Hiroshima Synchrotron Radiation Center at Hiroshima University

Kenya Shimada
Hiroshima Synchrotron Radiation Center (Hisor), Hiroshima University, Japan

Fig. 1: The Hiroshima Synchrotron Radiation Center, Hiroshima University.

INTRODUCTION

The Hiroshima Synchrotron Radiation Center is a common synchrotron facility located at the Higashi-Hiroshima campus of Hiroshima University in Japan (Fig. 1). The campus is about 30 km east of Hiroshima city and about 20 km south-east of Hiroshima Airport. The center was established in 1996, as part of the academic policies of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan [1, 2]. Since 2010, the center has been authorized as a Joint Usage / Research Center by MEXT.

The center has two missions, namely, the promotion of advanced research in the field of condensed matter physics using synchrotron radiation in the vacuum ultraviolet (VUV) and soft X-ray (SX) range, and the development of human resources as a facility established inside Hiroshima University [1, 2].

ACCELERATOR SYSTEM AND UNDULATORS

The accelerator system at the center consists of a 150 MeV injector microtron (Fig. 2), a beam transport line, and a racetrack-type 700 MeV electron-storage ring (HiSOR) (Fig. 3) [3]. HiSOR is now often used as a name of the center. The peak electron current from the microtron is 10 mA, and the repetition rate is variable between 0.2 and 100Hz. HiSOR is a racetrack-type electron storage ring with a circumference of 22 m. The 180° normal conducting bending magnets yield 2.7 T in the electron-storage mode, and the bending radius is 0.87 m, providing a critical wavelength of λ=1.42 nm (hν=873 eV). Table 1 lists parameters of the accelerator system [2, 3].

We operate HiSOR (machine tuning + user time) about 42 weeks (210 days), for 2,000 hours, a year. Typically, Monday is the day for machine tuning, and from Tuesday to Friday is for the beamline users. We inject HiSOR twice a day at 9:00 and 14:20, and stop at 20:00. The total user time is about 1,500 hours per year.

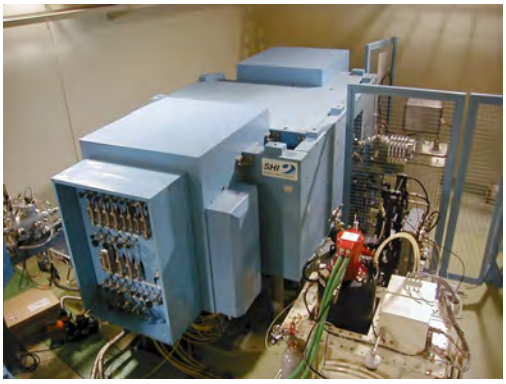

Fig. 2: 150 MeV racetrack microtron.

Fig. 3: 700 MeV racetrack synchrotron (HiSOR).

In the two straight sections of HiSOR, we installed a linear undulator [4] and an APPLE-II type undulator [5]. The linear undulator covers a photon energy range of 22 - 300 eV, and the APPLE-II undulator covers 6-300 eV. Figure 4 shows the HiSOR's spectrum.

Table I. Parameters of the HiSOR accelerator system.

Storage ring	Racetrack synchrotron
Injector	Pulsed racetrack Microtron
Circumference of storage ring [m]	21.95
Beam energy [MeV]: Injection / Storage	150 / 700
Magnetic Field of Bending Magnet [T]: Injection / Storage	0.6 / 2.7
Bending radius [m]	0.87
Betatron tune (ν_x, ν_y)	(1.72, 1.84)
RF Frequency [MHz]	191.244
Harmonic number	14
RF voltage [kV]	200
Maximum stored current [mA]	350
Natural emittance [π nmrad]	400
Beam lifetime [hours@200mA]	~10
Critical wavelength [nm] (photon energy [eV])	1.42 (873)

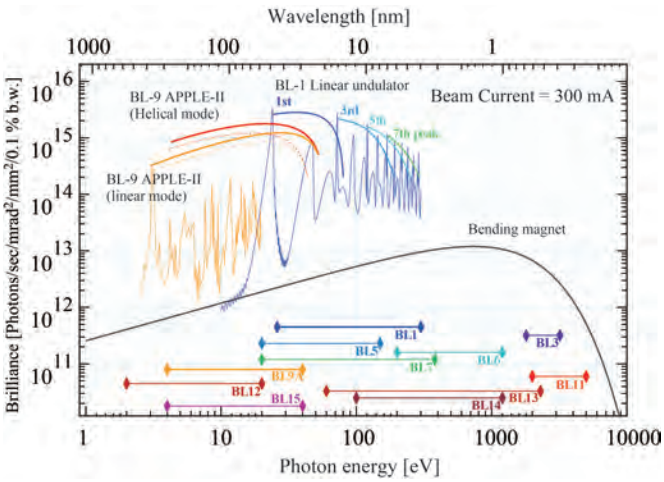

Fig. 4: The spectrum of HiSOR and the energy range covered by each beamline.

BEAMLINES

HiSOR has 16 beam ports: two ports for the undulator beamlines and 14 for bending magnet beamlines (Fig. 5) [1, 2]. We have constructed 15 beamlines in total, including two beam monitoring beamlines. The photon energy range covered by HiSOR is suitable for studying detailed electronic states in solids (energy-band dispersions, Fermi surfaces, spin polarization, and many-body interactions) as well as structural studies of biomolecules in solution using vacuum ultraviolet circular dichroism. Below, we describe the beamlines in our priority area. On our webpage, we provide a publication list of experiments performed from these beamlines [2].

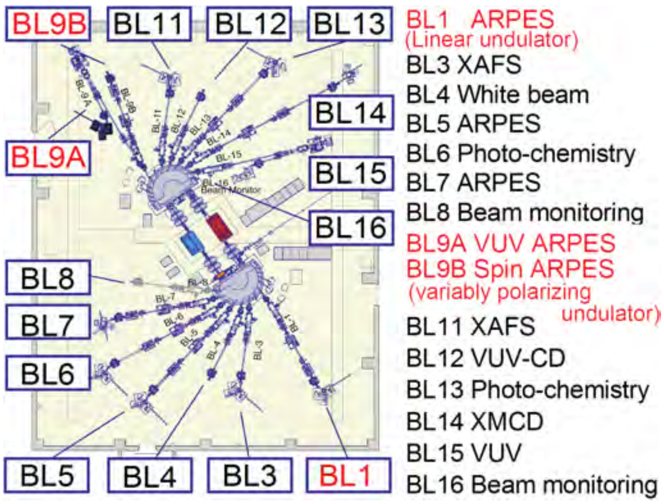

Fig. 5: Beamlines at HiSOR.

BL-1

On the linear undulator beamline BL-1 (photon energy range: hν = 22-300 eV) [4], we have installed a unique rotatable angle-resolved photoemission spectroscopy (ARPES) system [6]. The recent addition of a micro-focusing capillary-type mirror greatly improved the efficiency and capabilities of the end station. We have investigated fine electronic structures due to many-body interactions near the Fermi level, and the band structure and symmetry of wave functions of novel materials [7].

BL-9A/9B

On the APPLE-II undulator beamline, we have constructed two branch beamlines BL-9A (hν = 5-35 eV) equipped with an ultrahigh resolution ARPES system [8] and BL-9B (hν = 16-300 eV) equipped with a highly efficient spin- and angle-resolved photoemission spectroscopy (SARPES) system [9]. BL-9A has enabled many studies on the fine details of the electronic states in strongly correlated materials and topological materials with high momentum and energy resolutions as well as variable photon energy and polarization [10]. BL-9B allows examinations of the three-dimensional spin structure of magnetic materials, as well as spin texture induced by the strong spin-orbit interaction in topological systems [11]. BL-9A and 9B attract many proposals, and about half of the beamtime is allocated to collaborators from outside of Japan.

BL-12

On beamline BL-12 (hν = 2-10 eV), we have installed a vacuum ultraviolet circular dichroism (VUV-CD) spectrometer for the structural analysis of biomolecules (proteins, sugars, and nucleic acids) in solution [12]. The VUV-CD system was developed at our center and has been recognized as a powerful tool to clarify the structures of a wide range of samples under various solvent/environmental conditions [12].

BL-14

Beamline BL-14 (hν = 400-1200 eV) is used for soft X-ray magnetic circular dichroism (SXMCD) [13]. The beamline is specially designed to make atomically-controlled thin films or nanostructures on substrates in situ and to characterize their magnetic and electronic properties without exposing the films or nanostructures to air [13]. The beamline also accepts various magnetic thin films or bulk samples fabricated outside the center.

JOINT USAGE / RESEARCH

We call for proposals (category G) twice a year. The details of the application procedure can be found in our webpage [2]. The beamtime schedule had been planned, taking into account the preferences of the applicants. After the deadline for the category G, we may accept urgent proposals (category U), which should have significant academic importance and/or justification of urgency. We accept about 130 proposals a year, and 230 researchers (actual number), including undergraduate and graduate students, visit us to run experiments. About 30% of the users are international researchers, providing domestic students with an international atmosphere in the center. From 2004 to 2018, we collaborated with researchers from 75 institutions in Japan and 80 institutions abroad. More details of the joint usage / research are described in our annual Activity Report, available from our webpage [2].

HUMAN RESOURCE DEVELOPMENT AND OUTREACH

As a part of Hiroshima University, the center is involved in developing human resources, not only through lectures and seminars, but also through research activities using synchrotron radiation. Undergraduate and

Fig. 6: (Top) Junior high students visiting HiSOR. (Bottom) The 23rd Hiroshima International Symposium on Synchrotron Radiation.

graduate students can participate in domestic or international collaborative projects and directly learn about the latest research activities in the field. In the period from FY2016-2019, based on the synchrotron radiation experiments at HiSOR, 35 students each wrote a graduation thesis, 20 students each wrote a master thesis, and 6 students each received a phD. All of the faculty members at HiSOR (4 professors and 4 associate professors) give lectures for undergraduate/graduate students and supervise students.

Every year we accept about 500 visitors from elementary, junior high, and high schools, mainly from peripheral prefectures. We show advanced research facilities and provide an opportunity for students to experience some hands-on experiments while having fun. We also accept facility tours for overseas students and educators and provide seminars in English.

We also hold the Hiroshima International Symposium on Synchrotron Radiation in March every year, in addition to several seminars and workshops [2].

FUTURE PLANS

After the construction of HiSOR, many low-emittance storage rings have been constructed. While we have made efforts to keep HiSOR running and have continuously upgraded beamlines/end-stations for more than 20 years, we cannot compete with other state-of-the-art facilities if the experiments require a small and intense photon beam. To further extend research opportunities, it is high time to consider a compact low-emittance electron storage ring, HiSOR-II, as a crucial part of our future plans.

In the latest design study for HiSOR-II [14], we adopted a lattice structure (Fig.7) similar to ASTRID2, which is a compact storage ring located at Aarhus University, Denmark. In this study, we set the electron energy at 500 MeV and used a circumference of 50 m. Figure 8 shows

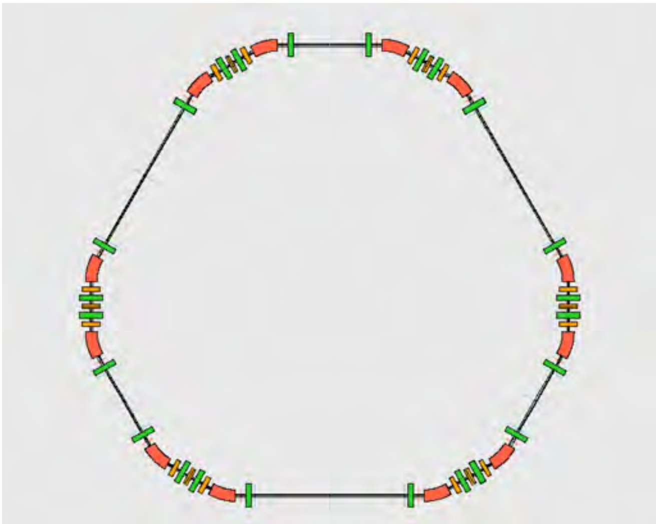

Fig. 7: Lattice of HiSOR-II in the design study [14].

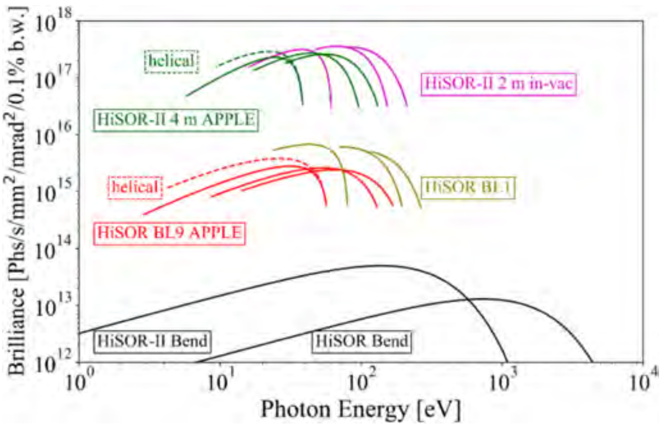

Fig. 8: Brilliance of the synchrotron radiation from HiSOR-II obtained from our recent design study [14].

the calculated brilliance of HiSOR-II being compared to that of HiSOR. We have found that the emittance (which is presently 400 nm) could go down to 9.4 nm and brilliances of photons with energies around 10 eV could exceed 10^{17} photons/mm^2/mrad^2/0.1%b.w.; our findings, therefore, show a promising forecast for HiSOR-II [14].

To prepare for HiSOR-II, we have already started R&D for measurement systems. Using ultraviolet lasers, we have developed an ultimate resolution ARPES system with high spatial resolution [15]. We have produced a less than 10 μm beam spot using a focusing lens, and have achieved energy resolution of 260 μeV and angular resolution of <0.05°. For this system, we have newly developed high-precision translators for sample positions, and a control system for spatial mapping [15]. The instruments have been already used for the joint usage / research proposals [16]. These systems are now being applied to the spin-resolved ARPES system, and would be also applied to the beamlines of HiSOR-II.

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Kenya Shimada has been the director of Hiroshima Synchrotron Radiation Center, Hiroshima University since 2017. He graduated from the Department of Physics, University of Tokyo, Japan in 1991, and received his PhD in physics from University of Tokyo in 1996. During his time in graduate school, he worked on the spin-polarized photoemission spectroscopy beamline at the Photon Factory, High Energy Accelerator Research Organization (KEK-PF). After receiving his PhD, he worked at the Hiroshima Synchrotron Radiation Center, Hiroshima University in 1996 and participated in the construction of the facility. He has worked as a research associate (1996-2002), associate professor (2002-2010), and professor (2010-) at the center. His research field is experimental condensed matter physics, especially the study of the electronic structures of correlated materials using synchrotron-based high-resolution photoemission spectroscopy.