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HIGH ENERGY SYNCHROTRON RADIATION SOURCES*

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ABSTRACT

In the world there are now about 43 laboratories in 16 countries engaged in the operation, construction or planning of electron storage rings, from a few hundred MeV to above 10 GeV, as sources of synchrotron radiation for basic and applied research. In this report we describe the new 3rd generation high energy (i.e.; hard X-ray) sources. The first of these, the 6 GeV European Synchrotron Radiation Facility (ESRF) in Grenoble, France started operation in mid 1992. The 7 GeV Advanced Photon Source (APS) at Argonne, USA and the 8 GeV Super Photon Ring (SPring-8) in Nishi Harima, Japan are expected to start operation for users around 1996-98.

INTRODUCTION

About 10,000 scientists now make use of the unique properties of synchrotron radiation; primarily the high and stable intensity, brightness, polarization and coherence from the infra-red through the UV and into the hard X-ray spectral regions. In use now are fourteen 1st generation sources (rings originally constructed for high energy physics research), thirteen 2nd generation sources (rings built as dedicated light sources) and three 3rd generation sources (dedicated light sources with lower electron beam emittance and many straight sections for insertion devices). Several reports [1-5] review these synchrotron radiation sources. About 15 rings, mostly 3rd generation, are in construction or commissioning and about 10 more are proposed. Here we discuss primarily the high energy (6-8 GeV), third generation, hard X-ray sources; ESRF [6], APS [7], and SPring-8 [8]. Rosei [9] discusses the third generation, 1-2 GeV, VUV/Soft X-ray sources. Workshops have been held on concepts for future fourth generation
sources [10, 11].

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THIRD GENERATION X-RAY SOURCES

The three major third generation hard X-ray sources are the European Synchrotron Radiation Source (ESRF) [6] in Grenoble, France (6 GeV, 844 m circumference, 32 straight sections), the Advanced Photon Source (APS) [7] in Argonne IL, USA (7 GeV, 1104 m circumference, 40 straight sections) and the SPring-8 facility [8] in Nishi Harima, Japan (8 GeV, 1436 m circumference, 48 straight sections).

A main feature of these rings is their ability to accommodate many wiggler and undulator insertion devices (periodic magnets which produce alternating deflections of the stored beam, but no net deflection or displacement). Such magnets, placed in the straight sections between storage ring bending magnets increase performance levels by several orders of magnitude.

Wigglers are periodic magnet arrays in which each pole produces a deflection large compared to the natural opening angle of synchrotron radiation given by mc^2/E. They produce a broad spectrum, similar to bending magnets, with flux and brightness enhanced by the number of poles. For wiggler fields higher than bending magnet fields, the spectrum is extended to higher photon energy.

Undulators are periodic magnet arrays in which each pole produces a deflection of the order of, or smaller than, the natural opening angle of the radiation. They produce a quasi-monochromatic spectrum with higher brightness and coherence than wiggler magnets. Undulator brightness is enhanced as the electron beam size and angular divergence is reduced; hence the use of low electron beam emittance in third generation rings. Emittance is essentially the product of the beam transverse size and divergence in each of the two transverse planes. Emittance is measured in meter-radians.

With their low electron beam emittance (~7 nm-radians) and many straight sections for wigglers and undulators up to about 5 m in length, the third generation X-ray rings will provide thousands of users with hard X-rays with brightness and coherence about 2-3 orders of magnitude higher than other sources. Experience has shown that each order of magnitude improvement in performance opens new research opportunities, although full exploitation usually takes several years. Thus, it is expected that these new rings will vastly expand research potential. Four of the straight sections on the SPring-8 ring will eventually be configured to accommodate undulators up to about 30 m in length, producing even higher brightness in the future. Another unique feature of the SPring-8 facility is the ability to accommodate several beam lines up to one kilometer in length for special applications and to reduce power density on beam line components and samples.

Third generation rings present severe challenges to accelerator designers. In particular, they must achieve a high level of stability and reproducibility of high current, low emittance circulating beams which have transverse dimensions of the order of tens of microns. Also, concentrated photon beams will result in heat loading, distortion and potential failure of the storage ring vacuum vessel and beam line components. Major engineering efforts are underway at several laboratories to develop concepts and designs for active interlocks to prevent photon beams from striking uncooled surfaces and for cooling beam line elements struck by power densities of several kW/cm^2. The first experience at the ESRF facility gives encouragement that solutions to the above challenges have been, or will be, found.

FUNDAMENTAL LIMITS AND FUTURE SOURCES

As powerful as they are, third generation rings are still far from fundamental diffraction limits on brightness and coherence at soft and hard x-ray wavelengths. Although many experiments make use of the high flux (photons/s/mrad within a unit bandwidth) and are well served by all storage rings, an increasing number require high brightness (photons/s/unit solid angle/unit source area within a 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. 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/4p.

Thus for a 1.2 nm wavelength (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 about 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.

Workshops have been held on ideas and proposals for 4th generation light sources [10, 11]. 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.

Experience with two high brightness, hard X-ray, undulator beam lines on the 2.2 km PEP storage ring at SLAC (Stanford, USA) has been reported [12]. Also studies have been carried out on the use of PEP [12] and the 3.0 km TRISTAN ring at KEK (Tsukuba, Japan) [13] at lower energy in low emittance modes to provide extremely low electron beam emittances, below 1 nm-rad. In such a mode these rings could be used as drivers for free electron lasers at wavelengths down to about 3 nm [14].

Although the PEP and TRISTAN rings are not now available for use as light sources, a project is now underway at the DESY laboratory in Hamburg, Germany to install an undulator beam line on the 2.3 km PETRA storage ring, operating at electron energies up to about 12 GeV. This beam line [15], expected to be operational in 1995, would be used for periods of several hours in duration at intervals in between the times that PETRA is used as an injector to the HERA colliding beam complex. This beam line will complement the capabilities of the lower energy third generation rings such as the ESRF by providing extremely high brightness X-ray beams in the 30-150 keV region for studies of elastic and deep inelastic scattering, structural biology, and nuclear resonant scattering.

In another example of the use of a high energy accelerator as a light source, a study has been made of the use of the SLAC linac as a driver for free electron lasers [16]. With the present understanding of the transport, acceleration, and compression of electron beams, and the present level of technology of rf photocathode guns and precision undulators, it should be possible to drive a 2-4 nm FEL using electron energy up to about 7 GeV. This and other proposals were reviewed in a recent workshop [11].

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STORAGE RING SYNCHROTRON RADIATION SOURCES (July, 1993)

LOCATION	RING (INST.)	ELECTRON ENERGY (GeV)	NOTES
BRAZIL			
Campinas	LNLS-1	1.15	Dedicated*
	LNLS-2	2	Design/Dedicated
CHINA (PRC)			
Beijing	BEPC (Inst.High En.Phys.)	1.5-2.8	Partly Dedicated
Hefei	HESYRL (USTC)	0.8	Dedicated
CHINA (ROC-TAIWAN)			
Hsinchu	SRRC (Synch.Rad.Res.Ctr.)	1.3	Dedicated
DENMARK			
Aarhus	ASTRID (ISA)	0.6	Partly Dedicated
ENGLAND			
Daresbury	SRS (Daresbury)	2	Dedicated
	DAPS (Daresbury)	0.5-1.2	Planned/Dedicated
FRANCE			
Grenoble	ESRF	6	Dedicated
Orsay	DCI (LURE)	1.8	Dedicated
	SuperACO (LURE)	0.8	Dedicated
	SOLEIL (LURE)	2.15	Planned/Dedicated
GERMANY			
Bonn	ELSA (Bonn Univ.)	1.5-3.5	Partly Dedicated
Dortmund	DELTA (Dortmund Univ.)	1.5	Dedicated/FEL Use*
Dresden	ROSY (Res. Ctr. Rossendorf)	3	Planned/Dedicated
Hamburg	DORIS III (HASYLAB)	4.5-5.3	Dedicated
	PETRA II (HASYLAB)	7-14	Partly Dedicated*
Berlin	BESSY I	0.8	Dedicated
	BESSY II	1.7	Dedicated*
INDIA			
Indore	INDUS-I (Ctr.Adv.Tech.)	0.45	Dedicated*
	INDUS-II (Ctr.Adv.Tech.)	2	Planned/Dedicated
ITALY			
Frascati	ADONE (LNF)	1.5	Shut down in 1993
	DAFNE	0.51	Parasitic*
Trieste	ELETTRA (Synch.Trieste)	1.5-2	Dedicated*

JAPAN			
Hiroshima	HISOR (Hiroshima Univ.)	0.4-1.0	Planned/Dedicated
Kyushu	SOR (Kyushu Univ.)	0.7	Planned/Dedicated
Nishi Harima	SPring-8 (Sci.Tech.Agency)	8	Dedicated*
Okasaki	UVSOR (Inst.Mol.Science)	0.75	Dedicated
Osaka	Kansai SR	1.8	Planned/Dedicated
Sendai	TSSR (Tohoku Univ.)	1.5	Planned/Dedicated
Tokyo	SOR-Ring (U of Tokyo-ISSP)	0.38	Dedicated
	HBLS (U of Tokyo-ISSP)	1.5	Planned/Dedicated
Tsukuba	TERAS (ElectroTech.Lab.)	0.8	Dedicated
	NIJI IV (ElectroTech.Lab.)	0.5	Dedicated/FEL Use
Tsukuba	Photon Factory (KEK)	2.5	Dedicated
	Accumulator Ring (KEK)	6	Partly Dedicated
	Tristan Main Ring (KEK)	8-32	Planned/Dedicate
KOREA			
Pohang	Pohang Light Source	2	Dedicated*
NETHERLANDS			
Eindhoven	EUTERPE (Tech.Univ.Eind.)	0.4	Planned Use*
RUSSIA			
Moscow	Siberia I (Kurchatov Inst)	0.45	Dedicated
	Siberia II (Kurchatov Inst)	2.5	Dedicated*
Novosibirsk	VEPP-2M (Inst.Nucl.Phys.)	0.7	Partly Dedicated
	VEPP-3 " " "	2.2	Partly Dedicated
	VEPP-4 " " "	5-7	Partly Dedicated
	Siberia-SM " " "	0.8	Dedicated*
Zelenograd	TNK (F.V. Lukin Inst.)	1.2-1.6	Dedicated*
SPAIN			
Barcelona	Catalonia SR Lab	2.5	Dedicated*
SWEDEN			
Lund	MAX (Univ. of Lund)	0.55	Dedicated
	MAX II (Univ. of Lund)	1.5	Dedicated*
SWITZERLAND			
Villigen	SLS (Paul Scherrer Inst.)	1.5-2.1	Planned/Dedicated
USA			
Argonne,IL	APS (ANL)	7	Dedicated*
Baton Rouge,LA	CAMD (Louisiana State Univ)	1.2	Dedicated
Berkeley,CA	ALS (LBL)	1.5	Dedicated
Durham, NC	FELL (Duke University)	1-1.3	Dedicated/FEL Use*
Gaithersburg,MD	SURF II (NIST)	0.28	Dedicated
Ithaca,NY	CESR (CHESS)	5.5	Partly Dedicated
Raleigh,NC	NC STAR (N.Carolina State U)	2.5	Planned/Dedicated
Stanford,CA	SPEAR (SSRL)	3-3.5	Dedicated
Stoughton,WI	Aladdin (SRC)	0.8-1	Dedicated
Upton,NY	NSLS I (BNL)	0.75	Dedicated
	NSLS II (BNL)	2.5	Dedicated

* In construction as of 7/93