II

Current Status of Light Sources and Beamlines

Light Source in 2020

1. Status of UVSOR Accelerators

In the fiscal year 2020, we had scheduled to operate UVSOR-III from May to March, for 36 weeks for users. Because of the COVID-19 pandemic, some of the users experiments were canceled. However, we operated the accelerators as scheduled. We had a few minor machine troubles, such as a discharge of the electron gun, malfunction of the cooling water system for the RF cavity, unstable operation of the klystron pulse modulator of the injection linac and unstable operation of the timing system. Fortunately, all of them could be solved quickly and we extended the operation time and compensated the scheduled users beam time.

We had a scheduled shutdown period in April for 4 weeks. This was for the scheduled maintenance works as usual. In addition, this year, we replaced the coils of one third of the multipole magnets as described later. We had one week shut down period in August and October, two week one around the New Year's Day and one week one at the end of March. We had 2 weeks for machine and beamline conditioning in May after the spring shut down. We had 4 weeks for machine conditionings and studies. One of them in November was mainly for the machine conditioning after the annual planned power outage.

We operated the machine for 34 weeks in the multi-bunch top-up mode at 300 mA, and 2 weeks in the single-bunch top-up mode at approximately 40 mA. The monthly statistics of the operation time and the integrated beam current are shown in Fig. 1.

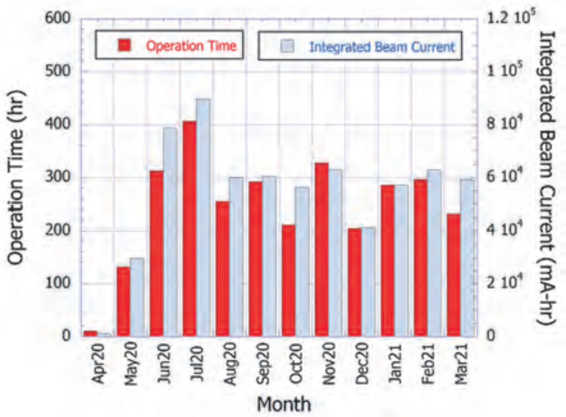


Fig. 1. Monthly statistics in FY2020.

The weekly operation schedule is as follows. On Monday, from 9 am to 9 pm, the machine is operated for machine conditionings and studies. On Tuesday and Wednesday, from 9 am to 9 pm, the machine is operated for users. From Thursday 9 am to Friday 9 pm, the machine is operated for 36 hours continuously for users. Therefore, the beam time for users in a week is 60 hours. In the single bunch operation weeks, the machine is operated for 12 hours per day from Tuesday to Friday.

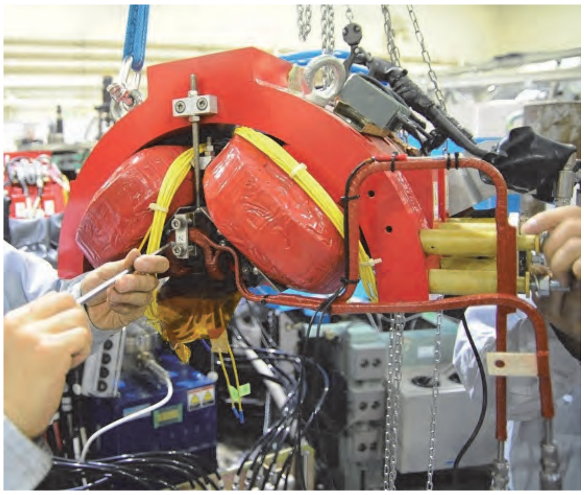


Fig. 2. Replacing sextupole coil for multipole magnets.

2. Improvements and Developments

The cooling water leakage from the sextupole coils wound on the pole faces of the multipole (quadrupole/sextupole) magnets had been getting more frequent. We confirmed that the hollow conductor walls have been eroded by the water flow during the fifteen-year operation. We decided replacing all the coils and, in March, 2020, we replaced the one-third of the coils. The remainder will be replaced in April, 2021.

We started a design study for the future plan of UVSOR, UVSOR-IV. As its first step, we have analyzed the present magnetic lattice, seeking a possibility to reduce the emittance more [1]. Although, we did not find a drastically low emittance solution, we have found a few interesting solutions which may be useful for some machine studies which requires lower emittance as possible.

We continue the efforts to develop novel light sources technologies and their applications such as free electron lasers, coherent harmonic generation, coherent synchrotron radiation, laser Compton scattering gamma-rays, intense polarized and vortex UV radiation at the source development station BL1U, which was constructed under the support of Quantum Beam Technology Program by MEXT/JST.

In these years, we are focusing on studying the temporal structure of undulator radiation and exploring its application. In collaboration with atomic physicists, we have successfully demonstrated ultrafast spectroscopy with undulator radiation [2] and polarization utilization of tandem undulator radiation [3].

Laser Compton gamma-ray source is another research subject which we are focusing in these years. The applications are spreading to a range of research fields, quantum electrodynamics, imaging technologies, material sciences and so on [4,5]. The research activity at the gamma-ray source is now shifting from source development studies to users experiments.

We have been collaborating with Nagoya University on the electron source development. In these years, we investigated utilizing graphene as a material for photocathode [6].

[1] E. Salehi and M. Katoh, presented at iPAC2021 (2021).
[2] T. Kaneyasu *et al*., Physical Review Letters **126**(11) (2021) 1132202.
[3] T. Kaneyasu *et al*., New J. Phys. **22**(8) (2020) 083062.
[4] K. Ali *et al*., IEEE Trans. Nucl. Sci. **67**(8) (2020) 1976.
[5] K Fujimori *et al*., Appl. Phys. Express **13**(8) (2020) 085505.
[6] L Guo *et al*., Appl. Phys. Lett. **116**(25) (2020) 251903

Masahiro KATOH (UVSOR Synchrotron)

UVSOR Accelerator Complex

Injection Linear Accelerator

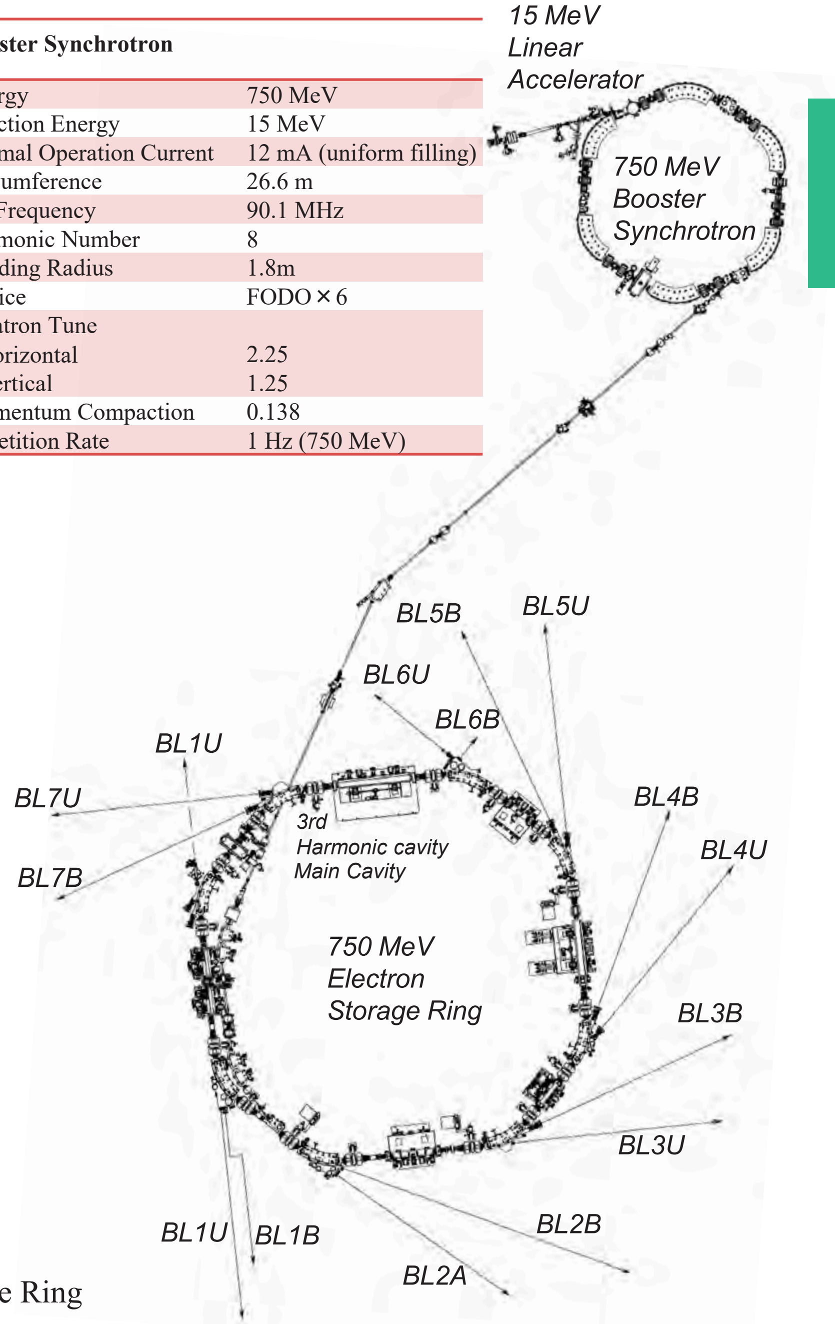
Energy	15 MeV
Length	2.5 m
Frequency	2856 MHz
Accelerating RF Field	2π/3 Traveling Wave
Klystron Power	1.8 MW
Energy Spread	~1.6 MeV
Repetition Rate	2.6 Hz

UVSOR-III Storage-Ring

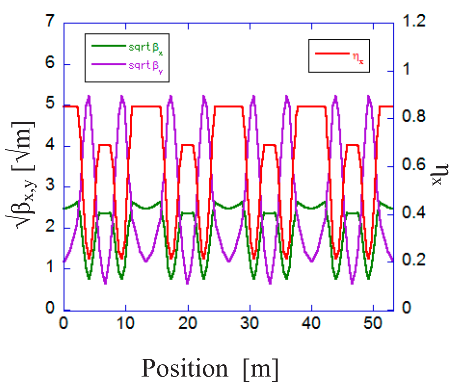
Energy	750 MeV
Injection Energy	750 MeV
Maximum Storage Current	500 mA (multi bunch)
	100 mA (single bunch)
Normal operation current	300 mA (multi bunch)
(Top-up mode)	50 mA (single bunch)
Natural Emittance	17.5 nm-rad
Circumference	53.2 m
RF Frequency	90.1 MHz
Harmonic Number	16
Bending Radius	2.2 m
Lattice	Extended DB × 4
Straight Section	(4 m × 4)+(1.5 m × 4)
RF Voltage	120 kV
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

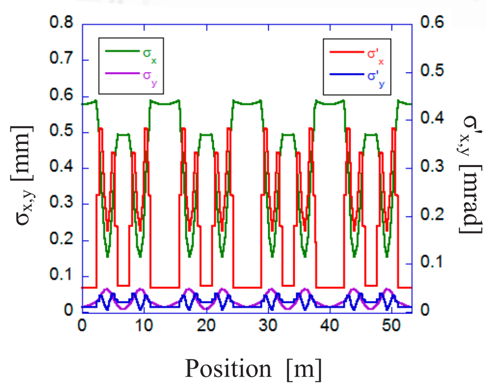
Energy	750 MeV
Injection Energy	15 MeV
Normal Operation Current	12 mA (uniform filling)
Circumference	26.6 m
RF Frequency	90.1 MHz
Harmonic Number	8
Bending Radius	1.8m
Lattice	FODO × 6
Betatron Tune	
Horizontal	2.25
Vertical	1.25
Momentum Compaction	0.138
Repetition Rate	1 Hz (750 MeV)



Electron Beam Optics of UVSOR-III Storage Ring

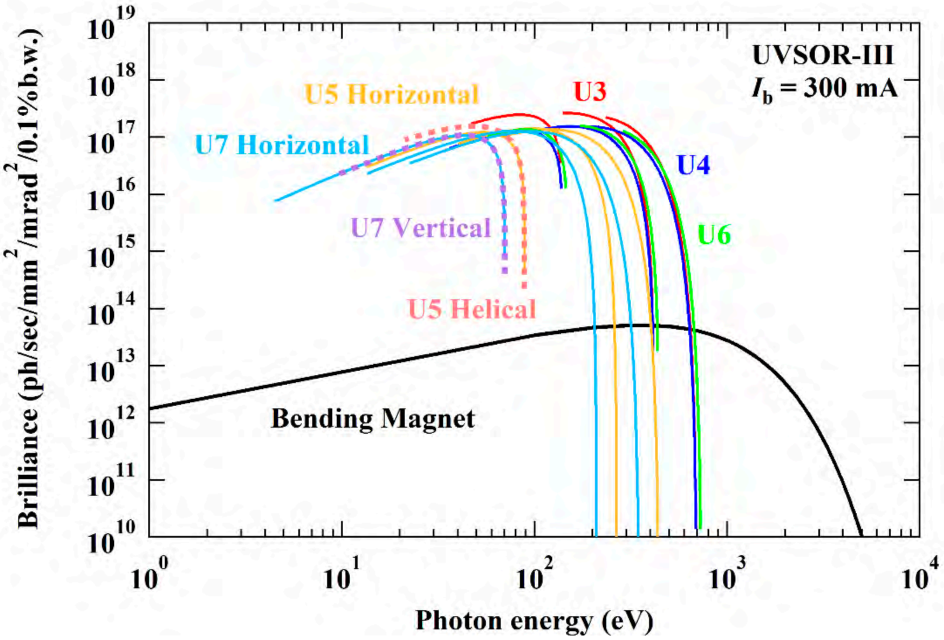


Horizontal/vertical betatron functions and dispersion function



Horizontal/vertical electron beam size and beam divergences

Insertion Device



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. Herical)

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

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	36 mm
Pole Length	0.94 m
Pole Gap	13-40 mm
Deflection Parameter	1.78 - 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)

Bending Magnets

Bending Radius	2.2 m
Critical Energy	425 eV

Beamlines in 2020

Yoshitaka TAIRA
UVSOR synchrotron Facility, Institute for Molecular Science

UVSOR is one of the highest-brilliance light sources in the extreme-ultraviolet region among the synchrotron radiation facilities with electron energies of less than 1 GeV. The natural emittance of the UVSOR-III storage ring is as low as 17.5 nm-rad after the successful completion of the storage ring upgrade project (the UVSOR-III project) in 2012.

Eight bending magnets and six insertion devices are available as synchrotron light sources at UVSOR. As of 2018 there are a total of fourteen operational beamlines, which are classified into two categories. Twelve of them are the so-called "Open beamlines", which are open to scientists from universities and research institutes belonging to the government, public organizations, private enterprises and also those from foreign countries. The remaining two beamlines are the "In-house beamlines", and are dedicated to the use of research groups within Institute for Molecular Science (IMS).

There is one soft X-ray station equipped with a double-crystal monochromator, seven extreme ultraviolet and soft X-ray stations with grazing incidence monochromators, three vacuum ultraviolet (VUV) stations with normal incidence monochromators, two infrared (IR) stations equipped with Fourier-Transform interferometers, and one direct radiation station located after two tandem undulators, as shown in the appended table (next page) for all available beamlines at UVSOR in 2020. The details of the updates for several beamlines are the followings.

A new associate professor, Yoshitaka Taira, was appointed in April 2020. He is in charge of BL1U. In BL1U, the development of a new light source and the utilization of gamma-rays is being carried out. Gamma-ray induced positron annihilation spectroscopy, which can analyze nanometer scale defects in bulk materials, is provided to users. Array detectors using eight BaF_2 scintillators were developed to increase the count rate of annihilation gamma-rays. The measurement can be completed in a few hours for metals.

BL4U, which is equipped with a scanning transmission soft X-ray microscope (STXM), is actively used not only by academic users but also by many industrial users. In FY2020, it became possible to image the lithium K-edge with a spatial resolution of 72 nm. Final adjustments for the airtight sample transport system and the sample transport container are being carried out in preparation for the organic substance analysis of the Hayabusa2 returned samples scheduled for the summer of FY2021.

At BL6U, one of the in-house beamlines, photoelectron momentum microscope (PMM), which is a new high-efficiency electronic structure measurement system with high resolution in real space and momentum space, has been installed and is in operation. Experiments such as valence band photoelectron spectroscopy on the micrometer scale and resonance photoelectron diffraction by soft X-ray excitation can be performed. In FY2020, resonant photoelectron spectroscopy of graphenes, high-temperature superconductors, dichalcogenides, and organic molecular adsorbates were conducted in collaboration with several groups.

Next generation spectro-microscopy and micro-spectroscopy workshop, involving BL4U and 6U, was held on October 28-29, 2020 (https://sites.google.com/ims.ac.jp/uvsor-ws2020/ home?authuser=0).

In BL5U, high energy resolution angle-resolved photoemission spectroscopy (ARPES) is available. Users can now use so-called "deflector mapping" for all kinetic energies and lens modes by using the latest version of ARPES analyzer. A system that can deposit alkali metals such as potassium while the sample is still mounted on the manipulator at low temperatures has been installed. As part of the development of spin-resolved ARPES, a two-dimensional image of the spin-resolved spectrum of the Rashba splitting of gold (111) surface has been successfully obtained.

Those wishing to use the open and in-house beamlines are recommended to contact the appropriate beamline master (see next page). Applications can be submitted at NOUS (https:// nous.nins.jp/user/signin). All users are required to refer to the beamline manuals and the UVSOR guidebook, on the occasion of conducting the actual experimental procedures. For updated information on UVSOR, please see http://www. uvsor.ims.ac.jp.

Beamlines at UVSOR

Beamline	Monochromator / Spectrometer	Energy Range	Targets	Techniques	Contact
BL1U	Free electron laser, Tandem undulator, LSC Gamma-rays	1.6 – 13.9 eV, 1-10MeV		(Irradiation)	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	585 – 4 keV	Solid	Reflection Absorption	K. Tanaka k-tanaka@ims.ac.jp
BL2B	18-m spherical grating (Dragon)	24 – 205 eV	Solid	Photoemission	S. Kera kera@ims.ac.jp
BL3U	Varied-line-spacing plane grating (Monk-Gillieson)	60 – 800 eV	Gas Liquid Solid	Absorption Photoemission Photon-emission	M. Nagasaka nagasaka@ims.ac.jp
BL3B	2.5-m off-plane Eagle	1.7 – 30 eV	Solid	Reflection Absorption Photon-emission	K. Tanaka k-tanaka@ims.ac.jp
BL4U	Varied-line-spacing plane grating (Monk-Gillieson)	50 – 770 eV	Gas Liquid Solid	Absorption (Microscopy)	T. Ohigashi ohigashi@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	Spherical grating (SGM-TRAIN†)	5 – 250 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	30 – 500 eV	Gas Solid	Photoionization Photodissociation Photoemission	F. Matsui matui@ims.ac.jp
BL6B	Michelson FT-IR	3 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	S. Ideta idetas@ims.ac.jp
BL7B	3-m normal incidence	1.2 – 25 eV	Solid	Reflection Absorption Photon-emission	K. Tanaka k-tanaka@ims.ac.jp

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

Countermeasures against COVID-19

Yoshitaka TAIRA
UVSOR synchrotron Facility, Institute for Molecular Science

In Japan, the first wave of covid-19 began at the end of March 2020, followed by the second wave in August and the third wave in January 2021. As a result, a state of emergency was declared twice, from April 7 to May 25, 2020, and from January 8 to March 21, 2021.

To avoid stagnation of research activities, UVSOR accepted users at all times after taking countermeasures to prevent the spread of infection. Users were asked to take and record their temperature two weeks before the start of the experiment. A non-contact thermometer was placed at the entrance of the user waiting room, as shown in the photo below, and users were asked to take and record their temperature and wear a mask every day. Chairs in the user waiting room were placed at intervals to ensure social distance (see photo below). By March 2021, no one has been infected from UVSOR.

In FY2020, all the first half-year proposals were copied and pasted into the second half-year proposals. The beam time allocated in the first half-year was still valid, and if uses were able to come to UVSOR according to the regulations of their institutions, users could carry out their experiments. New applications for beam time in the second half-year were suspended, and the remaining beam time was allocated to special calls for proposals as needed. UVSOR was able to accept users, but some proposals were canceled because the users could not travel due to the regulations of their institutions. The implementation rate of the proposals was 63 % in the first half-year and 86 % in the second half-year. There were five proposals that could not be implemented. Substitute measurements were conducted in 20 cases. The total number of visitors decreased by 23 % from the previous year to 2,806, due to a significant decrease in the number of domestic students and international visitors. We have started to examine technologies for automation, remoteness, AI analysis processing, and standardization.

BL1U

Light Source Development Station

II

▼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.

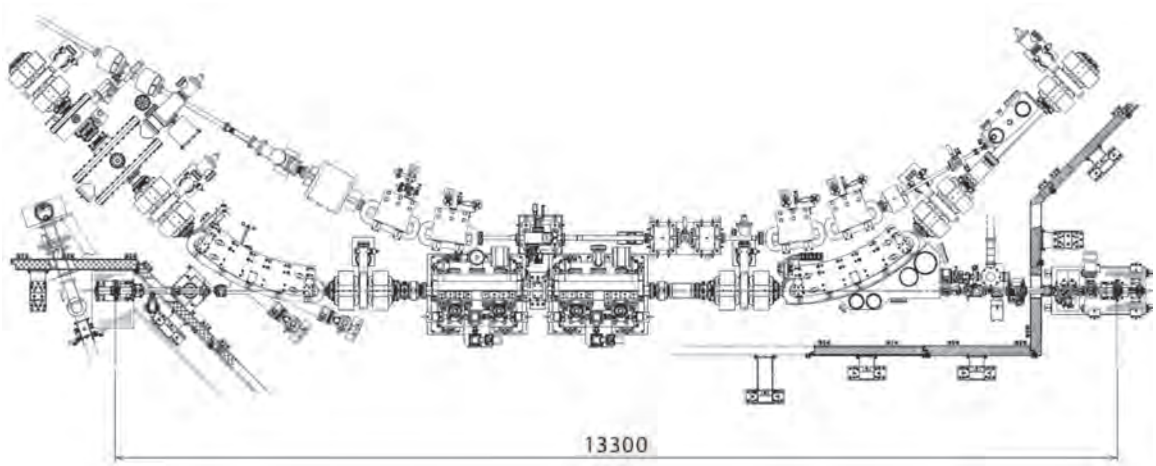


Fig. 1. Configuration of the free electron laser

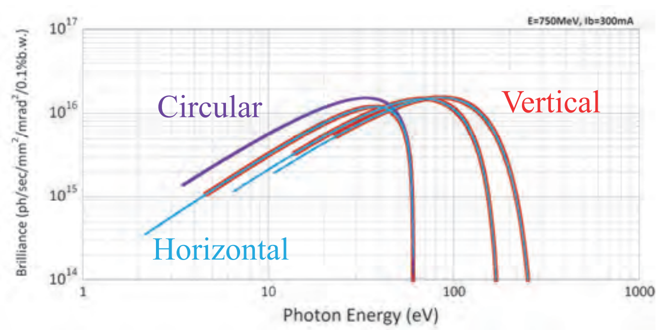


Fig. 2. Brilliance of BL1U Apple-II Undulator

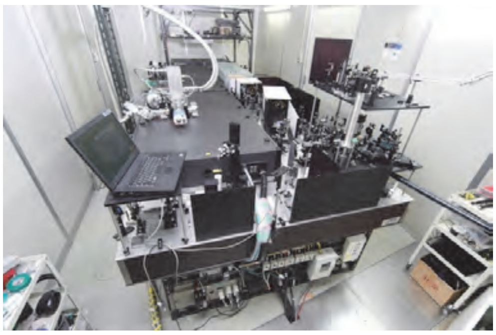


Fig. 3. Accelerator synchronized Laser System

▼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} ($h\nu$ = 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.

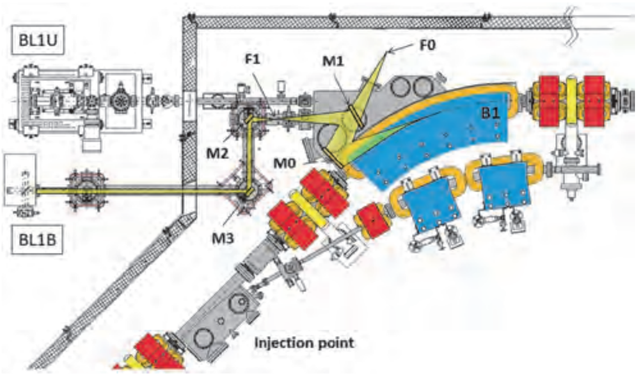


Fig. 1. Schematic top view of the beam extraction part of the THz-CSR beamline, BL1B. The three-dimensional magic mirror (3D-MM, M0) and a plane mirror (M1) are located in the bending-magnet chamber. A parabolic mirror (M2) is installed to form a parallel beam. The straight section (BL1U) is used for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

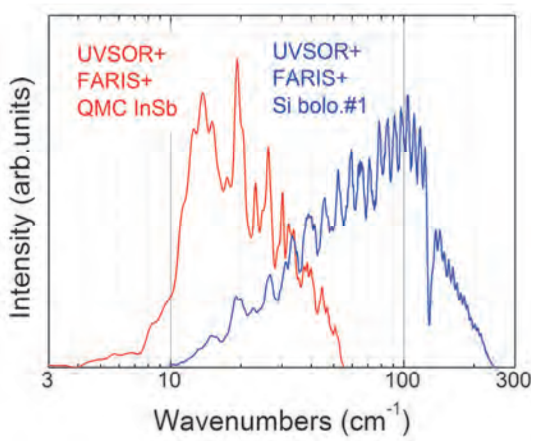


Fig. 2. Obtained intensity spectra with the combination of a light source (UVSOR), interferometer (FARIS-1), and detectors (Si bolometer and InSb hot-electron bolometer).

▼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.

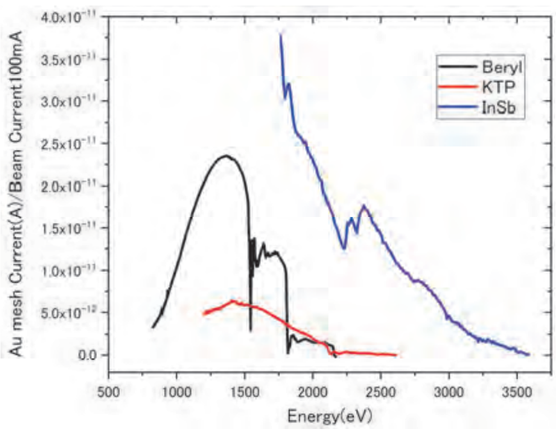


Fig. 1. Throughput spectra of the double-crystal monochromator at BL2A.

▼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/ΔE = 1500 for beryl and InSb
Experiments	Photoabsorption spectroscopy (total electron yield using EM and partial fluorescence yield using SDD)

BL2B

Photoelectron spectroscopy of molecular solids

▼Description

This beamline previously dedicated for experiments in the field of gas phase photoionization and reaction dynamics. Then, the beamline has been reconstructed for photoelectron spectroscopy of molecular solids with a new end station, and experiments can be performed from May 2014. The monochromator is a spherical grating Dragon type with 18-m focal length. High throughput (1×10^{10} photons s^{-1}) and high resolution ($E/\Delta E$ = 2000 - 8000) are achieved simultaneously under the condition of the ring current of 100 mA [1]. The optical system consists of two pre-focusing mirrors, an entrance slit, three spherical gratings (G1 - G3), two folding mirrors, a movable exit slit, and a refocusing mirror [2]. The monochromator is designed to cover the energy range of 23–205 eV with the three gratings: G1 (2400 lines mm^{-1}, R = 18 m) at 80–205 eV; G2 (1200 lines mm^{-1}, R = 18 m) at 40–100 eV; G3 (2400 lines mm^{-1}, R = 9.25 m) at 23–50 eV. The percentage of the second-order light contamination at $h\nu$ = 45.6 eV is 23 % for G2 or 7 % for G3.

A UHV chamber is placed downstream of the refocusing mirror chamber and equipped silicon photodiode, sapphire plate Au mesh and filters for absolute photon flux measurement, monitor the photon-beam position, relative photon flux measurements and attenuate higher order light, respectively.

The new end station consists of a main chamber with a hemispherical analyzer (SCIENTA R3000) and a liquid-He-cooled cryostat (temperature range of 15-400 K) with 5-axis stage, a sample preparation chamber with a fast-entry load-lock chamber and a cleaning chamber with LEED, ion gun for sputtering and IR heating unit.

[1] M. Ono, H. Yoshida, H. Hattori and K. Mitsuke, Nucl. Instrum. Meth. Phys. Res. A **467-468** (2001) 577.
[2] H. Yoshida and K. Mitsuke, J. Synchrotron Radiation **5** (1998) 774.

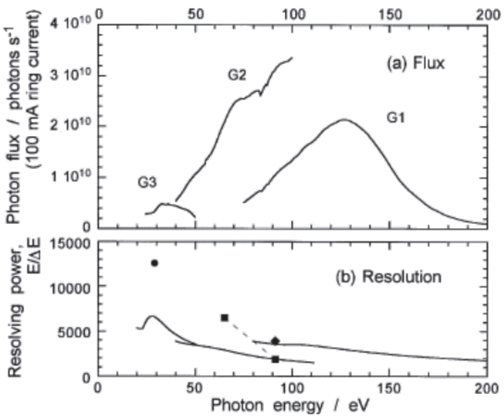


Fig. 1. Throughput from Dragon monochromator.

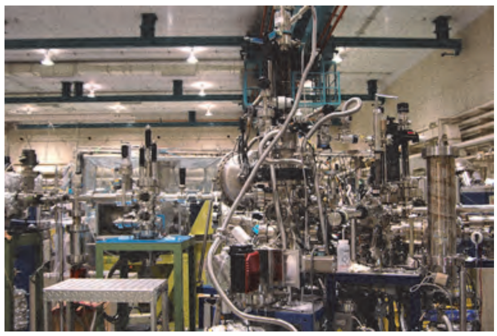


Fig. 2. End station of BL2B for photoelectron spectroscopy of molecular solids.

▼Technical Data

Monochromator	18 m spherical grating Dragon-type
Wavelength Range	23-205 eV
Resolution	2000–8000 depending on the gratings
Experiments	Angle-resolved ultraviolet photoelectron spectroscopy

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.

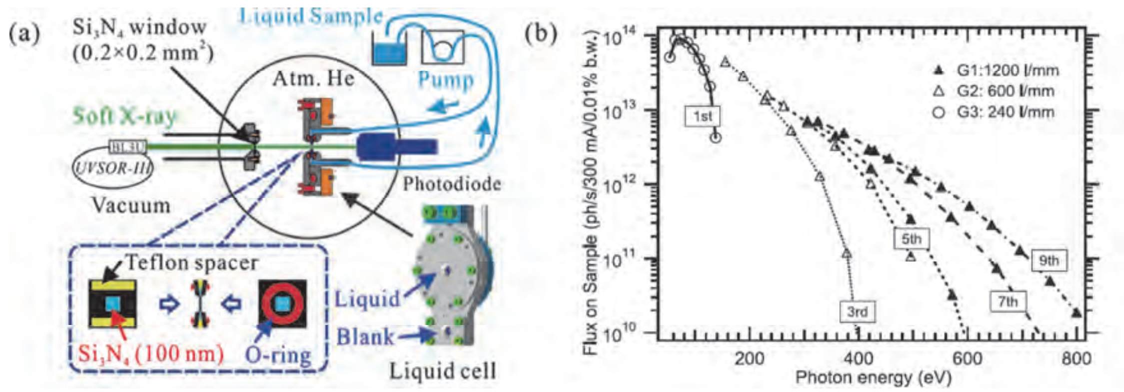


Fig. 1. (a) Schematics of a liquid cell for XAS in transmission mode settled in BL3U. The blowup shows a thin liquid layer assembled by two Si_3N_4 membranes with the thickness of 100 nm. (b) Flux at the sample position with the resolving power of $\lambda/\Delta\lambda=10^4$.

▼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.

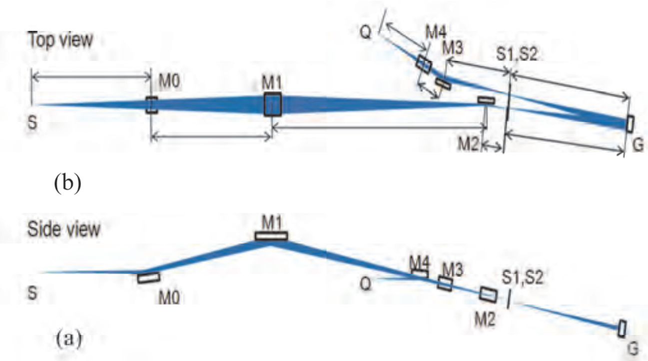


Fig. 1. Schematic layout of the BL3B (a) side view and (b) top view.

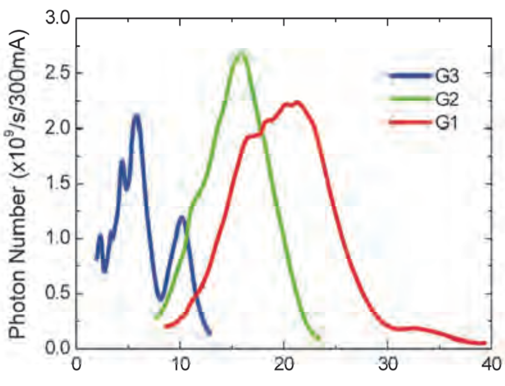


Fig. 2. Throughput spectra for each grating (G1:1200 l/mm, G2:600 l/mm and G3:300 l/mm) with S1 = S2 = 0.1 mm.

▼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

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/ΔE) 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.

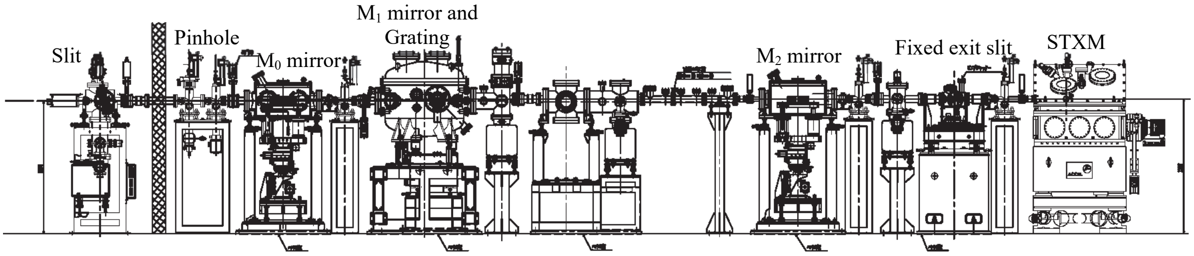


Fig. 1. Schematic image of BL4U

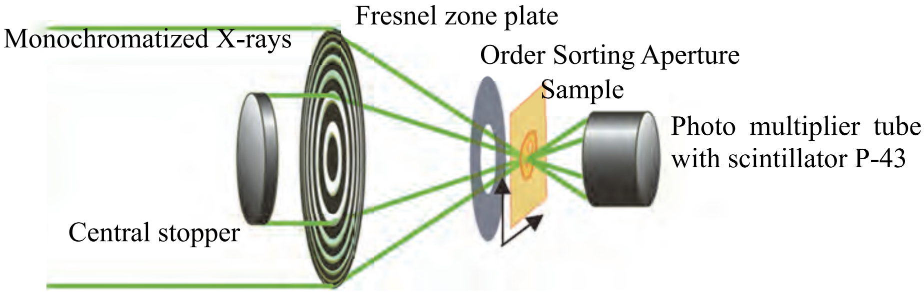


Fig. 2. Schematic image of STXM

▼Technical Data

Energy range (E)	50 -770 eV
Resolving power (E/ΔE)	~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 800 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 ($E/\Delta E$) achieved for each grating exceeds 5000.

There is no fixed endstation on this beamline. A small vacuum chamber equipped with an electron multiplier (EM) detector is available. Soft X-ray absorption spectra of solid samples are usually measured by means of the total electron yield method using EM, and the partial fluorescence yield method using a silicon drift detector (SDD).

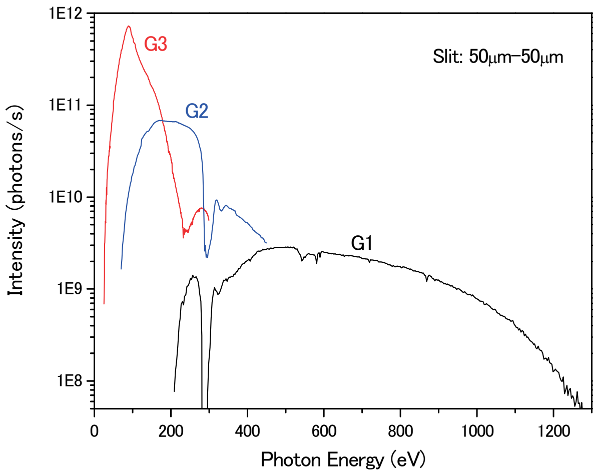


Fig. 1. Throughput from the VLS-PGM monochromator on BL4B.

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	Soft X-ray spectroscopy (mainly, photoabsorption spectroscopy for solid targets by means of total electron yield method using EM and partial fluorescence yield method using SDD)

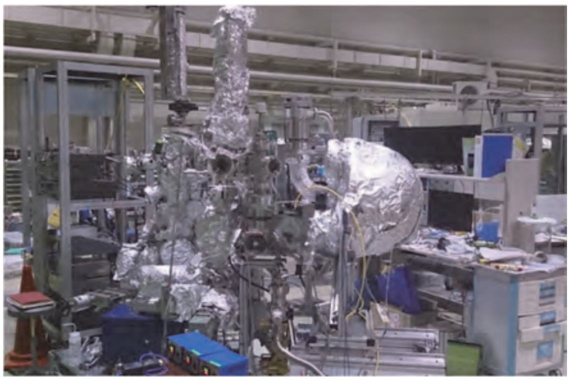
BL5U

Photoemission Spectroscopy of Solids and Surfaces

II

▼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.



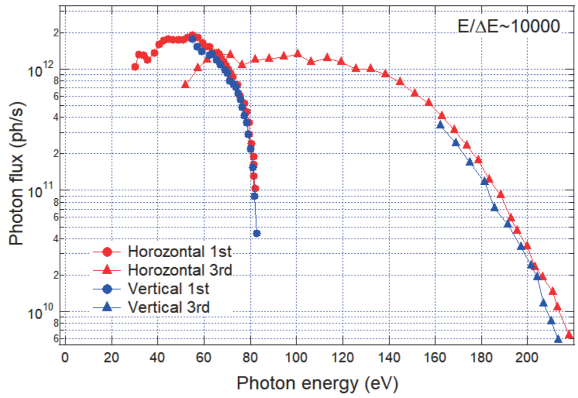


Fig. 1. Picture and photon flux of BL5U.

▼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).

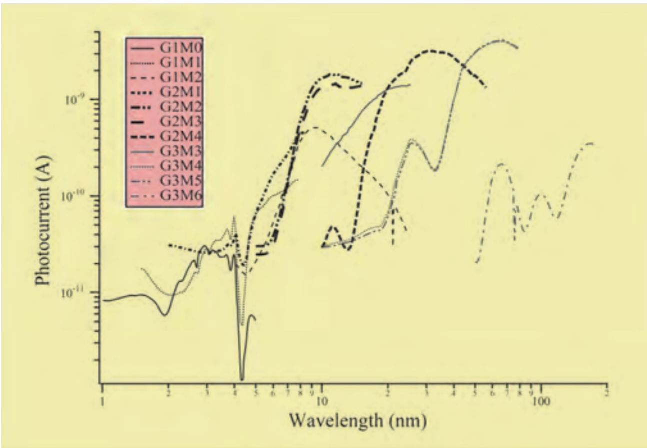


Fig. 1. Throughput spectra for possible combinations of gratings and mirrors at BL5B measured by a gold mesh.

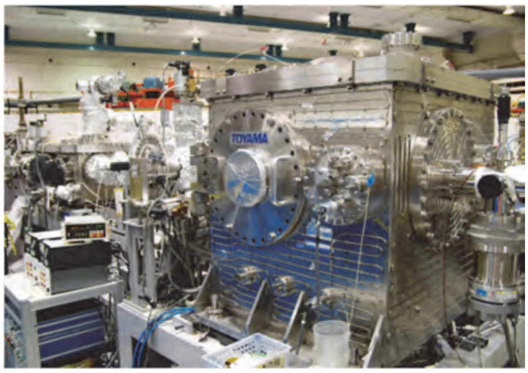


Fig. 2. A side view of the experimental chamber for calibration measurements.

▼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

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.

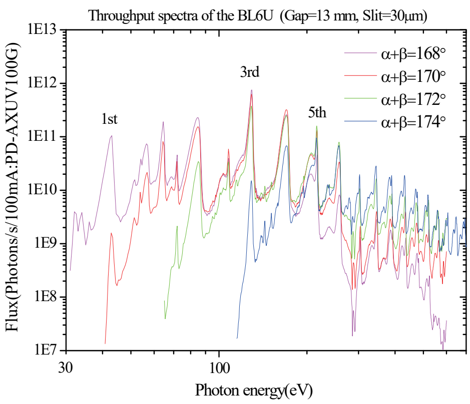


Fig. 1. Throughput spectra of the BL6U monochromator at various included angles.

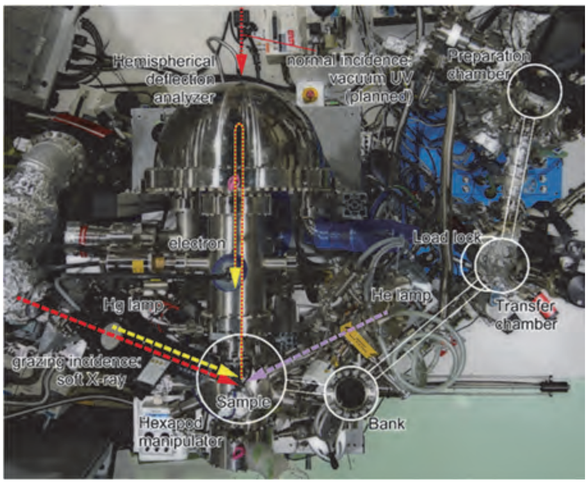


Fig. 2. Photograph of BL6U end station

▼Technical Data

Monochromator	Variable-included-angle Varied-line-spacing Plane Grating Monochromator
Energy range	45-600 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.

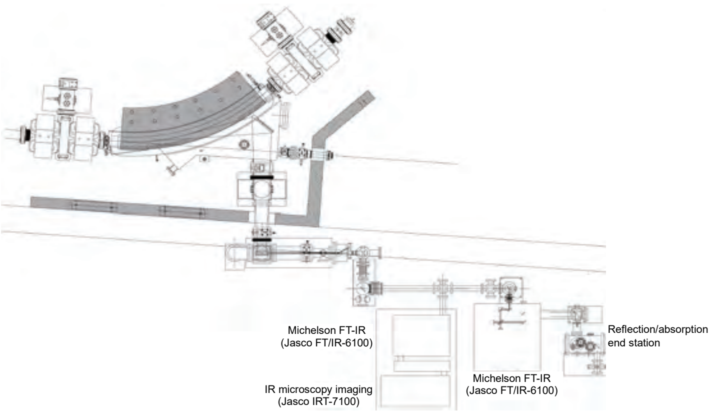


Fig. 1. Schematic top view of BL6B.

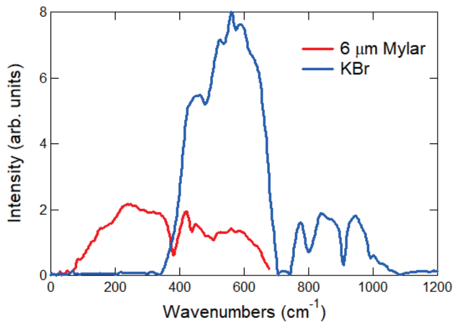


Fig. 2. Obtained intensity spectra with the combination of a light source (UVSOR), detector (Si bolometer), and interferometer (Bruker Vertex70v) with different beamsplitters (6 μm Mylar and KBr) . (Only low energy side is shown).

▼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, T. Ito, M. Sakai, E. Nakamura, N. Kondo, K. Hayashi, T. Horigome, M. Hosaka, M. Katoh, T. Goto, T. Ejima and K. Soda, Rev. Sci. Instrum. **81** (2010) 053104.

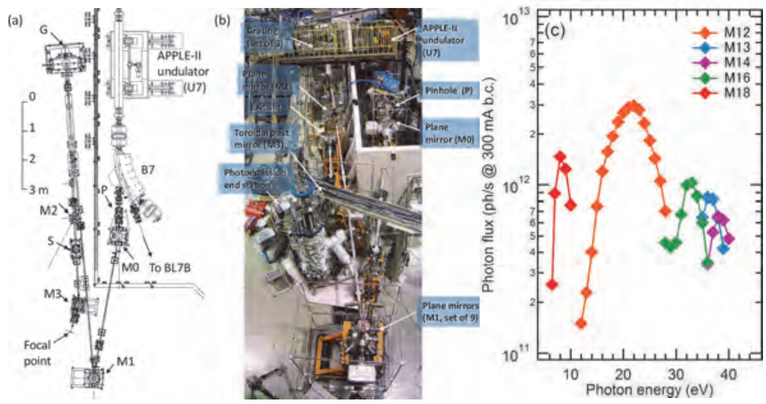


Fig. 1. SAMRAI beamline [(a), (b)] consisting of an APPLE-II type undulator (U7), a modified Wadsworth type monochromator (M0-S), and a high-resolution photoemission analyzer at the focal point. The monochromator has five major optical components: two plane mirrors (M0 and M1) with water cooling, one 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 ($h\nu/\Delta h\nu$)	$E / \Delta E$ > 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.

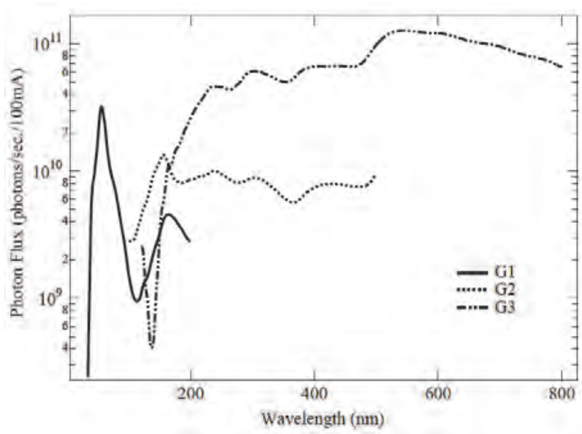


Fig. 1. Throughput spectra of BL7B measured using a silicon photodiode.

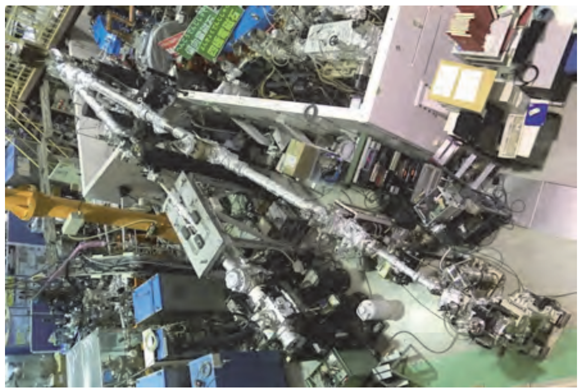


Fig. 2. Photo of BL7B.

▼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