Synchrotron radiation in Japan: status and new projects

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Abstract: A general overview is given on new activities in synchrotron radiation (SR) facilities. There are 15 compact SR sources in operation in Japan, and their applications beside of X-ray lithography are reported as a distinctive feature of Japan. The highlights of new projects are use of TRISTAN Main Ring with a circumference of 3 km for SR and the 3rd generation X-ray source "SPRING-8" (Super Photon Ring, 8 GeV): The former will be operated at 10 GeV with a beam current of larger than 10 mA (Emittance: 5 nmrad), probably for three months in spring, 1995. The latter will be opened with 10 public beam-lines in 1997, and its strategy to cover photon energy as low as 100 eV should be emphasized, because none of plans for VUV-SX brilliant sources has come on line at present in this country. The aim of the 3rd-generation sources is to make microscopic analyses and time-resolved measurements possible. The brilliant X-ray beams, however, have a possibility to exceed the intensity limit for non-destructive observation. This problem is discussed from optimistic and pessimistic views.

1. INTRODUCTION

According to Tomimasu's review [1], there are now 19 synchrotron radiation (SR) sources in operation and 1 under construction in Japan. Fifteen of total 20 are compact or small SR sources with a beam energy less than 1 GeV, 2 are the medium type in the energy range of 1 to 3 GeV, and 3 are the big type having beam energies larger than 3 GeV. For 3rd generation VUV-SX SR sources, there are several plans, but none of them have approved for funding. The distinctive feature of Japan is that the SR sources are separated into two extremes, big and small ones. Since the Photon Factory commissioned in 1982, there has been no construction of the medium type.

The activities in the SOR-RING (University of Tokyo), UVSOR (Institute for Molecular Science) and Photon Factory are reported by their annual reports. Recently, reports on almost all SR facilities in Japan were published in the Proceedings of the "Asian Forum on Synchrotron Radiation" [2]. The present review is focused on the compact and big SR sources in optimistic and pessimistic future aspects.

2. COMPACT SR SOURCES

The 15 compact SR sources in operation in Japan were reported by Tomimasu [1]. Some typical ones are listed in Table 1.

It has been expected that the world-smallest synchrotron light source can be realized by making a complete circular electron storage ring with one superconducting magnet. This was achieved in the SR source "AURORA" developed by Sumitomo Heavy Industries Ltd.[3]; the electron orbit is exactly circle with a diameter of 1 m, and

Table 1. Typical Compact synchrotron sources in Japan

Name	Shape of orbit	Lattice	circumference m	Beam Energy MeV	Stored current mA	Critical $h\nu$ keV	Emit- tance m ² rad	Life time h	Ref.
AURORA	Circle		3.14	575	500	0.84	2.2×10^{-6} 2.2×10^{-8}	17	[3]
Helios	Race track	DFD	10.8	700	300	1.48	1.3×10^{-6} 0.3×10^{-7}	>10	[4]
Super ALIS	Race track	DFD	16.8	600	500	0.73	1.5×10^{-6}	5	[5]
MITSUBISHI (MELCO)	Race track	FODO	9.2	600	250	0.81	7×10^{-7}		[6]
NIJI-III	Square	C-G	18.9	600	200	0.96	2.2×10^{-7} 2.2×10^{-8}	>4	[7]
LUNA	Square	FODO	23.5	800	80	0.57	6.2×10^{-7} 6.2×10^{-8}	5	[8]
NIJI-IV	square	TBA	29.6	500	200	0.23	4.9×10^{-8} at 300MeV		[9]

Emittance: the upper and lower indicate horizontal and vertical values, respectively
Helios will be introduced from UK.

Fig. 1. Spectrum of the compact SR source "AURORA" vs. that of a beam from a bending magnet in the Photon Factory which were calculated for points at distances 2 m and 25 m from the sources, respectively.

the beta-function is uniform all around in the orbit by employing weak focusing principle only. This type of sources have the following advantages: (1) the critical wavelength is relatively short even for a lower electron energy and safer radiation environments are provided, (2) high beam currents can be obtained with a small number

of electrons accumulated by the short circumference, (3) the simple configuration makes operation, control and maintenance easier. AURORA was constructed with a completely circular superconducting magnet and was operated for the first time by using the $1/2$ integer resonance injection method [10].

AURORA has been used for various experiments such as X-ray lithography, X-ray microscopy [11], fluorescent X-ray analysis and solid phase epitaxy with X-ray irradiation (SPEXI)[12]. It is emphasized that intensity can be increased with a short distance between the source and specimen; for example, the SPEXI experiment was made at a distance of 0.75 m from the source point and amorphous silicon films were grown into single crystal films within 2 minutes by irradiation at 300 C. In Fig. 1, the intensities are compared with those in Photon Factory by calculation including the emittance and size of light sources. The intensity available by AURORA in the soft X-ray region is an order of magnitude higher than that from the bending magnet in the Photon Factory.

It is also worthy of special mention that a free-electron laser in a tunable range of 100 to 600 nm was realized with a compact SR ring NIJI-IV in Electrotechnical Laboratory in Tsukuba [9].

In general, the compact synchrotron sources were developed primarily for X-ray lithography in semiconductor industry.

X-ray lithography [13] enables us to make IC patterns in a scale of 0.1 μm . This capability is beyond 0.15- μm rule required for 1-Gb DRAM (Dynamic Random Access Memory) which is expected to be in production in 1999. However, there are still many problems to be solved. The important issue is of deformation of masks by X-ray irradiation; Mask substances must be thin for soft X-ray transparency, but must be strong enough to keep a corner-to-corner precision of a mask with a size of 1X1 inch in a level of 0.01 μm [14]. Substrates of masks such as silicon nitride films suffer radiation damages [15] and are not yet strong enough for repeating use in IC production. At present, pilot production of 1 Gb DRAM is possible only with electron-beam lithography. In addition, optical lithography has been sophisticated to be useful for a rule of 0.15 μm . Thus, there is a pessimistic view for application of compact SR sources to lithography, although extensive studies on X-ray lithography are continuing because it is expected to have the highest yield in production.

In such circumstances, it is very important to bring the compact SR sources into real use, and new plans started to use them as powerful tool in materials research with the advantage of short beamlines as mentioned above. By financial assist from the government, three projects are running in the following organizations.

Ritsumeikan University in Kyoto is building a new branch campus in Kusatu City 30 km east from Kyoto, and the compact SR source AURORA will be installed and operated in 1995.

ALVALAB Consortium in Tsukuba has also decided to introduce a compact SR source "Helios" [4] from UK in 1995.

The third one for a compact source is now developing into a bigger project to build a new 3rd-generation VUV-SX SR source in Ichihara City, Chiba Prefecture, about 60 km east of the center of Tokyo and is called "Nano-Hana Project" according to the name of the symbol flower of the prefecture. Funding for construction has been arranged by Fujita Corporation and the Japan Manage-

Fig. 2. Layout of the electron and positron accelerators in the National Laboratory for High Energy Physics (KEK). PF, AR and MR stand for the Photon Factory, Accumulation Ring and TRISTAN Main Ring, respectively.

ment Association. A new company "Japan SOR Inc." has been established for construction and ownership of the SR facility, as a nonprofit organization to be funded by the government and some private companies.

These three facilities are devoted to developing use of SR in industry as well as in universities and national laboratories by their cooperation.

3. STATUS OF KEK

A layout of three electron and positron storage rings at National laboratory for High Energy physics (KEK) in Tsukuba are shown in Fig. 2. The 2.5 GeV PF (Photon Factory) ring has a circumference of 187 m, the 6.5 GeV AR (TRISTAN Accumulation Ring) 377 m and the 30 GeV MR (TRISTAN Main Ring) 3018 m. The research activities and programs have been reported recently [16,17].

3.1 Photon Factory

The PF ring produces a very wide spectrum of light with a critical photon energy of 4 keV from infrared to X-rays up to 25 keV in a practical use. The 5T superconducting wiggler serves as a wavelength shifter to provide with hard X-ray photons ranging higher than say 25 keV having the vertical E-vector polarization and has been used especially for protein crystallography, precision X-ray optics and live x-ray topography. The PF ring has been successfully in operation since 1982; The PF ring is now operated with an initial stored current of about 350 mA having life times of more than 50 hours, and about 50 stations are in simultaneous use in a variety of applications with an annual operation time of 3500 hours [16].

3.2 TRISTAN Accumulation Ring

The 6.5 GeV AR with a critical photon energy of 22 keV is currently used mostly in a parasitic mode and occasionally in a dedicated one. The effective total machine time for use of SR is 1000 to 2000 hours a year. Appreciating advantages of higher energy photons, four beamlines accommodating eight stations are in operation. Two of four beamlines hold two types of insertion devices: one capable of emitting intense circularly polarized X-rays or completely circularly polarized soft X-rays owing to not only vertical but also horizontal permanent magnet arrays which is called as the E-MPW [18] and as the second, an in-vacuum X-ray undulator, which can cover the photon energy ranging from 5 to 25 keV with the minimum gap, 9 mm, of the 120-pole magnet arrays [19]. Two other beamlines are at the bending magnets.

Research subjects at the AR are High momentum-resolution magnetic scattering, (magnetic) Compton scattering, phase transformation under high pressure, Mossbauer scattering, surface and interface structure study, angiography and computer tomography (CT), magnetic circular dichroism, X-ray microscopy (by use of the circular-polarization undulator with a larger gap of E-MPW), gas desorption of various kinds of metals, etc.[16]. These research buds mostly grown in beds at the PF have been moved to the field AR in a right time. This is a sort of advantages of having two types of light sources at KEK: one very user-oriented machine PF where using a quite reliable light source so variety of research programs are going on by so many users from all over the world and the other rather development-oriented machine AR where the frontier type of research can be done together with development of new light sources such as the in-vacuum undulator.

3.3 TRISTAN Main Ring

The SR community has been so fascinated and excited when heard about that the MR is capable of emitting extremely brilliant SR if it will run with the energy of 10 GeV instead of 30 GeV together with damping wigglers, by three orders of brilliance higher than those of the third generation light sources such as SPring-8. Furthermore, it has become clear that it has even a capability of producing coherent radiation in the wavelength range of 3-4 nm if FEL's will be installed in 200-m long straight sections.

However, the high energy community in Japan has made a decision of holding the MR tunnel to accommodate the B-factory ring. Thus the SR community has changed the

plan: not completely converting the MR into a super light source but performing a test run without damping wigglers just after the current physics run will be finished in 1995 until the present MR will be replaced by the B-rings sometime in the beginning in 1996.

The MR ring will be operated at 10 GeV with a stored current of 15 mA, and an emittance as low as 5 nm²rad can be achieved by choosing its operation parameters. For this test run, a prototype undulator with segment structure and its associated test beamline [20] are under construction. A submicron-size beam is expected to have a brilliance of 3×10^{18} photons/s/mm²/mrad²/0.1%b.w. at $h\nu_1 = 14.4$ keV. Several test experiments will be performed such as structure and electronic analysis of mesoscopic systems, structural phase transition under extreme conditions of pressure and magnetic field, ultra plane wave X-ray optics, super monochromatic X-ray optics using SR-excited Mössbauer source, time-resolved structural analysis, crystal growth from x-ray excited states, etc.

4. STATUS OF THE SPring-8

The 3rd generation X-ray synchrotron radiation source in Japan is named "SPring-8" (the 8-GeV Super Photon ring) which is now under construction in Harima Science Park City. The city has an area of about 20 km² and is located at about 100 km west from Osaka and is still under construction by the local government, Hyogo Prefecture.

Construction of SPring-8 started in 1991 and is going on one year ahead of the original schedule. During 1991 to 1998, the accelerators and their buildings, twelve beamlines, the central building, service facilities, and main utilities are to be constructed.

Beamline construction will start in the fiscal year of 1994. The first beam injection to the storage ring is planned to be made at the beginning of 1997.

SPring-8 [21] consists of a 1 GeV electron/positron linac, and 8 GeV synchrotron, and a storage ring with full energy injection having 61 beamlines, as shown in

Fig. 3. The SPring-8. After Hara [21]. (1)1 GeV linac. (2)8 GeV booster synchrotron. (3)Storage ring building. (4)Experimental hall. (5)Experimental room for radioactive specimens. (6)Users' laboratories. (7)Central Building. (8)1000-m-long beamlines. (9)300-m-long beamlines. (10)Control room. (11)Cafeteria. (12)345-m-height hill.

Table 2. Design Parameters of the SPring-8

Storage Ring		Injectors	
Energy of e ⁻ /e ⁺	8 GeV	Injector Linac	
Circumference	1,436 m	Energy	1 GeV
Natural Emittance	5.6 nmrad	Energy at e ⁻ /e ⁺ convertor	250 MeV
RF	508.6 MHz	Repetition Rate	60 Hz
Critical Photon Energy	28.9 keV(Bend.)	RF	2,856 MHz
Number of ID Sections	38	Injector Synchrotron	
Standard(6.6 m)	34	Injection/Final Energy	1 GeV/8 GeV
30-m-long	4	Repetition rate	1 Hz
Coverage of 1st harmonics from Undulators		Circumference	396 m
Planar	1 - 18 keV	Natural Emittance	192 nmrad
Helical	0.1 - 10 keV	RF	508.6 MHz

(By courtesy of H. Kitamura)

Fig. 4. Nearly monochromatic spectrum from a helical undulator ($\lambda_u=10$ cm, $N=45$, $K=3.34$). The higher harmonics are eliminated by an aperture on the axis. The inside figure shows brilliances of the 1st harmonic from in-vacuum type helical undulators.

Fig. 3. The design parameters of the SPring-8 are listed in Table 2.

SPring-8 has 34 straight sections each of which is 6 m long for an insertion device (ID) (The available length for undulators is 4.5 m). In addition to them, there are four 30-m-long straight sections which can accommodate a long insertion device to get ultra-bright and more coherent X-rays. The long straight sections can be used for development of free electron laser (FEL) technique at higher energies. General users require brilliant X-rays in the energy range up to 40 keV, and we have the following general policy of the ID development: (1) Hard X-rays should be obtained as the first harmonic of undulator radiation, (2) pursuit for high brilliance or high energy photons should not result in unreasonable heat load, 3) energy tuning of undulator radiations can be made at any time, and (4) simultaneous opera-

tion of undulators with scanning of monochromators. For hard X-rays, in-vacuum helical undulators are being developed (Fig. 4); Already, an in-vacuum ID was installed successfully at the Tristan AR in KEK by using newly developed NdFeB magnet. Their magnetic property does not change up to 160 C which is higher than the bake-out temperature of the aluminum vacuum chambers.

To reduce heat generation on the monochromators by the brilliant beam from SPring-8, it is recommended to use the fundamental harmonic beam from helical undulators; it has a peak intensity on the undulator axis, whereas all higher harmonics are in the directions deviated from the axis and can be rejected by an aperture placed on the axis because no parts of a helical beam trajectory are parallel to the axis. The first harmonic power is only 1/1000 of the total undulator power, and the heating problem does not take place at all.

Consequently, one can operate helical undulators with large K values without any damage on the monochromators; with K values of 2 to 5, the 8-GeV SPring-8 covers a low region in photon energy from 100 eV to 1 keV with a brilliance of 10^{18} photons/s/mm²/mrad²/0.1%b.w. [22].

Numbers of beamlines from insertion devices and from bending magnets are 38 and 23, respectively. At least twelve beamlines will be built by 1998 when the storage ring will be in full operation. The beamline length is 80 m in standard.

SPring-8 Users Association was established in 1993 and now has more than 800 members, expecting commissioning of the storage ring in the spring of 1997 [23].

5. OPTIMISTIC AND PESSIMISTIC VIEWS

Materials science has proceeded toward microscopic understanding of substances. Until 1970's three dimensional bulk states of substances had been studied. In 1980's, investigation on two-dimensional structures such as surfaces, thin films, and multilayers started and led to a key word "mesoscopic systems". Recently, micro-clusters such as Fullerene carbon C₆₀ have been studied extensively, and quantum effect has become a main subject of materials science. Also, properties and structures of protein, which is a unique substance produced by DNA information, are very important subjects in industrial applications as well as in life science. The bio-activity is originated from the small active part consisting of 10^3 to 10^4 atoms in the ultra large protein molecule and may be understood as a mesoscopic system. Fullerene clusters and virus have the similar structure, and are at a point of contact between inorganic and bio substances. Modern materials science may be by the common concept "mesoscopic system" from inorganic to bio materials. This trend in materials science coincides with advent of the 3rd generation SR sources; one may consider the aim of the brilliant sources as microscopic analysis as well as time-resolved measurement.

X-rays have short wavelengths and, in principle, are suitable for making a microbeam. For comparison, electron beams can be made as narrow as 1 nm, but diverge easily to 1 μ m owing to its strong interaction with matter, i.e., X-ray and electron beam analyses have the similar spatial resolution. It is the important advantage of X-rays that selective excitation of electrons in substances is possible. This leads to high signal-to-noise ratios. For example, X-ray fluorescence analysis by X-ray excitation has 3 orders of magnitude higher sensitivities than that by electron excitation [24]. With a 3rd generation SR source, it is expected to achieve a beam focal size of 10 nm in 2000; the volume analyzed by such a microbeam contains only a few ten thousands atoms, and one impurity atom correspond to a few 10 ppm. This may lead to an optimistic view of "single atom spectroscopy". However, it should be noted that both microscopic and time-resolved analyses are significant on the assumption that atoms in specimens are unmoved by X-ray beams used. Non-destructive character of X-rays is essential.

For unstable substances as observed during phase transition, however, radiation damage or destruction was found to occur drastically when X-ray intensity exceeds a certain threshold [12]. For example, amorphous silicon (a-Si) can be crystallized by X-ray irradiation at low temperatures, where the intensity is estimated to be $10^{16} \sim 10^{17}$ photons/s/cm². It was observed by ESR that inner-shell excitation by X-rays causes more than 6 orders of magnitude higher densities of dangling bonds in a-Si than excitation of bonding electrons. This result cannot be attributed simply to the high photon energy. In general, secondary electrons produced by X-rays recombine with ions within a few picosecond, and the irradiation effect disappears by recovering.

When the intensity exceed the threshold, the ions and/or point defects in high densities may form their clusters stable enough in low temperatures. The results are pessimistic for application of the 3rd generation SR sources; intensities of a brilliant microbeam exceed easily the threshold. In phase transition, there is a strong possibility for changing from the intrinsic structures in observation of phase transition by such a brilliant X-ray beam.

In an optimistic aspect, on the other hand, the results indicate a useful application to material fabrication; in the case of a-Si, dislocation free perfect single crystal films were formed from the X-ray excited state of amorphous solid at low temperatures of 300 to 500 C by a few minute irradiation [25]. It was observed that a-Si under the X-ray irradiation behaves as a new phase like a liquid state at the low temperatures where diffusion is greatly enhanced. Crystallization from amorphous states by X-ray irradiation has been confirmed for gallium arsenide and carbon.

Phase transition from high-density X-ray excited structures will be a new field.

Anyway, both the pessimistic and optimistic users are expecting completion of SPring-8 in 1997.

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