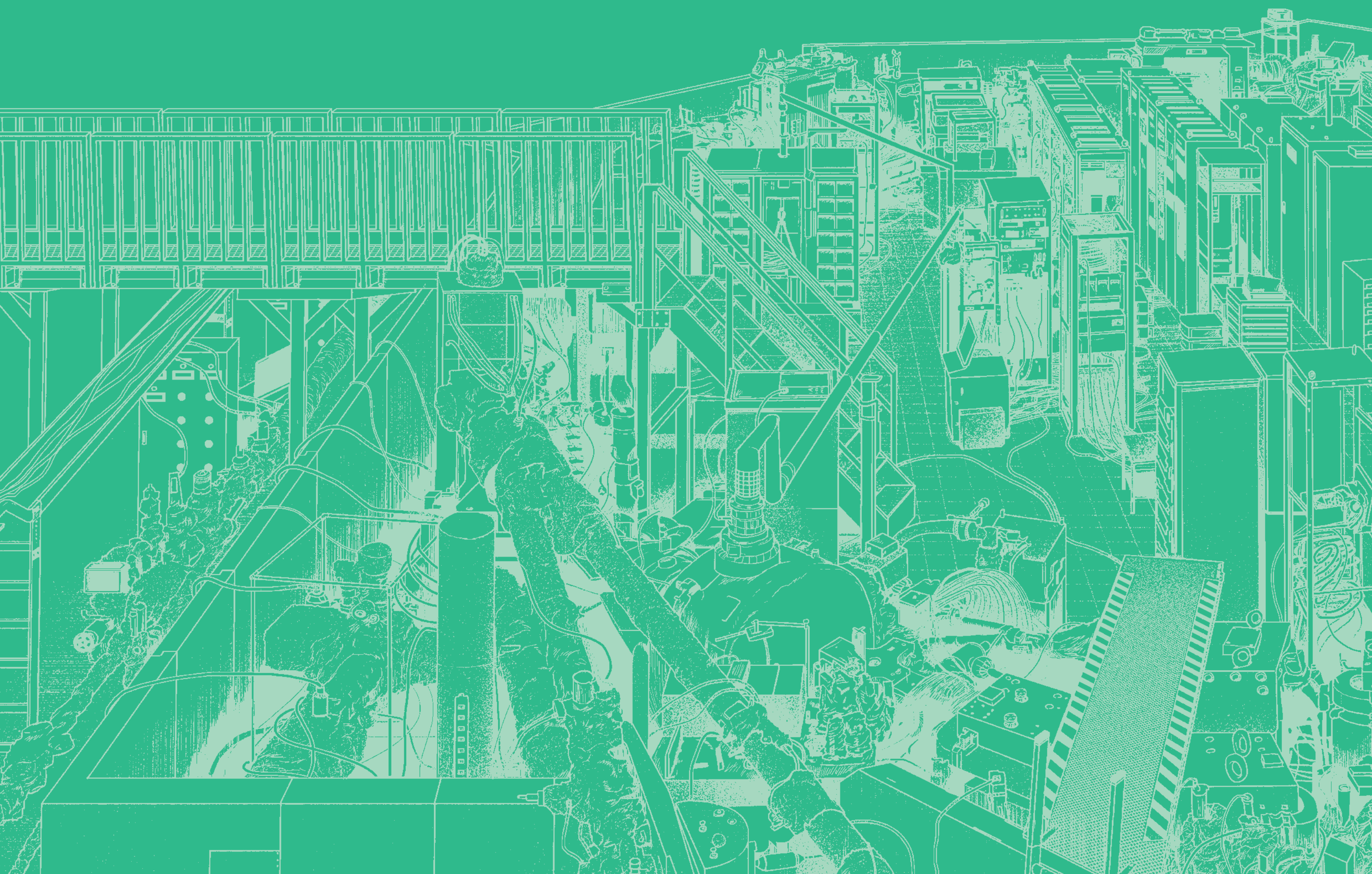
II

Current Status of Light Sources and Beamlines



Light Source in 2024

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In FY2024, UVSOR-III was operated for users as scheduled for 36 weeks from end of May 2024 to March 2025. Monthly statistics of operation time and integrated beam current are shown in Fig. 1. From the beginning of April to early May, during which periodic inspections were conducted. The two weeks following the shutdown were allocated to the adjustment of the accelerator and beamlines.

The weekly operation schedule is as follows. Mondays are assigned to machine studies from 9:00 AM to 9:00 PM. User operation is assigned Tuesday through Friday, with Tuesday and Wednesday operating from 9:00 AM to 9:00 PM, and Thursday from 9:00 AM to 9:00 PM on Friday for 36 continuous hours. Thus, the user's beam time per week is 60 hours.

A few mA loss in stored beam current has been occurring since FY2023 when the gap of a particular undulator is changed during user operation. As it has been observed that the electron beam size circulating the storage ring increases during loss, instantaneous beam instability is thought to occur. No significant change in betatron tune before and after the loss was observed, and the cause of the beam instability has not been identified. However, by changing the current value of sextupole electromagnets in March 2024, the loss of stored beam current almost did not occur thereafter.

Injection efficiency of the electron beam into the storage ring started to decrease around January 2023. The injection efficiency is calculated as the ratio of the increase in the stored current value, δI, to the current value passing through the transport line between the booster synchrotron and the storage ring. Under normal conditions, the injection efficiency was 60~70% and δI was 0.4~0.6 mA/shot, but after January 2023, the efficiency dropped to 20~30% and δI 0.1~0.3 mA/shot. The limited number of electrons that can be injected into the storage ring per week makes it difficult to continue 300 mA operation. Therefore, user operation has been conducted with the stored current value reduced to 200 mA since May 2023. Various investigations are continuing to determine the cause, but so far no clear cause has been identified. However, the betatron function and emittance of the booster synchrotron were found to deviate significantly from the design values. The vacuum ducts in the bending magnet section of the booster synchrotron have experienced multiple vacuum leaks, and there is concern that opening the ducts to the atmosphere may induce serious vacuum leaks, so it is currently impossible to visually check inside the ducts. All vacuum ducts in the bending magnet section are scheduled to be replaced with new ones in April 2025. At that time, we will check the inside of the vacuum ducts of the booster synchrotron.

We started a design study for the future plan of UVSOR-IV. As a first step, we have analyzed the present magnetic lattice, seeking a possibility to reduce the emittance more [1]. Although, we did not find a solution to drastically reduce emittance, we have found a few interesting solutions that achieved lower emittance than the current situation. As the second step, we have started designing a totally new storage ring, which is close to the diffraction limit in the VUV range [2].

The light source development and utilization beamline BL1U, constructed under the support of Quantum Beam Technology Program by MEXT/JST, continue to develop new light source technologies and their applications such as free electron laser, coherent harmonic generation, coherent synchrotron radiation, coherent control [3], laser Compton scattered gamma rays [4, 5], and optical vortices [6].

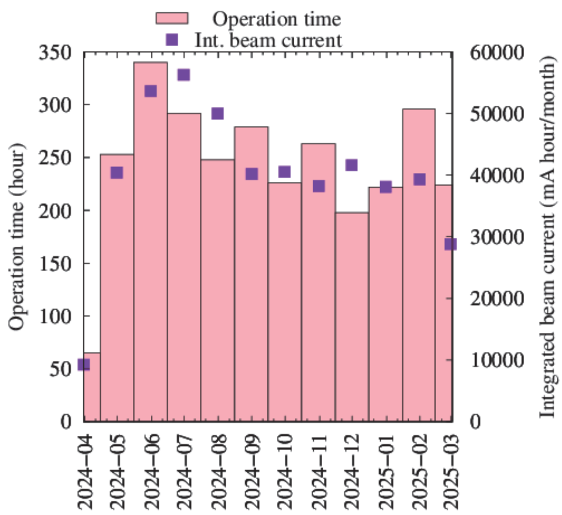


Fig. 1. Monthly statistics in FY2024.

[1] E. Salehi and M. Katoh, Proceedings of IPAC2021 (2021) 3970.
[2] E Salehi *et al.*, Phys.: Conf. Ser. **2420** (2023) 012062.
[3] Y. Hikoska *et al.*, Sci. Rep. **13** (2023) 10292.
[4] Y. Taira, Phys. Rev. A **110** (2024) 043525.
[5] S. Endo *et al.*, Eur. Phys. J. A **60** (2024) 166.
[6] S. Wada *et al.*, Sci. Rep. **13** (2023) 22962.

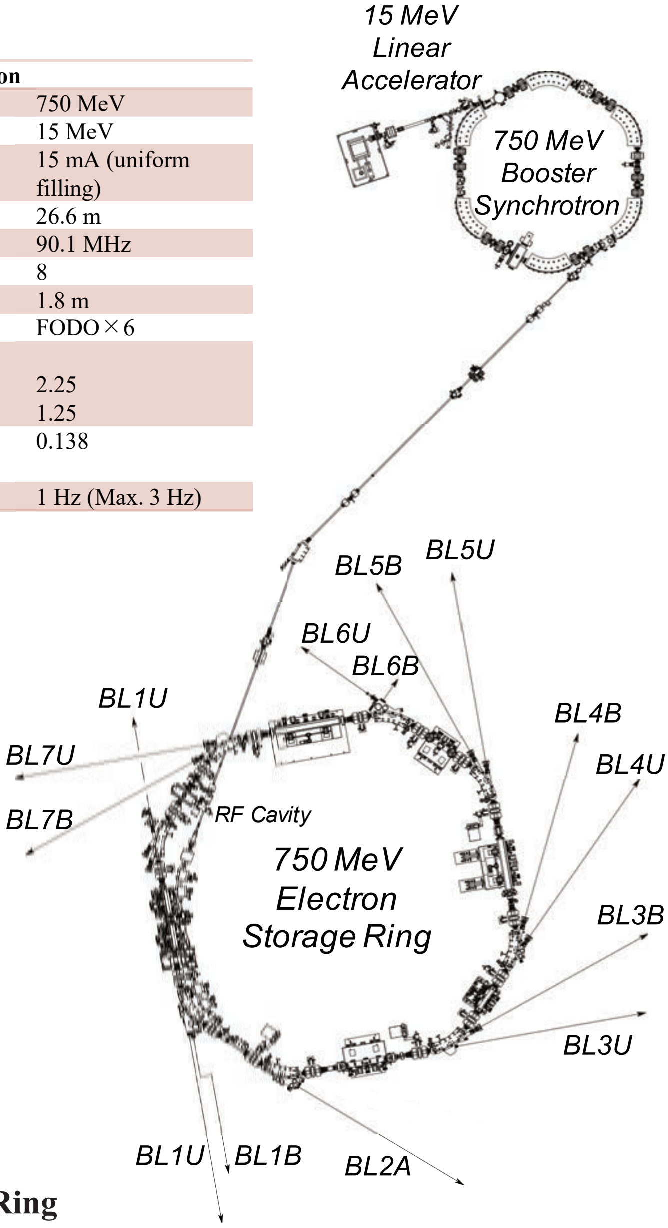
UVSOR Accelerator Complex

II

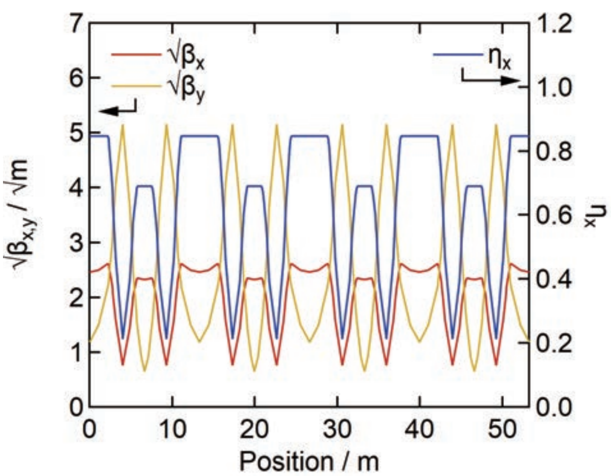
Injection Linear Accelerator	
Energy	15 MeV
Length	2.5 m
RF Frequency	2856 MHz
Accelerating RF Field	$2\pi/3$ Traveling Wave
Klystron Power	1.8 MW
Energy Spread	~1.6 MeV
Repetition Rate	1 Hz (Max. 3 Hz)

UVSOR-III Storage Ring	
Energy	750 MeV
Injection Energy	750 MeV
Normal Operation	300 mA (multi bunch)
Current (Top-up)	40 mA (single bunch)
Natural Emittance	17.5 nm rad
Circumference	53.2 m
RF Frequency	90.1 MHz
RF Voltage	120 kV
Harmonic Number	16
Bending Radius	2.2 m
Lattice	Extended DB × 4
Straight Section	(4 m × 4)+(1.5 m × 4)
Betatron Tune	
Horizontal	3.75
Vertical	3.20
Momentum Compaction	0.030
Natural Chromaticity	
Horizontal	-8.1
Vertical	-7.3
Energy Spread	5.26×10^{-4}
Coupling Ratio	1%
Natural Bunch Length	128 ps

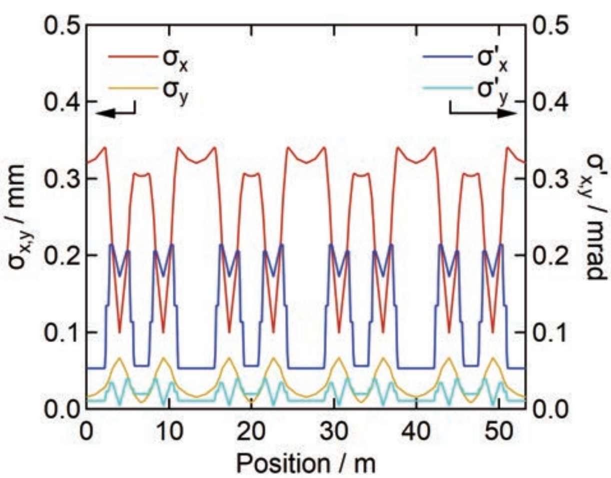
Booster Synchrotron	
Energy	750 MeV
Injection Energy	15 MeV
Beam Current	15 mA (uniform filling)
Circumference	26.6 m
RF Frequency	90.1 MHz
Harmonic Number	8
Bending Radius	1.8 m
Lattice	FODO × 6
Betatron Tune	
Horizontal	2.25
Vertical	1.25
Momentum Compaction	0.138
Repetition Rate	1 Hz (Max. 3 Hz)



Electron Beam Optics of UVSOR-III Storage Ring

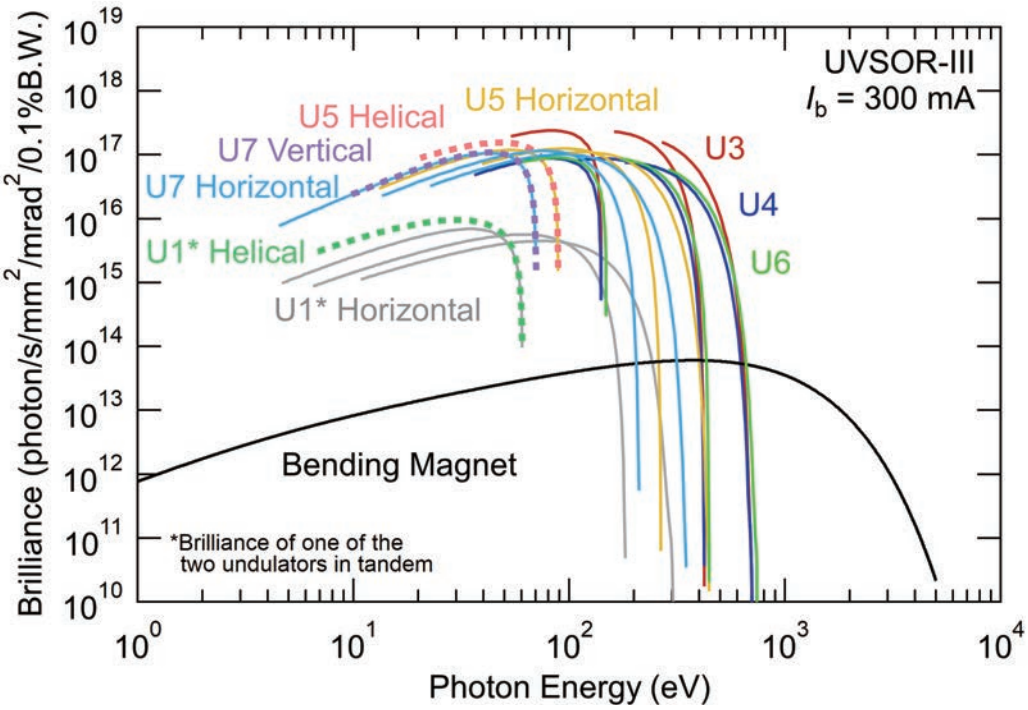


Horizontal / vertical betatron functions and dispersion functions



Horizontal / vertical electron beam size and beam divergences

Insertion Devices



Brilliance of radiation from the insertion devices (U3, U4, U5, U6 and U7) and a bending magnet of UVSOR-III

U1 Apple-II Undulator / Optical Klystron	
Number of Periods	10 + 10
Period Length	88 mm
Pole Length	0.968 m + 0.968 m
Pole Gap	24–200 mm
Deflection Parameter	7.36 (Max. Horizontal) 4.93 (Max. Vertical) 4.06 (Max. Helical)

U3 In-Vacuum Undulator	
Number of Periods	50
Period Length	38 mm
Pole Length	1.9 m
Pole Gap	16.5–40 mm
Deflection Parameter	1.8–0.24

U4 In-Vacuum Undulator	
Number of Periods	26
Period Length	38 mm
Pole Length	0.99 m
Pole Gap	13–40 mm
Deflection Parameter	2.4–0.19

Bending Magnets	
Type	Combined ×8
Magnetic Length	1.728 m
Bending Radius	2.2 m
Bending Angle	45 deg.
Pole Gap	55.2 mm
Pole Width	140 mm
Critical Energy	425 eV

U5 Apple-II Variable Polarization Undulator	
Number of Periods	38
Period Length	60 mm
Pole Length	2.28 m
Pole Gap	24–190 mm
Deflection Parameter	3.4 (Max. Horizontal) 2.1 (Max. Vertical) 1.8 (Max. Helical)

U6 In-Vacuum Undulator	
Number of Periods	26
Period Length	38 mm
Pole Length	0.94 m
Pole Gap	13–40 mm
Deflection Parameter	2.1–0.19

U7 Apple-II Variable Polarization Undulator	
Number of Periods	40
Period Length	76 mm
Pole Length	3.04 m
Pole Gap	24–200 mm
Deflection Parameter	5.4 (Max. Horizontal) 3.6 (Max. Vertical) 3.0 (Max. Helical)

(Last updated, August, 2025)

Beamlines in 2024

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The UVSOR facility stands as a premier synchrotron radiation source, offering exceptional brilliance in the extreme-ultraviolet (EUV) region, particularly among facilities with electron energies below 1 GeV. A significant milestone was achieved in 2012 with the successful completion of the UVSOR-III storage ring upgrade project, which dramatically reduced the natural emittance to a low 17.5 nm-rad.

UVSOR currently provides synchrotron light from eight bending magnets and six insertion devices. The facility houses a total of thirteen operational beamlines. Among these, eleven are designated as "Public beamlines", accessible to scientists from universities, government research institutes, private enterprises, and international collaborators. Beamline BL6U is an "In-house beamline", exclusively dedicated to research groups within the Institute for Molecular Science and their collaborators. Beamline BL1U operates as a hybrid, serving both "Public" and "In-house" research.

As of 2024, the beamlines at UVSOR are configured as follows (details are also provided in the appended table on the next page):

- One tender X-ray (TX) station equipped with a double-crystal monochromator [**BL2A**].
- Six extreme ultraviolet (EUV) and soft X-ray (SX) stations equipped with grazing incidence monochromators [**3U**, **4U**, **4B**, **5U**, **5B**, **6U**].
- Three vacuum ultraviolet (VUV) stations equipped with normal incidence monochromators [**3B**, **7U**, **7B**].
- Two infrared (IR) stations equipped with Fourier Transform interferometers [**1B**, **6B**].
- One direct radiation station positioned after two tandem undulators [**1U**].

The latest information on the undulator beamline is detailed below.

BL1U: A Unique Beamline for VUV and Gamma Rays

At the **BL1U** beamline, novel light source development and gamma-ray utilization are actively being pursued. This beamline is uniquely equipped with tandem undulators featuring a buncher section. This sophisticated setup enables a range of advanced capabilities:

- Free electron laser operation spanning from the visible to deep UV regions.
- VUV coherent harmonic generation.
- The creation of spatiotemporal structured light, including optical vortex beams, vector beams, and double-pulsed wave packets.

Furthermore, BL1U boasts a femtosecond laser system precisely synchronized with the accelerator. This system is crucial for the generation of Compton scattered gamma-rays. UVSOR provides users with gamma-ray induced positron annihilation spectroscopy, a powerful technique for analyzing nanometer-scale defects within bulk materials. To significantly boost the counting rate of annihilation gamma rays, an array detector with eight BaF_2 scintillators has been developed. This advancement enables the completion of measurements on metal samples within just a few hours.

Since fiscal year 2022, a modification to the storage ring electron beam's orbit has enabled continuous undulator light irradiation experiments at BL1U, significantly improving the efficiency of user operations.

BL3U: Advanced Soft X-ray Spectro-scopy for Soft-Matter Samples

At **BL3U**, significant progress has been made in low-energy X-ray absorption spectroscopy (XAS) with the development of an ultrathin-liquid cell. This innovation has enabled detailed studies of:

- The local structures of various aqueous solutions.
- Diverse chemical processes in solution, including catalytic and electrochemical reactions.
- Laminar flows in microfluidics, all demonstrated using operando XAS at the C, N, and O K-edges.

Furthermore, an argon gas window has been established, proving effective from 60 to 240 eV. This window, which also removes higher-order X-rays, is expected to significantly advance chemical research. It encompasses the K-edges of elements like Li and B, as well as the L-edges of Si, P, S, and Cl, opening new avenues for investigation.

Resonant soft X-ray scattering (RSoXS) for soft materials is also applicable at BL3U. Similar to small-angle X-ray scattering (SAXS), RSoXS provides valuable information on the mesoscopic structure (1-100 nm) of samples. This method offers crucial selectivity based on elements, functional groups, and molecular orientation. Given that the soft X-ray region includes the K-edge energies of light elements (C, N, O), RSoXS stands as a powerful tool for investigating soft matter.

During the first half of fiscal year 2024, a vacuum accident occurred due to a water leak from the cooling mechanism of the entrance slit. However, repairs have been completed, and we've confirmed that the performance, including soft X-ray intensity and resolution, has been restored to its previous levels. User beamtime that was canceled in the first half of fiscal year 2024 has been reallocated to the second half.

BL4U: STXM for Elemental and Chemical State Mapping

BL4U, equipped with a scanning transmission soft X-ray microscope (STXM), is a beamline that has been extensively utilized by both academic and industrial researchers. The STXM's versatility allows for its application across a wide range of scientific disciplines, including polymer science, materials science, cell biology, and environmental science.

We are currently investigating the potential of UVSOR to contribute to advancements in the life sciences through the exploitation of low photon energy techniques, particularly within the framework of the BL4U, leveraging soft X-ray spectromicroscopy.

BL5U: Enhancing Spin-Resolved ARPES Capabilities

At **BL5U**, high energy resolution angle-resolved photoemission spectroscopy (ARPES) is available to users. The latest version of the ARPES analyzer now allows for "deflector mapping" across all kinetic energies and lens modes, significantly enhancing experimental flexibility. Researchers can also investigate the spatial-dependence of electronic structures on solid surfaces using a micro-focused beam, which has a spot size of 50 µm.

To facilitate a wider range of experiments, an alkali-metal deposition system has been installed. This enables the deposition of materials like potassium onto samples while they remain mounted on the manipulator at low temperatures. As part of ongoing development in spin-resolved ARPES, two-dimensional images of the spin-resolved spectrum showing the Rashba splitting of the Au(111) surface have been successfully obtained.

In the latter half of fiscal year 2024, an automated spin target magnetization system was developed and implemented to enhance user access for spin-resolved Angle-Resolved Photoemission Spectroscopy (ARPES). This new system allows for free magnetization of the target via PC control.

While we currently offer spin-resolved ARPES measurements in two in-plane directions, the precise control afforded by the automated magnetization system has opened up the prospect of obtaining out-of-plane spin information from samples. Moving forward, we will be fine-tuning the final electron lens to achieve all-directional spin-resolved ARPES.

BL6U: Unveiling Electronic States with Momentum Microscopy

BL6U, one of UVSOR's in-house beamlines, now features and operates a photoelectron momentum microscope (PMM). This new-concept, multi-modal system offers high resolution in both real and momentum space for electronic structure analysis. A key advantage of the PMM is its ability to significantly reduce radiation-induced damage. It achieves this by directly projecting a single photoelectron constant energy contour in reciprocal space (with a radius of a few $Å^{-1}$) or real space (with a radius of a few hundred µm) onto a 2D detector.

Current experiments at BL6U include valence band photoelectron spectroscopy on the micrometer scale and resonant photoelectron diffraction using soft X-ray excitation. In FY2023, the PMM's capabilities were further expanded with the introduction of an additional 2D spin filter. This enhancement allowed for the successful acquisition of 2D images of the spin-resolved spectrum of the Rashba splitting on the Au(111) surface.

Beyond grazing-incidence soft X-ray excitation, a normal-incidence vacuum ultraviolet (VUV) beam with variable polarizations (horizontal/ vertical) has also become available at the PMM's focal position. The beamline was configured to use both BL6U and BL7U (branch) as light sources, allowing us to irradiate the same sample position with both beams. Performing full solid-angle photoelectron spectroscopy measurements using direct incidence linear polarization from 6 to 26 eV is now capable. This highly symmetrical measurement geometry completely eliminates the p-polarized linear dichroism effect in circular dichroism measurements of the valence band, significantly simplifying and increasing the reliability of transition matrix element analysis. However, since it is necessary to ensure sufficient activity at BL7U, advanced use of this configuration is currently only possible during limited hours and under coordination within the facility.

BL7U: A World-Class Beamline for High-Resolution ARPES

BL7U offers high-energy resolution angle-resolved photoemission spectroscopy (ARPES), allowing for experiments with exceptionally low photon energies, starting from 6 eV. This is facilitated by a low-temperature 6-axis manipulator, which maintains sample temperatures between 4.5 K and 350 K.

In FY2021, a deflector-type detector was installed for the hemispherical analyzer. This upgrade, combined with automated manipulator control, enables effective 2D measurements. Users can now conduct highly sensitive investigations into the bulk electronic structure of solids. Furthermore, the ability to utilize low-excitation photon energies with high photoionization cross-sections allows for high-throughput measurements of molecular materials.

For those interested in utilizing UVSOR's open or in-house beamlines, it's recommended to first contact the appropriate beamline contact persons, whose details can be found on the next page. Applications for beamtime can be submitted through the **NOUS system** at https://nous.nins.jp/user/signin. All users are required to consult the beamline manuals and the UVSOR guidebook prior to conducting any experimental procedures. For the most up-to-date information on UVSOR, please visit the official website: http://www.uvsor.ims.ac.jp.

Beamlines at UVSOR

Beamline	Monochromator / Spectrometer	Energy Range	Targets	Techniques	Contact
BL1U	Light Source Development Gamma-ray FEL	2.5 - 82 eV		Irradiation (UV and Gamma-rays)	Y. Taira yostaira@ims.ac.jp
BL1B	Martin-Puplett FT-FIR	0.5 – 30 meV	Solid	Reflection Absorption	K. Tanaka k-tanaka@ims.ac.jp
BL2A	Double crystal	800 – 4 keV	Solid	Reflection Absorption	F. Matsui matui@ims.ac.jp
BL3U	Varied-line-spacing plane grating (Monk-Gillieson)	60 – 800 eV	Gas Liquid Solid	Absorption Photoemission Photon-emission	H. Iwayama iwayama@ims.ac.jp
BL3B	2.5-m off-plane Eagle	1.7 – 31 eV	Solid	Reflection Absorption Photon-emission	F. Matsui matui@ims.ac.jp
BL4U	Varied-line-spacing plane grating (Monk-Gillieson)	55 – 770 eV	Gas Liquid Solid	Absorption (Microscopy)	T. Araki araki@ims.ac.jp
BL4B	Varied-line-spacing plane grating (Monk-Gillieson)	25 eV – 1 keV	Gas Solid	Photoionization Photodissociation Photoemission	H. Iwayama iwayama@ims.ac.jp
BL5U	Varied-line-spacing plane grating (Monk-Gillieson)	20 – 220 eV	Solid	Photoemission	K. Tanaka k-tanaka@ims.ac.jp
BL5B	Plane grating	6 – 600 eV	Solid	Calibration Absorption	K. Tanaka k-tanaka@ims.ac.jp
BL6U*	Variable-included-angle varied-line-spacing plane grating	40 – 700 eV	Solid	Photoelectron Momentum Microscopy	F. Matsui matui@ims.ac.jp
BL6B	Michelson FT-IR	4 meV – 2.5 eV	Solid	Reflection Absorption IR microscope	K. Tanaka k-tanaka@ims.ac.jp
BL7U	10-m normal incidence (modified Wadsworth)	6 – 40 eV	Solid	Photoemission	K. Tanaka k-tanaka@ims.ac.jp
BL7B	3-m normal incidence	1.2 – 25 eV	Solid	Reflection Absorption Photon-emission	F. Matsui matui@ims.ac.jp

Yellow columns represent undulator beamlines.
***In-house beamlines**

BL1U

Light Source Development Station

▼Description

BL1U is dedicated for developments and applications of novel light sources. This beamline is equipped with a dedicated tandem undulator for variable polarization with a buncher section, which can be used for free electron laser in the range from visible to deep UV, VUV coherent harmonic generation (CHG), and generation of spatiotemporal structured light such as an optical vortex beam, a vector beam and double-pulse wave packets. It is also equipped with a femto-second laser system synchronized with the accelerator, which is used for the generation of CHG, laser Compton scattered gamma-rays, and coherent THz radiation. Nowadays, material analysis by positron annihilation spectroscopy using laser Compton scattered gamma rays is actively used.

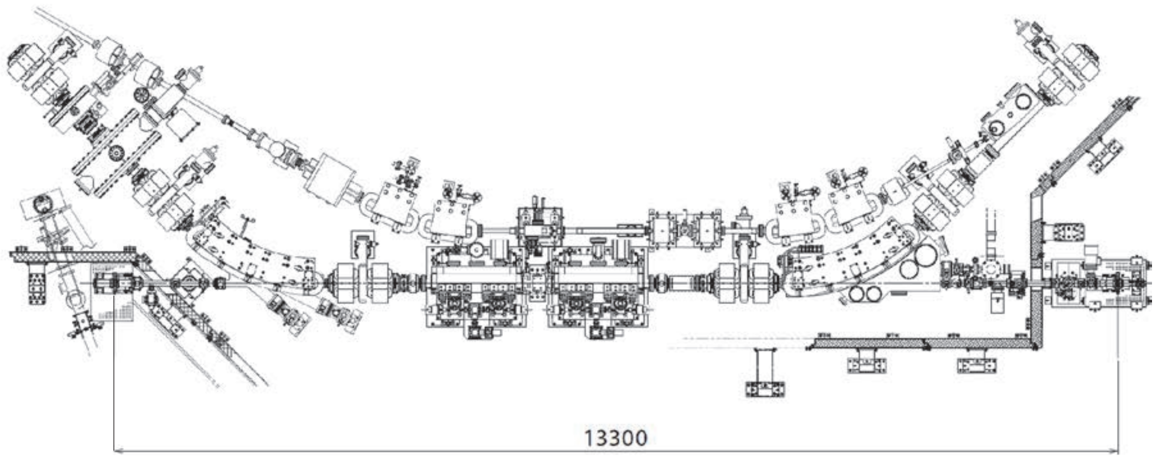


Fig. 1. Configuration of the free electron laser.

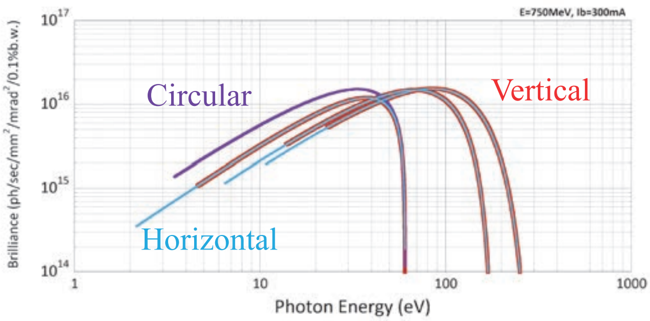


Fig. 2. Brilliance of BL1U Apple-II Undulator.

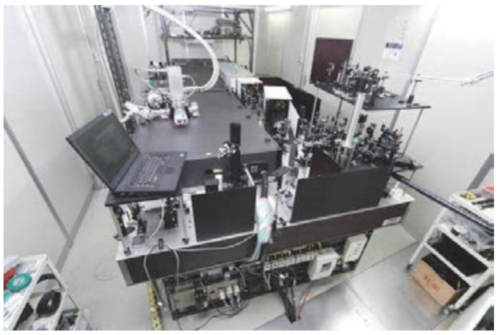


Fig. 3. Accelerator synchronized Laser System.

▼Technical Data of FEL

Wave Length	199-800 nm
Spectral Band Width	~10^{-4}
Polarization	Circular/Linear
Pulse Rate	11.26 MHz
Max. Ave. Power	~1 W

▼Technical Data of Ti:Sa Laser

Wave Length	800 nm		
Pulse Length	130 fsec		
Oscillator	90.1 MHz		
Pulse Energy	2.5 mJ	10 mJ	50 mJ
Repetition Rate	1 kHz	1 kHz	10 Hz

BL1B

Terahertz Spectroscopy Using Coherent Synchrotron Radiation

▼Description

Coherent synchrotron radiation (CSR) is a powerful light source in the terahertz (THz) region. This beamline has been constructed for basic studies on the properties of THz-CSR. However, it can be also used for measurements of reflectivity and transmission spectra of solids using conventional synchrotron radiation.

The emitted THz light is collected by a three-dimensional magic mirror (3D-MM, M0) of the same type as those already successfully installed at BL43IR in SPring-8 and BL6B in UVSOR-II. The 3D-MM was installed in bending-magnet chamber #1 and is controlled by a 5-axis pulse motor stage (x, z translation; θ_x, θ_y, θ_z rotation). The acceptance angle was set at 17.5-34 degrees (total 288 mrad) in the horizontal direction. The vertical angle was set at ±40 mrad to collect the widely expanded THz-CSR.

The beamline is equipped with a Martin-Puplett type interferometer (JASCO FARIS-1) to cover the THz spectral region from 4 to 240 cm^{-1} (*hv* = 500 µeV-30 meV). There is a reflection/absorption spectroscopy (RAS) end-station for large samples (~ several mm). At the RAS end-station, a liquid-helium-flow type cryostat with a minimum temperature of 4 K is installed.

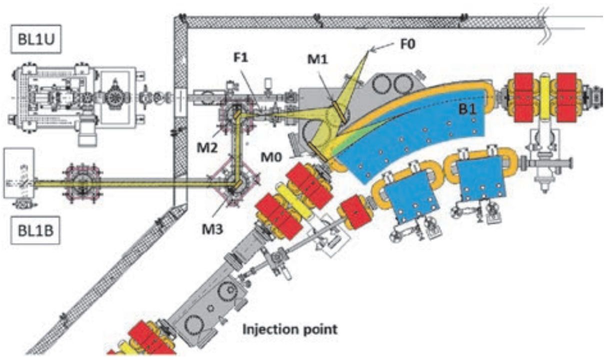


Fig. 1. Schematic top view of the beam extraction part of the THz-CSR beamline, BL1B. The three-dimensional magic mirror (3D-MM, M0) and a plane mirror (M1) are located in the bending-magnet chamber. A parabolic mirror (M2) is installed to form a parallel beam. The straight section (BL1U) is used for coherent harmonic generation (CHG) in the VUV region.

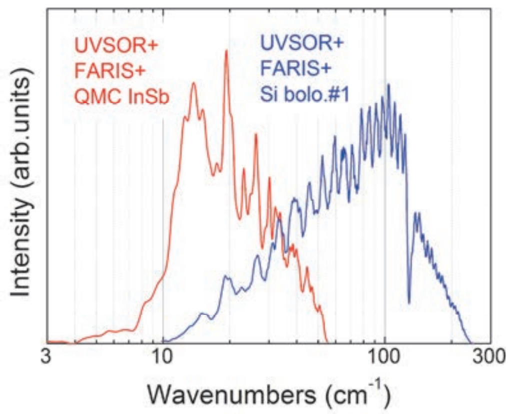


Fig. 2. Obtained intensity spectra with the combination of a light source (UVSOR), interferometer (FARIS-1), and detectors (Si bolometer and InSb hot-electron bolometer).

▼Technical Data

Interferometer	Martin-Puplett (JASCO FARIS-1)
Wavenumber range (Energy range)	4-240 cm^{-1} (500 µeV-30 meV)
Resolution in cm^{-1}	0.25 cm^{-1}
Experiments	Reflection/transmission spectroscopy
Miscellaneous	Users can use their experimental system in this beamline.

BL2A

Soft X-Ray Beamline for Photoabsorption Spectroscopy

▼Description

BL2A is a soft X-ray beamline for photoabsorption spectroscopy. The beamline is equipped with a pre-focusing mirror and a double-crystal monochromator [1]. The monochromator serves soft X-rays in the energy region from 585 to 4000 eV using several types of single crystals, such as beryl, KTP ($KTiOPO_4$), and InSb. The throughput spectra measured using a Si photodiode (AXUV-100, IRD Inc.) are shown in Fig. 1. The typical energy resolution (E / ΔE) of the monochromator is approximately 1500 for beryl and InSb.

There is a small vacuum chamber equipped with an electron multiplier (EM) detector. Photoabsorption spectra for powdery samples are usually measured in total electron yield mode, with the use of the EM detector. In addition, a hemispherical electron analyzer for photoelectron spectroscopy is equipped.

Recently, a new omnidirectional photoelectron acceptance lens (OPAL) has been developed aiming to realize 2π-steradian photoelectron spectroscopy and photoelectron holography [2]. By combining OPAL and the existing hemispherical electron analyzer, a photoelectron spectrometer with high energy resolution can be realized, and a full range (±90°) 1D angular distribution can be measured at once. This upgrade is currently in the commissioning phase.

[1] Hiraya *et al.*, Rev. Sci. Instrum. **63** (1992) 1264.
[2] H. Matsuda and F. Matsui, Jpn. J. Appl. Phys. **59** (2020) 046503.

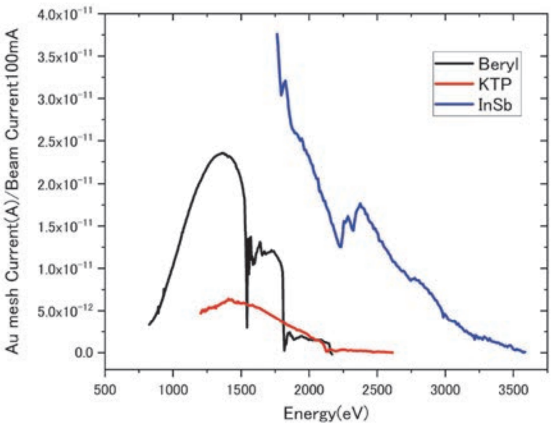


Fig. 1. Throughput spectra of the double-crystal monochromator at BL2A.

▼Technical Data

Monochromator	Double crystal monochromator
Monochromator crystals: (2d value, energy range)	beryl (15.965 Å, 826–2271 eV), KTP (10.95 Å, 1205–3310 eV), InSb (7.481 Å, 1764–4000 eV), Ge (6.532 Å, 2094–4000 eV)
Resolution	$E/\Delta E$ = 1500 for beryl and InSb
Experiments	Photoabsorption spectroscopy (total electron yield using EM and partial fluorescence yield using SDD)

II

BL3U

Varied-Line-Spacing Plane Grating Monochromator for Molecular Soft X-Ray Spectroscopy

▼Description

The beamline BL3U is equipped with an in-vacuum undulator composed of 50 periods of 3.8 cm period length. The emitted photons are monochromatized by the varied-line-spacing plane grating monochromator (VLS-PGM) designed for various spectroscopic investigations in the soft X-ray range. Three holographically ruled laminar profile plane gratings are designed to cover the photon energy range from 40 to 800 eV. The beamline has liquid cells for soft X-ray absorption spectroscopy (XAS) in transmission mode as shown in Fig. 1. The liquid cell is in the atmospheric helium condition, which is separated by a 100 nm thick Si_3N_4 membrane with the window size of 0.2 × 0.2 mm^2 from the beamline in an ultrahigh vacuum condition. The thin liquid layer is assembled by using two 100 nm thick Si_3N_4 membranes. The thickness of the liquid layer is controllable from 20 to 2000 nm by adjusting the helium pressures around the liquid cell in order to transmit soft X-rays. Liquid samples are exchangeable *in situ* by using a tubing pump. The liquid cell has two types of windows: one is the liquid part to obtain the soft X-ray transmission of liquid (I), and the other is the blank part to obtain the transmission without liquid (I_0). We can obtain the reliable XAS spectra based on the Lambert-Beer law $\ln(I_0/I)$. Since the liquid cell is in the atmospheric condition, we can measure XAS of liquid samples in the real environment. *Operando* XAS observation of several chemical reactions such as catalytic, electrochemical reactions are also possible by using our liquid cells developed for these purposes.

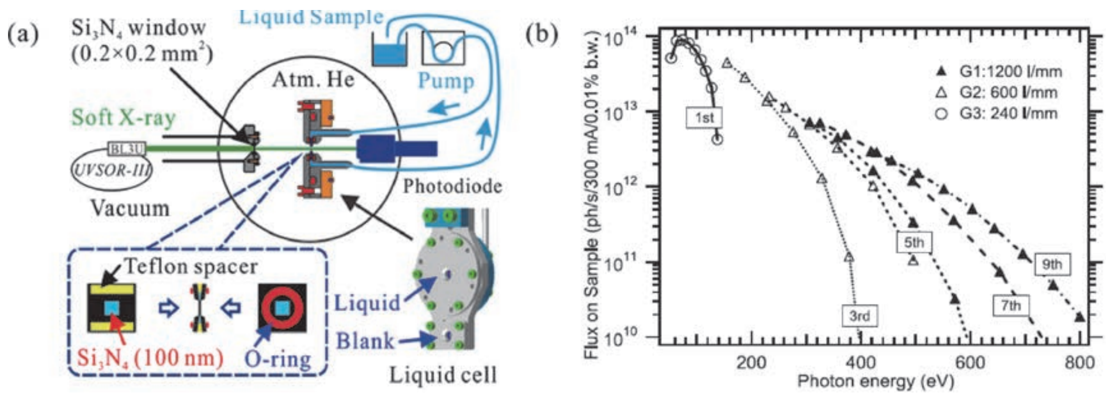


Fig. 1. (a) Schematics of a liquid cell for XAS in transmission mode settled in BL3U. The blowup shows a thin liquid layer assembled by two Si_3N_4 membranes with the thickness of 100 nm. (b) Flux at the sample position with the resolving power of $\lambda/\Delta\lambda=10^4$.

▼Technical Data

Monochromator	Varied-line-spacing plane grating monochromator
Energy Range	40-800 eV
Resolution	$E / \Delta E > 10\ 000$
Experiments	Soft X-ray absorption spectroscopy of liquid in transmission mode

BL3B (HOTRLU)

VIS-VUV Photoluminescence and Reflection/Absorption Spectroscopy

▼Description

BL3B has been constructed to study photoluminescence (PL) in the visible (VIS) to vacuum ultraviolet (VUV) region. This beamline consists of a 2.5 m off-plane Eagle type normal-incidence monochromator, which covers the VUV, UV, and VIS regions, i.e., the energy (wavelength) region of 1.7-31 eV (40-730 nm), with three spherical gratings having constant grooving densities of 1200, 600, and 300 l/mm optimized at the photon energies of ~20, ~16, and ~6 eV, respectively. The schematic side view and top view layouts are shown in Figs. 1(a) and 1(b), respectively. The FWHM of the beam spot at the sample position is 0.25 mm (V) × 0.75 mm (H). Low energy pass filters (LiF, quartz, WG32, OG53) can be inserted automatically to maintain the optical purity in the G3 (300 l/mm) grating region (1.7~11.8 eV). Figure 2 shows the throughput spectra (photon numbers at a beam current of 300 mA) for each grating with entrance and exit slit openings of 0.1 mm (resolving power $E / \Delta E$ of ~2000 (G3, ~6.8 eV)). Since both slits can be opened up to 0.5 mm, a monochromatized photon flux of 10^{10} photons/s or higher is available for PL measurements in the whole energy region.

The end station is equipped with a liquid-helium-flow type cryostat for sample cooling and two detectors; one of which is a photomultiplier with sodium salicylate and the other a Si photodiode for reflection/absorption measurement. For the PL measurements in the wide energy region from VIS to VUV, two PL monochromators, comprising not only a conventional VIS monochromator but also a VUV monochromator with a CCD detector, are installed at the end station.

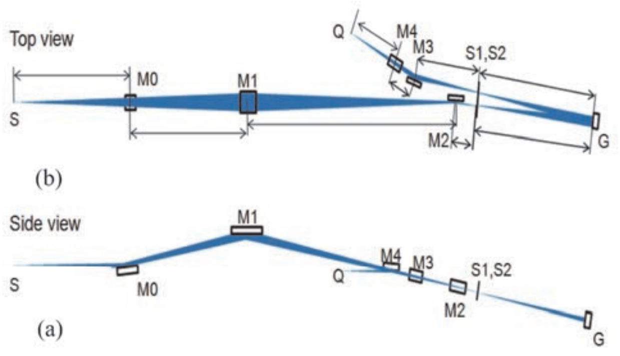


Fig. 1. Schematic layout of the BL3B (a) side view and (b) top view.

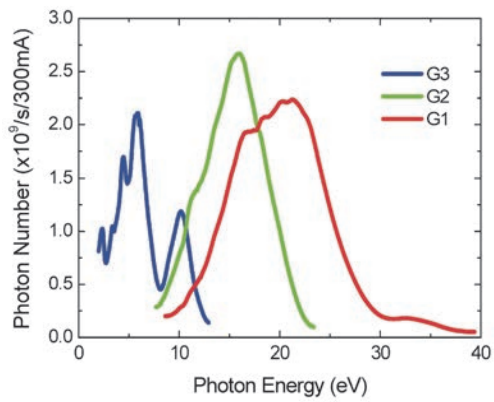


Fig. 2. Throughput spectra for each grating (G1:1200 l/mm, G2:600 l/mm and G3:300 l/mm) with S1 = S2 = 0.1 mm.

▼Technical Data

Monochromator	2.5 m normal-incidence monochromator
Energy range	1.7-31 eV (40~730 nm)
Resolution ($\Delta h\nu / h\nu$)	≥12000 (at ~ 6.9 eV, 0.02 mm slits, G1 (1200 l/mm)
Experiments	Photoluminescence, reflection, and absorption spectroscopy, mainly for solids

II

BL4U
Scanning Transmission X-ray Microscopy in the Soft X-ray Region

▼Description

In the soft x-ray region, there are several absorption edges of light elements and transition metals. The near edge X-ray absorption fine structure (NEXAFS) brings detailed information about the chemical state of target elements. A scanning transmission X-ray microscope (STXM) in the soft X-ray region is a kind of extended technique of the NEXAFS with high spatial resolution. The STXM has a capability of several additional options, for example, *in-situ* observations, 3-dimensional observation by computed tomography and ptychography, by utilizing the characteristics of the X-rays. The STXM can be applied to several sciences, such as polymer science, material science, cell biology, environmental science, and so on.

This beamline equips an in-vacuum undulator, a varied-line-spacing plane grating monochromator and a fixed exit slit. The soft X-ray energy range from 50 to 770 eV with the resolving power ($E/\Delta E$) of 6,000 is available. The aperture size of the fixed exit slit determines not only the resolving power but also the size of a microprobe. A Fresnel zone plate is used as a focusing optical device through an order select aperture and its focal spot size of ~30 nm is available at minimum. An image is acquired by detecting intensities of the transmitted X-rays by a photomultiplier tube with scintillator with scanning a sample 2-dimensionally. By changing the energy of the incident beam, each 2-dimensional NEXAFS image is stacked. A main chamber of STXM is separated from the beamline optics by a silicon nitride membrane of 50-nm thickness; therefore, sample folders can be handled in vacuum or in helium.

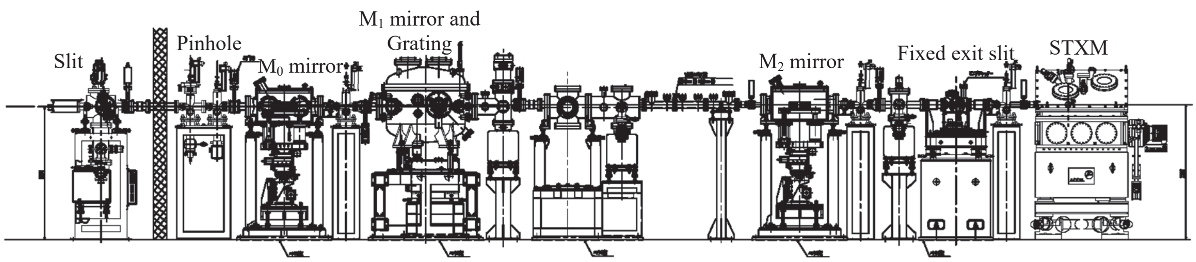


Fig. 1. Schematic image of BL4U.

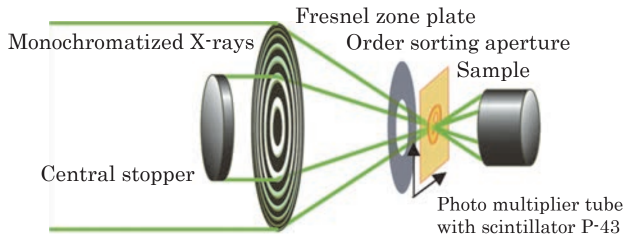


Fig. 2. Schematic image of STXM.

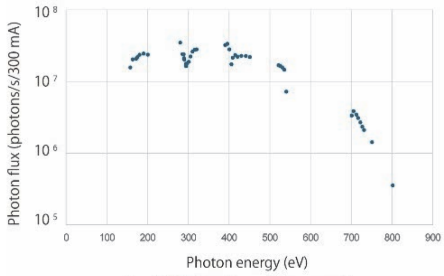


Fig. 3. Photon flux at the sample.

▼Technical Data

Energy range (E)	50 -770 eV
Resolving power ($E/\Delta E$)	~6,000
Photon flux on a sample (photons/s)	~2×10^7 @400 eV
Focusing optical element	Fresnel zone plate
Spatial resolution	~30 nm
Experiments	2-dimensional absorption spectroscopy
Measurement environment	Standard sample folder in vacuum or in helium, specially designed sample cell in ambient condition

BL4B

Varied-Line-Spacing Plane Grating Monochromator for Molecular Soft X-Ray Spectroscopy

▼Description

The beamline BL4B equipped with a varied-line-spacing plane grating monochromator (VLS-PGM) was constructed for various spectroscopic investigations in a gas phase and/or on solids in the soft X-ray range. Three holographically ruled laminar profile plane gratings with SiO_2 substrates are designed to cover the photon energy range from 25 to 1000 eV. The gratings with groove densities of 100, 267, and 800 l/mm cover the spectral ranges of 25–100, 60–300, and 200-1000 eV, respectively, and are interchangeable without breaking the vacuum. Figure 1 shows the absolute photon flux for each grating measured using a Si photodiode (IRD Inc.), with the entrance- and exit-slit openings set at 50 and 50 µm, respectively. The maximum resolving power (E/ΔE) achieved for each grating exceeds 5000.

By switching spectrometers at the end station, XAFS, XMCD and ARPES measurements are mainly carried out. Taking advantage of the low photon flux and low electric noise environment, XAFS and ARPES measurements are performed for fragile materials such as organic molecules and polymers.

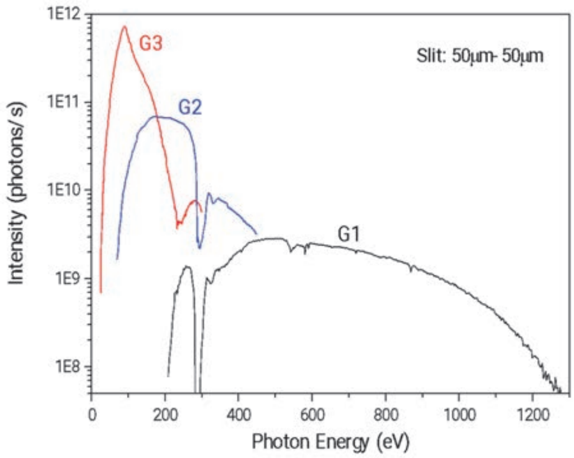


Fig. 1. Throughput from the VLS-PGM monochromator on BL4B.

Fig. 2. Photo of BL4B.

▼Technical Data

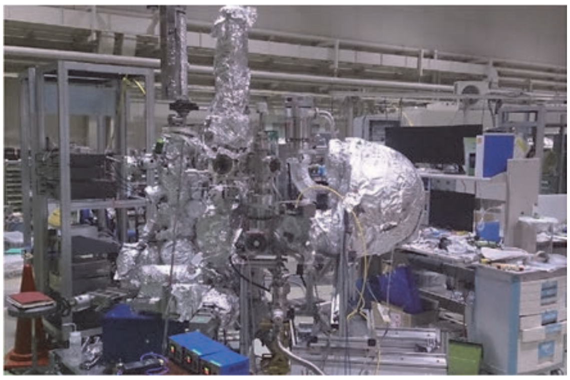
Monochromator	Varied-line-spacing Plane Grating Monochromator
Energy range	25-1000 eV
Resolution	$E / \Delta E > 5000$ (at maximum)
Experiments	X-ray absorption fine structure spectroscopy (XAFS) X-ray magnetic circular dichroism spectroscopy (XMCD) Angle-resolved photoemission spectroscopy (ARPES)

BL5U

Photoemission Spectroscopy of Solids and Surfaces

▼Description

Since the monochromator of BL5U was an old-style spherical grating type SGMTRAIN constructed in 1990s and the throughput intensity and energy resolution were poor, the whole beamline has been replaced to state-of-the-art monochromator and end station. The new beamline has been opened to users from FY2016 as high-energy resolution ARPES beamline. Samples can be cooled down to 3.8 K with newly developed 5-axis manipulator to perform high energy resolution measurements. Users can also obtain spatial-dependence of the electronic structure of solids using micro-focused beam (~ 50 µm). The new electron lens system makes it possible to obtain ARPES spectra without moving samples. This beamline will also have new capability to perform high-efficient spin-resolved ARPES in the future.



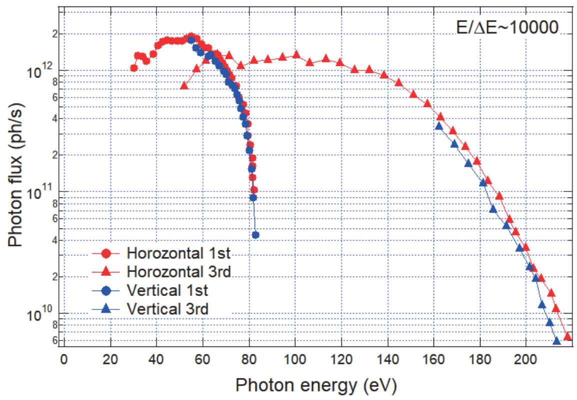


Fig. 1. Picture and photon flux of BL5U.

▼Technical Data (Expected Performance)

Light source	APPLE-II type undulator (λ_u = 60 mm, N = 38) vertical/horizontal, right/left circular (depending on *hν*)
Monochromator	Monk-Gillieson VLS-PGM
Energy Range	20-200 eV
Resolution	*hν*/ Δ*E* > 10,000 for < 10 µm slits
Experiment	ARPES, Space-resolved ARPES, Spin-resolved ARPES
Flux	<10^{12} photons/s for <10 µm slits (at the sample position)
Beam spot size	23 (H) x 40 (V) µm
Main Instruments	Hemispherical photoelectron analyzer with deflector scan (MBS A-1 Lens#4), Liq-He flow cryostat with 5-axis manipulator (3.8 K-350 K)

BL5B

Calibration Apparatus for Optical Elements and Detectors

▼Description

BL5B has been constructed to perform calibration measurements for optical elements and detectors. This beamline is composed of a plane grating monochromator (PGM) and three endstations in tandem. The most upstream station is used for the calibration measurements of optical elements, the middle one for optical measurements for solids, and the last for photo-stimulated desorption experiments. The experimental chamber at the most downstream station is sometimes changed to a chamber for photoemission spectroscopy. The calibration chamber shown in Fig. 2 is equipped with a goniometer for the characterization of optical elements, which has six degrees of freedom, X-Y translation of a sample, and interchanging of samples and filters. These are driven by pulse motors in vacuum. Because the polarization of synchrotron radiation is essential for such measurements, the rotation axis can be made in either the horizontal or vertical direction (s- or p-polarization).

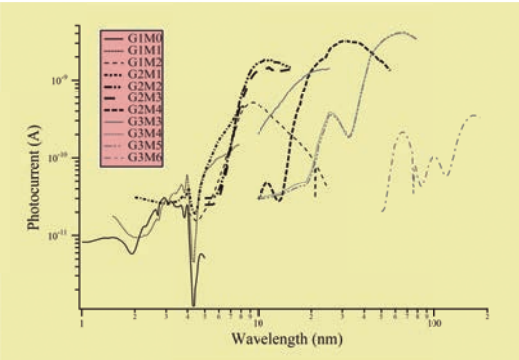


Fig. 1. Throughput spectra for possible combinations of gratings and mirrors at BL5B measured by a gold mesh.

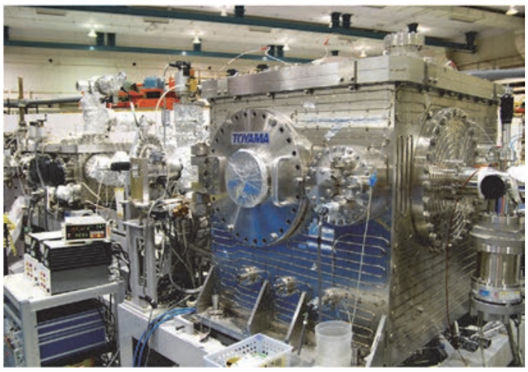


Fig. 2. A side view of the experimental chamber for calibration measurements.

▼Technical Data

Monochromator	Plane Grating Monochromator
Energy range	6-600 eV (2-200 nm)
Resolution	$E / \Delta E$ ~500
Experiments	Calibration of optical elements, reflection and absorption spectroscopy mainly for solids

II

BL6U

Variable-Included-Angle / Variable-Line-Spacing Plane Grating Monochromator for Soft X-Ray photoelectron Spectroscopy

▼Description

The beamline BL6U equipped with a variable-included-angle Monk-Gillieson mounting monochromator with a varied-line-spacing plane grating was constructed for various spectroscopic investigations requiring high-brilliance soft X-rays on solid surfaces. Through a combination of undulator radiation and sophisticated monochromator design (entrance slit-less configuration and variable-included-angle mechanism), using a single grating, the monochromator can cover the photon energy ranging from 40 to 500 eV, with resolving power of greater than 10000 and photon flux of more than 10^{10} photons/s. Figure 1 shows an example of the monochromator throughput spectra measured using a Si photodiode, with the exit-slit opening set at 30 μm, which corresponds to the theoretical resolving power of 10000 at 80 eV.

A new Momentum Microscope experimental station for photoelectron spectroscopy resolved in 3D momentum space with a microscopic field of view has been built at BL6U (SPECS KREIOS 150 MM). A momentum resolution of 0.01 Å^{-1} in $\boldsymbol{k}_x/\boldsymbol{k}_y$ as well as $\boldsymbol{k}_z$ is achieved. A spatial resolution of 50 nm, an energy resolution of 20 meV at 9 K, and a field of view of 2 μm for ARPES are successfully demonstrated. This experimental station specializes in characterizing the electronic structure of surface atomic sites, thin films, molecular adsorbates, and bulk crystals. This method opens the door to direct observation of the Fermi surface of μm-sized crystals, which was difficult with conventional ARPES-type hemispherical analyzers.

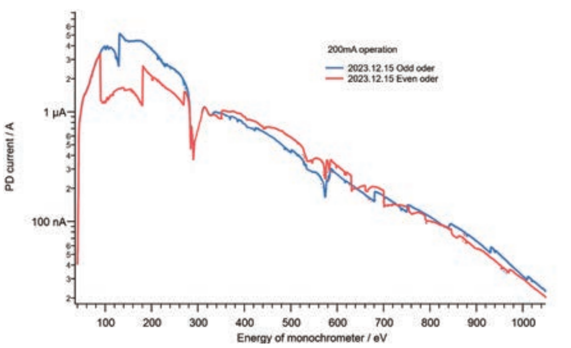


Fig. 1. Photodiode current after the BL6U monochromator versus photon energy.

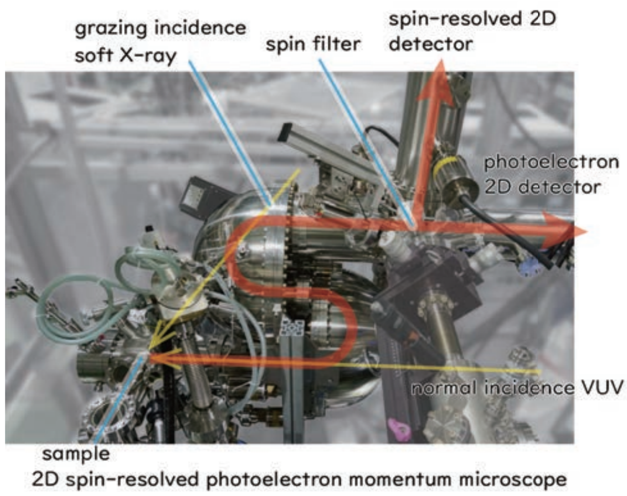


Fig. 2. Photograph of BL6U end station.

▼Technical Data

Monochromator	Variable-included-angle Varied-line-spacing Plane Grating Monochromator
Energy range	40-500 eV(practical)
Resolution	$E / \Delta E$ > 10000 (at maximum)
Experiments	High-resolution soft X-ray spectroscopy (photoelectron spectroscopy for solid surfaces)

BL6B

Infrared and Terahertz Spectroscopy of Solids

▼Description

Synchrotron radiation (SR) has good performance (high brilliance and high flux) not only in the VUV and soft X-ray (SX) regions but also in the infrared (IR) and THz regions. BL6B covers the IR and THz regions. The previous beamline, BL6A1, which was constructed in 1985, was the pioneer in IRSR research. The beamline was deactivated at the end of FY2003 and a new IR/THz beamline, BL6B (IR), was constructed in FY2004. The front-end part including bending duct #6 was replaced with a new part having a higher acceptance angle (215 (H) × 80 (V) mrad^2) using a magic mirror, as shown in Fig. 1.

There are two Michelson type interferometers in this endstation; with first one (Bruker Vertex70v), which covers a wide spectral region from 30 to 20,000 cm^{-1} ($h\nu$ = 4 meV-2.5 eV), reflection/absorption spectroscopy measurements of large samples (up to several mm) and IR/THz microscopy measurements of tiny samples (up to several tens of μm) can be performed. For reflection/absorption spectroscopy measurements, a liquid-helium- flow type cryostat with a minimum temperature of 4 K is installed. The other interferometer (Jasco FT/IR-6100), which covers 350 to 15,000 cm^{-1} ($h\nu$ = 45 meV-1.8 eV), has been available for IR microscopy imaging measurements from FY2014. One can also perform ATR measurements using diamond ATR prism.

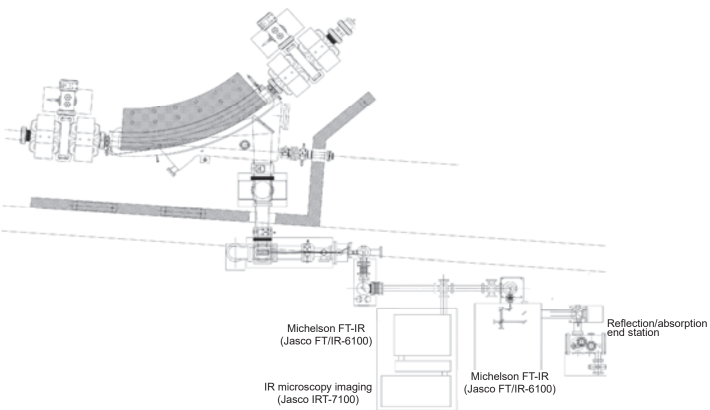


Fig. 1. Schematic top view of BL6B.

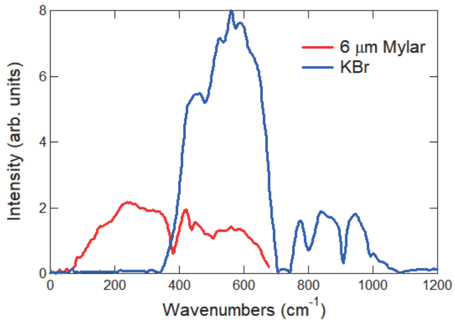


Fig. 2. Obtained intensity spectra with the combination of a light source (UVSOR), detector (Si bolometer), and interferometer (Bruker Vertex70v) with different beamsplitters (6 μm Mylar and KBr) . (Only low energy side is shown).

▼Technical Data

Interferometer	Michelson (Bruker Vertex70v)	Michelson (Jasco FT/IR-6100)
Wavenumber Range (Energy range)	30-20,000 cm^{-1} (4 meV-2.5 eV)	350-15,000 cm^{-1} (45 meV-1.8 eV)
Resolution in cm^{-1}	0.1 cm^{-1}	0.5 cm^{-1}
Experiments	Reflectivity and transmission spectroscopy THz Microspectroscopy	IR microscopy imaging (JASCO IRT-7000) ATR spectroscopy

BL7U (SAMRAI)

Angle-Resolved Photoemission of Solids in the VUV Region

▼Description

Beamline 7U, named the Symmetry- And Momentum-Resolved electronic structure Analysis Instrument (SAMRAI) for functional materials, was constructed to provide a photon flux with high energy resolution and high flux mainly for high-resolution angle-resolved photoemission spectroscopy, so-called "ARPES", of solids [1]. An APPLE-II-type variable-polarization undulator is installed as the light source. The undulator can produce intense VUV light with horizontal/vertical linear and right/left circular polarization. The undulator light is monochromatized by a modified Wadsworth type monochromator with three gratings (10 m radius; 1200, 2400, and 3600 lines/mm optimized at $h\nu$ = 10, 20, and 33 eV). The energy resolution of the light ($h\nu/\Delta h\nu$) is more than 10^4 with a photon flux of 10^{11}-10^{12} ph/s or higher on samples in the entire energy region. The beamline has a photoemission end-station equipped with a 200 mm-radius hemispherical photoelectron analyzer (MB Scientific AB, A-l analyzer) with a wide-angle electron lens and a liquid-helium-cooled cryostat with 6-axis pulse motor control. The main function of the beamline is to determine the electronic structure of solids and its temperature dependence in order to reveal the origin of their physical properties.

[1] S. Kimura *et al*., Rev. Sci. Instrum. **81** (2010) 053104.

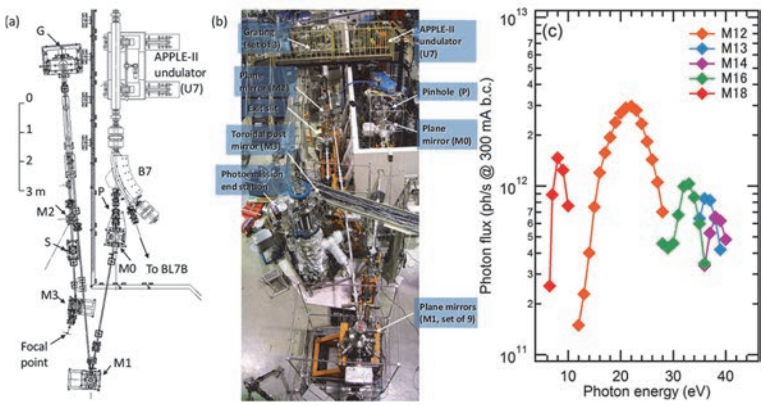


Fig. 1. SAMRAI beamline [(a), (b)] consisting of an APPLE-II type undulator (U7), a modified Wadsworth type monochromator (M0-S), and a high-resolution photoemission analyzer at the focal point. The monochromator has five major optical components: two plane mirrors (M0 and M1) with water cooling, one set of three spherical gratings (G), an exit slit (S), and one toroidal refocusing mirror (M3). (c) Example of flux intensity *versus* photon energy [1].

▼Technical Data

Light source	APPLE-II type undulator (λ_u = 76 mm, N = 36) vertical/horizontal, right/left circular (depending on $h\nu$)
Monochromator	10 m normal-incidence monochromator (modified Wadsworth type)
Photon energy range	6 – 40 eV (λ = 30 – 200 nm)
Resolution ($h\nu/\Delta h\nu$)	E / ΔE > 10000-50000
Photon flux on sample	≥ 10^{11}-10^{12} ph/s (depending on $h\nu$)
Beam size on sample	200 (H) × 50 (V) μm^2
Experiments	Angle-resolved photoemission of solids (MV Scientific A-1 analyzer, acceptance angle: ± 18 deg)

BL7B

3 m Normal-Incidence Monochromator for Solid-State Spectroscopy

▼Description

BL7B has been constructed to provide sufficiently high resolution for conventional solid-state spectroscopy, sufficient intensity for luminescence measurements, wide wavelength coverage for Kramers–Kronig analyses, and minimum deformation to the polarization characteristic of incident synchrotron radiation. This beamline consists of a 3-m normal incidence monochromator, which covers the vacuum ultraviolet, ultraviolet, visible, and infrared, i.e., the wavelength region of 50–1000 nm, with three gratings (1200, 600, and 300 l/mm). Two interchangeable refocusing mirrors provide two different focusing positions. For the mirror with the longer focal length, an LiF or a MgF_2 window valve can be installed between the end valve of the beamline and the focusing position. Figure 1 shows the absolute photon intensity for each grating with the entrance and exit slit openings of 0.5 mm. A silicon photodiode (AXUV-100, IRD Inc.) was utilized to measure the photon intensity and the absolute photon flux was estimated, taking the quantum efficiency of the photodiode into account.

The cooling system for the pre-focusing mirror has been removed, resulting in longer beam settling times. Currently, BL7B is opened during single bunch mode, but limited use is possible during multi bunch mode.

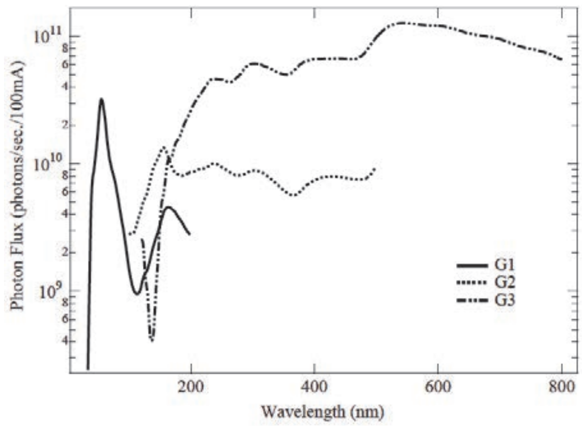


Fig. 1. Throughput spectra of BL7B measured using a silicon photodiode.

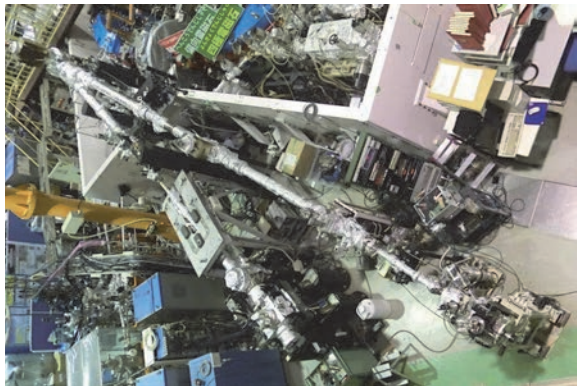


Fig. 2. Photo of BL7B.

▼Technical Data

Monochromator	3 m Normal-Incidence Monochromator
Wavelength Range	50-1000 nm (1.2-25 eV)
Resolution	$E / \Delta E$ = 4000-8000 for 0.01 mm slits
Experiments	Absorption, reflection, and fluorescence spectroscopy, mainly for solids

UVSOR User 5