [9], which locates in optical hutch just before the experimental hutch. This monitor was calibrated using photo-diode detectors having a wide dynamic range. The pulse energy much depends on both a laser wavelength and K-value as shown in Fig. 3. The higher intensity is obtainable in a longer wavelength and a higher K value. Pulse energy of more than 0.2 mJ is available at a wavelength of 1.2 Angstrom in a routine user operation. In a longer wavelength region at around 2 Angstrom, the laser pulse energy increases up to nearly 0.3 mJ/pulse. Recently, after replacing the gun cathode assembly, the pulse energy values at 2 Angstrom and longer are lower

compared with the value, 0.5 mJ/pulse achieved in autumn 2011. It may be due to the electron beam temporal profile having the smaller beam charge.

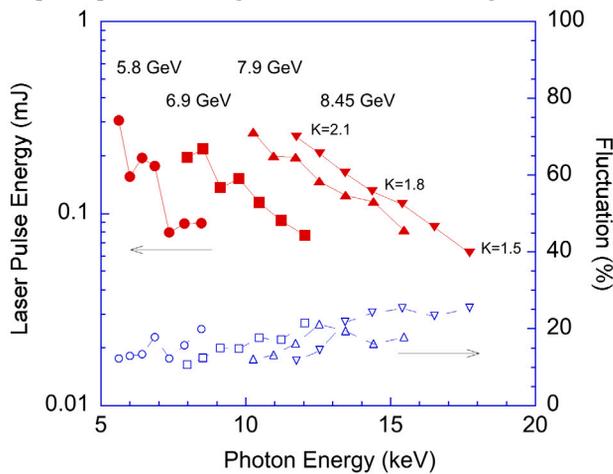


Figure 3: Dependences of pulse energy and intensity fluctuation on beam energy and a K-value. The symbols on each line for the constant operating energy show different K-values from 1.5 to 2.1.

### Peak Power

Although peak power of XFEL has not been directly measured yet, a temporal profile of the fully bunched electron beam is routinely measurable using the RF deflector system [10]. Figure 4 shows the typical temporal profile corresponding to the bunch envelope in which microstructures smear out due to the spatial resolution and vertical beam size. The typical value is 20~30 fs in FWHM. Envelope of the laser pulse temporal structure is shorter than this and the peak power based on the envelope width is estimated to be beyond 10 GW in the wavelengths longer than 1.2 Angstrom. We predict that the spike-based peak power is much higher than 10 GW.

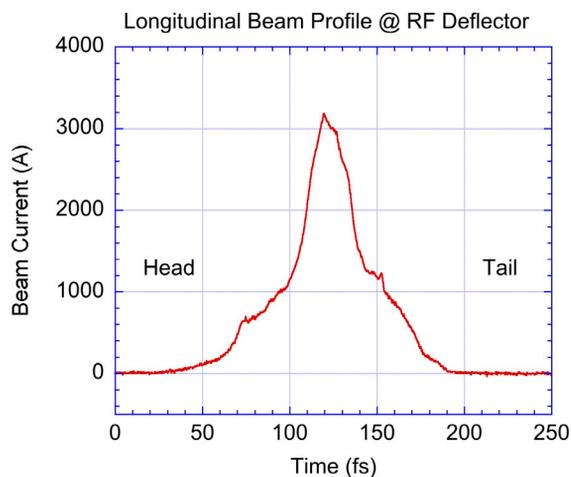


Figure 4: Typical electron beam temporal profile measured by RF deflector system after full bunch compression.

### Intensity Fluctuation

The intensity fluctuation of SASE XFEL is 10 to 20% in standard deviation ( $\sigma$ ) at the entry of the optical hutch. This closely depends on the laser wavelength. The fluctuation usually becomes smaller in a longer wavelength region. Figure 5 shows the intensity fluctuation over 1 hour at a wavelength of 2.3 Angstrom. In this example the intensity fluctuation was 13% in  $\sigma$ .

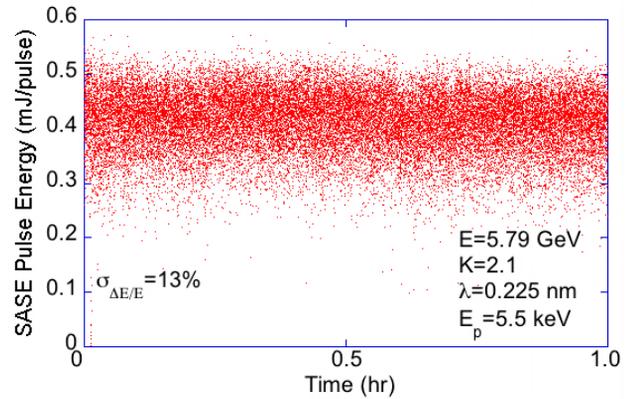


Figure 5: Intensity fluctuation of SASE XFEL over 1 hr.

### Others

The available energy range from ~0.7 to 3 Angstrom in the user operation is determined by two constraints; tuning ranges of a K-value (1.5 ~ 2.1) and electron beam energy (5 ~ 8.3 GeV). To make shorter wavelengths available, we are planning to increase the beam energy up to 9 GeV by installing additional four C-band accelerator units. These will be added in the section prepared for the dark current remover [11], which we already found to be unnecessary for the daily operation because of the extremely low dark current level.

Spatial coherence has been measured by X-ray interferometry using a double slit separated vertically by 60  $\mu\text{m}$ . Visibility was evaluated with the measured interference pattern and we found the visibility is around 98%, which shows XFEL at SACLA is spatially full coherent.

## OPERATIONAL PERFORMANCE

The present SACLA operational performance for the user experimental period is summarized in Table 2. In FY2012 annual operation time of 7000 hours has been scheduled and 1000 hours of them are assigned for pure machine tuning to reproduce the laser performance after regular shutdown periods. The remaining 6000 hours are dedicated to user experiments and R&D activities.

### Mean Fault Interval and Recovery from the Fault

The repetition rate is currently limited to 10 Hz (Max. 60 Hz) by a thyatron misfire, which is independent of the input RF power. The present mean fault interval is 30 ~ 40 minutes and this interval goes down as we increase in

repetition rate because the number of faults linearly depends on the repetition rate. To reduce dead time by the faults we are investigating relaxation of the trip condition for thyratrons. We will be able to dramatically reduce the fault frequency by this treatment and then, we will raise the repetition rate towards 60 Hz.

The recovery time from the single fault is 1 minute or less and the XFEL characteristics, i.e., intensity, wavelength and so on are well reproduced by a simple recovery procedure automatically performed.

Table 2: Operational Performance

Parameter	Achieved Value
Mean fault interval @10 Hz (min.)	30 ~ 40
Recovery time from the fault (min.)	1
Operation mode	24 hrs continuous
K-value change between 1.5 and 2.1	freely by users
Availability (%)	~ 90
Reproducibility (peak:100%)	60 ~ 70

### User Operation

SACLA is operated in the user experimental period by a 24-hours continuous mode. Prior to the experimental period, all parameter sets being necessary for the operation are prepared. The regular machine tuning is therefore not carried out during the experiments except for accidental cases. Figure 6 shows the XFEL intensity fluctuation and drift during the user experimental period

over three days. In this example, the mean fault interval was 30 minutes. We see that the laser pulse energy was well kept around 0.25 mJ over three days.

A major change of the laser wavelength is routinely done by the beam energy change, which is performed by machine operators. On the other hand, with respect to the minor change, experimental users carry out by themselves by changing the K-value at the experimental hall according to their experimental demands. Availability, which shows a ratio of the executed experimental time to the planed one, reaches around 90% constantly.

### UPGRADE PLAN

We are investigating the possibility to deliver higher pulse energy, nearly 1 mJ at the longer wavelength region. For this purpose, we need to enlarge the linearly compressive part of the electron beam by correcting the compression nonlinearity up to the third order.

We also started to introduce a self-seeding scheme into the central beamline #3 (BL3). The 9<sup>th</sup> undulator segments in BL3 will be removed to prepare space for the seeding apparatus and reinstalled the removed segment at the end of the undulator beamline. We will first install a small chicane in the vacant space to evaluate the electron beam temporal structure with high time resolution by constructing a kind of auto-correlator.

Towards efficient use of XFEL for various experiments, we have to increase the number of available beamlines together with a fast beamline switching. We started R&D on a pulse-by-pulse beam switching system in FY2012.

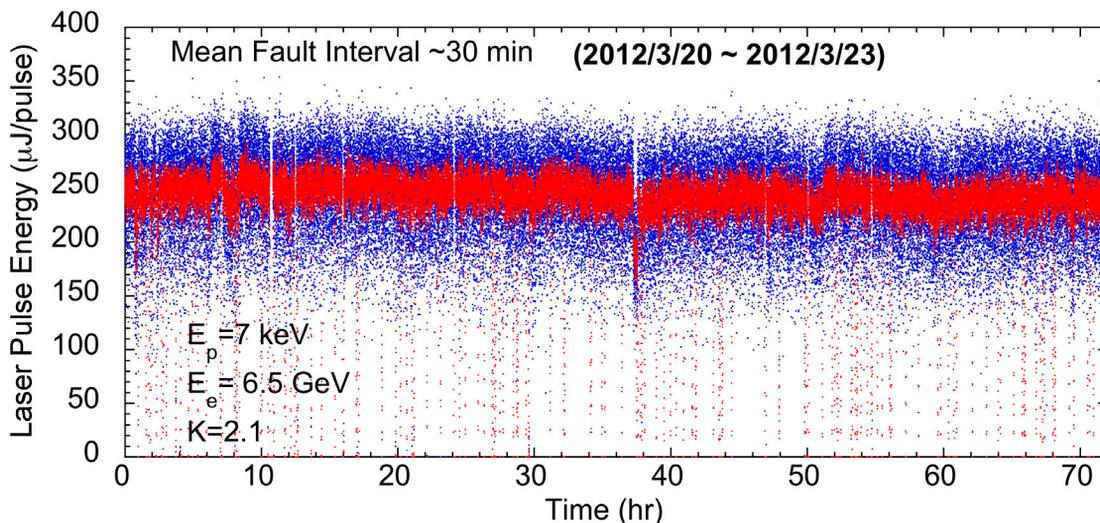


Figure 6: Intensity fluctuation and drift of SASE XFEL over 3 days. The blue and red points represent single shot pulse energy values and 10 shots moving averaged ones.

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