Report of the International Review Committee on the Meeting at Hiroshima Synchrotron Radiation Center March 1-2, 2012

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Executive Summary of the International Review Committee Meeting at Hiroshima Synchrotron Radiation Center, March 1-2, 2012

The International Review Committee (IRC) met at Hiroshima University March 1-2, 2012, to review the scientific activities at HiSOR. The IRC had been provided with extensive background material before the meeting and complementary information during the review. The HiSOR management was most helpful in answering questions during the review and the IRC commends it for a professionally organized meeting. The IRC also wants to express its gratitude for the great hospitality it was shown throughout its stay at HiSOR.

The review was in conjunction with the 16th International Symposium on Synchrotron Radiation. This gave the IRC the opportunity to listen to a number of excellent presentations by HiSOR scientists and interact with young scientists at a poster session that gave a panorama of recent research activities, consistently very well displayed, informative and of high quality.

In the opening address to the Symposium the President of Hiroshima University, Dr. Asahara, underlined the important role HiSOR has for research and education at his University. The IRC was very impressed by the commitment the University Administration has to the success of HiSOR. A recent demonstration is the establishment of two research positions for young scientists: one in Electronic Structure of Solids and the other in Structures of Bio-Materials. The IRC highly commends the Administration for this decision since it will greatly impact the excellence of science at HiSOR in two very important areas. The Director of HiSOR, Dr. Taniguchi, gave a most impressive summary of the HiSOR activities and provided highlights of some of the most remarkable research results.

The main focus of the review was on the quality of work in the five major categories including four scientific research areas: electronic structure analysis, spin structure analysis, nanomaterials analysis, and circular dichroism of biomaterials, and an R&D on accelerators and insertion devices. A detailed assessment is given in the Report proper. It is sufficient to say in this summary that the IRC gives the quality of the research in all these areas the highest mark. The research is consistently world-class and in many cases world-leading. This is demonstrated qualitatively by publications in the most prestigious science journals, e.g. in 2010 and 2011 there were 11 and 5 papers in Nature, Science and Physical Review Letters, and a remarkable overall high productivity with a total of 50 and 41 papers in peer-reviewed journals, respectively.

HiSOR has been highly successful in implementation of the “Joint Usage” concept, in which HiSOR staff members are directly involved in the collaborative research triggered by external users. It is a key concept in running the facility. The IRC congratulates

HiSOR to the success and strongly recommends that the “Joint Usage” model is continued.

Overall the IRC finds that HiSOR is doing exceptionally well in continued upgrades and incessant maintenance of beam line components and end-stations. This has been a key for the great success of the scientific programs at the facility up to now, and the IRC considers it of paramount importance that the support, human and financial, continues to be in the future.

The full Report provides ample samples where HiSOR is in the frontier world-wide in providing experimental capabilities. For example, there are only about 10 working instruments world-wide for spin-resolved ARPES and HiSOR has positioned itself excellently for research in the rapidly growing field of spintronics. The IRC welcomes and strongly endorses the implementation of the 3D spin polarimeter based on two orthogonal VLEED-type spin detectors. In the important field of nanomaterials HiSOR is pursuing, among other things, to combine soft x-ray magnetic circular dichroism (XMCD) with scanning tunneling microscopy (STM) for in situ studies. These techniques are complementary and will add significantly to the analysis of nanomaterials. The IRC gives its full endorsement to the planned move of the UV Circular Dichroism beam line to BL-12. This move will result in a significant increase in the flux and in combination with proposed upgrades will enhance the capabilities for CD research. For the long term the IRC recommends a replacement of the current instrument to establish a state-of-the-art facility for competitive future research.

The existing machine has an excellent stability and reliability. The IRC takes note of the fact that this is accomplished by a three person group and extends its congratulations and full appreciation to the dedicated machine team.

The IRC was very impressed by the upgrade program of insertion devices (e.g. APPLE II undulator) and beam lines (stabilization for environmental noise and temperature drifts) that are so crucial for successful user operation. The IRC fully supports the R&D activities related to an optimized quasiperiodic scheme for the APPLE II undulator, and the design of the new, so-called Leaf Undulator.

The IRC was presented with very compelling plans to replace the existing HiSOR race-track machine with a new storage ring with an emittance of about 20 nmrad, as compared to 400 nmrad for the present machine. In the opinion of the IRC there is an exceedingly strong scientific case for such a development, in fact a necessity if HiSOR is going to keep its position of producing world-class research 7-10 years from now. The analysis of the electronic structure, the spin structure and nanomaterials for ever-increasing advanced materials systems will require techniques that demand higher brightness, i.e. a low emittance storage ring. The IRC strongly endorses a vigorous R&D effort that defines this new machine, a machine that can fit into existing space next to the present facility. The IRC considers it urgent that the work on the very promising concept, that was presented to the Committee, is accelerated.

The knowledge and dedication of the scientific and technical staff at HiSOR made a very strong impression on the IRC. With this staff HiSOR is in excellent position to continue highly successful research programs, develop cutting-edge new instrumentation, and pursue its plans for a new source.

It was clear to the IRC that HiSOR fulfills the highest expectations the Hiroshima University has for this facility on Campus. The collaborations between scientists at HiSOR and other institutions, both in Japan and abroad, have been remarkably successful. As an example, between 25-35% of the proposals for research on BL-1 and BL-9A have been from abroad during the last four years. HiSOR also has a highly appreciated outreach program to the public.

In summary, the IRC was given the opportunity to carefully evaluate the quality, and related issues, of the science programs at HiSOR and concludes without any reservations that HiSOR is a superbly managed facility that produces outstanding world-class research.

Stanford, March 31, 2012.

Ingolf Lindau, Chair
(On behalf of the IRC)

Introduction

Hiroshima Synchrotron Radiation Center, HiSOR, was established in 1996 as a national facility located at Hiroshima University. The mission of HiSOR is the promotion of materials research and the development of human resources in the field of synchrotron radiation science. HiSOR was authorized as a Joint Usage/Research Center in April 2010 for a period of 6 years by the Ministry of Education, Culture, Sports, Science and Technology (MEXT). According to this authorization the mid-term plan of HiSOR is defined to focus on the following research areas:

- Researches on key problems in solid-state physics by means of ultra high-resolution photoemission.
- Researches on spin structures in magnetic and non-magnetic materials by high-resolution and spin-resolved photoemission.
- Researches on nano-materials using advanced equipment, which is particularly optimized to the research of nano-science.
- Researches on structure analysis of bio-molecules using original apparatus developed at HiSOR.
- R&D of high-brilliance compact light source

The MEXT is planning to have a mid-term evaluation of the HiSOR activities in 2013. The evaluation will include the quality of the science, the research productivity, efficiency of the organization, national collaborative efforts, international exchange programs, student education at undergraduate and graduate levels, and outreach program to the public.

In this context the International Review Committee (IRC) was charged to evaluate the scientific research activities at HiSOR. Below is a detailed assessment of the five research areas listed above.

The IRC had been provided with extensive background material in advance of the evaluation that took place March 1-2, 2012. The evaluation was in conjunction with the 16th Hiroshima International Symposium on Synchrotron Radiation. This gave the IRC an excellent opportunity for insights into the activities at HiSOR. In the opening address the President of Hiroshima University, Dr. Asahara, emphasized the important role HiSOR has for research and education at his university. Dr. Taniguchi, the Director of HiSOR, gave a clear perspective of the present activities and future plans for the facility. Five HiSOR scientists, Drs. Shimada, Sasaki, Matsuo, Okuda and Sawada gave excellent presentations of the key areas of research. In a lively poster session with 53 contributions young researchers presented their results on meticulously well-prepared posters. The IRC greatly appreciated the opportunity to interact with the enthusiastic and knowledgeable students and postdocs.

During the evaluation process on March 2 the HiSOR management was most helpful in answering all the questions and requested clarifications from the IRC members. The IRC wants to express their sincere thanks to the management for its extended efforts in making the evaluation process both informative and transparent.

Research Areas

1-1. Electronic structure analysis (BL-1, BL-9A)

Current Status

The linear and helical undulator beam lines BL-1 and BL-9A installed along the two straight sections of the HiSOR synchrotron radiation source, are designed for high-precision analyses of solid state electronic structures by high-resolution photoemission spectroscopy (PES) using high-brilliance synchrotron radiation in the vacuum ultraviolet (VUV) to soft X-ray range (SX, $h\nu$ < 300 eV) and to conduct the Joint Usage/Research programs at the frontier of knowledge. In 2009, the Hiroshima Synchrotron Radiation Center (HiSOR) increased the number of staff members dedicated to the beam-lines, and since 2011, two staff members are working at each of the two measurement stations. The HiSOR staff has been committed to the improvement and upgrading of the beam-lines and their end-stations on a continuous basis, providing an optimal environment for the Joint Usage/Research programs. In 2010, these two beam-lines hosted different projects in the frame of the "Invitation Program for Advanced Research Institutions in Japan" by the Japan Society for the Promotion of Science (JSPS). This is part of the ongoing effort to increase the number of international collaborations and to extend the scientific exchange. All joint research programs at HiSOR should in general involve the participation of the responsible staff members, which means that external scientists can acquire experimental data efficiently from the first day even if they are measuring at HiSOR for the first time.

Both undulator beam-lines are equipped with an up-to-date high-resolution angle-resolved photoemission spectroscopy (ARPES) analyzer (VG Scienta R4000) each and a high-precision low-temperature multi-axis goniometer, enabling detailed band-structure measurements and the efficient mapping of Fermi surfaces with high energy resolution (BL-1: ΔE = 5 meV, BL-9A: ΔE = 0.7 meV) and at low temperatures (5...8 K). The staff members are continuously updating existing hardware and software, including the development of an automatic data acquisition program that controls the goniometer. Non-evaporable getter (NEG) pumps have been installed at the ARPES analysis chamber, in addition to the standard pumping system to enhance the quality of the vacuum and to enable ARPES experiments under ultra-high vacuum (UHV, 2.0 x 10^{-9} Pa). Furthermore, various sample preparation tools, namely an annealing system, an Auger electron spectrometer, a low-energy electron diffraction (LEED) system, and an ion gun, have been installed in the attached preparation chamber to guarantee the reproducible *in situ* preparation and characterization of the single crystal surfaces.

In 2008, a completely new rotatable high-resolution ARPES system was constructed at BL-1, which allows a high-resolution analyzer to be rotated around the synchrotron radiation light axis and the sample. In addition to the change of the orientation of the linear polarized light, this option allows for an independent modification of the experimental geometry. This system has been used in the Joint Usage/Research programs since 2009. In 2010, a metal deposition source and a reflection high-energy electron diffraction (RHEED) system were installed in the sample preparation chamber, which in addition to the other preparational devices described above, enable the preparation and the *in situ* monitoring of the growth of epitaxial metallic thin films.

At BL-9A, an existing five-axis goniometer was upgraded to a six-axis goniometer in 2008. The increased number of rotation axes and the expanded range of motion made it possible to cope with diverse requests during the study of fine electronic structures close to the Fermi surface. In the same year, a temperature control system was introduced to the grating, and a water cooling system was set up at the entrance and exit slits to reduce stabilize the light intensity and the energy resolution. A xenon plasma discharge lamp (*hν* = 8.4 eV) was installed in 2009, which made it possible to conduct low-energy high-resolution PES experiments even when synchrotron radiation is not available, for example at night time.

Evaluation

BL-1 is characterized by its high-resolution ARPES capability with linearly polarized undulator radiation in the VUV and SX region (*hν*□~ 20...300 eV), whereas BL-9A is characterized by the same capability with left- and right-handed circular polarization in the low-energy VUV region (*hν* □~5...30 eV). Leading scientists from Japan and abroad have visited these beam-lines on the Joint Usage/Research programs, including researchers from the University of Tokyo, RIKEN, the Japan Atomic Energy Agency, the National Institute of Advanced Industrial Science and Technology, the University of Colorado (United States), the University of Nebraska-Lincoln (United States), Iowa State University (United States), the Institute of Physics, Chinese Academy of Sciences (China), Fudan University (China), Yonsei University (South Korea), the University of Würzburg (Germany), the University of Rome (Italy), and Synchrotron SOLEIL (France). This attests to the high international competitiveness of BL-1 and BL-9A.

Results of the Joint Usage/Research programs at BL-1 and BL-9A have received very favorable evaluations both in Japan and abroad, as many of them have been selected for keynote lectures, invited talks and symposium talks, including at the Physical Society of Japan, the Japanese Society for Synchrotron Radiation Research, the American Physical Society, and the International Conference on Vacuum Ultraviolet and X-ray Physics (VUVX2010, where HiSOR accounted for 36 of a total 465 presentations).

BL-1 is hosting the Joint Usage/Research programs enabled by its polarization-geometry control, a major feature of its new system. The use of linear polarization of incident light helps to determine the symmetry of electronic states and to measure Fermi surfaces and band dispersion on a separate and selective basis. Since the new system has been installed, many results on the electronic structure in multi-band systems, including topological insulators, iron-based superconductors and ruthenate superconductors, have been published in *Phys. Rev. Lett.* and *Phys. Rev. B*.

At BL-9A, the introduction of the new high-precision six-axis goniometer has made it possible to control the orientation of samples with enhanced precision in the ultra-high-resolution ARPES experiments in the low-energy region. Research results on electronic structures of a variety of strongly correlated materials have been published in *Nature*, *Science*, *Phys. Rev. Lett.* and *Phys. Rev. B*, including precise evaluation of superconducting gaps, fine changes in the quasi-particle band, orbital patterns of organic molecules, and studies on oxygen isotope effects in cuprate high-temperature superconductors. The increasing number of the Joint Usage/Research programs at BL-1 and BL-9A, as well as the improving levels of their research results, demonstrate clearly that the HiSOR staff has been improving and upgrading the experiment stations to high and competitive international standards, and the commitment of the staff members has guided these programs to successful scientific results on a sustained basis. This success is obviously a consequence of the efforts that have been expended to collect data with both high efficiency and high precision within the limited beam hours available.

The versatility of the two ARPES undulator beam-lines becomes also evident in the different preparation options, which allow the users to prepare and characterize single-crystalline samples, nano-structured bulk and surface systems - as *e.g.* layered oxide hetero-structures and thin self-assembled organic films - without changing the experimental setup. This flexibility in surface preparation together with the highly reliable spectrometers and the excellent technical support at the end stations makes HiSOR for high-resolution measurements strongly competitive among synchrotron radiation facilities world-wide.

Perspective

The Hiroshima Synchrotron Radiation Center is a national shared-use research facility that delivers synchrotron radiation in the vacuum ultraviolet (VUV) to soft X-ray (SX) range, and it was authorized in 2009 to become a Joint Usage/Research Center. It is aggressively promoting joint research programs with leading scientists both in Japan and from abroad. To promote shared-use and joint research programs further, it is desirable to extend the operating hours and user hours of the storage ring and to increase the personnel accordingly.

Because of the international competitiveness of the BL-1 and BL-9A stations, overbooking of the beam time is emerging as an inevitable problem, in particular with the present restriction of operating time. In addition, it is desirable to complement the experimental setup by additional light sources, such as a frequency multiplied laser source or a xenon discharge lamp at BL-1, so that complementary high-resolution PES experiments can be conducted even when synchrotron radiation is not available. However, these additional light sources have by far not the versatility of the synchrotron light and can only be seen as an extension of the portfolio of experimental options at HiSOR. Particularly for external users both the beam time extension and the availability of additional high-resolution light sources would increase the scientific attractivity significantly.

The upgrading of the end station at BL-1 has made it possible to perform high-resolution ARPES with a control of the light polarization and experimental geometry. To further promote the Joint Usage/Research programs, it would be an important improvement to upgrade the beam-line to a quasi-periodic undulator to reduce the contribution from the higher-order radiation, which is helpful for high-resolution ARPES near the Fermi level in the low photon-energy regime. Additional important upgrades concern the grating and a water-cooled entrance slit in order to enhance both the resolution and the intensity. It is also recommended to improve the re-focusing mirror to reduce photon beam spot size at the sample position.

An upgrade of BL-9A to an APPLE-II type variable polarization undulator is already planned. As seen from the successful results on BL-1, this upgrade will enhance the international competitiveness since the control of the polarization direction for low-energy synchrotron radiation extends the range of applications significantly. Further improvements include the reduction of the heat load at the monochromator, which becomes necessary because a new undulator will also increase the thermal loads of the optical elements. It is essential to make sure that the light intensity is stable at the measurement position, which means that energy drifts and intensity variations with time due to heat load of the optical components must be avoided.

In the future it will be necessary to conduct studies related to the realization of a new low-emittance light source, e.g. by parallel use of a frequency-multiplied laser source, while at the same time the steady improvement of the beam-lines and end-stations must be certainly continued to ensure the most efficient use of the existing light source.

1-2. Spin structure analysis (BL-9B, Spin-ARPES)

Current status

HiSOR has been developing and improving spin- and angle-resolved photoemission spectroscopy (spin-resolved ARPES) instrumentation that can measure spin-resolved electronic structures directly. In particular since the recent discovery of topological insulators and their spin-polarized surface states such instrumentation has been in high demand. A spin-resolved ARPES chamber with a Mott spin detector has been recently upgraded. Via in-house research and often via Joint Usage/Research Projects its use has been promoted nationally and internationally. In parallel, a novel spin-resolved ARPES instrument with highly efficient spin detection based on very-low-energy electron diffraction (VLEED) has been under development since 2010 as an endstation for the BL-9B helical undulator beamline.

These instruments represent excellent cases in point for a Joint Usage/Research facility: high expertise is required to operate these spin-resolved ARPES devices, because they are not commercialized products but were developed and upgraded at HiSOR. HiSOR therefore employs dedicated staff members who are versed in frontier technologies and know-how on these systems and have outstanding scientific achievements in spin structure analysis. HiSOR has maintained a high performance of these instruments through adjustments, improvements, and upgrades.

The Mott-type spin-resolved ARPES system has produced outstanding results using an intense He lamp, as illustrated prominently by direct measurements of a Rashba-type spin splitting in the monolayer of lead adsorbed on a semiconductor surface and, for the first time, in a bulk semiconductor (BiTeI). These results were published in Nature Communications and Nature Materials, respectively, and they have attracted a lot of attention within the surface science and condensed matter physics communities.

At HiSOR, a new spin-resolved ARPES system with a VLEED spin detector has been designed, which combines a high-resolution ARPES analyzer (VG Scienta R4000) with a VLEED spin detector that has more than 100 times the efficiency of a Mott spin detector. This pioneering development permits to carry out spin-resolved ARPES measurements much faster and with unprecedented energy and angular resolution. The system is also equipped with a high-precision low-temperature five-axes goniometer, which enables precise measurement of Fermi surfaces. Test measurements with an intense He lamp confirmed an angle resolution of $\Delta\theta < \pm 0.19$ and an energy resolution of $\Delta E \leq 10$ meV in the spin-resolved measurement mode. At the 16th Hiroshima International Symposium on Synchrotron Radiation, first results obtained with this system were presented on the peculiar spin texture in the surface state on Bi(111), resolving some inconsistency found in a study published by another group.

This new spin-resolved ARPES system is installed at BL-9B, a branch line of the BL-9 variable polarization undulator beam line, and further improvements are underway toward the realization of spin-resolved ARPES experiments with a control of incident light polarization, namely left- and right-handed circular polarization and horizontal and vertical linear polarization. The beam line is equipped with a Dragon-type grazing incidence monochromator, and the photon energy range of 16-300 eV is available. Along with these advanced features, an energy resolution of $\Delta E = 15$ meV or better is expected to be achieved in spin-resolved ARPES in the 16-40 eV range.

The sample preparation chambers of the Mott-type and VLEED-type spin-resolved ARPES instruments are each equipped with a high-temperature annealing system, an Auger electron spectrometer, a LEED, a RHEED, an ion gun and more than three deposition source ports. These facilities make it possible to prepare and characterize a variety of clean single-crystal surfaces, including single crystalline metal samples such as tungsten that need to be annealed at temperatures as high as 2000°C or more, as well as semiconductors and nanostructures.

Evaluation

The IRC emphasizes the importance of these two spin-resolved ARPES experiments and of maintaining their performance and stable operation, given the scarcity of places in the world where spin-resolved ARPES experiments can be conducted. The IRC also praises the strategy of having one system running with a well-established and reliably working Mott detector, while developing in parallel a new spin-resolved ARPES experiment based on a novel detector principle with much success and great promise for the near future.

The VLEED-type spin-resolved ARPES system has demonstrated an improvement of the spin detection sensitivity by more than 100 times compared to conventional spin detectors, and has also achieved an energy resolution of $\Delta E \leq 10$ meV and an angle resolution of 0.5° or better, which are among the highest resolutions reached in spin-resolved ARPES in the world. It currently enables precise spin-resolved measurements for materials or surfaces that require high energy and angular resolutions, such as topological insulators.

The Mott-type spin-resolved ARPES device has produced highly original results in the direct measurement of Rashba-type spin splittings of electronic bands on semiconductor surfaces with heavy elements deposited, such as Tl/Si(111) and Pb/Ge(111), and of bulk crystals, such as Bi(111) and BiTeI. These results were published in high-impact journals such as Nature Materials, Nature Communications, and Physical Review Letters.

In order to fully exploit the unique features of these spin-resolved ARPES experiments, versatile sample preparation facilities are needed. In the sample preparation chambers of both systems, it is possible to prepare and evaluate clean surfaces of single crystalline metals, nanostructures, and bulk samples including layered materials without changing the experiment setup. These features permit to prepare a variety of samples efficiently, and to respond quickly to new research trends in this fast moving field. For example, the high-temperature annealing system can heat samples up to 2000°C or more and clean the surfaces of tungsten and other metals, which has proven very useful. Clean tungsten surfaces are often used as substrates for the growth of ultrathin metal films.

The Joint Usage/Research programs using the spin-resolved ARPES instruments always involve the HiSOR staff members. This means that users can acquire high quality data efficiently from the first day even if it is the first visit for them. Due to the uniqueness and the complexity of the equipment there is no other way to operate.

At the VLEED-type spin-resolved ARPES system, which is installed at the end station of BL-9B, synchrotron radiation is currently unavailable at night. An intense He lamp has therefore been set up to enable nighttime measurements. While this definitely helps to increase the utilization and efficiency of the facility in preparing and characterizing samples and, in some cases also in obtaining high-resolution spin-resolved ARPES measurements, it would be highly desirable to be able to run experiments also during the night with synchrotron radiation excitation.

Perspective

The recent boom in spintronics and topological insulators research is raising demands for spin-resolved ARPES measurements. Given the global scarcity of spin-resolved ARPES instruments in operation, HiSOR can help to meet the demand by operating both systems in its possession, and thus play a prominent role in this research field. The demand is especially high for spin-resolved ARPES measurements using high-brilliance synchrotron radiation sources. Spin-polarized surface states on topological insulators are often located near bulk bands, hence high energy and angular resolutions are required and the possibility to tune the photon energy is crucial. HiSOR is expected to upgrade the BL-9B beam line and operate the VLEED-type spin-resolved ARPES system with synchrotron radiation especially in the vacuum ultraviolet range in the future. Presently, the system is mostly operated using an intense He lamp, but the use of tunable photon energy and polarization that are optimal for individual samples should enable precise measurement of their spin electronic structures. The use of synchrotron radiation is essential if the characteristics of the high-resolution spin-resolved ARPES systems are to be exploited to the fullest extent. Currently, companies like VG Scienta and SPECS are bringing commercial instruments on the market, but the development of the VLEED type spin detector at HiSOR will keep this facility ahead of the field.

On the other hand, the Mott-type spin-resolved ARPES systems, which uses an intense He lamp, has a large beam size that severely limits the attainable energy and angular resolution, and is not very well suited for small-size samples. Installing a mirror to reduce the spot size of the lamp at the sample position could help immensely. This should be implemented with high priority, as it represents a simple and relatively cheap way to make sure that this will remain a competitive instrument.

Both existing spin-resolved ARPES systems can only measure spin components in two of the three possible orthogonal directions. The measurement of the three-dimensional spin polarization vector provides essential information for research on unconventional spin textures in topological insulators, on spin-dependent electric conduction and spin fluctuations. The implementation of a three-dimensional spin polarimeter using a combination of two orthogonal VLEED-type spin detectors is currently underway. This is the world's first attempt to develop a highly efficient VLEED spin detector to determine three-dimensional spin polarization vectors. The IRC welcomes this development as it will help keeping HiSOR a world leading facility for spin-resolved ARPES, further increasing the demand for Joint Usage/Research projects.

Staff people at HiSOR have a long-term experience with designing and operating spin-resolved photoemission experiments, the institution is thus in an excellent position to develop a "multi-channel spin detector”, for which ideas are around. This would represent one of the world's most ingenious measurement systems for spin-resolved ARPES, not only to realize three-dimensional spin detection but also to dramatically enhance the energy and angle resolution, and potentially to introduce the possibility of ultrafast temporal resolution.

It is strongly desired that HiSOR engages in all these efforts in the future to enhance its capabilities and create the world’s finest environment for the most advanced spin-resolved ARPES experiments, make synchrotron radiation available at any time, and provide a stable supply of user beam time.

1-3. Nanomaterial analysis (BL-14, LT-STM)

Current Status

The BL-14 beam line supports experimental work on the magnetic properties of nanostructured matter by offering a suite of interconnected UHV chambers equipped for clean surface preparation, in situ deposition and morphology analysis with STM, allowing for well characterized samples to be exposed to circularly polarized synchrotron radiation and magnetic fields to perform soft X-ray magnetic circular dichroism (XMCD) measurements.

Sample growth has reached the capabilities of monoatomic layer control using real-time RHEED oscillation measurement, of depositing wedge-shaped over-layers with fine thickness control and sub-monolayer precision. The sample environment in the XMCD spectrometer includes a variable magnetic field application system that uses an electromagnet and a permanent magnet sliding system. The sample temperature is also monitored and controlled.

XMCD magnetic hysteresis loops can be acquired as well as spectra and the temperature dependence of magnetization can be measured. The experiment environment is well suitable to simultaneously investigate macroscopic and microscopic magnetic properties of monoatomic layer samples.

The upgrade of the equipment was specially motivated by the goal, set by the BL-14 group, to realize *in situ* experiments that combine a scanning tunneling microscope (STM) and XMCD. First results have been obtained on the Pd/Co/Pd(001) system, made of monoatomic palladium and cobalt layers laid on top of the single crystal substrate, that displays perpendicular magnetic anisotropy. A programme to study the structure and the magnetic properties of magnetic clusters and other nanostructures formed on surfaces is undeway. The STM activity is in fact broader at HiSOR and includes other systems, not directly hooked to the beam line, that are used for detailed investigations of surface structures and local electronic state densities. This is high quality complementary work, as given by the example of the study of the electronic structure of regularly structured aluminum nanoclusters fabricated on the surface of Si(111) or the early growth of graphene at step edges on a SiC(0001) substrate, and further growth of a graphene layer with the armchair and zigzag edges. This research result is expected to pave the way for a potential measurement of spin-polarized electrons at a graphene edge. Another recent study revealed the presence of a scattering channel between the Dirac surface state and the bulk valence band in the topological insulator Bi_2Se_3. This provides a guideline for future material design to create more ideal topological insulators.

Evaluation

The HiSOR BL-14 has reached a configuration that includes features of an advanced facility where material science experiments can be performed including some of the state of the art methods for ultrathin film growth and morphological characterization as well as the atom-specific magnetometry made possible by the circularly polarized synchrotron radiation. Relevant aspects that have been addressed are the control of deposition and growth by on-line RHEED oscillations, the surface chemical analysis by AES, the long range symmetry and domain size by LEED, and the fine morphology of the surface material by STM. The set-up is suitable for growing wedged films, allowing for simple "one dimensional sample libraries" to be prepared in situ and subsequently analyzed by XMCD at moderate focusing but with high thickness sensitivity. The effort to quantitatively characterize the source in terms of degree of circular polarization is very important. One needs to develop a reliable metrology for nanosystems and for fine analysis methods in order to provide quantitatively significant results, of possible use, beyond phenomenological analysis, for transferring quantitative information to the application developers. Along these lines the BL14 set-up represents a good effort towards the programme of testing and/or developing growth protocols, to make their reproducibility possible, and to perform magnetic analysis on the Fe, Co, Ni containing systems. The very local morphology and atomic structure information gained by STM can characterize the different thickness regimes allowing for a well supported interpretation of the XMCD data and the morphology/structure characteristics. HiSOR's strategy to use the STM to add this capability for comprehensive studies of characteristic surface nanostructures is well chosen: it integrates basic and applied experimental research to enhance the potential for practical development of materials. The Center is also making mutually complementary use of STM-based probing methods for local electronic state densities, and of electronic state probing methods using synchrotron radiation measurements, for a comprehensive understanding of the electronic states of surface nanostructures. This presents an interesting example of how an STM can be used at a synchrotron radiation facility.

BL14 is today a good basis for pushing ahead in the direction of a materials science beam line, specialized in 3d magnetic materials, with some important advanced features appealing to a broad users community.

Perspective

Much of the future perspectives do depend on the source evolution, being an APPLE undulator beam line on the new ring or other upgrades. Certainly the approach followed by the BL-14 team to build a users laboratory for controlled sample synthesis and fine analysis is a very good one. Moving forward one should consider: a) increase the capability of growing complex sample libraries under controlled in-situ conditions. Two-dimensional, or higher dimensional libraries can be grown by co-evaporation of materials and cross wedge control of thicknesses. Binary or ternary samples can be grown as well as hybrid inorganic/organic nanostructured surfaces. Doing this in a controlled way will then justify a fully automatic operation of the XMCD station to collect data on a variety of samples, moving towards a "high throughput" operation mode, *e.g.* by a stepper sample manipulator that can explore the whole sample surface. Adding a vectorial Kerr effect set-up to the system should be easy and this will allow even simultaneous measurements of Kerr and XMCD, or measurements in the same position in the chamber, i.e. exactly the same applied field and temperature etc. as for the XMCD. This would give a more bulk sensitive and non atom-specific information to complement the XMCD. Alternatively, or additionally, the vectorial Kerr effect set-up could be fitted in the preparation chamber and be used as a characterization tool "before" the XMCD. Similarly an "in-operando mode" could be developed by locally modifying the sample environment in the XMCD station. The beam spot should be optimised and the best spotsize/stability/intensity compromise must be found to fully benefit by such approach.

In situ equipment would greatly benefit from a SEM column in UHV. SEM, in particular if fitted with X-emission analysis, would definitely complement the STM analysis yielding in a time-efficient way the homogeneity control over areas actually averaged by the SR beam in the XMCD experiments.

A (partially) alternative approach to focusing SR is to image the surface. This may be a way to move towards higher throughput. A PEEM-type analyzer, or a scanning probe collector of the X-ray generated photoelectron yield may be considered in order to obtain much precious "local" information on micorstructures/nanostructured systems.

The full characterization of the effective magnetic field at the sample position, as well as possible schemes to apply "local" magnetic fields could also be considered.

Pump probe experiments are going to become ubiquitous at radiation sources, both for the advent of ultrashort pulses from FELs and for the possible use of the intermediate time resolution possible with individual SR pulses. Some consideration of this aspect should be given, particularly if a major source upgrade, or new construction, will be scheduled.

Developing a state of the art laboratory for materials science that "includes" the SR XMCD is probably easier to implement in a facility like HiSOR, and may become a reference for others. Adding to the synthesis/characterization of materials in connection with SR experiments will also increase the number of users who are experts of nanostructured materials and not yet experts of SR methods, further increasing the impact of the HiSOR installations.

The IRC believes that it is important that the users spend the time needed to fully qualify their samples before they want to interpret the SR spectroscopy or magnetometry results. This can be performed in a time efficient way by allowing people to work in good conditions on the preparation system without perturbing, or being impeded, by the beam line operation and data acquisition. An effort in the data and metadata structure management is also required in order to cover all the useful information and metrology.

1-4. Circular dichroism of biomaterials (BL-15)

Current Status

A vacuum ultra-violet circular dichroism (VUVCD) spectrophotometer is installed on beam line 15 as an experimental station for life sciences, and is used for the structural analysis of biomolecules (proteins, sugars, and nucleic acids) in solution. VUVCD measurements are able to examine a wide range of target samples under different solvent/environmental conditions, and hence this technique is powerful for the analysis of biomaterials, including a number of cases where high resolution techniques such as X-ray crystallography and nuclear magnetic resonance (NMR) studies are not possible.

In 2000 HiSOR was one of the world's first synchrotron radiation facilities to successfully develop a VUVCD beam line. By continually upgrading measurement and analytical techniques, and promoting joint research with scientists both in Japan and abroad, it has come to play an important role in VUVCD-based structural analyses of biomolecules. Since then, the number of VUVCD beam lines internationally has grown significantly, and now includes ones at the Aarhus Storage Ring (ISA) (Denmark), the Beijing Synchrotron Radiation Facility (BSRF) (China), the National Synchrotron Radiation Research Center (NSRRC) (Taiwan), the Berlin Electron Storage Ring Company for Synchrotron Radiation (BESSY2) (Germany), the Diamond Light Source (United Kingdom), the Ångströmquelle Karlsruhe (ANKA) (Germany), and the Synchrotron SOLEIL (France).

The HiSOR VUVCD spectrophotometer is composed of an optical system that generates left and right circular polarization at 50 kHz and a detection system that consists of two photomultipliers and a lock-in amplifier. This spectrophotometer has the capacity to evaluate the CD signal with high precision by connecting these two systems with an optical servo control system. Because it is equipped with a variable temperature system, it can also measure the CD spectra of biomolecules at temperatures in the range between -30 and 80°C.

Because VUVCD experiments require efficient measurements with high S/N ratios, the recent introduction of a higher-sensitivity detector (fiscal 2009) and a high-reflectivity diffraction grating (fiscal 2010) have approximately doubled the measurement efficiency. HiSOR is currently setting up a Wadsworth normal incident monochromator (BL-12) that is well-suited to VUVCD measurements. This is expected to make synchrotron radiation available at a photon flux of 10^{12} photons/sec, which will be comparable to the flux at other VUVCD beam lines worldwide, and which will enable improved precision and speed for the VUVCD measurements.

HiSOR was authorized as a national Joint Usage/Research Center starting in 2010. The numbers of national and international shared-use and joint research programs for the VUVCD device increased from 9 in 2009 to fourteen in 2010, and increase of over 50%. The VUVCD beam line was used for approximately 30 of the 52 weeks in the last year (fiscal 2010) for shared-use and joint research programmes, and about 10 weeks for adjustments and improvements of the experimental system. The participating research institutions in Japan included the National Institute of Advanced Industrial Science and Technology, RIKEN, the University of Tokyo, the National Institutes of Natural Sciences, and Osaka University. Kissei Pharmaceutical Co. Ltd. participated from the industrial sector. Foreign participation came from the United Kingdom, France, Hungary, Russia, China, Taiwan, and elsewhere. The users included experts in other areas of structural biology, including X-ray crystal structure analysis, NMR, and cryo-electron microscopy.

Evaluation

The VUVCD spectrophotometer provides for the measurements of CD spectra of many types of biomolecules and biomaterials. Since it was first built more than a decade ago, it has been upgraded to improve its measurement efficiency. Many important upgrades were made following the previous International Panel report, including replacement of the gratings, a new detector (which extends the wavelength range), revisions to the software, monitoring of high tension voltage, ability to make measurements under nitrogen atmosphere instead of vacuum, alterations to the sample chamber, and the availability of auxiliary sample preparation equipment. Continuous upgrading needs to remain as a goal for the future, to enable it to be a state-of-the-art facility. This will be considerably aided by the planned move to BL-12, which should increase the flux, thereby enhancing the quality and efficiency of measurements, and by introducing other methods including linear dichroism measurements and oriented CD experiments (which will be particularly valuable by extending measurements to work on materials such as fibres, membranes, films and emulsions). Other upgrades that could improve the system will include new software, drive motors, and replacement of windows/reflective surfaces to improve flux.

The VUVCD group is producing a steady stream of achievements, including publishing papers on the structural analyses of amino acids, sugars, proteins, and other biomolecules in international journals. A new structural analysis method for proteins, which combines VUVCD with leading-edge computational techniques, has been developed which could become a method used at other beam lines for the elucidation of protein structure and function. However, this will require that the software be made publicly-available in a simple manner (*ie.* via a dedicated calculation webserver or at least as a distributed downloadable software package). The HiSOR group has been world-leading in their application of VUVCD to the investigation of sugars, and again this could become widely used and cited if the data were made available to other researchers, for instance through public deposition data banks; making data accessible in this manner has led to high citations of publications on VUVCD protein spectra produced at other beam lines.

The work at BL-15 is being recognized in the VUVCD community. It was presented at 17 invited national and international lectures during the last five years, including the RIKEN Symposium (2009, Wako), the 2nd International Workshop on Synchrotron Radiation Circular Dichroism Spectroscopy (2009, Beijing), the Toyoichi Tanaka Memorial Symposium (2010, Kyoto), the Chemical Society of Japan (2010, Tokyo), the Physical Society of Japan (2010, Hyogo), the International Circular Dichroism and Bioinformatics Conference (2010, London), and others. Also, a research paper on a polysaccharide, published in *Biosci. Biotech. Biochem.* (2009), was awarded as BBB article prize from the Japan Society for Bioscience, Biotechnology, and Agrochemistry. A paper that attempted to elucidate mechanisms of protein-biomembrane interactions and mechanisms of drug transport by proteins, published in *Biochemistry* (2009), was cited in the weekly *Kagaku Shimbun* (*The Science News*) newspaper and the *Nikkei Sangyo Shimbun* (*Nikkei Business Daily*) newspaper. These illustrate the high international esteem for the VUVCD group. It is suggested that the beam line can be further promoted nationally and internationally to the life sciences community by presentations and publications focused on the biological sciences (as opposed to the more specialist CD and instrumentation communities).

The excellent work at this beam line has been further recognized by a Grant-in-Aid for Scientific Research (C) for fiscal 2006-07, a Grant-in-Aid for Young Scientists (B) for fiscal 2006, a Grant-in-Aid for Scientific Research (C) for fiscal 2008-10, a Grant-in-Aid for Research Activity Start-Up for fiscal 2010-11, and a Grant-in-Aid for Young Scientists (A) for fiscal 2011-14, which illustrate how successful the group has been in acquiring external funding.

The number of research proposals adopted for shared-use and joint research programmes at the VUVCD beam line has expanded dramatically over the last several years. The number of scientific articles by external users of the VUVCD beam line is also increasing steadily. In addition, the increasing number of foreign users indicates that the HiSOR-VUVCD device is functioning as a venue for international exchanges. Improvement in the efficiency of CD measurements through the above-mentioned upgrading is expected to further increase the number of shared-use and joint research programmess. It is recommended that to additional new external users the outreach programme be extended to include a dedicated website (in Japanese and English) with beam line specifications, examples of applications of the method, information about the technique, and access to publications on the technique from HiSOR and other beam lines. In addition, organization of a national (or international) meeting/workshop specifically for users of conventional CD spectroscopy, showing the additional value of using synchrotron radiation, could enhance the number of external joint users of the facility.

A major and very important development described at the 2012 HiSOR Symposium and International Panel meeting was the appointment of a full-time permanent beam line scientist, Dr. Koichi Matsuo, who has been responsible for the beam line developments and productivity for the past several years, on a series of temporary appointments. The appointment of Dr. Matsuo provides the essential stability and future for VUVCD science at HiSOR. At a later date, appointment of an assistant for Dr. Matsuo could further enable the outreach and development upgrades described in the report as well as helping run the experimental programmes with the increasing number of external users.

Perspective

The VUVCD research at HiSOR is well regarded within the community of VUVCD researchers (made up of leading members from the United Kingdom, France, Germany, Denmark, the United States, China, Taiwan, and Japan) and by participants (users) in the shared-use and joint research programmes.

On the other hand, VUVCD equipment technologies in other countries are improving every year, and measurement systems of higher precision have been established. Therefore, in order to retain the current international status of HiSOR-VUVCD, it is essential to both continue to improve the existing facility and to introduce a variety of new measurement options such as fast temperature scanning, linear dichroism and oriented CD experiments for the structural analyses of solid and fiber samples. Furthermore, more than 10 years have passed since the VUVCD equipment was first developed. It is highly desirable that the transition to BL-12 is followed quickly by the construction of a next-generation VUVCD device that incorporates leading-edge optical and detection systems.

The VUVCD beam line is a valuable resource for both the HiSOR and life sciences communities. It is the only beam line at the Hiroshima Synchrotron dedicated to biological/biomaterials research and is an important component for meeting the "Joint Usage/Research Center" remit. It has dramatically broadened the usefulness of CD spectroscopy for the structural analysis of biomolecules. Its application in a broad range of research areas, not limited to basic research in structural biology but also including research in areas of industrial interest such as heat-resistant enzymes and drug developments, is eagerly anticipated. Further improvements to the existing beam line, and plans for development of a new next-generation beam line will enable it to retain its important role in the life sciences at HiSOR and to contribute to international developments in the field.

1-5. Light source accelerators and insertion devices

Current Status

The light source accelerator system at the Hiroshima Synchrotron Radiation Center (HiSOR) consists of a 150 MeV injector microtron, a beam transport line, and a racetrack type storage ring. The circumference of this ring is 22 m, and the bending radius is 0.87 m in the normal conducting 2.7-T bending magnet. Stored electron beam energy is 700 MeV, and synchrotron radiation having the critical photon energy of 873 eV from two 180-degree bending magnets can be extracted from 14 photon beam ports. The original AURORA-2 racetrack design was modified by SHI in order to extend the length of the straights between the 180° dipoles and to provide space for two undulators. One of them is a linear undulator (2.4 m long, 57 mm period) that generates 26-300 eV linearly polarized radiation. Another one was a multi-mode undulator (1.8 m long, 100 mm period) that generated 4-40 eV circularly polarized radiation and 3-300 eV linearly polarized radiation by changing the relative positions of 3-row magnet arrays in each jaw. This multi-mode undulator was removed from the ring at the end of July, 2011. Only recently it was replaced by an APPLE II type undulator.

The HiSOR ring has been successfully operated and has been delivering stable photon beams for HiSOR users since 1996. Operation hours exceed 2,000 h/year, and users' operation hours are about 1,600 h/year. The machine is running 11 h a day (with 2 injections) and 4 days a week. Monday is foreseen for maintenance. The machine startup in the morning takes only 30 min. In order to deliver the stable beam, the Light Source Group has been dealing with various tasks including: beam lifetime improvement (the bunch lengthening by using HOM in RF-cavity), countermeasures for beam instabilities during the injection at 150 MeV and lumping-up from 150 to 700 MeV (suppression of instability by the RF-shake), improving efficiency of monitoring, and minimizing control errors by dispersing various types of controlling units.

Beam instabilities which we are observing are mainly due to a small ring size and/or a low-energy beam injection. To cure such instabilities specific for a small storage ring, continuous efforts for technical development are putting in since some techniques used for a large ring, such as the phase modulation RF cavity, cannot be used. In addition to the effort for improving the present HiSOR ring, the design study of next generation small light source ring HiSOR-II and R&D of accelerator components for such a ring are underway.

In regard to insertion devices, the multi-mode undulator was replaced with a newly built 78-mm-period quasi-periodic APPLE-II type variably polarizing undulator on July 31, 2011. This undulator can generate radiation with right and left circular polarization in the photon energy range of 5-50 eV. In the horizontal and vertical linear polarization modes, it generates 3.1 eV and 6.5 eV radiation at the minimum (23 mm) gap, respectively. Also, it can generate a tilted linear polarization by introducing a counter parallel motion between the diagonal magnet rows (*e.g.* top-right and bottom-left rows).

With this new undulator, the flux in usable photon energy range increased more than twice of that from a previous undulator. Furthermore, by adopting the quasi-periodic structure of magnet array, the monochromaticity after the monochromator improved drastically for the horizontal linear mode. To date, the HiSOR-II (40 m circumference) design study during past six years has led to the conclusion that the achievable minimum emittance is as low as 14 nm-rad. The HiSOR-II lattice was designed based on the MAX-III lattice of MAX-lab in Lund, Sweden. To achieve such a low emittance for a small ring, bending magnets should have a combined function for generating focusing force. Since the stored beam lifetime is short (below 3h), the 3 Hz top-off operation is planned.

In 2010, we originally found there is a totally new lattice structure usable not only for a light source ring but also for various types of synchrotron accelerators and accumulator rings. In a conventional storage ring, the electron beam orbit closes in one turn around the ring. On the other hand, the beam orbit closes after multiple turns in the ring with a new lattice structure. By applying this new concept to the next generation compact light source, the closed orbit length of stored electron beam can be three times longer than the ring perimeter. In addition, the 15-m-diameter ring equipped with 11 bending magnets has 11 long (3.6 m) and 11 short (1.8 m) straight sections capable for installing insertion devices and other necessary accelerator components.

In combination with the efforts for new lattice design, design studies for various undulators are underway.

Evaluation

Over 15 years of operation the HiSOR SR-facility developed to a highly recognized research facility providing extraordinary conditions for photoelectron emission studies, CD-research with biological systems and research on nanostructured materials. It is attracting many researchers from abroad. The high flux as produced from the two undulator beam lines is used in angle resolved photoemission spectroscopy, partly with high resolution. One of the beam lines has the additional feature of spin resolved measurements. Though the light source has an emittance as high as 400nmrad the data taken from these beam lines are highly competitive worldwide. There are several reasons for this:

i) The light source runs very reliable, which is very much appreciated since the accelerator group consists of only 3 persons;
ii) the beam lines are well maintained and permanent effort is spent to improve in various details: *e.g.* only recently, the grating chamber and slit unit of BL-9A were mounted on stones to reduce vibrations, and they were thermally insulated to reduce thermal drifts;
iii) the experimental chambers (ARPES, SARPES) are owned by HiSOR and they are well supervised by HiSOR personal. Involvement of HiSOR staff into experiments guarantees a top performance at all times. Apart from the Okayama University setup it is a general HiSOR policy to operate all beam lines by HiSOR beam line scientists and students. These people are involved in the research activities by 20-30% which guarantees a high quality standard and continuous development of the experimental conditions;
iv) a key feature is the sophisticated combination of *in situ* sample preparation and sample analysis prior to measurements which are done in the same environment. Usually, this approach is not consequently followed in other laboratories;
v) the rather large beam spot at the sample may be of help to improve stability. Minor electron beam orbit changes or beam line component drifts are lingered if the electron spectrometer transmits only a fraction of the photo electrons originating from the beam spot at the sample.

With the installation of the APPLE undulator the Beam line 9A and 9B performance increased significantly. One has to keep in mind that optical components may alter the degree and state of polarization as produced by the APPLE undulator. Circularly polarized light might change drastically when transmitted to the sample. Principally, this can be compensated for by running the undulator in universal mode. A simple polarization detector at the experiment (e.g. Rabinovich detector, which cannot measure the complete Stokes vector) would be rather helpful for cross checks.

The new APPLE undulator is of the quasiperiodic type. The higher order contamination is reduced significantly in the horizontal linear mode. In the vertical linear mode the 3rd harmonic suppression is incomplete and the 3rd harmonic splits into several peaks reducing the usable flux. This is an inherent problem of APPLE type magnet structures. Currently, alternative quasiperiodic schemes are explored to improve the performance in vertical linear mode. The quasiperiodic scheme can easily be adapted within hours by retracting the undulator on an existing rail system and rearranging some of the magnets.

The undulator is equipped with a bunch of longitudinally aligned current strips above and below the vacuum chamber to compensate the 2nd order kicks which are strongest in the vertical and the inclined mode of operation. Experiences at BESSY II proof the value of such current strips in particular in low electron energy machines.

Apart from the bright undulator radiation the radiation of the 2.7 T normal conducting bending magnets is used. The high field results in a high critical energy and 2 double crystal monochromators provide photons even in the several keV regime. Off-axis dipole radiation is used for XMCD studies as well.

The 14 dipole beam lines are used extensively and the undulator beam lines tend to be overbooked in the future. Several experiments would profit from an extension of beam time. This could be accomplished without hiring new staff by implementing a so-called “Dawn Special”: Within existing safety regulations last injection could be done shortly before midnight and the machine could run without further supervising for the whole night. The high reliability of the HiSOR machine and the lifetime of 7h @ 350mA and 10h @ 200mA guarantees excellent performance over many hours.

It is highly valuable that continuous effort by a small number of staffs is made for maintaining and improving the light source ring performance in order to supply stable photon beams to user’s experiments. Also, the effort for increasing stored beam current and curing various beam instabilities are highly appreciated. These efforts have contributed to expanding research activities of synchrotron radiation users.

It is noticeable that a revolutionary progress in solid state physics researches by means of high resolution angle and spin resolved photoelectron spectroscopy can be expected by increasing the photon flux and providing the variable polarization (helical, elliptical, linear inclined) with a newly installed quasi-periodic variably polarizing undulator.

The large emittance of HiSOR of 400nmrad cannot be reduced with the racetrack type machine layout. With a new storage ring, HiSOR II, the emittance can be reduced by more than a factor of 20. Many experiments would benefit from the increased brightness which manifests in a smaller spotsize at the sample. In particular the ARPES, SARPES experiments would benefit from an improved match of the sample beam spot and the photoelectron acceptance of the spectometers. Furthermore, new experiments would become possible at HiSOR such as microscopy of magnetic domains, spectromicroscopy, imaging etc. There is no doubt that the unique idea of the lattice design for a compact light source ring is appreciated by HiSOR user community.

Design studies for a new light source have been done over the last years. The MAX-III lattice has been adopted for the HiSOR II design employing 4 long straights (3.4m) and 4 short straights (2.0m). Gradient dipoles (including quadrupole and sextupole components) and additional quadrupoles are combined within the same iron yoke. The success of such a solution has been proven with MAX III. Besides the compactness it has the benefit of easy installation and alignment. The magnetic cross talk between the gradient dipole and the quadrupoles has been evaluated numerically and it turns out to be negligible. The emittance for the DBA lattice is expected to be 35nmrad. Skipping the constraint of dispersion free straights, which is a reasonable and non-risky assumption today, permits an emittance as low as 17nmrad. The lifetime shrinks below 3h in this case.

Two years ago a completely new lattice design, called HiSOR II+, has been proposed by S. Sasaki and A. Miyamoto. Following a projected torus knot geometry the electron orbit closes only after several turns. Assuming the same circumference as the existing HiSOR II design an 11-fold symmetry with an orbit closing after 3 cycles has been chosen. The multi turn layout provides much more flexibility in terms of the number of straights (11 long straights with 3.6m and 11 short straights with 1.8m). Injection and RF can be placed in the short straights and even damping wigglers or other accelerator components can be placed in the short straights keeping all 11 long straights open for insertion devices. Thus the design provides more and longer straights as compared to HiSOR II. Additionally, a lot of space for accelerator diagnostics is available which is extremely valuable. Usually, this space is rather limited in today's 3rd generation machines. Another advantage of the new design is an extended bunch separation in single bunch mode which is beneficial for time resolved spectroscopy.

The concept of the HiSOR II lattice is well developed and it may serve as a reference design. It is strongly recommended to proceed with R & D on the new design concept of HiSOR II+. This includes: i) a detailed magnetic design of the rather complicated combined function magnets which allow for crossing trajectories; ii) extensive tracking and dynamic aperture simulations incorporating the real 3D-properties of these specific magnets; iii) top up schemes *etc*.

It seems that the HiSOR II design can immediately be constructed because each accelerator component of this ring is conventional and hence no challenge for fabrication. However, to materialize the construction project in a short term, collaboration with accelerator experts in other facilities is inevitable. The HiSOR II+ design is more sophisticated and requires further detailed studies. The new low emittance machine will require stable conditions of accelerator and beam line components. One prerequisite for stable operation is Top Up injection. This feature has become a standard operation mode in many 3rd generation light sources and a full energy booster for top up should be included from the beginning. It is worth mentioning that an emittance of 14nmrad (HiSOR II) or 17nmrad (HiSOR II+) is accompanied by short lifetimes and top up injection is the only measure to avoid an artificial emittance blow up to achieve reasonable lifetimes which are in accordance with user needs. Furthermore, a 24h operation should be foreseen to minimize thermal drifts.

In the past S. Sasaki proposed various new undulator concepts which became working horses worldwide (APPLE undulator, quasiperiodic undulator). This thorough knowledge on SR-radiation instrumentation is extremely useful for further development of HiSOR and for strategic plans of HiSOR II(+). Within the design considerations for HiSOR II(+) new undulator concepts are evaluated. As an example, the so-called leaf undulator has been proposed. This device provides a mode with strongly reduced higher harmonics on axis. Concerning this feature it outperforms the well-known figure-8 undulator. By moving magnet rows other operation modes can be established such as a helical mode or a planar mode with higher harmonics in case they are needed.

Perspective

Since the present HiSOR ring is a racetrack type ring with 22-m circumference, it is extremely difficult to make further improvements such as larger beam current and beam lifetime, lower emittance/higher brightness *etc*. Also, one can easily imagine a large increment of maintenance cost to keep the current machine performance due to aging of the facility. By considering these circumstances, it is strongly recommended to design and construct a new state of the art compact high brightness light source. The emittance should be reduced by one order of magnitude and the number of straight sections for the installation of undulators should be about 8-10.

The new low emittance machine will be more sensitive to environmental noise and thermal drifts and the users can take advantage of the ultimate performance only if the accelerator and beam line components are stabilized passively or actively. E.g. sophisticated diagnostics, fast orbit feedback and top-up operation will be essential to be competitive with other light sources.

At Hiroshima University a profound knowledge on accelerator issues exists, nevertheless, additional personal is required to cover all necessary fields. Tight collaborations with other Japanese and international accelerator groups are inevitable. Many well developed systems can be adapted from existing light sources in order to save human resources. For a fast and smooth startup collaborations with users should be intensified concerning a joint development of beam lines and end stations.

The HiSOR facility is operated with only 3 persons in the accelerator group and 10 persons taking care of beam lines and end stations. This is possible because the machine was bought as a turnkey ready device from SHI. Maintenance and repairs are still done by this company. One engineer of the accelerator group organizes these activities. Due to the limited human resources a similar scheme is strongly recommended for HiSOR II(+). There are several companies around the world who are able to build and install the complete machine. Though maintenance and service of the new ring could be outsourced to a high degree more in-house technical support will be essential for a reliable operation of the new more versatile machine. This machine should employ another beam time schedule providing more beam time hours/year and a 24h service.