Intermediate energy light sources and the SSRF project

ZHAO Zhen-Tang

(Shanghai Institute of Nuclear Research, the Chinese Academy of Sciences, Shanghai 201800)

Abstract Advances in insertion device technology, top-up operation and superconducting RF cavities make it possible to generate high brightness X-ray with intermediate energy light sources, which leads a new trend in designing and constructing third generation light sources around the world. The development status and the remarkable technical features of intermediate energy light sources are reviewed, and the main SSRF properties are described in this paper.

Keywords Light source, Storage ring, Insertion devices, Beam stability, Superconducting RF

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1 Introduction

Third generation synchrotron radiation light sources have rapidly advanced in the past two decades. In their beginning phase, these light source storage rings energies fell into two distinctly different energy bands. Low energy facilities (<2GeV) have been developed for VUV and soft X-ray science to investigate electronic and chemical structure of matter, and high energy ones (6-8GeV) for hard X-ray science to determine the geometrical structure of matter. However, the increasing demands of the hard X-ray applications in recent years, especially in protein crystallography, drove a new campaign to design and build intermediate energy light sources (2.5-4GeV), a new class of cost effective third generation light source facilities for X-ray user community.[1, 2]

The development of intermediate energy light sources benefits mainly from the continued advances in insertion devices (IDs) over the past decade.[3-5] The matured undulator technology, including manufacturing and shimming the undulators with low phase errors, by which theoretical brightness is nearly obtained at high harmonics, and including operating the pure permanent magnetic poles with mini-gap in ultra high vacuum, makes it possible to generate high brightness X-ray with intermediate energy storage ring beams. In comparison with the expensive large scale high energy light sources like ESRF, APS and SPring-8, where the high brightness X-ray beams are generated by undulators operating at fundamental and low odd harmonics (3 or 5), these intermediate energy light sources have lower construction and operation costs and are able to provide comparable performance in the X-ray of 10-20 keV,[3] the most demanding photon energy range for life science. It is these features that attract many countries to build their own national X-ray light sources to meet the strong regional needs.

Intermediate energy light sources lead a new way to generate high brightness and high flux X-ray. However, to compensate the photon brightness drop of undulators at high harmonics, the smaller ring emittance and larger beam current as well as the high quality undulator shimming at high harmonics are highly required. This in turn imposes stringent constraints to the design of intermediate energy machines and the technical performances of their sub-systems[6-9]. Several critical ones are described as follows: (1) low emittance storage ring lattice with adequate number and length of straights, and desirable horizontal and vertical beta functions at straights; (2) high quality in-vacuum mini-gap undulators with precisely blocks sorting and shimming, and the small gap adverse effect on beam scattering lifetime; (3) high beam current associated with Touschek beam lifetime, coupled bunch instabilities and energy widening which spoils the undulator radiation at high harmonics; (4) beam stability for high performance with position stability of micron to sub-micron level achieved by means of controlling tunnel air and cooling water temperature fluctuations within ±0.1℃ and using digital beam position monitor (BPM) and orbit feedback systems as basic measures.

The recent accelerator advances, including top-up injection and superconducting RF cavity system, provide crucial and solid technical solutions to handle the problems associated with intermediate energy light source

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machines. Other matured accelerator technologies, such as high field multipole wigglers and superconducting bending magnets (superbends), are able to extend the high flux photon energy up to ~40keV.

2 Intermediate light source projects

The term “intermediate energy light sources” refers to third generation light sources with storage ring energy in the 2.5-4.0 GeV range. At present, there are about 14 such kinds of light source projects in various phases of planning, construction or operation throughout the world. Table.1 lists the main parameters of these intermediate energy light sources. These new sources can be classified into two types, low emittance and compact structure ones. Their design appearances reflect various budgetary conditions, various users requirements and light source expertise in different countries. Under the same objective of stepping into the hard X-ray with intermediate energy machines, the compact light sources are mainly cost optimized. Their circumferences are around 200 m with about 12 straight sections and their corresponding DBA lattice structure is relatively simple using fewer quadrupoles and sextupoles as well as combined function magnets. The other type of design optimization is performed for extreme high performance with emittance down to ~3 nm·rad and various straights for accommodating different types of IDs, resulting in the X-ray brightness up to ~10^{20} phs/(s·mm^2·mrad^2·0.1%BW) in the energy range of 5-20 keV. Their circumferences are varying from nearly 300 m to 560 m. They are medium scale intermediate energy light source facilities.

These intermediate energy light source projects under planning, construction and operation are widely distributed on the earth. The typical facilities include the SLS[10] at PSI in Switzerland, the ANKA[11] at Institute for Microstructure Technology, Karlsruhe in Germany, the SOLEIL[12] at CEA/Saclay in France, the DIAMOND[13] at CLRC Rutherford Appleton Laboratory in UK, the LLS[14] at the Universitat Autonoma de Barcelona in Spain, the SPEAR3[15] at SLAC in USA, the CLS[16] at University of Saskatchewan in Canada, the Boomerang[17] at Monash University in Australia, the CANDLE[18] in Armenia, the Indus-II[19] in India and the SSRF[20] in Shanghai, China.

Table 1 Parameters for intermediate energy machines under planning, construction and operation

Name	E (GeV)	I (A)	ε_{x0} (nm·rad)	Tunes Q_x/Q_y	f_{RF} (MHz)	Lattice	No.of Straights	Circum. (m)
ANKA[11]: O	2.5	400	90	6.8	3.3	DBA	8	110.4
Boomerang[17]: C	3.0	200	11.4 (1)	11.2/4.3	499.65	DBA	12	187.20
CANDLE[18]: P	3.0	350	8.4 (1)	13.22/4.26	499.65	DBA	16	216
CLS[16]: C	2.9	500	18.1 (1)	10.22/3.26	500	DBA	12	170.88
DIAMOND[13]: C	3.0	300	2.7 (1)	27.23/12.36	500	DBA	24	561.6
ESSQ[24]: P	3.5	200	1.6	39.84/10.77	500	DBA	24	452.15
INDUS-II[19]: C	2.5	300	58.1	9.2/5.2	505.81	DBA	8	172.47
LLS[14]: C	2.5	250	8.5	14.3/8.2	500	TBA	12	251.8
MAX 4[25]: P	3.0	200	~1		100		14	277
SLS[10]: O	2.4 (2.7)	400	5	20.38/8.16	499.65	TBA	12	288
SOLEIL[12]: C	2.75	500	3.7 (1)	18.28/10.26	352.20	DBA	24	354.10
SPEAR3[15]: C	3.0	500	18	14.19/5.23	476.3	DBA	18	240
SSRF[20]: P	3.5	300	4.8 (1) -11.8	22.19/8.23	499.65	DBA	20	396
TLS-II[26]: P	3.0	400	9.8 (1) -28.3	12.2/5.2	500	DBA	16	240

(1)Natural emittance of dispersion-distributed mode, O: Operation, C: Construction, P: Planning

In addition, the ELETTRA in Trieste, Italy, running its 25% of the time at 2.4 GeV[21] and the PLS at PAL in Korea, upgrading its energy to 2.5 GeV,[22] have been converted to intermediate energy light sources according to users demands. Furthermore, the ESRF in Grenoble, France runs the machine at 4 and 5 GeV to obtain a smaller horizontal emittance down to 1.8 nm · rad, aiming at providing photon beams with increased transverse coherence to a number of experiments.[23]

Intermediate energy light sources, together with high gain FEL and ERL-based light sources, form the main stream of light source developments. It will further lead to a diffraction limited light source in the future.

3 Technological features

It is interesting to notice the technological features that adhere to the intermediate energy light sources, which indicate the concept of using the limited budget and ultimate technology to get and improve the light source performance. These facilities pursue extremely low emittance for obtaining high undulator brightness at both fundamental and higher harmonics, high stable photon beams and variable polarisation for complex forms of experiments. Here we do not try to give an exhausted summary of these technological features, but place the emphasis on what have crucial impact on the design and construction of intermediate energy light sources.

3.1 High performance magnet lattice

The performance of light source ring is determined primarily by its magnet lattice.[27] In large scale light sources, such as ESRF, APS and SPring-8, the double bend achromat (DBA) is the exclusive choice, since the larger dispersion inside the DBA arc makes the chromatic correction with sextupoles easier. In intermediate energy light sources, DBA is still the dominated one. The high performance is achieved from complex and lower symmetry lattices, where there are more changes in the arrangement of storage ring straights. Normally one machine has 2 to 3 types of straights with different lengths and different horizontal and vertical beta functions. They are arranged for accommodating different types of IDs: short straights for mini-gap and high field IDs, middle ones for standard undulators and long ones for injection system and the twin polarized undulators with opposite helicity. Moreover, the space between two dipoles in DBA structure is also designed as the ID straights.[12] In addition, the gradient bending magnets and sextupole plus corrector combined magnets are also widely used for shortening the length of achromat to optimise the figure of merit, the ratio of straight length to circumference.

There are different objectives to optimise intermediate energy storage ring lattices, aiming at high flux and reasonable brightness or pursuing extreme low emittance. The low emittance is optimised by choosing the number and gradient of dipoles as well as distributed dispersions. In two typical cases, SLS[10] uses gradient TBA structure and DIAMOND[13] employs 24 DBA cells to achieve the low emittance. For example, the emittance can be reduced by a factor of about 3 by increasing the number of DBA cells from 16 to 24. Increasing the cell number can not only enhance the light source capability with more straights for IDs but also reduce the beam emittance. On the other hand, ESRF and ELETTRA upgraded their achievable minimum emittance with distributed dispersion scheme,[9] and MAX-II incorporated this idea from its design stage.[28] Now almost all intermediate energy light sources have chosen the distributed dispersion lattice configuration, which can reduce the emittance by a factor of 2 compared with the zero dispersion configuration.

Ensuring reasonable lifetime is one of the major concerns for the low emittance intermediate energy machines. The momentum acceptance determined from dynamic aperture, RF and physical aperture is highly maximised to get longer lifetimes, among which the optimisation of nonlinear dynamic plays the most important role. For intermediate energy light sources, the linear optimisation and nonlinear lattice optimisation are coupled together,[27] therefore, one cannot conduct them in distinct sequential steps. Nonlinear effects have to be seriously taken into account and highly suppressed from the beginning of lattice optimisation process, and then followed by the optimisation of sextupole families and the optimisation of section phase advance of lattice for cancelling nonlinear terms.[29,30] In conclusion, the dynamic aperture of intermediate energy storage rings has to be maximised by increasing energy acceptance and reducing nonlinear effects in their lattices.[27]

3.2 Beam orbit stability

The beam stability is a measure of performance of light sources and becomes more and more important as beam sizes get smaller and smaller. Although the photon beam stability requirements from synchrotron radiation users are diverse, the specification for beam stability is widely recognized to be 10 percent of transverse beam size and 10 percent of beam divergence.[31] This implies a beam position stability criterion at few tens of microns in horizontal plane and about micron to submicron level in vertical plane, and a beam angular stability criterion at a few microradians horizontally and sub-microradian vertically.

Disturbance to beam orbit stability can be categorized on various time scales.[32] On long term scale ranging from months to years, the orbit motion due to ground motion and seasonal changes is able to reach few millimetres, which is normally corrected by regular realignment， or by advanced dynamic alignments using hydrostatic leveling system or motorized girder and magnet movers.[33] Medium term orbit motions with amplitudes up to a few hundred microns last from days to weeks. They are mainly induced by environment temperature changes, diurnal variations, rains and tides, thermal effects due to various machine operation states including start-up, injection, bunch filling patterns and currents, IDs working status, tunnel air and cooling water temperature fluctuations. Medium term disturbance can be alleviated by the top up injection. Short term effects from milliseconds to hours, are mainly from ground and girder vibrations, cooling water induced vibrations, power supply ripples and noises.

Medium and short term beam orbit motions are more deleterious to SR experiments. Medium term effects cause photon beam intensity fluctuations while short term ones make the effective beam emittance increased. Stabilization of these beam orbit motions requires both passive and active measures including the beam orbit feedback and the careful electrical, mechanical and civil engineering of storage rings. The passive measures include making solid machine settlement, building high stable girders, precisely stabilising ring tunnel air temperature and cooling water temperature to about ±0.1℃, fixing the BPM directly on the girders or the tunnel floor through low thermal expansion materials (invar, carbon fiber or concrete) supports. The active suppression methods involve global (fast and slow, 0.001~200 Hz) and local feedback systems, feed forward compensations and RF frequency feedback.

Tremendous efforts on beam orbit stability have been made over the past five years, and beam position stability has been improved to a sub-micron to micron level at many light sources.[34] Obviously, orbit feedback systems are essential to beam orbit stability, which have been extensively and effectively used in the light source storage rings. The sub-micron level of orbit stability is only achievable when orbit feedback systems are in operation. Currently, beam stability issue has already become a vital part in design optimizations as well as construction and operation of intermediate energy light sources. Besides the high demands on construction of tunnel foundation and control of thermal effects around storage ring, more stringent requirements for power supply stability, BPM resolution and support stability, girder mechanical stability and wide band correctors, are specified in detail. All of these lead to the comprehensive and persistent studies on the beam stability issue from the early design stage. All the passive and active measures to stabilise beam orbit need to be grouped and optimised together with the design of light sources. In fact, the top-up injection and the rapid technologic progress such as that in digital RF BPM and photon BPM, has profited the beam orbit stability, which give an impact on the measures for obtaining high stable and reproducible beam orbit in light source storage rings.

3.3 In-vacuum mini-gap undulators

There are a variety of undulators and wigglers developed for modern light sources,[3-5] which produce high brightness and high flux synchrotron radiation with required photon energy and polarizations. In fact, the progress in IDs technology has given a dynamic drive to intermediate energy light sources, in-vacuum, mini-gap and higher harmonics are their main representatives.

In-vacuum undulators,[35,36] in which the magnet arrays are placed inside of storage ring vacuum systems and therefore there is no vacuum chamber between the magnet poles, are the most ideal insertion devices for protein crystallography beamlines in intermediate energy light sources. Such undulators with short periods about 20 mm and minimum gaps around 5 mm, namely in-vacuum mini-gap undulators, can generate photons with energy up to more than 20 keV at ninth to eleventh harmonics. In intermediate energy light sources, they are able to compete with wiggers for getting high flux photon beams for small beamline apertures at photon energy below 25 keV and provide a comparable photon brightness with that from high energy light sources in the range of 10 to 20 keV. In addition, in-vacuum undulators have a parasitic flexibility for changing magnet gaps at various operation states, which is more favorable during light sources under commissioning.

In-vacuum undulator technoloy is now at a level of maturity thanks to international experience accumulated over the past 10 years, particularly at SPring-8,[35] where there are more than 18 in-vacuum undulators under operation. ESRF, NSLS, ALS and SLS have also timely developed and operated such kind of insertion devices,[4,5] and there are total 5 in-vacuum mini-gap undulators under operation and 3 ones under construction at ESRF for the time being.[37] Actually, in-vacuum undulators have become the indispensable IDs widely incorporated into the newly designed intermediate light sources, such as those in CLS,[16] SOLEIL[38] and DIAMOND.[39] Table.2 lists a few of in-vacuum mini-gap undulators. Meanwhile, there are two approaches to expand the photon energy range. Using high harmonics up to the eleventh from single undulator concept, one can obtain a tunable range from 2 keV to 30 keV for 3.5 GeV light sources. Differently, the multi-undulator concept is able to expand the tunable range by a rotating undulator poles structure, which can be mechanically grouped into more than 4 kinds of undulator parameters. In the near future, the in-vacuum superconducting mini-gap undulator, now under development,[40] could further increase the photon brightness in the range of 10-20 keV.

Table 2 Parameters of in-vacuum mini-gap undulators

Facility	IDs	Period (mm)	Gap (mm)	L (m)	No.
SPring-8	^{O} U24	24	5	4.5	1
	^{O} Fig-8U	26V	5	4.5	1
NSLS	^{O} U11	11	3.3	0.32	1
ESRF	^{O} U23	23	6	1.6/2	2
	^{O} U21	21	6	2	1
	^{O} U18	18	6	2	1
	^{O} U17	17	6	2	1
	^{C} U23	23	6	2	2
	^{C} U22	22	6	2	1
SLS	^{O} U17	17	4	2	1
DIAMOD	^{P} U23	23	7	2	3
	^{P} U27	27	7	2	1
SOLEIL	^{P} U20	20	5.5	1.8	1
CLS	^{P} U22	22	5	3.2	1
Boomerang	^{P} U14	14	5	1.4	1

O: Operation, C: Construction, P: Planning

In-vacuum mini-gap undulators working at high harmonics have a few of adverse effects, which place several stringent requirements on light source storage rings.[3,8] The following are two examples. (1) Low emittance and small energy spread are the essential factors for not causing a significant reduction in photon beam brightness, thus asking for the storage rings with a low emittance lattice and strongly suppressed collective beam effects. (2) The mini-gap of the undulators causes a reduction of the beam gas scattering life time, and in turn imposes on an optimum relation between the undulator length L and its associated vertical beta function β_y, which is $\beta_y = L/2$.

Additionally, variable polarized undulators, high field multipole wigglers, twin-undulator operation schemes, rotating undulators and superbends will be employed at intermediate energy light sources to serve the various user requirements.

3.4 Top-up injection

Top-up injection is a more favorable operation mode for getting high stable beam orbit and using mini-gap undulators in modern light sources.[7,8] This operation mode is routinely running at the APS and the SLS, where the single bunch injection is repeated continually every 2 minutes.[41,42] As stated above, high brightness, high stable beam orbit, highly constant heat load and longer lifetime are more demanding in synchrotron radiation experiments, which in turn require a constant beam current circulating in storage rings. To intermediate energy light sources, the top-up injection is more essential because of its high beam current up to 300-500 mA, low emittance down to 2-3 nm and short Touschek and gas scattering lifetimes due to the medium operating energy and the use of mini-gap undulators.

With the top-up injection, the light source storage rings are able to keep stored current within 0.1% variation, and in turn eliminate short lifetime problem and the thermal effects due to the beam current variation. This makes it possible to operate storage rings with even lower emittance and high average current or high bunch current as well as relaxed requirements of dynamic aperture and energy acceptance.

Top-up operation is performed with beamline shutters open, which arouses a few side effects. The biggest concern is the radiation safety problems associated with the beam losses or injection efficiency of storage rings. Another issue is the disturbance to user experiments, which cannot be eliminated completely. Users need to gate out the data acquisition during top-up injection period for about one millisecond.

Top-up injection imposes a strong impact on light source accelerators.[42] (1) It requires a highly stable and reliable injector consisting of linac and booster, which has to be always available for continuously delivering beam to storage ring during operation period. In addition, low booster emittance down to smaller than 150 nm is highly desired for getting high efficient injection and not using collimators in the beam transport line to the ring. There are two types of boosters, the normal booster like the DIAMOND one[43] with emittance about 144 nm·rad at 3 GeV and the larger booster as the SLS one[44] with emittance of 9 nm·rad at 2.4 GeV. (2) It demands highly efficient and reliable injection system in storage rings to minimize beam losses during the top-up operation. Furthermore, an ideal scheme is placing all the injection kickers within a long straight section of the storage ring, which avoids the interference between injection system and the nearby magnets. (3) It needs a highly sensitive diagnostic system for accelerators and transport lines between them. The low current in injector and the bunch current as well as the beam orbit distortion and the turn-by-turn beam losses in storage ring have to be precisely monitored with high priority. (4) It looks for an economic booster for both construction and continuous operation, therefore the minimum repetition rate and the low power consumption are the main optimization conditions.

The above requirements indicate that top-up operation mode needs to be integrated into the light source design from the earliest design phase and considered as another vital part of light sources optimizations.

3.5 Superconducting RF cavities

For intermediate energy light sources with current up to 300-500 mA, the suppression of the longitudinal and transverse coupled bunch instabilities driven by the HOMs of RF cavities is one of the crucial issues to ensure their performance, such as maintaining stably stored beams, eliminating multi-bunch oscillations and controlling energy widening. These are the essentials to get the high brightness photon beams from mini-gap undulators working at higher harmonics. Single cell superconducting cavities, with better damped HOMs and higher accelerating gradient as well as extremely lower cavity wall power losses, exhibit a few of attractive advantages over normal conducting cavities.[45] The strongly damped HOMs and a small number of cavities for providing the required RF voltage in superconducting RF system lead not only to high current thresholds of beam instabilities but also to at least one more straight section saved for installing insertion devices, which is very valuable for light sources. In the meantime, it indicates that the longitudinal beam feedback may be excluded and the transverse beam feedback be simplified with single cell superconducting cavities. In addition, it will take very little power for superconducting RF system to establish higher RF voltage, which is required to get larger off -momentum dynamic aperture and large energy acceptance for increasing Touschek lifetime.

Although there is no superconducting RF system operated for light sources, the experience accumulated in the long time operation at colliders like KEK-B and CESR is very promising.[46-48] The existing TLS at SRRC is upgrading its RF system with 500 MHz CESR type superconducting cavity to increase stored beam current up to 500 mA.[49] This new superconducting RF system is expected to start commissioning in the summer of 2003. In cooperation with CEA, CNRS, CERN and ESRF, SOLEIL is developing and testing a cryo-module housing two 350 MHz superconducting cavities.[50,51] This cryo-module has been installed in the ESRF storage ring and its beam test has been performed with good progressive results in 2002. The CLS has contracted with ACCEL to construct its superconducting cavity,[16] which is scheduled to start commissioning in 2003. Moreover, DIAMOND has decided to use superconducting RF system,[46] and SSRF is considering to engage in this technology too.

A rough cost estimation shows that for a required RF voltage and beam power the superconducting RF system has a comparable investment with the normal conducting one, but its operation cost is cheaper. However, superconducting RF system is more complicated and its reliability is of great concern, such as trip rates, vacuum and cryogenic incident recovery time, for which experience needs to be gained during the commissioning and operation of the superconducting RF systems for light sources.

Additionally, there is a number of superconducting harmonic cavities under development for lengthening the bunch,[52,53] which are the later upgrading options for intermediate energy light sources.

4 The SSRF project

The Shanghai Synchrotron Radiation Facility (SSRF) is an intermediate energy light source proposed by the Chinese Academy of Sciences (CAS) and the Shanghai Municipal Government. It consists of a 3.5 GeV electron storage ring, a full energy injector including a 0.3 to 3.5 GeV booster and a 300 MeV linac, and a dozen of beamlines and experiment stations.

During the SSRF R&D period from 1999 to 2001, the light source technical design has been performed, and 80 M RMB has been used to develop the prototypes of the SSRF accelerator and beamline components. Totally 41 prototypes have been constructed and tested up to their specifications.

The SSRF as a future third generation light source aims at providing powerful X-ray to the Chinese SR users in a variety of research fields. Because of the recent growing demands of the SR application in protein crystallography, the SSRF design has been evolved to produce high brightness and high flux X-ray in the photon energy range of 0.1-40 keV, with the emphasis placed on 5-20 keV. The SSRF storage ring energy of 3.5 GeV has been determined following the concept of using intermediate energy beam and advanced insertion devices to produce X-ray for majority of the SR users. This concept foresees the use of mini-gap undulators and the use of SR from the high harmonics of undulators, which also implies that the in-vacuum IDs are preferable. The small gaps in IDs make a critical challenge to the ring beam lifetime as stated in Section 3.3, which in turn make the top-up injection more demanding in the SSRF.

The design of the SSRF storage ring has been smoothly evolved to a cost effective machine over the past five years.[20,54,55] Its existing specifications are featured with robust and flexible lattice configuration and advanced mature technology. The lattice is a flexible Double-Bend-Achromatic (DBA) structure composed of 40 bending magnets and 20 straight sections, yielding an emittance of 4.8-12 nm·rad at 3.5 GeV. Among the 20 straight sections, 17 are dedicated to install insertion devices. The main parameters of the SSRF ring are shown in Table 3, and its corresponding photon brightness is depicted in Fig.1.

The SSRF specifications have been detailed with the completion of the technical design, and the prototypes made under the SSRF R&D program are qualified for formal construction by minor modifications. However, as technologic progress going on, the SSRF design optimisation has been carrying on to achieve even better performance using newly developed technologies while waiting for the final project approval of the central government of China.

Table 3 Main parameters of the SSRF storage ring

Energy (GeV)	3.5
Circumference (m)	396
Harmonic number	660
Nat. emittance (nm·rad)	4.8~12
Multi-bunch (mA)	200~300
Single-bunch (mA)	>5
Straight lengths (m)	10×7.2, 10×5.0
Betatron tunes, *Qx/Qy*	22.19/8.23
Momentum compaction	7.7×10-4
RF frequency (MHz)	499.654
RF voltage (MV)	4
Energy loss/Turn (MeV)	1.256
Bunch length (mm)	4.59
Beam lifetime (h)	>20

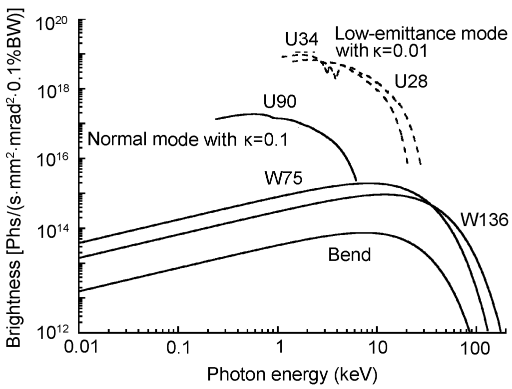

Fig.1 Spectral brightness of SSRF

5 Conclusion

New development trend in light sources benefits from the recent technologic progress, particularly in undulators, beam orbit stabilisation, top-up injection and superconducting cavities. Low emittance, high current and high harmonic radiations of in-vacuum mini-gap undulators make it possible for a few of intermediate energy light sources to generate high brightness 5-20 keV X-ray with the properties comparable to those obtained with high energy light sources like ESRF, APS and SPring-8. Under this concept many counties, that can bear the modest construction and operation cost of intermediate energy light sources, are designing and building their own X-ray light sources to meet the regional requirements in a broad range of photon energies. Especially, these light sources will well serve the life science user community that needs high brightness photon beams in the energy range of 10 to 20 keV for performing protein crystallography experiments. With high field wigglers and superbends, intermediate energy light sources are able to extend their high flux hard X-ray energy up to 40 keV.

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