Progress of the XFEL Project at SPring-8

The X-ray free electron laser (XFEL) project started in FY2006 as one of the key technologies of national importance. The 8 GeV XFEL facility is being constructed along the 1-km-long beamline of SPring-8 (Fig. 1). The construction project is favorably progressing toward completion in FY2010 (Fig. 2).

At the first stage, XFEL radiation is generated based on a self amplified spontaneous emission (SASE) scheme. The radiation properties are characterized by fully spatial coherence, an ultra-short pulse of less than 100 fs, and peak brilliance that is 10^9 times higher than that of a typical undulator at SPring-8. The shortest target wavelength is 0.6 Å in the hard X-ray region.

The machine, which has a total length of 710 m, is much compact than LCLS at SLAC or the European XFEL at DESY. This compactness is realized by a unique system, which is composed of a low emittance injector with a single crystal thermionic gun, C-band accelerators, and in-vacuum undulators [1,2]. For performing the R&D of the whole FEL system, the SCSS test accelerator was constructed in 2005, and the lasing of EUV light was successfully achieved in June 2006. In September 2007, we achieved the saturation of radiation power in the extreme ultraviolet (EUV) region. The test operation for user experiments started in October 2007.

1. Status of XFEL Construction

In FY2006 the design of the accelerator was carefully investigated on the basis of the results obtained by operation at the SCSS test accelerator. Figure 3 shows the arrangement of the main components together with schematic diagrams of beam acceleration and pulse compression. The 500 keV pulsed thermionic gun generates uniform and cylindrical electron beams with a sharp edge [3]. This condition approximately satisfies a Kapchinskij-Vladimirskij (KV) distribution, which leads to a perfect linear space-charge force within the beam radius that well conserves the electron beam emittance through the following bunch compression process under reasonable transversal focusing and beam handling. By efficient nonlinear chirp correction, the peak current of the electron beam is increased from 1 A up to more than 3 kA through velocity bunching and a

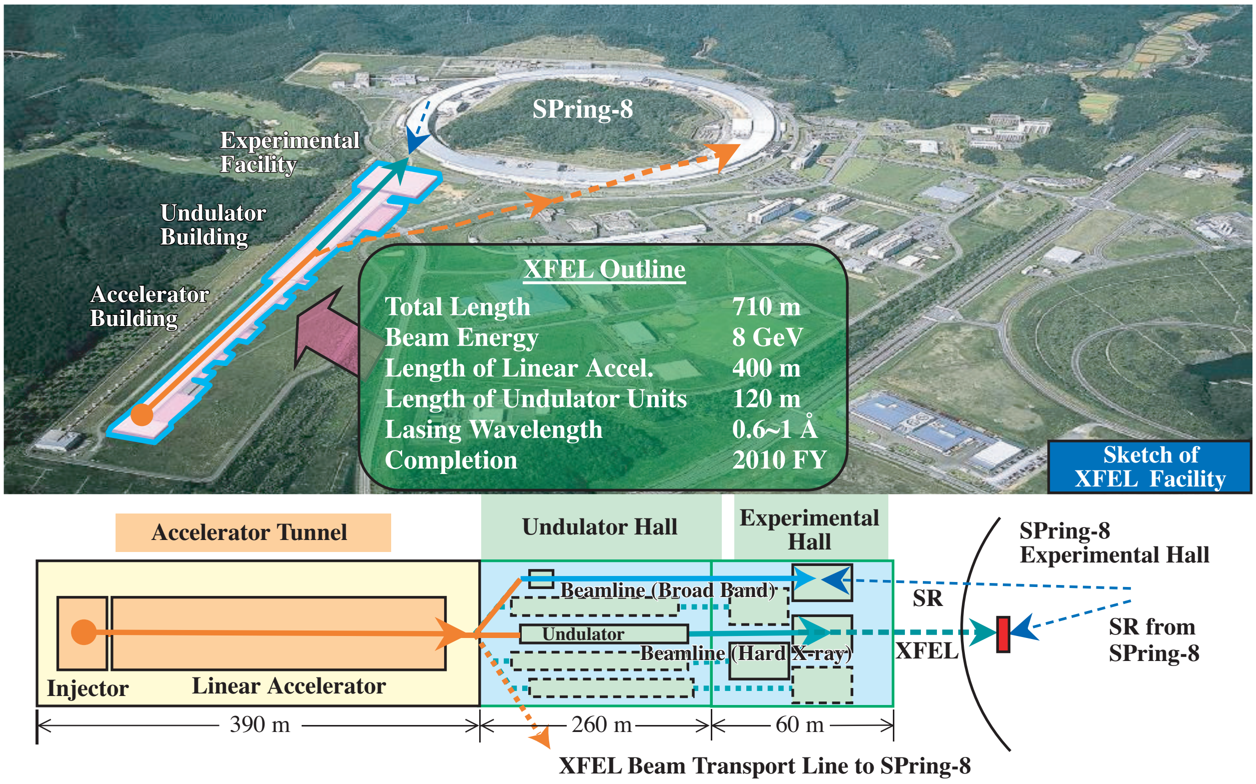


Fig. 1. Aerial photograph of the XFEL/SPring-8 facility (upper) and schematic layout (lower).

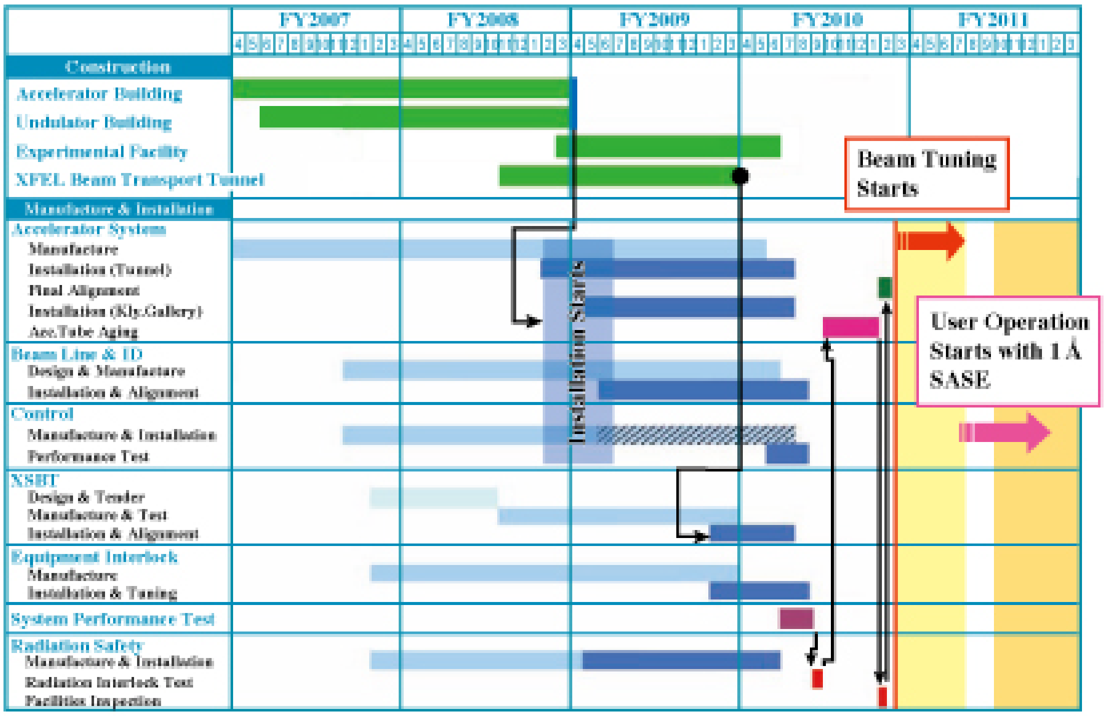


Fig. 2. XFEL/SPring-8 construction schedule.

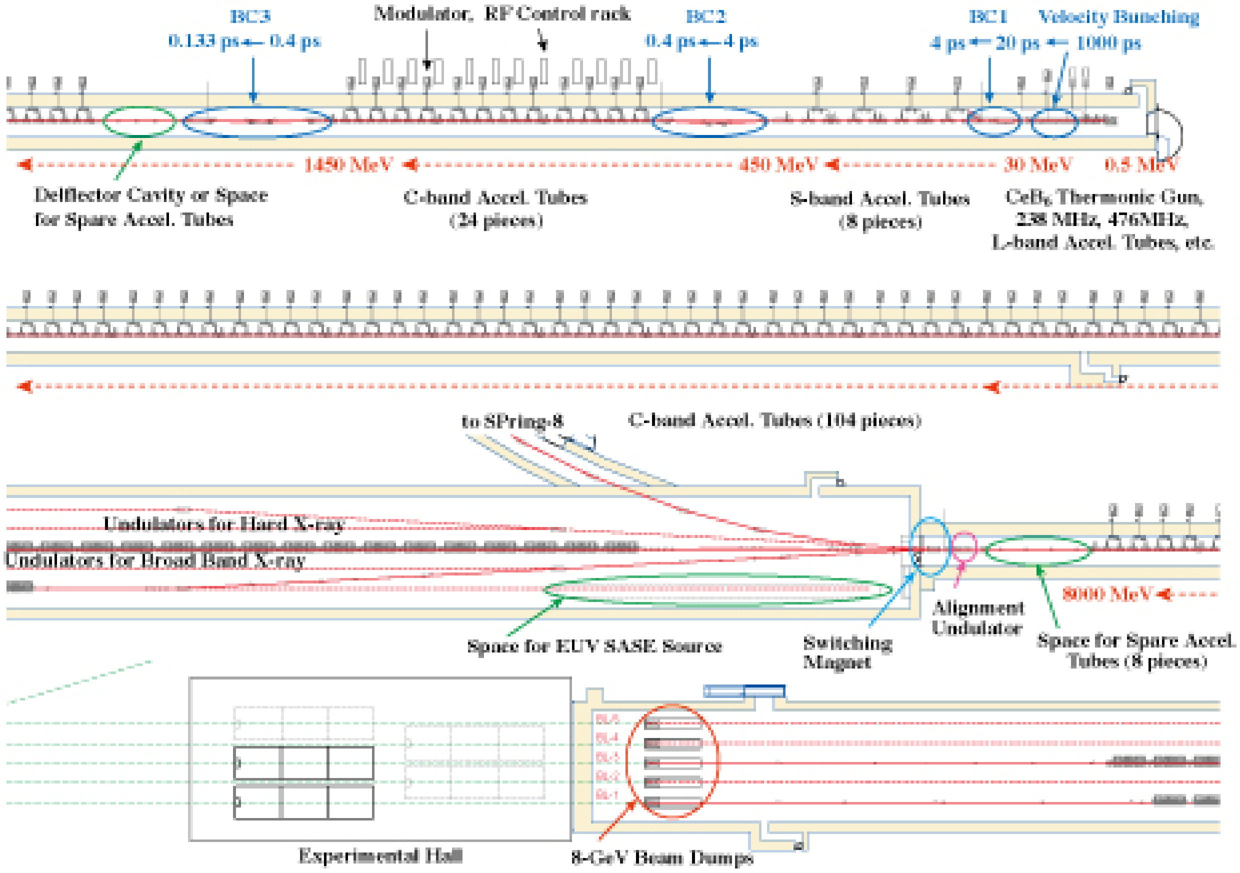


Fig. 3. Arrangement of the main accelerator and insertion device components with schematic diagrams of beam acceleration (red numbers with red dashed arrows) and pulse compression (blue numbers with blue dashed arrows).

three-stage bunch compression system based on magnetic chicanes. The stability requirements of RF voltages and phases for every RF component were evaluated. The key factors for achieving stable bunch compression have been studied to reduce the sensitivity of the peak current against RF voltage and phase errors.

In FY2007, intensive R&D was continued in order to meet the stability requirement. Inverter power supplies for an electron gun and klystrons have been developed for achieving extremely high stability. Although this was initially thought to be one of most difficult targets, a peak-to-peak voltage stability of 0.0045%, which surpasses the target value of 0.01%, has been achieved. A new compact modulator, which contains a klystron and a modulator in a single oil tank (Fig. 4), was developed for reducing RF noise and avoiding troubles with high-voltage cables. A high-power test was successfully completed to verify the noise reduction and reliable operation. Purchase orders for all accelerator components will be finished by FY2007.

The design of the undulator was revised, because the operation of the test accelerator revealed that one of the two undulators based on the original design [2] generated significant multipole error fields, which seriously degraded the beam quality. The new design (Table I) is expected to minimize the error components. A prototype undulator based on this design was manufactured. The field quality and its correction scheme will be studied using this prototype. We are developing a new technique of *in situ* field measurement, which aims to measure the field distribution even after the installation of undulators in the undulator hall.

Fig. 4. Photograph of the developed compact modulator.

Table I. List of new parameters of the XFEL undulator

Magnet Structure	**Hybrid type**
Material	**NdFeB**
Length (m)	**5**
Period Length (mm)	**18**
Number of Periods	**277**
Minimum Gap (mm)	**3**
Maximum *K*	**2.2**
Gap @ 1Å (mm)	**4.5**
***K* @ 1 Å**	**1.9**

The piling for the foundations of the accelerator tunnel has been completed. Since the tunnel floor stability is quite important for the XFEL, piles with a maximum length of 50 m were used so that all piles reach the stable semi-hard rock bed, of which the ground vibration is sufficiently low, of nm order. Figure 5 shows the distribution of piling depth along the accelerator building. The construction of the concrete floor and wall casting for the accelerator tunnel is also in progress. The ground stability at the undulator building will be improved by replacing the earth method with crushed stones.

A basic plan of the experimental facility was investigated in FY2007. This facility is located on a stable ground. The experimental hall (56 × 30 m^2) contains five beamlines. Several rooms designed for experimental preparation, computer analysis, and remote control of instruments are adjacent to the hall.

The design of the photon beamline was investigated. A radioprotective consideration requires the elimination of energetic γ-rays from XFEL radiation for experimental utilization. For this purpose, two optical devices are installed in the optics hutch: a pair of plane mirrors and a double-crystal monochromator.

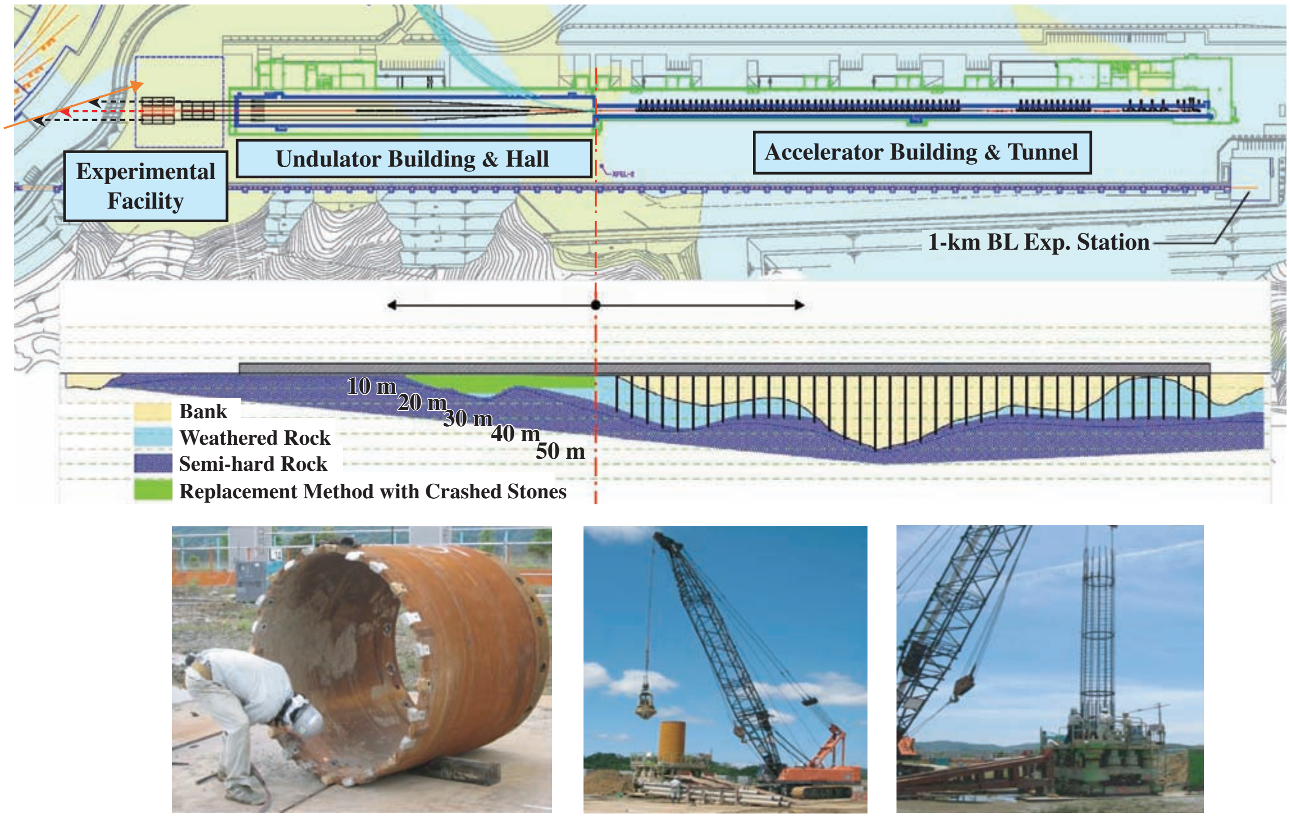
The former works as a low-pass filter for photon energies smaller than ~15 keV, while the latter sets a narrow band-pass in a photon energy range of 4 to 30 keV with a resolution of 10^{-4}. The qualitiy of the optical components should be severely controlled to avoid unwanted speckles under coherent illumination. The exit beam positions of these devices are designed to remain fixed during operation. The optics hutch also contains monitors, a beam shutter, collimators, and a pumping system for maintaining the ultrahigh-vacuum condition.

The XFEL beam is transported to experimental hutches, which contain experimental equipment, as well as to beam-conditioning devices such as a Kirkpatrick-Baez (K-B) mirror system for nano-focusing. Optical lasers, which are synchronized with FEL pulses, are introduced for pump-probe experiments.

X-ray diagnostic systems play a key role in the initial commissioning stage. In particular, the precise tuning of undulators is crucial for efficient lasing. We have investigated the effectiveness of several tuning methods. Semi-transparent monochromators are useful for checking the straightness of the electron-beam trajectory over undulator segments. A dispersive spectrometer is introduced to monitor the undulator spectra with single-shot detection for the precise tuning of *K*-parameters between the segments.

2. Saturation Achieved at the SCSS Test Accelerator

In summer 2007, the RF system in the injector section was stabilized to increase the lasing power. To reduce the fluctuation sources, (i) the temperature of the cooling water supplied to the RF cavities was stabilized, and (ii) the resolution of feedback loops for the RF phase and voltage was improved by adopting a time-resolved method for parameter setting. The attained phase and amplitude variations are 0.02 deg. and 0.03% in STD, respectively, which almost reach the target performance for the XFEL machine. Under the achieved stable condition, the machine parameters for RF, focusing, and steering were optimized. The precise tuning strongly enhanced the amplification gain.



Casing Bit for Excavation **Excavation** **Reinforcing Rod of Pile**

Fig. 5. Distribution of piling depth along the XFEL/SPring-8 facility (upper) and photograph of piling operation (lower).

In September 2007, the second undulator, which did not sufficiently contribute to the first lasing because of the large multipole field errors, was replaced by the new one. This enabled the successful observation of continuous SASE saturation at a wavelength ranging from 50 to 60 nm in late September. A pulse energy of 30 uJ is now routinely obtained at 60 nm with a repetition of 10 Hz and a small intensity fluctuation of ~10%. Figure 6 shows the fluctuation of the saturated SASE pulse energy over 40 min.

For user experiments, an experimental building was constructed in March 2007. A beam transport system, which includes a couple of mirrors, monitors, and vacuum pumps, were succeedingly installed. The beamlines in the experimental building are under construction. A transparent intensity monitor, focusing systems, an optical laser, and a data acquisition system will be installed. User operation is scheduled to start in spring of 2008.

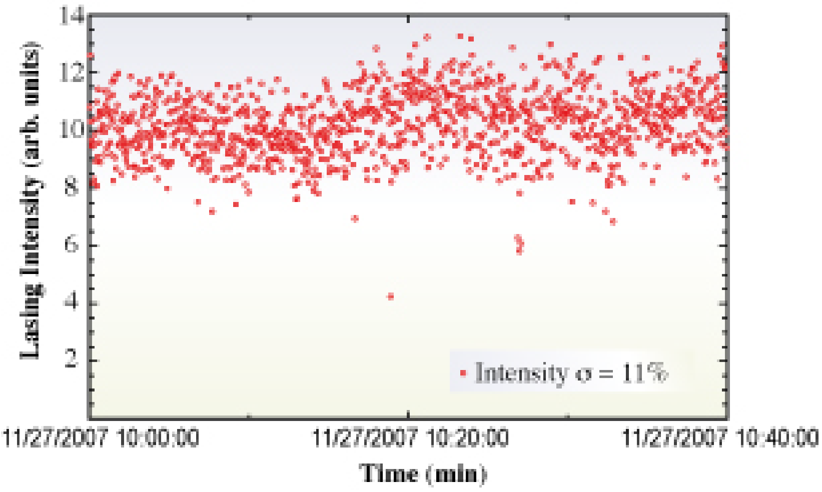


Fig. 6. Achieved intensity stability of SASE lasing.

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References
[1] T. Shintake *et al.*: Proc. SPIE **4500** (2001) 12.
[2] SCSS X-FEL Conceptual Design Report, RIKEN (2005).
[3] K. Togawa *et al.*: Phys. Rev. ST Accel. Beams **10** (2007) 020703.