Progress of the XFEL Project

1. Status of XFEL Construction

A five-year construction project for an 8-GeV XFEL facility, which was started in FY2006 as one of the Key National Technologies for Japan, has been going well in FY2009, the fourth year of construction. This progress in four years promises the start of beam commissioning by the end of FY 2010.

The manufacture of all the components is in progress so as to start full power rf aging at the beginning of October 2010. Installation and alignment of system components were started in the undulator hall, klystron gallery, and accelerator tunnel except for the injector section.

The manufacture of the S-band and C-band rf acceleration systems was completed in FY2009. Ninety percent of accelerating tubes were installed in the accelerator tunnel with rf waveguides connected, as shown in Fig. 1. Half the number of rf sources, each of which is composed of a modulator, a klystron, and a charging power supply, were installed in the klystron gallery, as shown in Fig. 2. Prior to the installation, high power performance was tested for all the rf sources. Figure 3 shows a typical measurement data to assure the required performance.

Low level rf (LLRF) and timing systems driving and controlling rf high power equipment were tested using a full set of the C-band acceleration system. The achieved results confirmed the sufficient performance of the systems. Figure 4 shows the obtained ambient temperature stability in the water-cooled rack, which is critically important for stabilizing the rf system. Installation and parameter tuning of the LLRF and timing systems are on schedule.

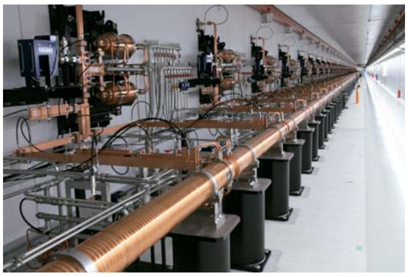

Fig. 1. C-band acceleration units installed in the accelerator building.

Fig. 2. Oil tank of the compact C-band oil-field modulator (left middle) and the racks to contain LLRF and timing systems in the klystron gallery.

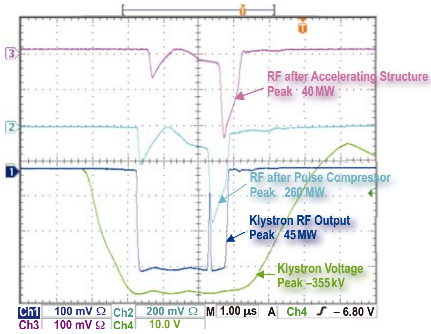

Fig. 3. Typical waveforms of the high power C-band rf components measured in the test bunker.

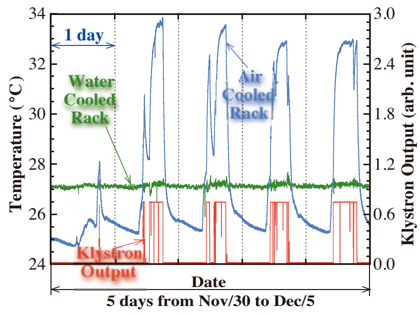

Fig. 4. Ambient temperature stabilities in the water-cooled rack and air-cooled rack together with the klystron output driven by the stable LLRF and timing systems contained in the water-cooled rack.

The manufacture of in-vacuum undulators progresses on schedule so as to install all the undulators until the middle of September 2010. Six undulators were installed and aligned to the specified positions along the BL3 line with a precision of 100 μm. Figure 5 shows the six installed in-vacuum undulators in the undulator hall.

The manufacture of magnets and their power supplies was completed. Installation and alignment of the magnets were also finished in the accelerator tunnel except for the injector part, together with those of beam position monitors (BPMs). Installation of the magnet power supplies in the gallery is scheduled in July 2010.

Seventy percent of the vacuum system composed of chambers, gages, bellows, pumps and so on was manufactured and installed in the accelerator tunnel. A vacuum leak test was also performed, showing the

Fig. 5. Six in-vacuum undulators installed in the undulator hall.

effectiveness of the newly developed flange system [1] because no leakage was detected.

For the photon beamline, detailed design works and the fabrication of key components, which include mirrors, an ultrahigh-vacuum (UHV) compatible double-crystal monochromator, front-end system, interlock system, and experimental hutches, were carried out. In particular, the performance of new monochromator mechanics, which aims to control and stabilize the angular position of crystals on the order of sub-microradian under UHV condition, has been studied. R&D on XFEL diagnostics have been advanced. For monitoring the total intensity and center of mass of XFEL radiation, a thin-foil scattering monitor has been studied at beamline BL29XU. For a profile monitor under high-intensity field, a fluorescence property from a CVD diamond has been examined. The development and evaluation of a thin-silicon crystal for the XFEL beam splitter have been carried out.

In the XFEL experiments, X-ray two-dimensional (2D) detectors and their data acquisition (DAQ) systems are to be developed on top of the existing standard beamline control system. As the standard X-ray 2D detector of the facility, multiport CCD detector development was launched in March 2009. The design of the chip layout, control and readout electronics, as well as the detector mechanics, was completed this year. The mass production of the sensor chips is under way, and the assembly of the first detector system is in progress. The DAQ system to store and monitor the data stream up to 4 Gbps consists of the DAQ front-end, 10 G network, high-performance high-reliability storage, and software to control the equipment. The performance evaluation for all the components to be installed in June 2010 has been completed. The detailed technical design of the control software has been completed and its implementation has been started.

In FY2009, the construction of the XFEL beam transport tunnel building and XFEL experimental facility has progressed. The transport tunnel building adopted a cast-in-place concrete pile method to support piles of 1000 mm ϕ firmly on the rock bed to suppress building deformation. The building frame was made with radiation-shielding concrete, the thickness of which is 1.1 m at the floor, wall, and ceiling in order to achieve the required shield performance. Completion of the beam transport tunnel building is scheduled in March 2010.

The experimental facility adopted a trussed girder structure to provide a pillar less wide space as an experimental hall. As foundation, spread foundation directly set on the rock bed was used in order to achieve the required stability without ground sinkage and sufficiently small ground vibration. The experimental facility will be completed in May 2010.

2. Operation Status of the SCSS Test Accelerator

After the proof-of-principle experiment showing that an FEL system based on the SCSS concept can generate a high-performance SASE FEL, the test accelerator has been improved aiming at ideal FEL operation. Despite the day-by-day operation, the continuous power saturation of a SASE FEL has been routinely obtained over wavelengths from 50 to 60 nm. In FY2009 (9 months from April to December), the total beam time is 1393 h (139 days) and 49% or 684 h (77 days) was provided to user experiments. The downtime rate for the user beam time was 4%. The regular beam time in a day is currently 9 h from 10:00 a.m. to 7:00 p.m.

Our present efforts are categorized into the following four parts: (I) R&D on beam feedback for stabilizing a SASE FEL, (II) development of key optical components for EUV-FEL utilization, (III) R&D on a seeded FEL with temporal coherence, and (IV) summary of user experimental programs.

(I) Beam feedback development: In order to stabilize the FEL position at the experimental hutch, a simple two-stage orbit feedback correction has been introduced in the undulator section. Here, the horizontal and vertical positions are corrected first at the entrance of the undulator section using the upstream single steering magnets. The angle errors are then corrected in both planes using the single-steering magnets just downstream of the BPM used in the first stage to minimize the displacements over the undulator section. The correction is currently performed with a cycle of 0.2 Hz using the orbit estimated by averaging 45 shot-by-shot data [2]. By this correction, the horizontal and vertical orbit drifts have been reduced to 6.4 and 2.3 μm, respectively. Figure 6 shows the vertical orbit drifts between the two undulators over 2 hours with

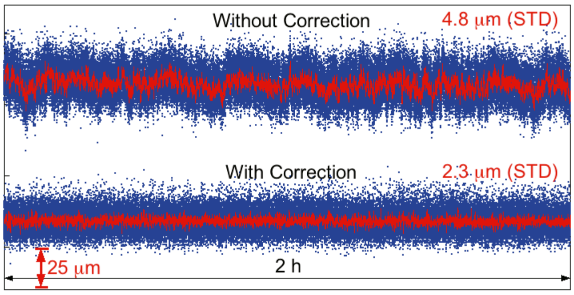

Fig. 6. Vertical orbit drifts over 2 h with and without the correction. The blue dots and red lines represent the shot-by-shot data and moving-averaged orbit with the 45 data. The measurement position is the middle of the undulator section.

and without the correction.

The XFEL at SPring-8 has a multiple-stage bunch compression system composed of one velocity bunching and three magnetic-bunching processes. To achieve the stable SASE FEL, local beam feedback loops fixing the beam current distribution at the exit of each bunching process are crucial as demonstrated at LCLS. Key points in the development are a feedback model for the velocity bunching and the separation between the velocity bunching and the first magnetic bunching. To test the feedback model for the velocity bunching and stabilize SASE intensity further in the SCSS test accelerator, a simple feedback loop has been introduced, in which an energy variation of the magnetic chicane is returned to a phase of the 238 MHz SHB [3]. Here, it is assumed that a voltage drift of the electron gun mainly causes the energy variation in such day-by-day operation. Figure 7 shows the SASE intensity and beam energy variations at the magnetic chicane with and without the correction. It is found that the energy-correlated SASE intensity variation is suppressed to some extent by the

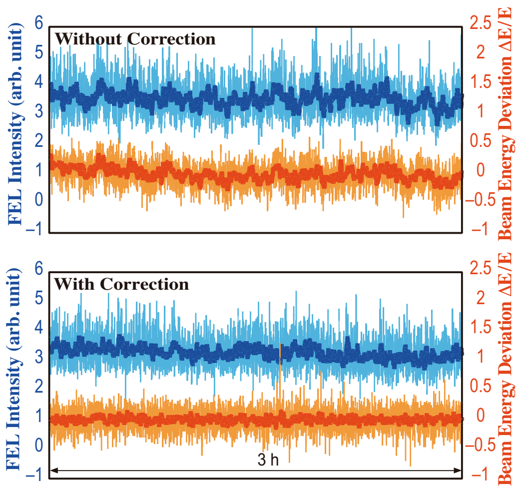

Fig. 7. Shot-by-shot SASE intensity and beam energy variations at the magnetic chicane over 3 h with and without the feedback correction. The blue and red bold lines represent the moving-averaged variables with 20 shot-by-shot data.

correction. To complete the two-stage feedback loops for stabilizing the beam current distribution, a beam arrival timing detection system and an intensity detection system of THz coherent SR (CSR) are under development. Figure 8 shows the firstly observed THz CSR signal measured using a pyroelectric detector.

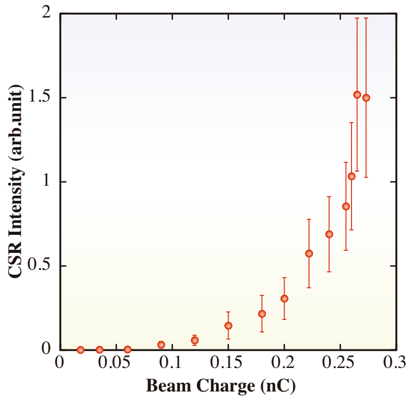

Fig. 8. THz CSR signals measured using a pyroelectric detector at the magnetic chicane just before the undulator section.

(II) Development of key optical components for EUV-FEL utilization: We have installed a focusing optical system at branch E of the EUV-FEL beamline in the experimental facility. The beamline has no stationary endstation in the experimental facility to conduct different scientific experiments by users. The focusing system was designed to be able to conveniently connect different endstations as follows: a working distance of 1 m from the center of the last mirror to the focusing point, the exit beam lying on the horizontal plane of the incident beam, the focusing point near the unfocusing beam, which passes through the focusing system without reflection, and the focused spot size below 30 μm diameter. To satisfy the above requirements, the focusing system consists of a pair of elliptical and cylindrical mirrors.

The profile of the focused beam was measured using a scanning pinhole with a diameter of 10 μm, as shown in Fig. 9. The focused spot size was 22 μm (V) × 26 μm (H) (FWHM), which was obtained by a deconvolution of the measured spot size with the diameter of the pinhole. Since the pulse energy of the focused beam using a cryogenic radiometer was 10 μJ, the beam power density was estimated to be ~20 TW/cm^2 as a pulse duration of 100 fs.

(III) R&D on a seeded FEL with temporal coherence: An amplifying process based on the self-amplified spontaneous emission (SASE) scheme, which is the most popular technique in the single-pass FEL methods, produces a spiky longitudinal profile at each shot owing to its limited temporal coherence. A full

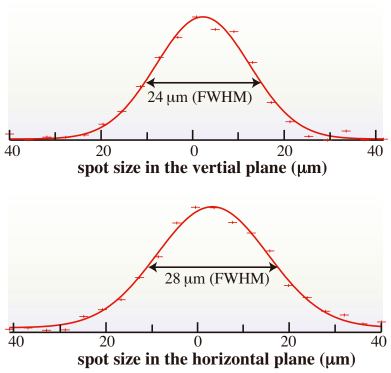

Fig. 9. Focused spot size measured using a scanning pinhole.

coherent FEL can be realized by injecting coherent light produced by an external seeding source to undulators. High order harmonics (HH), which are generated from rare gas targets interacted with intense femtosecond near-infrared laser pulses, is one of the most suitable seeding sources in the EUV region because of its excellent coherence and sufficient power (Fig. 10(a)).

The seeded FEL had been realized with 160 nm wavelength in 2002 [4]. For injection with shorter wavelength, about 10 nJ HH power is required in an undulator from the numerical simulations. A high power Ti:sapphire laser system, which produces 0.2 J and 150 fs pulses at 30 Hz repetition rate, has been developed for high-order harmonic generation. Figure 10(b) illustrates the schematic diagram of the seeded FEL. The HH from a Xe gas cell is directed to the undulators from the magnetic chicane of the SCSS test accelerator. The seeded FEL will operate with 50-60 nm wavelength for user experiment in 2010.

(IV) Summary of user experimental programs: During 2009, the EUV-FEL experimental facility has accommodated about 100 scientists representing 19 scientific groups not only from Japan but worldwide, such as Germany and Italy. The research using EUV-FEL is carried out in a large variety of disciplines, including technical research preparatory for XFEL

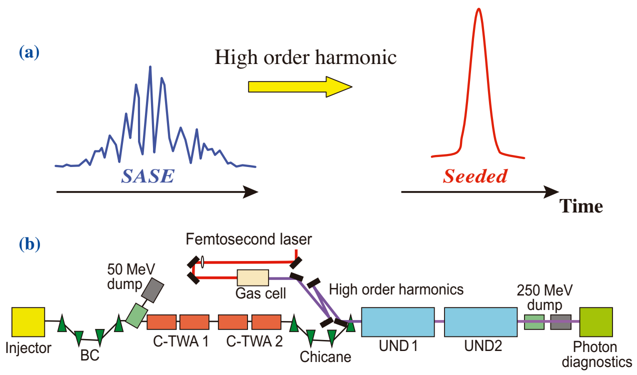

Fig. 10. **(a)** Temporal profiles of SASE and seeded FEL. **(b)** Schematic of seeded FEL.

experiments, atomic and molecular physics, coherent diffraction imaging methods, materials science such as advanced scintillators, and nonlinear X-ray devices. The number of publications from the users of EUV-FEL in FY2009 was nine papers [i-ix].

Here, we show one of the specially chosen research highlights. The group of H. Yoneda has observed a strong nonlinear absorption of Sn film at a wavelength of 61 nm from EUV-FEL [iii]. The transmission of the film is dramatically changed at a threshold energy of 6 J/cm^2, as shown in Fig. 11. This can be applied to new photonic devices for the EUV region, such as for spatial model cleaning and ultra-pulse slicing to the short-duration pulse generation.

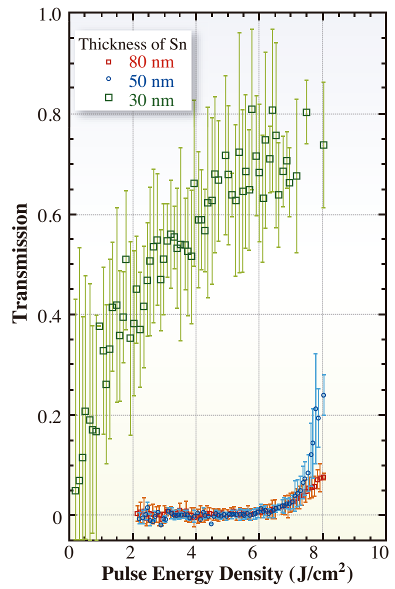

Fig. 11. Nonlinear response of transmission of the EUV-FEL.

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[iii] H. Yoneda *et al*.: Opt. Express **17** (2009) 23443.
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