Design of a High Resolution and High Flux Beamline for VUV Angle-Resolved Photoemission at UVSOR-II

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Abstract. A high-energy-resolution angle-resolved photoemission beamline in the vacuum-ultraviolet (VUV) region has been designed for a 750 MeV synchrotron light source UVSOR-II. The beamline equips an APPLE-II-type undulator with the horizontally/vertically linear and right/left circular polarizations, a modified Wadsworth-type monochromator and a high-resolution photoelectron analyzer. The monochromator covers the photon energy range of 6 – 40 eV. The energy resolution ($h\nu/\Delta h\nu$) and the photon flux on samples are expected to be 2×10^4 and 10^{12} photons/sec at 10 eV, 4×10^4 and 5×10^{11} photons/sec at 20 eV, and 6×10^4 and 10^{11} photons/sec at 40 eV, respectively. The beamline provides the high-resolution angle-resolved photoemission spectroscopy less than 1 meV in the whole VUV energy range.

Keywords: Wadsworth monochromator, APPLE-II undulator, high-resolution angle-resolved photoemission
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INTRODUCTION

Recently, the energy resolution of photoemission experiments is dramatically improved by using a He discharge lamp and a VUV laser [1]. Due to the improvement, the thermodynamical properties of solids can be understood by the change of the electronic structure detected by photoemission. In the case of the angle-resolved photoemission spectroscopy (ARPES) using such light sources, the wavenumber along the normal direction of sample surface (k_z) cannot be set at a high symmetry point because the excitation photon energy that directly connects to k_z cannot be tuned. Then it is important to determine the three-dimensional band structure at the high-symmetry points by ARPES with tunable photons to compare with the band structure calculation [2]. Since synchrotron radiation (SR) is suitable for the use of the various photon energies, so many photoemission beamlines have been constructed in the world up to now. Because of the low photon flux of SR, however, the energy-resolution in ARPES was lower than the other sources mentioned above. Then we plan to construct a new undulator beamline in the vacuum-ultraviolet (VUV) region at a 750 MeV synchrotron light source, UVSOR-II, Institute for Molecular Science, for the purpose of the high-energy-resolution ARPES with the total energy resolution less than 1 meV in the excitation energy of 6 – 40 eV and with the various (vertically/horizontally linear and right/left circular) polarization of excitation photons. In 2003, UVSOR-II has been upgraded to the lowest emittance (27 nm rad) ring among SRs with the acceleration energy below 1 GeV [3]. The electron beam size (2σ) was reduced to 0.04(H) $\times$ 1.2(H) mm^2 in the 1-% coupling machine operation. To use the small beam size, we designed a various polarized APPLE-II-type undulator [4] and a VUV monochromator without an entrance slit, so-called the Wadsworth monochromator [5, 6, 7], in which the grating moves not only rotationally but also translationally to focus the monochromatized light on the exit slit. In this paper, the beamline design is reported.

DESIGN CONCEPT OF BL7U

The design concept of the VUV-ARPES beamline, BL7U, at UVSOR-II is as follows; (1) Both of the high photon flux ($N_{ph} \geq 10^{11}$ photons/sec) and the high energy resolution ($h\nu/\Delta h\nu \geq 2 \times 10^4$) are achieved simultaneously. (2) Various polarizations of vertically/horizontally linear and right/left circular ones are available because the symmetry of the electron orbital and spin directions can be selected. (3) The beamline space from the center of the undulator to a passage is limited to be about 12.5 m.

The schematic drawing of BL7U is shown in Fig. 1. To achieve the first two points of the design concept, we employed the APPLE-II-type undulator with 3-m long, the periodic length λ_u = 76 mm and the number of periods N = 38. Some types of undulators and multipole wigglers have been proposed to make various polarizations up to

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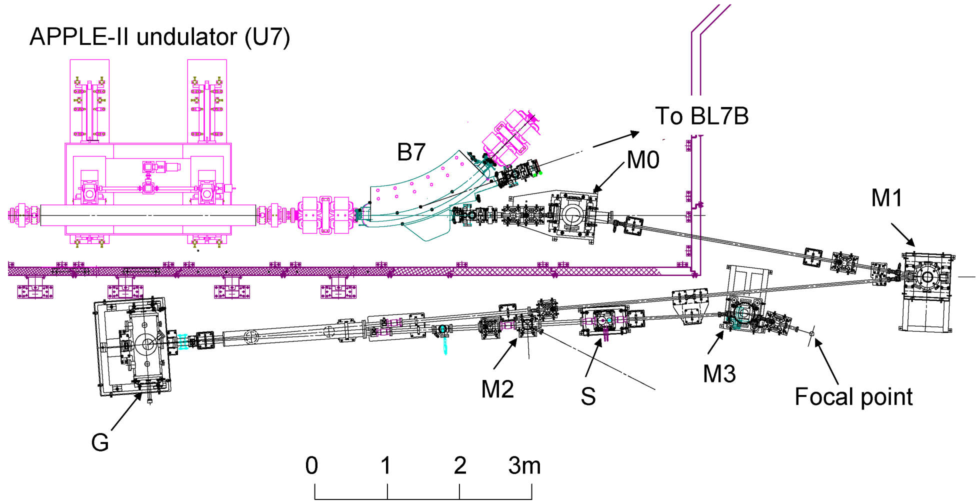

FIGURE 1. The schematic figure of the high-resolution photoemission beamline BL7U that consists of the APPLE-II-type undulator (U7), the modified Wadsworth-type monochromator (M0 – S) and the high-resolution photoemission analyzer sitting at Focal point. In the monochromator, there are five optical components, two plane mirrors (M0 and M1) with water cooling, one spherical grating (G), an exit slit (S) and one troidal refocusing mirror (M3). The spherical grating with the radius of 10 m is located at 22 m from the center of the undulator. There are no entrance slit and an exit slit (S) locating at 6.47 m from G. The second branch is separated by a plane mirror (M2) located between G and S.

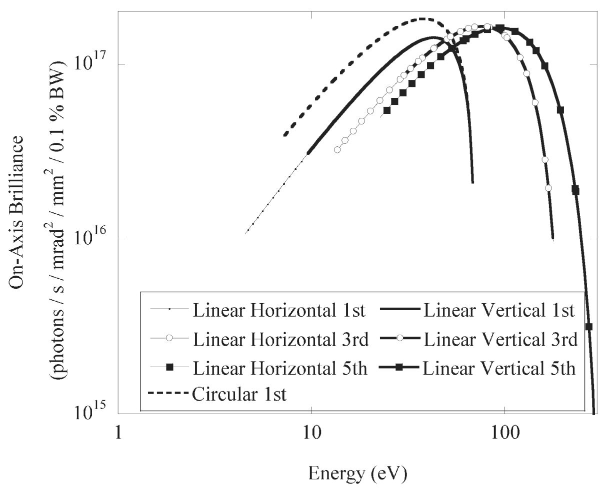

FIGURE 2. Brilliance spectra of the APPLE-II-type undulator of BL7U at UVSOR-II with the circular and linear polarizations at the beam current of 500 mA. 1-% coupling machine operation is expected in the calculation.

now [4, 8, 9, 10, 11]. Among these undulators, only the APPLE-II-type one can make various polarizations of the horizontally/vertically linear and right/left circular polarizations of light even though the large acceptance angle is adopted. The minimum gap is expected to be 24 mm and then the magnetic fields in the horizontal and vertical directions are 0.498 and 0.764 T, respectively. The calculated brilliance with the linear and circular polarized light is shown in Fig. 2. The first order light with the horizontally linear and circular polarizations covers the photon energy ranges of 4 – 50 eV and 7 – 50 eV, respectively. The peak brilliance of the circularly polarized light at around 35 eV reaches 1.7×10^{17} photons/sec/mrad^2/mm^2/0.1%b.w. at 500-mA beam current, which is comparable to that of third generation SR sources.

We employed the Wadsworth-type monochromator, which has no entrance slit to obtain the high photon flux. In this case, the light source size determines the energy resolution. Since the UVSOR-II is the lowest emittance ring in the group of SRs with the acceleration energy below 1 GeV, we can use the very small beam size (2σ) of

TABLE 1. Optical components of the modified Wadsworth monochromator of BL7U.

	Distance from emission point (m)	Size	Shape	Horizontal incident angle	Material
Pinhole (P)	5.4	–	0.1, 0.2, 0.4, 1.0, 2.0, 4.0, 8.0 mmϕ	–	Cu
Mirror (M0)	5.0	100×30×20 mm^3	plane	85 deg.	Au on Si
Mirror (M1)	11.0	25.4×25.4×10 mm^3	plane	7.5 deg.	Au on Si, SiC, Si, Mo/Si multilayer (total nine mirrors)
Grating (G)	22.0	30×30×10 mm^3	spherical (r = 10 m, Line density = 1,200, 2,400, 3,600 lines/mm)	1 deg.	Au on SiO_2
Slit (S)	28.67	3–200 μm	–	–	SUS/BeCu
Mirror (M3)	30.67	100×15×10 mm^3	troidal (r_l =7678.4 mm, r_s = 231.5 mm)	80 deg.	Au on SiO_2

0.04(V) × 1.2(H) mm^2 in the 1-% coupling operation at the center of the undulator. The schematic drawing and the parameter of the optical components are shown in Fig. 1 and Table 1, respectively. The undulator light is guided to the spherical gratings (G) by two plane mirrors (M0 and M1) with water cooling. The heat load from the undulator light is reduced by these two plane mirrors. Since the emission angle of the undulator is small, the distance from the emission point to G must be long to irradiate the wide area on the grating. To keep the polarization of the undulator radiation, the incident angles of M0 and M1 are 85 and 7.5 degree, respectively. Normally incident mirrors lose photon flux at higher energy regions because the reflectivity of all materials decreases with increasing photon energy. Then M1 equips nine plane mirrors, Si coated by Au, SiC, Si and a maximum of six Mo/Si multilayers. The mirrors can be set on the light axis without breaking vacuum and be aligned by the pulse motors. The reflectivity of Au, SiC and Si mirrors rapidly decreases with increasing photon energy above 25 eV. Then the Mo/Si multilayer mirrors cover above 25 eV [12]. One Mo/Si multilayer mirror has the peak reflectivity of 40 % and the band width of about 3 eV in the energy range above 25 eV. Then five multilayer mirrors covering the energy ranges of 25 – 28 eV, 28 – 31 eV, 31 – 34 eV, 34 – 37 eV and 37 – 40 eV are employed.

The grating (G) is set at 11 m from M1 as shown in Fig. 1. G equips three spherical gratings of 10-m radius with the constant line density of 1,200, 2,400 and 3,600 lines/mm optimized at the photon energies of 10, 20 and 33 eV, respectively. G moves not only rotationally for selecting photon energy but also for focusing the monochromatized light on the exit slit (S) locating at 6.47 m from G like an off-plane Eagle-type monochromator. The off-axis angle of G is 1 degree to keep the similar focal length between the horizontal and vertical direction. The image of the selected photon energies at around 40 eV with the grating of 3600 lines/mm and 1-% coupling machine operation at S is plotted in Fig. 3(a). The focus image at 39.999 eV ($h\nu/\Delta h\nu = 4 \times 10^4$) can be separated from that at 40 eV by using the 20-μm slit, but that at 40.0004 eV ($h\nu/\Delta h\nu = 1 \times 10^5$) cannot be separated. The energy resolution is evaluated to be about 6 × 10^4 in the 3,600 lines/mm region. After taking the same process, the energy resolution in the 1,200 and 2,400 lines/mm region is evaluated to be 2 × 10^4 and 4 × 10^4, respectively. The photon flux can be kept above 10^{11} photons/sec in the 0.01-% band width as shown in Fig. 3(b). Therefore the target performance of the beamline is achieved.

The beamline has three branches. The main end station is for ARPES in which a 200-mm-radius hemispherical photoelectron analyzer (MB Scientific AB, A-1 analyzer) and a liquid-helium-cooled cryostat with a 6-axes pulse motor control (A-VC Co. Ltd., i-GONIO) are installed. The main purpose is to determine the three-dimensional Fermi surface of strongly correlated materials at low temperatures and its temperature dependence to reveal the origin of the unconventional physical properties. The beam size on samples is reduced to 1/2 size of the image on the slit shown in Fig. 3(a) by M3. Since the monochromator reduces the beam size to about 1/3, the total reduction ratio from the electron beam size at the emission point is about 1/6. Then the beam size (2σ) on samples is expected to be $200(H) \times 10(V)$ μm^2 in the 1-% coupling operation. The second is for photochemistry synchronized with lasers. The second end station is located at the branch line separated from a plane mirror set at the M2 position. The last is for a micro-focus ARPES of solids using a multilayer-coated Schwarzschild mirror. The beamline is constructed in the summer season of 2006 and the ARPES end station will be opened to users in FY2007.

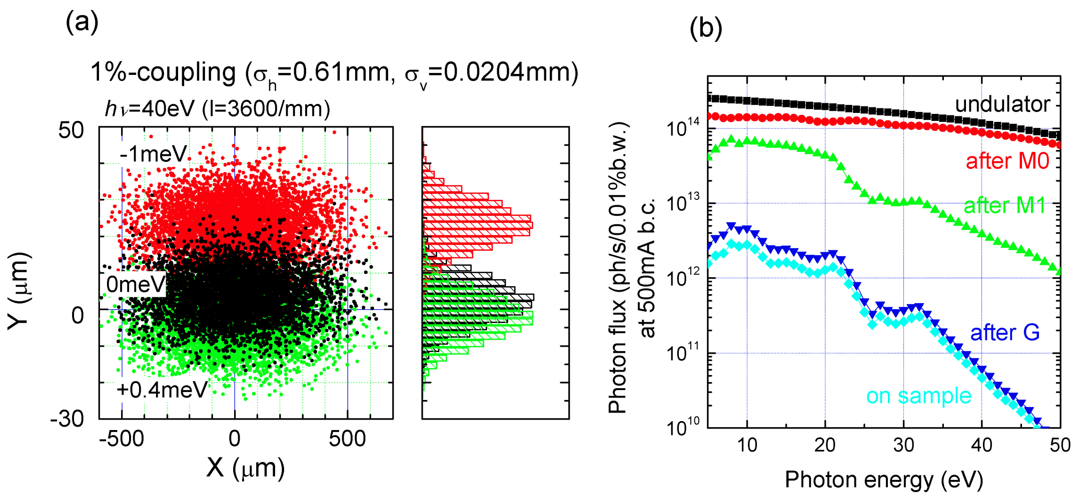

FIGURE 3. (a) Focus image at the exit slit (S) in Fig. 1. In this case, $h\nu$ = 40 eV and 1-% coupling machine operation are assumed. Three images at $h\nu$ = 39.999, 40, 40.0004 eV on the slit are plotted. The energy resolution ($h\nu/\Delta h\nu$) is evaluated to be about 6×10^4 by using the 20 μm slit. (b) The evaluated photon flux after optical components. In the second mirror (M1), the reflectivity below and above 25 eV originates from that of SiC and Au mirrors, respectively. In the grating (G), the efficiency of gratings with 1,200, 2,400 and 3,600 lines/mm is used in the energy range of 5 – 13, 13 – 25 and 25 – 50 eV, respectively. When the Mo/Si multilayer mirrors are used for M1, the throughput intensities after M1, G and on sample are expected to be several times larger than those of the figure above 25 eV.

CONCLUSION

In conclusion, a new VUV beamline for angle-resolved photoemission at UVSOR-II was designed. The beamline equips an APPLE-II-type undulator with various polarizations and a modified Wadsworth monochromator. The energy resolution ($h\nu/\Delta h\nu$) is expected to be 2×10^4, 4×10^4 and 6×10^4 in the photon energy ranges of 6 – 15, 12 – 30 and 25 – 40 eV with the line density of 1,200, 2,400 and 3,600 lines/mm, respectively.

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