5-4. SACLA Beamlines

In September 2017, SACLA entered a new operation phase called “Phase 2”, where three beamlines (BL1–BL3) are operated in parallel [1]. Table 1 summarizes the major operational parameters of the three beamlines. The soft X-ray free-electron laser (SX-FEL) beamline (BL1) has a dedicated linac to operate independently. The SACLA main linac can switch an electron-beam route in a pulse-by-pulse manner to simultaneously drive the two X-ray FEL (XFEL) beamlines, BL2 and BL3. The multiple-beamline operations have substantially increased the user beamtime from ~4,020 hours in FY2016 to ~6,270 hours in FY2018. The enhanced availability should produce more research outcomes. A list of recent publications is on SACLA’s website [2]. Phase 2 operations include a beam injection into the storage ring of SPring-8. The injection tests began in FY2018, and regular operations should commence in FY2020.

The new operation scheme has brought more opportunities for R&D activities by the facility. The beamlines and experimental stations have been upgraded to enable more efficient experiments and more advanced research. To further promote R&D through close collaborations with outside experts, the facility has three strategic programs:

(1) SACLA Basic Development Program

(2) SACLA Industry–Academy Partnership Program

(3) SACLA Research Support Program for Graduate Students

These programs have developed new methods and instruments [3], widened the application scope [4], and introduced young researchers to XFEL science [5]. Below the major upgrades of the beamlines and experimental stations in FY2018 as well as an example of recent research activities, especially for industrial applications, are described.

1. Soft X-ray FEL beamline (BL1)

1-1. FEL pulse arrival–time monitor

A new photon-diagnostic system was installed at BL1 to measure the relative arrival time of an SX-FEL pulse against an optical laser pulse [6]. In this system, a beam-branching mirror splits a small portion from an SX-FEL beam and one-dimensionally focuses the branch beam onto a GaAs wafer (Fig. 1). The focused FEL pulse induces a transient change in the optical reflectivity of GaAs, which is subsequently probed by an optical-laser pulse. The arrival time is obtained using a spatial decoding method [7]. The resolution

Table 1. Major operational parameters of SACLA [1].

	BL1	BL2 and BL3
Electron beam energy	800 MeV max.	8.5 GeV max.
Repetition	60 Hz max.	60 Hz max.
Undulator period	18 mm	18 mm
Undulator K value	2.1 max.	2.7 max.
Photon energy	40–150 eV	4–20 keV
FEL pulse energy	0.1 mJ at 100 eV	0.7 mJ at 10 keV

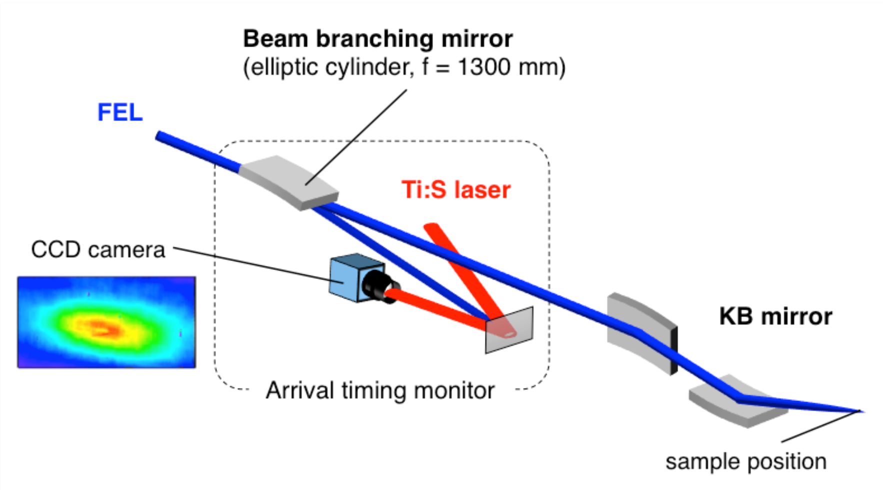

Fig. 1. FEL pulse arrival–time monitor at SACLA BL1.

of this system is ~20 fs in full width half maximum, which is sufficiently short compared with the durations of the SX-FEL and optical-laser pulses. This monitor is mainly used in ultrafast pump-probe experiments to compensate for the timing jitter by recording the time difference between the SX-FEL and optical-laser pulses in a shot-by-shot manner.

1-2. Submicron focusing system for SX-FEL

A submicron focusing system has been developed at BL1 under the SACLA Basic Development Program and SACLA Research Support Program for Graduate Students [3]. It is a two-stage focusing optics system, which is composed of Kirkpatrick-Baez mirrors (first stage) and an ellipsoidal mirror (second stage). The beam size at the second focus is 480 nm (vertical) and 680 nm (horizontal) in the full width at half maximum at a photon energy of 120 eV. The focusing system can observe nonlinear optical phenomena and characterize the magnetic properties of micrometer-scale domains in solid-state materials.

2. Hard X-ray FEL beamlines (BL2 and BL3)

2-1. Split-and-delay optics (SDO)

An X-ray split-and-delay optical (SDO) system was developed in collaboration with Prof. K. Yamauchi's group (Osaka University) [8]. This system produces double monochromatic XFEL pulses with a well-controlled time separation. Figure 2 shows the SDO system, which is installed in the optics hutch of BL3. The coming XFEL pulse is divided into two pulses by a beam splitter (BS). The split pulses propagate through different branches and spatially overlap at the sample position. The upper (lower) branch has a variable (fixed) path length. The delay time is controlled by changing the upper-path length in a jitter-free manner with a femtosecond resolution. This system was opened for users at BL3 in the 2018B term.

2-2. Experimental platforms with high-power optical laser systems

Two experimental platforms with high-power laser systems became operational at the SACLA-SPring-8 Experimental Facility in FY2018. The high-power

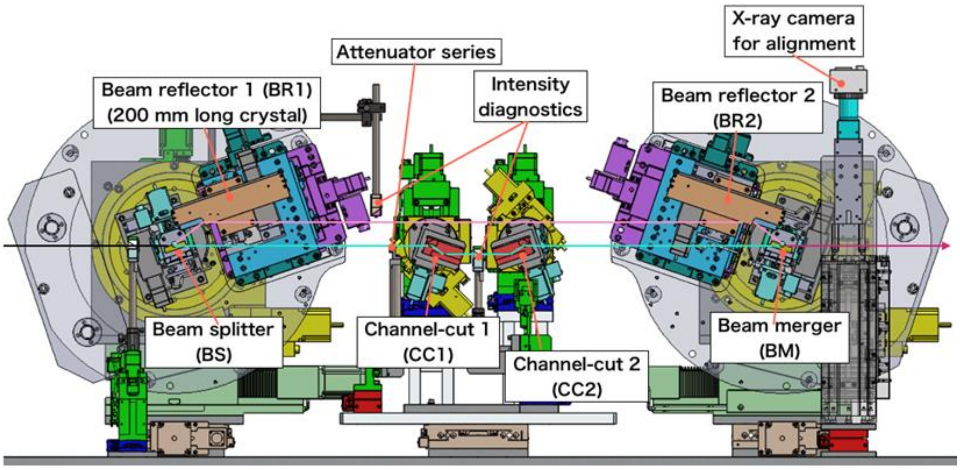

Fig. 2. Split-and-delay optical system at SACLA BL3.

femtosecond laser system was developed mainly for research on high energy density science (HEDS) [9]. The Ti:sapphire laser system can deliver 800-nm light pulses with a power above 100 TW to a vacuum interaction chamber at BL2 EH6. The laser pulse is then focused by an off-axis parabolic mirror to reach intensities far above 10^{18} W/cm^2. A radio-frequency (RF) signal at 5.7 GHz from SACLA is used for the time synchronization of the laser and the XFEL with a low timing jitter of about 20 fs in rms. The XFEL is typically used to diagnose the laser–matter interactions or the states of matter produced by the ultra-intense laser irradiation. Sets of compound refractive lenses adjust the spot size and the beam divergence of the XFEL beam without a significant change in the beam pointing.

The other experimental platform at BL3 EH5 was developed for combination use of a high-power nanosecond laser and the XFEL in collaboration with Prof. R. Kodama's group (Osaka University). The main target of the platform is matter under high-pressure states produced by laser-induced shock waves. The XFEL beam, which can be focused with a set of KB mirrors, is mainly used for ultrafast X-ray diffraction (XRD) or small-angle X-ray scattering experiments on shock compressed matter.

3. Research highlight

In situ X-ray diffraction study on steel under ultrafast heating

Yonemura and colleagues developed a technique for *in situ* XRD measurements under the SACLA Industry–Academy Partnership Program. They applied their technique to the evaluation of the phase transformation kinetics in steel under thermal treatment. Figure 3 shows the setup for experiments on Fe–0.1mass%C martensitic steel during resistive heating at ultrahigh rates up to 10^4 °C/s [4]. The results reveal that steel undergoes a massive reverse transformation during rapid heating to form a fine microstructure where the dislocation densities and carbon concentrations remain high. These findings will help develop and improve production processes of functional steels.

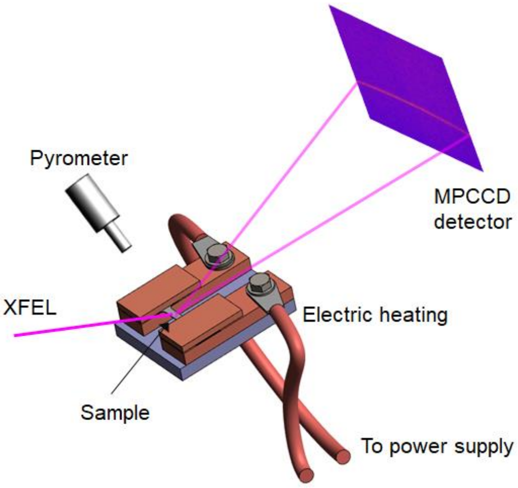

Fig. 3. Experimental setup for *in situ* XRD measurements of steel samples under ultrafast heating up to 10^4 °C/s.

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