

ACTIVITY REPORT

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Hiroshima Synchrotron Radiation Center, HiSOR **Hiroshima University**

HiSOR ACTIVITY REPORT

2015

Hiroshima Synchrotron Radiation Center, HiSOR Hiroshima University

Edited by H. Sato

The annual report is available from

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Preface

Hiroshima Synchrotron Radiation Center (HiSOR), Hiroshima University, celebrated its 20-year anniversary ceremony and held the 20th international symposium on synchrotron radiation on March 10 and 11, 2016.

We are promoting research in materials science using synchrotron radiation from ultraviolet (VUV) to soft x-ray region. In particular, high-resolution electronic structural analysis using high-brightness ultraviolet undulator emission and the structural analysis biomaterial in water using circularly polarized VUV are attracting much international cooperative research.

HiSOR is a Joint Usage/Research Center, which is a national cooperative research system to promote joint research since 2004. External evaluations were conducted for the activities of joint research/joint use in 2015, and we achieved an A-rank score.

HiSOR has promoted high-resolution electronic structure analysis and the improvement of related techniques. BL1, a linear undulator beam line, enables linear-polarization-dependent measurements using a rotatable photoemission spectrometer. BL9A, an Apple II-type variable polarization undulator beam line, the improvement of normal incidence monochromator and the replacement of the magnetic shield vacuum chamber to mount new motorized 6 axis low temperature goniometer were conducted. Furthermore, a new laser system has been introduced as an advanced VUV light system to enhance synchrotron radiation experiments. BL9B, the branch beam line of the Apple-II undulator, is three-dimensional spin-resolved ARPES beam line. The electron energy analyzer incorporating two new high-efficiency spin detectors has enabled the visualization of spin dependent electronic states.

The number of cooperative researchers not from Hiroshima University was 125 (49 researchers were from foreign countries) from 39 institutions in 2015. The number of research institutions, which has the researchers using HiSOR, is 48 (overseas) and 54 (in Japan) since 2004.

Finally, I thank all users of HiSOR and other related research institutions and appreciate the financial support of the Joint Usage/Research Center project of MEXT.

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September 2016 Hirofumi Namatame Director for Hiroshima Synchrotron Radiation Center

Hirofumi Namatome

Table of Contents

Preface

Current Status of HiSOR

Status of the HiSOR storage ring	1
Beamlines	6

Reseach Activities

– Accelerator Studies –
Magnetic design of Knot-APPLE undulator and its performance9
N. Kawata, S. Sasaki
Sound of quasi-periodic undulator 11
Y. Ichioka, S. Sasaki
Design for new type quasi periodic undulator
H. Mima, A. Miyamoto, S. Sasaki
– Instrumental Developments –
Present status of VUV-laser based spin-ARPES system
K. Sumida, K. Miyamoto, E. Annese, K. Taguchi, T. Yoshikawa, Y. Okuda, A. Kimura, M. Taniguchi, H. Namatame, T. Okuda
 Synchrotron Radiation Experiments –
Angle-resolved photoemission study of hybridization effect in YbInCu ₄
S. Ishihara, K. Ichiki, K. Abe, T. Matsumoto, K. Mimura, H. Sato, M. Arita, E. F. Schwier, H. Iwasawa, K. Shimada, H. Namatame, M. Taniguchi, T. Zhuang, K. Hiraoka, H. Anzai
Multi-band electronic structure of Eu ₃ F ₄ Bi ₂ S ₄ 19
T. Mizokawa, T. Sugimoto, E. Paris, N. L. Saini, T. Asano, H. Endo, M. Mita, R. Higashinaka, T. Matsuda, Y. Aoki, E. F. Schwier, M. Zheng, K. Kojima, H. Iwasawa, K. Shimada, H. Namatame, M. Taniguchi
Spiral structure in the intensity distribution of the photoelectron emission from the Dirac cone of graphene $$ $^{\circ\circ}$ 21
S. Tanaka
Symmetry resolved surface-derived electronic structure of WSe ₂ 23
I. Tanabe, T. Komesu, E. F. Schwier, Y. Kojima, M. Zheng, H. Iwasawa, K. Shimada, D. Le, T. Rahman, P. A. Dowben

Large area, nearly free-standing monolayer graphene on Pt
W. Yao, E. Wang, A. V. Fedorov, E. F. Schwier, H. Iwasawa, K. Shimada, S. Zhou
Spin- and angle-resolved photoemission study of oxygen adsorbed Fe/MgO(100)27
M. Zheng, E. F. Schwier, K. Miyamoto, T. Okuda, K. Shimada, H. Iwasawa, T. Horike, Y. Nagata, Y. Kojima, H. Namatame, M. Taniguchi
ARPES studies on the electronic structure of a new diluted ferromagnetic semiconductor with Curie temperature
Y. Hu, Y. Xu, S. He, M. Zheng, E. F. Schwier, H. Iwasawa, K. Shimada, H. Namatame, X. Zhou
Electron doping to rutile TiO ₂ surface by Na deposition
RY. Liu, K. Ozawa, E. F. Schwier, M. Zheng, H. Iwasawa, K. Shimada, H. Namatame, M. Taniguchi, I. Matsuda, Y. Aiura
Dirac-cone surface state influenced by vicinal surface of W(110)
K. Miyamoto, C. Lamgenkämper, E. F. Schwiwer, H. Sato, H. Iwasawa, K. Shimada, M. Donath
A systematic study on the interlayer electronic structure and electron-phonon coupling in the novel graphite intercalation superconductors
C. Wang, Y. Zhang, G. Liu, M. Zheng, M. Nakatake, K. Shimada, W. Zhao, H. Namatame, M. Taniguchi, X. Zhou
Fermi surface of heavy-fermion compound EuNi ₂ P ₂ revealed by angle-resolved photoemission spectroscopy · 38
H. Anzai, K. Ichiki, E. F. Schwier, H. Iwasawa, M. Arita, K. Shimada, H. Namatame, M. Taniguchi, A. Mitsuda, H. Wada, K. Mimura
Angle-resolved photoelectron spectroscopy study of Ce(Ru _{1-x} Rh _x) ₂ Al ₁₀
H. Yamaoka, E. F. Schwier, Y. Yamamoto, F. Tajima, T. Nishioka, H. Iwasawa, K. Shimada, J. Mizuki
ARPES research of a possible weyl semimetal material 42
J. Huang, A. Liang, Q. Gao, S. He, M. Zheng, E. F. Schwier, H. Iwasawa, H. Sato, K. Shimada, H. Namatame, X. Zhou
A study on thermal reaction with sulfenamide as vulcanization accelerator by means of S K-edge NEXAFS 44
S. Tanaka, C. Tsukada, S. Ogawa, G. Kutluk, T. Murai, S. Yagi
Adsorption behavior between L-cysteine and Au nanoparticles precovered with different order of PC layer … 46
C. Tsukada, K. Matsuo, T. Murai, T. Nomoto, G. Kutluk, H. Namatame, M. Taniguchi, T. Yaji, T. Ohta, H. Nameki, S. Ogawa, S. Yagi
Current activities of research and education on BL-5
T. Yokoya, T. Wakita, Y. Muraoka
X-ray photoelectron spectroscopy study of YbCu _{1-x} Ga _x (x = 0.5, 1.0, 1.2, 1.5)
H. Yamaoka, H. Sato, A. Rousuli, N. Tsujii, K. Shimada, Y. Yamamoto, J. Mizuki
Angle-resolved photoemission spectroscopy in topological crystalline insulator Pb _x Sn _{1-x} Te thin films
R. Akiyama, T. Yamaguchi, D. Fan, Y. Otaki, H. Sato, A. Kimura, S. Hasegawa, S. Kuroda
Photoemission study on electronic structure of Yb ₂ Pt ₆ X ₁₅ (X=Al, Ga)
S. Nakamura, A. Rousuli, T. Nagasaki, H. Sato, T. Ueda, Y. Matsumoto, S. Ohara, K. Mimura, H. Anzai, K. Ichiki, S. Ueda, K. Shimada, H. Namatame, M. Taniguchi

Valence band structures of the layered oxychalcogenides 55
K. Takase, K. Kanno, S. Ishiwata, K. Kawamoto, A. Rousuli, T. Nagasaki, S. Nakamura, H. Sato, A. Higashiya
Metal-semiconductor transition of mineral tetrahedrite Cu ₁₂ Sb ₄ S ₁₃ investigated by photoemission and soft x-ray
absorption spectroscopies
T. Nagasaki, A. Rousuli, S. Nakamura, H. Sato, H. I. Tanaka, K. Suekuni, M. Nakatake, G. Kutluk, M. Sawada, K. Mimura, H. Anzai, K. Ichiki, S. Ueda, K. Shimada, T. Takabatake, H. Namatame, M. Taniguchi
Electronic states and glass-forming ability of Zr-Cu-Ag bulk metallic glasses
S. Hosokawa, H. Kato, M. Nakatake, H. Sato
Angle-resolved photoemission study of BaFe ₂ S ₃ : possibility of excitonic instability
T. Mizokawa, S. Iwasaki, K. Yamamoto, N. L. Saini, T. Aoyama, K. Hashizume, K. Ohgushi, M. Arita, H. Namatame, M. Taniguchi
Electronic structure of K-doped iron-selenide superconductor studied by polarization-dependent angle-resolved
photoemission spectroscopy
M. Sunagawa, K. Terashima, T. Hamada, H. Fujiwara, M. Tanaka, H. Takeya, Y. Takano, M. Arita, K. Shimada, H. Namatame, M. Taniguchi, K. Suzuki, H. Usui, K. Kuroki, T. Wakita, Y. Muraoka, T. Yokoya
Replica of the Dirac cone in the epitaxial graphene due to the periodic potential of the SiC substrate
S. Tanaka
Resonance photoelectron spectroscopy of strongly spin-orbit coupled surface states
H. Bentmann, H. Maaß, C. Seibel, F. Reinert
Superconducting gap and low-energy kink structure in the high-T _c cuprates La _{2-x} Sr _x CuO ₄
D. Shimonaka, D. Ootsuki, D. Shibata, A. Fujimori, M. Arita, H. Namatame, M. Taniguchi, S. Komiya, Y. Ando, T. Yoshida
Extremely correlated Hund metal emerging on the topmost layer of Sr ₂ RuO ₄
T. Kondo, M. Ochi, M. Nakayama, S. Akebi, K. Kuroda, H. Taniguchi, M. Arita, S. Sakai, H. Namatame, M. Taniguchi, Y. Maeno, R. Arita, S. Shin
Angle resolved photoemission study of Yb _{1-x} Tm _x B ₆
M. Arita, H. Sato, K. Shimada, H. Namatame, M. Taniguchi, H. Tanida, Y. Osanai, K. Hayashi, F. Iga
Synchrotron-radiation photoemission spectroscopy of layer-structured superconductor ZrP _{2-x} Se _x
T. Kubo, H. Takita, W. Mansuer, M. Arita, K. Shimada, H. Namatame, M. Taniguchi, S. Ueda, H. Kito, S. Ishida, K. Oka, Y. Gotoh, H. Fujihisa, Y. Yoshida, A. Iyo, H. Eisaki, K. Kawashima, Y. Yanagi, A. Ino
Electronic structure studies of oxygen-concentration-controlled n-type HTSC, (Pr,La) _{1.85} Ce _{0.15} CuO _{4-δ}
D. Song, S. Park, S. Cho, H. Eisaki, C. Kim
Protected spin polarized topological surface state on PbBi ₄ Te ₄ S ₃ 78
K. Sumida, T. Natsumeda, K. Shirai, K. Kuroda, S. Zhu, K. Miyamoto, T. Okuda, M. Arita, H. Namatame, M. Taniguchi, J. Fujii, E. V. Chulkov, K. A. Kokh, O. E. Tereshchenko, A. Kimura
Study of spin-polarized states in the 2D electron system at the AlO×(2Å)/SrTiO ₃ interface
T. C. Rödel, F. Fortuna, J. Scarpaci, P. Le Fèvre, Y. Ishida, K. Kuroda, K. Minamoto, K. Taguchi, T. Okuda, A. F. Santander-Syro

Spin and electronic structure of a magnetic/topological insulator ultrathin film heterostructure
Y. Okuyama, K. Sumida, K. Miyamoto, T. Okuda, T. Hirahara
Exchange coupling and spin structure in cobalt-on-chromia thin films
T. Komesu, K. Taguchi, T. Okuda, K. Miyamoto, R. Choudhary, P. Sahota, P. Manchanda, R. Skomski, A. Kashyap, P. A. Dowben
Spin-polarization in the electronic structure of strongly correlated surface alloys
H. Bentmann, H. Maaß, C. Seibel, F. Reinert
Spin-split surface bands of Si(111)5×2-Au
K. Taguchi, K. Sumida, K. Miyamoto, H. Namatame, M. Taniguchi, A. Kimura, T. Okuda
Change of electronic structure of Ir(111) by Pb adsorption
Y. Okuda, K. Miyamoto, K. Sumida, K. Taguchi, T. Yoshikawa, N. Takagi, R. Arafune, T. Okuda
Identifying sulfur species in marine sediments collected from Osaka Bay using XAFS
XAS study of hydrogenetics properties of Pd TM alloys
K. Fujii, N. Ishimatsu, S. Hayakawa, T. Shishidou, H. Maruyama
An XAFS study on the local structural changes around titanium in the lithium secondary battery during the
T Mari S Minagi H Sumida X Yamada A Munaz Naval A Tamura H Namatama S Havakawa
Electrochemical formation of copper sulfide thin films and their characterizations
M. Tanase, T. Hayasaka, A. Munoz Noval, A. Tamura, H. Namalame, S. Hayakawa
Qualitative and quantitative x-ray fluorescence analysis of light elements and trace fluorine using soft x-ray • 99 M. Kondo, A. Tamura, A. Munoz-Noval, H. Namatame, S. Hayakawa
Vacuum-ultraviolet circular-dichroism spectra of polysaccharides and cyclic oligosaccharides
Effects of liposome surface charges on membrane-induced conformations of α1-acid glycoprotein characterized
by vacuum-ultraviolet circular-dichroism spectroscopy103
K. Matsuo, H. Namatame, M. Taniguchi
Synergistic gelation of xanthan and locust bean gum studied by vacuum-ultraviolet circular dichroism104
Y. Maki, K. Toriba, K. Ishizaka, K. Matsuo
VUV-CD measurements of proteins relating to DNA repair106
Y. Izumi, K. Fujii, S. Yamamoto, K. Matsuo, A. Yokoya
Contributions of aromatic side chains to the vacuum-ultraviolet circular dichroism spectra of escherichia coli dihydrofolate reductase
S. Tanaka, E. Ohmae, Y. Miyashita, K. Matsuo, K. Katayanagi
Characterization of green fluorescent protein monolayers utilizing controllable self-assembled monolayers 109

Non-contact evaluation of molecular conductivity of organic molecules utilizing core-excitation dynamics measurements
S. Wada, M. Ogawa, S. Hosoda, R. Koga, A. Hiraya
Magnetic properties of Fe ultrathin films in h-BN/Fe/Ni(111) and Fe/h-BN/Ni(111)113
W. Tadano, M. Sawada, H. Namatame, M. Taniguchi
XMCD study of magnetic proximity effect in Co / Y ₃ Fe ₅ O ₁₂ Heterostructures
V. V. Fedorov, A. M. Korovin, S. M. Suturin, M. Sawada, N. S.Sokolov
XAS and XMCD study of Pd(100) and Fe/Pd(100) ultrathin films117
S. Sakuragi, M. Sawada, S. Nakahara, T. Sato
Temperature evolution of the density of states near the Fermi level of Ce ₃ Pd ₂₀ Si ₆ and Ce ₃ Pd ₂₀ Ge ₆ 119
H. Yamaoka, E. F. Schwier, Y. Yamamoto, N. Tsujii, H. Kitazawa, H. Iwasawa, K. Shimada, J. Mizuki
Laser µ angle-resolved photoelectron spectroscopy on CeT ₂ Al ₁₀ (T = Ru, Os)
K. Terashima, T. Nagayama, H. Iwasawa, E. F. Schwier, J. Kawabata, Y. Yamada, T. Takabatake, Y. Muraoka, T. Yokoya

Appendices

Organization	123
List of Publications	128
List of Resarch Proposals	132
Symposium ·····	138
Plan of the Building	139
Location	140

Current Status of HiSOR

Status of the HiSOR storage ring

1. Introduction

The HiSOR is a synchrotron radiation (SR) source of Hiroshima Synchrotron Radiation Center, Hiroshima University, established in 1996. It is a compact racetrack-type storage ring having 21.95 m circumference, and its natural emittance of 400π nmrad is rather large compared with those of the other medium to large storage rings. The most outstanding advantage of the facility lies in good combination with state-of-the-art beamlines (BL's) for high-resolution photoelectron spectroscopy in the photon energy ranges between VUV and soft X-ray. The principal parameters of HiSOR are shown in Table 1.

Table 1. Main parameters of the HISOK Storage Hig.				
Circumference	21.95 m			
Туре	Racetrack			
Bending radius	0.87 m			
Beam energy at Injection	150 MeV			
at Storage	700 MeV			
Magnetic field at Injection	0.6 T			
at Storage	2.7 Т			
Injector	150 MeV Racetrack Microtron			
Betatron tune (v_x , v_y)	(1.72, 1.84)			
RF frequency	191.244 MHz			
Harmonic number	14			
RF voltage	200 kV			
Stored current (nominal)	350 mA			
Natural emittance	400π nmrad			
Beam life time	~10 hours@200 mA			
Critical wavelength	1.42 nm			
Photon intensity (5 keV)	1.2×10 ¹¹ /sec/mr ² /0.1%b.w./300mA			

Table 1: Main parameters of the HiSOR Storage ring.

The originally designed maximum stored current of HiSOR was 300 mA. However, after the improvement of the control system and the RF system in 2003, HiSOR has been in operation with 350 mA maximum stored current since. Fig. 1 shows an example of typical one-day operation. Beam injection for HiSOR is executed twice a day, at around 9:00 and 14:30.



Fig. 1: Typical daily operation status.

HiSOR has two 180-deg. Normal-conducting bending magnets which generate a strong magnetic field of 2.7 T. This storage ring is equipped with two insertion devices, a linear undulator and a quasi-periodic APPLE-II undulator which replaced to the previous helical undulator in summer 2012. Major parameters of these undulators are listed in Table 2. The photon energy spectra of the SR from HiSOR are shown in Fig. 2.

Tuble 2. Main parameters of the undulators.				
Linear undulator (BL-1)				
Total length	2354.2 mm			
Periodic length λu	57 mm			
Periodic number	41			
Pole gap	30-200 mm			
Maximum magnetic field	0.41 T			
Magnetic material	Nd-Fe-B (NEOMAX-44H)			
Quasi-Periodic APPLE-II				
undulator (BL-9A,B)				
Total length	1845 mm			
Periodic length λu	78 mm			
Periodic number	23			
Pole gap	23-200 mm			
Maximum magnetic field	0.86 T (horizontal linear mode)			
	0.59 T (vertical linear mode)			
	0.50 T (helical mode)			
Magnetic material	Nd-Fe-B (NEOMAX-46H)			

Table 2: Main parameters of the undulators.



Fig. 2: Photon energy spectra of the SR from HiSOR.

2. Operation status in FY 2015

Fig. 3 shows monthly operation time of HiSOR storage ring in FY 2015. HiSOR has a long term cease period to have routine inspections in summer every year. The total user time of FY2015 achieved 1338 hours. Fig. 4 shows bar graph of total operation days in each fiscal year. It shows that days for user operation in FY2015 was the highest for the last decade. Operation times of the storage ring and the Microtron from FY 2006 to FY 2015 are shown in Fig. 5.

To solve the problem of the water leakage from the absorber completely (see 'HiSOR Activity Report 2014' in detail), a new absorber was constructed with an improved design. It was installed during the regular maintenance period at the summer shutdown. Because of recovering the degree of vacuum, commissioning operation of the storage ring was additionally needed in October and the first week in November. As the result, the operation time and user time was gradually recovered at the end of this fiscal year.







Fig. 4: Operation days of HiSOR storage ring.



Fig. 5: Annual operation time of Storage ring and Microtron.

Beamlines

A total of 13 beamlines has been constructed so far; three normal-incidence monochromators, seven grazing-incidence monochromators, two double crystal monochromators and apparatus for white beam irradiation (Fig. 1). Table 1 lists the beamlines at present together with the main subject, energy range and monochromators.

beamline	source	monochro- mator	subject	energy range (eV)	status
BL-1	LU	GIM	Polarization dependent high-resolution ARPES	22-300	in use
BL-3	BM	DCM	Surface XAFS	1800-3200	in use
BL-4	BM		White beam irradiation		closed
BL-5	BM	GIM	ARPES and PEEM	40-220	in use
BL-6	BM	GIM	Gas-phase photochemistry	200-1200	in use
BL-7	BM	GIM	ARPES	20-380	in use
BL-8	BM		Beam diagnosis		
BL-9A	HU/LU	NIM	UV-VUV high-resolution ARPES	5-35	in use
BL-9B	HU/LU	GIM	High-resolution spin-resolved ARPES	16-300	in use
BL-11	BM	DCM	XAFS	2000-5000	in use
BL-12	BM	NIM	VUV-CD of biomaterials	2-10	in use
BL-13	BM	GIM	Surface photochemistry	60-1200	in use
BL-14	BM	GIM	Soft-XMCD of nano-materials	400-1200	in use
BL-15	BM	NIM	VUV-CD of biomaterials	4-40	closed
BL-16	BM		Beam profile monitor		

Table 1: List of Beamlines

At present, nine beamlines BL1, BL3, BL6, B7, BL9A, BL9B, BL11, BL12, BL13 and BL14 are opened for users. Furthermore, three off-line systems, spin- and angle-resolved photoemission (SARPES) spectrometer, inverse-photoemission (IPES) spectrometer and low-temperature scanning tunneling microscope (LT-STM) system have also opened for users (Fig. 2).



Fig. 1: Schematic view of the experimental hall.



Fig. 2: Experimental apparatus for Joint usage and Joint research. (a) BL-1, (b) BL-3, (c) BL-6, (d) BL-7, (e) BL-9A, (f) BL-9B, (g) BL-11, (h) BL-13, (i) BL-14, (j) BL-12, (k) Spin resolved photoemission (offline), (l) Resonant inverse photoemission (offline), (m) LT-STM (offline).

Research Activities

- Accelerator Studies -

Magnetic design of Knot-APPLE undulator and its performance

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Keywords: undulator

In order to generate a low energy photon beam in a high energy storage ring with an insertion device, it is necessary to increase the undulator's deflection parameter, K. If this is the case, a high heat load on beamline elements is a serious problem because the on-axis radiation power increases drastically as increasing the value of K parameter for a linear undulator. To reduce the on-axis heat load, the Figure-8 undulator, the Knot undulator and other exotic undulators were proposed [1-4].

In a Figure-8 undulator, the period length of horizontal magnetic field is twice as large as that of vertical field, and hence the projected beam orbit draws a figure of number 8. The direction of velocity vector of electrons always deviates from the undulator axis, and projected motion of electrons draws alternately a clockwise and anti-clockwise orbit, which results in the cancellation of circular polarization of the photons and leaves a remanent linear polarization.

In a Knot undulator, the magnetic field period in horizontal direction is 1.5 times larger than that of the vertical direction, and hence the undulator period is 3 times larger. The direction of velocity vector never coincides to but rather always deviates from the undulator axis. The spatial distribution of corresponding power density draws a knot-like figure.

However, neither Figure-8 nor Knot udulator has the capability to change polarizations. On the other hand, the APPLE undulator is capable to generate variable polarization, but is not capable to reduce on-axis power density in linear modes. We propose a novel Knot-APPLE undulator which is capable to reduce an on-axis high heat load and generate every polarization state.

Firstly, we designed Knot-APPLE undulator for Shanghai Synchrotron Radiation Facility (SSRF). Figure 1 and 2 show magnet structure of Knot-APPLE undulator. Second, we modified magnet structure suitable for low energy storage ring such as the HiSOR-II ring to evaluate the performance of Knot-APPLE undulator.

Figure 3 and 4 show examples of magnetic field distribution and expected angular power distributions, respectively.



FIGURE 1. This is the RADIA model of magnet structure for a Knot-APPLE undulator.



FIGURE 2. Another RADIA model of magnet structure for a Knot-APPLE undulator.



FIGURE 3. Magnetic distribution of Knot-APPLE undulator (horizontal linear mode).



FIGURE 4. Angular power distribution of Knot-APPLE undulator (horizontal linear mode).

Expected radiation spectra and power densities of various mode for Knot-APPLE undulator are presented in the presentation.

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Sound of Quasi-Periodic Undulator

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Keywords: Undulator

The synchrotron radiation generated by a periodic linear undulator contains higher harmonics of integral multiple of fundamental harmonic in the spectrum. These higher harmonics are usually harmful for user's experiments. In many cases, it is not so easy to eliminate unwanted higher harmonics by using conventional optical elements such as a single grating monochrometer. In order to solve this problem, a scheme of QPU(Quasi-Periodic Undulator) was proposed. The QPU is realized by modifying the magnetic structure so that the sequence of phase slip in each half period is corresponding to the order of quasi-periodicity. A conventional QPU is realized by introducing a smaller phase slip at appropriate positions in a periodic undulator. A new type QPU can be realized by introducing a larger phase slip. Figure 1 shows the magnetic field distribution for two different types of QPU. The light spectral features of two different types of QPU are shown in Fig.2.



Fig.1. Magnetic field distribution (a) conventional QPU, (b) new type QPU



Fig.2. Radiation spectrum (a) conventional QPU, (b) new type QPU

For the intuitive grasp of differences between two undulators, there is a method of converting the light spectrum to the sound. The light is a transverse wave propagating in vacuum. The sound is longitudinal wave propagating in the medium. The light and sound are considered equivalent in terms of vibration felt by the five senses. In this study, we convert the light spectrum to the sound in the audible range, and investigate the possibility to clearly distinct the differences in spectrum. Figure.3 shows waveform of sound normalized by the first harmonic. These results indicate that the spectral differences of radiation spectra can be clearly distinguished by hearing the sound.



Fig.3. Wave forms of (a) periodic undulator, (b) conventional QPU, and (c) strong field QPU radiations

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Design for New Type Quasi-Periodic Undulator

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The synchrotron radiation generated by a periodic linear undulator contains higher harmonics of integral multiple of fundamental harmonic in the spectrum. These higher harmonics are usually an obstacle to user's experiments. Therefore, to reduce higher harmonic contamination, such a user has to use many optical elements such as a monochromator, a band-pass filter, and a mirror to eliminate unwanted harmonics. However, such kind of beamline setup between an undulator and an end-station may cause a reduction of photon beam intensity. In order to ease such difficulties, quasi periodic undulator was developed in which higher harmonics appear at irrational positions instead of rational positions in the spectrum. A combination of a quasi-periodic undulator (QPU) and a single monochromator can provide purely monochromatic photon beam for end-users.

Until today, quasi periodic undulators used in all over the world are designed such that the peak magnetic field strength at certain positions representing the quasi-periodicity is reduced to introduce a smaller phase advance of photon wave at every QP position in an undulator. In this study, we design a new type quasi periodic undulator by increasing the magnetic field strength at every QP position to introduce a larger phase advance of photon wave. Fig.1 shows the magnetic structure of new QPU. The field variation of this undulator is presented in Fig.2. The spectral feature of this new QPU is shown in Fig.3. In the poster presentation, we introduce a new QPU model, and compare capabilities of new type QPU and conventional QPU by various conditions as shown in Fig.4 and Fig.5.



Fig.1. RADIA model of a new QPU



Fig.2. Magnetic field distribution of new QPU



Fig.3. Radiation spectrum from new QPU calculated by the code SPECTRA



Fig.4: Comparison spectra of three different type of undulator ($E_{1st} = 30 \text{ eV}$).



Fig.5: Comparison spectra of three different type of undulator ($E_{\sim 3rd} = 90 \text{ eV}$).

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Research Activities

- Instrumental Developments -

Present status of VUV-laser based spin-ARPES system

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Keywords: Spin- and angle-resolved photoemission, VUV-Laser, VLEED

Spin- and angle-resolved photoemission spectroscopy (SARPES) is a very powerful tool to investigate the spin-dependent electronic structure in materials. Combination of the hemispherical electron analyzer with the state-of-the-art spin detector based on very low energy electron diffraction (VLEED) scheme utilizing the ferromagnetic target allows us to reveal the detailed spin texture of strong spin-orbit coupled materials such as Rashba systems, topological insulators and Weyl semimetals [1,2]. However, in the case of magnetic materials *e.g.* time-reversal symmetry breaking Weyl semimetals, it is difficult to get signals solely from a single magnetic domain, which is typically smaller than the light spot size. To overcome this problem a high spatial resolution is prerequisite. The use of the laser light source is one solution because it is easy to obtain the well-focused light with a small spot size. Furthermore, the highly efficient VLEED is advantageous to obtain the signal from the quite small spot with a diameter (< 10 μ m). Therefore, in this apparatus, we combined VUV-laser light source with the VLEED spin detectors.

Figure 1 shows the schematic image of our VUV-laser based SARPES system. The system consists of hemispherical electron analyzer, double VLEED-type spin detector, motorized 5axis goniometer (i-Gonio) with cryostat, the ultra-high vacuum chambers and VUV laser system. The hemispherical electron analyzer DA30-L has the horizontal and vertical electron deflectors (30 degrees full cone acceptance), which enables us to measure the spin integrated/resolved band dispersion and the constant energy contours without sample rotation by manipulator. This is a good advantage for the measurement of very small or the magnetic samples. Two VLEED spin detectors are attached orthogonally to the electron analyzer to make a vector analysis of spin polarization with three components in the Cartesian coordination system $(P_x, P_y, \text{ and } P_z)$ possible. This system equips two photon sources: (1) non-monochromatized He discharge lamp, and (2) photon energy tunable VUV laser (5.90 – 6.49 eV).



FIGURE 1. Schematic image of the VUV-laser based high efficiency SARPES system. The two VLEED detectors (VLEED White and VLEED Black) are orthogonally set each other.

In order to check the performance, we have performed ARPES and SARPES experiments for Bi(111) single crystal with He discharge lamp. Figs. 2(a) and 2(b) show the band dispersion of Bi(111) along $\overline{\Gamma K}$ and $\overline{\Gamma M}$ lines, respectively. Fig. 2(c) shows the constant energy contours acquired at several binding energies (E_B). The observed band dispersions and the hexagonal Fermi surface shape are consistent with the former results [3] though they are a little broadened due to an insufficient surface preparation. We have tried to measure spin polarizations in two ways. One is to acquire spin polarizations with deflector while the orientation of the sample surface fixed. The other is to measure spin polarizations by changing the surface orientation. Figures 2(d) and 2(e) show spin-resolved energy distribution curves (EDCs) obtained at $\pm 7^{\circ}$ from $\overline{\Gamma}$ point along $\overline{\Gamma K}$ and $\overline{\Gamma M}$ lines [white dashed lines in Figs. 2(a) and 2(b)]. The spin-up (I_{\uparrow}) and spin-down (I_{\downarrow}) intensities obtained from $I_{\uparrow} = (1 + P)I/2$ [$I_{\downarrow} = (1 - P)I/2$] with deflectors are denoted with open circles. The corresponding intensities denoted with filled circles are the results taken with sample rotation. Since these results are quite similar to each other, the results indicate that the data acquisition by deflectors works accurately as the conventional method with the sample rotation does. The effective Sherman function was also estimated to be ~0.25 by comparing to the previous study [1].

The installation of focusing lens and the modification of manipulator for high precision position control are now in progress for the measurement with higher spatial resolution.



FIGURE 2. Band dispersions and spin-resolved intensities of bulk Bi(111) crystal with He discharge lamp. (a),(b) ARPES images along $\overline{\Gamma K}$ and $\overline{\Gamma M}$ lines, respectively. (c) Constant energy contours acquired at $E_{\rm B} = 0.0$, 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 eV. (d),(e) Spin-resolved EDCs obtained with/without the deflector at $\pm 7^{\circ}$ from $\overline{\Gamma}$ point shown by dashed lines in (a) and (b).

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