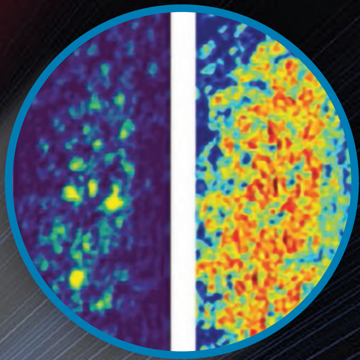
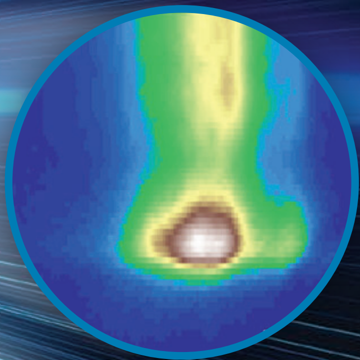
ADVANCED LIGHT SOURCE

5-Year Strategic Plan

2024–2029





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Cover images (top to bottom):

- Coherent x-ray scattering from iron germanium (Fe-Ge) magnetic thin films. The speckle patterns reflect nanoscale fluctuations in the spin texture of the material, allowing characterization of phase transitions, independent of underlying magnetic interactions. A. Singh et al., *Adv. Funct. Mater.* 33, 2300224 (2023).

- An x-ray micro-computed tomography model of a whole fruit fly, showing details of its digestive tract. This imaging technique enabled the investigation of structural changes in a small, delicate organ of a tiny insect, providing valuable insight into the dynamic nature of its digestive system in response to bacterial colonization. (Credit: Marco Voltolini/LBNL). R. Dodge et al., *Nat. Commun.* 214, 1557 (2023).

- Resonant inelastic x-ray scattering (RIXS) data from a spectroscopic study of cathode materials for high-capacity lithium batteries. The results helped untangle the distinct contributions of nickel vs cobalt, pointing the way to a compositional approach to optimizing lithium-rich oxide cathodes. B. Li et al., *Nat. Mater.* 22, 1370 (2023).

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Executive summary

The Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory (Berkeley Lab) is on the cusp of a transformative upgrade that will position the facility for soft x-ray leadership and impactful scientific discoveries across a broad range of fields. This strategic plan presents our five-year goals and objectives toward our long-term vision.

The ALS offers a synergistic portfolio of synchrotron light source capabilities, ranging from the extreme ultraviolet through x-rays, to the global scientific community. As a user facility funded by the US Department of Energy's Basic Energy Sciences program, the ALS is a critical resource for researchers nationwide, providing fundamental insights into the chemical, electronic, and physical characteristics of materials and processes that underpin energy technologies, microelectronics, quantum information science, carbon management, biopreparedness, and more. Over its 30-year history, the ALS has contributed to more than 17,000 refereed journal articles and Nobel Prize–winning research and made fundamental advances across a wide range of fields. The facility has also played a role in the commercialization of new technologies, ranging from advanced instrumentation to pharmaceuticals and computer-chip technologies.

The ALS's vision is to be the premier synchrotron facility where team science and cutting-edge light source technologies converge to drive scientific discovery and address pressing global challenges. To realize this vision, the ALS will be upgraded to a fourth-generation diffraction-limited electron storage-ring facility. This upgrade, known as ALS-U, will enhance the facility's specialization in soft x-ray science, providing a 100-fold improvement in coherent soft x-ray flux and brightness compared to today's ALS. This will maintain the ALS as a world leader in soft x-ray capabilities, filling a niche that hard and intermediate x-ray sources, as well as free-electron lasers, cannot meet.

The dramatic improvements in soft x-ray brightness and coherent flux imparted by the upgrade will unlock new possibilities in imaging, time-resolved spectroscopy, and high-throughput experiments, offering nanometer-scale spatial resolution and dramatically enhanced sensitivity. These advancements will create exciting new scientific opportunities in areas such as materials discovery, molecular biology, and geochemistry. They will also deepen our understanding of electronic structures and chemical processes at the nanometer scale, particularly in heterogeneous and quantum materials, interfaces, phase boundaries, edges, and atomic-scale defects.

The ALS's next five years will be a period of significant change and opportunity, culminating in a new era that we call "ALS 2.0." Our top priority is to support the successful completion of the ALS-U project and transition the facility to a fourth-generation light source. To fully leverage the upgraded source, we must renew our instrument portfolio and upgrade our supporting capabilities, infrastructure, and business systems. We will face the challenge of balancing user experiment time with ALS-U construction, followed by recommissioning the accelerator and beamlines after a one-year dark period without user operations. A critical focus during this time will be on developing our workforce and partnerships to meet the needs of the future user community.

Our strategic plan outlines four primary goals to steer the ALS's future:

1. **Develop and deliver world-class capabilities.** The ALS will focus on exploiting the upgraded facility's coherence and brightness for high-resolution imaging and spectroscopy, high-speed, time-resolved techniques, and high-sensitivity, high-throughput experiments. This will involve renewing and enhancing the portfolio of beamlines, developing new instrumentation technologies, and integrating beamlines with advanced computing infrastructure as well as automation and analysis tools driven by artificial intelligence (AI) and machine learning (ML), to provide fast, real-time data analysis and experimental control.

2. **Usher in a new era following the ALS Upgrade.** The ALS will optimize user operations leading up to the one-year dark time, ensuring continued engagement with the user community throughout the transition. Plans are being developed in collaboration with the ALS-U project so our team can smoothly and safely return the facility to full scientific use.

3. **Ensure mission success through operational excellence.** The ALS will emphasize safety**,** security, and sustainability in its operations, with a commitment to delivering state-of-the-art infrastructure and services. Efforts will focus on strengthening the user experience, maintaining key supply chains, updating critical infrastructure, and improving business systems.

4. **Foster an innovative and collaborative environment.** The ALS is committed to attracting a diverse, vibrant scientific community and cultivating partnerships with academic and industry stakeholders. Key initiatives include building up and developing our workforce and promoting inclusion, diversity, equity, and accountability.

By accomplishing these goals, the ALS will remain at the forefront of innovation, tackling global scientific challenges—from energy and environmental sustainability to human health—for many decades to come.

Introduction

ALS overview

The Advanced Light Source (ALS) is a synchrotron light source user facility located at Lawrence Berkeley National Laboratory (Berkeley Lab) in the San Francisco Bay Area. It is one of five x-ray facilities supported by the US Department of Energy's Office of Science, Basic Energy Sciences (DOE-BES) program and specializes in science conducted with lower-energy "soft" x-rays. Although optimized for soft x-ray spectroscopy, microscopy, and scattering, the ALS also supports research using hard x-rays, infrared (IR), vacuum ultraviolet (VUV), and extreme ultraviolet (EUV) radiation. Since it began operation in 1993, the ALS has continuously evolved to remain one of the brightest and most productive soft x-ray light sources in the world. Currently, the ALS is undergoing a major accelerator upgrade—the largest project Berkeley Lab has undertaken since the ALS's original construction—which will transform the ALS into a next-generation facility with world-leading soft x-ray brightness and coherent flux.

The ALS's mission is to advance science for the benefit of society by providing our world-class synchrotron light source capabilities and expertise to a broad scientific community. With over 40 beamlines, the ALS typically serves around 2000 users annually, resulting in nearly 1000 peer-reviewed publications each year. These users conduct basic and applied research in fields spanning energy science, earth and environmental science, materials science, biology, chemistry, and physics. As a major contributor to the national research enterprise, ALS capabilities provide insights into the chemical, electronic, and physical characteristics of a wide range of molecules, materials, and chemical processes. The ability to understand these fundamental building blocks enables the design and control of properties and phenomena that underpin energy technologies, microelectronics, quantum information science, carbon management, biopreparedness, and more.

The ALS substantially contributes to and benefits from the local ecosystem of expertise, tools, and programs. Its location at Berkeley Lab, combined with strong ties to the University of California (UC) system and collaborations with local industry, creates a dynamic environment that fosters impactful research and innovation. ALS capabilities and expertise are integral to BES core programs as well as substantial DOE-supported initiatives in solar fuels, energy storage, hydrogen, quantum information science, bioscience, microelectronics, direct air capture, and computational science, among others. Its support of user research is bolstered by its colocation and partnership with other Berkeley Lab user facilities, including synthesis, characterization, and theory capabilities at the Molecular Foundry and computational resources at the National Energy Research Scientific Computing Center (NERSC). Participating Research Teams (PRTs), almost all of which comprise Berkeley Lab scientists, operate one-third of ALS beamlines, bringing additional capabilities, expertise, user support, and, in some cases, significant industry collaborations.

Over its more than 30-year history, the ALS has contributed to more than 17,000 refereed journal articles and Nobel Prize–winning research and made fundamental advances across a wide range of fields. The facility has also played a role in the commercialization of new technologies, ranging from advanced instrumentation to pharmaceuticals and computer-chip technologies. Through the ALS Upgrade (ALS-U) project, the ALS is poised for 30 more years of science discovery and societal impact.

The ALS Upgrade project

The global landscape of light source scientific user facilities is evolving. The number of newly commissioned light sources and beamlines is rapidly increasing, with most of this expansion happening outside the United States. Fourth-generation storage rings, which use advanced multibend magnetic lattices, generate 100–1000 times more brightness compared to their third-generation counterparts. As these advanced capabilities come online, international competition is intensifying, not only in terms of performance but also in scientific breakthroughs. To maintain leadership, the US is investing in cutting-edge hybrid multibend achromat (MBA) lattices incorporating innovative technologies such as anti-bends and swap-out injection schemes at the ALS and Advanced Photon Source (APS) at Argonne National Laboratory. These upgrades aim to achieve the lowest beam emittance for a given ring size, positioning the US to remain at the forefront of fourth-generation synchrotron development across the DOE complex.

After more than 30 years in operation, the ALS is undergoing a major upgrade to become a fourth-generation electron storage-ring facility through a major DOE investment known as the ALS-U project. This upgrade will provide a state-of-the-art source for soft x-ray science, filling a niche that cannot be met by hard and intermediate x-ray sources or free-electron lasers. This MBA-enabled upgrade of the ALS is optimized to generate nearly continuous soft x-rays with a 100-fold improvement in soft x-ray coherent flux and brightness compared to today's ALS. To maximize the performance of the MBA-based electron storage ring, the upgraded ALS will employ a new, concentric accumulator ring and an electron bunch-train exchange process. Operating at a relatively low electron-beam energy of 2 GeV (comparable to today's 1.9 GeV) and a high current of 500 mA, the upgraded ALS will produce world-leading soft x-ray coherent flux. The project will leverage the ALS's existing buildings, storage-ring tunnel, linear accelerator, booster ring, most of its 40 beamlines, shielding, and other infrastructure. It entered the construction phase in late 2022, and work will be ongoing over the next several years to complete the upgrade and bring the facility back into full, steady-state operation.

The dramatic improvements in soft x-ray brightness and coherent flux from the upgrade will unlock new possibilities in imaging, time-resolved spectroscopy, and high-throughput experiments with nanometer-scale spatial resolution and dramatically enhanced sensitivity. Sensitivity for coherence-dependent experiments will increase up to tenfold compared with the current facility, while temporal resolution for coherent scattering will improve by a factor of up to 10,000, enabling wavelength-limited resolving power and temporal resolution down to the nanosecond scale. Additionally, in the low-emittance regime enabled by ALS-U, it is possible for a coherent source to produce orbital angular momentum (OAM) beams that can be tailored to have various quantum properties like topological charge. These advancements will open up exciting new scientific opportunities in areas such as materials discovery, molecular biology, and geochemistry. They will deepen our understanding of electronic structures and chemical processes at the nanometer scale, particularly in heterogeneous materials, interfaces, phase boundaries, edges, and atomic-scale defects.

Vision for the future

The ALS's next five years will be a period of significant change and enormous opportunity, culminating in a new era that we refer to as "ALS 2.0." Our vision is to be the premier synchrotron facility where team science and cutting-edge light source technologies converge to drive scientific discovery and address pressing global challenges. Bolstered by recently increased operating budgets, we have the opportunity to grow our workforce, forge new partnerships, foster staff development, and approach all we do with renewed innovation.

The ALS of the future will exploit the brightness and coherence offered by ALS-U through world-leading feature beamlines. These unique instruments will be complemented by world-class capacity beamlines, whose capabilities supplement the feature beamlines in high-demand areas, and commodity beamlines optimized for high-throughput and autonomous measurements that form the foundation for more-complex experiments.

While beamline performance is important, other factors are equally critical, such as optimized sample environments, a comprehensive set of probes, and the ability to rapidly extract insights from increasingly complex datasets. Fully leveraging the new source and suite of beamlines to answer the intricate scientific questions posed by the research community will require significant investments into the underlying beamline technologies, endstation instrumentation, and integrated data and computing technologies.

Together, these capabilities, combined with experienced experts and enhanced levels of staffing, will ensure the ALS's tradition of outstanding scientific productivity and excellent user support will continue and grow as we build new partnerships. Our core values of collaboration, dedication, diversity, innovation, integrity, and safety guide our strategy and practices and shape our working environment and culture for staff, users, and other visitors who are part of our community. To support our scientific and instrumentation aspirations, we must also re-evaluate and renew our operational processes and infrastructure, from user access modes and proposal review processes to business systems, safety, and utilization of space.

The upgrade of the ALS and our goal to renew our portfolio of capabilities and beamlines is set in the context of a larger and longer-term Berkeley Lab vision to create a multidisciplinary materials and chemistry campus located on the Charter Hill site (Fig. 1), which encompasses the ALS and buildings that house the Lab's solar fuels and energy-storage programs. New laboratory spaces in three envisioned buildings would be designed to transform capabilities from the Lab's best-in-class interdisciplinary facilities and centers for serial discovery into a suite of tightly integrated facilities equipped for parallel design, linking theory, synthesis, and characterization in unprecedented ways and enabling understanding and control of materials phenomena and chemical transformations across multiple length and time scales. New ALS capabilities are central to this vision, particularly in relation to the proposed Chemical Observatory concept, which would integrate multiple probes, including ALS x-rays, into laboratory spaces to enable multimodal in situ and operando studies. The focus would include complex chemical transformations, heterogeneous material synthesis, geochemistry under extreme conditions, and biochemical systems, driving a new era of discovery and control over material and chemical phenomena.

Fig. 1. Architectural rendering of the vision for the future Charter Hill site, including three new buildings (two beige buildings in the back and grass-roofed building in the center). These multiprogrammatic facilities would be adjacent to buildings hosting research programs in solar fuels, energy storage, and biosciences (white buildings in back), materials and chemistry core-program research (out of frame, to the right), and the ALS. ALS beamlines could be extended into the new buildings, bringing synchrotron x-rays and IR into functioning laboratory spaces, enabling the Chemical Observatory concept.

Strategic plan

The ALS's long-term planning and strategic priorities are driven by the scientific needs of the international research community and the context of national priorities, including DOE initiatives and priority research directions and opportunities. Our vision is informed by diverse input through a recent set of science visioning workshops open to the community, large-scale workshops focused on opportunities enabled by ALS-U, smaller-scale User Meeting and one-off workshops, cross-cutting ALS program reviews, and ALS staff retreats.

This strategic plan begins by outlining the long-term scientific opportunities for the ALS as identified by the research community. These aims fuel our mission and drive the goals and objectives that follow. Our first goal is to develop and deliver world-class capabilities by curating a portfolio of advanced instruments that will push scientific boundaries, leveraging the upgraded ALS source along with necessary accelerator, beamline, endstation, and computational technologies. Next, we focus on the transition to the post-upgrade era, detailing how we will optimize operations leading up to the dark time, ensure ongoing scientific activity and user engagement during the downtime, and return the facility to full operation. Our third goal centers on achieving operational excellence, addressing areas such as safety, security, user services, infrastructure, and supply chain management. Finally, we set forth our vision for fostering an innovative, collaborative environment. This includes strategies to attract and cultivate a vibrant, productive user community and workforce, strengthen partnerships, and promote inclusion, diversity, equity, and accountability.

Science opportunities for ALS 2.0

Over the past three decades, the ALS has evolved into one of the world's leading synchrotron light sources, enabling a diverse range of scientific discoveries across multiple disciplines. Initially focused on physics and materials sciences, the ALS has expanded its scientific portfolio to include significant contributions in chemistry, biology, earth and environmental science, and energy research.

The ALS's high-brightness x-ray, ultraviolet, and infrared light has been pivotal in advancing research in nanoscience, quantum materials, and soft matter. For instance, the ALS has been central to breakthroughs in understanding high-temperature superconductivity, developing next-generation battery materials and computer chips, and revealing the atomic-scale structures of biological molecules. Our ability to perform advanced imaging, spectroscopy, and scattering experiments has also driven innovations in catalysis, environmental monitoring, and drug discovery, leading to numerous awards, including Nobel Prizes.

We envision that the scientific discoveries in the ALS 2.0 era will be even more diverse and impactful. The ALS-U project will pave the way to new knowledge by enabling the study of nanometer-scale features and interactions and the real-time observation of evolving chemical processes and functioning materials. This information will lead to scientific advances in areas like microelectronics, efficient chemical synthesis, high-capacity energy storage, highly selective ion transport and water purification, and artificial photosynthesis. The increased brightness of ALS-U's beams will benefit techniques across the ALS's energy range, including enabling higher-throughput experiments that will be enhanced by automation and machine learning. Importantly, ALS-U's new capabilities, particularly the nearly fully coherent beam, hold the potential to inspire new areas of science we cannot yet envision today.

The science opportunities outlined below reflect the collective vision of ALS users and the broader scientific community. Most recently, the ALS held workshops[1] as part of the 2023 User Meeting, where participants identified key scientific challenges and long-term research opportunities that the ALS could evolve to address 10 years from today. Participants also focused on how the ALS could evolve its capabilities and partnerships to realize those opportunities. The workshops built on previous ones held in 2017[2] and 2014[3] that focused on scientific opportunities stemming from ALS-U, a series of workshops convened by Berkeley Lab's Energy Sciences Area in 2020 and 2021 to outline the science case for an envisioned materials and chemistry campus in the Charter Hill area of Berkeley Lab (which includes the ALS), and numerous other smaller-scale workshops and discussions. These opportunities and the new capabilities required to achieve them motivate the capabilities discussed in Goal 1 of this strategic plan, the partnerships we need to maintain and grow discussed in Goal 4, and access modes in Goal 3.

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[1] "Reports from the Science Visioning Workshops held September 13–15, 2023 at Berkeley Lab as part of the ALS User Meeting," (2024). https://als.lbl.gov/2023-visioning-workshops/

[2] "Solving Scientific Challenges with Coherent Soft X-Rays," (2017). https://als.lbl.gov/wp-content/uploads/2017/08/ALS-U-Early-Science-Workshop-Report-Full.pdf

[3] "Soft X-Ray Science Opportunities Using Diffraction-Limited Storage Rings," (2014). https://als.lbl.gov/wp-content/uploads/2016/09/sxr_workshop_report.pdf

Condensed matter and quantum materials

Condensed matter research holds immense potential for addressing pressing challenges in energy efficiency and sustainability. New quantum materials, for instance, can increase computing capabilities and efficiency by improving classical computing and creating new paradigms such as quantum and neuromorphic computing, and can also affect chemical reactivity and battery performance. Research at the ALS, in collaboration with Berkeley Lab core programs, US universities, quantum centers, and Energy Frontier Research Centers (EFRCs), has led to foundational discoveries in magnetism, high-temperature superconductivity, tunable bandgaps and plasmonics in graphene, lead-free perovskites for solar applications, and the first observations of topological insulator electronic structure and room-temperature skyrmions.

The ALS is uniquely suited for correlative electronic and chemical studies, offering near-diffraction-limited performance in the soft x-ray range. ALS-U beams will be optimized at wavelengths corresponding to length scales at which new quantum properties emerge, providing the smallest probes and highest coherent flux where today's limited spatial resolution has prevented deeper understanding. Nanoscale, and potentially nanosecond, time-resolved electron and x-ray probes will provide access to dynamic magnetic phases, electronic structures, and excitations that ultimately determine quantum material functionality. Due to the multitude of degrees of freedom in synthesis and experiments, artificial intelligence (AI) and machine learning (ML) techniques will be essential to direct searches for new electronic and magnetic phases, uncover hidden correlations with multimodal experiments, and steer experiments toward the most insightful results. EUV lithography, developed at the ALS by the Center for X-Ray Optics (CXRO) in partnership with the semiconductor industry, is the basis of current and future industrial-scale patterning techniques for microelectronics. The upgraded ALS's coherence-enabled tools will allow nanometer-scale imaging to study the fundamental photochemical processes taking place during the exposure step, helping guide the development of next-generation resists.

Opportunity 1: Reveal and understand coherent quantum and spin interactions in new topological states

Topological states form at the edges of certain insulators with unique bulk electronic structures and are protected by lattice symmetries. Their spin- and momentum-dependent conduction can remain robust and dissipation-free despite imperfections, offering potential for low-power electronics. However, the effects of many-body interactions and defects remain unclear, and further synthesis and characterization of new topological materials are crucial to advance understanding. These states can exist in zero, one, or two dimensions, requiring surface- and momentum-sensitive probes with atomic-level spatial resolution for study.

The dramatically enhanced soft x-ray coherent flux of ALS-U will enable the exploration of low-dimensional states and their interactions with the environment with unprecedented sensitivity to electron coherence. New angle-resolved photoemission spectroscopy (ARPES) instruments, offering ~10-nm resolution and supplied by a fully transversely coherent beam within the electron coherence length, could employ a ptychography-like approach to extend spatial sensitivity to atomic dimensions. This would provide insights into the wave functions of topological edge states, their resilience to many-body interactions, and their response to atomic-scale disorder.

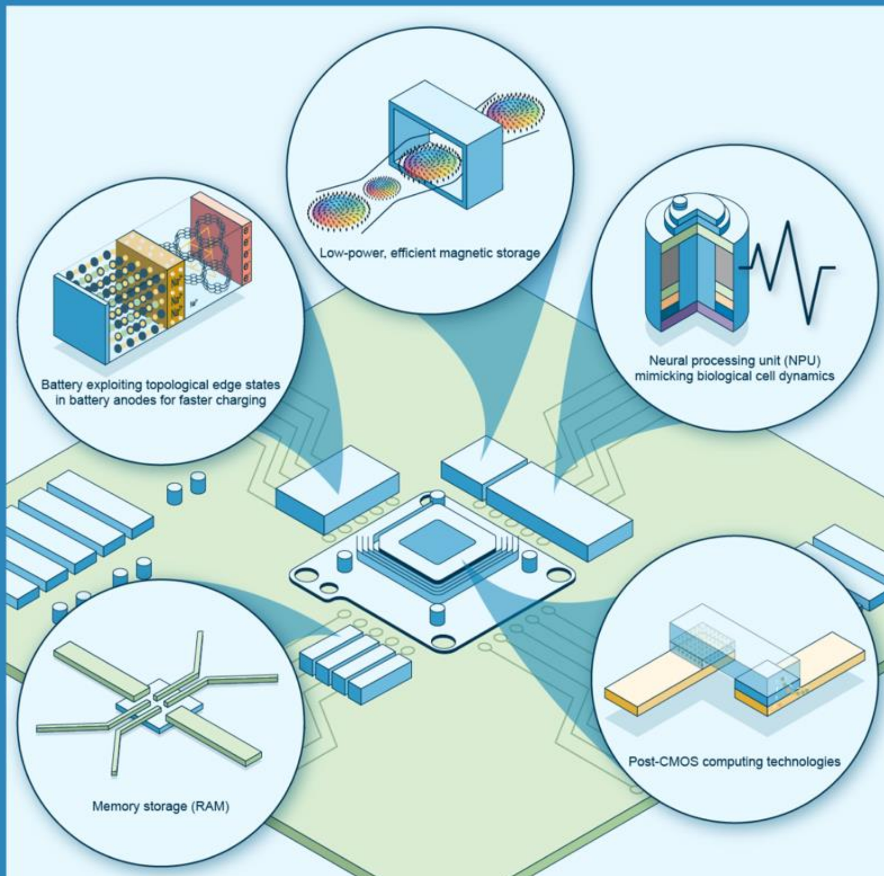

Fig. 2. Clockwise from top: Magnetic skyrmions are topological structures in real space that can revolutionize low-power, high-density RAM and storage, for example, in fast read/writing "racetrack" memory as illustrated. Metal–insulator transitions can be exploited to create highly energy-efficient and scalable neuromorphic computing devices with tunable synaptic strengths, for example in neural processing units (NPUs). Exploiting magnetoelectric (ME) and spin-orbit (SO) effects, so-called MESO devices have higher density than today's CMOS logic, and hence run faster at lower energy. Using spins to store data bits can be more efficient than using electrons, and new magnetic 2D van der Waals materials are expected to play a big role. Battery performance can be enhanced by using topological materials, whose protected states are beneficial to charging speed, and which can be tuned to reduce interfacial chemical degradation to improve safety.

Opportunity 2: Understand and control magnetic behavior in complex systems over a range of time and length scales

Magnetism, which is essential for power generation, data storage, microelectronics, and emerging fields like quantum information and spintronics, is shaped by electron correlation, spin-orbit coupling, and wave-function topology. Recently discovered electron-spin configurations, such as valley, orbital, and lattice pseudo-spins, generate novel magnetic states, while new phases like altermagnetism present challenges in identifying and exploiting their unique spin structures. Understanding spin and pseudo-spin textures across time and space is crucial for developing new storage and computation paradigms based on these magnetic and electronic properties.

The speed of new coherent scattering and spectromicroscopy tools at the upgraded ALS will be well suited to interrogate dynamic magnetic textures down to nanometer resolution, the scale of magnetic features like skyrmions. The high coherent flux will also enable the creation of OAM beams to directly interact with spin and orbital angular momentum in materials. Cryogenic environments, with temperatures down to 1 K and fields of several tesla, would further support these multimodal measurements. The deployment of new "spin-momentum microscopes" at ALS-U-powered beamlines would give both real-, spin-, and momentum-space information on the same sample under identical conditions. Furthermore, developing new time-stamping detectors would enable GHz-range time-resolved measurements, allowing the correlation of real-space and momentum-space spin textures, spin-wave energetics, and dynamics, and providing a unified view of these phenomena for the first time.

Opportunity 3: Uncover new insights into the dynamic heterogeneity of quantum and spin phenomena across multiple time, length, and energy scales

Understanding the emergence of exotic quantum phases is fundamental to our knowledge of the universe and for advancing spintronics, where manipulating spins without moving charges could lead to more-efficient computation. These phases, characterized by spatial and temporal fluctuations, include quantum spin liquids with fluid-like spin states, spin glasses and spin ices with frustrated localized spins, coexisting superconducting and magnetic states, and quantum magnetism in strongly correlated materials. Furthermore, quantum and classical phase transitions involve critical-point fluctuations in microscopic properties, which are key to understanding the system's energy landscape. These emergent phenomena arise from collective modes that remain poorly understood, requiring a correlative approach to investigate electron charge, spin, and orbital degrees of freedom.

ALS-U will offer superior coherent flux for correlative scattering measurements using x-ray photon correlation spectroscopy (XPCS), revealing the coherent motion of atoms, charges, spins, and quasiparticles on nanosecond, and perhaps picosecond, time scales and nanometer length scales. Since time and energy are conjugates, energy- and time-resolved spectroscopies will offer complementary insights into electronic phases and phase transitions in materials like cuprates. The development of picosecond to nanosecond time-stamping detectors for electrons would enable correlative photoelectron measurements, revealing entangled photoelectron pairs originating from different locations in real and momentum space. This will advance our understanding of spatial and spin coherence in strongly correlated materials with significant implications for quantum information science.

Opportunity 4: Unravel the role of structure and interfacial phenomena in creating emergent material properties

At the boundary between materials, interfaces give rise to emergent states completely unlike those of the adjoining materials due to changes in chemistry, symmetry, and topology. These interfacial properties can result in wave functions that dominate the transport properties of the system.

Interfaces can also serve as locations to introduce charge, spin, or optical excitations that propagate through the material, or as filters that allow only desired quantum information to pass through a device. Tunable heterostructure engineering leverages these interfacial phenomena by introducing multiple interfaces with tailored functionality.

The ALS is part of a broader ecosystem at Berkeley Lab that has advanced synthetic and predictive tools necessary to discover and optimize new functional quantum materials. However, a key gap is the ability to quickly produce and measure heterostructures at beamlines, which hinders the ability to rapidly optimize the synthesis or assembly of the material for desired properties. This could be addressed by better integrating Berkeley Lab's synthesis capabilities with ALS x-ray characterization tools. Additionally, incorporating AI/ML algorithms would help process complex, multimodal data and theoretical models, accelerating the discovery of new materials.

Energy sciences

Fundamental energy sciences research underpins advances across a broad range of renewable energy technologies, reducing the energy consumption and carbon footprint of manufacturing processes, facilitating environmental remediation, and more. The ALS offers a range of well-developed tools to elucidate chemical- and element-specific processes relevant to improving energy technologies, including x-ray spectroscopy, scattering/diffraction, and imaging, which are paired with in situ and operando capabilities that include environmental sample holders, electrochemical cell designs, and detectors that operate in the nanosecond regime. The ALS's culture of innovation has led to many technical breakthroughs that later became popular tools in energy sciences at synchrotron facilities worldwide, including inventions that led to the first commercial ambient-pressure photoelectron analyzer as well as ambient- and high-pressure x-ray absorption spectroscopy (XAS) and resonant inelastic x-ray scattering (RIXS). Many of these tools have been developed in collaboration with users, including through BES-funded core programs and broader center- and hub-level efforts. The

Fig. 3. Scientific questions for energy sciences span the entire life cycle of a product, from sourcing raw material to application and recycling.

This entire loop can be investigated with the upgraded ALS, using scattering to study the kinetics of mixing and material nucleation and growth at microsecond time scales (bottom left), microdiffraction to study the manufacturing of components undergoing processing and treatment conditions (top left), spectromicroscopy to see how ions are moving throughout cells during operation (top center), and microtomography of real devices to see inside various layers undergoing repeated cycling until failure (top right).

upgraded ALS will offer the opportunity to broaden ALS characterization capabilities along energy, momentum, spatial, and temporal dimensions, and further integrate computing, controls, theory, and AI/ML capabilities. This will allow for virtual experimentation and real-time analysis, enabling the ALS to scale its impact and create collaboration centers and ecosystems.

Opportunity 1: Develop a multiscale understanding of interfaces and interphases

The field of energy sciences focuses on the transfer of charge, mass, and energy, often driven by processes occurring at phase interfaces. These processes are key to the efficiency and stability of systems such as catalysts and electrochemical devices. In a battery, for example, electrons flow through an external circuit to generate power, while charged ions move through an electrolyte and critical interphases, eventually recombining with the electrons. These interfaces and interphases govern every aspect of battery performance, from kinetics to safety, spanning length scales from atoms to centimeters and time scales from sub-nanoseconds to years (the lifespan of a device).

The ALS's high brightness, tunable energy and polarization, and coherence, along with in situ and operando capabilities, can reveal a wide range of vibrational and spectroscopic chemical and electronic information, as well as structural data. The increased coherent flux provided by ALS-U, combined with new, more stable beamlines and instrumentation for faster detection and data processing, would significantly improve the ability to capture kinetics, deepening our understanding of transport, stability, and life-cycle factors. Additionally, ALS-U's dramatically smaller source size and improved coherence will allow access to nanoscale features, enabling new beamlines to provide a comprehensive physical and chemical understanding from interface to device scale.

Opportunity 2: Reveal the impact of rare and minority events on the function and performance of energy materials across various time and length scales

Defects are crucial in determining the performance of a system, and they can also lead to its eventual failure. While the link between defects and performance is well understood in silicon photovoltaic devices, our understanding of rare and minority events that affect performance and contribute to degradation in emerging energy materials, such as high-efficiency perovskite photovoltaics, remains limited. High-speed, nanoscale probes with chemical sensitivity are needed to fill this gap.

The dramatically higher coherent flux of the upgraded ALS will enable correlation spectroscopy and microscopy with greatly improved signal-to-noise ratio to reveal these rare and minority events. ALS-U's enhanced beam properties, combined with the ALS's existing characterization capabilities, will allow for improved probing of spatial dimensions, chemical sensitivities, and energy resolutions. By investing in integrated computation, theory, and instrument development, the ALS can routinely capture the data needed to understand rare and minority events, making today's heroic studies routine.

Opportunity 3: Achieve a holistic understanding of complex, real-world energy systems across their entire life cycle

Bridging the divide between fundamental science and real-world systems is essential for practical applications. Traditional systems that synchrotrons like the ALS are capable of studying today are relatively simple and static, whereas real-world counterparts involve complex interactions across mixed phases and materials in changing environments over sustained periods. This complexity is evident in polymers for electrochemical technologies, which require consideration of catalyst activity, ion and electron conductivity, mass transport, and hard–soft material interactions within 3D electrode structures. The challenge of gaining a holistic picture of these systems lies in their complexity and susceptibility to radiation damage, requiring innovations in detection sensitivity and efficiency.

The ALS's current capabilities and ongoing development of multimodal, operando characterization are critical for understanding these systems, revealing links between chemical and structural data, performance, and device lifespan, and for bringing models to application. Multimodal and operando measurements allow direct observation of transient, metastable, and intermediate states critical to understanding operation, performance, and lifetime and to improve models that inform theory and AI/ML methodologies for predicting, understanding, and improving these technologies. Additionally, modular, mobile endstations and experimental cells could allow systems to be intermittently measured and moved between beamlines, enabling long-term analysis and a deeper understanding of evolving heterogeneous interfaces during an electrochemical cell's lifetime.

Biosciences

The ALS is a unique facility for characterizing biological materials and their interactions, thanks to its high brightness, photon flux, and broad spectral range, alongside a wide array of experimental techniques, expert staff, and its role as a national hub for biotech and pharmaceutical companies. Current structural biology methods at the ALS offer information that spans the atomic scale (macromolecular crystallography, x-ray footprinting), through the nanometer scale (x-ray scattering, IR nanospectroscopy), to the micron scale (x-ray tomography, IR microspectroscopy, x-ray fluorescence). Historically, most of the ALS beamlines that measure biological materials have been funded and operated through external partners, including DOE's Biological and Environmental Research (BER) program, the National Institutes of Health (NIH), and the Howard Hughes Medical Institute (HHMI), and are led by scientists in Berkeley Lab's Biosciences Area. The protein crystallography beamlines, in particular, have had a tremendous impact on structural biology and the science output of the ALS, where they have collectively deposited over 8000 structures into the Protein Data Bank, shed light on diseases such as COVID-19, and contributed to Jennifer Doudna's 2020 Nobel Prize on CRISPR-Cas9. The renewal of the ALS offers opportunities in improved source characteristics, new infrastructure, and updated access models. It can leverage strategic partnerships with Berkeley Lab's Biosciences Area, the Molecular Foundry, the National Energy Research Scientific Computing Center (NERSC), and the DOE Joint Genome Institute (JGI) to achieve campaign-style approaches to discovering and harnessing biological processes in health, energy, and the environment. The following three objectives align with the strategic needs identified by the scientific community and ALS partners, including the Berkeley Lab Biosciences Area.[4]

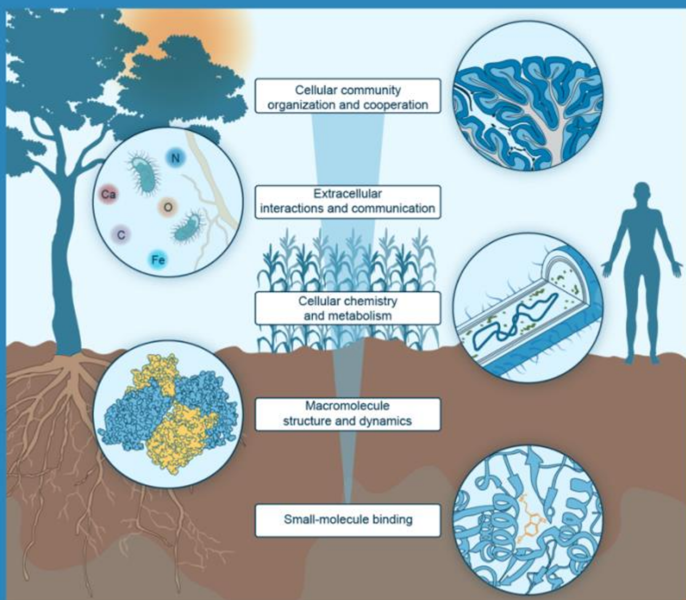

Fig. 4. Unraveling the subtle variations that influence the structure and function of biological materials across diverse spatial, temporal, chemical, and energy scales will provide groundbreaking advances in environmental sustainability, energy innovation, and medical care.

The multimodal scattering, footprinting diffraction, imaging, and spectroscopic techniques of ALS-U will enable studies ranging from the atomic level to the organism level, including drug and other small-molecule binding events (bottom right), the structure and dynamics of biological macromolecules (bottom left), subcellular chemical processes (middle right), microbial interactions within the rhizosphere or human gut (top left), and cooperation of cellular communities within tissues or biofilms (top right).

Opportunity 1: Identify and connect how small genomic and environmental differences dramatically influence hierarchical structure and function

Biological reactions are highly regulated and complex across multiple scales, unlike material-based reactions. Most notably, small changes at the genomic level and environmental factors can dramatically alter outcomes. For example, a single gene mutation at the near-atomic scale can cause 3D structural changes in a protein, inhibiting or modifying its function and leading to diseases like cystic fibrosis or sickle cell anemia. The goal is to understand how small changes in biological processes impact hierarchical assembly and function, from the genome and atomic scale to the cell, tissue, and organism levels. This knowledge could lead to advancements in human health, such as developing personalized drugs, or innovations in sustainable energy, like artificial photosynthetic materials.

Achieving this requires collecting data from structural, imaging, and spectroscopic methods under functional conditions across multiple spatial, chemical, and time scales. The current suite of ALS x-ray and IR beamlines, along with a new x-ray spectroscopy beamline dedicated to biological materials, would be well equipped to meet this challenge, particularly with the increased data acquisition rates possible with ALS-U and the necessary beamline optics upgrades. Additionally, investments in advanced data analysis will be essential to correlate and integrate data from different techniques, creating models that predict biological system behavior. This will require developing databases and

[4] "Biosciences 10-year scientific strategic plan," accessed September 14, 2024, https://biosciences.lbl.gov/strategy/.

metadata structures for diverse data types and using AI-driven models to efficiently predict large-scale hierarchical structural changes due to atomic- or nanometer-scale perturbations.

Opportunity 2: Observe the dynamics of biological macromolecules and how small molecules (metabolites, drugs, and ligands) bind to them

Traditionally, crystallography has focused on capturing steady-state configurations, yielding incredible insights into the structure of critical macromolecules. However, biological processes are dynamic and often occur under nonequilibrium conditions. ALS-U's small, bright beams will enable serial crystallography at physiological temperatures, allowing visualization of atomic motions and revealing how sequential reactions drive the formation or breaking of chemical bonds and how small molecules influence the local structure of macromolecules, altering their functionality or reaction kinetics.

Achieving this goal requires developing high-throughput sample delivery, in situ reaction triggering, and enhanced data analysis. X-ray footprinting combined with high-sensitivity mass spectrometry will leverage ALS-U's high brightness, offering greater sensitivity through increased x-ray absorption at lower energies and higher time resolution due to a more focused beam. While the x-ray footprinting beamline will benefit from the lower critical energies of the ALS-U bend magnets, the crystallography and small-angle x-ray scattering beamlines will need upgraded optics to preserve brightness and eliminate optical aberrations. Integrating ancillary methods, such as fluorescence microscopy, with ALS structural biology beamlines and x-ray spectroscopy would enable real-time monitoring of metal redox states in biological samples where metal cofactors are critical. These capabilities are critical for drug-discovery workflows that enable accurate computer-assisted prediction of small-molecule binding, which could accelerate development and reduce the time needed to cure diseases, restore function, or reduce death tolls in global pandemics.

Opportunity 3: Elucidate and harness cellular biochemical processes and responses to dynamic environmental conditions

Modeling a cell in three dimensions over time requires precise 3D structure measurements of macromolecules, complexes, organelles, and intra-organelle spaces, as well as spatially resolved spectroscopy to track dynamic chemical interactions such as nutrient flow, vesicle trafficking, energy transfer, and trace-element distribution within the cell. These interactions also extend beyond the cell, where cell membranes and associated proteins serve as gateways for communication between similar cells within an organism, among diverse cells within a biofilm community, or between microbes and plants. Understanding these interactions could lead to improvements in cancer treatment or more efficient methods for improving nutrient uptake in crops.

BER currently sponsors three structural biology and imaging resources[5] at the ALS, including the Berkeley Synchrotron Infrared Structural Biology (BSISB) Imaging Program,[6] the National Center for

[5] "BER Structural Biology and Imaging Resources," U.S. Department of Energy, Biological and Environmental Research Program, accessed August 31, 2024, https://www.berstructuralbioportal.org/.
[6] "Berkeley Synchrotron Infrared Structural Biology Imaging Program," accessed August 31, 2024, https://bsisb.lbl.gov/wordpress/.

X-Ray Tomography (NCXT),[7] and the Structurally Integrated Biology for the Life Sciences (SIBYLS) Beamline,[8] led by scientists in Berkeley Lab's Biosciences Area. The brighter and more stable beams of ALS-U will improve the signal-to-noise ratios of these existing techniques, enable near-diffraction-limited imaging of subcellular structures, and offer opportunities for the development of a dedicated x-ray biospectroscopy beamline for coordinated, multimodal in situ and in vivo analyses of cells in hydrated environments. Because biological samples are easily damaged and have associated biosafety controls, the development of biological laboratories integrated with ALS beamline endstations would offer the opportunity to address real-world systems, particularly those related to human health.

Earth, environmental, and planetary sciences

The ALS combines high x-ray brightness, coherence, and a broad spectral range with expertise in non-ambient-condition diffraction, microdiffraction, microtomography, and soft x-ray and IR spectromicroscopy. Its beamlines provide world-leading spatial resolution and specialized in situ capabilities, enabling direct probing of the chemistry and structure of minerals and molecular species to better understand complex geologically relevant processes under Earth-relevant conditions.

The ALS serves a broad community of researchers funded by the National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), DOE, and the United States Geological Survey (USGS), and is expected to continue doing so. Long-term partnerships—most notably the DOE-funded Geosciences core program and Berkeley Synchrotron Infrared Structural Biology imaging program, and the NSF-funded Synchrotron Earth and Environmental Science program—actively contribute to operations and development in this field. ALS tools have been instrumental in physically and chemically characterizing unique and invaluable samples from meteorites, comets, and asteroids, deciphering the deformation and rupture of rocks in the Earth's crust and mantle, as well as revealing the chemical transformations of aerosol particles that affect the climate, environment, and human health—among other areas. Looking ahead, the ALS user and broader scientific communities have identified four science objectives that will benefit from the enhanced speed, sensitivity, and spatial resolution provided by the ALS upgrade, motivating new capabilities like the planned Tender Imaging Beamline.

Opportunity 1: Develop a predictive understanding of the dynamic equilibria controlling the global carbon cycle

To improve predictive models that can effectively inform strategies for managing carbon levels in the atmosphere, we must advance our understanding of how carbon is stored within and exchanged between various Earth reservoirs—specifically rocks, soils, oceans, and the atmosphere. Moreover, these interactions need to be studied in response to environmental changes. By characterizing the chemical and physical properties of carbon-hosting entities from the solid, liquid, and gaseous phases of Earth, researchers can improve knowledge of how carbon is stored and released into the atmosphere, informing strategies for developing new and enhancing existing inert carbon sinks.

[7] "The National Center for X-Ray Tomography," accessed August 31, 2024, https://ncxt.org/.
[8] "The SIBYLS Beamline," accessed August 31, 2024, https://bl1231.als.lbl.gov/.

Advanced scattering, diffraction, high-resolution spectromicroscopy, 3D imaging, and time-resolved x-ray and IR spectroscopies are required to study the dynamic equilibrium between the lithosphere, hydrosphere, and atmosphere. Precise analysis of mineral–water interactions and atmospheric gas compositions is critical to understand how Earth's systems exchange carbon and other elements. To enable high-throughput in situ and 3D characterizations of carbon-mineralization-related physics and chemistry, the ALS must develop microscopy, scattering, and diffraction beamlines that can exploit the high x-ray flux provided by ALS-U. These beamlines should also be capable of chemically analyzing the unique fine structure of carbon as well as key mineral-forming elements like Al, Ca, and Si. Co-registration of multiple probes (diffraction, microscopy, lab-based optical characterization) will be needed. Upgraded beamline and microscope optics, high-performance detectors, and automated high-speed sample handling would enable the next generation of carbon-cycle science by improving resolution, sensitivity, and throughput.

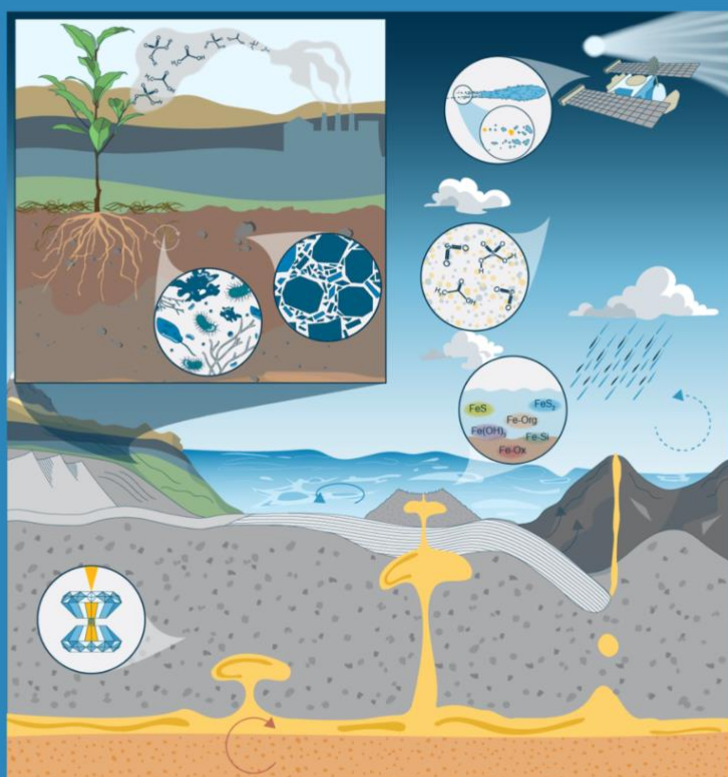

Fig. 5 Complementary and multimodal scattering, diffraction, imaging, and spectroscopic techniques are critical tools for deciphering complex, planetary-scale phenomena.

These include structure and dynamics of the deep Earth (bottom); carbon cycling and nutrient exchange in soils, oceans, and the atmosphere (center and inset); chemical reactions of atmospheric aerosols (center right); and the characterization of material returned from space missions (upper right).

Opportunity 2: Understand and mitigate the effect of climate change on ecosystems

The biotic–abiotic interfaces in soils and oceans play a crucial role in the causal chain of climate change, yet the complexity of these interfaces poses multidimensional challenges for characterization. The ALS's complementary capabilities with high spectral and spatial resolution are well suited to address biotic–abiotic interfaces at the nanometer and micron length scales and the effects of these interfaces at the ecosystem level. The conversion of waste or brackish water to usable water and the design of strategies for more heat- and drought-resilient crops are critical for mitigating the effects of climate change.

Multimodal characterization tools at the ALS, like 2D and 3D spectromicroscopy with IR and x-ray photons, as well as x-ray micro- and nanotomography, will aid the development of novel water filtration materials and the understanding of nutrient management processes in crop plants. A critical enabling development is the Tender Imaging beamline, which will provide in situ ptychographic and fluorescence-based imaging and tomography.

Opportunity 3: Uncover the origin and history of the solar system

Studying the solar system offers insights into how Earth responds to extraterrestrial and anthropogenic effects. This includes analyzing the geological and mineral composition of comets, planetary debris, and terrestrial planets, as well as their atmospheres, by analyzing materials from Earth's interior and samples returned from missions like Stardust, OSIRIS-REx, and the proposed Mars Sample Return mission.

Characterizing these extremely rare materials requires nondestructive, in situ diffraction, imaging, and x-ray and IR spectroscopy on the same region of interest. ALS-U's new capabilities, such as fluorescence/ptychographic microscopy at the Tender Imaging beamline and higher-intensity focal spots at diffraction and scattering beamlines, will significantly enhance the study of minor phases. Multimodal characterization of these unique samples will also demand advanced sample preparation and fiducialization techniques.

Opportunity 4: Unravel the connection between environment and human health

Air pollution and water contamination are environmental factors that pose risks to human health. Understanding how toxic substances are stored and transported in the environment is essential for designing and implementing cleanup strategies that protect people from harmful exposure. Using techniques like x-ray absorption spectroscopy and x-ray spectromicroscopy, researchers can analyze the chemical composition of aerosols and trace gases, study their interactions, and evaluate their effects on climate and air quality. X-ray scattering and high-spatial-resolution x-ray fluorescence spectroscopy can reveal the speciation and pathways of toxic components in soils and water colloids. Planned optical upgrades will boost the flux on samples in infrared and x-ray spectromicroscopy, increasing throughput. These higher-flux instruments will enable the study of microbial interactions during biofilm formation and monitor bioremediation reaction products.

Goal 1: Develop and deliver world-class capabilities

The renewal of the ALS accelerator complex through the ALS-U project offers an enormous opportunity to enable transformative new science, as outlined in the previous chapter. Since the majority of ALS beamlines and endstations were constructed to take advantage of the existing accelerator ring, we are compelled to thoroughly assess the portfolio of capabilities required for future science needs. ***To fully leverage the improved source brightness of the upgraded ALS, we will invest in beamlines specialized for enhanced spectromicroscopy, time-resolved, and high-throughput techniques as well as advanced optics, detectors, sample environments, sample delivery systems, multimodal setups, and computational tools, all integrated into future scientific workflows.*** Moreover, the revolutionary characteristics of the source itself have the potential to inspire new experimental techniques and, in turn, open the door to new scientific discoveries.

Toward these long-term goals, the ALS will focus the next five years on instrumentation that exploits coherence and brightness, renewing the dynamic balance between established and cutting-edge technologies in the beamline portfolio, upgrading science capabilities and computing infrastructure, and advancing future accelerator technologies.

Objective 1.1: Exploit coherence, brightness, and advanced new technologies

The diffraction-limited capabilities of the upgraded ALS open new opportunities for scientific exploration and discovery in condensed matter, energy, environmental, and biological systems. The ALS will focus on three key areas of instrumentation to push forward the frontiers of science. Our efforts will exploit the high beam coherence at 1 keV, a two orders of magnitude gain in brightness, and new advances in synchrotron instrumentation:

1. **Exploit coherence for spectromicroscopy:** High-spatial-resolution imaging and spectroscopy techniques will resolve nanoscale electronic and chemical heterogeneity, enabling a deep understanding of how structure promotes functionality and guiding the design of materials and chemical systems.

2. **Leverage brightness for time-resolved capabilities:** High-speed, time-resolved techniques will reveal fluctuations, transformations, and flows of energy, angular momentum, and matter in quantum and energy systems, elucidating the origins of electronic phases, spin textures, and chemical transformations.

3. **Employ new technologies for high-throughput autonomous beamlines:** High-sensitivity, high-throughput spectroscopy, scattering, and diffraction techniques will make full use of adaptive sample environments, multimodal probes, and AI/ML, providing information about the fundamental properties of natural and artificial systems.

The following sections outline our strategy for advancing these three areas to enable the science opportunities detailed in the previous chapter and realize the ALS 2.0 vision.

Exploit coherence for spectromicroscopy

The upgraded ALS will allow researchers to probe the electronic and magnetic states of matter with unprecedented fidelity and nanometer resolution, transforming our understanding of novel states of matter. Nearly-diffraction-limited soft x-rays from the upgraded ALS will speed up today's ptychography experiments by a factor of 100. Leveraging computation and ALS-U's transverse coherence, we will enhance images down to the diffraction limit. This will reduce the time needed to acquire 3D chemical and magnetic maps from hours to a few minutes. The coherence of the beam can also be used for high-speed diffraction imaging techniques, allowing researchers to create millisecond or faster electronic, magnetic, and chemical maps.

Two imaging beamline upgrades included in the ALS-U project, MAESTRO-U and COSMIC-U, will make full use of the new source properties. MAESTRO-U is an upgrade to our nanoscale ARPES (nanoARPES) beamline. The renewed instrument will allow researchers to study electronic structures to elucidate the action of quantum effects in confined or patterned systems. MAESTRO-U will be capable of multimodal, comprehensive studies of how emergent properties arise under the combined influences of strain, electric and magnetic fields, currents, and structural and chemical transformations for actual devices with operando controls. COSMIC-U is an upgrade to our coherent imaging beamline, enabling the instrument to interrogate nanoscale chemical, magnetic, or structural phases and their responses to external drivers by employing ptychography. COSMIC-U will resolve 3D vector magnetic fields and chemical states near surfaces and interfaces of electrochemical systems. A proposed Major Item of Equipment (MIE) project, Coherence-Enabled Synchrotron Instrumentation (CESI), includes a new soft x-ray beamline branch for randomized-probe imaging, a technique using highly coherent light to take very fast, single-shot images of dynamic systems, and a tender x-ray beamline nanoprobe branch, which will use the hundred-fold enhanced coherent flux in the tender x-ray energy range to extend coherent microscopy to larger systems that require more-penetrating light and to chemical constituents that are ideally probed in that energy range.

As part of our strategy, we will actively pursue emerging opportunities to further extend nanoARPES toward diffraction-limited, phase-sensitive imaging of coherent electronic states at one-dimensional and two-dimensional interfaces in quantum-confined and low-dimensional structures, for instance near edges or defects. We will use new imaging and spectroscopic modalities such as OAM beams to access and control chiral and magnetic states, and explore orbital momentum transfer to develop new types of spectroscopies. In addition, there is a growing need to study chemical transformations on the nanoscale, prompted for example by heterogeneous catalysis, which requires existing chemically sensitive spectroscopic techniques such as RIXS and x-ray photoelectron spectroscopy (XPS) complemented by their imaging analogs. We also anticipate adding coherence-enabled capabilities for biological imaging and the study of lithographic patterns, devices, and nanoscale materials relevant for microelectronics.

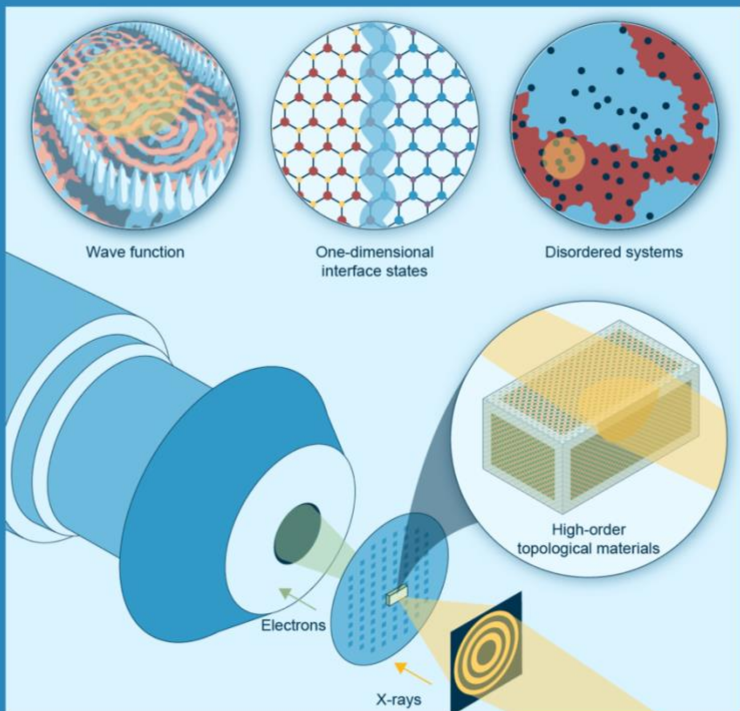

Fig. 6. The high flux of ALS-U's coherent soft x-rays (bottom right) will enable a new ultra-resolution angle-resolved photoemission spectroscopy (ultraARPES) that will allow phase-sensitive imaging of electronic wave functions with sensitivity down to atomic-scale features (top left), analogous to existing scanning tunneling microscopy techniques (upper left).

These wave functions are of fundamental interest in one-dimensional interfaces (top center), disordered systems (top right), and high-order topological states at material edges (middle right). Especially important will be the ability to do this with simultaneous spin and chemical resolution, making ultraARPES a uniquely impactful tool.

Leverage brightness for time-resolved capabilities

The at least two orders of magnitude higher coherent flux delivered by the ALS upgrade will revolutionize the ability to study chemical kinetics and electronic and magnetic fluctuations using XPCS by increasing the speed of the technique by factors of up to 10,000, approaching time resolutions within and perhaps below the nanosecond range. The high coherent flux, subnanosecond x-ray pulse lengths, and very high repetition rate of x-ray pulses from the ALS accelerator are particularly suited for the study of molecular dynamics, chemical kinetics, phase transitions (electronic, structural, and chemical), ionic flows, and magnetization dynamics.

The proposed CESI project includes two new beamline branches for coherent resonant scattering and XPCS in the soft and tender x-ray ranges, respectively. They are designed to investigate chemical kinetics, electronic fluctuations, ionic transports, and transformations of chemical, electronic, and spin textures in biological and soft-matter systems and in quantum materials. In addition, we envision developing beamlines specialized to relate chemical dynamics to physical changes by combining chemical probes such as ambient-pressure x-ray photoelectron spectroscopy (APXPS) and RIXS with structural probes such as coherent small-angle x-ray scattering (SAXS) and grazing-incidence small-angle x-ray scattering (GISAXS). Chemical XPCS in particular is a capability ripe for development that requires a high-brightness source, sophisticated sample delivery systems to replenish samples before they are damaged, and fast detectors that are isolated from the reaction area. The proposed Interfacial Chemical and Materials Sciences Beamline will support research on chemical processes at surfaces and in liquids and provide the nanoscale temporal and spatial information needed to understand fundamental chemical processes governing electrochemistry, the production of solar fuels, CO_2 capture, corrosion, and more. New beamlines will follow that will incorporate multimodal setups and integration with synthesis capabilities, ideally in facilities that are part of Berkeley Lab's envisioned redevelopment of the Charter Hill campus.

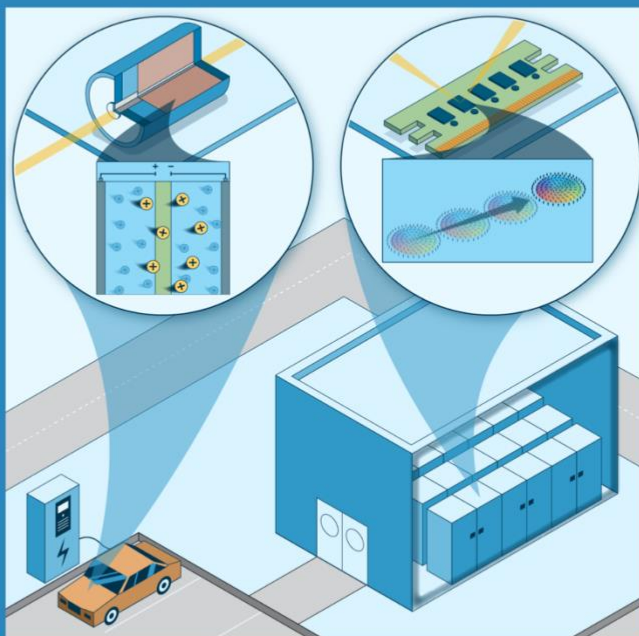

Fig. 7. The high coherent flux and pulse repetition rate made possible by ALS-U will enable new capabilities, including coherence-based x-ray photon correlation spectroscopy (XPCS), which can reveal crucial time-dependent properties in energy, environmental, electronic, and biological systems. For example, new coherent scattering methods could uncover the flow of ionic species through a battery electrolyte or membrane (left inset), which may be used in the electric vehicles of the future, or magnetic fluctuations (right inset) in materials relevant for future data-storage technologies.

Employ new technologies for high-throughput autonomous beamlines

Scientific innovation at the ALS is propelled by the user community's need to study and understand systems of increasing complexity in real-world or extreme environments. The continuous refinement of x-ray methods and the integration with innovative sample environments and detection schemes lead to a vastly increased capacity to study complex spatial and temporal processes and relationships in samples. New AI- and ML-driven workflows promise to greatly accelerate the materials discovery process and create new avenues for users to study and understand complex electronic, chemical, and structural relationships. Full integration of AI tools into beamline controls will revolutionize the user experience, resulting in experimental systems that self-optimize, autonomously search for regions of interest, and assist users to plan and execute complex experiments.

The ALS plans to upgrade high-throughput capabilities at a significant number of beamlines in the long term by adding robotic sample loading, AI-powered automated beamline and sample tuning, and ML-supported data analysis workflows, and by upgrading the beamline optics and detector systems. The recent refurbishment of the MERLIN beamline and the new AMBER and QERLIN beamlines, currently in commissioning, are designed to improve both capability and capacity for ARPES and RIXS spectroscopy. The addition of momentum microscopy to MERLIN will provide a higher-throughput imaging ARPES capability that complements nanoARPES and conventional ARPES. Future planned beamline upgrades include the development of a highly efficient and flexible beamline for small- and wide-angle x-ray scattering (SAXS/WAXS) at the new ALS-U high-field bend 4.3.1 port and transitioning the existing highly impactful program from its warm-bend location at 7.3.3.

In addition, we envision deploying new multiplexing spectrographs for high-throughput experiments by replacing some of the existing bending magnet spectroscopy beamlines. This will result in increases of several orders of magnitude in data and information output and will allow researchers to acquire spatial, temporal, and spectroscopic information in parallel, leveraging new AI/ML-powered analysis workflows to synthesize information. New multimodal capabilities will be deployed at an increasing number of beamlines, combining structural and chemical or chemical and electronic probes. We will also consider the combined deployment of soft x-ray scattering techniques and IR spectroscopy in combination with ARPES, photon-in/photon-out spectroscopy, and APXPS.

Fig. 8. Scientists (back) can use AI-assisted autonomous experiments to quickly discover and understand complex new materials by combining ALS multimodal in situ x-ray experiments (front) with robotic sample synthesis and handling (right) and advanced controls combined with high-performance computing (left).

Objective 1.2: Sustain and advance a balanced portfolio of beamlines

The long-term success of the ALS requires continual investments in new state-of-the-art facilities that enable the measurement of previously inaccessible physical and chemical properties as well as in established techniques that provide high-throughput, foundational characterization tools. We strive to maintain balance in our portfolio as techniques mature and become more widely available and user friendly. For example, solving a crystal structure using macromolecular crystallography once required heroic experiments spanning years of effort but now is highly automated and has become essential for structural biology and drug development. A similar trend is seen with other techniques: as they evolve, the emphasis moves from pushing the limits of brightness to discover unknown material properties to harnessing that brightness for high-speed, standardized experiments in specialized environments to understand material characteristics. These experiments are often multimodal, highly automated, and supported by optimized data pipelines. Our long-term goal is to maintain a balanced, curated portfolio of three classes of beamlines: capability, capacity, and commodity.

Capability beamlines will fully harness the x-ray coherence and ultimate brightness of the ALS-U source to characterize the structure and dynamics of correlated electronic phases and complex chemical systems, pushing the envelope of speed and resolution. Examples of capability beamlines include the MAESTRO (nanoARPES) and COSMIC Imaging (ptychography) beamlines, both of which will be upgraded as part of the ALS-U project, as well as the proposed new FLEXON beamline, which will host the present COSMIC Scattering endstation for world-leading XPCS measurements, and RIXS capabilities at the new QERLIN beamline.

Capacity beamlines will provide sophisticated, highly productive, well-developed techniques, often in multimodal arrangements and customizable, specialized environments to study transformations and interactions in energy, environmental, and biological systems. These beamlines will rely on relatively mature synchrotron techniques but will push the envelope of endstation sophistication and data analysis, which are major foci of upcoming R&D and investments. Examples of capacity beamlines include those featuring ambient- and extreme-condition XPS, x-ray diffraction (XRD), resonant soft x-ray scattering (RSoXS), scanning transmission x-ray microscopy (STXM), x-ray magnetic circular dichroism (XMCD), GISAXS, IR, and RIXS.

Commodity beamlines will offer high-throughput physical and chemical characterization capabilities for artificial and natural samples, providing well-understood, high-utility tools that many ALS users need to measure basic system properties. To achieve this goal, these beamlines must provide standardized, easy-to-use, highly automated methods for sample loading, experiment tuning, and data processing. Examples of techniques featured at commodity beamlines include macromolecular crystallography, materials and biological SAXS/WAXS, microtomography, XRD, and XAS for materials, chemical, and biological samples.

Objective 1.3: Renew the beamline portfolio

In collaboration with our PRT partners, the ALS goal is to upgrade or replace our 44 beamlines at a rate of one to two per year. These instruments will optimize beamline performance to fully utilize the accelerator’s capabilities, leverage innovations in beamline and endstation instrumentation, and benefit from increased automation of tuning, controls, and data analysis through AI/ML.

Beamline projects will be organized into "waves," typically including one capability beamline that pushes technical boundaries and at least one capacity beamline offering widely applicable, high-throughput measurement tools (Fig. 9). This balanced approach of linking capability and capacity will maximize the productivity and utilization of the source, providing the community both highly specialized tools for pioneering science and refined standardized setups to enhance our understanding of complex systems.

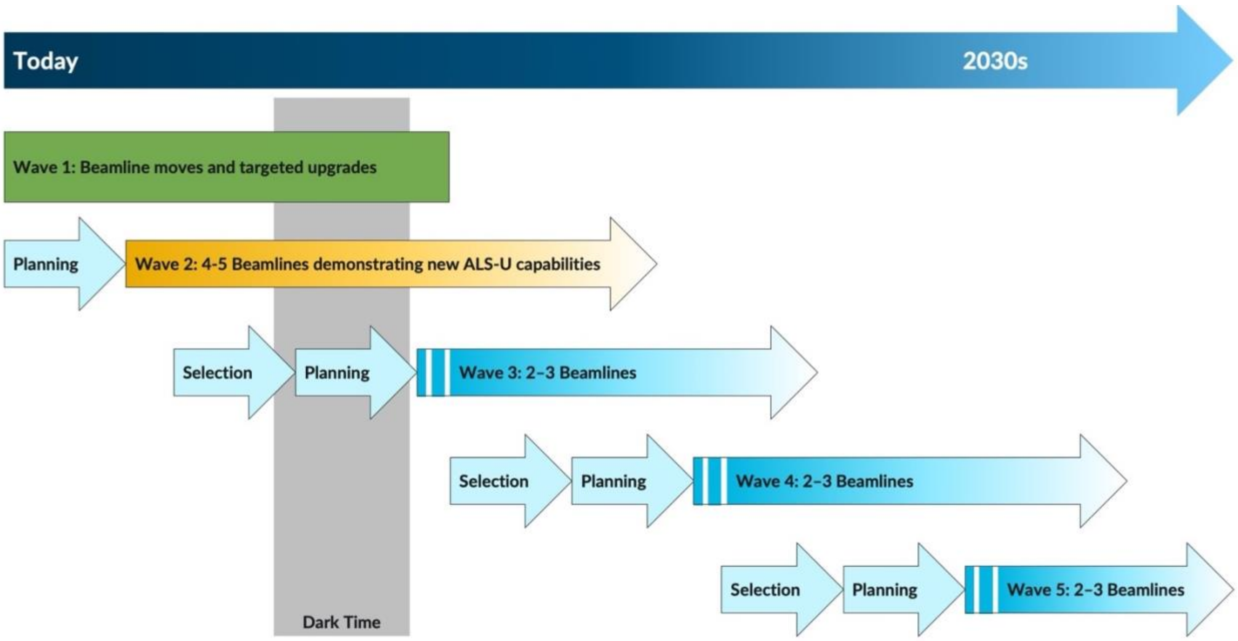

Fig. 9. Several waves of beamline projects will prepare ALS beamlines for the upgrade, demonstrate new ALS-U capabilities, and deploy capability, capacity, and commodity instruments to serve the ALS user community.

As the ALS develops and deploys new facilities, we will sunset beamlines that have lower demand or are sufficiently supported at other facilities or by laboratory sources. Since the ALS is space limited and currently hosts a full complement of beamlines, existing beamlines must be decommissioned to create headroom for new instruments and to stay responsive to emerging scientific opportunities and research needs. In making these decisions, the ALS will weigh each beamline's productivity, current and expected scientific impact, and alignment with the broader community's needs. We will also consider the ALS's ability to maintain a technically and operationally world-class or world-leading program and the possible alternative uses of space, resources, and source points. Input from stakeholders and advisory committees will be considered, and the planning process will be guided by the ALS's mission and vision.

Objective 1.4: Upgrade science capabilities

Our goal is to develop a technology ecosystem that delivers extraordinary beam properties during routine operations. The ALS will invest in hardware, optics, endstations, and detectors, while tightly integrating advanced computing and controls to handle data in transformative, cross-cutting ways.

The proliferation of these new tools and approaches will transform the coming generation of beamlines. We will focus on transformative instrumentation R&D in the following areas:

1. **Coherence-preserving optics:** Deliver high-brightness beam from the source to the sample.
2. **Wavefront diagnostic and autonomous instrument control:** Enable finer control over the beam properties to modulate intensities, modify wavefronts and polarizations, shape beam profiles, and synchronize high-speed measurements with rapid scanning.
3. **Multimodal instrumentation:** Correlate physical and chemical properties across scales by integrating multicolor beams and multiple probes into measurement workflows.
4. **Detectors:** Integrate spectrographs and fast detectors into a unified workflow to study material and chemical dynamics at nanometer and nanosecond scales.
5. **Sample delivery and environments:** Adopt specialized sample fabrication and preparation facilities and rapid sample delivery techniques to gain statistical information or cover a large range of sample conditions or compositions.
6. **Testing facilities:** Provide platforms to test developments and prepare them for deployment to push frontiers in instrumentation.

Coherence-preserving optics

Fourth-generation synchrotrons enable new science by harnessing the coherent power and x-ray wavefront properties from source to sample. This drives the need for improved spectral, temporal, and spatial resolutions to probe matter at ever-finer scales, which hinges on advances in x-ray optics. Achieving these goals requires high-efficiency, high-quality monochromator gratings and diffractive optics for tender x-ray energies, holographic and adaptive wavefront control to shape coherent-beam properties, improved metrology for ever-tightening mirror specifications, and high-efficiency aberration-free, two-dimensional free-form mirror shapes. New beamline designs require the support of advanced modeling and digital twins to predict, control, and optimize high-coherent-flux x-ray beams as well as engineered solutions to manage high-power loads on optical elements.

With advances in optics and mechanical systems, new ALS beamlines will deliver dynamic control, variable polarization and angular momentum, wavefront shaping, and higher efficiency, going far beyond the capabilities of any current soft x-ray beamline. Stabilizing beams in a noisy environment will allow us to increase spectral resolutions tenfold with high throughput. Dynamic control can also facilitate x-ray Fourier ptychography for full-field transmission or reflection imaging, providing access to complex amplitudes beyond simple intensities. X-ray polarization has long been used in magnetism and dichroism studies, while x-ray OAM is attracting attention for its unique sensitivity to magnetism and correlated-electron systems. Wavefront shaping creates structured light in sample-imaging modes to increase their sensitivity and resolution. We will continue to innovate for increased efficiency and control—preserving more of the available power allows experiments to run faster, with higher signal-to-noise ratios.

Additional critical development targets include three capabilities accessed through partnerships with CXRO, in Berkeley Lab's Materials Sciences Division, and the Molecular Foundry: thin-film and multilayer coatings, zone-plate and diffractive-optic development and fabrication, and at-wavelength reflectometry. These technologies expand R&D boundaries and enable the creation of unique components for ALS experimental systems. We aim to strengthen these collaborations to ensure a long-term plan for sustained success.

Wavefront diagnostic and autonomous instrument control

New ALS beamlines will achieve light control at a precision beyond nanometers, guided by multiple feedback mechanisms. Picometer-scale sensitivity provided by a new class of wavefront sensors will give direct feedback to adaptive x-ray optics. Real-time beam-position monitors (BPMs) will drive fast-acting beam stabilization systems built into mirror systems. Additionally, DiagOn-type white-light BPMs will track and correct long-term alignment drift. These photon diagnostics, working across different time scales, will enable us to achieve and maintain optimal beamline performance.

A diffraction-limited ALS will present unprecedented opportunities to control x-ray beam properties to match the demands of new experimental techniques. Beamline optical systems will need to modulate intensities, shape wavefronts and beam profiles, tune polarization, and synchronize high-speed measurements with rapid scanning. Digital twins, powered by machine learning, are gaining essential predictive capabilities for real-time beamline alignment and performance optimization. Due to the complexity and risks involved, beamline scientists often avoid re-aligning mirrors for months or even years, even as throughput declines. To maintain optimal performance, we will implement computer-controlled, ML-driven, continuous fine alignment. Beyond alignment, digital twins can integrate theoretical models and learn from experiments to maintain optimized conditions.

Multimodal instrumentation

Spectrographs, fast detectors, and ancillary probes need to operate within a unified workflow to deliver multifaceted, multimodal insights. Combining multiple tools and techniques within a single experimental chamber, or across facilities and disciplines, will reveal scientific phenomena that isolated measurements cannot. Multimodal approaches may be the only way to uncover some phenomena. Examples we will pursue include delivering multicolor beams, such as x-rays combined with infrared light for chemical studies, extreme ultraviolet and x-rays for chemical patterning, and soft and tender x-rays for chemical and structural analysis. Simultaneously delivering these probes into operational sample-preparation systems could dramatically accelerate materials discovery. The Chemical Observatory concept, part of Berkeley Lab's future vision for the Charter Hill site, would enable this new measurement modality.

Furthermore, multimodal approaches will integrate multiple techniques within a single endstation—such as combining x-ray methods with electrical transport measurements or atomic force microscopy (AFM). These approaches could survey samples quickly at low resolution before transfer to higher-resolution or higher-information instruments. Increased automation and AI-driven, autonomous experiments can boost throughput and efficiency by processing data into information in real time. Unique and varied sample environments will further enhance our understanding of interconnected physical mechanisms that drive observed and probed phenomena.

Detectors

Speed will be an essential tool. Our new ultrafast detectors capture subtle, dynamic, and correlated phenomena that would have been averaged out in older experiments. The advances in data rates, complexity, automation, and rising user expectations place new demands on beamline controls. We are developing controls to facilitate automation, rapid data visualization, and secure access to experiments and data. Our focus on advanced computing will enable autonomous data collection and handling, rapid analysis, and multimodal data synthesis across experiments, techniques, and time. Improvements in novel and emerging detectors will extend our imaging and spectrometry capabilities, especially in the soft and tender x-ray ranges where the ALS is brightest. To achieve this vision, we have initiated a radical upgrade to our computational and controls framework and will continue working closely with DOE peer facilities to achieve these goals.

Beamlines and endstations are routinely designed around the properties of available detectors. We seek to open new frontiers with our research on the VeryFastCCD (VFCCD) platform while exploring other form factors and available detectors. Our research focuses on several key areas: parallel detection of sample emissions (photons, ions, and electrons) across position, angle, energy, and time for soft and tender x-rays, with single-particle detection capabilities; using spectrographs instead of serial detection and scanning; high-speed detection down to the repetition rate of the x-ray pulse; correlated detection of multiple events to study correlated electron and chemical effects; and high-speed data pipelines for real-time feedback.

Sample delivery and environments

To gain statistical information and cover a wide range of sample conditions or compositions, specialized facilities for sample fabrication and preparation and rapid delivery techniques are essential. Unique sample environments and high-throughput detectors will allow researchers to probe dependencies on a host of physical and time-sensitive parameters. Integrating sample growth and materials synthesis facilities at or near beamlines will streamline previously separate materials discovery workflows. Standardized, modular environments and vacuum suitcases will allow transport between sample growth stations and various experimental tools. As scientific goals require, we are prepared to develop capabilities for serial delivery (e.g. jets, droplets, tape, molecular beams), sample highways and transfer systems, and dedicated lab space for safe sample preparation, synthesis, and growth.

Testing and R&D facilities

Our R&D facilities must also adapt to evolving needs. Progress in many areas requires access to beam properties comparable to those found at advanced user beamlines. We are developing beamline testing facilities to host multi-Lab collaborations focused on instrumentation and technique development. Such facilities, available at multiple light sources, will host research on prototype optical elements like adaptive x-ray optics and nanodiffractive lenses, testing of new endstations and capabilities before deployment, vendor R&D that cannot be done elsewhere, and quality assurance for specialized instrumentation and optics. By supporting these facilities and opening them to collaboration with leading instrumentation and optics groups, the ALS will become a hub for innovation in our field. We will coordinate closely with peers at the Advanced Photon Source (APS), National Synchrotron Light Source II (NSLS-II), Stanford Synchrotron Radiation Lightsource (SSRL), and Linc Coherent Light Source II (LCLS-II) to propose, promote, and develop facilities of this type for shared use.

Objective 1.5: Deliver a transformative computational framework for the ALS and BES light sources

To realize the full benefits of the ALS upgrade, integrating beamlines with advanced computing infrastructure and modern analysis tools will be essential to provide fast, real-time analysis of vast amounts of data. AI/ML-driven enhancements are set to transform experimental workflows by connecting materials synthesis with probes of electronic, chemical, and extrinsic sample properties, forming unified analytical pipelines. Rapid analysis of multidimensional, heterogeneous datasets will unveil hidden patterns, rare events, and elusive correlations, improving beamline efficiency and the user experience through faster, more intuitive data-processing solutions. By embedding computing resources directly into experimental systems, a continuous loop will form between data collection, processing, and analysis, allowing real-time optimization and supporting autonomous data collection and the directed synthesis of new materials. Intuitive visual interfaces will provide a clear view of experimental progress, data flow, and analysis to users, reducing the need for technical expertise and streamlining the transition from raw data to meaningful scientific insights.

Realizing this vision requires a cohesive framework that integrates advanced control systems, efficient data handling, and AI-driven workflows, enabling seamless coordination between beamlines and computational resources to unlock deeper scientific insights and accelerate groundbreaking discoveries.

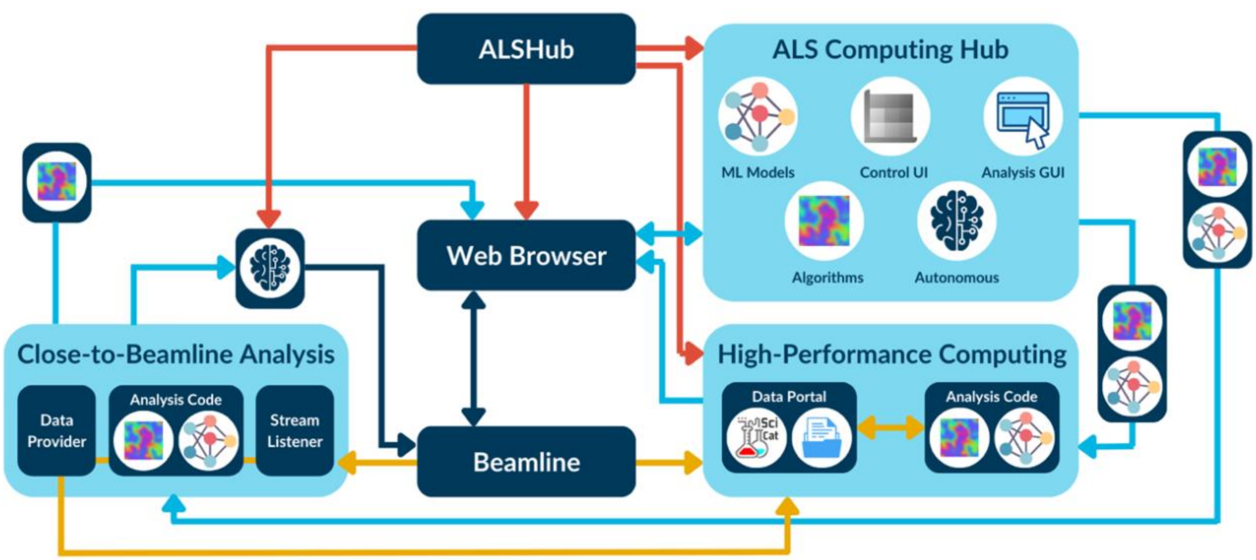

Fig. 10. The above framework illustrates the interconnectedness of various computing advancements, beamlines, the ALSHub, and high-performance supercomputing capabilities. Its objective is to expedite the creation of scientific knowledge from synchrotron.

Control systems and analysis workflows

Our strategy is to develop a new class of experiment-control systems that integrate computing resources and data handling in innovative ways. By adopting control-system and interface standards shared with other leading facilities, this work has already spurred robust collaboration among DOE light sources and peer labs. We are implementing an EPICS/Bluesky stack for some current and all future beamlines to promote this integration. New control systems under development will seamlessly interact with data-collection and analysis software, enabling automation driven by the analysis pipeline. In some cases, these systems will perform complex tasks with minimal human intervention, enhancing efficiency. In collaboration with NSLS-II and a private company, we have recently demonstrated automatic beamline alignment, a critical procedure that benefits from standardized, programmable approaches. Additionally, legacy control systems on existing beamlines are being retrofitted for two-way communication with the new controls infrastructure, gaining new capabilities and facilitating the transition.

In addition, we will develop graphical user interfaces (GUIs) that present clear, concise overviews of experimental progress, data flow, and the status of analytical and machine-learning tasks, requiring minimal technical expertise or training. Visualizations of the experimental system will assist in guiding sample movement and beam positioning, offering intuitive and efficient feedback.

Data life cycle

By optimizing the intersection of data and computation, our data strategy will accelerate the transfer of files and streamed data to computing and storage infrastructures for improved scalability, efficiency, and accessibility of data processing. We will implement this approach at all new beamlines and at legacy beamlines in time.

In autonomous data collection, rapid analysis is essential. The choice of computing strategy—edge computing, server-based processing, cloud computing, or supercomputing centers such as NERSC, the Argonne Leadership Computing Facility, or the Oak Ridge Leadership Computing Facility—will depend on the specific needs of the analysis and the algorithms or ML models driving it, and the location of computing resources will be determined case by case, based on the required turnaround time.

This approach requires a flexible deployment strategy, adaptable to various computational demands and data types. A smart data portal will be developed to align with FAIR principles, ensuring data is findable, accessible, interoperable, and reusable. This will require significantly expanded data management capabilities to accommodate not only ML-ready datasets but also enable data sharing across facilities and user groups. The catalog of datasets taken at the ALS is a natural foundation for data sharing and post-experiment analysis routines.

Analysis and machine learning as a service

In the near future, AI-augmented scientific workflows will guide users through their experiments and help manage large-scale data challenges. One key initiative involves training AI models to associate user proposals from specific scientific fields with relevant existing literature and FAIR data previously collected at the ALS or other facilities. Making these models available during user beamtimes will streamline scientific inquiry by connecting current research with past work. This will be achieved using large language models that span proposals and published papers. AI training datasets will be generated from existing data in conjunction with generative AI and digital twins.

Our goal of creating user-friendly interfaces for model training and deployment is inspired by machine learning as a service (MLaaS) and tailored for our light source. We will use a combination of local clusters, edge devices, cloud resources, and DOE supercomputing centers. Traditionally, deploying such solutions required significant manual intervention and specialized expertise. By centralizing these processes, the burden on researchers and operators is greatly reduced and access to the latest code and advances is automatic. As data volumes grow, this approach to computing and locality should scale dramatically in response to user needs, optimizing efficiency and cost-effectiveness.

Objective 1.6: Advance future accelerator technologies

The global shift toward higher-brightness x-ray light sources, reflected in numerous upgrade projects, stems from the recognition of the transformative impact of coherence on scientific exploration. Advances in accelerator design will deliver low-emittance, round electron beams, which create transversely coherent, high-power x-ray beams with exquisite wavefront quality. The ALS's upgrade to a nine-bend-achromat storage ring will reduce the electron beam emittance from 2 nm to 75 pm, boosting photon brightness in the soft x-ray region by two orders of magnitude. Despite this impressive upgrade to the storage ring and the addition of the accumulator ring, significant legacy accelerator systems remain at the ALS that are ripe for upgrades and R&D, and the development and deployment of new types of insertion devices promises to open the door to new capabilities as well.

Accelerator R&D

Our accelerator R&D activities will continue to focus on the injector chain, which includes the electron gun, linear accelerator (linac), and booster ring. While these systems are not part of the ALS-U project, they will need to serve the new accumulator and storage rings for many years to come. To ensure the necessary control, reliability, and resilience, a systematic upgrade campaign was initiated years ago and will continue until all obsolete components are replaced. Key future upgrades include replacing outdated tube-based radio frequency (RF) sources with solid-state amplifiers and upgrading the analog low-level RF (LLRF) controls to modern field-programmable gate array (FPGA)-based digital controls.

ALS accelerator performance has benefitted from advanced AI/ML applications that were not possible with previous tools. These approaches have improved electron-beam-size stability during routine user operations and enhanced ring-design capabilities. Looking forward several years, our AI/ML efforts will target automated accelerator tuning, beam stability improvements for both electron and photon beams, and preventative failure detection for accelerator components.

Longer term, we aim to explore options that complement the new source capabilities and expand the impacts on different scientific areas. One promising area is improving timing capabilities by producing shorter electron bunches alongside the standard longer bunches during user operations, enabling new research opportunities in dynamics on short time scales.

Insertion-device R&D

Insertion devices deliver tunable, highly coherent x-ray beams optimized for the spectral ranges of the experimental systems they support. The current ALS features 13 undulators and one wiggler source, some of which are more than 20 years old. Most of these devices will be reused during the upcoming ALS upgrade. Over the next 5 to 10 years, as new beamline projects are developed to harness higher coherent flux, the older insertion devices will be replaced with state-of-the-art, high-performance sources that fully leverage the upgraded accelerator. To achieve this, the ALS will pursue an internal R&D program and seek collaborations with other national and international labs and industrial partners to develop these future insertion devices.

Development has already begun on a Delta-type insertion device, but other magnet configurations will be targeted by R&D activities as well. For example, helical undulators would allow for higher photon fluxes while generating photon beams with an angular momentum component; undulators with a transverse field gradient could enable novel operation schemes; “revolver” insertion devices would extend the photon spectrum covered by a single beamline; and shorter-period undulators with high-intensity fields would extend the tunability and the spectrum covered by the ALS toward higher photon energies.

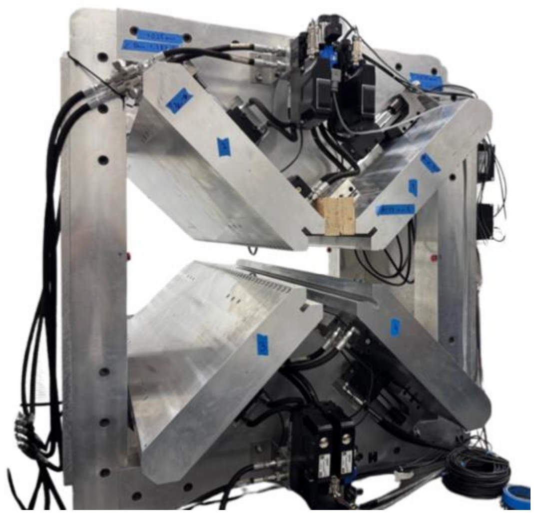

Fig. 11. The ALS's R&D program is developing the above-pictured Delta insertion device (ID) prototype as part of a program to develop new-generation IDs capable of fully leveraging ALS-U's coherence and brightness.

Goal 2: Usher in a new era following the ALS Upgrade

The ALS Upgrade project presents a tremendous opportunity to transform the ALS's capabilities, positioning us to lead the next generation of groundbreaking scientific discoveries for decades to come. However, realizing this vision will require navigating a challenging period of disruption over the next few years. User hours will be reduced to install a new accumulator ring, followed by a one-year shutdown, or "dark time," to replace the storage ring. Afterward, the accelerator and beamlines will be commissioned and performance gradually ramped up, ushering in the ALS 2.0 era of pioneering science. ***Our top priority is to support the successful completion of the ALS-U project and transition the facility to a fourth-generation light source.***

Realizing the ambitious goals of the ALS-U project will require the collaboration of hundreds of individuals across the ALS facility, the ALS-U project team, and Berkeley Lab. Transparent communication and attention to interfaces between teams and systems will be critical to a successful outcome. The following sections outline our objectives for ensuring a smooth transition into and out of the dark time, engaging with the user community, and supporting ongoing scientific and development activities to the extent possible during this period.

Objective 2.1: Optimize user operations until the ALS-U dark time

The ALS-U dark time, the one-year timeframe without any user operations, is when the current ALS storage ring will be removed and a new ring built and commissioned in its place. Leading up to this, increased downtime is necessary to perform preparatory work and install a new accumulator ring inside the storage-ring tunnel to reduce electron-beam emittance. This will require a significant reduction in user operating hours. During this period, the ALS's priority is to maximize user operating hours within the existing constraints to support ongoing world-class science while keeping major projects like ALS-U on schedule and within budget.

From the start of the ALS-U project, minimizing the dark time has been a key goal. To limit this period to one year and reduce the complexity and risk of the work, the ALS-U and ALS teams agreed to install and commission the accumulator ring before shutting down the facility to replace the storage ring. Since installation can only occur when the accelerator is offline, it must take place during maintenance periods or longer scheduled shutdowns. However, traditional shutdown durations were insufficient to install the accumulator ring and complete other preparations, requiring a careful balance between user beamtime and shutdowns to keep the project on track. Under normal circumstances, the ALS aims for 5,000 operating hours per fiscal year, but in the lead-up to the dark time, a more realistic target is 2,500 hours, although there may still be periodic challenges to meeting this goal while the ALS-U project works to maintain its schedule.

Outside of extended installation shutdowns, regular maintenance shifts and accelerator physics studies remain important. Upgrading and maintaining legacy equipment, which will continue to be used after completion of the ALS-U project, is vital for ensuring reliable beam delivery and achieving our internal goal of 97% reliability. Accelerator physics studies will allow the ALS to maintain beam quality in the short term and prepare for ALS-U commissioning, reducing future risks as we bring the accumulator and new storage ring online.

In this context, we aim to deliver beam at reasonable and reliable intervals to meet user needs while ensuring reasonable breaks for our beamline operations staff to maintain work-life balance. The scheduling of installation shutdowns will be continuously assessed to balance the needs of both the ALS and ALS-U project, ensuring maximum productivity for all stakeholders.

We are also committed to keeping user experiments running for as long as possible before the dark time. The ALS will continue allocating beamtime until the ALS-U dark time begins, at which point active general user proposals will end and Approved Programs (APs) will pause until the relevant beamlines are operational again. While most beamlines will operate until the dark time, some will need to be shut down a few weeks or months earlier to clear spaces designated for storage-ring equipment removal and replacement, as well as other preparatory work.

Objective 2.2: Facilitate continued research, development, and user engagement during the dark time

Although the synchrotron will be offline during the one-year dark period, with no light available to users, it is essential to keep user engagement, scientific progress, and instrumentation development moving forward. Retaining our user community, sustaining research momentum, and advancing our technological capabilities are top priorities. To support these goals, we will explore opportunities to continue research during the upgrade, including by utilizing lab-based x-ray, IR, and EUV sources and relocating select endstation equipment to laboratories for limited use.

We will also leverage existing partnerships and pursue new collaborations with other facilities to help ALS users find alternative capabilities, ensuring their research can continue. Additionally, the dark time presents a unique opportunity for ALS staff to spend time at other light sources, gaining valuable experience while potentially supporting ongoing R&D efforts. As part of this strategy, we are negotiating collaborations with US and international facilities whose capabilities and beam characteristics best match those of the ALS, allowing us to continue instrument development and support user experiments at those facilities. We will also continue to develop and upgrade instruments to ensure they are ready to take full advantage of the enhanced capabilities of the upgraded ALS.

Our goal is not only to retain our current user base but also to grow our future community during the dark time by involving staff and users as partners in planning, education, outreach. We will keep the user community informed and engaged through regular communications, town halls, and updates on the upgrade and recommissioning progress. We will hold workshops on future capabilities and instrumentation advancements leading up to and during the dark time to ensure users are well prepared for the opportunities that the upgrade will bring.

Objective 2.3: Return the ALS to full scientific use following the upgrade

Completing the ALS upgrade and bringing the ALS back to full scientific use safely are the most important overall objectives for the ALS during the next five years. The ALS-U project is acutely focused on upgrading the ALS accelerator systems, delivering two upgraded beamlines (with the ALS providing the endstations), and seismically strengthening the accelerator tunnel. Returning the facility to full scientific use requires extensive safety assessments and realignment of beamlines due to changes in photon source locations. Additional upgrades to radiation protection systems and infrastructure, such as increased roof-block thickness and added lead shielding on the storage-ring enclosure, are also necessary. This work must be completed by the ALS and is a top priority, as experiments cannot proceed without its completion. Our strategy is to closely collaborate with the ALS-U project team to develop a unified plan for upgrading the storage ring and preparing all beamlines for scientific use. Although project plans are evolving, we aim to begin this work before the dark time starts.

Accelerator commissioning is crucial, as all accelerator subsystems must be fully tested, fine tuned, and optimized for performance. Ring components must be carefully monitored to ensure they can safely handle the rising heat load from increasing stored beam currents. This phase can last up to a few years, depending on the number and severity of issues that arise. The time required for this phase will directly impact how quickly we can return to the target of 5,000 user operation hours per year. To minimize the duration of this critical phase, ALS technical teams will work systematically to identify potential failure points, prevent them, and develop mitigation plans. Our approach draws on previous ALS upgrade experience and lessons learned from recently upgraded facilities like the Advanced Photon Source and the European Synchrotron Radiation Facility.

As beam current ramps up, the focus will shift toward bringing all beamlines back online for scientific use. Bend-magnet beamlines must be reoriented to the new photon source points, and insertion-device beamlines will have new front-end components. Some entirely new beamlines are being constructed, while a few existing ones will be decommissioned. All beamlines will have modified shield-wall penetrations and need updated radiation shielding documentation and hardware. Each beamline will go through an orchestrated process of physical moves, hardware installation and verification, full readiness reviews, and commissioning. This will be followed by endstation commissioning, experiment calibration, and finally, the start of scientific commissioning and user operations. The order in which beamlines are brought back online will depend on several factors, including the complexity of physical moves, availability of technical experts and workforce, the amount of science that can be conducted with early beam conditions, and relative priorities within each science program.

The ALS will gradually bring users back as beamlines become available and the electron-beam current is sufficient for scientific studies at each beamline. In the early stages, the beam will be unstable and prone to frequent interruptions, so initial users will likely be partners and local users who are experienced. To start, we will use RAPIDD proposals (Rapid Access Proposals, Industry, and Director's Discretion) to allow access to the facility. Once a sufficient number of beamlines are operational and the beam quality stabilizes, we will open a call for general user proposals.

Goal 3: Ensure mission success through operational excellence

The ALS is committed to providing a robust and stable operational platform to support both staff and users, enabling innovative and productive science. We do this by maintaining a safe work environment with all the necessary support services for a productive workforce. As a learning organization, we embrace continuous improvement. Over the next five years, our goal is to enhance business systems, processes, physical spaces, utility infrastructure, and operational reliability to ensure mission success through operational excellence. Achieving this requires cross-functional collaboration across the organization and with Laboratory operating groups. Our objectives in this area focus on safety and security, user services and systems, infrastructure, and supply chains.

Objective 3.1: Maintain safe and secure operations

Berkeley Lab staff are passionate about bringing science solutions to the world in a safe and environmentally responsible manner. At the ALS, we uphold a strong safety culture and follow work practices that promote a safe environment for everyone at our facility, including staff, affiliates, users, contractors, and other visitors who are part of our community. In addition to ensuring physical safety, we aim to ensure the security of our operations as well.

Environment, health, and safety

To ensure safety for all those performing work inside the ALS, we strive toward open communication and collaborative partnerships to increase learning and foster a “one team” approach, particularly as we move through the ALS-U project and beyond. Work planning is a critical part of all work at the ALS, including maintenance and projects as well as user experiments and staff research and development. We aim to achieve the highest level of safety through identifying hazards and implementing controls. A culture of continuous feedback and improvement is a key aspect to improve safety. We value being a learning organization and consistently solicit input in order to grow stronger. We share our experiences with others through lessons learned and foster an environment that emphasizes psychological safety to support reporting and accountability.

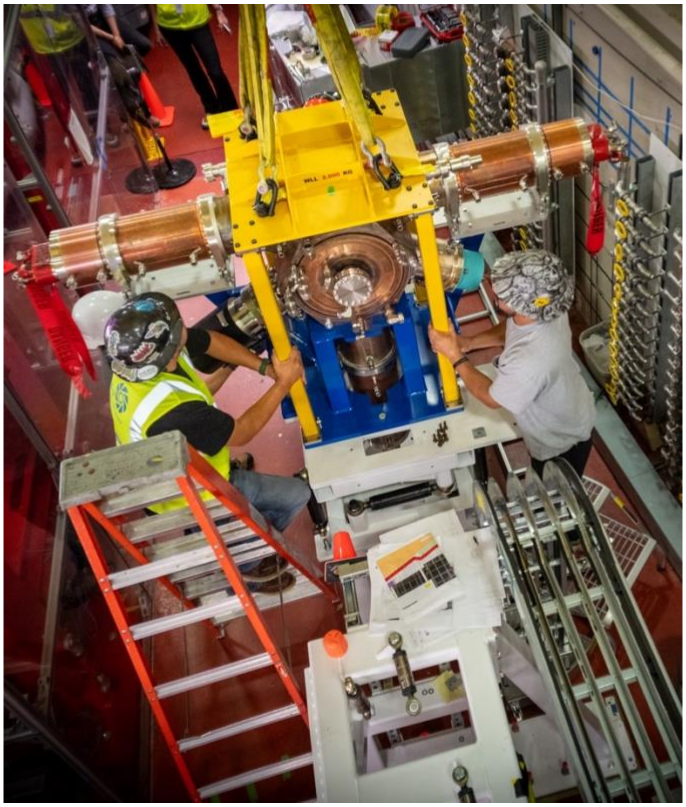

Fig. 12. Successful installation of the RF cavities for the ALS-U accumulator ring in the tunnel, July 2024. This critical task involved careful and detailed Integrated Safety Management (ISM) to ensure safety.

Moving forward, the ALS will be implementing strategies to increase our awareness of error precursors. Anticipating situations that will put workers in unsafe conditions allows us to proactively implement strategies to enhance human and organizational performance. We will also continue working collaboratively with ALS staff, Berkeley Lab partner divisions, and users to develop comprehensive controls to expand the portfolio of samples we can safely accept at ALS.

Given the highly matrixed organizational structure of the ALS, coordination among the safety teams of our partner divisions is increasingly important as we move through the dark time and beyond. ALS and ALS-U staff will continue to work closely together to identify and mitigate legacy hazards, while developing guidelines and policies to ensure a safe environment during the dark time and after operations resume post-upgrade. This includes addressing radiation shielding, hazardous materials like lead, and electrical installations.

Cybersecurity

Cybersecurity is vital for all of our networked systems and can be divided into two main areas: the more centralized accelerator operations and the decentralized beamline control, data acquisition, and data handling systems, which often have unique configurations. We are developing a secure network design for beamlines based on Berkeley Lab's cybersecurity framework. We will test this design on a few early-adopter beamlines and devise a transition plan to replicate these changes across the remaining ALS beamlines. As beamline needs evolve over time, we will continue to adapt the ALS network security environment to meet those demands.

Objective 3.2: Enhance user services and systems

Delivering exceptional customer service to our users is a top priority. Our aim is to create a fully integrated, seamless experience across all stages of the user experience, from proposal submission and beamtime allocation to user registration and onboarding, experiment safety, data analysis, and publication.

Software systems

Recent software developments have equipped ALS users with a suite of modern, effective tools accessed through the ALSHub interface. These include the ALS Scheduler for centralized scheduling, the Experiment Safety Assessment Form (ESAF) system for managing experiments, and upgraded publication reporting and search tools. The ALS regularly assesses and upgrades these tools to ensure they remain fit for purpose.

Over the next few years, we plan to update several software systems and processes. After more than 20 years of service, the main ALS user database, which handles the initial stages of user registration, stores user and proposal data as well as ESAFs, manages beamtime allocation, tracks publications, and generates reports, will be replaced. The new system will retain existing functionalities while adding new integrations for beamlines. We will also replace or update the current proposal administration system. Across all software platforms, our focus is on building flexible systems that can adapt to changing user access and partnership needs, for instance to accommodate new types of access modes or to select resources across multiple Berkeley Lab user facilities.

User access

Ensuring that access to Berkeley Lab and ALS resources is easy and efficient for users is another priority. Many users begin preparing for their experiments months in advance, often traveling from across the country or the world for just a few shifts of beamtime. The current registration and onboarding process involves multiple steps across several Berkeley Lab departments, so clear interfaces and communication are essential. We see opportunities to improve this process and will collaborate with our partners across Berkeley Lab to shorten onboarding times, enhance communication, and streamline access to the facility.

As remote use becomes more common, we are also dedicated to enhancing the user experience for those who access our resources from offsite locations. The ALS computing team is working closely with beamline scientists to develop a new web portal that allows approved users to remotely access beamline computers through the ALS user portal's authentication system. This portal will also offer additional APIs for external beamline applications, expanding the functionality and accessibility of our resources.

Proposal review

We will conduct a thorough review and revision of our proposal review process to adopt best practices from other user facilities, clarify and align the proposal format and scoring criteria, improve the reviewer experience, and minimize potential bias. We also aim to increase transparency by publishing details of the review process online, including steps, timelines, and policies covering reviewer code of conduct and conflicts of interest. The review process will continue to rely on the existing reviewer pool and Proposal Study Panel (PSP), which will expand slightly as new beamline capabilities are developed. In the future, we hope to use AI to assist with reviewer assignments, moving away from keyword-based matching that can sometimes result in expertise mismatches. AI has the potential to speed up reviewer assignments, making the process more efficient, and reduce the number of reviewers declining because of mismatches in expertise.

Across all these efforts, we recognize the importance of collaboration with other light-source and scattering facilities and other user facilities at Berkeley Lab. We maintain close collaborations with our partner facilities and will continue to look for opportunities to employ common practices and solutions for our users.

Objective 3.3: Deliver infrastructure for sustainable operations and future growth

As a large-scale science facility, the ALS requires significant power, heat rejection, and space. Our top priority is to maintain the infrastructure required to run the accelerator reliably and enable user science. However, to accommodate future staffing needs and expand capabilities to enable future user science, we must invest in significant upgrades and expansion of our infrastructure as well.

Utility infrastructure

The ALS utility infrastructure is aging, with many systems dating back over 30 years to the facility's original construction. We rely heavily on Berkeley Lab's infrastructure and services and work closely with centralized operations departments to meet our needs. Recent Berkeley Lab and DOE investments have supported key upgrades, including the refurbishment of the low-conductivity water plant for process cooling, an upgrade to the building control systems, and an upcoming replacement of the high-voltage switch station that powers the ALS. However, significant additional investments are required, including in our chilled-water plant, high-voltage transformers, and facility-wide electrical distribution systems. These upgrades are not driven by changes from the ALS upgrade but are essential reinvestments in aging infrastructure to ensure reliable operations for decades to come. Historically, our infrastructure improvements have been opportunity-driven or reactive to failures. Moving forward, in collaboration with Berkeley Lab and the DOE, we aim to adopt a proactive, risk-based approach to address these infrastructure needs.

Space and facilities

Space is a precious commodity at Berkeley Lab due to its constrained hillside location and the high local cost of construction. Substantial additional space will be needed for the significant growth in staffing and laboratory space envisioned for the future, and also to enable concepts like long beamlines that extend into functioning laboratories or modular, mobile endstations. Our first priority is to optimize the use of existing space, including taking advantage of flexible work arrangements prompted by the pandemic. We are also partnering with the Lab to secure more on-site and off-site space.

Laboratory space and tools are essential for the timely in-house development, assembly, and staging of equipment ranging from small systems to entire beamlines. In addition to areas for endstation and sample-environment assembly, we have dedicated spaces for instrumentation development, with plans to create more clean assembly areas on-site as needed. For the assembly and staging of full beamlines and endstations, Berkeley Lab is committed to providing appropriate off-site spaces, which will be crucial as space on-site is prioritized for the ALS-U project. Looking further ahead, the anticipated redevelopment of the Charter Hill site could provide state-of-the-art lab facilities, improved shipping and receiving areas, and much-needed office space.

Objective 3.4: Secure supply chains for critical systems and components

ALS users rely on the dependable operation of the ALS accelerator and beamlines to perform their experiments. Since beamtime is highly competitive and tightly scheduled, the ALS has an accelerator reliability goal of 97%. When unexpected equipment failures inevitably happen, having spare parts and the necessary experts on hand is critical to return to user operations safely and quickly. In addition, our ability to maintain, develop, and upgrade our accelerator and beamline infrastructure depends on robust vendor relationships and in-house capabilities.

Supply chain management

Accelerator supply chains are challenged by the relatively small, fluctuating market, with demand spikes during major facility upgrades followed by long periods of low activity. This instability has led to the closure of several US companies in this field, leaving critical components primarily available from single suppliers in Europe or Asia. For example, RF klystrons supply the energy needed to store beam in a ring. These large, high-power components are expensive, have long lead times, and are currently produced by only one European company, which may abandon the market in the next few years. To mitigate this risk, we have partnered with Brookhaven National Laboratory on a DOE-funded initiative to develop a US supplier, with the first klystron prototype expected for testing in the coming years.

Fig. 13. The operational Thales klystron pictured above is an essential part of the ALS storage-ring radio frequency system. Sourcing of these original equipment manufacturer units or alternatives requires special attention to the supply chain.

For high-quality modern beamlines, the supply chain is a mix of large, established vendors and small specialists providing bespoke solutions. The global surge in facility and beamline upgrades has spurred competition among companies to provide high-quality beamline components and entire turnkey systems. Consistent approaches among facilities and standardizing key elements across facilities helps advance beamline engineering and benefits the broader community through vendor engagement.

Even within small companies, increasing worldwide demand for optical elements reaching diffraction-limited quality has pressed vendors to innovate and steadily improve. However, the worldwide market for x-ray optics is small, the volume is low, and the companies providing critical elements are vulnerable to market forces. We rely on several key domestic and foreign vendors, but we have no control over their long-term survival. Critical beamline components include mirrors of all kinds, gratings, crystals, nanodiffractive optics (e.g., zone plates), and specialized coatings. These require either vendors willing to make custom designs with timely delivery or Lab investments in in-house infrastructure and expertise. Other elements, such as detectors, optical modeling and design software, and control and computing infrastructure, are more broadly applicable but are still affected by the same small-market challenges.

Our plan for the next five years is to nurture and expand core competencies that give the ALS its unique capabilities while maintaining strong relationships with key vendors for external elements. Our in-house efforts on gratings focus on developing new technologies for efficient tender x-ray gratings and novel patterning approaches. In optical metrology, we are advancing techniques to measure and perfect variable-line-space gratings and mirrors with high sagittal curvature. For optical design, we are pioneering aberration-correction techniques for hard x-ray beamlines and developing adaptive optical elements for speed and for accurate wavefront control. For mirror coatings and nanodiffractive optics, we are continuing to collaborate closely with Berkeley Lab's Center for X-Ray Optics to develop new optical elements for tender x-ray focusing, nanoARPES, soft x-ray microscopy, and ptychography. These efforts align with our strategic priorities and long-term vision of scientific leadership. In areas requiring external support, we keep our vendors informed about our anticipated future needs and timelines, allowing them to plan effectively.

The ALS depends on reliable power delivery to meet the facility's needs. Our local power provider has recently made significant infrastructure improvements in response to scrutiny for past incidents, greatly improving power delivery quality and reliability. As a DOE-supported facility, Berkeley Lab is able to purchase power at wholesale rates, shielding us from local market fluctuations and the sharp cost increases experienced by many European facilities.

Both experiments and accelerator operations rely on specialty gasses, particularly helium and nitrogen. Helium costs have surged over the last two years because of supply shortages, and even with closed-loop systems and multiple suppliers, availability has been unreliable. However, once the new ALS-U storage ring is operational, helium will no longer be needed for the accelerator. Although nitrogen is generally abundant, regional production issues have twice led to recent shortages that impacted our experiments. The Lab is exploring helium recapture and on-site nitrogen production to address these challenges.

Spare-part inventory

The current ALS spare-part management system for accelerator components is not integrated, and instead consists of multiple systems developed by each subsystem group to address their specific needs. Despite this less-than-ideal configuration, it has been refined over decades and meets the needs of the facility's current operations. However, the increased complexity of the upgraded ALS accelerator will require a management system upgrade. The new storage ring will have approximately three times the components of the existing ring, and the accumulator ring will match the complexity of the current storage ring. This dramatic increase in components will lead to greater demands on the spare-part inventory and workforce. To meet these needs, we will scale up our management system and replace the current spare-parts software with a modern, more-integrated spare-parts database.

For beamlines, our approach to spare parts is evolving as we transition to the upgraded ALS. Historically, generic beamline elements like vacuum systems were relatively easy to replace. However, the specialized nature of individual beamlines and their customized experimental systems reduce the ability to have spare parts on hand for maintenance and replacement. Beamlines built over the last 30 years have varied designs that reflect the best approaches of their time. Our new approach is to increase standardization and regularity in both design and infrastructure across all new beamline projects. This will reduce redundancy and promote the availability of interchangeable parts, including mirror-cooling systems, photon diagnostics, and carbon mitigation.

Goal 4: Foster an innovative and collaborative environment

The ALS is dedicated to fostering a collaborative and innovative environment that supports our mission to advance science for the benefit of society by providing our world-class synchrotron light source capabilities and expertise to a broad scientific community. As we move into the ALS 2.0 era, we aim to expand our user base, strengthen partnerships, and cultivate a diverse and skilled workforce in order to maximize the new capabilities offered by the ALS upgrade. By engaging and educating current users while attracting new researchers from diverse institutions and industries, we seek to broaden access to these transformative resources and lower barriers to participation.

In addition to outreach, the ALS is committed to building strong partnerships with the broader research community, from Berkeley Lab programs and other DOE facilities to industry and the larger academic community. These collaborations are key to driving scientific innovation and advancing our collective knowledge. At the same time, investing in workforce development is essential for maintaining the ALS's leadership in cutting-edge science. Through targeted recruitment, career development programs, and an emphasis on inclusion, diversity, equity, and accountability, we aim to build a vibrant, dynamic workforce that will continue to shape the future of the ALS and drive scientific discovery.

Objective 4.1: Attract a vibrant, productive user community

As the ALS prepares for the ALS 2.0 era, our user outreach strategy must promote the facility's transformative new capabilities. ALS-U and planned ALS investments will bring unprecedented opportunities for scientific discovery, especially through enhanced soft x-ray coherence, brightness, and multimodal and high-throughput techniques. Our goal is to engage, educate, and expand our user base while retaining the most productive current members of our community.

A central focus of our outreach efforts will be to educate researchers about how the upgraded ALS's coherence and brightness can benefit their work. Recent engagement with the scientific community, especially through the 2023 science visioning workshops, has revealed a lack of awareness about how to utilize x-ray coherence. While the full utility of this burgeoning capability will be revealed with time and further development, we can already begin educating the scientific community through workshops and tutorials about the fundamentals and the readiest prospects for transformative science. We will also look to educate the community in partnership with other facilities who have recently undergone or plan to implement coherence upgrades.

While it is essential to maintain support for our productive existing users and prospective new users of coherence, our mission calls for us to ensure our capabilities are available to a broad scientific community. By expanding our outreach to institutions that have not traditionally accessed the ALS—such as non-R1 minority-serving institutions, emerging research institutions, and local community colleges—we will foster a more diverse and inclusive user base. We also aim to increase our connections to industry, particularly in scientific areas where the ALS has historically had less industry engagement. In all of these cases, we will also aim to understand barriers to access beyond lack of awareness, so we can implement plans to lower barriers where possible.

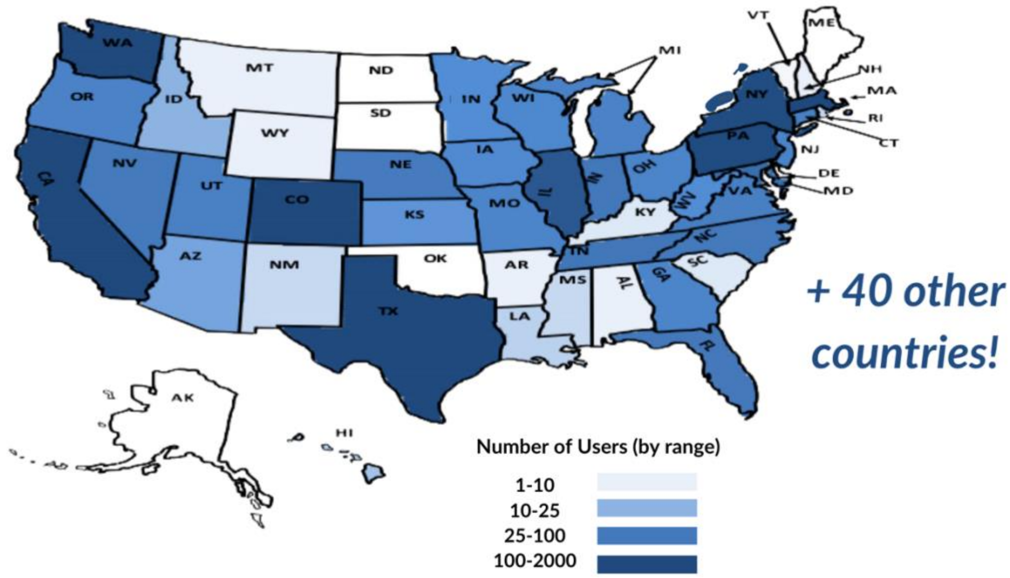

Fig. 14. Our goal is to attract the most diverse, productive users from research institutions across the country each year. This map represents the number of US users from each state (based on institution) who have visited the ALS for beamtime from FY21–23. Additionally, the ALS has been a resource for hundreds of scientists from 40 different countries.

As we seek to increase the diversity of our user base and incorporate new communities to leverage the upgraded ALS's new capabilities, we will move beyond an outreach approach focused almost exclusively on individual beamline scientist efforts and incorporate a much larger element of centrally driven and supported outreach strategy. A thoughtful, balanced approach will be needed. Since the ALS has traditionally been highly oversubscribed, we must avoid expanding our outreach efforts to new communities only to deny them access. In particular, outreach should not outpace the ramp up in user hours and beam quality that will follow the ALS-U dark time. We must also ensure we have adequate beamline staffing support for first-time users, who typically need more hands-on guidance. By managing beamtime allocations effectively, we can ensure that both new and experienced users benefit from the upgraded ALS's transformative capabilities while maintaining the high level of user support and scientific output for which the ALS is known.

Objective 4.2: Cultivate and strengthen partnerships

Partnerships are a key pillar of the ALS's strategy for advancing scientific discovery and innovation. The ALS's location at Berkeley Lab, its direct ties to the UC system, and its collaborations with local industry create a unique and fertile environment that benefits the research community and, in turn, the ALS itself. As ALS-U transforms the facility's capabilities, strategic partnerships will play a crucial role in realizing continued success into the ALS 2.0 era.

Berkeley Lab ecosystem

Berkeley Lab is home to vibrant, interdependent, and synergistic programs, hubs, centers, and user facilities. For example, its multidisciplinary, multi-principal-investigator (PI) Materials Sciences and Engineering (MSE) and Chemical Sciences, Geosciences, and Biosciences (CSGB) BES core programs are among the nation's most distinguished and impactful, and they are enhanced by strong relationships with the UC Berkeley campus and faculty. Many core-program PIs are ALS users, and several ALS scientists are themselves core-program PIs, mutually benefiting the ALS and core programs. The ALS also has a substantial user base among Berkeley Lab faculty and staff scientists in biosciences, energy technologies, and earth and environmental sciences programs supported through funding from DOE BER and EERE, among other sources.

In recent years, a few ALS beamline scientists have taken on second affiliations with the Chemical and Materials Sciences Divisions at Berkeley Lab. We see opportunities to expand the ALS's integration with Berkeley Lab scientific programs and local UC campuses further and will particularly aim to grow the number of ALS-scientist core-program PIs, increase and formalize joint appointments between the ALS and other divisions, and enhance the direct involvement of ALS beamline scientists in UC campus departments. This deeper integration offers the opportunity to leverage our partners' instrumentation expertise and design impactful experimental programs while fostering the development and bolstering the reputation of ALS staff as leading scientists. In addition, ALS instrumentation development benefits from the capabilities of Berkeley Lab's Engineering Division in beamline and detector technology, which are further strengthened by the R&D conducted by the ALS-U project.

Four other DOE Office of Science user facilities are hosted at Berkeley Lab—the Molecular Foundry nanoscale science research center, the National Energy Research Scientific Computing Center (NERSC), the Energy Sciences Network (ESnet), and the DOE Joint Genome Institute (JGI)—creating connectivity across diverse areas of science. In particular, the ALS has many users who also use the Molecular Foundry and leverage its capabilities and expertise in theory, synthesis, characterization, and fabrication. There are also several cases of longstanding collaborations between scientific staff at the two facilities. A joint access mechanism supports user projects that can benefit from capabilities at both facilities, yet there is considerable room to expand its use. We aim to increase awareness of the combination of capabilities at the two facilities that can be brought to bear on particular scientific areas and lower the logistical barriers leveraging joint access. We are also in the early stages of introducing instrumentation that can support multimodal studies, like transferable sample holders for x-ray and electron characterization of air-sensitive materials.

The ALS has direct links, via ESnet, to NERSC, which allows users to store, process, and analyze large datasets. Additionally, the ALS has collaborations with scientists at JGI that aim to make fundamental discoveries of high-resolution, dynamic genomic architecture. These relationships are also ripe for further development, as detailed in Objective 1.5 for ESnet and NERSC and toward a more general goal of deepening our partnership with Berkeley Lab's Biosciences Areas, in the case of JGI.

ALS partnership modes

Partnerships increase the ALS's capacity to enable scientific discoveries, most directly through Participating Research Teams (PRTs). Two-thirds of ALS beamlines are supported directly by the ALS;

the other one-third are operated and maintained by groups comprising multi-PI teams, some based in other Berkeley Lab divisions, or representing consortia of universities or companies. They are provided a large percentage of their beamline's operating time and, in return, support general user operations at that beamline. These longstanding partnerships, which provide the vast majority of the ALS's biosciences capacity among other areas and predominantly focus on nonproprietary research, are responsible for some of the ALS's most impactful societal contributions, including cancer and COVID treatments, Nobel-prize-winning work in CRISPR-Cas9 gene-editing technology, and the development of EUV computer-chip manufacturing technology. The ALS values the contributions of the PRT program and will continue to support these partnerships and their integration into ALS strategic planning.

To foster deep collaborations with the broader user community, the ALS offers the AP mechanism, which gives longer-term, guaranteed access to beamtime for an individual or group proposing a high-quality research program. Under this framework, the AP offers resources, such as a postdoc stationed at the ALS to perform experiments or develop a new sample cell that will later be made available to the general user community. The AP mechanism promotes the ALS's substantial involvement in hubs and centers across the country that are supported by DOE and other funding agencies. Continuing this program is vital to the ALS's success, and AP users, as experienced collaborators, will be among the first users to perform experiments as the facility is recommissioned following the ALS upgrade.

Instrumentation developments at the ALS have often emerged from deep collaborations with community partners, including researchers from Berkeley Lab and institutions across the US research complex. For example, the ALS, through collaborations with Office of Science–funded core programs, Energy Frontier Research Centers, and Innovation Hubs, has been at the frontier of developing ambient-pressure techniques to study and understand the chemical origins of catalytic, electrochemical, and photochemical processes. The ALS has built strong relationships with computational scientists at Berkeley Lab and other national laboratories to extract key information from increasingly complex datasets, reducing the need for users to develop difficult analysis methods on their own.

Industry collaboration

High-impact collaborations with industry have been among the ALS's greatest success stories during the past 30 years. In the fields of EUV lithography and macromolecular crystallography, in particular, strong PRT programs have built long-term industry relationships that have produced globally significant impact, often capitalizing on the Bay Area's concentration of leading tech and biotech industries. Since only a few percent of today's ALS general users are affiliated with industry or cite industry support for their research, we see significant potential for growth in this area. Recognizing that the lengthy proposal process is not suitable for all kinds of research, the ALS offers a mechanism for Rapid Access Proposals, Industry, and Director's Discretion (RAPIDD). It accommodates users who require limited or prompt access to ALS beamtime and can support the more immediate needs of industry. Moving forward, we will raise awareness of how our capabilities can be applied to industry challenges while exploring other possible access mechanisms. Likewise, we see opportunities to partner with industry toward shared goals like instrument and computing capability development. In recent years, collaborations based on DOE Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) grants have enabled specialized instrumentation research, such as optical metrology and mirror cryo-cooling, that brings us closer to domestic small-business partners. We will look for ways to lower barriers associated with partnership agreements with the Laboratory.

Finally, collaborations with other x-ray and neutron scattering facilities in the US and internationally offer the opportunity to develop common instrumentation and computing solutions. ALS development staff collaborate closely with DOE peer laboratories and international light sources, whether through formal working groups, DOE-funded projects, or informal partnerships based on shared technological goals. Key areas of domestic collaboration include wavefront sensing, adaptive optics, cryo-cooling technologies, grating fabrication, optical metrology, EPICS/Bluesky beamline controls, high-performance computing, and data-analysis pipelines. Other areas include workforce development and operational improvements. The ALS will continue to actively participate in these efforts moving forward.

Objective 4.3: Build and develop our workforce

Staff are the lifeblood of the ALS, providing the operational infrastructure and expertise that enable users to achieve their scientific goals. They drive innovation by developing new instruments, software, and workflows that not only enable user experiments but also inspire new research directions. Their dedication and institutional knowledge ensure the smooth and safe operation of the facility and outstanding user support, which are crucial to our mission.

Over the next five years, our complement of staff must significantly grow to meet our goals for instrument development and delivery, computational infrastructure deployment, user support at modernized beamlines, and bringing the ALS back into full scientific use more generally. We will focus attention on recruitment strategies, including broadening our outreach efforts, streamlining our hiring processes, and strengthening how we highlight the benefits of working at Berkeley Lab and the ALS.

We must also strengthen the pool of qualified applicants for ALS positions. For more than 20 years, the ALS has offered the Doctoral Fellowship in Residence and Collaborative Postdoctoral Fellowship programs, which provide the opportunity for graduate students and postdoctoral researchers to spend a year at the ALS acquiring hands-on scientific training and collaborating with beamline staff. This program has been successful at exposing early career researchers to synchrotron career opportunities, and several have gone on to become staff members at the ALS or sister facilities, or have become long-term ALS users. Moving forward, we plan to better leverage this program and the portfolio of internship programs offered through Berkeley Lab to draw qualified applicant pools for future positions.

Fostering the professional growth and career development of our staff is essential for retaining talent and expanding skills and is a frequently cited priority for staff on internal culture surveys. Equally important is cultivating an environment that nurtures and recognizes innovation, encouraging creative ideas and resourceful problem-solving. This combination of talent development and a supportive culture is key to our success and achieving our long-term goals.

Fig. 15. ALS Research Scientist Tanny Andrea Chavez Esparza provides hands-on experience to Bryan Ochoa, a California State University, East Bay student, through the ASPIRES internship program (left). The 2023 User Meeting's earth and environmental sciences visioning workshop provided a platform for ALS Doctoral Fellow in Residence Michelle Devoe from UC Berkeley to present her research to the broader scientific community (right).

Over the next five years, we will maintain several existing best practices and leverage unique opportunities toward these aims. In addition to meeting operational needs, we must build up our staffing support in key areas to allow time for development, innovation, and collaboration. Over the past few years, we have increased our emphasis on work–life balance, supporting beamline staff for instance in operating their beamlines fewer hours when necessary and particularly when only one scientist supports a beamline's operations. The accelerator has been running at significantly reduced levels for a few years to accommodate ALS-U preparation, and returning to 5,000 hours a year of user operations will have a substantial effect on staffing resources required, from operators and user administrators to beamline scientists and engineers. It will be essential as we ramp up operations post-ALS-U that we establish realistic priorities and expectations for staff across all roles, even as we seek to leverage recently increased budgets to bolster staffing.

To support staff scientific development, we have recently instituted an option for beamline scientists to schedule up to 15% of the beamtime at their beamline to support their own research and development. Under their direction, this time can be used to seed new partnerships, support their own funded projects, or develop new techniques.

As our facility grows, we are investing in staff development and emphasizing teamwork and cross-training in the creation of new experimental systems. This renewed approach moves us away from one-off solutions, and toward new capabilities that can be applied to both current and future projects, ensuring continuous improvement. To support this, we are promoting a staffing pipeline model that hires and trains junior staff and prepares them to advance into leadership roles over time. Our strategy emphasizes knowledge transfer as an important part of succession planning, particularly in areas that require specialized skills.

The one-year dark time for ALS-U storage-ring installation allows for additional opportunities for staff career growth. We are planning for some staff to be able to visit other facilities to conduct beamtime, learn new experimental methods and analytical tools, and enhance collaborations across the DOE user facilities and light sources worldwide. The work of bringing the ALS back to full scientific use after the dark time will also give many photon science staff the chance to use and grow new skills to help move, align, and commission all of our beamlines.

In addition to opportunities particularly centered on scientific staff, the ALS is investing in programs for career development, mentorship, and leadership skill development for staff in all types of roles. These programs aim to increase management's awareness of staff career goals, provide guidance for navigating career paths and improving professional skills, and strengthen supervisory and leadership abilities across the organization.

Objective 4.4: Promote inclusion, diversity, equity, and accountability

The ALS has a strong commitment to inclusion, diversity, equity, and accountability (IDEA) and supports a culture in which the entire ALS community, including staff, users, affiliates, and visitors, feels welcomed and valued.

Berkeley Lab and the ALS believe that our values promote the Lab's vision of bringing science solutions to the world. As critical components of the Lab's stewardship efforts, these values unlock innovation, produce high-performing teams, and drive meaningful impact and outcomes. As part of Berkeley Lab, the ALS continues the rich tradition of team science that began with the Lab's founder, E.O. Lawrence, and strives to cultivate a working environment in which everyone belongs (inclusion); to welcome and engage all people and perspectives (diversity); to ensure fair access to opportunities (equity); and to take responsibility for making progress (accountability).

As a publicly supported resource, it is incumbent upon the ALS to ensure fair access to our capabilities. Over the next few years, the ALS will update its proposal review process to reduce potential sources of bias by raising reviewer awareness of conscious and unconscious bias and de-emphasizing past ALS performance, which will create more equity among experienced and new users and has the potential to increase the diversity of our user population. We also emphasize fair hiring practices, promoting open, broadly advertised searches that follow best-practice guidelines. The ALS was an early proponent of search-process standards to reduce bias, developing Berkeley Lab–approved guidelines that were later expanded in collaboration with Molecular Foundry staff to serve the entire Berkeley Lab Energy Sciences Area.

The ALS also strives to ensure that our advisory panels represent the topical diversity of our science portfolio and that the demographic composition of the membership reflects, at a minimum, the demographics of our current user community. The demographics of our PIs and user population are also important to track. Our goal is for our user community to be at least as diverse in a particular scientific field as the general population of that field. Moving forward, we plan to monitor these factors more closely and, if misaligned, investigate the source, which could point to a need to improve outreach efforts, reduce bias in the peer-review process, or lower barriers to accessing and performing experiments at our facility.

As detailed earlier, we will bolster our outreach efforts to support our ALS 2.0 aspirations. While some of these efforts will target specific scientific communities that would benefit from our new capabilities, we must put equal attention on outreach efforts to improve the diversity of users and staff. The ALS will continue to be involved in DOE programs like Funding for Accelerated, Inclusive Research (FAIR) and Reaching a New Energy Sciences Workforce (RENEW) to foster collaborations with minority-serving institutions and emerging research institutions. ALS scientists participate in funded projects in both of these programs, and we aim to leverage them to cultivate continued relationships with the collaborating users. The ALS also participates in other programs aimed at expanding awareness and access to facilities like the ALS, including the Berkeley Lab Energy Sciences Area's ASPIRES (Advancing STEM Pioneers in Research in Energy Sciences) internship program, which provides summer internships for undergraduates from California State University, East Bay, a minority-serving and emerging research institution.

As we increase the number and diversity of our staff and user community, our attention to culture becomes even more important. When Berkeley Lab first established the IDEA initiative in 2019 and became the first national laboratory to name a chief diversity, equity, and inclusion officer in 2018, it began a longstanding campaign to increase awareness and understanding of the issues affecting Laboratory culture and diversity and to promote direct staff involvement in solutions. At the ALS, dozens of staff participate in volunteer task forces in support of IDEA improvements. We aim to foster a welcoming atmosphere, supported by a code of conduct and our Laboratory's stewardship values. We will continue to improve our onboarding processes and evaluate our progress with culture surveys. We strive for transparent decision-making and clear communications, enabled by mechanisms like our weekly all-staff, "all-to-all" meetings. We also promote work–life balance in support of the personal responsibilities and priorities of our staff.

Abbreviations

AFM	atomic force microscopy
AI	artificial intelligence
ALS	Advanced Light Source
ALS-U	Advanced Light Source Upgrade project
AMBER	Advanced Materials Beamline for Energy Research
AP	Approved Program
API	Application Programming Interface
APS	Advanced Photon Source
APXPS	ambient-pressure x-ray photoelectron spectroscopy
ARPES	angle-resolved photoemission spectroscopy
ASPIRES	Advancing STEM Pioneers in Research in Energy Sciences
BER	Biological and Environmental Research
BES	Basic Energy Sciences
BPM	beam-position monitor
BSISB	Berkeley Synchrotron Infrared Structural Biology
CESI	Coherence-Enabled Synchrotron Instrumentation
CSGB	Chemical Sciences, Geosciences, and Biosciences
COSMIC-U	COherent Scattering and MICroscopy upgrade
CXRO	Center for X-Ray Optics
DOE	Department of Energy
EFRC	Energy Frontier Research Center
EPICS	Experimental Physics and Industrial Control System
ESAF	Experiment Safety Assessment Form
ESNet	Energy Sciences Network
EUV	extreme ultraviolet
FAIR	findable, accessible, interoperable, reusable (principles for scientific data)
FAIR	Funding for Accelerated, Inclusive Research (DOE program)
FLEXON	FLuctuation and EXcitation of Orders in the Nanoscale
FPGA	field-programmable gate array
GISAXS	grazing-incidence small-angle x-ray scattering
GUI	graphical user interface
HHMI	Howard Hughes Medical Institute

IDEA	inclusion, diversity, equity, and accountability
IR	infrared
JGI	Joint Genome Institute
LCLS-II	Linac Coherent Light Source II
LLRF	low-level radio frequency
MAESTRO-U	Microscopic And Electronic STRucture Observatory upgrade
MERLIN	Milli-Electron-volt Resolution beamLINe
MBA	multibend achromat
MIE	Major Item of Equipment
ML	machine learning
MLaaS	machine learning as a service
MSE	Materials Sciences and Engineering
NASA	National Aeronautics and Space Administration
NCXT	National Center for X-Ray Tomography
NERSC	National Energy Research Scientific Computing Center
NIH	National Institutes of Health
NSF	National Science Foundation
NSLS-II	National Synchrotron Light Source II
OAM	orbital angular momentum
PI	principal investigator
PRT	Participating Research Team
PSP	Proposal Study Panel
QERLIN	Q-rEsolved high ResoLutIoN Beamline
R&D	research and development
RAPIDD	Rapid Access Proposals, Industry, and Director's Discretion
RENEW	Reaching a New Energy Sciences Workforce
RF	radio frequency
RIXS	resonant inelastic x-ray scattering
RSoXS	resonant soft x-ray scattering
SAXS	small-angle x-ray scattering
SBIR	Small Business Innovation Research
SIBYLS	Structurally Integrated Biology for the Life Sciences
SSRL	Stanford Synchrotron Radiation Lightsource
STEM	science, technology, engineering, and mathematics
STTR	Small Business Technology Transfer
STXM	scanning transmission x-ray microscopy

UC	University of California
USGS	United States Geological Survey
VFCCD	VeryFastCCD
VUV	vacuum ultraviolet
WAXS	wide-angle x-ray scattering
XAS	x-ray absorption spectroscopy
XMCD	x-ray magnetic circular dichroism
XPCS	x-ray photon correlation spectroscopy
XPS	x-ray photoelectron spectroscopy
XRD	x-ray diffraction