AN OVERVIEW OF LIGHT SOURCE DEVELOPMENT IN ASIA*

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Abstract

In this paper we will give an overview of the latest development of the light sources in Asia. The synchrotron light source facilities have covered all major regions of Asia in recent years. While the storage ring-based synchrotron radiation facility are considered 'mature' technology, the free-electron lasers (high gain type) are starting to serve the scientific community with much higher peak brilliance and other features. The new light source projects tend to significantly improve the performance by lowering the beam emittance even to the diffraction limit. The possibilities of combining latest development of storage ring, linac and free-electron laser technology are being investigated to achieve better goals.

INTRODUCTION

The accelerator-based light sources are the most successful scientific instruments of the past decades. These facilities produce high-flux, high-brightness radiations that span a large spectral region from infrared to hard x-rays. The accelerator-driven light sources can be categorized as follow,

- Storage ring-based synchrotron radiation facility,
- Free-electron Lasers,
- Energy recovery linac (ERL),
- Laser-electron scattering type sources, etc.

In this paper the ERL and laser-beam scattering type sources will not covered. Since there were several overviews of the historical development on the Asian light sources since 1980's in the previous conferences, we are going to focus on the latest developments with the emphases on new synchrotron facilities and high gain free-electron lasers. A brief description and discussion will be made on the newly planned light source projects.

Storage ring light sources have many attractive features, including high stability and reliability, with simultaneous cost-effective service to many users with diverse requirements hence have become essential tools for many fields of science. Currently there are more than 50 synchrotron light sources in operation, and in addition there are 15 in various stages of construction, design or planning. In Asia (here including Oceania), there are nearly 20 synchrotron light sources have been built in more than 15 countries/areas [1, 2, 3, 4, 5, 6].

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Table 1: @Synchrotron Light Sources in Asia

Facility Name	Location City	Energy (GeV)	Circ. (m)	Emit. (nm·rad)	Current (mA)	Completion Year(status)*
KEK-PF	Tsukuba	2.5	187	34.6	450	1982(O)
UVSOR	Okazaki	0.75	53.2	17	300	1984(O)
KEK-AR	Tsukuba	6.5	377	293	60	1986(O)
BSRF	Beijing	2.5	240.4	76	200-250	1991(O)
HLS	Hefei	0.8	66.1	160	250-350	1991(O)
TLS	Hsinchu	1.5	120	25	240	1994(O)
PLS	Pohang	2.5	280	18.9	200	1995(O)
AURORA	Kusatsu	0.7	11	2400		1995(O)
Spring-8	Hyogo	8.0	1436	2.8	100	1997(O)
HiSOR	Hiroshima	0.7	22	400	300	1997(O)
NSUBARU	Hyogo	1.5	119	38	500	1999(O)
Indus-I	Indore	0.45			100-200	1999(O)
SSLS	Singapore	0.7			400	2001(O)
SPS	Bangkok	1.2	81.3		100	2005(O)
SAGA-LS	Tosu	1.4	75.6	25	300	2006(O)
Austr. Syn.	Melbourne	3.0	216		300	2007(O)
Indus-II	Indore	2.5	172	58	300	2008(O)
SSRF	Shanghai	3.5	432	3.9	300	2009(O)
PLS-II	Pohang	3.0	282	5.9	400	2012(O)
CJSRF	Nagoya	1.2	72	53	300	2012(O)
TPS	Hsinchu	3.0	518	1.7	400	2014(C)
SESAME	Amman	2.5	133	26	400	2015(C)
ILSF	Tehran	3.0	297	3.3	400	2018(C)
CANDLE	Armenia	3.0	216	8.4	350	2018(C)
TAC	Ankara	3.0	467	0.68	500	Plan(D)
SLiT-J	Sendai	3.0	340	1.12	400	Plan(D)
Spring-8 II	Hyogo	6.0	1436	0.067		Plan(D)
BAPS	Beijing	5.0	1284	0.5	200-300	Plan(D)

* O: Operation, C: Construction, D: Design

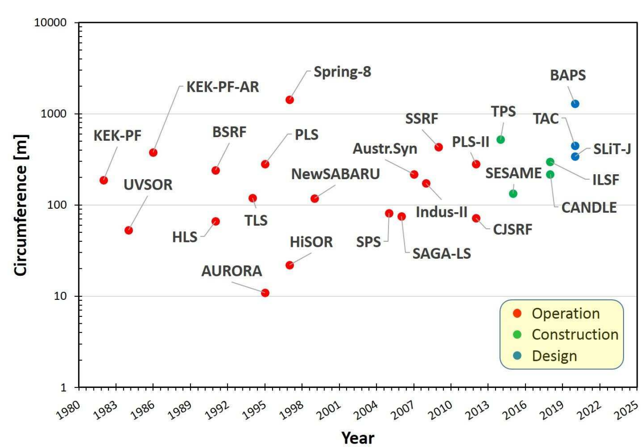

Figure 1: Synchrotron light sources in Asia, circumference V.S. completion year.

SYNCHROTRON LIGHT SOURCES IN RECENT YEARS

A new development in Asia is that intermediate energy (2.5 ∼ 4.0 GeV) third generation synchrotron light sources

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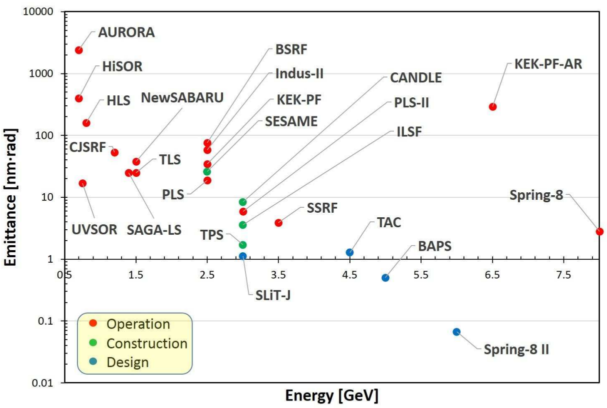

Figure 2: Synchrotron light sources in Asia, emittance V.S. energy.

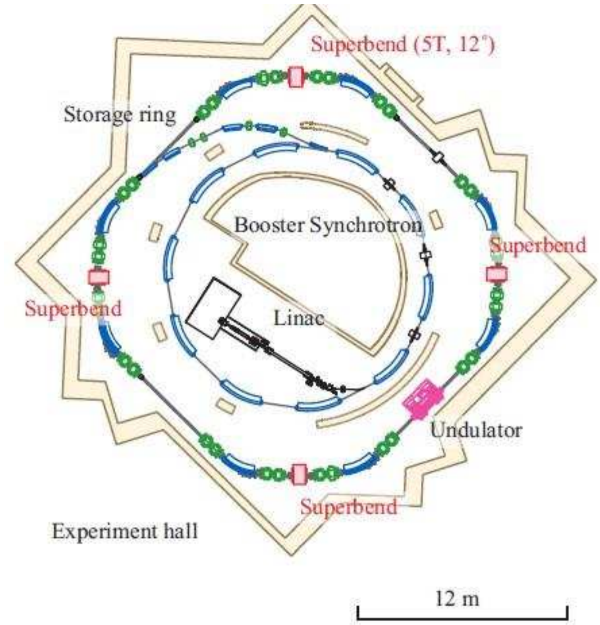

Figure 3: A 1.2GeV low energy compact light source CJSRF [12] is completed in Nagoya.

came to the stage, as cost-effective light sources in the past decade, they use ∼ 3 GeV low emittance electron beam and mini-gap in-vacuum undulators to generate high brightness x-ray radiations. INDUS-II [7] and SSRF [8] became operational before 2010. TPS [9], PLS-II [10], SESAME [11], are now being constructed and will be operational before 2015.

The 3.5 GeV SSRF has been in user operation for almost three years since its formal opening in May 2009, new beamline programs are now underway to meet the strong user demands. The 3.0 GeV PLS-II upgrade project has been just completed with a very aggressive schedule. It was opened for user experiments in March 2012. The 3.0 GeV TPS has entered the third year of construction since its ground breaking in February 2010. The civil construction was completed April, 2013 and it is scheduled to start users' operation by the end of 2014.

Continuous advancements in accelerator science and technology have made it possible to further enhance the performance of storage ring light sources, with higher brightness, higher flux, higher stability, shorter pulse durations, and partial coherence. Synchrotron radiation facilities will continue to be the principal light sources in the following decades.

HIGH GAIN FREE-ELECTRON LASERS

In a free-electron laser (FEL), a high-quality relativistic electron beam propagates through a long undulator, composed of two vertical series of alternating magnetic poles, which establish a periodic magnetic field. The horizontally wiggling particles radiate synchrotron radiation—the spontaneous emission, which interacts with the electron beam through energy exchange along the undulator. Then, the electron bunch density is modulated in the longitudinal dimension by a period close to the spontaneous emission wavelength (micro-bunching), so that the different slices start to emit in phase. Nowadays the high gain FELs have been proved to be the brightest light sources in the X-ray regime, ten orders of magnitude higher of peak brilliance

Figure 4: PLS-II upgrade project was completed in 2012, shown here is the newly installed superconducting RF sections.

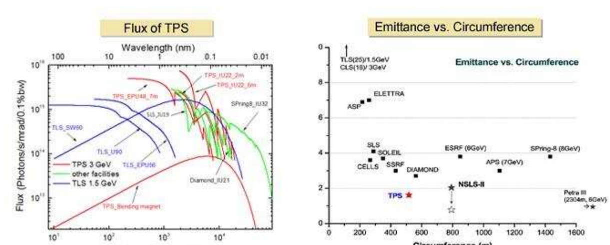

Figure 5: TPS will be the next new light source, with ultra low emittance at 1.6 nm·rad@3 GeV.

than that in the existing third generation light sources.

In Asia there are six high gain FEL projects, three in operation (SCSS, SDUV, SACLA) and other three are under construction (PAL-XFEL, DCLS, SXFEL). See Table 2. The largest free-electron laser facility in Asia so far is the

Table 2: List of High Gain Free-electron Laser Facilities in Asia

HG-FEL	Location	E Gev	Type	Length m	Wavelength nm	Rep-rate Hz	Driver	FEL type	Status	First Lasing
SCSS	Hyogo	0.25	T,U	55	50-60	10-60	LINAC (C)	SASE,DS	O	2006
SDUV	Shanghai	0.2	T	65	150-350	1-10	LINAC (S)	Seeded	O	2010
SACLA	Hyogo	8.0	U	700	0.08-0.8	60	LINAC (C)	SASE,SS	O	2011
PALXFEL	Pohang	10.0	U	1100	0.1-4	100	LINAC (S)	SASE,SS	C	2015
DCLS	Dalian	0.3	U	150	50-150	50	LINAC (S)	HGHG	C	2015
SXFEL	Shanghai	1.0	T	300	9-30	10	LINAC (C)	Seeded	C	2015
BAPSII	Beijing	3-5	U	1250	1-5	>kHz	Ring		D	plan

* T: Test facility, U: User facility, LINAC: linear accelerator, C: C-band, S: S-band, DS: Direct-seeding, SS: Self-seeding, O: Operation, C: Construction, D: Design

Figure 6: SESAME, a light source being constructed in Amman, Jordan by an international collaboration by 12 member states and 9 observer states.

SACLA at SPring-8 lab, Japan. Powered by an 8 GeV linac with high gradient C-band structures and small-period in-vacuum undulators (IVUs) it has reached sub-ångström wavelength with ultra-high brilliance, shown in Table 3.

Table 3: Achieved Performances of SACLA

Parameter	Value
Pulse Energy	0.3 mJ@10 keV
Peak Power	30 GW
Wavelength range	4.5 to 15 keV
Spatial Coherence	nearly full
Stability (unit: normalized standard deviation)	
Intensity $\sigma_{\Delta I/I}$	$< 10\%$
Pointing $\sigma_{\Delta z/z}$	$3 \sim 7\%$ (FWHM)
Wavelength $\sigma_{\Delta\lambda/\lambda}$	$< 0.1\%$
Repetition	20 Hz (Max.60 Hz)

In self-amplified spontaneous emission (SASE), the amplification starting from SE requires long undulators to reach saturation. Moreover, the micro-bunching takes place independently in different parts of the bunch and limits the temporal coherence of the radiation. The saturation is then achieved over shorter undulator length, resulting in a more compact source. Because amplification is coherently triggered within the seed pulse length, instead of erratically from SE in the SASE, the pulse temporal/spectral profiles should no longer present statistical fluctuations (spikes). The direct seeding with HHG (High-order Harmonic Generation) seed at 160 nm and 60 nm was successfully demonstrated on SCSS in SPring-8, Japan [19]. The SDUV at SINAP, China, lased with the Echo-Enabled Harmonic Generation (EEHG) FEL scheme that promised superior properties for bunching at very high harmonics [20]. The SACLA, initially designed to working with SASE mode, is now equipped with the self-seeding section to significantly improve the bandwidth of the FEL signals [21]. The three FEL projects under construction, PAL-XFEL, DCLS (Dalian Coherent Light Source) and, SXFEL (Shanghai X-ray FEL), covers wide spectra from VUV to the hard x-ray, with the envisions of seeding schemes (Self-seeding, High Gain Harmonic Generation (HGHG) and EEHG, respectively) to provide transversely and temporally coherent radiations.

NEW LIGHT SOURCE PROJECTS

The newly planned light sources in Asia area can be categorized as,

- Typical third generation synchrotron light source, ILSF (Iran Light Source Facility) [16], CANDLE [17], SLiT-J [14], TAC (Turkish Accelerator Centre) [18], BAPS-I (Beijing Advanced Light Source),
- Diffraction-limit or ‘ultimate storage ring (Spring-8-II) [13],
- New scheme that combines synchrotron ring, energy recovery linac (ERL) or FEL (3 GeV ERL at KEK, BAPS-II) [15].

Figure 7: Spring-8, SCSS and SACLA form the largest light source complex in Asia.

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While storage rings are a 'mature' technology, they nevertheless have the potential for significantly enhanced performance. One can imagine an 'ultimate' storage ring that produces high-brightness, transversely coherent x-rays while simultaneously serving dozens of beamlines and thousands of users annually. For such a source to maximize transverse photon coherence, the beam emittance must be extremely small in both transverse planes, approaching and even exceeding the wavelength-dependent diffraction limit. Storage ring sources have achieved diffraction limited emittances for hard X-rays in the vertical plane by minimizing horizontal-vertical electron beam coupling, but horizontal emittance must be reduced by a factor of 100 or more from the lowest emittance values achieved today to reach that limit. An ultimate storage ring would retain all the general strengths of today's storage rings mentioned above while delivering high transverse coherence up to the 10keV energy regime. Ultimate rings would have brightness and coherent flux one or two orders of magnitude higher than the highest performance ring-based light sources in operation or presently being constructed.

The Spring-8-II is considering an option of lowering the ring emittance significantly in a systematic way,

- Optimization of dipole field (r) in longitudinal (inside dipole and/or inside unit cell),
- Reduction of stored energy (g) with the help of advanced undulator design,
- Damping partition number (J_x) control,
- Damping enhancement by additional radiation
- Sophisticated optimization to approach to the theoretical minimum ($\epsilon_{design}/\epsilon_{min} < 3$),
- Other reduction schemes.

This would be a major upgrade that requires substantial R&D work to address the issues on beam dynamics and technical aspects like very strong and compact magnets, etc.

The Beijing Advanced Photon Source (BAPS) is a major facility being planned for a new research centre in northeast Beijing by Chinese Academy of Sciences. The current design envisions two rings in a wide tunnel with different

Figure 8: SDUV is a seeded FEL test facility.

Figure 9: Schematic view of BAPS in Beijing.

vertical positions to allow the extraction of light from both rings. The outer ring will be a synchrotron light source in hard x-ray regime with an emittance of 0.5 nm at 5 GeV and such a facility can be realized with the proved technologies. With a large circumference over 1.2 km, there are several options for the inner ring including ERL-based light source, diffraction limit ring, or ring-based free-electron lasers. While the R&Ds on ERL technology are actively pursued at KEK, IHEP and other Asian institutions the ring-based FELs (high gain and x-ray) are gaining momentum in recent years thanks to the advancements in following aspects

- USR provides low emittance comparable to linac,
- TGU (Transverse Gradient Undulator) can help cure large energy spread in ring [23],
- Short bunch techniques in rings enhance peak current,
- Long straights are available in large rings like PEP-X (over 100 meters length for each straight) [22] or new rings like BAPS (over 200 meters for each of two bypasses) [24] for high gain FEL amplifications.

The simulation studies show that a ring-based FEL at soft X-ray on BAPS is feasible with the parameters listed in the Table 4. With the help of TGU the FEL gain is large enough to produce very intense and coherent photon pulses. The damping is needed in to restore the equilibrium of the energy spread and the emittance spoiled by the amplification process. On the other hand the arc part of the inner ring will offer synchrotron radiations by insertion devices and dipoles for many beamlines simultaneously.

Table 4: Possible Parameters of Ring Based High-gain FEL at BAPS

Parameter	Symbol	Value	Unit
Peak Current	I_p	300	A
Undulator Period	λ_u	0.03	m
Undulator Parameter	K_0	1.61	
Undulaotr Length	L_u	180	m
Average beta x	$\bar{\beta}_x$	70	m
Average beta y	$\bar{\beta}_y$	20	m
Transverse Dispersion	η	4.5	cm
Transverse Gradient	α	40	m^{-1}
FEL wavelength	λ_s	1.0	nm
FEL peak power	P_{pk}	~ 200	MW
FEL pulse energy	W_{FEL}	~ 200	μJ
FEL flux	F_{FEL}	1×10^{12}	#/pulse

SUMMARY

In this paper we have shown the latest developments of light sources in Asia. Synchrotron light sources facilities have covered all major regions in Asia and Oceania and made tremendous contributions to areas scientific community. High-gain Free-electron Lasers are starting to serve the scientific community with high brilliance and short pulse from VUV to hard X-ray wavelengths. There are much more potential to explore. New light source projects feature better performance in all aspects, brilliance, coherence, short-pulse, multi-user, polarization, etc. Study on novel light source schemes and technology continues, in collaboration with worldwide efforts.

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