REVIEW OF THIRD GENERATION LIGHT SOURCES*

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Abstract

In 1994, ESRF in Grenoble opened the era of the third generation light sources, and the first batch of machines are immediately followed at ALS, ELETTRA, TLS, PLS, APS, and SPring-8 in hard and soft X-ray regimes. For high-brightness, these facilities adopted a low-emittance storage-ring lattice and many straight sections for advanced undulators. With ever-growing users' demands from materials science to biology/life science research, many more facilities are followed in the past decade. The machine operations are dramatically improved for more effective users' service along with technological advancement, such as advanced diagnostics and controls, survey and alignments, top-up injections, super-conducting RF cavities, in-vacuum undulators. There are now about 70 light sources in the world, and important scientific discoveries are driven from these facilities with a few Nobel Prizes. In this paper, we review the advancement of the third generation machines.

INTRODUCTION

Man-made synchrotron radiation was first observed at the GE Synchrotron in 1947 by F. R. Elder, A. M. Gurewitsch, R. V. Langmuir, H. C. Pollock [1]. It was immediately recognized very useful for diversified research fields, especially for solid-state physics and crystallography research. A few accelerators built for high-energy physics research were used for light sources. These facilities are called the first generation light sources; such as, SURF at NBS, CESR at Cornell, ARCO and DCI at Orsay, INS-SOR at Tokyo, Tantalus 1 at Wisconsin, SPEAR at SLAC, DORIS at DESY, and VEPP-3 at BINP.

There were a few dedicated facilities constructed for lights source users. These are called as the second generation light sources, such as, SRS at Daresbury in 1981, NSLS at BNL, Photon Factory (PF) at KEK in 1982, SPEAR-II at SLAC, Super-Arco at LAL, BESSY in Berlin, SOR at INS in Tokyo, and NSRL in Hefei, China. One may note that there were two users groups for VUV (or soft X-rays) and hard X-rays, for example, the 800-MeV and 2.5-GeV rings, respectively at NSLS.

On the other hand, in mid-1980s, insertion devices using permanent magnets were developed, and these are implemented to the 2nd generation machines. Therefore, the third generation light sources have been suggested for the maximum use of undulators. The US National Research Council recommended "major facilities for materials research and related disciplines" [2]. This report resulted in ALS for VUV at LBNL, APS for hard X-rays at ANL, SNS for neutron users at ORNL, and it also triggered the world-wide race on the 3rd generation light source construction. Table 1 shows facilities opened for users in 1990s.

The big three economic blocks of US, EU and Japan engaged in hard X-ray machines of higher energy than 6.0-GeV, while intermediate economic groups started medium energy machines of around 2.0-GeV for VUV or soft X-ray users. Currently there are about 70 light sources operating in the world [3], and an extensive review was presented at PAC'07 by Z. T. Zhao [4].

In 2003, US DOE made a plan on "Facilities for the Future of Science: a Twenty-Year Outlook," in which there are 14 accelerator-based programs out of the total 26 programs [5]. One may note that LCLS at SLAC takes a high-priority and the most of light sources would be upgraded including a new facility at BNL, NSLS-II.

Table 1: Main Parameters of Third Generation Light Sources opened in the 1990s

Light Source	Energy (GeV)	Circumference (m)	Emittance (nm-rad)	Current (mA)	Straight Section	Operation year
ESRF	6.0	844.4	4.0	200	32 × 6.3 m	1994
APS	7.0	1104	3.0	100	40 × 6.7 m	1996
SPring-8	8.0	1436	3.4	100	44 × 7 m, 4 × 30 m	1997
ALS	1.9	196.8	6.3	400	12 × 6.7 m	1993
TLS	1.5	120	25	240	6 × 6 m	1994
ELETTRA	2.4	259	7.0	300	12 × 6.1 m	1994
PLS	2.5	280.6	12.0	200	12 × 6.8 m	1995
LNLS	1.37	93.2	100	250	6 × 3 m	1997
MAX-II	1.5	90	9.0	280	10 × 3.2 m	1997
BESSY-II	1.7	240	6.1	200	8 × 4.9 m, 8 × 5.7 m	1999
Siberia-II	2.5	124	98	200	12 × 3 m	1999

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THIRD GENERATION FACILITIES IN THE 1990s

In the middle of 1980s, US, EU and Japan proposed hard X-ray machines with beam energy of higher than 6.0-GeV. The governmental budget approval had been in order of EU, US and Japan. Therefore, with the initial beam energy of 6.0-GeV, the operating energy in following facilities was increased as 7.0-GeV and 8.0-GeV to take the position of the world largest machine. ESRF completed the machine construction in 1992 and opened the facility for users' service in 1994. APS started its users' service in 1996 and SPring-8 did it in 1997.

.ALS at LBNL, the highest priority project recommended by the National Science Council, started its construction first in 1987. And Italy, Taiwan and Korea also followed their light source projects with the equal to or less than 2.0-GeV. ALS, ELETTRA at Trieste in Italy and TLS at Hsinchu in Taiwan were completed in the early 1993 and PLS at Pohang in Korea was completed in 1994. Users' service started at ALS in 1993, TLS and ELETTRA in 1994, and PLS in 1995. There were more facilities in the rest of 1990s: LNLS in Brazil, MAX-II in Sweden, BESSY-II in Berlin and Siberia-II at BINP in Novosibirsk.

The main issues in the early third generation machines were the operating energy and storage ring lattice, the beam life-time and injection intervals, the length of straight sections, lower emittance and stored beam currents for higher brilliance. Since NSLS had 2.5-GeV and 800-MeV rings for X-ray and VUV, 2.0 GeV was considered as a kind of reference. ALS, TLS and PLS adopted the TBA lattice and ESRF, ELETTRA, APS, SPring-8 adopted the DBA lattice. The positron option was seriously considered at ESRF and APS. Actually, APS conducted the positron operations briefly. One may note that PLS adopted the full-energy injector linac, and its operation energy was changed to 2.5 GeV later without any serious modification in 2001. Many engineering issues were also in hot-debated subjects, for example, vacuum chamber materials between stainless steel and aluminium.

When the top-up injection mode was suggested in 1998 and demonstrated later at APS, light source users were very much satisfied on the constant synchrotron light intensity. It becomes a standard option in the following machine designs. It also resulted in the beam-life time issue less important due mainly to frequent injections.

During the design and construction periods for third-generation light sources between the late 1980s and the early 1990s, there were dramatic changes in available technologies. One may note that the computer technology and networks were available in machine design, simulations and machine control areas. The precision alignment technology by laser trackers made it possible for a very high accuracy in survey and alignments.

THIRD GENERATION FACILITIES IN THE 2000s

When the third generation programs were initiated in the mid-1980s, materials science research was one of the main disciplines. However, in the early 1990s, there were exploding demands for biology/life science applications, especially research on protein structures and new drug R&D. The users' community has been expanding beyond biology/life science research to many other research areas. Therefore, in the decade of 2000s, more facilities were implemented to meet ever growing users' demands, for example, SLS in Switzerland, CLS in Canada, SOLEIL in France, DIAMOND in UK, ASP in Australia, SSRF in China, ALBA in Spain. Table 2 shows light source facilities opened for users in 2000s.

Table 2: Main Parameters of Third Generation Light Sources Opened in the 2000s

Light Source	Energy (GeV)	Circumference (m)	Emittance (nm-rad)	Current (mA)	Straight Section	Operation . Year
New SUBARU	1.5	118.7	38	500	4 x 2.6 m, 2 x 14 m	2000
SLS	2.4-2.7	288	5.0	400	3 × 11.7 m, 3 × 7 m, 6 × 4 m	2001
ANKA	2.5	110.4	50	200	4 × 5.6 m, 4 × 2.2 m	2002
CLS	2.9	170.88	22.7	300	12 × 5.2 m	2003
SPEAR-3	3.0	234	18	500	12 × 3 m, 4 × 4.5 m, 2 × 7.5 m	2004
SAGA-LS	1.4	75.6	7.5	300	8 × 2.5 m	2006
SOLEIL	2.75	354.1	3.74	500	4 × 12 m, 12 × 7 m, 8 × 3.8 m	2007
DIAMOND	3.0	561.6	2.7	300	6 × 11.3 m, 18 × 8.3 m	2007
ASP	3.0	216	10	200	14 × 5.4 m	2008
INDUS Ⅱ	2.5	172.5	58.1	300	8 × 4.5 m	2008
SSRF	3.5	432	3.9	300	4 × 12 m, 16 × 6.5 m	2009
ALBA	3.0	268.8	4.3	400	4 × 8 m, 12 × 4.2 m, 8 × 2.6 m	2010
PETRA Ⅲ	6.0	2304	1.0	100	20 × 4 m	2010

One of important technological advancements is the invention of in-vacuum undulators. The in-vacuum undulators mainly developed at SPring-8 made it possible for shorter straight sections for third generation machines. With a given machine size, one can employ more insertion devices which are favourable by users. Users prefer to have the top-up operation and more insertion devices which, in turn, require better stability and lower emittance. The top-up injection mode was adopted at SLS, New SUBARU, SPring-8, and TLS following APS

The other technological advancement is superconducting RF cavities. It is capable to provide higher RF voltages for better beam stability and HOM controls. One may also note that the beam energy is moved up to the 2.5-3.5 GeV range and emittance is a single digit in the nm-rad unit. With higher beam energy, higher beam current and more insertion devices, it requires much more RF powers. The solution is superconducting RF cavities developed for high-energy physics accelerators. The SC RF cavities were adopted at TLS, CLS, SOLEIL and SSRF.

SPEAR-3 is upgraded from SPEAR-II, and PETRA-III is converted from a high-energy machine with energy of 6 GeV and emittance of 1.0 nm-rad [6]. There are two lower energy machines of 1.5 and 1.4 GeV in Japan, New SUBARU at SPring-8 and SAGA-LS in the Saga prefecture, respectively. They are considered as dedicated VUV-rings. One also notes that ANKA in Karlsruhe at 2.5 GeV, CLS in Canada at 2.9 GeV and ASP in Melbourne at 3.0 GeV have relatively shorter circumferences compared to other machines in the energy range. SLS is designed to have a lower emittance of 5.0-nm-rad, and it adopts the top-up injection only.

SOLEIL in France began users' service in 2007 with beam energy of 2.75 GeV in a 354 m circumference and emittance of 3.74 nm-rad. One may note that the beam current is 500 mA with SC RF cavities. DIAMOND in UK employs a 561 m ring for 3.0 GeV and emittance of 2.7 nm-rad. SSRF in Shanghai chose the operating energy of 3.5 GeV with a 432 m circumference, the highest energy in the intermediate size light sources, so far [7]. It uses SC RF cavities and top-up injection. It completed the machine commissioning and opened for users' service in 2009. One may also note that ALBA at Barcelona in Spain is completed in 2009, and it plans to open the facility to users in 2010 [8]. The ring size is 269 m and emittance of 4.3-nm-rad.

FACILITIES UNDER CONSTRUCTION

Table 3 shows the new facilities under construction. One may note that the operation energy is mostly 3.0 GeV with larger circumferences and a lower emittance of order of 1.0 nm-rad or less. They are TPS at Hsinchu in Taiwan, NSLS-II at BNL, MAX IV at Lund in Sweden and PLS-II at Pohang in Korea. There are two facilities in the Middle-East region, CANDLE at Yerevan in Armenia with 3.0 GeV and SESAME at Allan near Amman in Jordan with 2.5 GeV, which have relatively shorter circumference. SESAME is an international project sponsored by UNESCO and 9 member states in the Middle-East including Israel [9], [10].

MAX IV has two rings of 1.5 GeV and 3.0 GeV [11]. MAX IV, TPS and NSLS-II are 3.0-GeV machines with large circumferences longer than 500 m and emittance of in the order of 1.0 nm-rad or less. TPS is designed to have emittance of 1.7-nm-rad with circumference of 518 m, and it uses SC RF cavities [12]. MAX IV is designed for emittance of 0.24-nm-rad and NSLS-II of 0.9-nm-rad with damping wigglers [13]. Therefore, the new trend takes the beam energy around 3.0 GeV and larger in size. The top-up injection is a standard operation, and most of them uses superconducting RF cavities to cover high beam currents and many insertion devices. These facilities are expected to serve users by 2014.

Table 3: Main Parameters of Third Generation Light Sources under Construction

Light Source	Energy (GeV)	Circumference (m)	Emittance (nm-rad)	Current (mA)	Straight Section	Status
CANDLE	3.0	216	8.4	350	16 x 4.8 m	Planned
MAX IV	1.5/3.0	96 / 528	5.6 / 0.24	500	12 / 20 - straight sections	(2010)
PLS-II	3.0	281	5.8	400	12 X 6.8 m, 12 x 3.1 m	(2011)
TPS	3.0	518	1.7	400	18 x 7 m, 6 x 12 m	(2013)
NSLS-II	3.0	792	0.9	500	15 x 6 m, 15 x 9.3 m	(2014)
SESAME	2.5	133	26	400	4 x 5 m, 8 x 3.5 m, 4 x 1.9 m	(2014)

PLS-II is also a 3.0 GeV facility by upgrading energy from 2.5 GeV and changing the lattice structure in the same machine tunnel. Table 4 shows the parameters of PLS-II. The lattice structure is changed from TBA to DBA to use the short straight sections for in-vacuum undulators. Out of 24 straight sections, there are 20 straight sections used for insertion devices to meet the users' demands of higher brilliance beamlines. Again, they plan to employ the top-up injection and SC RF cavities. Since it plans to use the same beam tunnel originally built for the 2.0 GeV ring, there is a tight space for re-arrangement. The shut-down time for dismantling and installing new components is only for one-year in 2011 to reduce users' experimental stop-gap. One may note that it uses a full energy injection linac upgraded to 3.0 GeV in the same linac tunnel.

Table 4: PLS Upgrade Parameters

Parameters	PLS	PLS-II
Beam Energy (GeV)	2.5	3.0
Beam emittance (nm-rad)	18	5.8
Beam Current (mA)	200	400
IDs	10	20
Tune (H/V)	14.28 / 8.18	15.24 / 9.17
Natural Chromaticity (H)	-23.36	-32.95
Natural Chromaticity (V)	-18.19	-14.88
Harmonic Number	468	470
Circumference	280	281
RF voltage (MV)	NC/2.0	SC (3)/3.3
Lattice	TBA	DBA
Operation	Decay	Top-Up
Brightness	~2E18	~E20

The distributions of the third generation facilities are plotted in Figure 1 and 2. Figure 1 shows circumference vs. energy. In both figures, facilities under construction are denoted triangles and facilities in operation are denoted in dark circles. Most of them are less than 300 m with around 3.0 GeV. The upper right corner shows larger machines.

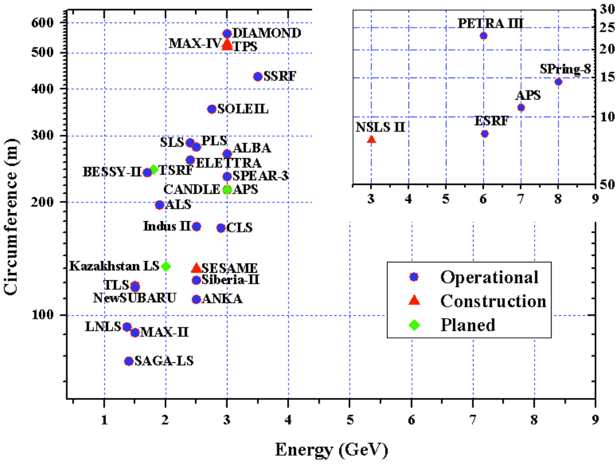

Figure 1: Circumference vs. Energy distribution of the third generation light sources.

Figure 2 shows facilities for emittance vs. energy. One may note that the new machines, TPS, NSLS-II and MAX IV have emittance of in the order of 1.0 nm-rad or less with damping wigglers. Figure 3 shows trend of third generation facilities comparing early phase machines and newly constructed machines in number of insertion devices and emittance. In the horizontal axis, the left side is for larger emittance, and the right side is for lower emittance. Again, the number of straight sections is increased for insertion devices, and emittance is decreased for new third generation facilities.

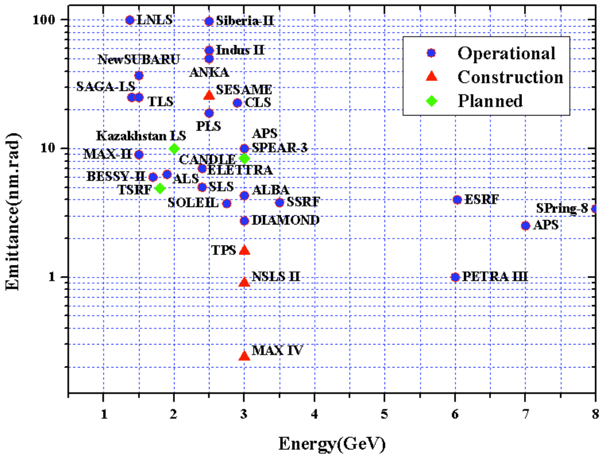

Figure 2: Emittance vs. Energy distribution of third generation light sources.

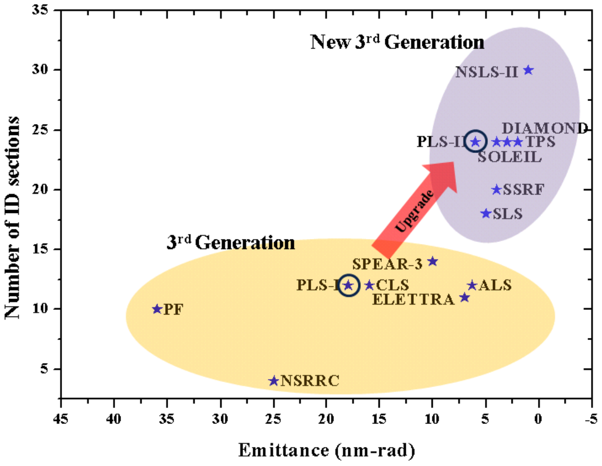

Figure 3: Trend of third generation facilities grouped in early phase machines and newly constructed machines in number of straight sections for insertion devices vs. emittance.

DISCUSSIONS ON USERS AND SCIENCE

The third generation light sources are considered as the essential facilities for advanced science research in national and international users. The number of users' community has been grown to more than 100,000 in the world. The disciplines served by these facilities are so much diversified that it is hard to identify them.

For an example, we may review users in PLS in Pohang, Korea. When PLS was proposed in 1988, there were a few users, less than 10 young scientists in Korea. When PLS opened the facility for users in 1995, it had only two beamlines from bending magnets. Beamlines have been increased by two or three units yearly. Figure 4 shows the statistics for the number of experimental projects and users. In 2009, there were more than 800 experiments and 2,800 users.

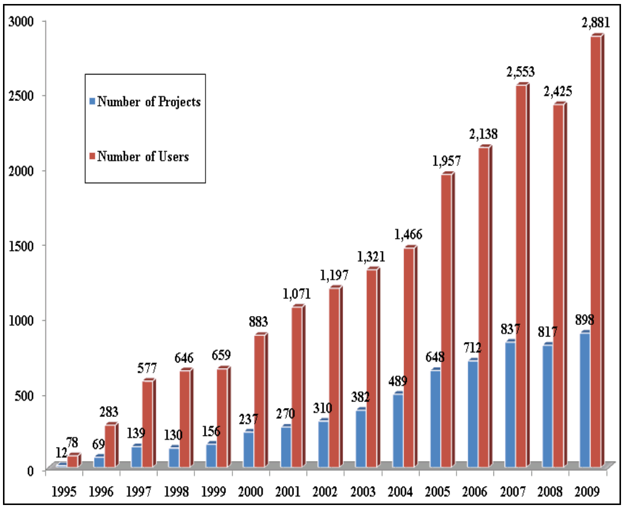

Figure 5: Statistics for users and projects at PLS.

The users' community has been changed dramatically compared with the initial phase of operations. Figure 6 shows users' disciplines at PLS. Biology/life science projects are now increased to be comparable to that of materials science. Taking into account of the situation in Korea, an emergent country, we would imagine the users' demands in the advanced countries, US, EU, Japan and others in the world.

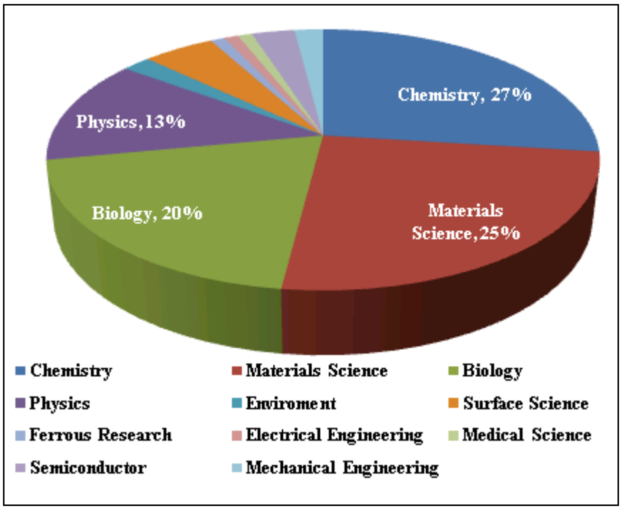

Figure 6: Users' distribution at PLS at Pohang in Korea.

In recent years, one may note that there are a few Nobel Prize winners from research results in light sources. They are listed as follows.

1997 Chemistry
John E. Walker
"Structure of F1-ATPase"

2003 Chemistry
Roderick McKinnon
"Structure of Cellular Ion Channels"
2006 Chemistry
Roger D. Kronberg
"Structure of RNA polimerase"

2009 Chemistry
Ada E. Yonath
"Structure and function of the ribosome"

SUMMARY

When third generation light sources were initiated in the 1980s, there were strong demands in materials science research, but not much for biology/life science. Nowadays, users are very much diversified and expanding rapidly to other research areas, especially biology/life science research. There are more facilities under construction and planning, especially in the intermediate energy range of 2.5-3.5 GeV with higher brilliance and top-up operations, namely NSLS-II, TPS and MAX IV by 2015. Starting with LCLS at Stanford in 2009, more fourth generation facilities will be available by 2015, for example, SCSS at SPring-8, Euro-XFEL at DESY, and others. Energy Recovery Linac (ERL) and XFEL Oscillator (XFELO) are other new schemes in competing with the 4th generation machines. One may expect unforeseen results from these facilities in the near future.

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