PROGRESS OF THE SCSS TEST ACCELERATOR FOR XFEL/SPRING-8

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Abstract

The SPring-8 compact SASE source (SCSS) test accelerator was constructed in 2005 to demonstrate a new concept for x-ray free electron lasers composed of a low-emittance thermionic electron injector, a high-gradient normal conducting C-band accelerator, and a short-period in-vacuum undulator. With a 250-MeV electron beam, continuous SASE saturation was achieved at the wavelength range from 50 to 60 nm, with the maximum pulse energy of 30 μJ and the intensity fluctuation of ~10%. Analysis of the SASE saturation data with a 3-dimensional FEL simulation code suggests negligible degradation of the electron beam emittance during the high bunch compression process. We also succeeded in operating the C-band accelerator with a high accelerating gradient of 37 MV/m and a repetition rate of 60 pps. Now, the FEL beam is routinely delivered for various user experiments. In this paper, the machine performance and recent progress of the SCSS test accelerator together with the anticipated performance of 8-GeV XFEL under construction are reported.

INTRODUCTION

An x-ray free electron laser (XFEL) based on the process of self-amplified spontaneous emission (SASE) is one of the most promising light sources that can open up new science fields. Several XFEL projects are now under way in the world [1-4]. In Japan, an XFEL facility is under construction at the SPring-8 site (XFEL/SPring-8, Fig. 1) [5]. The design of the accelerator is based on three key technologies; a low-emittance injector using a single-crystal thermionic cathode, a high-gradient C-band linac, and a short-period in-vacuum undulator. Combining these technologies, the facility can be significantly downsized and the total construction cost can be reduced. This new concept is called the SPring-8 compact SASE source (SCSS) concept [6].

Figure 1: XFEL/SPring-8 and SCSS Test Accelerator.

In order to demonstrate this concept, the SCSS test accelerator was constructed in 2005. The 250-MeV electron beam generates an extreme ultraviolet (EUV) SASE-FEL beam at the wavelength range from 50 nm to 60 nm. Since the observation of the first lasing at 49 nm in June 2006 [7], we have made several machine improvements toward stable EUV-SASE saturation. In October 2007, the saturation was achieved and characteristics of the EUV-SASE was evaluated [8, 9]. From the analysis using a 3-dimensional FEL simulation code, it became clear that the initial beam emittance of the thermionic gun was barely degraded in the bunch compression process with a high compression factor of ~300. These results show the validity of the SCSS concept [10].

Right after the SASE saturation, user experiments have been started. In parallel with the operation of the SCSS test accelerator, the construction program of the XFEL/SPring-8 is underway. In the final section, the present status of the XFEL/SPring-8 is reported briefly.

OVERVIEW OF THE SCSS TEST ACCELERATOR

The SCSS test accelerator consists of main five sections; a low-emittance thermionic injector, a chicane-type bunch compressor (BC), a high-gradient C-band linac, a short-period in-vacuum undulator, and an EUV photon diagnostic system. A photograph and a schematic layout of the accelerator system together with 1-dimensional simulation of the beam evolution through the accelerator are shown in Fig. 2.

The 500-keV thermionic gun with a single-crystal CeB_6 cathode generates a 2-μs long pulsed beam with a peak current of 1 A and a normalized core emittance of 0.6π mm mrad [11]. The following beam deflector with a ϕ5-mm collimator cuts out a 1-ns short bunch, then it is injected to the buncher system composed of a 238-MHz pre-buncher cavity and a 476-MHz booster cavity. Velocity bunching is completed at the first few cells of

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the S-band cavity with an alternating periodic structure (APS). Here, the peak current reaches to ~100 A and the bunch length becomes ~2 ps. The S-band travelling wave accelerator (TWA) accelerates the beam off crest to make a negative energy chirp so that magnetic compression is performed at the following BC. The peak current and the bunch length at the exit of BC are ~300 A and ~0.7 ps, respectively.

The C-band linac boosts up the beam energy from 45 MeV to 250 MeV. Two high-power rf units are used, namely, two klystrons equipped and each drives two 1.8-m accelerating structures. A choke-mode type structure that can remove unwanted wakefields is adopted for the future option of multi-bunch operation at the XFEL/SPring-8. Now, the second unit is operated at a high accelerating gradient of 37 MV/m without any obvious troubles [12]. The maximum repetition rate is 60 pps. This performance satisfies the demand of the XFEL/SPring-8.

Since the dark current from the C-band accelerating structures demagnetizes the undulator magnet, it is removed by the following chicane. Although the dark current was measured to be about 30 pC/pulse at the exit of the final structure, no such current was observed after the chicane. Removal of the dark current becomes more important in a higher-energy FEL accelerator. A special measure will be taken for the 8-GeV XFEL/SPring-8 [13].

Two undulator units are used to achieve EUV-SASE saturation. Each undulator has 300-periods of permanent magnets. One periodic length is 15 mm. These magnets are located in a vacuum chamber. The magnet gap can be changed from 3 mm to 20 mm. The maximum K-value is 1.5 [14].

The photon diagnostics system composed of a gold-coated mirror to remove γ-ray background, a photodiode to measure the pulse energy of the EUV laser light, a single-shot spectrometer to measure the wavelength spectrum, and a profile monitor [15]. The EUV laser light is transported to an experimental hall built 15-m downstream from the undulator exit.

Fig. 3 shows dependence of pulse energy and intensity fluctuation on radiation wavelength. The wavelength has been tuned by changing the undulator gap. At wavelength longer than 50 nm (K-value larger than 1.23), the pulse energy is saturated and the power fluctuation decreases drastically. This behavior provides an evidence of SASE saturation at 50-60 nm. From the analysis of this data with a 3-dimensional FEL simulation code, SIMPLEX [16], the normalized slice emittance of the electron beam in the undulator was estimated to be 0.7π mm mrad. This result suggests that the initial core emittance of the CeB_6 gun (0.6π mm mrad) is barely degraded during the bunch compression process with a total compression factor of ~300. On the velocity bunching process, this result satisfies the demand for the XFEL/SPring-8. Additional two chicane-type BCs will be added to obtain 3-kA peak current at the XFEL/SPring-8.

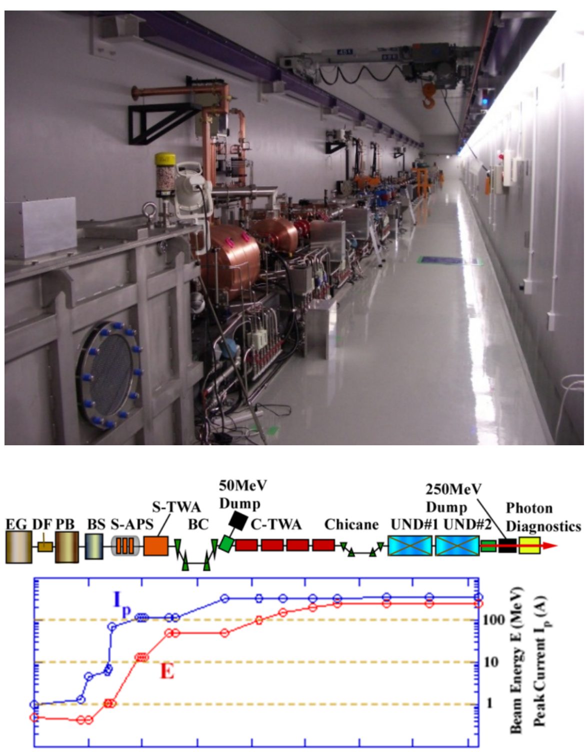

Figure 2: Photograph and schematic layout of the SCSS test accelerator with the beam evolution through the accelerator simulated using a 1-dimensional code. EG: 500-keV electron gun; DF: deflector with collimator; PB: 238-MHz pre-buncher; BS: 476-MHz booster; S-APS: S-band alternating periodic structure (APS) typed standing-wave multi-cell cavity; S-TWA: S-band traveling-wave accelerating structure, BC: bunch compressor, C-TWA: C-band traveling-wave accelerating structure, UND: in-vacuum undulator.

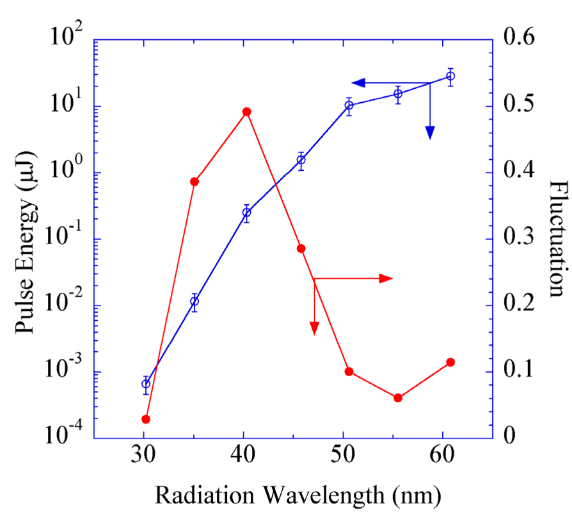

Figure 3: Dependence of pulse energy and intensity fluctuation on radiation wavelength.

STABLE EUV-SASE FOR USER EXPERIMENTS

The saturated EUV-SASE light is delivered to various experiments; atomic-molecular science, coherent imaging, solid-state physics, etc [17, 18]. A long-time trend graph of the laser pulse energy is shown in Fig. 4. Stable laser pulse with very low fluctuation has been demonstrated. Such a stable lasing was achieved after improvements of rf stabilization and replacement of the second undulator magnet. The details are described in ref. 8, 9, and 19.

A transverse profile of the EUV-SASE measured using a Ce:YAG screen located 16-m downstream from the undulator exit is shown in Fig. 5. The full diameter is ~7 mm. A clear profile with good symmetry is routinely obtained.

The specifications of the EUV-SASE laser are summarized in Table 1. At the moment, the machine repetition rate for user experiments is restricted to 20 pps due to a fault problem of the modulator power supply of the gun. The source of the fault is an excessive reverse voltage on the thyratron anode. This problem will be overcome by improving the modulator circuit.

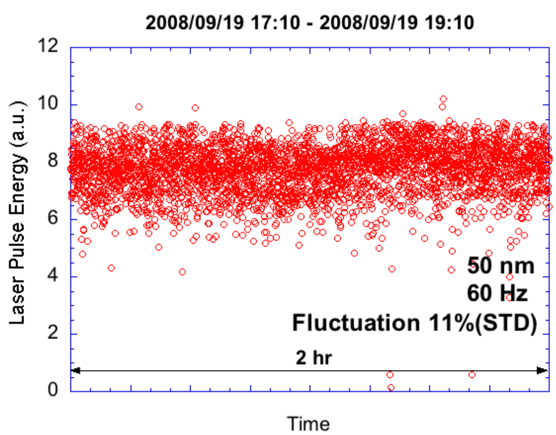

Figure 4: Trend graph of the EUV-SASE pulse energy.

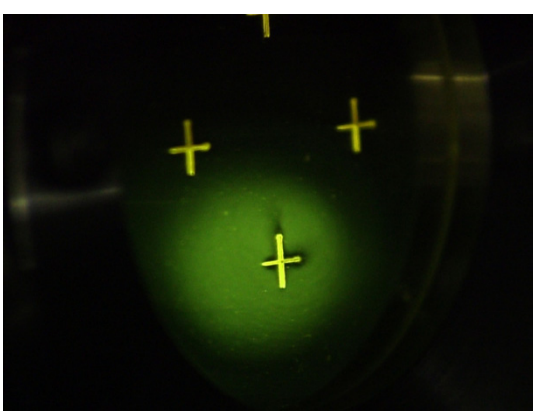

Figure 5: Transverse profile of the EUV-SASE laser measured using a Ce:YAG screen.

Table 1: Specifications of EUV-SASE laser at the SCSS

Property	Performance
Wavelength range	50-60 nm
Repetition rate	20 pps (max. 60 pps)
Pulse energy	~30 μJ/pulse
Power fluctuation	~10%
Laser spot size	~3mm (FWHM)
Pointing stability	~5% of spot size
Averaged spectrum width	0.6% (FWHM)

In FY2008, 11 research groups including that from overseas used the SCSS facility. The total operation time for the user experiments was 95-days (840 hours) with downtime rate of 4%. Approximately 80-days were spent for the machine studies, whose purposes were improvements of the SCSS test accelerator and R&Ds for the XFEL/SPring-8.

SOME TOPICS ON THE SCSS TEST ACCELERATOR

No Coherent OTR from the Thermionic Beam

Recently, anomalous amplification of an optical transition radiation (OTR) signal was observed at SLAC [20]. It makes difficult to diagnose an electron beam profile. This anomaly is considered to be a coherent OTR from an unwanted micro-density-modulation in the bunched beam. The source of the density-modulation and the generation mechanism are under investigation in the world's laboratories [21].

In order to check whether the coherent OTR is generated in the thermionic injector of the SCSS test accelerator, we have measured the OTR signal as a function of the compression rate of the BC. The compression ratio was changed by tuning the phase of the S-band TWA. The OTR signal was measured at the exit

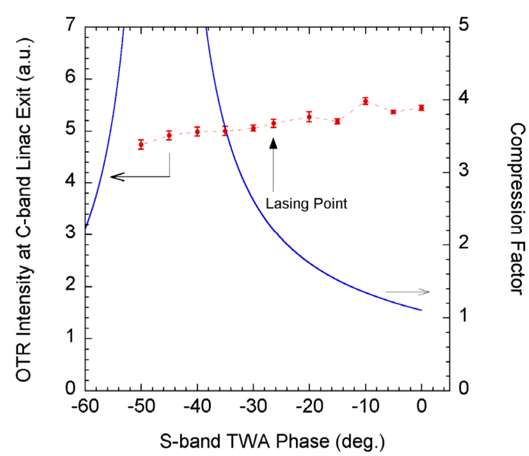

Figure 6: OTR intensity and calculated compression factor of the BC measured at the C-band linac exit as a function of the phase of the S-band TWA.

of the C-band linac. The beam energy was 250 MeV, and the charge was about 0.3 nC/bunch. Fig. 6 shows the OTR signal normalized by the charge as a function of the phase of the S-band TWA together with a calculated compression factor of the BC. The error bar shows shot-by-shot intensity fluctuation. Even at the high compression rate, the OTR signal did not amplified and the shot-by-shot signal intensity was kept stable. This result shows that the short bunch generated by the thermionic cathode and compressed by the rf buncher system does not have a significant micro-density-modulation.

FEL Output Sensitivity

Since the SASE-FEL power strongly depends on the peak current of the electron beam, the gun and every rf components must be highly stabilized. We investigated the sensitivities of the FEL power against the variation of the rf phase and amplitude for the SCSS test accelerator by means of a 1-dimensional accelerator simulation code and SIMPLEX. It was found that the extremely sensitive parameters were the gun voltage and the phase of the 238-MHz pre-buncher.

In order to check the validity of the estimation, we measured the dependence of the EUV-FEL power upon the gun voltage and the pre-buncher phase at the wavelength of 60 nm. Preliminary results are shown in Fig. 7. To compare the experiment with the simulation, a reference point of the variation was chosen to be a border between a saturated region and an unsaturated region. Fairly good agreement between the experiment and the simulation was obtained. For the stable lasing at the SCSS test accelerator, the voltage stability of the gun and the phase stability of the 238-MHz pre-buncher must be below 0.01% and 0.02degree, respectively. We will perform further measurements, also for the other components.

A remarkable point is that these stabilities almost satisfy the requirements of the XFEL/SPring-8. Developments of machine stabilization toward the XFEL/SPring-8 are summarized in ref. 22.

Measurements of Longitudinal Electron Beam Properties by EOS Method

Recently, shot-by-shot electron beam timing and its longitudinal bunch structure in sub-picosecond range can be measured nondestructively by means of an electro-optical sampling (EOS) method [23]. These measurements give very important information not only for user experiments that need accurate beam timing but also for reliable beam commissioning.

In order to introduce this diagnostic system to the XFEL/SPring-8, an R&D has been conducted at the SCSS test accelerator. A ZnTe crystal with a thickness of 0.5 mm was used as an EO-crystal. It was located 3-mm from electron bunch to detect its electric field in a vacuum chamber. A temporal decoding method using a BBO

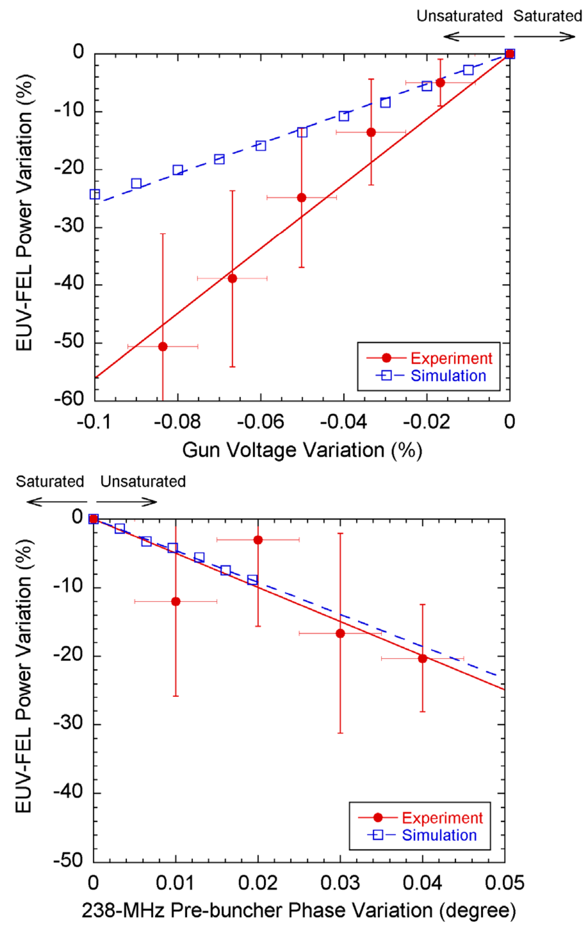

Figure 7: Variation of the EUV-FEL power as a function of the gun voltage variation (upper) and the phase variation of the 238-MHz pre-buncher (lower).

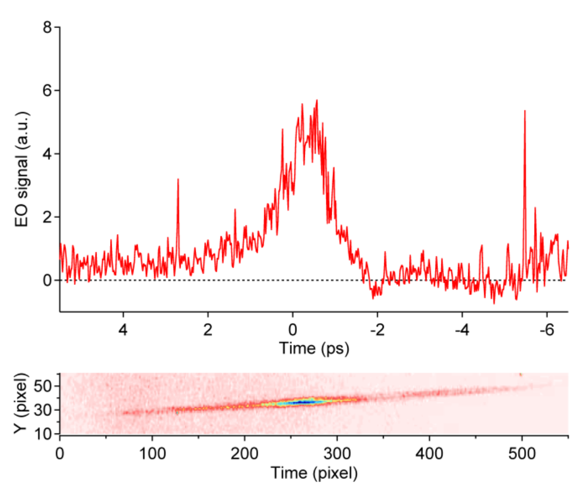

Figure 8: Preliminary data of the single-shot longitudinal bunch structure measured by an electro-optical sampling method. A reconstructed temporal profile of the EO-signal (upper) and a CCD image generated by a BBO crystal in which the temporal profile of the EO-signal was encoded (lower).

crystal and a femtosecond laser was adopted to analyze the EO-signal that includes the information of the longitudinal electron bunch structure. A preliminary data is shown in Fig. 8. The measurement was done at the entrance of the first undulator at 250 MeV. The measured bunch length of 1.5 ps was somewhat longer than that estimated by an rf zero-phasing method [24] of 0.7 ps. Improvements to obtain better resolution will be done for the XFEL/SPring-8.

CONSTRUCTION STATUS OF THE XFEL/SPRING-8

The XFEL/SPring-8 aims to generate a high-brilliant short-pulse x-ray SASE laser. The electron beam energy is 8 GeV and the minimum x-ray wavelength is 0.06 nm. The expected peak power and pulse width of the x-ray laser are 20-30 GW and <100 fs, respectively. The construction of the new facility started in 2006. In March 2008, the construction of the building for the accelerator and the undulator was completed (Fig. 1). Approximately 70% of the main rf components; klystrons, accelerating structures, rf pulse compressors, etc., were fabricated. The installation of the C-band main linac will start in the summer of 2009. The equipment installation will be finished in the fall of 2010, then after rf aging and equipment of the accelerator system, beam commissioning toward stable x-ray SASE saturation will start. We are aiming to start user operation in 2011.

SUMMARY

In summary, the SCSS test accelerator has successfully delivered stable EUV laser pulses for various user experiments through a year. The experience of the machine operation is being fed back to the construction of the 8-GeV XFEL/SPring-8. Beam commissioning toward stable x-ray SASE saturation will be started in 2011.

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