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PRESENT AND FUTURE SYNCHROTRON RADIATION SOURCES+

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ABSTRACT

There are now 43 laboratories in 16 countries engaged in operating, constructing or planning about 60 electron storage rings, ranging from a few hundred MeV to above 10 GeV, as sources of synchrotron radiation for basic and applied research. We classify these sources by "generation" with emphasis on 3rd generation light sources (low emittance rings with many straight sections for insertion devices) now coming on line in several countries, and on 4th generation sources, including proposed VUV/x-ray free electron lasers (FELs) which promise many orders of magnitude higher photon beam brightness and coherence at wavelengths down to 0.1 nm.

1 INTRODUCTION

Synchrotron radiation research [1] and sources [2] have grown explosively in the past decade. At present, the main sources are storage ring bend magnets. Wiggler and undulator insertion devices offer higher flux and brightness to an expanding and ever more demanding user community. New rings now in construction will offer still higher performance levels. Most work is done in the VUV/soft x-ray (10-2000 eV) and hard x-ray (above about 2000 eV) spectral regions.

All present sources are far from fundamental diffraction limits on brightness and coherence at soft and hard x-ray wavelengths. Experience has shown that each order of magnitude improvement in performance opens new research opportunities, although full exploitation usually takes several years. Future sources were the subject of the Workshop on 4th Generation Light Sources [3]. Possible directions for future sources include new ultra-low emittance storage rings, conversion of existing high energy colliders, quasi-isochronous rings producing picosecond pulses, and short wavelength FELs driven by linacs or storage rings [4].

Particularly noteworthy is the expectation that rf linac-based FELs can now reach the VUV and x-ray spectral regions. Such FELs would provide photon beam brightness and coherence far exceeding the most advanced storage rings. The prospects for extending FEL operation to shorter wavelengths was the subject of a recent workshop [5].

2 BRIGHTNESS AND EMITTANCE

Although most experiments make use of the high flux (photons/s/mrad/unit bandwidth) and are well served by all storage rings, an increasing number of experiments require high brightness (photons/s/unit solid angle/unit source area/unit bandwidth) or high coherent power, which is proportional to brightness. Brightness increases as electron beam emittance decreases and undulator length increases, ultimately limited by diffraction effects.

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The brightest source possible emits into an angle-length product about equal to the wavelength. For gaussian beams the diffraction limited emittance is given by the wavelength/4π.

Thus for a wavelength of 1.2 nm (1 KeV photon energy) the diffraction limited electron beam emittance (i.e.; the lowest that is useful in producing 1.2 nm light) is about 0.1 nm-radian. Present synchrotron radiation sources have much higher emittance. First generation rings generally have emittances of one hundred to several hundred nm-radians, while second generation sources go below 100 nm-radians in some cases. Third generation sources aim at lower emittance, typically 5-20 nm-radian, resulting in a major increase in brightness at all wavelengths within their spectral range, and diffraction limited light at photon energies up to 10-20 eV.

Clearly even lower emittance would further increase brightness and coherence and approach diffraction limits at higher photon energies. The quest for lower emittance beams has therefore been central to the evolution of light sources and is key to improved scientific opportunities in brightness limited applications. The electron beam must by extremely stable against drift, vibrations and collective instabilities in order to preserve the effective emittance.

The horizontal emittance of the beam in an electron storage ring is determined by an equilibrium between the random excitation of transverse (betatron) oscillations due to the quantum nature of the radiation process, and the damping of these oscillations due to the fact that the energy lost is restored by rf cavities, which impart momentum only in the longitudinal direction. The resultant emittance depends on the magnet lattice and varies quadratically with electron energy. The vertical emittance is usually a small fraction of the horizontal, primarily determined by coupling.

3 STORAGE RING-BASED SOURCES

More than 10,000 scientists now use synchrotron radiation from 32 operational rings in a wide range of studies in biology, chemistry and physics and their numerous subfields [1]. The most developed facilities (e.g.; the NSLS at Brookhaven and the Photon Factory at KEK) each serve more than 2000 users on more than 50 experimental stations.

In spite of the impressive growth in facilities in the past decade, availability is still far short of the need in many cases. Requests for beam time on many user facilities are often more than double the available time, which is sometimes limited by inadequate operations budgets. Several new rings (ALS, CAMD, ESRF, Taiwan, Trieste) have come on line during the past few years. Over the next few years, as beam lines are added to these rings and their research capability grows, more of the needs will be met.

Even more capability will be added when additional rings come on line. About 13 rings intended for research are now in construction and about 11 more are proposed. Several new rings will greatly extend research opportunities by offering orders of magnitude higher brightness and coherence because they are designed for lower emittance and more straight sections than most present rings. i.e.; they are better optimized for producing radiation from undulators. However, the number of users is also growing, as new groups turn to synchrotron radiation for new applications such as micro-machining and environmental studies.

3.1 GENERATIONS OF STORAGE RINGS: It is now common to refer to storage ring sources by generation, based on their original design. In general, performance increases with generation, except for the very large, high energy colliding beam rings which can be operated as very high brightness light sources.

3.1.1 First generation rings (table 1) were built for high energy physics research. In many cases the synchrotron radiation programs, which started in a parasitic mode, has grown to the point where the facility is now partly or fully dedicated. Long straight sections in rings such as DORIS, SPEAR and VEPP-3 can be used for long undulators, optical klystrons (as implemented on VEPP-3) or bypasses accommodating many insertion devices (as implemented on DORIS).

By our definition, the very large, high energy colliders (e.g.; PEP, PETRA and TRISTAN) are first generation rings. However, with their ability to operate at very low emittance and with their very long straight sections (100-200 m) for damping wigglers and long undulators, they offer opportunities to achieve brightness exceeding the level projected for rings now in construction.

Experience with two high brightness undulator beam lines on PEP and studies of PEP's potential as a light source have been reported [6]. An undulator beam line is now in construction on PETRA [7], aimed at producing very high brightness at photon energies above 50 KeV. Plans for modifications to TRISTAN include the use of a 70 m undulator delivering a brightness 2-3 orders of magnitude higher than rings now in construction [8]. Studies of PEP [9] and TRISTAN [8,10] as drivers for 3-4 nm FELs with peak power approaching 1 GW have been reported. PEP is now being reconstructed into a B-Factory. A similar plan has been proposed for TRISTAN. B-Factories involve collisions between currents in excess of one ampere in each of two storage rings, one with energy around 3 GeV and the other around 9 GeV. These rings could serve as sources of extremely high flux from bending magnets or insertion devices.

3.1.2 Second generation rings (table 2) were designed specifically as dedicated light sources. The first of these is the 380 MeV SOR-Ring at the University of Tokyo, which started operation in 1974. In general these rings have a large number of beam lines and experimental stations, primarily from bend magnets, and they serve very many users. The immense research productivity of 2nd (and 1st) generation rings and the successful experience with wigglers and undulators has led to a new generation of more advanced rings.

3.1.3 Third generation rings (table 3) are distinguished by lower electron beam emittance and many straight sections for insertions. They offer much higher brightness, particularly from undulators. Most of these rings employ full energy injection, which enhances orbit reproducibility and minimizes time spent filling and ramping the energy. Some store positrons to eliminate the deleterious effects sometimes caused by the trapping of positive ions or positively charged dust particles in electron beams.

Most third generation rings fall into two broad categories; 1-2 GeV rings with 100-200 m circumference primarily for the spectral region below about 2 keV (VUV and soft x-rays) and 6-8 GeV rings with a circumference of 800-1500 m, primarily for harder x-rays, above about 2 keV. We also include rings intended primarily for short wavelength FELs.

A major concern in third generation rings is the high power and power density in the photon beams which will result in heat loading, distortion and potential failure of the storage ring vacuum vessel and beam line components. Major engineering efforts at several laboratories have been directed to the development of concepts and designs for active interlocks to prevent photon beams from striking uncooled surfaces [11] and for cooling beam line elements [12] struck by power densities of several kW/cm^2. The experience to date, particularly on the high power beams produced at the ESRF, is very encouraging.

3.1.4 Future ring concepts, reaching 10^{-11} m-rad range emittances while preserving dynamic aperture, were presented at the Workshop on 4th Generation Light Sources [3]. In one [13] a large ring with many short FODO cells and long, dispersion free straight sections filled with damping wigglers is used. Another [14] uses short cells with combined function bend magnets, including a sextupole component providing local chromatic correction. Low emittance, with large momentum and betatron acceptance were achieved in a ring of moderate size. Quasi-isochronous, or low momentum compaction, rings [15] would reduce bunch duration to about 1 ps.

Recently designs of possible future sources have been produced at Daresbury (Diamond, 3 GeV and Sinbad, 0.6 GeV), Orsay (Soleil, 2.15 GeV), and at the Paul Scherrer Institute (Swiss Light Source, 2.1 GeV). These designs include features such as lower emittance, superconducting bending magnets incorporated in the lattice, and long straight sections for FELs.

3.2 STORAGE RING-BASED FELs: Storage rings have been used to drive FELs in the visible and UV at Orsay [16], Tsukuba (Electrotechnical Laboratory) [17] and Novosibirsk [18]. The shortest wavelength reached to date is 240 nm at Novosibirsk. A 170 nm FEL is in construction at the Photon Factory [10]. New rings optimized as FEL drivers down to 30 nm are in construction at Dortmund [19], and at Duke University [20]. Shorter wavelength (3-4 nm) FELs have been proposed on PEP [9] and TRISTAN [8,10].

3.3 STORAGE RINGS FOR X-RAY LITHOGRAPHY AND OTHER SPECIALIZED USES: There is interest in storage rings as sources of soft x-rays to produce electronic circuits with sub-micron features by the lithographic process [21]. At present circuits are produced with visible or UV lithography with features as small as about 1/3 micron, limited by diffraction effects. Storage rings provide intense beams at shorter wavelength, overcoming diffraction limitations. Seven industrial storage rings primarily used for x-ray lithography are in operation in Japan and one in the US.

A related application, micromechanics [22], involves the lithographic production of high aspect ratio, miniature mechanical devices (gears, motors, transducers) on the 10-100 micron scale using x-rays with energy around several kilovolts. Future developments in this area could lead to the need for commercial storage ring sources.

There is also the possibility that dedicated rings optimized for less-invasive coronary angiography [23] will be needed if clinical quality images can be obtained with synchrotron radiation. Rings operating at two GeV with multipole high field superconducting wigglers can provide the required flux at 33 keV, the K-absorption edge of iodine.

4 LINAC-BASED SOURCES (VUV/X-RAY FELs)

Developments in high-brightness electron guns greatly improve the prospects for linac-based FELs to reach VUV and x-ray wavelengths [4]. High gradient rf photocathode guns [24] delivering 1-2 nC, in pulses a few picoseconds long, with small energy spread, and with a normalized emittance of about 3 mm-mrad (rms) have been operated. Further reduction in gun emittance is anticipated.

Since electron beam emittance varies inversely as linac energy ($\varepsilon = \varepsilon_n/\gamma$), lower normalized emittance makes it possible to reach the diffraction limited emittance required for VUV and x-ray FEL operation at lower electron energy. Such FELs would deliver orders of magnitude higher peak and average brightness than storage rings, albeit to a smaller number of simultaneous users.

Examples of proposed short wavelength FELs include the following: A BNL design [25] for 75-300 nm subharmonically seeded FELs is based on an 80 MeV superconducting linac recirculated twice to achieve 250 MeV. A Los Alamos design [26] uses a 1 GeV linac to drive a series of FEL oscillators from 125 nm down to 1 nm using multifaceted grazing incidence mirrors forming ring resonators.

A study [27] has been reported of the use of the SLAC linac at energies around 7 GeV to drive a "water window" (2.3-4.4 nm) FEL using self-amplified-spontaneous-emission. In principle, this approach can be extended to shorter wavelength, down to about 0.1 nm, using higher electron energies, up to the 50 GeV capability of the SLAC linac. These devices would deliver several gigawatts of peak power with an rms pulse duration of 0.2 ps at 120 Hz. The "water-window" would deliver about 10^{14} coherent photons in a single sub-picosecond pulse, enough to make a hologram of a live biological sample before it is changed or damaged.

Technical problems that must be faced to develop short wavelength, linac-based FEL sources include preservation of electron beam emittance during beam transport, acceleration and bunch compression; control of beam energy spread; and steering. The successful experience with the linear collider project at SLAC [28] shows that these problems can be met. Also, very long (>30 m) and precise undulators are needed to reach saturation. Again, the successful experience with undulators up to 5 m long at third generation light sources and even longer (up to 25 m) undulators for previous FEL projects [29] shows that these needs can be met.

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TABLE 1
1st GENERATION SYNCHROTRON RADIATION SOURCES

LOCATION	**RING**	**ENERGY** (GeV)	**NOTES**
CHINA			
Beijing	BEPC	1.5-2.8	Partly Ded.
DENMARK			
Aarhus	ASTRID	0.6	Partly Ded.
FRANCE			
Orsay	DCI	1.8	Dedicated
GERMANY			
Bonn	ELSA	1.5-3.5	Partly Ded.
Hamburg	DORIS III	4.5-5.3	Dedicated
	PETRA II	7-13	Beam line in constr.*
ITALY			
Frascati	DAΦNE	0.51	Parasitic*
JAPAN			
Sendai	TSSR	1.5	Proposed
Tsukuba	Accum. Ring	6.5	Partly Ded.
	TRISTAN MR	6-30	Planned Use
NETHERLANDS			
Amsterdam	AmPS	0.9	Planned Use
Eindhoven	EUTERPE	0.4	Planned Use
RUSSIA			
Kharkov	N-100	0.1	Dedicated
Novosibirsk	VEPP-2M	0.7	Partly Ded.
	VEPP-3	2.2	Partly Ded./FEL use
	VEPP-4	5-7	Partly Ded.
USA			
Gaithersburg,MD	SURF II	0.28	Dedicated
Ithaca,NY	CESR	5.5	Partly Ded.
Stanford,CA	SPEAR	3-3.5	Dedicated

* In Construction as of 11/93

TABLE 2
2nd GENERATION SYNCHROTRON RADIATION SOURCES

LOCATION	RING	ENERGY (GeV)	NOTES
BRAZIL			
Campinas	LNLS-1	1.15	Dedicated*
CHINA (PRC)			
Hefei	HESYRL	0.8	Dedicated
ENGLAND			
Daresbury	SRS	2	Dedicated
GERMANY			
Berlin	BESSY I	0.8	Dedicated
INDIA			
Indore	INDUS-I	0.45	Dedicated*
JAPAN			
Okasaki	UVSOR	0.75	Dedicated
Osaka	KANSAI SR	2.0	Design/Proposed
Tokyo	SOR-Ring	0.38	Dedicated
Tsukuba	TERAS	0.8	Dedicated
Tsukuba	Photon Fact.	2.5-3	Dedicated
SWEDEN			
LUND	MAX	0.55	Dedicated
USA			
Baton Rouge, LA	CAMD	1.2	Dedicated
Stoughton, WI	Aladdin	0.8-1	Dedicated
Upton, NY	NSLS I	0.75	Dedicated
	NSLS II	2.5-2.8	Dedicated
RUSSIA			
Kharkov	HP-2000	2.0	Dedicated*
Moscow	Siberia I	0.45	Dedicated
	Siberia II	2.5	Dedicated*
Zelenograd	TNK	1.2-1.6	Dedicated*

* In construction as of 11/93

TABLE 3
3rd GENERATION SYNCHROTRON RADIATION SOURCES

LOCATION	RING	ENERGY (GeV)	NOTES
BRAZIL			
Campinas	LNLS-2	2.0	Design/Proposed
CHINA (ROC-TAIWAN)			
Hsinchu	SRRC	1.3	Dedicated
ENGLAND			
Daresbury	Sinbad	0.6	Design/Proposed
	Diamond	3.0	Design/Proposed
FRANCE			
Grenoble	ESRF	6	Dedicated
Orsay	SuperACO	0.8	Dedicated
	SOLEIL	2.15	Design/Proposed
GERMANY			
Dortmund	DELTA	1.5	FEL Use*
Berlin	BESSY II	1.5-2	Dedicated*
INDIA			
Indore	INDUS-II	2	Design/Proposed
ITALY			
Trieste	ELETTRA	1.5-2	Dedicated
JAPAN			
Hiroshima	HISOR	1.5	Design/Proposed
Kyushu	SOR	1.5	Design/Proposed
Nishi Harima	SPring-8	8	Dedicated*
Tsukuba	NIJI IV	0.5	FEL Use
KOREA			
Pohang	PLS	2	Dedicated*
SPAIN			
BARCELONA	Catalonia SR	2.5	Approved for construction
SWEDEN			
LUND	MAX II	1.5	Dedicated*
SWITZERLAND			
Villigen	SLS	1.5-2.1	Design/Proposed
USA			
Argonne, IL	APS	7	Dedicated*
Berkeley, CA	ALS	1.5	Dedicated
Durham, NC	FELL	1-1.3	FEL Use*
Raleigh, NC	NCSTAR	2.5	Design/Proposed

* In construction as of 11/93