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CONF-8708180--4

Presented at the International Symposium on
X-Ray Microscopy, Brookhaven National Laboratory
Upton, New York, August 31-September 4, 1987

BNL 40633

Experience with Synchrotron Radiation Sources*

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BNL--40633

DE88 005610

Abstract

The development of synchrotron radiation sources is discussed, emphasizing characteristics important for x-ray microscopy. Bending magnets, wigglers and undulators are considered as sources of radiation. Operating experience at the National Synchrotron Light Source on the VUV and XRAY storage rings is reviewed, with particular consideration given to achieved current and lifetime, transverse bunch dimensions, and orbit stability.

1. Development of Synchrotron Radiation Facilities

Throughout the world synchrotron radiation facilities are being built and operated as sources of ultraviolet and x-radiation for research in the basic and applied sciences [1]. The capacities of existing facilities are being strained by the ever increasing number of scientists using synchrotron radiation, and large new facilities are being planned in the United States, Europe, Japan, and elsewhere. Early work with synchrotron radiation was performed parasitically on synchrotrons and storage rings designed and operated for high energy physics. Over the last decade, new facilities designed specifically for synchrotron radiation research have been successfully constructed and operated. Examples are the NSLS and ALLADIN in the United States, the SRS at Daresbury in England, BESSY in Germany, SUPERACO in France, and the PHOTON FACTORY in Japan. At the new dedicated facilities, advances in storage ring design together with improvements in beamline instrumentation have resulted in a significant increase in the quality of the radiation sources available to experimenters.

Of particular importance has been the increase of spectral brightness of the new sources. Brightness [2] is the proper figure of merit for experiments requiring photon beams with small angular divergence incident upon small samples, and in experiments utilizing spatially coherent radiation [3]. Spectral brightness is defined as the number of photons per unit source area, per unit solid angle, per unit bandwidth. In order to increase the brightness of the radiation sources in a storage ring, one must reduce the volume of phase space occupied by the electron beam. Accelerator physicists use the term "emittance" to refer to the area in horizontal or vertical phase space occupied by the electron beam. The condition for optimizing the luminosity for colliding beam experiments in high energy physics requires large horizontal emittance, whereas high brightness radiation sources result from small emittance. Using existing technology, it was possible to design low emittance storage rings dedicated to synchrotron radiation research, with significantly higher brightness than the sources available on high energy physics machines. The benefits expected from providing higher brightness sources have been realized, e.g. reduction of deleterious effects due to aberrations in beamline optics, higher resolution, improved spatial coherence, and this has motivated the development of

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*This work was performed under the auspices of the U.S. Department of Energy.

the next generation of synchrotron radiation sources, which are being designed to have even smaller electron beam emittances and, consequently, even higher brightness than the existing facilities.

Another important development leading to enhanced radiation sources has been the use of insertion devices [4], see Fig. 1. Early work with synchrotron radiation was done exclusively using the radiation emitted from electrons bent in circular arcs in the dipole magnets of a storage ring. More recently, improved sources have been obtained by placing special magnets called "wigglers" in the straight sections (insertions) of the storage ring. These magnets produce along the electron trajectory a magnetic field alternating in polarity, causing the electron to wiggle transversely. If we assume the wiggler magnetic field to be approximately sinusoidal,

$$B = B_w \sin (2\pi z/\lambda_w) \ ,$$

then the resulting angular deviation of the electron trajectory can be written

$$x' = \frac{K}{\gamma} \sin (2\pi z/\lambda_w) \ ,$$

where λ_w is the period length of the static wiggler magnetic field, γ is the electron energy measured in units of its rest mass, and

$$K = 0.93 \ B_w(T) \ \lambda_w(cm)$$

is a dimensionless parameter determining the maximum angular deviation.

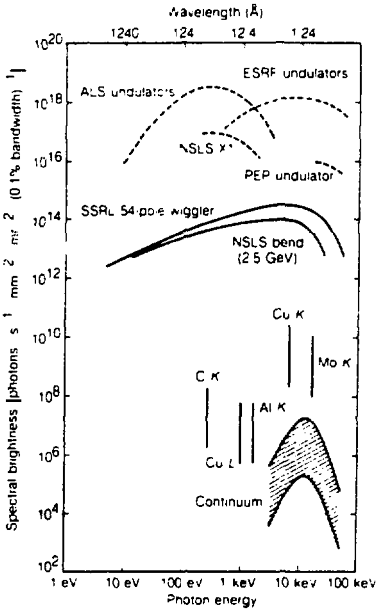

Fig. 1. Comparison of spectral brightness of some conventional X-ray sources, and synchrotron sources from bending magnets and insertion devices.

Electrons passing through a wiggler magnet radiate due to the transverse acceleration they experience. When K<<1, the radiated spectrum is peaked about the fundamental wavelength

$$\lambda_1 = \frac{\lambda_w}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) ,$$

and there is little intensity at the higher harmonic wavelengths $\lambda_k = \lambda_1/k$ ($k = 2, 3, 4, \ldots$). As K is increased toward unity, the third harmonic becomes important, and for large K many harmonics have significant intensity.

The radiated spectral intensity from a bending magnet is characterized by a critical wavelength $\lambda_c(\text{Å}) = 18.6/B(T)E^2(\text{GeV})$, where B is the magnetic field strength and E the electron energy. The spectral intensity is roughly constant for $\lambda > \lambda_c$, and falls off rapidly for $\lambda < \lambda_c/3$, see Fig. 2. When an insertion device is operated with K large, the radiated spectrum is similar to that of synchrotron radiation from an arc source, and we speak of "wiggler" radiation. Wigglers provide an enhancement in the radiated flux per unit solid angle, relative to an arc source. Also, by designing the wiggler to operate at higher magnetic field than the arc sources, one can obtain a source of harder photons.

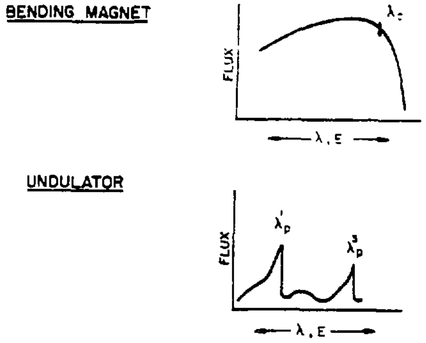

Fig. 2. Qualitative features of radiated spectrum from bending magnet and undulator sources.

When the insertion device is operated with K small, there is a high intensity at only a few harmonics, Fig. 2, and one speaks of "undulator" radiation. Although there is no clear dividing line between the undulator and wiggler regimes, there is a difference between undulator radiation and that from an arc source. Consider turning down the magnetic field strength on the undulator. The number of radiated photons decreases as K^2, but the first harmonic wavelength approaches a limit, $\lambda_1 = \lambda_w/2\gamma^2$, independent of K. Hence, in the limit of K very small, there is the emission of only a few photons, but they are still hard. In contrast, when the magnetic field in an arc source is reduced, the radiation becomes softer. Storage rings operating with electrons energy between 0.5-1GeV are appropriate for the production of ultraviolet and soft x-rays from bending magnets and wigglers, and ultraviolet radiation from undulators. Facilities in this class are the NSLS VUV-RING, ALLADIN, BESSY and SUPERACO. Storage rings operating with electron energies between 1.5-3GeV can deliver soft x-rays from undulators, and hard x-rays from bending magnets and wigglers.

Examples are the NSLS XRAY RING, DARESBURY, THE PHOTON FACTORY, and the planned rings at Berkeley, Trieste, and BESSY II in Germany. Hard x-rays from undulators can be produced from electrons with energy 6-8 GeV. At present, CESR at Cornell, and PEP at SLAC can run in this energy range. New facilities dedicated to synchrotron radiation research are planned in the 6-8 GeV range at Argonne and Grenoble, and also in Japan.

The reduction of the emittance of a storage ring necessary to achieve high brightness requires an increase in the size and cost of the machine. The emittance is roughly proportional to $\gamma^2\theta^3$, where θ is the bend angle per dipole magnet. The larger the electron energy γ, the smaller θ must be to achieve low emittance. Small bend angle per dipole is accompanied by increased numbers of quadrupole magnets to focus the electron beam, leading to increased ring circumference.

In addition to the development of high brightness sources there has been recent interest in producing compact storage rings for industrial applications of x-ray lithography [5]. These machines are being designed to have a critical wavelength near 10Å, and although the emittance should not be too large, it need not be exceptionally low. Therefore, these rings can be smaller and less expensive than the machines being built for synchrotron radiation facilities. In Japan, Germany and the United States, there are two approaches to the design of compact sources. One approach uses superconducting magnets with fields of about 4T, with the ring circumference ≈12m and the electron energy ≈600 MeV. The second approach uses conventional magnets operating at about 1.6T, with ring circumference ≈30m and electron energy ≈1GeV. Compact storage rings may one day be useful for x-ray microscopy techniques not requiring high brightness.

2. Performance of the NSLS Storage Rings

The storage rings at the NSLS were specifically designed for use as dedicated synchrotron radiation sources. Their basic parameters as achieved in normal operations, are summarized in Table 1.

Table 1. NSLS Storage Rings

	XRAY RING	VUV RING
Energy	2.5 GeV	0.75 GeV
Circumference	170 m	51 m
Critical Wavelength	2.5 Å	25 Å
Current	200 ma	700 ma
Lifetime (1/e)	10-20 hrs	2-4 hrs
Emittance ϵ_x	10^{-7} m-rad	1.5×10^{-7} m-rad
ϵ_y	10^{-9} m-rad	1.5×10^{-9} m-rad
Typical Source Size σ_x	0.35 mm	0.40 mm
σ_y	0.12 mm	0.25 mm

The lifetime of the XRAY ring corresponds to an exponential decay of the beam current due to scattering off of the residual gas in the vacuum chamber. At 200 ma, the pressure is about 2nT, and the observed lifetime is 10-20 hrs. The XRAY ring is normally run with 25 consecutive electron bunches and a gap of 5 empty buckets. Leaving a gap in the bunch distribution is found to alleviate ion trapping.

In contrast, the lifetime in the VUV ring is determined not by the vacuum, but by scattering between electrons in the same bunch (Touschek scattering). The Touchek lifetime is inversely proportional to the bunch density and, therefore, is reduced as the transverse dimensions are decreased. In the VUV ring, when the vertical emittance of the electron beam is reduced using skew quadrupoles, one observes that the lifetime decreases. Also, the lifetime depends only on the individual bunch currents, and not on the average current. The VUV ring is normally run with five consecutive bunches and a gap of four empty buckets. Again the gap helps eliminate ion trapping. A 4th harmonic cavity is planned to increase the bunch length and thus increase the beam lifetime.

Of key importance to the optimum utilization of the high-brightness sources is the achievement of a stable orbit with movements small compared to the dimensions of the electron beam. At present orbit motions of 50-100μ are observed, and much effort is aimed at identifying and eliminating the source of these variations. There is an active R&D program to develop improved detectors of orbit position using synchrotron radiation. Key issues are intensity dependence of the position measurements and long term stability. New high resolution RF detectors for the pick-up electrodes in the storage rings are also being designed. A vigorous program is underway to develop and implement orbit feedback systems, and a prototype system was successfully operated on X17T for the mini-undulator discussed at this conference. With the feedback 5μ stability was achieved, [6] as illustrated in Fig. 3.

In conclusion, the operation of the VUV and XRAY rings has been in accordance with the expectations based on the original design. The experimental program has grown rapidly, and in the near future there will be ≈30 beamlines on the VUV ring and ≈50 on the XRAY ring. Work on x-ray microscopy will continue to be one of the most exciting programs at the NSLS, and the high quality of the source required for this work will stimulate further advances in the design of synchrotron radiation facilities.

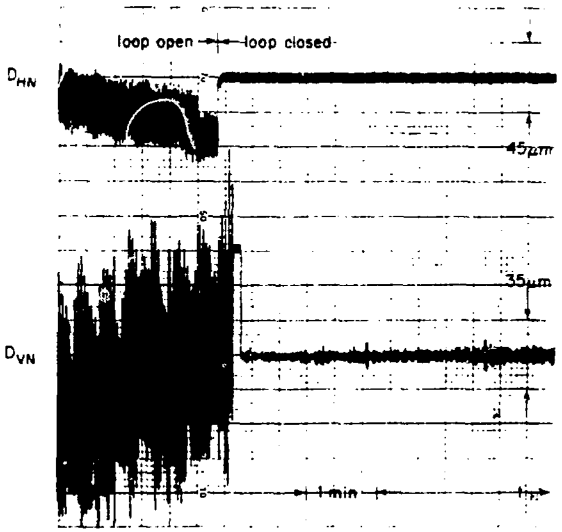

Fig. 3. Improvement of orbit stability resulting from closing the feedback loop on X17T.

Acknowledgement

I wish to thank Harvey Rarbach for several useful discussions.

References

1. The development of synchrotron radiation sources is reviewed by H. Winick: In Scientific American (Nov. 1987), p 88.

2. The importance of optimizing the brightness of synchrotron radiation sources was emphasized by G.K. Green: Spectra and Optics of Synchrotron Radiation, Brookhaven National Lab Report, BNL 50522 (1976).

3. Coherence of synchrotron radiation is discussed by D. Attwood, K. Halbach, and K.J. Kim: Science 288, 1265 (1985).

4. See e.g. S. Krinsky, M.L. Perlman and R.E. Watson: In Handbook on Synchrotron Radiation, Vol. 1, edited by E.E. Koch (North Holland, 1983); and S. Krinsky: IEEE Trans. Nucl. Sci. NS-30, 3078 (1983).

5. See e.g. R.P. Haelbich, J.P. Silverman, and J.M. Warlaumont: Nucl. Inst. Methods 222, 291 (1984); and A.D. Wilson: In SPIE Vol. 537 Electron-Beam, X-ray, and Ion-Beam Techniques for Submicron Lithographies IV (1985), p 85.

6. R.J. Nawrocky, L. Ma, H.M. Rarbach, O.V. Singh and L.H. Yu: In Proc. of the 1987 Particle Accelerator Conference, Washington, D.C., March 15-19, 1987.