OVERVIEW OF SYNCHROTRON RADIATION FACILITIES *

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Abstract

Around the world, there are now 32 laboratories in 12 countries engaged in the operation, construction or planning of electron storage rings, ranging from a few hundred MeV to above 10 GeV, as sources of synchrotron radiation for basic and applied research. More than 6000 scientists now use radiation from 27 operational rings in a wide range of studies in biology, chemistry and physics and their numerous subfields. About 10 more rings intended for research are in construction or design. The new rings are mostly designed with low electron beam emittance and many straight sections to optimize the performance of undulator insertion magnets.

In addition, companies in England, Germany, Japan and the United States are designing and constructing storage rings to produce high fluxes of soft X-rays around 1 keV for the production of integrated circuits with line features of 0.25 microns or less using the X-ray lithographic process. If, as expected by many in the semiconductor field, X-ray lithography becomes the technique of choice for the production of submicron structures, perhaps 100 storage rings in the 0.5 to 1 GeV range will be needed by industry.

It is also possible that present programs using synchrotron radiation above 30 keV to develop less invasive procedures for coronary angiography will lead to a need for many multi-GeV rings designed for this purpose.

Introduction

The explosive growth of activity and interest in synchrotron radiation as a scientific and technological tool is an unprecedented phenomenon. It is all the more remarkable considering that the radiation was originally regarded largely as an unfortunate drain on the energy of electrons in circular accelerators; a nuisance and an unavoidable waste product which made it difficult and costly for high energy physicists to push circular electron machines to higher and higher energy.

Storage rings provide radiation from the infrared through the visible, near ultraviolet, vacuum ultraviolet, soft X-ray and hard X-ray parts of the electromagnetic spectrum extending to 100 keV and beyond. The flux [photons/(s,unit bandwidth)], brightness (or brilliance) [photons/(s,unit source area,unit solid angle,unit bandwidth)] and coherent power [proportional to brightness] available for experiments, particularly in the VUV, soft X-ray and X-ray parts of the spectrum, are many orders of magnitude higher than is available from any other source.

Specialized instrumentation has been developed for the beam lines to collect, condense, deflect, select certain wavelengths and deliver the radiation from the ring to the experimental stations. Handling the high power and power density from wiggler and undulator magnets up to several meters long has become a major engineering challenge. Devices now in operation at several facilities deliver 5-10 kW/cm^2 of X-ray beam power to the front end components of beam lines. This is about the same as the power density in a welding arc!

Sophisticated cooling techniques are needed, such as liquid gallium flowing in microchannels and long absorbers which intercept the beam at grazing incidence angles of a few degrees. Care must be taken to assure that powerful X-ray beams do not accidentally strike inadequately cooled surfaces. This might happen, for example, if there is a large distortion in the closed orbit such as might occur if a power supply trips out. This has led to the development of protection systems which dump the stored beam in the event of a large orbit distortion to prevent melting that might occur in a fraction of a second. Severe demands are placed on beam line components such as focussing mirrors, diffraction gratings and crystals which must maintain tight optical tolerances under intense thermal loads.

With new facilities coming on line and with the continued development of source capability, particularly the brightness and coherent power levels from undulators in low emittance rings, the number of practitioners, new areas of application and overall scientific impact of synchrotron radiation are expected to grow. Figure 1 shows the development of source brightness.

Today the impact of synchrotron radiation on basic and applied research in physics, chemistry, biology and their numerous subfields has led to an intense activity around the world to more fully exploit existing electron storage rings and to construct more storage ring sources of this radiation. This interest is further fueled by the expectation that synchrotron radiation will, via the X-ray lithographic process, enable large scale production of higher density integrated circuits and the possibility that it can be used in less invasive procedures for coronary angiography. For recent reviews of synchrotron radiation facilities in the USSR and elsewhere see Kulipanov[1] and Winick[2] respectively.

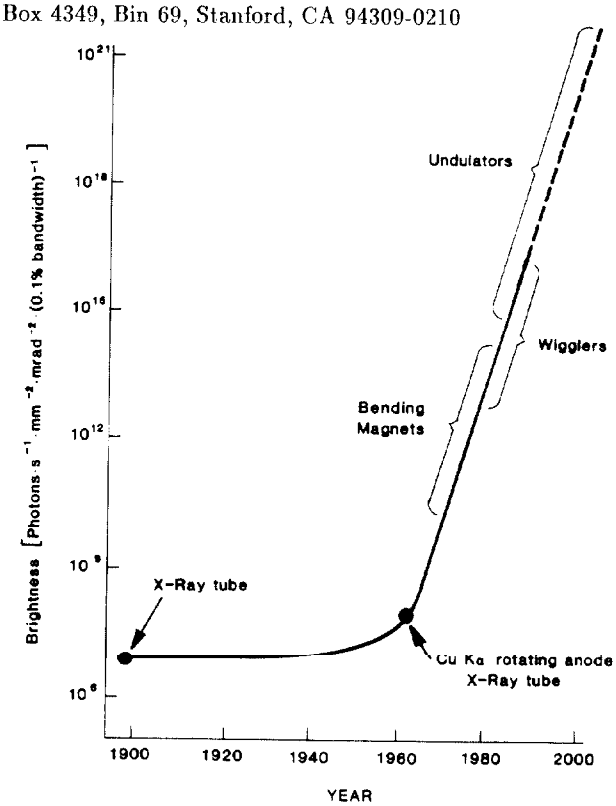

Figure 1: Development of Source Brightness

The rings now in design and construction as dedicated light sources range from 0.5 GeV superconducting devices for X-ray lithography that could fit into a large living room, to rings up to 1.5 kilometers in circumference. There is also increasing interest to exploit the recently demonstrated capabilities and potential of very high energy colliding beam rings such as PEP and Tristan as very high brightness sources, particularly when they are operated at lower energy in low emittance modes. The most advanced rings for basic research are based on a magnet lattice with two main characteristics: low electron beam emittance and many straight sections for insertion devices. Below we discuss insertion devices and emittance in more detail.

The use of storage rings for both high energy physics and synchrotron radiation research has resulted in important discoveries in both fields. The synchrotron radiation community owes a great deal to the high energy physics community for providing the first sources and for assistance in adapting their rings and making them available for synchrotron radiation research.

Insertion Devices (Wiggler and Undulator Magnets)

Much of the development of synchrotron radiation facilities is linked to the increasing use of wiggler and undulator magnet insertion devices as sources. Wiggler and undulator magnets are arrays of alternating polarity magnetic poles which can be inserted between the bending magnets of storage rings. By deflecting the beam in alternate directions they produce radiation with no net deflection. They can be several meters long, depending on available straight section space, and most or all of the radiation produced can be delivered to a single experimental station. This is to be compared with bending magnet sources where typically a few centimeters of continuously curving path radiates into a single station. Figure 2 gives a comparison of the spectra from bending magnets, wigglers and undulators. The continuous spectrum from a bending magnet is characterized by the critical energy given by $\epsilon_c(keV) = 0.665B(T)E^2(GeV)$. Half of the power is radiated above the critical energy and half below.

An insertion device is called a wiggler if the deflection of the electron beam in each pole is large compared with the instantaneous emission angle (given by mc^2/E) of synchrotron radiation. In this limit, the device can be considered as a succession of bending magnet sources, each producing the continuous

*Work supported by U.S. Dept. of Energy, Office of Basic Energy Sciences; contract DE-AC03-82-ER13000 and the National Institutes of Health

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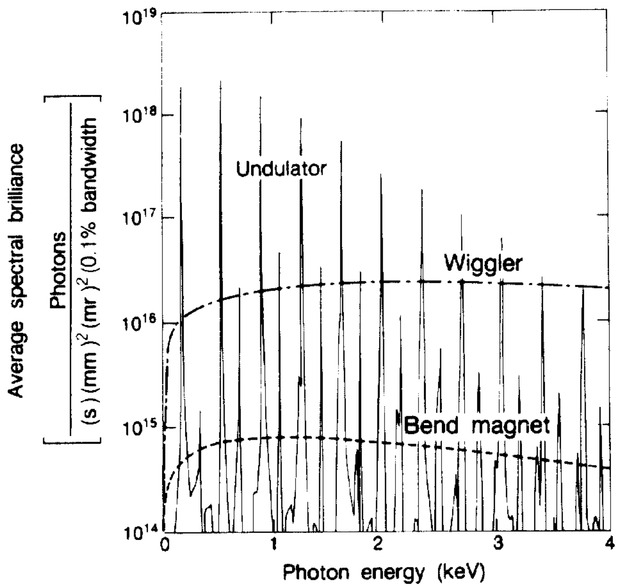

Figure 2: Comparison of the Spectra from Bending Magnets, Wigglers and Undulators. The undulator peaks can be tuned by varying the magnetic field. (Courtesy K.-J. Kim, LBL)

spectrum of a bending magnet at the same magnetic field. The superposition of the radiation from each pole results in an overall enhancement of the radiation given by the number of poles. Permanent magnet devices with more than 50 poles have been built, so this enhancement can be quite large.

The device is called an undulator if the deflection angle in each pole is less than, or comparable to, the instantaneous emission angle. In this limit, interference effects in the radiation by individual electrons traversing the many poles produce large enhancements at certain wavelengths and suppression at other wavelengths. If the ensemble of electrons in the stored beam has angular divergence less than the instantaneous emission angle, radiation with the highest brightness and coherent power is produced. Most present storage rings have large emittance (see next section) and do not satisfy this criterion; hence the interest in lower emittance rings.

The photon wavelength of the lowest energy, or fundamental, peak in the spectrum from an undulator is given by $\lambda = (\lambda_u/2\gamma^2)(1+K^2/2+\gamma^2\Theta^2)$ where λ_u is the period length of the undulator magnetic field, $\gamma = E/mc^2$, $K = eB_o\lambda_u/(2\pi mc) = 0.934B_o(T)\lambda_u(cm) = \gamma\delta$, B_o is the peak magnetic field, 2δ is the angular deflection of the electron and Θ is angle of observation. For $K \ll 1$, only a weak fundamental peak is present. As K increases, the fundamental becomes stronger, reaching a maximum around K=1, and harmonics appear. For $K \gg 1$, the many closely spaced harmonics blend into the smooth continuum characteristic of wigglers and bending magnets.

As can be seen from above, at any particular electron energy the shortest wavelength that can be reached with significant intensity by an undulator is determined by the period length and the magnetic field strength. The latter falls exponentially with the ratio of the magnet gap to period. This fact makes permanent magnet devices particularly well suited for undulator applications. Heating effects in the coils of conventional electromagnets and the space required for coils, even in superconducting magnets, make it difficult for these devices to reach adequate field strength with the desired short period lengths. With permanent magnet arrays, it is possible to reach periods of 3-6 cm with gaps of 1-2 cm and with K values around 1 or greater. This leads to electron energy requirements of 1-2 GeV to reach fundamental wavelengths around 10-30 Å (or 0.4-1.2 keV), 3-4 GeV for 2-6 Å (or 2-6 keV) and 6-8 GeV for 0.5-1 Å (or 12-24 keV). Micropole undulators[3] with periods and gaps of one millimeter or less could extend the spectral range if such devices could be implemented in low beta sections of storage rings. Important contributions to the development of insertion device technology, particularly the early development of strong, short period permanent magnet devices, have been made by K. Halbach at LBL and by G. Kulipanov and N. Vinokurov at Novosibirsk.

Electron Beam Emittance and Photon Beam Brightness

Emittance is the phase space area of the beam in each of the two transverse directions and is given essentially by the product of the transverse size and divergence of the beam at a symmetry point (where the emittance ellipse is upright). The recognition in 1976, by Ken Green and Rena Chasman at Brookhaven, of the importance of low electron beam emittance to achieving high brightness radiation was a major step in source development.

The horizontal emittance of the beam in an electron storage ring is determined by an equilibrium between the excitation of 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 to synchrotron radiation is restored by RF cavities which impart momentum only in the longitudinal direction. The resultant emittance depends on the magnet lattice of the ring. The emittance is a constant around the ring (Liouville's theorem) and varies quadratically with electron energy for constant lattice optics. The vertical emittance is usually primarily determined by coupling to the horizontal.

A low emittance lattice generally has short bending magnets (since emittance grows in the bending magnets as the third power of the angle of bending) separated by strong quadrupoles to focus the beam tightly. Chromatic aberrations in the strong quadrupoles must be corrected by sextupole magnets in order to store high currents. But the non-linear fields of the sextupoles cause a reduction of dynamic aperture. Non linear fields of wiggler and undulator magnets also cause a reduction in dynamic aperture. Therefore the main challenge in the design of advanced light sources is to achieve the desired low emittance while maintaining adequate dynamic aperture for injection and long beam lifetime (10 hour or longer lifetime is highly desirable) in the presence of many insertion devices. Figure 3 illustrates the reduction of dynamic aperture of an assumed ideal machine (in this case the ALS at LBL) due to random error imperfections in the ring magnets and also due to a particular array of insertion devices. Although there is a significant reduction, the final aperture still exceeds that of the small gap vacuum chambers planned for the undulators, and is sufficient for injection and long beam lifetime.

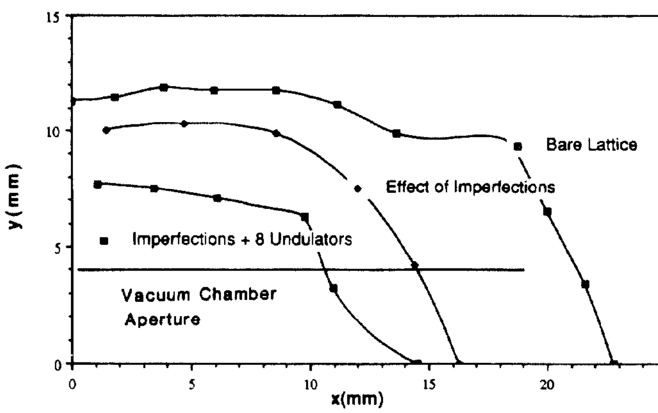

Figure 3: Effect of Random Ring Magnet Errors and Effect of Insertion Devices on the Dynamic Aperture. (Courtesy A. Jackson, LBL)

At constant stored current, the photon beam brightness and coherent power level increase as electron beam emittance decreases until fundamental diffraction effects are reached. These diffraction limits set the lowest useful electron beam emittance at a value numerically equal to the photon wavelength divided by 4π. Thus a 'diffraction limited' electron beam for producing X-rays with a wavelength of 1 nm (or 10 Å or 1.2 keV) would have an emittance of about 0.1 nm-radians, forty times less than the lowest emittance yet measured in a synchrotron light source. For 0.1 nm (or 1 Å or 12 keV) radiation, the 'diffraction limited' electron beam emittance is a daunting 0.01 nm-radians.

Sources and Research Facilities

The first synchrotron radiation research was carried out using electron synchrotrons starting in the 1950's, after the discovery of the radiation in 1946. Although some synchrotrons are still used as sources in the Soviet Union, storage rings have largely replaced them as sources because the constant intensity and spectrum they provide is more suitable than the fluctuating source properties of cyclic synchrotrons. Table 1 lists storage ring sources around the world now in operation, construction or design. Layout drawings for several of these facilities are given in Figures 4-9. The table does not include about 10 storage rings now in operation, construction or design by industry as sources for X-ray lithography.

First Generation Sources and Facilities

The first storage rings to become available as light sources were rings built for high energy physics purposes, starting with the pioneering work of Ed Rowe in developing the Tantalus 240 MeV ring at the University of Wisconsin as a light source in 1968. An exception is the SOR-Ring at the University of Tokyo, built from the start as a dedicated light source in the early 1970's. The SOR-Ring is still in operation, but the Tantalus ring and other high energy physics storage rings that have also been used as light sources (e.g., the 540 MeV ACO and the 3.5 GeV CEA) are no longer used as light sources due to the availability of newer rings at the same laboratory or, in the case of the CEA, the closing of the laboratory.

Programs are now underway on the Accumulator Ring (AR) in Tsukuba, ADONE in Frascati, CESR at Cornell University, DCI at Orsay, DORIS at

STORAGE RING SYNCHROTRON RADIATION SOURCES (MARCH 1989)

LOCATION	RING (LAB)	ELECTRON ENERGY (GeV)	NOTES
BRAZIL			
Campinas	LNLS	2.0	Dedicated*
CHINA (PRC)			
Beijing	BEPC (IHEP)	2.2-2.8	Partly Dedicated
Hefei	HESYRL (USTC)	0.8	Dedicated*
CHINA (ROC-TAIWAN)			
Hsinchu	SRRC (Sync.Rad.Res.Ctr.)	1.3	Dedicated*
ENGLAND			
Daresbury	SRS (Daresbury)	2.0	Dedicated
FRANCE			
Grenoble	ESRF	6.0	Dedicated*
Orsay	DCI (LURE)	1.8	Dedicated
	SuperACO (LURE)	0.8	Dedicated
GERMANY			
Bonn	ELSA	3.5	Partly Dedicated
Dortmund	DELTA	1.5	Design/FEL Use
Hamburg	DORIS II (HASYLAB)	3.5-5.5	Partly Dedicated
West Berlin	BESSY	0.8	Dedicated
	BESSY II	1.5-2.0	Design/Dedicated
INDIA			
Indore	INDUS-I (CAT)	0.45	Design/Dedicated*
	INDUS-II (CAT)	2.0	Design/Dedicated*
ITALY			
Frascati	ADONE (LNF)	1.5	Partly Dedicated
Trieste	ELETTRA	1.5-2.0	Dedicated*
KOREA			
Pohang	Pohang Light Source	2.0	Design/Dedicated*
JAPAN			
Kansai area	STA Ring	8.0	Design/Dedicated
Okasaki	UVSOR (IMS)	0.6	Dedicated
Tokyo	SOR-Ring (ISSP)	0.4	Dedicated
Tsukuba	TERAS (ETL)	0.6	Dedicated
Tsukuba	Photon Factory (KEK)	2.5	Dedicated
	Accumulator Ring (KEK)	6.0-8.0	Partly Dedicated
	Tristan Main Ring (KEK)	8.0-30.0	Planned Use
SWEDEN			
LUND	Max (LTH)	0.55	Dedicated
USA			
Argonne, IL	APS (ANL)	7.0	Design/Dedicated
Baton Rouge, LA	LSU	1.0	Design/Dedicated*
Berkeley, CA	ALS (LBL)	1.5	Dedicated*
Gaithersburg, MD	SURF II (NIST)	0.28	Dedicated
Ithaca, NY	CESR (CHESS)	5.5-8.0	Partly Dedicated
Stanford, CA	SPEAR (SSRL)	3.0-3.5	Partly Dedicated
	PEP (SSRL)	5.0-15.0	Partly Dedicated
Stoughton, WI	Aladdin (SRC)	0.8-1.0	Dedicated
Upton, NY	NSLS I (BNL)	0.75	Dedicated
	NSLS II (BNL)	2.5	Dedicated
USSR			
Karkhov	N-100 (KPI)	0.10	Dedicated
Moscow	Siberia I (Kurchatov)	0.45	Dedicated
	Siberia II (Kurchatov)	2.5	Dedicated*
Novosibirsk	VEPP-2M (INP)	0.7	Partly Dedicated
	VEPP-3 (INP)	2.2	Partly Dedicated
	VEPP-4 (INP)	5.0-7.0	Partly Dedicated

* In construction or approved for construction as of 3/89

Table 1: Storage Ring Sources Around the World Now in Operation, Construction or Design.

DESY, SPEAR and PEP at Stanford, SURF II at NIST and VEPP-2M, VEPP-3 and VEPP-4 at Novosibirsk. Plans are being made to utilize the Tristan ring as a synchrotron radiation source[4]. The AR has recently been equipped with a unique permanent magnet undulator that produces elliptically polarized radiation[4].

SURF II, a converted synchrotron, has a circular orbit well suited for use as an absolute standard for radiometry. The DCI and SURF II rings are now fully dedicated to synchrotron radiation research. The other rings operate parasitically during colliding beam runs and also have dedicated single beam runs for synchrotron radiation research. All except SURF II (which has no straight sections) have implemented or are planning to implement wigglers and/or undulators.

The DORIS ring will be modified with the addition of a bypass to accommodate up to 6 insertion devices in addition to the three now in operation. The VEPP rings have been equipped with unique insertion devices including a helical undulator (producing circularly polarized radiation) and superconducting wigglers (8 T, 4 poles and 3.4 T, 19 poles). SPEAR has space for more than 12 insertion devices with 5 in operation now. DCI, DORIS, SPEAR and the VEPP rings serve major user communities with many simultaneously operating stations.

Second Generation Sources and Facilities

The experience using high energy physics rings as light sources and the growing number of users competing for beam time led, in the mid to late 1970's, to the design and construction of new storage rings to be used as fully dedicated radiation sources. Many of these second generation dedicated light sources are now in full operation including major national research facilities in England (SRS), Germany (BESSY), Japan (UVSOR and the Photon Factory) and the USA (Aladdin and the NSLS rings). These rings have an immense capacity (some with 50 or more experimental stations) and serve several hundred to more than 1000 users.

Several of these rings have electron beam emittances of 40-150 nm-radians, whereas most first generation rings have several hundred nm-radian emittances. Two rings (SRS and the Photon Factory) have recently had additional quadrupoles installed to reduce the emittance to this level. At the SRS a permanent magnet undulator and a 3 pole, 5 T wiggler serving 6 stations are in use. At the Photon Factory several insertion devices are in use including a 3 pole, 5 T wiggler with a horizontal field to produce vertically polarized radiation and several permanent magnet undulators. At NSLS permanent magnet undulators have been in use on the 0.75 GeV ring for several years and several wiggler and undulator magnets are now coming on line in the 2.5 GeV ring, including a 5 T, 6 pole superconducting wiggler for angiography and other studies.

The use of positrons rather than electrons for the stored beam results in improved beam stability and lifetime, important considerations for all synchrotron light sources. Positive ions produced in the residual gas of the vacuum system, or dust particles that tend to become positively charged, can be trapped by an electron beam, but are repelled by a positron beam. Trapped ions or dust particles can cause abrupt beam losses, reduction in lifetime and tune changes. The DCI and Photon Factory rings now routinely use positrons. Most new facilities are designed either to use positrons from the start or to add a positron capability at a later date if measures to prevent ion trapping (such as leaving a gap in orbital filling pattern) prove inadequate.

Third Generation Storage Rings

Present rings cannot achieve the full performance potential of insertion devices, particularly the high brightness that can be produced by undulators. This has led to an intense worldwide activity to design and construct the next generation of storage rings with lower emittance and many straight sections for insertion devices. These are briefly described below with the numbers in parentheses giving the emittance in nm-radians and the number of straight sections available for insertion devices respectively.

The first of these, the 0.8 GeV Super-ACO[5] ring (30,5) in Orsay, France, began operation in early 1987. Several others have been authorized for construction. This includes the 6 GeV European Synchrotron Radiation Facility (ESRF)[6] (7,28) in Grenoble, the 1.5 GeV Advanced Light Source (ALS)[7] (7,11) at Berkeley, the 1.3 GeV Taiwan Light Source (20,5), the 1.5-2 GeV Elettra ring[8] (4,11) in Trieste and the 2.5 GeV Siberia II ring[1] in Moscow. The 7 GeV Advanced Photon Source[9] (7,34) at Argonne National Laboratory is in advanced stages of design with a construction start expected in the FY90 budget now being considered by Congress. The 1.5 GeV BESSY II ring[10] (8,8) in Berlin and the 8 GeV STA ring (5,40) in Japan[11] are also in an R&D phase with construction approval expected soon. A 1-3 GeV ring is planned in Brazil.

There is great expectation in the synchrotron radiation community that these new sources will open the way to important new science. Indeed, our experience with synchrotron radiation over the past two decades has shown that with each order of magnitude improvement in flux or brightness has come new applications, in many cases unimagined until the source was available. Recent examples include the use of the coherence properties of VUV and soft X-ray synchrotron radiation to make holograms in this new spectral region and the use of X-ray scattering as a probe of the magnetic properties of materials and in the study of phase transitions in two dimensional systems such as surface monolayers, lipid bilayers and liquid crystal films.

The goal of the third generation rings now being designed and constructed is to achieve a brightness of 10^{18} to 10^{19} photons/(s.mm^2.mrad^2.0.1% bandwidth). This can be reached with 5 meter long undulators in rings operating at about 100 mA with a horizontal emittance of 5-10 nm-radians. These performance levels will require meeting stringent tolerance requirements in the storage ring (e.g., magnet quality and alignment, orbit stability and reproducibility) and in the precision and quality of the insertion devices. It will also require solution to difficult engineering problems, particularly those associated with the high thermal loading on beam line front ends and optical components.

Future Sources

The many third generation storage rings now in design and construction will offer extremely bright and increasingly coherent soft X-ray and X-ray photon beams to a very large scientific community. When beams from these rings become available in the mid 1990's they will be more than two orders of magnitude brighter than is routinely available now, opening up entirely new scientific opportunities. It appears likely, however, that brightness and coherent power will continue to be the frontiers in source development since, as explained earlier, we are still far from fundamental diffraction limits at these short wavelengths. Higher brightness and coherent power can be reached with longer undulators, higher stored current and lower emittance. Significant advances in any of these areas requires solution to even more difficult engineering problems and meeting even tighter tolerances than for third generation rings. Some of the possible development directions for the fourth generation sources can be explored with high energy electron-positron colliders such as PEP (15 GeV)[12,13] and Tristan (30 GeV)[4]. Since emittance decreases as the square of the electron energy, by operating these rings at 1/2 to 1/3 their maximum energy the emittance is reduced by a factor of 4 to 9. Low emittance optics can be used to further reduce the emittance by about a factor of 4 or more. For example, PEP has been operated in a low emittance optics at 7.1 GeV with a measured emittance of 6 nm-radians with the usual damping partition and 4 nm-radians with a modified damping partition[12,13].

Also, these rings have long, dispersion-free straight sections which can be used for very long undulators and also for damping wigglers[14] to reduce the emittance by another factor of 5 or more. Using damping wigglers it should be possible to achieve an emittance of less than one nm-radian in these rings. They could therefore be prototypes of future high performance rings, offering higher brightness and coherent power and approaching diffraction limits at shorter wavelengths.

At some point technical or fundamental limits will be reached in reducing electron beam emittance and increasing photon beam brightness using circular electron machines and other directions may become more promising. As has been pointed out by Fuoss[15], high energy electron beams from linear accelerators offer very low emittance and shorter bunches than storage rings. For example linear collider devices such as the SLAC linac aim at producing an emittance of about 0.3 nm-radians at 50 GeV with 5×10^{10} electrons in bunches that are only a few picoseconds long. Such beams could be passed through long undulators generating very high peak power, brightness and coherent power even though the time averaged value of these quantities is lower than could be produced in storage rings[15].

It might also be noted that the design emittance of the SSC is a respectably low 0.05 nm-radians at 20 TeV. Although protons radiate much more weakly than electrons (by the ratio of the masses raised to the fourth power if other conditions are the same) one could imagine overcoming this with a very long undulator. For a 1 km undulator with a period length of 33 cm and a peak field of 6 T (K=0.1), the time averaged stored current of 73 mA would produce about 50 W of radiation within a very narrow bandwidth at 3 keV, resulting in exceedingly high brightness. If the proton beam were stored for a day or so, the emittance would further decrease due to radiation damping which has a one day time constant[16].

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[16] The ideas expressed here were stimulated by discussions with Albert Hofmann and Alex Chao.

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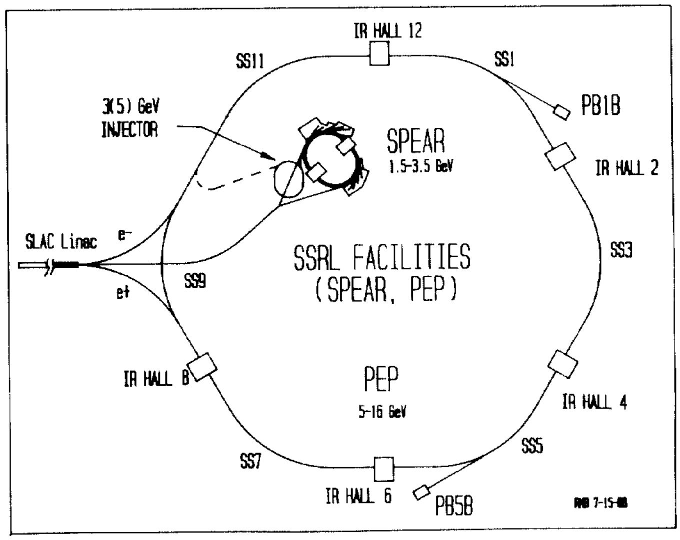

Figure 4: Layout of the SPEAR and PEP rings at Stanford showing the 9 existing beam lines serving 22 experimental stations on SPEAR and the 2 existing undulator beam lines on PEP. Also shown is the SPEAR 3 GeV injector, now in construction, and a possible transfer line to PEP so that this injector could serve PEP after upgrading it to 5 GeV.

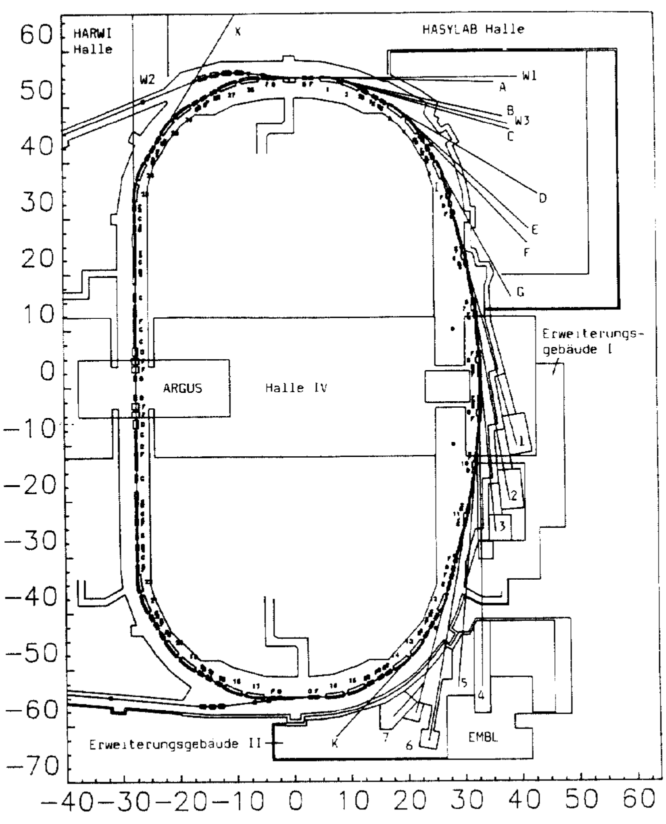

Figure 5: Layout of synchrotron radiation beam lines on the DORIS storage ring at DESY. The bulge on the right side is a bypass, now in design, that will accommodate 6 insertion devices. (Courtesy W. Brefeld, HASYLAB)

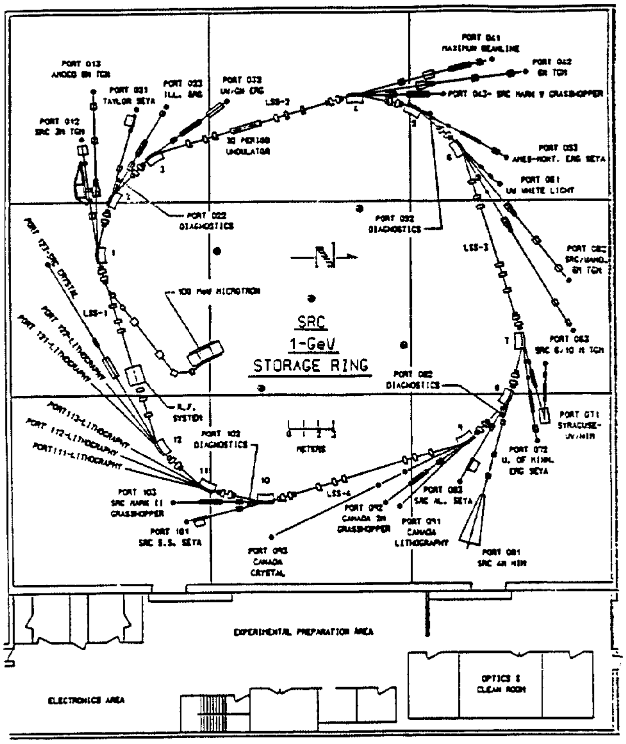

Figure 6: Layout of the Aladdin 0.8-1.0 GeV dedicated light source at the University of Wisconsin. Injection is provided by a 108 MeV microtron. (Courtesy E. Rowe, University of Wisconsin)

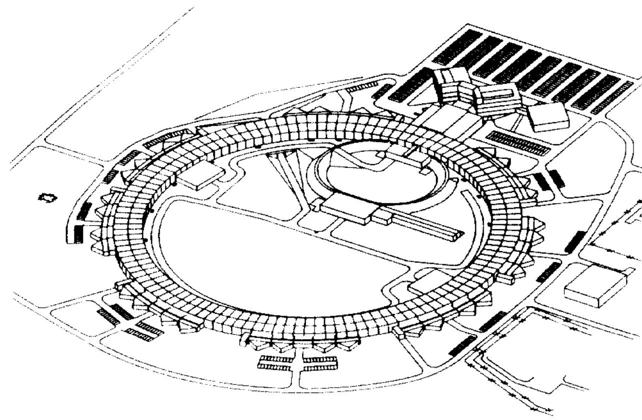

Figure 8: Layout of the 7 GeV Advanced Photon Source at Argonne National Laboratory. The ring circumference is 1 km and can accommodate 34 insertion beam lines plus 35 bending magnet lines.

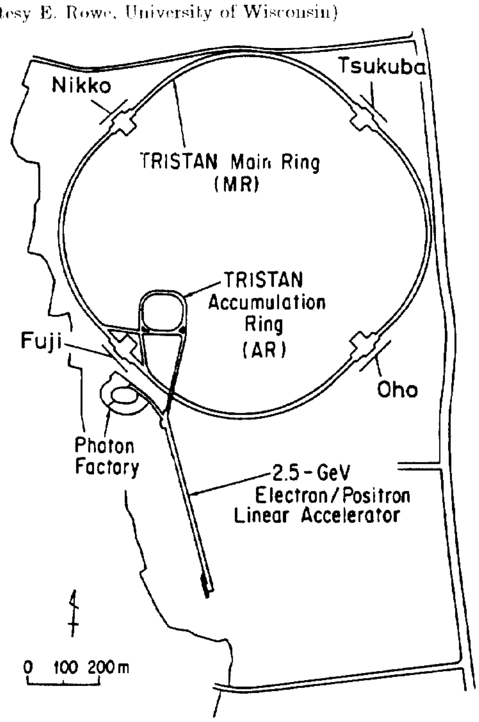

Figure 7: Storage rings at KEK, Tsukuba, Japan. The 2.5 GeV Photon Factory is a fully dedicated light source. Several beam lines have been implemented on the 6-8 GeV Tristan Accumulator Ring. Plans are being made to utilize the 30 GeV Tristan main ring (3 km in circumference) as a low emittance light source operated around 10 GeV. (Courtesy M. Ando, KEK)

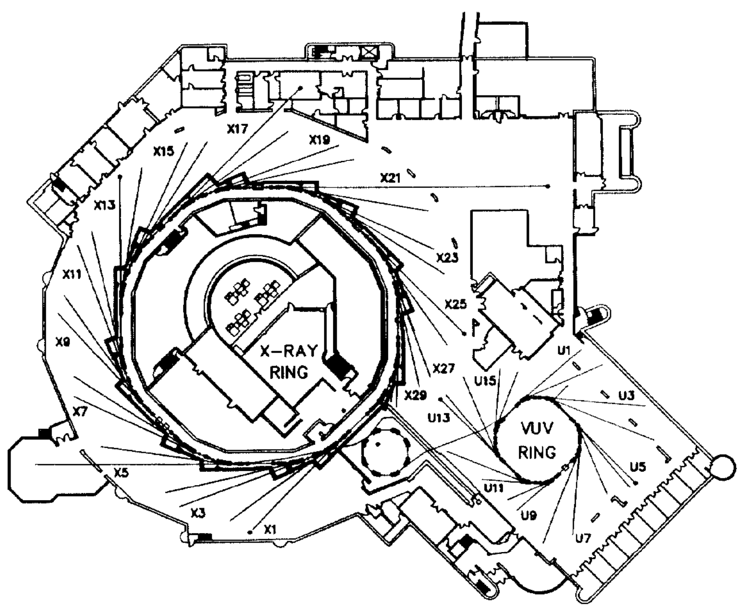

Figure 9: Layout of beam lines at NSLS storage rings. Many beam lines serve multiple experimental stations. The total capacity is about 100 experimental stations. (Courtesy S. White-DePace, NSLS)