3. Beamlines

In this section, we describe the activity status of the beamlines in FY2024, including the frontend, optics and transport channel, radiation shielding of SPring-8, and SACLA beamlines. In addition to routine maintenance, several component upgrades and R&D were performed. Beamline upgrade and portfolio rearrangement are ongoing toward the SPring-8 major upgrade. Some beamline reconstructions were carried out during this period.

1. High-heat-load handling at X-ray beamlines

1-1. Liquid nitrogen supply system

Since FY2022, we have been developing a system to directly supply liquid nitrogen (LN2) to each beamline in the experimental hall. To enable rapid and efficient LN2 delivery with stable performance, four large cold evaporators (CEs) were installed outdoors at the inner side of each storage ring building (A–D) in FY2022, and 196 vacuum-jacketed pipes (VJPs), each approximately 7.5 m long, were laid in an annular shape on the ceiling of the storage ring tunnel in FY2023.

In FY2024, the CEs and annular VJP were connected while the associated peripheral devices, such as the pressure control valve unit and emergency shut-off valve, were serviced. Additionally, branch lines were extended from the annular VJP to three existing LN2 collecting stations (#1, #3, and #4) in the experimental hall, as well as to selected beamlines (BL05XU, BL15XU, and BL40XU).

For the purpose of notification under Class 2 classification in the High-Pressure Gas Safety Act, the annular VJP was divided into two separate zones (A+B and C+D). This was achieved by removing non-branching sections of VJP and installing sealing valves at the separation points. To minimize the LN2 loss caused by continuous heat ingress from the VJPs, a “bump” structure was introduced by modifying the VJP height, enabling localized LN2 supply only to the required areas. Figure 1 shows a schematic of the VJP system in zones A+B after separation. For instance, in zone B, LN2 is supplied exclusively to BL15XU and LN2 collecting station #3.

Since the VJP system on the storage ring tunnel ceiling covers a wide area and is not easy to access, fiber-optic thermometers have been installed along the outer surfaces of the VJPs to enable the early detection of LN2 leakage. Furthermore, to facilitate safe and efficient LN2 filling at the collecting stations, we have developed a system that automates the entire filling process. This includes user and LN2 container authentication, pre-filling operations, real-time monitoring during filling, and completion, all of which are controlled via a graphical user interface (GUI).

1-2. Improvement of frontend slits

Frontend slits are primarily designed to absorb peripheral high-heat-load radiation and to shape beams with widths typically smaller than 1 mm. To prevent material melting, long copper-alloy absorbers are placed at a small incident angle and are slightly convex in shape, allowing them to receive the maximum heat load around the center of the absorber. The beams are then shaped using tungsten blades. However, owing to the poor machining of the convex shape, the partial shadowing of the main beams has occurred at many beamlines. Recently, this shadowing has become critical, as it affects the precise determination of the virtual source size using the slit at several beamlines.

In FY2024, we replaced the old frontend slits with modified ones at three beamlines (BL19LXU, BL29XU, and BL40XU). The absorber shapes of spare slits were precisely measured at an off-line test bench, after which the tungsten blades were custom-machined. The blade edges were tapered to prevent melting. After attaching the blades, the slit openings were measured again to confirm their accuracy. The modified slits were then installed at the beamlines during shutdown periods. The removed slits will be refurbished.

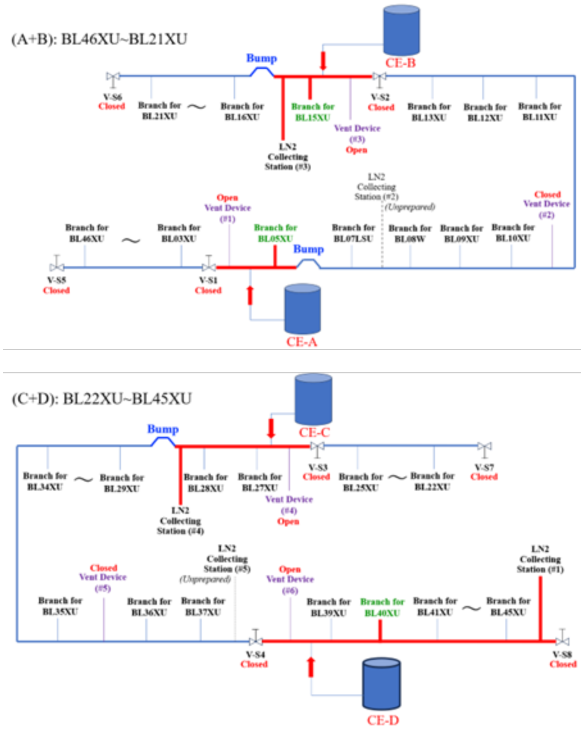

Fig. 1. Schematic of the VJP system in zones A+B and C+D.

2. X-ray optics and beam transport

2-1. Improvement of double-crystal monochromator

BL16XU, originally constructed by SUNBEAM, has been partially dedicated to user operation for diffraction experiments since 2024 in order to alleviate the congestion of experiment time at BL13XU. However, the optical components inherited from SUNBEAM were inferior to those of BL13XU, which had been fully upgraded in FY2021. In particular, the double-crystal monochromator required improved stability, as it caused a gradual reduction in beam intensity over time and needed the repair of several stages. In addition, new users requested access to high-energy (70 keV) X-rays using silicon (311) crystals.

The monochromator was fully upgraded during the summer shutdown. Both silicon (111) and (311) crystals were installed and made switchable via translation stages X1 and X2. To enhance the cooling efficiency of the first crystals, the liquid-nitrogen inlet and outlet pipes were enlarged from a half-inch to 10A in diameter, with internal paths branched into half-inch tubes for the first crystals and quarter-inch tubes for the second crystals. The tubes consisted of low-vibration flexible hoses developed at SPring-8. To further increase the rigidity of the crystal units, the tilt stage of the first crystals was removed, while that of the second crystals was widened to extend the distance between its guide rails. This upgrade has significantly improved stability, eliminating the time-dependent reduction in intensity. However, short-term intensity fluctuations remain due to vibrations from the liquid-nitrogen circulator and utility pipes. Although these fluctuations do not currently hinder user experiments, we plan to install a newly developed circulator and reconfigure the utility pipes in FY2025.

BL19B2, the beamline for X-ray diffraction and scattering experiments, employed a double-crystal monochromator with silicon (111) crystals, where the diffraction plane could be switched to 311 reflection by using inclined geometry with tilt stages α1 and α2. However, the beam size of high-energy X-rays in the 311 reflection was inevitably reduced by the limited acceptance of this geometry. During the summer shutdown, this monochromator was replaced with a new one containing both silicon (111) and (311) crystals that are switchable with translation stages X1 and X2. To fully utilize the horizontally wide beams emitted from the bending-magnet source, the width of each crystal was increased to 50 mm. Consequently, the translation length of the new X1 and X2 stages was extended to more than 80 mm, and the vacuum chamber was replaced with a round lid to secure sufficient translation space.

2-2. Reconstruction of BL40XU

BL40XU was reconstructed from a high-flux multipurpose beamline into a dedicated small- and wide-angle X-ray scattering (SAXS/WAXS) beamline. Beamline optics, as shown in Fig. 2, was implemented in response to requests from the upgrade working group, including the generation of a pink beam by total-reflection mirrors and a monochromatic beam by a double channel-cut monochromator (DCCM), a soft focus of approximately 100 μm at various detector positions, and micro-focusing at the sample position. M1H is a horizontally deflecting plane-bent mirror that provides horizontal soft focusing at each detector position. M2V and M3V are vertically deflecting mirrors that maintain the outgoing beam axis in the horizontal direction, and M3V, designed as a bent mirror, provides vertical soft focusing. The reflecting surfaces of these mirrors are coated with Si and Ru stripes, allowing selection in accordance with the X-ray energy used, and these three mirrors are always positioned on the optical axis. By retracting or inserting the Si (111) DCCM, either a pink beam or a monochromatic beam can be selected. In EH1, a horizontally deflecting plane-bent mirror (M4H) and a monolithic Wolter mirror (M5W), both retractable from the optical axis, are installed to provide a microbeam at the sample position. The M4H bender is employed to compensate for the astigmatism of M5W focusing. A new detector booth for USAXS is constructed downstream of EH2. In addition, the insertion device is replaced with IVU-28, which is compatible with the future SPring-8-II upgrade. The reconstruction started in December 2024, and commissioning tests are scheduled to start in May 2025.

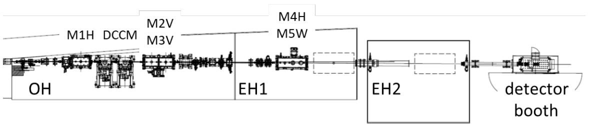

Fig. 2. Design of reconstructed BL40XU.

2-3. Commissioning of BL39XU

BL39XU was upgraded in 2023 to focus on magnetism research, and commissioning was initiated in January 2024.

A newly developed higher-order suppression mirror system [1] was implemented. The reflectivity for the fundamental beam was confirmed to be nearly equal to the design values at photon energies of 4.9, 10, and 30 keV, while the third harmonic beam was suppressed by approximately four to five orders of magnitude. When the incidence angle was varied from 2 to 8 mrad, the beam displacement observed in EH3 was corrected by the internal adjustment mechanism, achieving ±33 μm in the vertical direction and ±4 μm in the horizontal direction. In EH1, a new Kirkpatrick–Baez (KB) mirror system was installed. The design of these mirrors was optimized for use up to 20 keV, and their reflecting surfaces were coated with platinum and rhodium stripes. The focus size of 1 μm (Vertical)×10 μm (Horizontal) was verified at 10, 20, and 30 keV. In EH2, a new monolithic Wolter mirror designed for operation up to 20 keV was introduced. At 12.4 keV, a focal size of 1 μm (V)×16 μm (H) and a flux of 1.3×10^{13} photons/s were confirmed without a virtual source. The existing KB mirrors in EH3 were readjusted, and the previously obtained focal spot size of 100 nm×100 nm using a virtual source was confirmed again at 6.72 keV.

2-4. Flux improvement using large-area multilayer mirrors for a double multilayer monochromator (DMM) at BL05XU

At BL05XU, we developed a DMM to generate high-energy, high-flux X-rays. The DMM delivers 100 keV X-rays, which are used in advanced X-ray analytical techniques (Yumoto et al., in press).

To achieve a high-flux, high-stability beam, a DMM was designed based on the parameters shown in Table 1 and equipped with an alignment mechanism. Advances in multilayer coating technology allowed the coating length to be extended from 300 mm to 500 mm. The substrate dimensions were increased from 400 mm long×50 mm wide×50 mm thick to 550 mm long×50 mm wide×90 mm thick. The longer multilayer coatings provide an aperture large enough to reflect almost all incident X-rays generated at the light source with minimal loss. Increasing the substrate thickness enhanced the second moment of area by approximately 5.8-fold, reducing distortion during clamping to the LN2 cooling blocks. Compared with previous designs, the mirror alignment mechanism was simplified by modifying the clamping method. The clamping configuration was also revised to enhance cooling efficiency. Additionally, the number of motor-driven stages was minimized to enhance long-term stability. The multilayer mirrors were coated at the SPring-8 campus.

The installation of the new multilayer mirrors and alignment mechanism increased the flux by 1.7-fold, reaching 6×10^{13} photon/s with an energy bandwidth of 1.0% (Fig. 3). As shown in Fig. 4, a clear 100 keV beam was achieved without any noticeable distortion from the clamping. Furthermore, the DMM enabled the extraction of higher-energy X-rays from undulator radiation. A flux of 3×10^{12} photons/s was achieved at 200 keV, and high-energy X-rays up to 543 keV were successfully extracted using the DMM (Yumoto, H., unpublished data).

2-5. Launch of a 100 keV high-energy, high-flux beamline using a DMM at BL15XU

At BL15XU, beamline design, refurbishment, and the preparation of optical instruments began in 2022. This beamline was constructed to provide a high-flux beam at 100 keV for advanced X-ray analyses, including 3D X-ray diffraction (3D-XRD) and diffraction experiments under high-pressure conditions. All optical components in the optics hutch were replaced, and a DMM was installed to extract 100 keV X-rays. By applying the optical technologies developed for the DMM at BL05XU, the beamline was able to rapidly implement an advanced monochromator system.

Table 1. Optical parameters of multilayer mirrors for DMM at BL05XU.

Material	$(Cr/C)_{150}$
Period (d-spacing)	3.17 nm
Grazing incident angle at 100 keV	2.0 mrad
Spatial acceptance for 100 keV beam	1.0 mm (vertical)

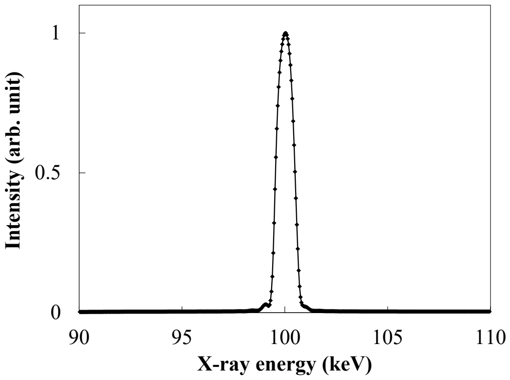

Fig. 3. Measured energy spectrum of 100 keV X-rays from DMM.

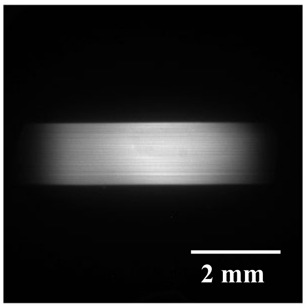

Fig. 4. Observed beam image of 100 keV X-ray beam from DMM.

Optical instruments in the optics hutch were installed by the summer shutdown period of 2024. Multilayers of the DMM were coated at the SPring-8 campus using the same parameters as those at BL05XU (Table 1). At the start of the 2024B operation cycle, the DMM was constructed as a water-cooled system, and initial performance evaluations were conducted. The light source of BL15XU is an in-vacuum undulator (IVU-II) with a device length of 3.3 m and a period length of 22 mm, compatible with the SPring-8-II scheme. This undulator can produce 100 keV X-rays at the 7th harmonic.

As a result of the DMM evaluation, a 100 keV high-flux beam with a flux of 6×10^{13} photons/s, an energy bandwidth of 0.75%, and beam dimensions of 1.2 mm (vertical)×1.6 mm (horizontal) (FWHM) was successfully achieved (Yumoto, H., unpublished data). The resulting beam was immediately used by the beamline staff and subsequently applied to X-ray analytical experiments.

3. Beamlines of SACLA

The two hard X-ray FEL beamlines (BL2 and BL3) are operated concurrently and share an accelerator that produces 8 GeV electrons. The concurrent operation is achieved with a fast-switching magnet located at the end of the accelerator. Following the completion of the optics upgrade in the optics hutch for BL2 in FY2022, the coverage of photon energies (4–22 keV) is equivalent in these two beamlines. However, advanced operation schemes, including self-seeded XFELs, two-color operations, and double-pulse operations, have only been available at BL3. These advanced capabilities enhance the distinctive features of BL3, particularly in nonlinear X-ray sciences, in combination with the nano-focusing capabilities of precise optical systems at the beamline.

As previously reported, a portable nano-focusing mirror system has been developed at SACLA. The new instruments enable the generation of intense X-rays in any experimental hutch. This development strengthens the demand to introduce the two-color operation scheme at BL2 for capability expansion. In 2024A, the production of two-color XFELs was tested at BL2. The two-color XFELs, which consist of two XFEL pulses with different photon energies, were realized by dividing the undulators into two groups and independently tuning the undulator conditions for each group. The production of two-color XFELs at BL3 follows the same process. However, since an electron beam chicane in the undulator section is equipped only at BL3, a time delay between the two XFEL pulses cannot be introduced at BL2. The output pulse energies depend on the photon energies and the desired intensity ratio of the two pulses.

Additionally, several minor instrumental improvements and maintenance were implemented at the hard X-ray FEL beamlines during FY2024.

An X-ray phase retarder (XPR) has been operational at BL3 to control the polarization of the XFEL beam. The polarization state of the X-rays is modulated by adjusting the incident angle of the XPR crystal using a piezoelectric actuator. By applying a square-wave voltage to the actuator, left- and right-circular polarizations can be alternately switched at a repetition rate of 15 Hz. This alternate operation of XRP enabled shot-to-shot polarization switching for magnetism studies in general user experiments in FY2024. Furthermore, polarization-controlled seeded XFEL pulses, generated by applying the XRP for the self-seeded XFELs, were employed in experiments investigating magnetic materials excited by intense X-rays.

In hard X-ray FEL beamlines, double-crystal monochromators (DCMs) with silicon (111) crystals are employed to monochromatize XFEL beams. Piezoelectric stages are used for precise adjustments of the height (ΔZ) and angle ($\Delta\theta$) of the first crystal as well as the tilt (Ty) of the second crystal. During FY2024, a malfunction occurred in the ΔZ stage in the DCM at BL3, which made the DCM inoperable. The issue was resolved by replacing the malfunctioning stage within the fiscal year. The failure analysis and subsequent repair of the piezoelectric stage, if feasible, are planned in FY2025.

The SACLA BL1 provides an intense soft X-ray pulse with a photon energy range of 40 eV to 150 eV. In FY2023, a quasi-in-line spectrometer (I-spec) was installed to provide pulse-to-pulse spectral information within the photon energy range, including the capability to monitor third-harmonics utilizing tin (Sn) filters and the third-order diffraction of the grating. Starting in FY2024, this spectral data has been applied for the automated tuning of BL1, similar to the hard X-ray FEL beamlines.

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