OVERVIEW OF SACLA MACHINE STATUS

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Abstract

SACLA, part of an X-ray free-electron laser, has been constructed, and was successfully lased at 0.06 nm in 2011. SACLA mainly comprises a low-emittance thermionic electron gun, an 8-GeV linear accelerator using C-band (5712 MHz) cavities and 18 in-vacuum undulators. A concept used to develop this machine involves compactness compared with the other machine, such as LCLS with a length of more than 1 km. Stable X-ray lasing of up to 0.06 nm to also be a concept demands extremely stable accelerator components, such as a 50 fs temporal stability of an rf phase at a cavity in an injector. We have now realized a 700 m compact machine by using low-emittance at an electron gun, an accelerating gradient of more than 35 MV/m by a C-band accelerator, and short-period undulators. Continuous lasing for more than several days is strongly supported by these stable components and small operator's trimming, and has also been established by reducing perturbation sources to laser instability. SACLA is regularly operated for user experiments, such as material imaging with an extreme amount of data.

INTRODUCTION

SACLA has been constructed in order to generate an X-ray laser of up to a wavelength of around 0.06 nm, and is now under operation for user experiments [1]. We can explore new science, such as revealing protein membrane structures, by this machine.

SACLA was designed in accordance with the following two concepts, called SCSS concepts [2]. One is a short machine length, like compactness, which is associated with low construction costs. Next, is an ultra stable machine, which guarantees stable laser intensity, contributing to reliable experiments. In order to realize this concept, we employ a method using a high-brightness, low-emittance thermionic electron gun operated at a 500 kV high-voltage pulse [3], a C-band accelerator with a high-gradient acceleration of more than 35 MeV/m [4] and an in-vacuum undulator with a short period and a narrow gap [5]. Their high-brightness electron beam and narrow gap as well as short period, λ_u, associated with a large undulator parameter, K, and a short radiation wavelength, λ, allow us to reduce the gain length of self-amplified spontaneous emission (SASE) along the undulator beam line. High-gradient acceleration is also effective to make a short accelerator. Hence, the machine length becomes shorter than other X-ray free electron laser (XFEL) machines of over 1 km, such as the linac coherent light source (LCLS) at SLAC [6] and Euro-XFEL at DESY [7]. This SCSS concept is the most prominent characteristic of our SACLA.

Ultimate stability of an X-ray laser, which is guided by ultra-stable accelerator components, is also a crucial part of SACLA. As examples to realize stable X-ray lasing conditions, it is necessary that the electron beams and related undulator radiation should spatially overlap within 4 µm in STD along the undulator line [8], if we allow for reduction of the SASE intensity up to half of the peak intensity (design value). The demanded rf phase (temporal) stability at cavities in an injector is around 100 fs in STD, if we also accept a peak electron-intensity fluctuation of 10% in STD, corresponding to a peak X-ray laser intensity fluctuation of 10% in STD [9], which is almost the intrinsic intensity jitter of statistical SASE generation. The amplitude of the Pierce gain parameter, ρ, for FEL amplification along an undulator section directly reflects the overlap factor, OF, between the electron beam and its radiation [10], and also the charge density of the electron beam [2]. For example, these component stabilities mean a stable low-emittance value and electron beam energy stability established by the emission stability of the electron beams form the thermionic electron gun, the rf phase and amplitude stabilities of acceleration cavities, the magnetic field stabilities of beam-transport magnets, undulator magnetic field stability, and components alignment in order to secure the interaction between the electron beams and the beam radiated field along the undulator line.

We must realize these required values to secure stable X-ray laser radiation, as well as the concept. This paper introduces accelerator components and their performances, X-ray lasing performance, and the present issues to deteriorate the lasing performance of SACLA.

SACLA'S MACHINE LAYOUT, ITS FUNCTION AND COMPONETS

Layout and Function

Figure 1 shows the machine configuration of SACLA, which mainly comprises a 500 kV thermionic electron gun, a 238, 476, 1428 MHz multi-sub harmonic bunching and accelerating system as an injector, 8 S-band detuned-accelerating structures, 128 C-band choke-mode accelerating structures, 18 in-vacuum undulators and an X-ray beam line. The individual components of SACL work as follows. At first, the electron gun emits electron beams with a low emittance of 0.6 πmm-mrad in rms, a pulse width of 3 µs in FWHM and a 1A peak current.

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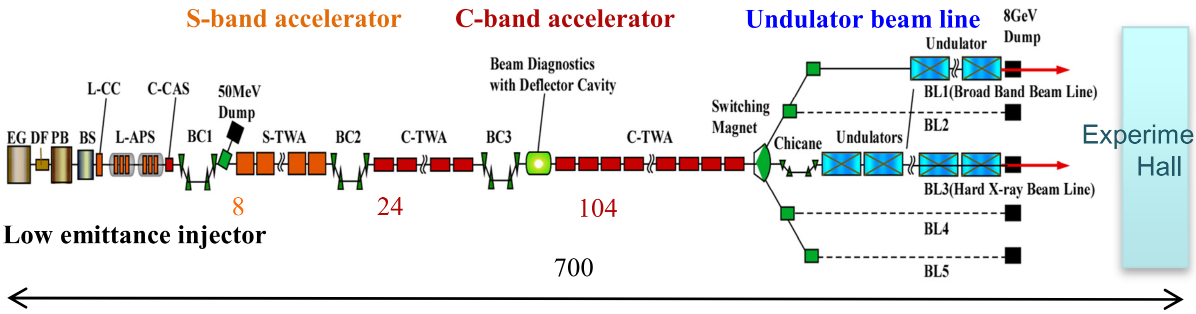

Figure 1: Machine layout of SACLA. SACLA comprises a low-emittance injector including a CeB6 500 kV thermionic electron gun (EG), a beam chopper (DF), a 238 MHz sub-harmonic buncher (SHB or PB), a 476 MHz booster cavity (BS), an L-band correction cavity (L-CC), L-band alternating periodic structures (L-APS) and a C-band correction accelerating structure (C-CAS)), a bunch compressor 1 (BC1), 8 S-band accelerating structures, a bunch compressor 2 (BC2), 24 C-band accelerating structures, a bunch compressor 3 (BC3), 104 C-band accelerating structures and undulator beam lines (BL1 and BL3) with 18 undulators.

Table 1: Present parameters of the X-ray and electron beam of SACLA

X-ray	
Wavelength (Å)	~ 0.6
Peak Power (GW)	10
Pulse Length (fs)	200 ~ 30
Photons per pulse	2 x 10^{11}
Pulse Energy (mJ)	0.1 ~ 0.5
Bandwidth	10^{-3}
Peak brilliance (ph/s/mm^2/mrad^2/0.1% BW)	1x 10^{33}
Coherence (transverse) (longitudinal)	2D coherent Multimode
Electron Beam	
Energy (GeV)	~ 8.5
Charge (nC)	0.2 ~ 0.3
Peak current (kA)	~ 3
Pulse width (fs)	10 ~ 70
Normalized Emittance (π mm mrad)	0.1 ~ 0.5
Repetition rate (Hz)	~ 60 (Max.)

Then, a high-voltage chopper forms a 1 ns beam width in FWHM from the 3 µs width to fit the rf phase space of a 238 MHz sub-harmonic buncher (SHB) in order to make velocity bunching. After this, the electron beam is accelerated up to 1 MeV by a 476 MHz booster cavity (booster), and the booster makes velocity bunching. Following the booster, L-band (1428 MHz) alternating-periodic structures (APS) develop further velocity bunching up to about a beam pulse width of 10 ps, produces energy chirp along an electron bunch for the following magnetic bunching process and accelerates up to a beam energy of around 30 MeV. Next, magnetic bunching using 4 bending magnets chicane as a bunch compressor 1 (BC1) compresses a bunch length up to about 3 ps. 8 S-band accelerating structures also cause energy chirp along the bunch for the bunch compression of BC2, and accelerate the electron beam up to 450 MeV. Following this, 24 C-band accelerating structures accelerate the beam up to 1.4 GeV, and provide energy chirp for bunch compression at BC3, which is the final bunch compression stage. These bunch compression processes correspond to an off-crest rf wave acceleration part, which is very sensitive to any outside perturbation, such as an environmental temperature change. A successive part of the bunch compressors, as mentioned above, is 104 C-band accelerating structures, which only accelerate the electron beam at the rf crest part up to an energy of ~ 8.5 GeV. The rf crest acceleration is relatively ten-times more insensitive to perturbations from the environment compared with off-crest acceleration. After obtaining full energy, such as 8.5 GeV, the electron beam passes through an undulator line with an effective length of 90 m in order to amplify an X-ray laser up to a wavelength of 0.063 nm by the SASE process, and to emit the laser to an experimental hall. Table 1 summarizes the characteristics of both the electron beam and the X-ray laser beam. In addition to the present configuration of SACLA, as mentioned above, we have a spare room for 4 other beam lines of BL1, 2 ,4, 5 to meet the requirements of multi-users. BL1 already and partly works for electron-beam tuning and emitting wide-band spontaneous light.

Low-emittance Thermionic Electron Gun

One of the key instruments of the SCSS concept is a thermionic electron gun [3], which is crucial to obtain a low-emittance electron beam. This electron gun uses cathode material of a CeB$_6$ single crystal heated up to about 1550 ºC; a high voltage pulse of around 500 kV with a pulse width of 3 µs in FWHM is added to the cathode. This single-crystal material is usually used for an electron microscope. This cathode with 3 mm in diameter and 5 mm long radiates an intense electron beam with

Figure 2: Outlook of the 500 kV, CeB_6 thermionic electron gun.

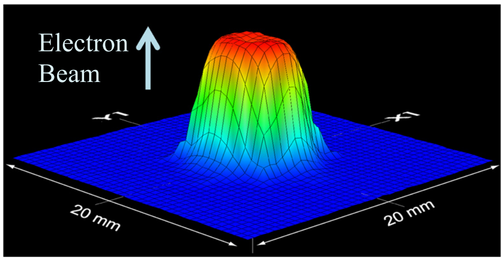

Figure 3: Spatial transverse profile of the beam emitted from the electron gun with a 0.6 πmm-mrad emittance.

a low emittance of 0.6 πmm-mrad from a very smooth surface within a flatness of several µm, when applying a high-voltage pulse. Figure 2 shows the outlook of the electron gun installed in to a SACLA accelerator tunnel. Figure 3 also shows the transverse profile of the radiated electron beam having 0.6 πmm-mrad emittance. The 500 kV high-voltage pulse is generated by almost the same high-voltage pulse modulator as in the klystron case, mentioned below. This modulator generates a 37.5 kV pulse. Then, this pulse is stepped up to 500 kV with a transformer. For impedance matching and interchangeability to a C-band high-power rf system, as also mentioned below, a 500 kV klystron like dummy tube without cavities is employed, because of the high-impedance of our cathode.

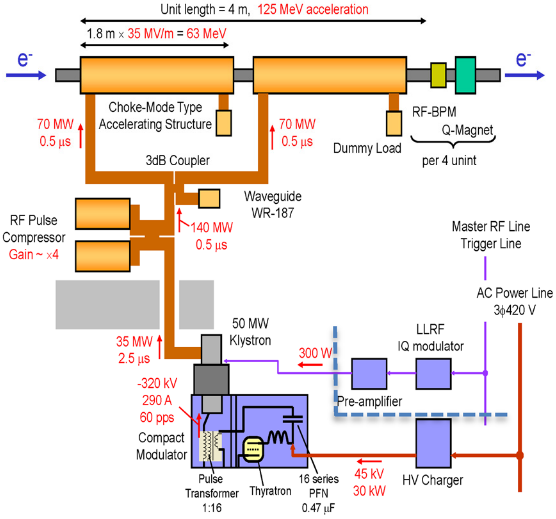

Figure 4: Schematic diagram of the C-band accelerator system. The system comprises 2 C-band accelerating structures, high-power waveguide components, a 50 MW klystron with a 2.5 µs rf output pulse width, a pulse modulator and a high-voltage inverter power supply.

C-band High-gradient Acceleration System

A C-band acceleration unit is depicted in Fig. 4 [4]. There are 64 units in a SACLA accelerator building. Each unit has two 1.8 m choke mode accelerating structures, a vacuum waveguide system including an rf pulse compressor, SLED, with an rf multiplication factor of 4, a 50 MW klystron generating a 2.5 µs width rf pulse, a 350 kV pulse modulator to drive the klystron, a 45 kV inverter power supply, and a low-level rf (LLRF) and timing system. When the klystron generates a 35 MW rf pulse, the SLED generates a 200 MW peak rf pulse fed into the 2 accelerating structures. Then, these structures provide a 35 MV/m acceleration gradient. Figure 5 shows the preset acceleration gradient produced by the C-band system. The 350 kV high-voltage pulse is formed with a pulse transformer placed under the klystron from a 45 kV pulse, which is generated by a pulse forming network (PFN). This PFN is charged with the 45 kV inverter power supply, and the 45 kV pulse is made by switching charge in capacitors constituting the PFN with a thyratron.

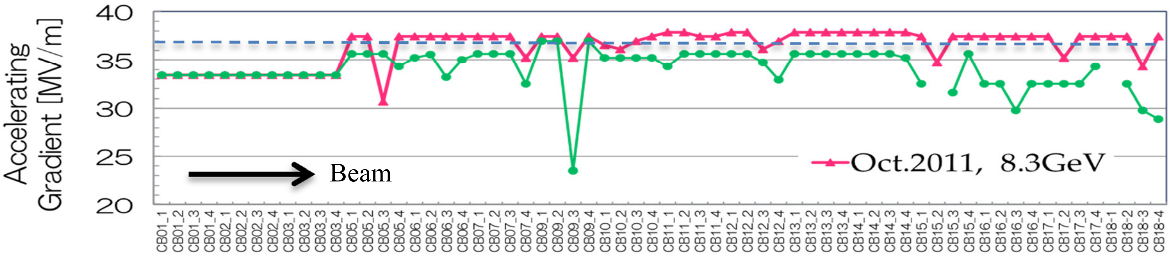

Figure 5: Acceleration electric-field gradients of all the C-band units along the SACLA accelerator. The electric-field gradients of almost all the C-band units after BC3 reach values of more than 37 MV/m. The red line with the solid triangle dots shows the case at a beam energy of 8.3 GeV; the green line with the solid round dots shows the case of 7 GeV. The blue dotted line is a reference value of 37 MV/m.

In-vacuum and Short Period Undulator

One of the effective methods to reduce a gain length of FEL amplification is an in-vacuum undulator [5], in which short period permanent magnets assemblies are installed into a vacuum chamber. Therefore, the gap distance between the magnets, which the electron beam passes through, is as narrower as possible compared with an out-vacuum undulator having a vacuum beam duct in the gap. This means we can obtain a large K value by a strong magnetic field conducting a large ρ value and a short gain length. Furthermore, since the gap is movable, the wavelength of the X-ray laser generated with the undulator is changeable. The present minimum gap is 3.5 mm. Figure 6 shows a view of SACLA's 18 undulators installed into a radiation shield room, and Table 2 summarizes the fundamental parameters of our in-vacuum undulator.

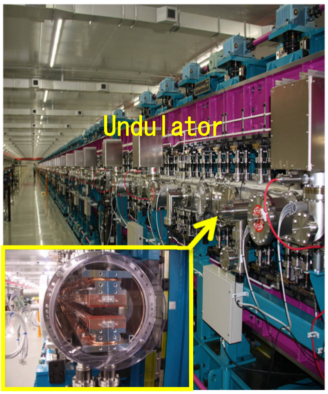

Figure 6: 18 undulators along the BL3 of SACLA.

Table 2: Fundamental parameters of the undulator of SACLA.

Magnet Structure	Hybrid Type
Permanent Magnet Material	NdFeB
Length (m)	5
Period Legth (mm)	18
Number of Periods	277
Number of Undularors for BL3	18
Minmum Gap of Magnet (mm)	3.5
Maximum K value	2.2
K at 0.12 nm, E = 7 GeV	1.8

Key Components to Support Stability

There are many crucial devices to secure SACLA's lasing stability. However, we do not have much space in this paper. Hence, the 2 key components of SACLA, as most important devises, are explained as follows. One is the inverter power supply for the klystron modulator, which decides the rf phase and amplitude stability of a klystron output. Because a change in the output voltage of the inverter power supply is associated with a klystron high-voltage change, it varies the electron beam velocity (energy) in the drift tube of the klystron. The demanded voltage stability of the power supply is less than 100 ppm (rms), which comes from a required rf temporal (phase) stability of 100 fs in the accelerating structures of the off-crest part, as mentioned in the introduction. Our developed inverter power supply employs hybrid coarse and fine voltage-control power supplies working in parallel. Figure 7 shows the voltage-control performance of the inverter power supply, which is sufficient for our demand.

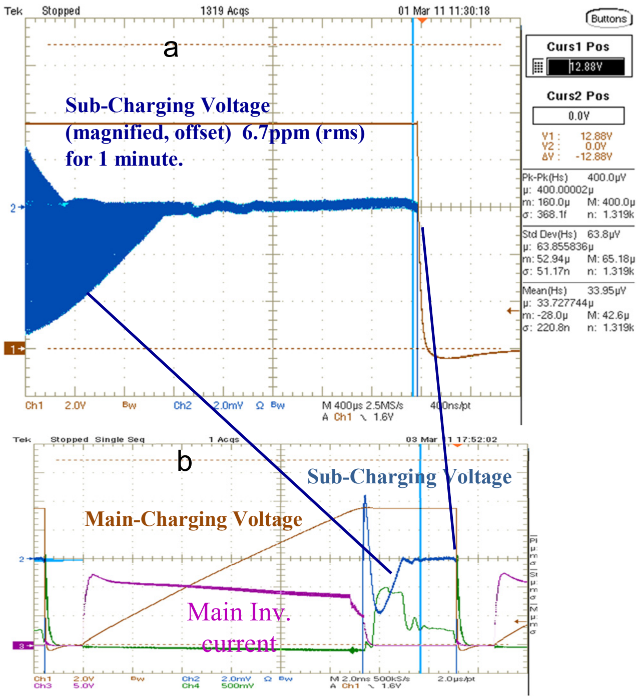

Figure 7: Voltage stability of the inverter power supply. The stability is 6.7 ppm in rms for 1 minute. The upper "a" drawing shows the magnified amplitude and time scales case. The lower "b" shows the reduced amplitude and time scales case.

Next, an indispensable part is the LLRF system [11], which mainly determines the beam temporal stability associated with lasing instability. This system comprises a master oscillator that generates 238, 476, 1428, 2856, 5712 MHz reference signals to drive the high-power rf source, like the klystron, through an in-phase quadrature modulator for pulse modulation and rf amplitude and phase control, and a 500 W solid-state pulse amplifier. These signals are transmitted by phase-stabilized optical fibers with a thermal optical length coefficient of 2ppm/K. The temperatures around these LLRF components, as well as the optical fibers, are controlled by cooling water within 0.1 K to reduce any rf phase and amplitude drifts. One of the performances of the LLRF system is shown in Fig. 8, which is the rf amplitude and phase stabilities at 238 MHz SHB driven with a 10 kW solid-state pulse amplifier. This amplifier is directly connected to the LLRF system. The rf phase and amplitude stabilities are 0.0067 deg. and 1 x 10^{-4} in rms for 24 hours, respectively. These values are almost sufficient for our demand.

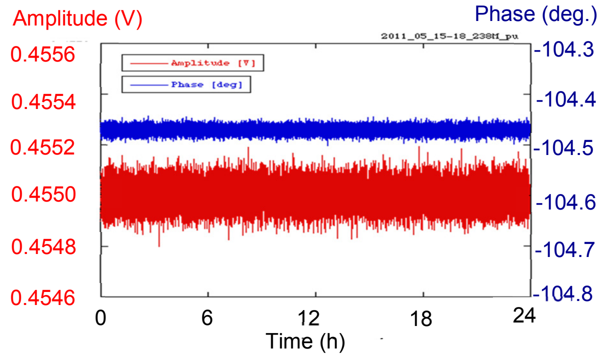

Figure 8: Phase and amplitude stabilities of the 238 MHz SHB. The phase stability is 0.0067 deg. in rms and the amplitude stability is 1 x 10^{-4} in rms for 24 hours.

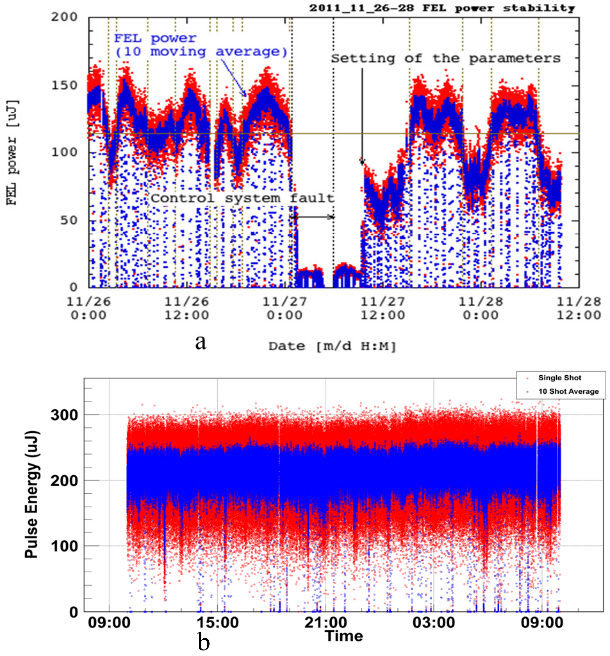

Figure 9: Lasing intensity stabilities. a, intensity variation for 3 days with the rf phase and amplitude control of all SACLA's cavities and the incident beam orbit control for BL3; b, lasing intensity stability with the operator's fine trimming for the rf phase and amplitude of the injector cavities.

LASING PERFORMANCE AND PROBLEM

SACLA lased at 0.1 nm in June, 2011, after beam commissioning by using the above-mentioned instruments. Then, the lasing intensity stability of SACLA, as shown in Fig. 9-a, was not sufficient. For 3 days, we could keep the X-ray lasing with only feedback control loops of the rf phases and amplitude of all the cavities and an incident beam orbit on the undulator of BL3. After this, improvements of the instrument stabilities, such as temperature regulation betterment in the injector cavities (e.g. SHB) from within 0.1 K to within 0.004 K, were performed [12]. Finally, we obtained further lasing intensity stability, as described in Fig. 9-b. However, this intensity stability was established by the operator's fine trimming of the rf phases and amplitude at the cavities around the injector. The frequency of the trimming is once or twice an hour.

SUMMARY

SACLA, 700 m long, which is shorter than the other XFEL machines, lased at up to 0.063 nm in 2011. This is the world shortest wavelength of a laser. The lasing intensity stability is an acceptable level for user experiments. This means the short-term instrument stabilities already reached at our demanded values, like a temporal electron beam stability of 100 fs. However there is still laser intensity drift caused by the characteristic drifts of accelerator instruments, such as insufficient temperature regulations of the rf cavities in an injector. Operator trimming of the rf phases and amplitude at the injector cavities cures the lasing intensity drift up to an acceptable level. We are now planning and executing improvements to obtain further laser-intensity stability without operator trimming.

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