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A New Light for Berkeley Lab—the Advanced Light Source Upgrade

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On October 4, 2018, the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory (LBNL) celebrated its twenty-fifth anniversary of first light. Just two weeks earlier, news arrived from Washington, DC, that the ALS Upgrade Project—which will leverage multibend achromat (MBA) technology to endow the ALS with revolutionary soft X-ray capabilities (Figure 1)—had received formal approval to proceed to the preliminary design phase. That same day, the fiscal year 2019 budget for the U.S. Department of Energy was signed, providing $62 million to propel the project forward.

Designed in the 1980s and commissioned in 1993, the ALS was the first third-generation storage-ring-based light source optimized for soft X-rays. For most of the last quarter of a century, the ALS has been the brightest source of soft X-rays in the world and has continuously evolved, taking advantage of undulator technology and lattice modifications to improve its capabilities. Currently, there are 43 beamlines providing more than 2,100 unique users each year capabilities extending from infrared to harder X-rays.

Scientific research at the ALS is enhanced by the facility's location at LBNL. LBNL maintains a dynamic and diverse research program across 21 scientific divisions and operates four national user facilities in addition to the ALS—the Joint Genome Institute, the Energy Sciences Network, the National Energy Research Scientific Computing Center, and the Molecular Foundry. The co-location of these research programs and facilities offers a prime environment for collaborative science.

Relative to many other synchrotron light source upgrade projects or new facilities being built today, the upgraded ALS will operate at a low electron-beam energy of 2 GeV and a high current of 500 mA, and is optimized for soft X-rays. Its soft X-ray coherent flux will be orders of magnitude higher than that of the existing ALS and beyond the coherent flux of any storage-ring-based light source operating, under construction, or currently planned (Figure 2). In total, the upgraded facility will provide an unprecedented combination of high stability, quasi-continuous radiation, and the highest possible coherent soft X-ray flux.

Soft X-rays are a critical diagnostic tool for enabling the understanding and control of heterogeneous, hierarchical functional materials and chemical synthesis platforms, since they can reveal chemical, electronic, and magnetic properties with very high sensitivity. Although the ALS has a strong track record in soft X-ray science over the last 25 years, it, like most other existing storage-ring-based X-ray light sources, lacks the simultaneous combination of nanometer spatial reso-

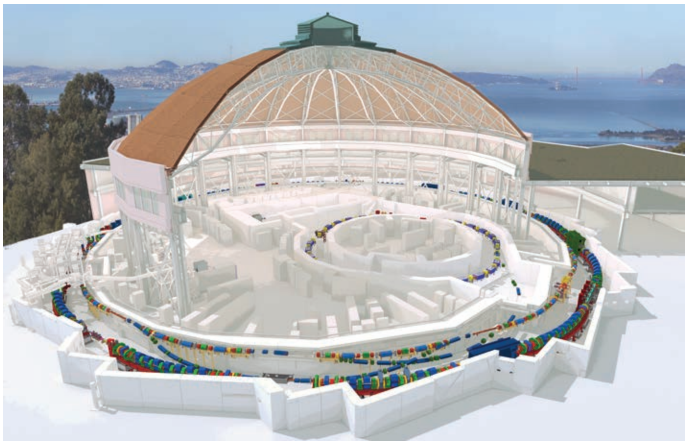

Figure 1: The Advanced Light Source Upgrade Project will leverage multibend achromat technology and on-axis, swap-out injection (made possible with the addition of an accumulator ring) to endow the ALS with revolutionary soft X-ray capabilities. (Credit: M. Leitner/Berkeley Lab).

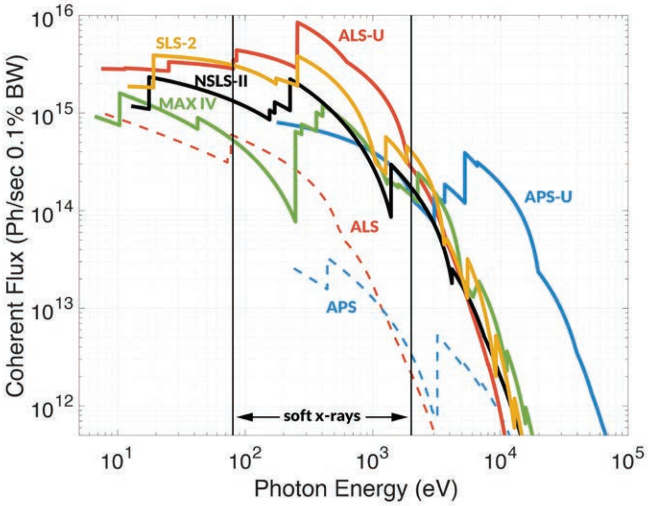

Figure 2: Coherent flux for undulator sources at ALS, the upgraded ALS, and several other operating and planned X-ray facilities. (Credit: Berkeley Lab).

lution, diverse spectroscopic contrast, and broad temporal sensitivity required to image the location of molecules, ions, and electrons, and to measure how their components migrate and interact to support efficient function.

The high coherent flux of the upgraded ALS will enable a suite of tools that encompass 3D nanoscale imaging with high spectral sensitivity over broad space and time scales, dramatically amplifying the already high impact of ALS soft X-ray spectroscopies. As depicted in Figure 3, the upgraded source will be small and collimated enough that the soft X-ray wave fronts produced will be smooth and coherent. In the nanoprobe modality, these are focused with high efficiency into a diffraction-limited spot, which in turn can be scanned across the sample to apply soft X-ray spectroscopies with nanoscale resolution. Alternatively, the coherent soft X-ray beam can be scattered in transmission through or reflection off a heterogeneous sample to produce a speckle/diffraction pattern with chemical or magnetic contrast that can be set by tuning the X-ray energy near absorption resonances. New computational approaches like ptychography or fluctuation X-ray scattering can transform these speckle patterns into 2D or, with tomography, 3D images. As another option, temporal sample fluctuations can be mapped onto fluctuations in the speckle pattern, and these can be analyzed to probe motion over broad spatial and temporal scales.

Chemical imaging experiments at the ALS have recently achieved few-nanometer spatial resolution in 2D on a model material, but on a more typical, realistic object can provide only 15 nm resolution with limited spectral coverage and temporal sensitivity. The upgraded ALS, on the other hand, will allow spectroscopies like angle-resolved photoemission spectroscopy to be applied to functional systems as nanoprobe techniques with natural or designed spatial or temporal heterogeneity.

This combination of capabilities, and their concerted application to diverse research problems, will enable a key goal of nanoscience—the understanding, rational design, and assembly of structures that exhibit emergent functionalities needed to address the world's most pressing technological challenges. These include: materials and structures that can store and process classical and quantum information with ultralow power dissipation; microbial cells engineered to produce commodity and specialty chemicals from abundant starting materials; chemical microreactors designed to achieve efficient and selective multistep chemical syntheses; photoelectrochemical cells that enable artificial photosynthesis; nanoporous membranes optimized for ion transport and water purification with high selectivity and efficiency; and many more.

Project scope

The scope of work for the ALS Upgrade Project (ALS-U) includes (Figure 4):

- Replacement of the existing triple-bend achromat storage ring with a new, 2 GeV high-brightness, nine-bend-achromat storage ring that reduces the horizontal emittance by a factor of about 30 relative to today's ALS storage ring.
- Addition of a low-emittance, full-energy accumulator ring in the existing storage-ring tunnel to enable on-axis swap-out injection (an exchange of electron bunch trains between the accumulator ring and storage ring) using fast magnets.
- Installation of new insertion devices optimized for high brightness and flux.
- Addition of a suite of new and upgraded beamlines designed to exploit the high-brightness source.

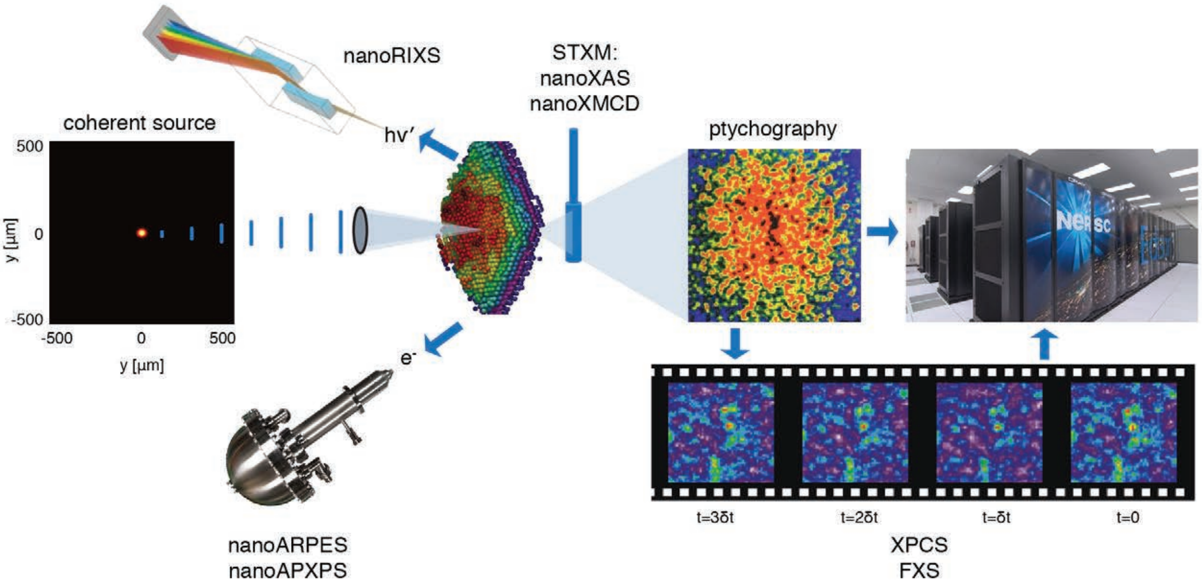

Figure 3: ALS-U will accelerate the transformation of soft X-ray spectroscopy and scattering tools into powerful nanoprobe and coherent scattering techniques, respectively. (Credit: Berkeley Lab).

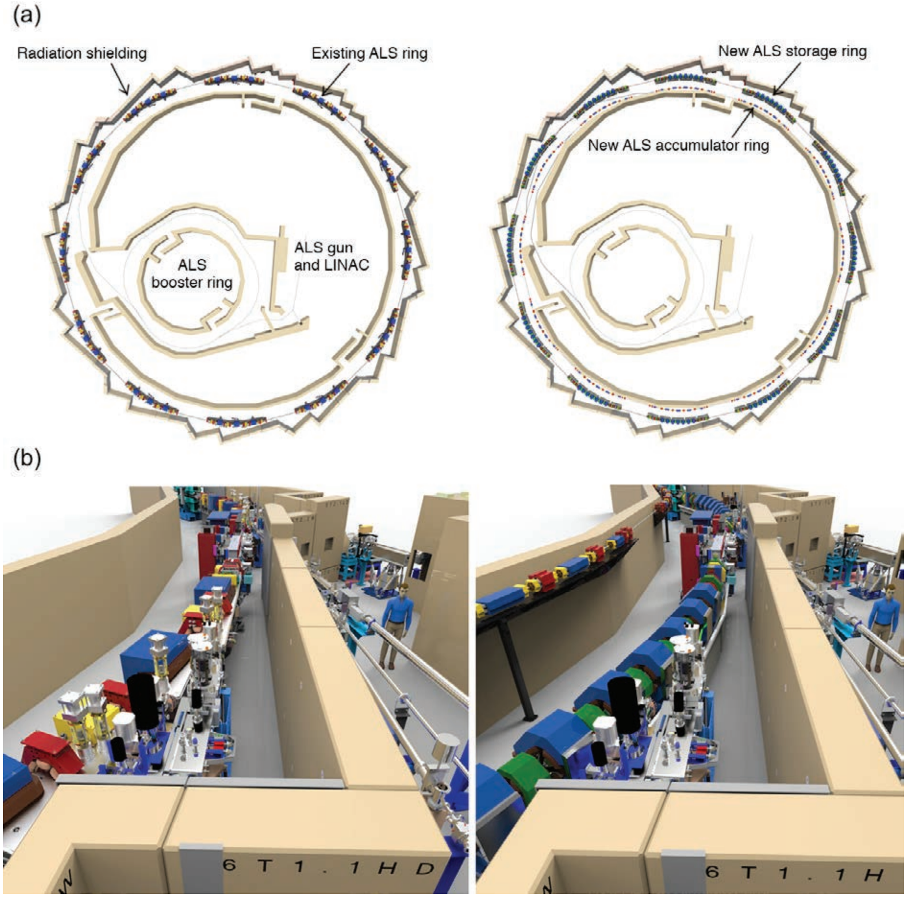

Figure 4: Comparison of the ALS accelerator complex as it exists today (left) and after ALS-U (right). (a) Plan views of the tunnel and rings. (b) A sector inside the tunnel. The bottom right-hand image shows the accumulator ring to the left (inside) of the storage ring. (Credit: Berkeley Lab).

- Relocation and adjustment of beamlines where required to preserve existing insertion-device and bend-magnet beamline capabilities.

The project will take advantage of the ALS's existing buildings, shielding, injector, and most beamlines and instrumentation. By leveraging these existing assets, ALS-U will provide a state-of-the-art facility for soft X-ray science at a fraction of the cost and time required for a new facility with a similar suite of beamlines. The upgrade also leverages the intellectual capital of the ALS's expert scientific and technical staff and vibrant, experienced user community.

Reaching the soft X-ray diffraction limit

The improved performance of the ALS that is achieved by replacing the ALS storage ring's triple-bend-achromat magnetic lattice with a stronger-focusing nine-bend achromat is partly enabled by advances in non-evaporable getter (NEG) coated vacuum chambers that allow apertures below 20 mm in diameter (2.5 times smaller than the current ALS sector vacuum chambers). A comparison of current and planned storage-ring and beam parameters (Table 1) shows that the future electron beam will be round and approximately 14 µm in diameter, in contrast to the present-day beam, which is 20 times wider horizontally (Figure 5). Also, the bunch lengths of the upgraded ALS will be more than two times longer to mitigate the impact of intrabeam scattering, making the source more continuous and enabling a duty cycle of almost 10%, which is higher than other electron storage rings.

One of the consequences of producing such a small emittance is a reduced dynamic aperture—the region around the center of the electron beam where the motion of the electrons is stable. At the upgraded ALS, the dynamic aperture will be significantly smaller than at the present-day ALS, making traditional off-axis injection difficult; however, the momentum acceptance will remain large enough to support good beam lifetime. To overcome this challenge, the ALS-U design uses on-axis "swap-out" injection to exchange beam bunch trains between the storage ring and a new, low-emittance, full-energy accumulator ring (Figure 6).

During operation of the upgraded ALS, the storage ring will contain about 11 bunch trains (each in turn containing about 25 bunches spaced 2 ns apart), while the accumulator ring will contain one bunch train. The emittance of the beam in the accumulator will be approximately 2 nm rad (similar to the current ALS). Approximately twice a minute, a storage-ring bunch train will trade places with the accu-

Table 1: Parameter list comparing the present-day and future ALS.

Parameter	Current ALS	Future ALS
Electron energy	1.9 GeV	2.0 GeV
Beam current	500 mA	500 mA
Horizontal emittance	2,000 pm rad	<75 pm rad
Vertical emittance	30 pm rad	<75 pm rad
Beam size at insertion-device center (σ_x/σ_y)	251/9 µm	≤14/≤14 µm
Beam size at x.3 bend source points (σ_x/σ_y)	40/7 µm	≤7/≤10 µm
Energy spread	9.7×10^{-4} ΔE/E	1.1×10^{-3} ΔE/E
Typical bunch length (fwhm)	60–70 ps (harmonic cavity)	100–200 ps (harmonic cavity)
Circumference	196.8 m	≈196.5 m
Number of main bend magnets per sector	3	9

mulator-ring bunch train. Fast kicker magnets will generate a pulse, sending a train from the storage ring to the accumulator. At the same time, the accumulator train will be moved to the storage ring. Between swap-outs, the train in the accumulator will be topped off by the existing LINAC/booster injector, similar to the current top-off injection into the storage ring. By swapping a storage-ring bunch train that has lost a portion of its current with the topped-off bunch train from the accumulator, the overall current in the storage ring will be maintained at 500 mA.

This swap-out mechanism will enable a generational leap in performance. Not only does it allow operation with ultralow emittance, it also enables the use of very small, round vacuum chambers in the insertion device straight sections. These small chambers, in turn, make it possible to use higher-performance helical or Delta undulators with small apertures, which will generate unprecedented high coherent flux. On-axis swap-out injection requires fast pulsers and state-of-the-art strip-line kicker magnets. Prototypes of this hardware have been developed, and tests have shown that they meet the requirements of the upgraded ALS.

The ALS-U design also incorporates new developments in magnet supports and beam diagnostics, as well as improvements in utilities that will further increase beam stability. The existing building infrastructure provides an excellent foundation with ground vibration levels that meet the ALS-U design requirements. In addition, very high reliability is a critical goal that has guided several parts of the R&D program and will remain a central consideration as the design evolves. Normalized to the beam size, the beam stability and reliability are expected to surpass the current ALS.

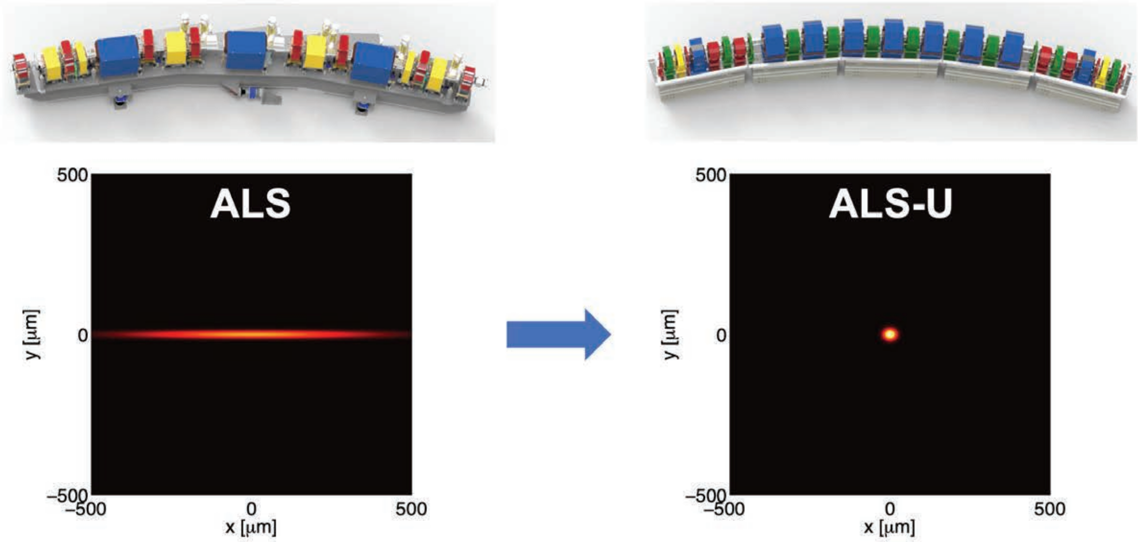

Figure 5: (Left) The existing ALS triple-bend achromat and electron beam profile. (Right) The nine-bend achromat and lower-emittance electron beam profile of the upgraded ALS. Bend magnets are shown in blue. (Credit: Berkeley Lab).

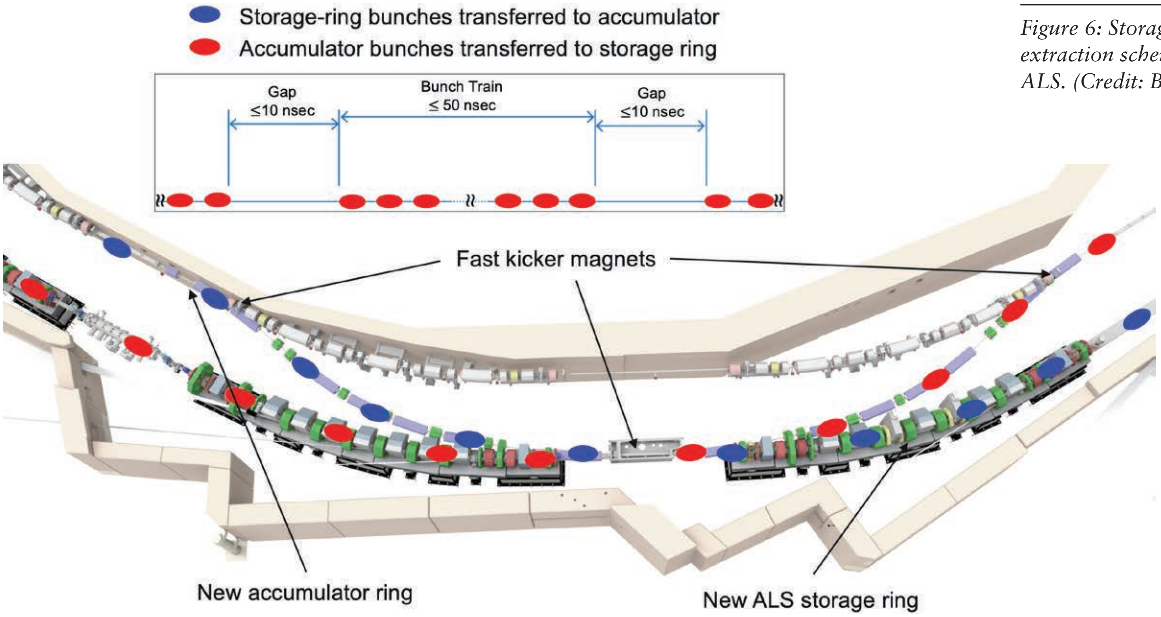

Figure 6: Storage-ring injection and extraction scheme for the upgraded ALS. (Credit: Berkeley Lab).

Experimental systems

In addition to updating the accelerator systems, the ALS-U Project touches every aspect of the experimental systems at the ALS. Implementation will require the creation of bold new capabilities and the preservation of strong programs built over time around many of the existing beamlines. In addition to state-of-the-art soft X-ray beamlines, today's ALS also has a set of infrared, tender (2–5 keV), and harder-energy X-ray beamlines offering capabilities that are complementary to the soft X-ray beamlines. The goal is to ensure that the performance of the new and upgraded beamlines built as part of the project takes full advantage of the characteristics of the upgraded source, and that the major scientific capabilities of the current facility are preserved through the transition.

Some insertion-device beamlines will be upgraded to utilize the new source's extreme brightness. The anamorphic optical systems of current ALS beamlines are designed for the ALS's highly elliptical beam shape. Because the upgraded ALS will have a narrow, round beam, comparable to the current vertical beam size, new and upgraded beamlines will require an improved level of high-quality focusing that preserves the wavefront and transmits the high coherent flux to the endstation.

Although most existing ALS beamlines will remain as part of the upgraded facility, the ALS-U Project's scope includes a small number of new and rebuilt insertion-device beamlines. To select the future beamline configuration and capabilities, the ALS solicited input from its user community. A working group, consisting of ALS staff and Users' Executive Committee leadership, synthesized the input into a set of possible scenarios. External advisory committees have evaluated the scenarios for: (1) scientific importance; (2) relevance of characteristics imparted by the upgrade and potential world leadership; (3) technical feasibility and fit to project resources; and (4) strength of the relevant user community and expected productivity. The final selection decision is anticipated in early 2019. In parallel to the ALS-U Project, the ALS will continue to advance beamline projects outside the scope of the project itself and to undertake smaller facility upgrades, just as it has done throughout its 25-year history.

Removal, installation, and commissioning

An important objective for the project is to minimize the down time of the ALS user program. As such, a detailed strategy is being crafted to expeditiously disassemble and remove the more than 400 tons of equipment in the storage ring and install and commission the new ring. The new MBA lattice will require individually powered magnet supplies and new vacuum, controls, and diagnostic equipment, adding to the project's complexity. To minimize the installation time, many of the new accelerator components will be pre-assembled and pre-staged. The accumulator ring is based on a more conventional storage-ring design and will be built earlier in the project. This strategy will permit installation during regular annual shutdown periods and commissioning during normal ALS operations.

The project team has already developed improved beam-based commissioning techniques involving the use of the on-axis injected beam in single or multiturn mode to accurately identify lattice errors. Existing methods for beam-based diagnostics (e.g., orbit-response matrix analysis) usually require stored beam, which results in stringent requirements for magnet quality and alignment. In addition, the accelerator and beamline commissioning periods will overlap, which will expedite the process of bringing the experimental capabilities back online.

At the conclusion of the ALS-U Project, the ALS will be prepared to welcome a full complement of users to perform outstanding science for at least another 25 years to come. ■