An Upgrade for the Advanced Light Source

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One of the first third-generation synchrotron light sources, the ALS, has been operating for almost a decade at Berkeley Lab, where experimenters have been exploiting its high brightness for forefront science. However, accelerator and insertion-device technology have significantly changed since the ALS was designed. As a result, the performance of the ALS is in danger of being eclipsed by that of newer, more advanced sources. Enhanced brightness is the key not only to remaining competitive but also to setting a new performance standard.

Significant brightness improvements can be realized in the core soft x-ray region by going to top-off operation, where injection would be quasi-continuous. In top-off mode with higher average current, a reduced vertical emittance and beta function, and small-gap permanent-magnet or superconducting insertion devices, one to two orders of magnitude improvement in brightness can be had in the soft x-ray range. These improvements also extend the high energy range of the undulator radiation beyond the current limit of 2000 eV. Most important, top-off avoids the penalty of a much reduced lifetime that would otherwise come with increased brightness, a penalty that is totally unacceptable to the user community.

In brief, the ALS upgrade that we are planning includes full-energy, top-off injection with higher storage-ring current and the replacement of five first-generation insertion devices with nine state-of-the art insertion devices and four new application-specific beamlines now being identified in a strategic planning process. The upgrade will involve no major disruption to the experimental program of the ALS, since it can be accomplished in a phased sequence of short (six week) shutdowns.

Science at the Forefront

Exploitation of the high brightness of a third-generation synchrotron light source translates into four areas: (1) high resolving power for spectroscopy; (2) high spatial resolution for microscopy and spectromicroscopy; (3) high temporal resolution for diffraction and spectroscopy; and (4) high coherence for experiments such as speckle and lensless imaging. Capabilities in these areas will also enable the ALS to support the Molecular Foundry, a U.S. Department of Energy Nanoscale Science Research Center that is now under construction at Berkeley Lab with construction, equipment installation, and commissioning expected by the end 2006. The ALS offers a variety of characterization and diagnostic capabilities applicable to nanoscale science and technology, including diffraction, photoemission, absorption, and fluorescence spectroscopy, often with temporal as well as spatial resolution.

The physics of complex materials studied by photoemission with high energy and high momentum resolution has benefited enormously from the availability of high brightness sources. Improvement in the energy resolution from 50 meV to 10 meV has enabled investigation of low-energy excitations, such as the dispersion "kink" and bilayer splitting in the high T_c superconductors [1, 2]. Seven photoemission papers have made it to the "ten most cited physics papers" at one time or another. Further improvement in resolution down to the meV range will provide even sharper experimental incisiveness for the understanding of complex materials ranging from strongly correlated electron systems and magnetic materials to systems with reduced dimensionality.

Inelastic x-ray scattering (IXS) is a complementary but more demanding spectroscopy. As a photon-in/photon-out technique, it has the advantage over photoemission of greater penetration and the ability to look at bulk properties and buried interfaces. IXS is the only direct probe of charge-charge correlations that offers momentum resolution. Moreover, unlike photoemission, it is possible, to apply a magnetic field to the sample. The disadvantage of IXS is its inherently low cross-section, so that the state-of-the-art resolution is 250 meV. We have dedicated the last remaining straight section at the ALS to MERLIN, a new beamline mainly for IXS that will reach a resolution of 10 meV. (A second dedicated end station will be for photoemission with sub-meV resolution). This performance will be achievable only below a photon energy of 100 eV, so that only momentum transfers close to the Brillouin-zone center (q=0) can be investigated. To reach the zone edge it would be necessary to work closer to 1000 eV. This can in principle be done but only after the upgrade described below.

Understanding fundamental magnetic interactions is at the frontier of solid-state physics but also driven by the technology of thin-film magnetic devices. At the ALS we have pioneered the development of new techniques, one example being magnetic imaging for the elucidation of exchange bias in the coupling of the antiferromagnetic (AF) to ferromagnetic (FM) materials that lies at the heart of magnetic spin valves. This problem could only be solved with our new ability to image AF and FM domain structures at high spatial resolution, with interfacial sensitivity, and with elemental and chemical selectivity, by means of photoemission electron microscopy (PEEM). These techniques are revolutionizing our understanding of thin-film magnetism [4-8], and we expect PEEM 3, the next generation microscope, to begin commissioning in 2005 [9].

Manipulation of spin directly by optical or electrical means leads to the concept of "spintronics"[10]. The fundamental lateral length scale now shrinks to the magnetic exchange length measured in nanometers with a temporal scale set by magnetization precession time of picoseconds. On the horizon are devices such as spin transistors, spin-transfer devices or even spin-based quantum computers. Together with complementary laser probes, time-resolved soft x-ray probes will lead to major advances. Experiments in this domain are brightness limited and are at the edge of viability at the ALS today. They would become practical with the enhancements envisioned for this upgrade.

The structure of condensed matter is not static, and to understanding the behavior of condensed matter at the most fundamental level requires structural measurements on the time scale on which atoms move. The evolution of condensed matter structure, via the making and breaking of chemical bonds and the rearrangement of atoms, occurs on the fundamental time scale of a vibrational period, ~100 fs. Atomic motion and structural dynamics on this time scale ultimately determine the course of phase transitions in solids, the kinetic pathways of chemical reactions, and even the efficiency and function of biological processes. A thorough understanding of such dynamic behavior is a first step to being able to control structural evolution and will have important scientific applications in solid-state physics, chemistry, materials science, and biology [11]. The tremendous potential scientific impact of this research area is largely unfulfilled, owing to the inadequacy of present zeroth-generation short-pulse x-ray sources (roughly analogous to rotating-anode sources in comparison with modern synchrotrons).

We have made considerable progress on the construction of a user facility, Beamline 6.0.1, which will fill a critical need for the growing ultrafast x-ray research community [12]. It will also serve as a stepping stone for developing femtosecond techniques in advance of the LCLS x-ray laser at the Stanford Linear Accelerator Center. An in-vacuum, permanent-magnet undulator/wiggler will radiate both soft and hard x-rays from 120 eV to 10 keV. The device has 50 periods with a period of 30 mm and a peak magnetic field of 1.5 T. There will be two branch lines, one with a variable-line-space grating spectrograph and the other with a Ge (111) or Si (111) crystal monochromator. On the soft x-ray branch, a streak camera will serve as the detector for measurements on picosecond time scales. The ultrafast facility will make use of an already installed wiggler (which now serves a protein-crystallography beamline) for generating femtosecond x-rays via laser-modulation (slicing) of the stored electron beam. A 40-kHz femtosecond laser system will be located at the end of the beamline and will serve the dual purposes of providing laser pulses for slicing the synchrotron beam and providing tunable "pump" pulses for sample excitation. Based on the present storage-ring parameters, we expect that x-ray pulses of 200 fs duration will be produced.

The high brightness of an optimized third generation source not only translates directly into high average coherent x-ray flux but the quasi-dc nature of synchrotron radiation is essential for many experiments. For example, the diffraction of a coherent x-ray beam from a sample has information at the spatial scale of the wavelength and over a lateral dimension of the coherence width. Two ways to use the information encoded are illustrated below. The upgrade is key in providing much higher coherent flux at the optimum energies.

Zone plate-based x-ray microscopes can now achieve spatial resolutions down to 18 nm at soft x-ray energies, and with improvements in fabrication, some further progress can be expected. However, for the imaging of three-dimensional objects, the thickness of the object places severe restrictions on resolution because the depth of field scales as the square of the resolution. For many applications, such as cellular biology, materials engineering, in-situ study of materials in reactive conditions, and nanotechnology, there is a pressing need to find a technique that can look at thick objects at nanometer resolution. It has recently been found that coherent diffraction patterns can be reconstructed back into real space without prior knowledge of phase information. The key is that the transform of a non-periodic object is continuous in Fourier space and can be "oversampled." Electron-density positivity and the sample boundary are then sufficient constraints for convergence on a unique phase set and hence an image [12, 13]. We now have the prospect of being able to image thick objects at nanometer resolution in liquids or under reaction conditions. This capability will give us a revolutionary new tool.

The interplay between spin, charge, lattice, and orbital degrees of freedom produces very complex phase diagrams and nanoscale phase behaviors in transition metal oxides. These microphases are thought to play a key role in the properties of high-temperature superconductivity in the cuprates and colossal magnetoresistance (CMR) in the manganites. Again, these length scales map directly to soft x-ray probe wavelengths. Soft x-ray coherent x-ray scattering offers important advantages, such as high coherent flux, excellent chemical contrast, an adequate scattering wave vector to probe nanoscale features, and access to core levels of interest, such as oxygen and the transition metals. These advantages should enable a much more complete characterization of these materials, including their response to external control parameters, such as field, temperature, and current, as well as their related dynamical properties.

Increased Brightness with Top Off and Advanced Undulators

At present, the ALS is operated in a mode where beam is injected three times daily to 400 mA. In the eight hours between fills, the beam decays to 200 mA with a time-averaged current of about 250 mA. Machine performance of the ALS is lifetime limited. While substantial improvements in brightness and current have always been technically feasible, they incur the penalty of a much reduced lifetime, an option totally unacceptable to our users. In top-off mode, injection would be quasi-continuous, so that the lifetime impediment disappears. In addition, because of the nearly constant current in the storage ring, beamline optics would not suffer the large thermal fluctuations associated with large changes in storage-ring current. These greatly reduced thermal fluctuations of beamline optics would result in enhanced photon position stability at all ALS beamlines.

It is also possible to increase the current in the machine to 500 mA (Figure 1). In terms of raw flux, the combination of top-off and increased current would therefore increase our capacity to the equivalent of two ALSs, which must surely rank as a dramatic example of cost effectiveness. More important than capacity, however, is enhanced capability. The proposed upgrades will enable the newer and more revolutionary experiments briefly outlined above.

The other half of the enhanced-brightness strategy is the insertion device. At present, the "workhorse" at the ALS is a 4.45-m-long, linearly polarizing undulator. The ALS has five of these insertion devices with periods of 5, 8, and 10 cm that were designed and installed about a decade ago. Each of these devices require one full storage ring straight section. With subsequent significant advances in undulator technology, the currently favored design is the 2-meter elliptically polarizing undulator (EPU). Of these, we have two installed, one under construction, and one proposed. Together with one wiggler, these undulators fill all available ALS straight sections.

However, insertion-device technology continues to advance, with small-gap, short-period, in-vacuum undulators and superconducting undulators emerging as the insertion devices of choice. So, in addition to top-off operation with higher average current, further brightness improvements can be realized in the core soft x-ray region by reducing the vertical emittance and beta function of the storage ring, which allow us to install such small gap, permanent-magnet or superconducting insertion devices.

In Figure 2 and Table 2, we compare the brightness of the old workhorse with the present storage ring parameters to four new small-gap devices with the upgraded ring parameters shown in

Table 1. The new devices all have a vacuum gap of 5 mm, in contrast to the 9 mm of the older undulators. The first two are 30-mm-period in-vacuum devices of lengths 4.3 m (long) and 1.8 m (short), respectively. These two devices could be constructed with hybrid permanent magnets [14, 15]. The second two are 14.5-mm-period superconducting devices of lengths 4.3 m (long) and 1.5 m (short), respectively [16, 17].

We see that there are one to two orders of magnitude improvement in brightness obtainable in the soft x-ray range. In reducing the vertical emittance after the upgrade, we also reduce the wavelength at which the undulators become diffraction limited to 0.57 nm, i.e., the ALS will be diffraction limited in the vertical direction throughout the whole of the soft x-ray energy range. It should also be noted that the proposed upgrades extend the high-energy range of the undulator radiation, which is currently limited at 2000 eV.

A full conceptual design report for the top-off portion of the upgrade will be completed by the end of the year. In the meantime, the ALS is working closely with the Office of Basic Energy Sciences at the U.S. Department of Energy on ways to implement the upgrade in a timely fashion.

More Beamlines to Exploit the Brightness

The ALS, unlike the larger x-ray machines, has a severely limited number of straight sections. This has meant that several world-class programs, which would normally command one or more insertion devices, have multiple end stations sharing a single beamline. One example is the combination of the condensed-matter physics and atomic and molecular physics programs on Beamline 10.0.1, each of which is world leading and would merit a beamline of its own. It would be preferable to design optical systems fully optimized to the type of science on each beamline.

Consequently, an important aspect of the upgrade is to replace some full-length, linearly polarized undulators with chicaned straights containing two shorter, more advanced devices. With the increased flux and brightness available, each of these devices will perform far better than the current devices, but at the same time allow simultaneous operation of two fully optimized, independent, application-specific beamlines.

Our plan is to replace five workhorse insertion devices with nine newer more advanced insertion devices plus four new beamlines that are responsive to the scientific drivers, such as those discussed above (Figure 3). A strategic planning process involving the full complement of ALS management, scientific staff, user community, and advisory bodies has been under way with the aim of identifying the scientific areas that would benefit from such independent beamlines and the types of beamlines needed to serve them.

It is important that the upgrade not interrupt the ongoing experimental programs more than necessary. To this end, we are planning an orderly upgrade in which obsolescent insertion devices are progressively replaced by state-of-the-art insertion devices. All upgrades envisioned can be executed in a phased sequence of short (six weeks) shutdowns.

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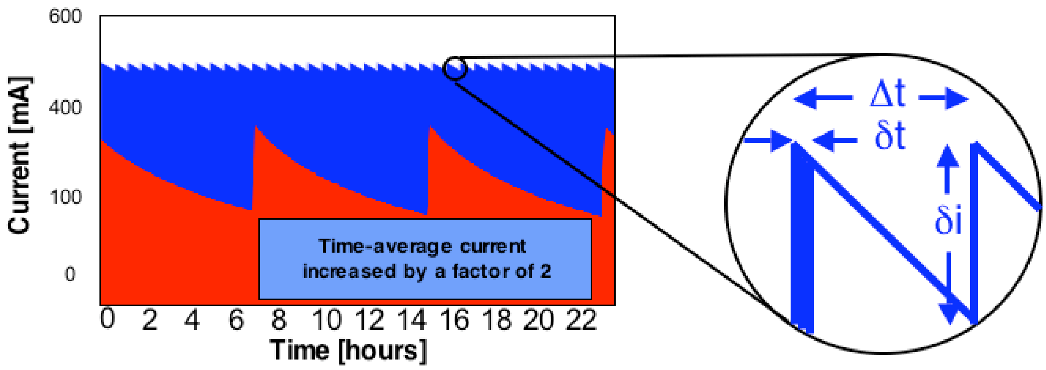
Table 1. Comparison of Present and Future Storage-Ring Parameters

Parameter	Present	Future
Time Average Current (mA)	250	500
Veritcal Emittance (nm•rad)	0.15	0.02
Vertical Beta Function (m)	3.6	2.25
Vertical Magnetic Gap (mm)	14	5

Table 2. Comparison of Present and Future Brightness (photons/sec/0.01%bw /mm^2/mrad^2)

Photon Energy	Present Brightness	Future Brightness (ID length, period, technology)	Improvement
500 eV	5.70×10^{18}	2.04×10^{19} (short, 30 mm, IVU)	3.58
		6.93×10^{19} (short, 30 mm, IVU)	12.2
1000 eV	3.49×10^{18}	1.88×10^{19} (short, 30 mm, IVU)	5.39
		4.29×10^{19} (long, 30 mm, IVU)	12.3
		5.83×10^{19} (short, 14.5 mm, SCU)	16.7
		2.02×10^{20} (long, 14.5 mm, SCU)	57.9
2000 eV	6.07×10^{17}	3.71×10^{19} (short, 14.5 mm, SCU)	61.1
		1.25×10^{20} (long, 14.5 mm, SCU)	206
4000 eV	not accessible	2.35×10^{19} (short, 14.5 mm, SCU)	—
		4.81×10^{19} (long, 14.5 mm, SCU)	—

Figure 1. Top-off injection with reduced vertical emittance.



δi	Δt	δt
1.5mA	32.0s	≤50ms

Figure 2. Brightness comparison of new ALS insertion devices to current insertion devices.

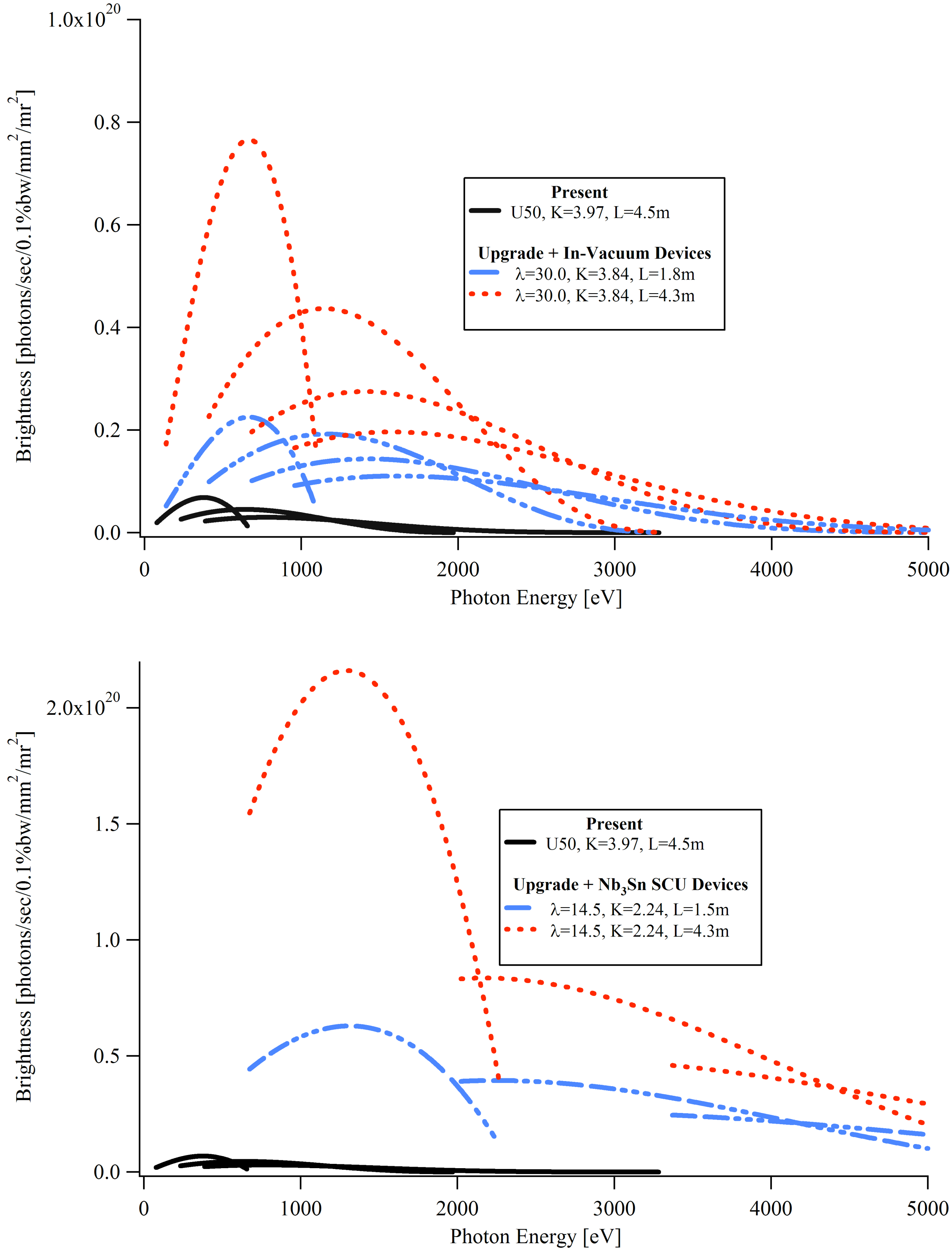


Figure 3. Beamlines at the ALS. In the upgrade, the five “workhorse” 4.45-m-long U5, U8, and U10 undulators would be replaced with nine shorter, small-gap devices with higher brightness in an orderly, phased manner to minimize disruption of the experimental program.