SYNCHROTRON RADIATION FACILITIES IN THE USA *

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Abstract

With the successful commissioning and achievement of significant milestones at both the 7-GeV Advanced Photon Source (APS) at Argonne National Laboratory and the 1.5-GeV Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory, synchrotron radiation research capability in the United States holds the promise of many important discoveries in the decade to come. An overview of current accelerator commissioning performance at the American third-generation light sources, state-of-the-art developments at first- and second-generation sources, and a preview of fourth-generation source progress is presented.

1 INTRODUCTION

Over the past twenty-five years, the United States' synchrotron radiation community has blossomed into its own scientific niche, from the early second-generation light source efforts at Wisconsin, which are still active [1,2,3], to third-generation light sources such as the Berkeley Advanced Light Source (ALS) [4], Argonne's Advanced Photon Source (APS) [5], and beyond. Accelerator improvements continue to push the limits of light source performance, particularly in the areas of beam stability, emittance, and brightness. Particle and photon beam diagnostics have advanced to a level where micron-scale, short-term particle beam stability is almost routinely achieved. Emphasis on component reliability has resulted in user availabilities commonly exceeding 95%.

The intent of this paper is to give an overview of progress and performance highlights at U.S. light sources and to discuss developments toward fourth generation sources.

2 SYNOPSIS

Table 1 summarizes first-, second-, and third-generation light source user facilities presently operational in the United States [6,7]. In addition to listing the operating particle beam energies in use at the various labs, the natural emittance, ε_N, and critical energy, ε_C , of bending magnet radiation are given. It is interesting to note the trend toward small emittance/high brightness in both the hard and soft x-ray regimes. A comparison of photon beam spectral properties in terms of average and peak brilliance is shown in Fig. 1 for the various sources.

3 THE NATIONAL SYNCHROTRON LIGHT SOURCE FACILITY (NSLS)

The dedicated second-generation light sources at Brookhaven National Laboratory, brought on-line in the early 1980's, represent the state of the art in mature light source development. For example, beam lifetime in the vacuum ultraviolet ring (VUV), which is dominated by the Touschek effect, has been more than doubled through the introduction of a harmonic cavity to lengthen the bunch [8].

Table 1: Synchrotron light user facilities in the U.S.

Machine	E (GeV)	ε_N (nm-rad)	ε_C (keV)
VUV NSLS BNL Upton, NY	0.744	138.0	0.48
ALADDIN SRC Madison, WI	0.8	97.6	0.54
CAMD LSU Baton Rouge, LA	1.2 - 1.5	211.0	1.31 @ 1.2 GeV
ALS LBL Berkeley, CA	1.3 - 1.9	3.4	1.53 @ 1.5 GeV
XRAY NSLS BNL Upton, NY	2.5 - 2.8	102.0	5.55 @ 2.584 GeV
SPEAR SSRL Stanford, CA	3.0	130.0	4.67
CESR / CHESS Cornell, Ithaca, NY	4.7 - 5.6	214.0	10.3@ 5.3 GeV
APS ANL Argonne, IL	7.0 - 7.5	8.2	19.5@ 7.0 GeV

Low-frequency beam stabilization efforts in some of today's third-generation sources have benefitted signifi-

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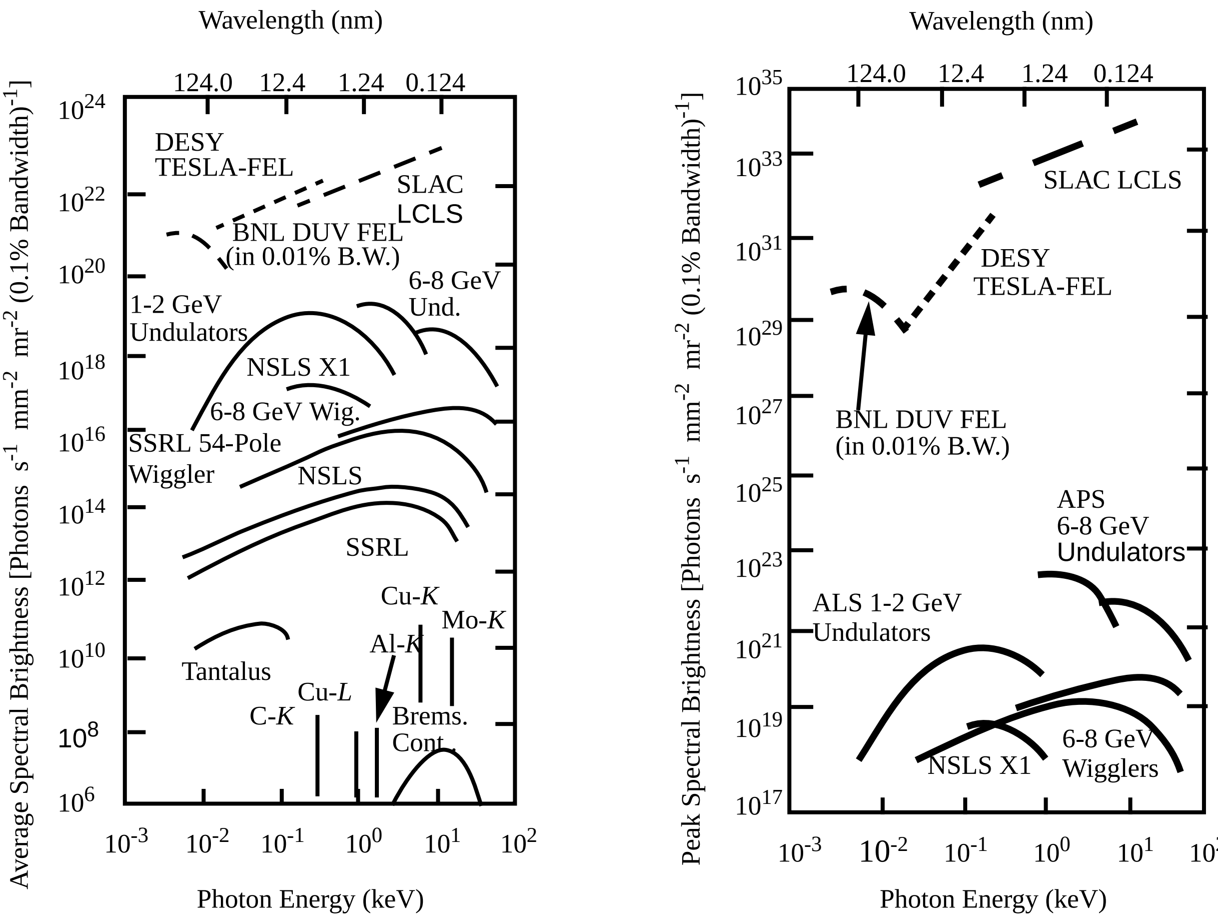

Figure 1: Comparison of average and peak spectral brightness for existing and proposed light sources

cantly from the pioneering work carried out at NSLS [9], and in particular from the switched-receiver beam position monitor electronics design developed there [10]. These receivers have formed the basis for the sophisticated closed-orbit feedback systems presently in operation at NSLS [11,12,13].

In terms of source development, operation with insertion-device accelerator vertical full-apertures as small as 3.8 mm with no appreciable effect on x-ray ring beam lifetime has been demonstrated, as well as 2-mm aperture operation, but with some lifetime degradation [14,15]. Additionally, operation of an elliptically polarized wiggler with AC polarization has been accomplished with active compensation such that beam stability specifications have been met [16,17].

Lattice modelling techniques developed recently, in combination with the excellent beam position monitoring system at NSLS, have made possible the determination of quadrupole gradients down to 0.04% rms resolution, for example. The method employs measured steering corrector response matrices as input to a least-squares algorithm fitting literally hundreds of possible error sources, including quadrupole gradient and roll errors, beam position monitor (BPM) gain and rotation errors, corrector magnet strength errors, and linear lattice functions [18].

4 THE STANFORD SYNCHROTRON RADIATION LABORATORY (SSRL)

The 3.0-GeV SPEAR storage ring at SSRL has enjoyed a long career first as a high energy physics machine and now near the completion of its evolution from a first-generation source into an advanced synchrotron radiation user facility. Beam stabilization efforts are now moving towards real-time, digital, combined global and local closed-orbit feedback, which are becoming almost commonplace at synchrotron radiation facilities [19,20]. New optics have been implemented to reduce the effects of strong quadrupoles dating back to a high-luminosity colliding beam design [21]. These “mini-beta” quads, mounted in a cantalevered configuration extending over the high energy physics detector pits, were the cause of significant low-frequency beam motion, a consequence of resonant mechanical support vibrations.

5 THE LBNL ADVANCED LIGHT SOURCE (ALS)

The ALS at Berkeley is well into user operation mode, having started beamline commissioning in October 1993 [4]. With the smallest natural emittance of all U.S. light sources and its relatively low beam energy (1.5 GeV), the

ALS is operating in a fundamentally new regime of accelerator parameters, which allows for some interesting and novel diagnostic and control techniques and some unique beam characteristics. Due to rf cavity higher-order modes, a number of longitudinal-coupled bunch modes are excited using the 320-bunch fill mode (harmonic number = 328). The all-digital, bunch-by-bunch longitudinal feedback system, in addition to damping these modes, provides a powerful diagnostic into the dynamics of longitudinal instabilities [22].

During commissioning of the longitudinal feedback system it was found that stabilization of the longitudinal phase space had the undesirable effect of inducing a transverse multibunch instability. The longitudinal stabilization also caused reduction of the bunch length by a factor of ten, reducing the Touschek lifetime accordingly [23]. The transverse multibunch betatron motion concurrent with this bunch length reduction has now been eliminated using an analog feedback system [24]. Activation of the longitudinal feedback has also been observed to decrease undulator sprectral line widths, resulting in brighter beams. The ALS lifetime is typically on the order of 12 hours at 400 mA in multibunch mode and 2 hours in two-bunch mode, with 20 mA/bunch, again a result of the Touschek effect.

With regard to low frequency beam motion and drift, the largest beam jitter component has been traced to a 14-Hz magnet support mechanical resonance, but is still less than 10% of the source sizes in both transverse planes. Long-term drift has been brought under control to a large extent through improvements in accelerator component cooling water temperature stabilization, now in the ± 0.1 C°. Investigations continue into a one-hour-scale horizontal drift component, with regulated air temperatures suspected as the cause.

6 CORNELL ELECTRON STORAGE RING (CESR)

Still providing x-ray beams primarily parasitically to high energy physics with some periods of dedicated synchrotron radiation user time, the Cornell machine continues to break colliding beam luminosity records while providing high-quality bending-magnet, wiggler, and insertion-device photon beams to users at the Cornell High Energy Synchrotron Source (CHESS) [25,26]. Of particular interest to the synchrotron radiation community is that injections occur quite frequently, typically every ten to fifteen minutes to maximize integrated luminosity, and that synchrotron radiation beamline shutters are kept open the whole while. Such an operating mode (top-up) is clearly of interest to synchrotron radiation users, since thermal loading of photon optics components can be held quite constant, and in principle the normalization of user data to the net photon flux can be eliminated when stored beam intensity is tightly regulated.

7 THE ADVANCED PHOTON SOURCE

The Advanced Photon Source (APS) achieved first stored beam on March 25, 1995 following a fast-paced installation effort and extensive subsystem tests [5,27,28]. First insertion-device beam extracted from the storage ring enclosure occurred on August 9, 1995 from beamline 1-ID using the Undulator A device with a 12.5-mm, full-aperture vacuum chamber. Shortly thereafter, on August 18, stored beam with an 8-mm, full-aperture chamber installed in another sector was attained within minutes of the arrival of beam at the injection septum, following a 24-hour access for the small-gap chamber installation, and with negligible impact on machine performance. Since that time, all insertion devices (IDs) have been installed with 8-mm aperture chambers, each 5 meters in length, configured to accommodate two 2.5-meter insertion devices. The next operating period, scheduled to begin June 18, 1996, will take place with 10 insertion devices installed, marking the halfway mark for phase I APS insertion device installation. Thirty-five straight sections are available for insertion devices.

The design 100-mA stored beam current was attained January 12, 1996 following vacuum chamber cooling system upgrades and radio-frequency cavity tuner improvements completed in September and December 1995, respectively. During the March and May operating periods a total of 20 Amp-hours of stored beam has been made available for machine studies and x-ray experiments, with routine beamline commissioning and user beam time anticipated this summer. A summary of APS design vs. achieved performance parameters is shown in Table 2.

Table 2: APS performance

	Design	Actual
Beam Current	100 mA	102. mA
Single Bunch Current	5 mA	17 mA
Lifetime @100mA	> 10 Hours	10.7 Hours
Avg. Vacuum @100 mA	1 nTorr	2.2 nTorr
RMS Beam Motion @ ID Source Point	< 4.4 µm V, 17µm H, 4-50 Hz	4 µm V, 16 µm H, 4-50 Hz
Horz. Emittance	7.45 nm-rad	7.6 +/- 0.8 nm-rad
H-V Coupling	< 10 %	<3% w/o correction

As can be seen, all specifications have been met, with the exception of average ring vacuum, which is expected to improve as more operational time is accrued, allowing synchrotron radiation desorption at absorber locations to improve vacuum performance.

The low-frequency beam stability specification has been achieved without feedback during periods of minimal activity on the experiment hall floor. Commissioning efforts are underway for the closed-orbit feedback system, which will be necessary to reduce beam motion during noisy periods, and for very low frequencies, i.e. long-term drift [29]. Initial results for the APS beam position monitor system, which is based on an amplitude-to-phase modulation technique, indicate that resolution significantly less than 1 micron is attainable in a 100-Hz bandwidth [30]. Custom-designed 4-mm-diameter button pick-up electrodes are mounted directly on the small-gap insertion-device vacuum chambers to provide accurate steering of ID beams.

In the area of x-ray beam characterization, many excellent results can be found in the literature, including transverse and longitudinal particle beam imaging [31,32].

8 THE LINAC COHERENT LIGHT SOURCE (LCLS) AT SLAC/SSRL

Coherent infrared source development to date based on free electron lasers (FELs) in the U.S. is well documented [33,34]. The prospects for a very short, 0.1-nm-wavelength free electron laser based on the SLAC linac were discussed at a workshop held in 1992 [35]. In light of recent advances in radio-frequency laser photocathode electron gun technology, a grass-roots R&D effort to study the problems associated with such a device has grown, with participation from individuals from universities and national laboratories, and extending into the industrial sector in the area, for example, of undulator development. These developments have crystallized in the formation of an organized effort centered at SLAC, the purpose of which is to put together a detailed design study including cost estimates and schedule, by August of 1997 [36].

An overview of efforts to date were summarized in a workshop held in Grenoble in January 1996 [37] which is, in fact, the source of the comparisons shown in Fig. 1. The evident advantage of this technique over present light sources is the improvement in peak brightness by as much as ten orders of magnitude, in addition to orders of magnitude improvements in peak power, coherence, and shortness of the light pulse

Accelerator R&D has focused principally in the areas of electron gun development, proof of principle of the Self-Amplified-Spontaneous-Emission (SASE) mechanism at very short wavelengths, bunch compression techniques, and cost-effective, precision undulator development. The evolution of an electron gun capable of producing greater than 1 nC in a 150- to 200-Ampere peak pulse with normalized emittance less than one π mm-mrad is one essential ingredient. Simulations and cold tests for a BNL design have been published [38,39], and a high power version is presently undergoing tests [40]. Many theoretical investigations relevant to predictions of SASE behavior, emittance preservation, and bunch compression can be found in the literature [33,34,41]. Shown in Table 3 are a set of the latest Linac Coherent Light Source (LCLS) design parameters being considered by the SLAC design group.

Table 3: Parameters for a Linac Coherent Light Source at SLAC

Undulator Type	Helical	Planar	
Wavelength	1.5	1.5	Angstroms
Norm. Emittance	1.0	1.0	mm-mrad
Peak Current	5	5	kA
E	15	15	GeV
sigma E/E	0.02	0.02	%
Pulse Duration	100	100	fs
Pulses / 120 ns macropulse	10	10	
Repetition Rate	120	120	Hz
Undulator Period	2.0	3.0	cm
Peak Field	1.8	1.4	Tesla
Gain Length	2.5	5.3	meters
Saturation Length	25	52	meters
Peak Power	50	30	GW
Average Power	15	10	Watts
Energy per Pulse	12	8	mJ
Coherent Photons per pulse	9.3E12	6.3E12	
Peak Brightness	4E33	4E33	**
Average Brightness	9E23	7E23	**
Transverse Size	13	18	µm rms
Trans. Divergence	1.0	0.7	µrad rms

** photons/(s, mm^2, mrad^2, 0.1% BW)

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