OPERATION STATUS OF THE SCSS TEST ACCELERATOR: CONTINUOUS SATURATION OF SASE FEL AT THE WAVELENGTH RANGE FROM 50 TO 60 NANOMETERS

H. Tanaka[#], K. Togawa, T. Hara, T. Tanaka, M. Yabashi, T. Fukui, A. Higashiya, N. Hosoda, T. Inagaki, S. Inoue, M. Kitamura[*], H. Maesaka, M. Nagasono, T. Ohshima, Y. Otake, T. Sakurai, K. Shirasawa, H. Kitamura, T. Ishikawa, T. Shintake, RIKEN/SPring-8, Hyogo, Japan
T. Asaka, T. Hasegawa, H. Ohashi, S. Takahashi, S. Tanaka, JASRI/SPring-8, Hyogo, Japan
T. Tanikawa, RIKEN SPring-8 Harima, Hyogo, Japan

Abstract

Continuous saturation of SASE lasing at the wavelengths ranging from 50 to 60 nm has been achieved in the SPring-8 compact SASE source (SCSS) test accelerator after machine improvements and fine beam tuning. A pulse-energy of ~30 μJ with a fluctuation of ~10 % in STD is routinely obtained at 60 nm. This stable and intense EUV SASE has been offered to user experiments since October 2007. Analysis of the obtained lasing data with the measured electron beam density profile indicates that the normalized slice emittance at the lasing part is ~0.7 πmm.mrad. This paper presents the machine improvements towards the continuous saturation, current lasing performance as well as the latest analysis result on the electron beam quality.

INTRODUCTION

The Japanese X-ray free electron laser at the SPring-8 site (XFEL/SPring-8) aims to achieve excellent laser performance with a compact machine, which can reduce construction cost and improve the reliability of machine operation [1]. The unique design based on the above concept, which is composed of a low emittance injector with a single crystal thermionic gun, high gradient normal conducting C-band accelerators, and short period in-vacuum undulators, significantly differs from those in other FEL projects [2, 3]. The SCSS test accelerator [4, 5], shown in Fig. 1, was thus designed and constructed in 2005 in order to perform proof-of-principle experiments on the FEL operation by the compact SASE source. The maximum beam energy of the test accelerator is 250 MeV and the design shortest wavelength of SASE saturation is around 50 nm.

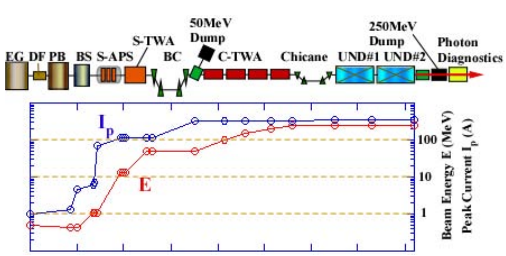

Figure 1: Schematic of the SCSS test accelerator (upper) together with simulated peak current and beam energy along the accelerator (lower). EG: 500-keV electron gun; DF: deflector with collimator; PB: 238-MHz pre-buncher; BS: 476-MHz booster; S-APS: S-band alternating periodic structure (APS) typed 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: undulator.

Although the first lasing at 49 nm was observed in June 2006 [4, 5], the SASE saturation was not achieved at that time. The achievement of the saturation, which proves the compact SASE source concept valid for XFEL, is critically important for the XFEL/SPring-8 project. We have therefore improved the test accelerator and refined the machine tuning.

ACCELERATOR IMPROVEMENTS TOWARDS SASE SATURATION

Stabilization of Injector RF System

Towards the saturation, we started stabilizing the injector RF system. This is because instability of the injector RF system fluctuates the laser intensity through the peak current fluctuation. The stable lasing condition is indispensable for the fine beam tuning, in which the laser intensity is directly used as a probe. In order to find the main source for the RF instability, we investigated the correlation with other machine parameters. We found that the temperature variation of cooling water supplied to the pre-buncher, booster and S-APS causes the RF instability. Since the type of these cavities is a standing wave one with a high Q-value, the RF phases are sensitive to the cavity-body temperature. For example, the phase sensitivity to the temperature is ~0.01 deg./1 mK in the pre-buncher. Although a precise temperature control system for the cavity cooling water [6, 7], which can control the water temperature variation less than 10 mK, was installed, this temperature control caused the cavity temperature variation due to the inadequate control point with a serious time lag. By changing the control point from the cavity body to the cooling water inlet, re-optimizing the PID parameters, and introducing the low-pass filter, the cavity body temperature is presently controlled within 10 mK and the RF phase and amplitude are remarkably stabilized.

[#]tanaka@spring8.or.jp
[*]on leave from Nichizou Electronic & Control Corp.

Slow drifts of the RF phase and amplitude still remained as a perturbation source after the stabilization of the cavity body temperature. The RF phase-locked loops and auto level control (PLL and ALC) with RF cavity pick-up signals were employed to suppress the slow drifts [7]. However, 12-bit DAC for the PLL and ALC severely restricted the setting resolution. For instance, the PLL resolution was limited to ~0.09 deg., which was insufficient to achieve the stable lasing. In order to improve the setting resolution, a time-resolved method on the parameter setting was introduced, which varies the parameter value during the cavity filling time. This modification can effectively enhance the resolution of the integrated parameter. Together with other improvements on the phase/amplitude control algorithm, the resolution was improved by about one order in total [7].

Figure 2 shows the RF phase and amplitude stabilities of the pre-buncher. After the improvements, the phase and amplitude variations are 0.02 deg. and 0.03 % in STD, respectively. These values almost satisfy the RF stability requirement for XFEL.

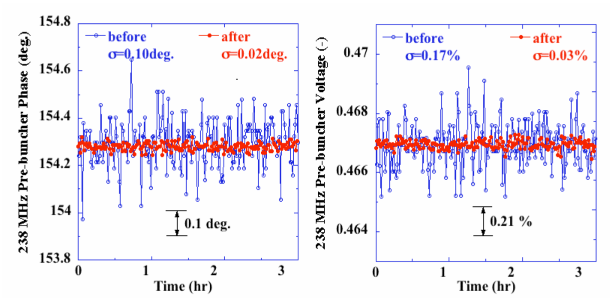

Figure 2: RF phase (left) and amplitude (right) variations of the 238-MHz pre-buncher before and after the improvements.

Replacement of 2nd Undulator

A special permanent magnet structure named by "45-deg. tilted Halbach type" [8] was adopted for the SCSS prototype undulator to satisfy sever requirements, a short period of 15 mm with high field quality. However, one of the two manufactured undulators had large multipole components beyond an error tolerance. Especially, the skew quadrupole component was so strong that the beam profile at the downstream location of the 2nd undulator rotated as closing the 2nd undulator gap. The field adjustment by exchange of the magnet structures could not recover the undulator field-quality up to the required level for the SASE saturation. Hence, the magnet array of the 2nd undulator was replaced by new one in the summer shutdown period of 2007. To assure the field quality, the new magnet array employs the hybrid structure instead of the tilted Halbach type.

Precise Orbit Setting in Undulator

The undulator magnetic field with a peak value of about 1 T has a strong vertical focusing effect on 250-MeV electron beam. Also, the gap-dependent field error of the undulator is not negligible for the beam orbit distortion. Thus, the optimum orbit as well as the optimum envelope matching, which maximize the laser intensity, should be searched for each combination of the beam energy and undulator gap. The procedure of the optimum beam orbit search is as follows. The beam orbit is tentatively set so that the orbit passes through the field center of each quadruople at the up- and down-stream locations of the undulators. The height of each undulator is then adjusted fixing the undulator gap by using the laser intensity as a probe. Finally mapping of the incidence orbit condition is carried out for each undulator to maximize the laser intensity.

In order to match the phases of the radiations from two undulators, a phase matching section was installed between the two undulators. However, the phase matching is not presently carried out. When the amplification gain of the second undulator is high enough, ~10^3, the phase matching condition does not affect the saturated SASE intensity, because the first undulator works as a modulator and the second as a radiator.

Transverse Envelope Matching

It is difficult to extract transverse envelope information of the electron beam at a lasing part, because the observed beam profile on a conventional screen is integrated over the whole electron bunch. There is no diagnostic system to evaluate the time-sliced envelope information in the SCSS test accelerator. We therefore have to tune beam-focusing parameters over the accelerator so as to maximize the laser intensity. This was impossible until the stable lasing was achieved. As a result of the beam tuning, we found that certain magnetic lenses and quadrupoles have the high sensitivity to the laser intensity. These lenses and magnets are routinely used as a knob for the transverse envelope matching.

LASING PERFORMANCE

After the machine improvements and fine beam tuning described in the previous section, the continuous saturation of the SASE lasing at the wavelengths ranging from 50 to 60 nm has been achieved with excellent reproducibility. The SASE saturation was confirmed by measuring the pulse energy (power) dependence on the undulator *K*-value (radiation wavelength). The *K*-value was scanned by changing undulator gaps keeping the same beam energy and current. Since the FEL parameter and gain length depend on the *K*-value, a clear transition from the exponential gain region to saturation one was observed. Table 1 and Figure 3 show the currently achieved SASE FEL performance and shot-by-shot SASE intensity variation (σ=11%) for the continuous saturation period, respectively.

User experiments using this stable and intense SASE have been started since October 2007. The pulse repetition rate is presently restricted to 20 Hz due to the problem of the voltage feedback module in the inverter power-supply of the electron gun. During the user time, the machine operation is started at 9 AM. After one hour of warning up of the RF equipment and tuning of the SASE lasing condition, the user experiment begins regularly at around 10 AM and closes at 7 PM. In addition to the PLL and ALC to stabilize the RF parameters, a simple orbit feedback system is used to correct the slow orbit drift in the two undulators every 30 sec. Since the monitoring resolution of the electron gun charging voltage is so far insufficient for a feedback control, the gun voltage is manually adjusted to maintain the lasing intensity, which is measured by a non-destructive intensity monitor installed in the EUV beamline.

Table 1: Summary of Achieved SASE Performance

SASE Property	**Achieved Performance**
Wavelength range	50 ~ 60 nm
Repetition rate	< 20 Hz
Pulse energy	~30 μJ @60 nm
Pulse energy fluctuation (STD)	~10 %
Laser spot size## (FWHM)	~3 mm
Pointing stability##	~5 % of the beam size
Averaged spectrum width (FWHM)	0.6 %

##~10 m downstream from the source point

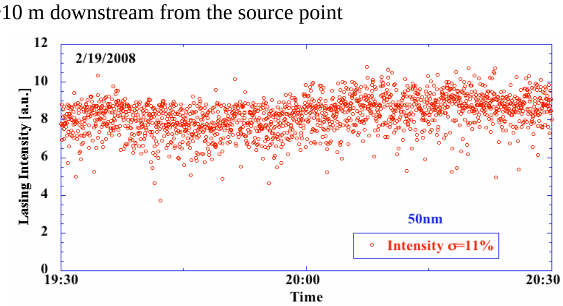

Figure 3: Stability of SASE lasing intensity over 1 hr. The lasing wavelength is 50 nm and the repetition is 10 Hz.

DISCUSSION

From the analysis of the SASE output, the ratio of the peak current to the normalized slice emittance at the lasing part can be estimated. In order to evaluate the normalized slice emittance, the longitudinal beam density profile was measured by an RF zero phasing method [9]. To generate a linear energy chirp on the electron bunch, the 2nd C-band accelerator unit is used. The measurement example is shown in Fig. 4. The open circles show the longitudinal density profile of the electron bunch compressed by the velocity bunching in the injector. After the bunch compressor, the bunch is further compressed as shown by the filled circles in Fig. 4. The ratio of the two cases in Fig. 4 roughly gives the compression factor of the bunch compressor 330A/135A, ~2.4, which agrees well with the value calculated by a linear model describing a bunch compression.

The measured dependence of the laser intensity on the *K*-value was compared with the 3D-FEL simulation performed by SIMPLEX [10]. In this simulation, the measured longitudinal density profile was assumed and the normalized slice emittance was only used as a variable parameter. As a result, the normalized slice emittance of 0.7 πmm.mrad reproduced the measured data fairly well. We note that this emittance is consistent with the preliminary result reported in 2006 [5], where 1-D and 3-D analyses showed that the ratio of the peak current to the normalized slice emittance is 480 ~ 540 A/πmm.mrad.

The achieved continuous saturation of the SASE FEL and the estimated slice emittance of 0.7 πmm.mrad support the expected high performance of the X-ray compact SASE source.

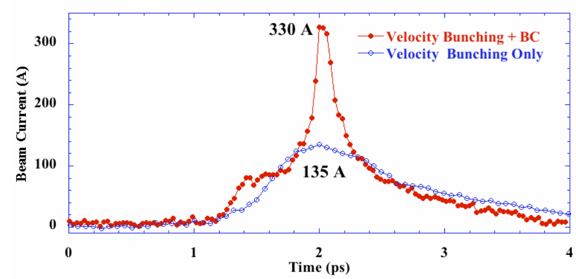

Figure 4: Measured longitudinal density profile of the electron beam with only velocity bunching (empty circles) and both velocity bunching and the bunch compressor (filled circles).

REFERENCES

[1] T. Shintake et al., "SPring-8 Compact SASE Source (SCSS)", SPIE, Optics for Fourth-Generation X-Ray Sources, Bellingham, August 2001, p. 12.

[2] "Linac Coherent Light Source (LCLS) Conceptual Design Report", SLAC-R-593, April 2002.

[3] "TESLA Technical Design Report, PART V, The X-ray Free Electron Laser", ed. G. Materlik and Th. Tschentscher, March 2001.

[4] T. Shintake, "Status of the SCSS Test Accelerator and XFEL Project in Japan", EPAC'08, Edinburgh, June 2006, p. 2741.

[5] H. Tanaka et al., "Low Emittance Injector at SCSS", FEL'06, Berlin, Aug. 2006, p. 769.

[6] S. Takahashi et al., "Precise Temperature Regulation System for C-Band Accelerating Structure", APAC'04, Gyeongju, March 2004, p. 678.

[7] H. Maesaka et al., in these proceedings.

[8] T. Tanaka et al., "Development of the Short-Period Undulator for the X-ray FEL Project at SPring-8", SRI'03, San Francisco, Aug. 2003, p. 227.

[9] D. X. Wang et al., "Measurement of femtosecond electron bunches using a RF zero-phasing method", Phys. Rev. E **57** (1998) 2283.

[10] T. Tanaka, "FEL Simulation Code for Undulator Performance Estimation", FEL'04, Trieste, Aug.-Sep. 2004, 2283; http://radiant.harima.riken.jp/simplex/