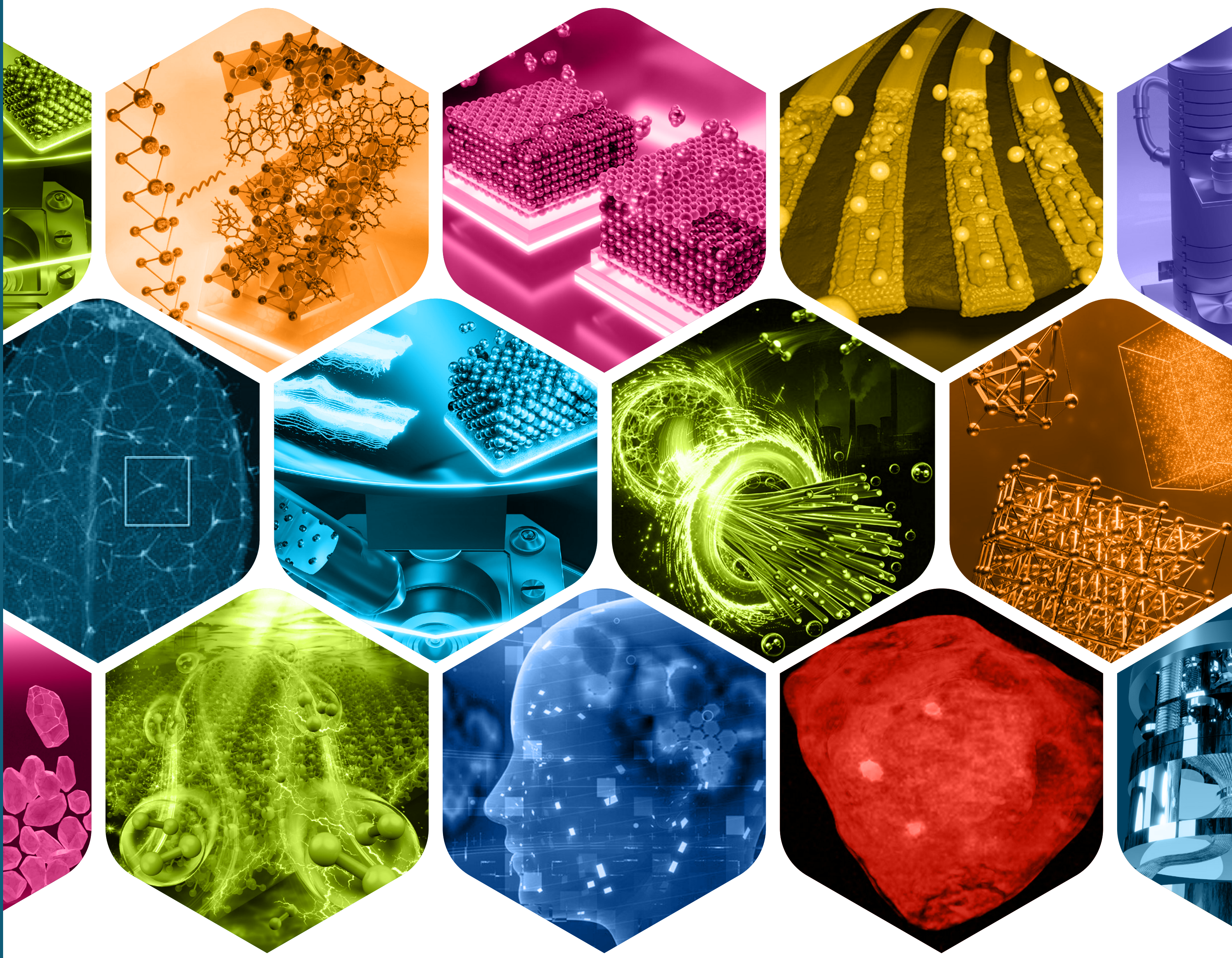
National Synchrotron Light Source II Strategic Plan 2025-2029



Brookhaven National Laboratory

Managed by Brookhaven Science Associates
on behalf of the U.S. Department of Energy

U.S. DEPARTMENT of ENERGY

Contents

Letter from the Director

I am excited to share with you the strategic plan of the National Synchrotron Light Source II (NSLS-II) that highlights how the research goals of our seven science focus areas inspire our strategic goals to develop new synchrotron capabilities that meet scientific needs, foster a collaborative scientific community and maintain operational rigor.

As a state-of-the-art synchrotron facility, we provide bright photon beams from the far infrared through the hard X-ray range, enabling multimodal research on a wide range of materials and systems. As part of the Department of Energy's (DOE) Office of Science (SC) user facility network, we are committed to driving scientific discovery and addressing critical global challenges in close collaboration with the scientific community.

As of March 2025, our accelerator operates with 98% reliability at 400 mA and we are in the midst of a multi-year accelerator development plan to ensure exceptional performance for the future.

Since beginning user operations in 2015, we have had the privilege of supporting more than 6,000 researchers at an ever-increasing number of beamlines and experimental stations. In the 10 years since first light, NSLS-II capabilities have contributed to more than 3850 publications, half of which appeared in high-impact journals. And we continue to grow (!), with 10-15 new beamlines slated for completion over the next decade.

Recognizing the importance of data science, we have made significant upgrades to our computing infrastructure, enhanced remote access capabilities, and implemented AI/ML approaches to optimize data collection and experimental planning. Over the next five years, we will continue leveraging these advancements to enhance data acquisition rates, accelerate data processing and analysis and enable autonomous experimentation across NSLS-II.

We are committed to and will continue fostering a vibrant and innovative research environment that empowers scientists across disciplines to make groundbreaking discoveries. We plan to deepen and expand our partnerships with academic institutions, government agencies, and industry leaders to ensure our research remains at the cutting edge.

A huge "thank you" to the NSLS-II staff and user community for incredible contributions to our success as facility. As we look ahead, we will continue to explore new directions and push the boundaries of groundbreaking research together.

We will drive progress towards the NSLS-II Upgrade Project (NSLS-IIU) to transform NSLS-II capabilities from "source-to-sample" including the accelerator, beamlines, sample environments, detectors, data handling and processing tools as well as auxiliary sample preparation and processing capabilities.

I am proud of what NSLS-II has accomplished in the 10 years since first light on October 23, 2014, and I look forward to continuing our efforts to transform research capabilities, support a wider range of scientific communities, and collaborate to address pressing research challenges. With the continued support and collaboration of all stakeholders, NSLS-II will remain a premier synchrotron facility that empowers scientists to push the boundaries of discovery. I look forward to the next 10 years of our journey together at NSLS-II.

-Elke Arenholz

Introduction to NSLS-II

NSLS-II is one of the newest, most advanced synchrotron light sources in the world providing research capabilities to scientists working on complex scientific challenges in materials science and processing, condensed matter physics, chemistry, life and biosciences, as well as earth and planetary sciences.

The NSLS-II electron storage ring operates at 3 GeV, with 30 pm-rad vertical emittance and top-off injection at a current of 400 mA with a reliability of 97.8% in 2024. The accelerator research and development program continuously improves the performance of the NSLS-II accelerator complex. The "Reaching Ultimate Performance" (RUP) plan will achieve our goal of 500 mA and 8 pm-rad vertical emittance as routine operation by 2029.

NSLS-II is designed to support up to 58 beamlines with 29 beamlines currently in operation (**Figure 1**). Each beamline offers state-of-the art capabilities for characterizing the electronic, chemical, and atomic structures of systems and materials, allowing researchers to explore their function at the most fundamental level. About 25% of NSLS-II experiments combine results from two or more beamlines, demonstrating that NSLS-II provides the multimodal capabilities needed to understand complex, dynamic, and heterogeneous systems of interest today.

To meet the needs of the scientific user community, existing beamlines are continuously upgraded with new optics, detectors, endstations and sample environments to enhance scattering, diffraction, imaging, and spectroscopy capabilities.

New NSLS-II beamlines are identified, designed, and constructed based on proposals from the scientific community. During the first four years of operation, NSLS-II delivered a new beamline into user operations every two months. Since 2020, the pace of adding new beamlines has been adapted to allow for 4800 - 5000 hours of user operation each year while we continue to expand the NSLS-II portfolio with new beamlines and endstations. Three new undulator beamlines are currently under construction as part of the NSLS-II Experimental Tools II (NEXT-II) project. They will become available to users by 2028. In addition, 8-12 new beamlines are under development within the scope of the NSLS-II Experimental Tools III (NEXT-III) project that is expected to conclude in 2035.

To accelerate the pace of discovery, NSLS-II develops new data infrastructure and secure access for remote experiments. The integration of robotics and automation, combined with AI/ML into beamline operations and data processing, enables real-time feedback as well as autonomous experiments and workflows at NSLS-II.

Outstanding scientific, engineering, and technical staff support the operations of beamlines and collaborate with the NSLS-II user community on experiments across a vast range of subjects, ranging from 3D imaging of dinosaur bones to real-time characterization of catalysts to identifying the intriguing properties of quantum materials.

NSLS-II by the Numbers (2024)

- *3 GeV state-of-the-art electron storage ring*
- *400 mA current with top-off injection*
- *792-meter circumference*
- *29 beamlines with space for 58 beamlines*
- *Wide spectral range, from the far infrared (down to 0.1 eV) to the very hard X-ray region (>300 keV)*
- *>2300 users from over 350 institutions*
- *>3000 proposals submitted for beam time and >1100 proposals receive beam time*
- *~230,000 hours of beam time requested and ~88,000 hours allocated*
- *>630 papers published with >50% in high impact journals (JIF > 7)*
- *15 conferences, workshops, training courses organized and over 100 facility tours lead in 2024*

The NSLS-II scientific community has grown from 110 users in fiscal year (FY) 2015 to 2340 users in FY 2024. About 75% of the users travel to NSLS-II and conduct experiments on-site while about 25% of the users access NSLS-II experimental tools remotely. Each year about a quarter of NSLS-II users are conducting experiments at our facility for the first time.

The NSLS-II user community is highly productive, generating 630+ peer-reviewed publications in FY24 with more than 50% in high impact journals (impact factor >7).

NSLS-II contributes to training the next generation of scientists in synchrotron science by hosting a wide range of training courses and workshops. Moreover, we educate the public about NSLS-II's unique capabilities, and the impact of government sponsored research through monthly public tours, an annual open house, accessible videos, as well as web stories and highlights.

As NSLS-II moves into its second decade of operations, we plan to transform facility performance "from source to sample" through an upgrade impacting all aspects of NSLS-II capabilities. The NSLS-IIU upgrade will enhance the brightness of the photon beams by up to two orders of magnitude over the spectral range covered by the facility. Existing beamlines will be upgraded to maintain leadership in key science focus areas, and new flagship beamlines taking full advantage of the upgraded source will be developed.

Further integrating automation, robotics and AI-driven research tools into automated and even autonomous workflows will enable a faster pace of discovery. The execution of these ambitious projects by outstanding, dedicated NSLS-II staff, in collaboration with the user community, partners, Brookhaven National Laboratory, and our sponsors, will solidify NSLS-II's role as a world-leading research hub for decades to come.

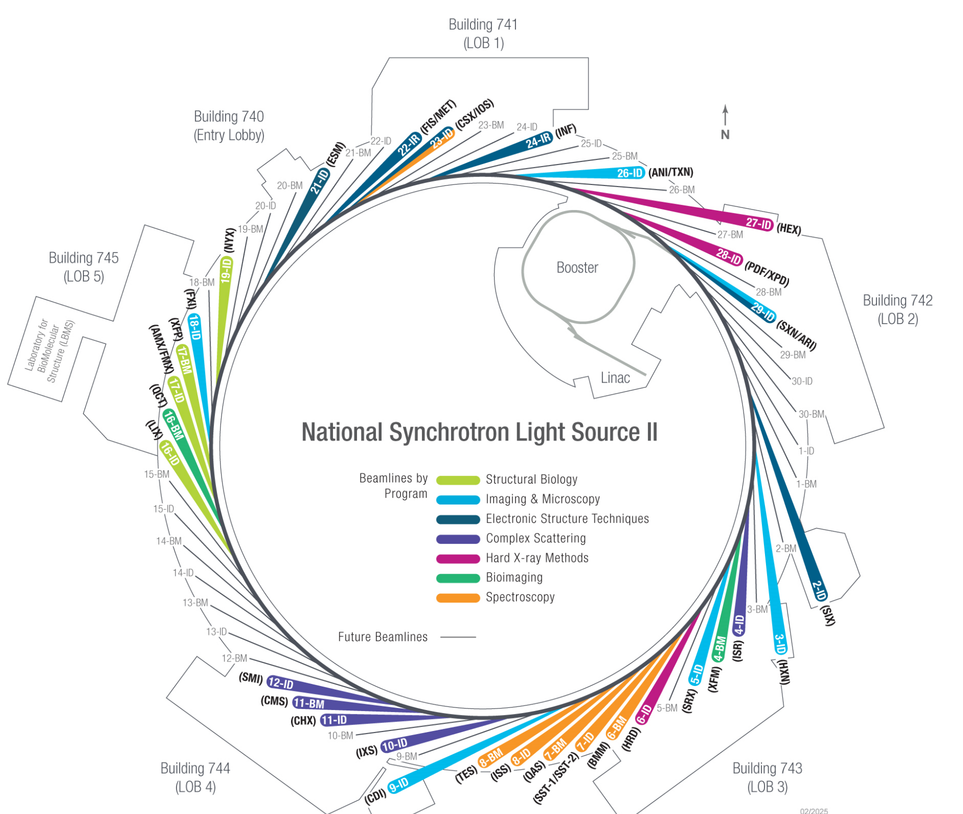


Figure 1. *As of March 2025, NSLS-II has 29 operational beamlines with capacity for 58 beamlines when fully built out. The beamlines are grouped into programs according to the methods and techniques they provide to users. Color code: Bioimaging (green), Complex Scattering (purple), Electronic Structure Techniques (dark blue), Hard X-Ray Methods (pink), Imaging & Microscopy (light blue), Spectroscopy (orange), Structural Biology (light green).*

Science Focus Areas

By analyzing the evolving landscape of science and technology research needs, we have identified seven Science Focus Areas (SFAs) that guide our development of research tools, as well as our engagement with and outreach to the scientific community (**Figure 2**). These SFAs include materials science and processing, condensed matter physics, chemical transformations and catalysis, life and biosciences, earth and planetary sciences, accelerator science, and data science.

In this section, we provide a brief overview of the SFAs and explain how they shape the goals and objectives that form the core of our strategic plan.

Materials Science and Materials Processing

Advances such as additive manufacturing and AI guidance of processes in materials synthesis and characterization are rapidly changing the landscape of materials science. They have the potential to enable energy- and material-efficient, cost-effective manufacturing of materials (**Figure 3**). From high-strength aerospace components to flexible biosensors and biocompatible scaffolds for organ growth, the applications are wide-ranging.

The fundamental mechanisms behind materials synthesis, processing, and the development of material functionalities are only partially understood today. To be fully uncovered and utilized requires fundamental research. For example, the DOE/BES Basic Research Needs (BRN) Workshop on Transformative Manufacturing (2020) identified that key scientific challenges in this area include: (1) Achieving precise, scalable synthesis and processing of atomic-scale building blocks for components and systems, (2) Unraveling the fundamentals of manufacturing processes through innovations in operando characterization, and (3) Directing atom and energy flow to realize cost-effective manufacturing.

NSLS-II is ideally positioned to address these challenges through multimodal experiments. The variety of available scattering, spectroscopy, and imaging techniques, combined with a high-brightness source, makes novel measurements possible. Strengthened by existing and emerging capabilities in high-throughput, in-situ, and operando characterization, experimental control and automation, and enhanced by AI/ML methods in experimental workflows, considerable opportunities exist for NSLS-II to impact priority research directions as identified in the BRN report.

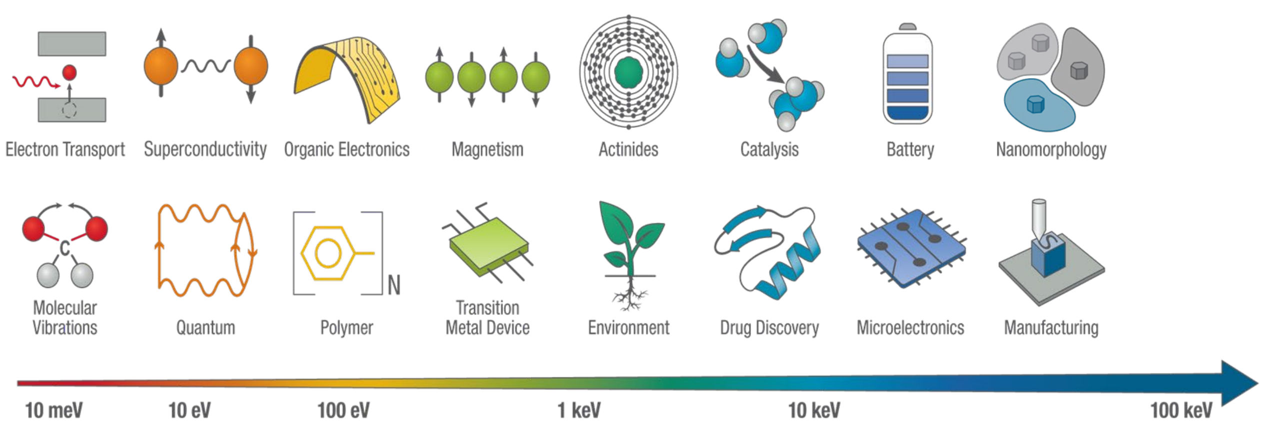


Figure 2. *NSLS-II provides synchrotron radiation from the infrared to hard X-ray region, enabling the characterization of low energy excitations as well as chemical, electronic, magnetic, and structural properties of systems and materials across disciplines.*

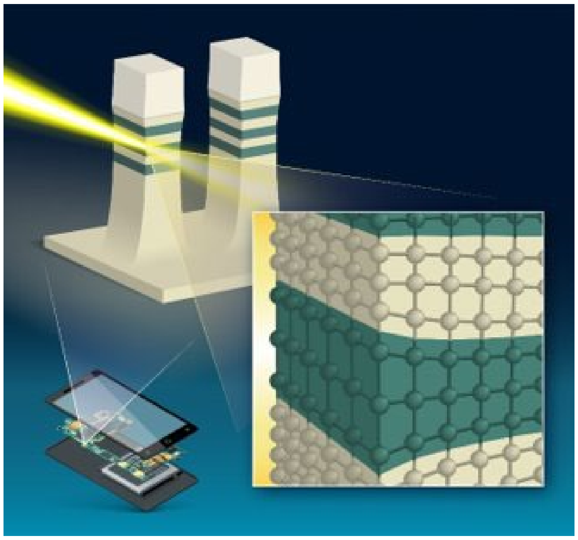


Figure 3. *X-ray diffraction mapping at the HXN beamline was used to study local distortions in nanoelectronics devices and tie atomic structure to essential performance parameters such as carrier mobility. [DOI: 10.1038/s44172-022-00011-w]*

NSLS-II's strategy to advance materials science and materials processing includes:

- Expand NSLS-II's multimodal in-situ and operando experimental capabilities for studying synthesis and processing of soft and hard materials. This includes prioritization of a dedicated beamline for advanced materials processing for real-time operando studies of the critical processes in synthesis and manufacturing.
- Develop and deploy AI/ML guided workflows for experiment design and smart and efficient experiment execution.
- Continue the engagement with users and collaborative partners to expand the advanced synthesis and processing research activities at NSLS-II.

Condensed Matter Physics

Quantum materials and quantum phenomena play a central role in condensed matter physics. These materials exhibit a rich interplay of charge, spin, and lattice degrees of freedom, giving rise to distinctive properties such as high-temperature superconductivity, topological phases, and metal-insulator transitions. These behaviors are caused by strong electronic correlations and spin-orbit coupling. By adjusting doping, pressure, and external fields, we can manipulate these emergent phenomena and uncover complex electronic phase diagrams. Gaining insight into the tunability not only reveals new fundamental physics but also opens pathways to new applications in information technology. Continued advances in X-ray instrumentation will be essential for exploring and understanding quantum materials and their unique behavior.

NSLS-II experimental tools provide insights into the atomic structure of quantum materials, their functionality, and their potential for devices. Key experimental tools include nanoscale spectroscopy probes (RIXS, ARPES) (**Figure 4**) as well as structural probes (XRD, PDF) in complex sample environments (extended temperatures, fields, pressures), and the control of beam properties such polarization, coherence, and orbital angular momentum.

To further advance condensed matter physics, NSLS-II plans strategic developments in the following areas:

- Implement stimuli (in-situ and operando if possible) to facilitate discoveries of new, sometimes subtle correlations and interactions in quantum materials.
- Increase capabilities in the tender X-ray range to perform resonant scattering (elastic, inelastic,

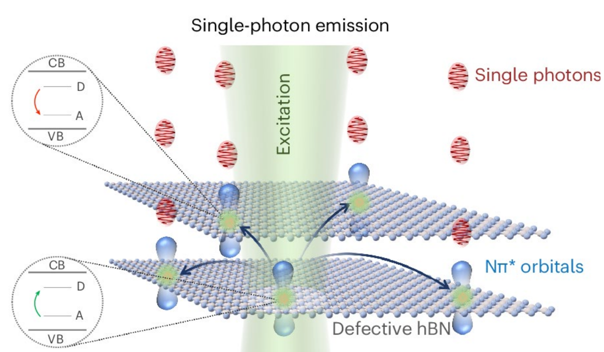


Figure 4. *Resonant inelastic X-ray scattering (RIXS) at the SIX beamline uncovered an elementary excitation in hexagonal boron nitride that is crucial for its electronic properties and its potential in quantum photonics applications. [DOI: 10.1038/s41563-024-01866-4]*

coherent) and elucidate the role of 4*d* transition metals in quantum materials.
- Further the development of ultra-fast pump-probe experimental capabilities enabled by alternative storage ring electron bunch patterns, complementing those provided by free electron lasers.

Chemical Transformations and Catalysis

The chemical reactions and transformations used in industrial production typically utilize catalysts to increase reaction rates and lower energy barriers. Understanding how intermediates interact with catalytic sites is crucial for optimizing selectivity and efficiency in chemical processes. X-ray methods naturally address key questions in catalyst characterization, particularly under working conditions, through atomic resolution characterization with elemental and chemical specificity (**Figure 5**). Capturing interfacial processes experimentally is essential for refining theoretical models and advancing predictive capabilities in catalysis research.

In collaboration with the user community, we will expand our spectroscopy and imaging capabilities to further develop molecular-level characterization of catalysts under in-situ conditions. Our focus is on understanding electronic and structural properties and tracking chemical reactions across relevant spatial, temporal, and energy scales.

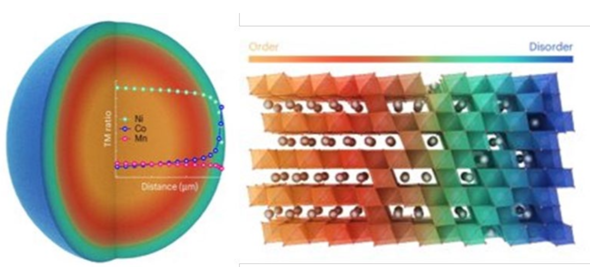


Figure 5. *Multimodal X-ray spectroscopy and imaging at the QAS, FXI, and HXN beamlines were used to characterize the ultrastable layered oxide cathode in Li-ion batteries that will enable a new generation of Li-ion batteries with both higher voltage and capacity. [DOI: 10.1038/s41560-024-01605-8]*

Key initiatives will be to:

- Advance real-time, in-situ X-ray spectroscopy and imaging techniques such as RIXS, XANES, and EXAFS for a comprehensive view of catalytic reaction mechanisms.
- Incorporate complementary non-synchrotron analytical tools to enhance NSLS-II capabilities.
- Develop automation, robotics, and remote-access systems for efficient data acquisition and processing.

Life and Biosciences

Essential processes in cells are carried out by proteins, enzymes, and their assemblies. The use of X-ray crystallography and single particle cryo-EM has been uniquely successful in delineating the atomic structures of many of these molecules and machines (**Figure 6**). However, the next challenge is to understand how these molecules are organized and interact at the cellular level, and how they are reorganized in different physiological states. Meeting these challenges requires scientific platforms that integrate synchrotron and complementary experiments while fostering collaboration among researchers to create a productive environment for tackling these complex scientific problems.

Given the range of cellular functions, the opportunities for breakthroughs are almost boundless. Examples of unanswered scientific questions include: How does the structural organization of molecules that function inside membrane-bound organelles enable them to perform specific functions? How are molecules organized as they transmit signals from the cell surface to internal components? The disease states of cells may be morphologically different; can we devise more sophisticated imaging techniques to understand the impact of disease on cell morphology and, thus, function? Ultimately, we need a four-dimensional (3D spatial and time) understanding of the structure, function, and dynamics of molecules in a cellular context.

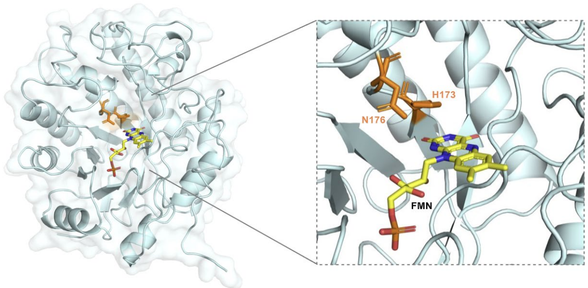


Figure 6. *X-ray crystallography at the AMX and FMX beamlines showed how enzymes can be designed to form unique C-C bonds with high selectivity*. This discovery *enables the targeted synthesis of molecules under nature's mild reaction conditions with applications for fine chemicals and pharmaceuticals. [DOI: 10.1038/s41586-022-05167-1]*

Our strategy to address these questions at NSLS-II is to pursue developments in three directions:

- Continue to develop cutting-edge *integrated structural biology* methods, including tools for measurements at ambient conditions, and establish new methods for studies of dynamic processes in both the solution state and from crystals of macromolecules.
- Seize the opportunity from advances in cell imaging and the associated improvements in image analysis to understand biomolecular structure and function in the cellular context through correlative light microscopy and electron tomography.
- Take advantage of the enormous quantities of data that will be generated. We will work with our stakeholders to ensure that data processing, analysis, management, and curation align with agreed-upon norms. Standardization of data management and analysis will facilitate the transition from data acquisition, through interpretation, to publication.

Our intention is to empower hypothesis-driven science with technology development focused on plants and microbial systems. We will enable multidisciplinary studies of complex interactions specifying the function of entire biological systems *from molecules to single cells to multicellular organisms*. We work with researchers to recognize new trends and will adapt accordingly, developing the NSLS-II beamlines with emphasis on ease of use and quality of their output.

Earth and Planetary Sciences

Earth Sciences focus on chemical speciation, bioavailability, redox behavior and cycling of nutrients and other elements at various spatial and temporal scales in the heterogeneous materials of Earth's near-surface environment (or Critical Zone), continental crust, oceanic crust, oceans, and atmosphere (**Figure 7**). The complexity of these molecular interactions poses interesting challenges for all branches of earth science, as do the range of length scales (from nano- to mega-meters) and enormous temporal range (from pico- to peta-seconds) over which these interactions occur. To further complicate the picture, biology (notably through carbon) has a profound influence on the cycling of critical elements on the Earth's surface, and

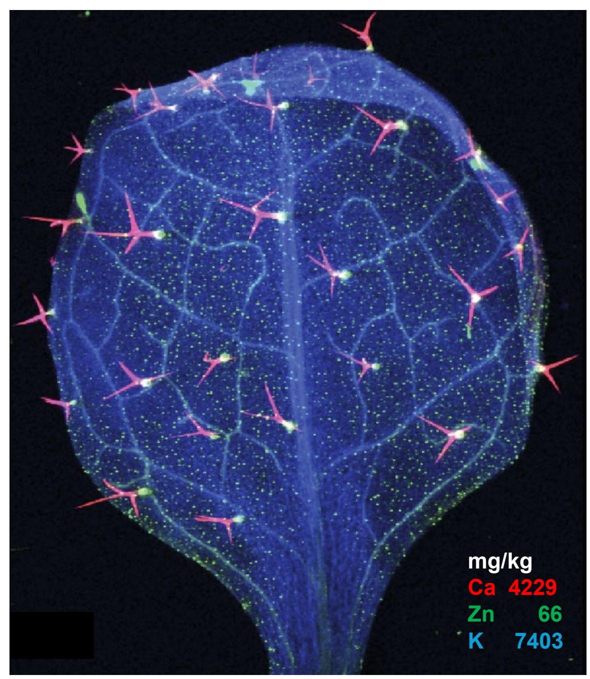


Figure 7. *X-ray fluorescence microscopy at the XFM beamline combined with other techniques established that hydrogen- and calcium-ion exchange in plant cells contributes to plant growth and stress response and showed how suppressed ion uptake can improve anoxia tolerance. [DOI: 10.1111/pce.14756]*

the pathways of carbon cycling are linked intimately to biogeochemical processes of other life-sustaining elements (e.g., Fe, S, P).

These complexities over large length and time scales provide an exciting opportunity for NSLS-II to leverage its multimodal, multiscale capabilities and enable forefront research in earth sciences. Integration of synchrotron approaches (microscopy, microprobe, bulk) that characterize a variety of properties (electronic structure, atomic structure) is important to study earth systems (rocks, soils, sediments, water, and atmosphere). There is no single spatial scale or element that can adequately describe Earth's surface processes. However, integration across spatial scales and elements (e.g., C, Ca, Fe) is a unique strength of NSLS-II and allows addressing some of the most pressing Earth science questions. Many of these questions relate directly to changing environments, complex feedback mechanisms, buffers, and tipping points, and link chemical, physical, and structural aspects of both bulk and surface processes. To further our understanding of whole-Earth and environmental systems, their components, and cycles as systems in motion, we need to answer these questions.

In planetary science, future return missions (to Mars for example) will yield samples sealed in Ti-alloy sample containers. To analyze these (and other) samples, complementary, non-destructive, in-situ synchrotron-based techniques that yield high-resolution, high-sensitivity, structural, mineralogical, morphological, and chemical characterization without breaking containment will be extremely impactful.

Our overall strategy to grow Earth and planetary sciences at NSLS-II focuses on further developing multimodal capabilities that span a wide range of energy and spatial scales. Some specific goals are:

- Bridge the current spatial resolution gap between existing microscopy beamlines and expand spectroscopy in the soft/tender energy range from the micro- to nanoscale resolution.
- Pursue in-situ, non-destructive synchrotron-based techniques for contained samples that yield complementary structural, mineralogical, and chemical information.
- Develop high-throughput imaging modes and deliver new capabilities of interest to this community such as micro-CT and scanning transmission X-ray microscopy (STXM).

NSLS-II will continue developing synchrotron-based analytical techniques to meet the research needs of the earth and planetary sciences community.

Accelerator Science

The NSLS-II accelerator performance has advanced towards its design parameters in routine operations of a stored beam current of 500 mA with emittances of 1 nm·rad and 8 pm·rad in the horizontal and vertical planes, respectively. The Reaching Ultimate Performance (RUP) Plan (2017–2029) serves as the roadmap for the next five years for accelerator developments, including projects enhancing the resilience of critical accelerator systems and completing the RF system construction.

NSLS-II will also continue to invest in advancing storage ring operations through studies of alternative bunch patterns for timing experiments, the development of broadband hybrid feedback systems for stabilizing beam orbit and X-ray beam trajectories, lattice optimization, and innovations in beam diagnostics—all aimed at increasing the facility's scientific

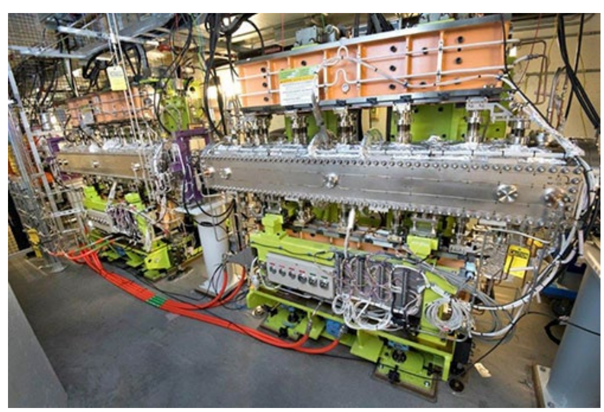


Figure 8*. The undulators inside the storage ring are one source of NSLS-II's bright X-ray beams.*

productivity.

The design and construction of longer insertion devices (IDs) with shorter periods and higher peak fields, as well as new front-end designs, are of particular interest for maximizing the performance of new NSLS-II beamlines, i.e. increasing brightness, photon flux and/or coherence (**Figure 8**).

The NSLS-II upgrade project, NSLS-IIU, currently under consideration, is designed to achieve a horizontal emittance of 20 pm·rad, enabling unprecedented brightness and coherent flux for experiments at NSLS-II. Several technical and engineering questions are being addressed to reduce and mitigate the risks associated with the upgrade project.

The accelerator science research directions align with the following key objectives:

- Achieve and maintain beam reliability, stability, and intensity in NSLS-II operations.
- Enable advanced accelerator capabilities—introducing novel timing modes, sub-picosecond pulses, and access to far-infrared and terahertz radiation—while evaluating the potential for a free-electron laser at Brookhaven and exploring compact light source technologies. Simultaneously, advance research for next-generation light sources and the NSLS-II upgrade.
- Enhance simulation methods, design tools, and AI/ML-driven tools for operations and R&D.

These priorities drive us to lead or contribute to collaborations with partner organizations, leveraging developments across the global accelerator community.

Data Science

NSLS-II beamlines provide researchers with a wide range of world leading scientific capabilities. Acquiring, storing, processing, and analyzing data are fundamental for each experiment. Our data acquisition infrastructure is based on Bluesky, a modern open-source toolbox for experiment control, data acquisition and data management (**Figure 9**). It was initially developed in the early years of the NSLS-II and has since grown into a worldwide collaboration and is maintained by the broader synchrotron community.

To meet the needs for future experiments, we are employing automation and robotics, and secure remote access. AI/ML will be deeply integrated into beamline optimization, as well as experiment planning and execution. As an indication of what will be possible, we have demonstrated autonomous, simultaneous multimodal synchrotron experiments guided by real-time data analysis using the tools within Bluesky Adaptive.

A crucial part of our strategy is integrating NSLS-II with self-driving materials discovery platforms. These platforms can enhance experimental throughput, optimize parameter spaces and accelerate materials characterization. To date, many existing materials discovery systems operate within isolated feedback loops – often constrained by their infrastructure – limiting their impact, especially where multi-technique analyses are necessary. NSLS-II is addressing this

Figure 9*. Bluesky (indicated by a "b" in a cloud in the bottom center of the diagram) is a software toolbox for experimental control, collection, management, and analysis of scientific data. Developed at the NSLS-II using an open development model and released under an open-source license, Bluesky is adopted as a standard across BES light sources and is increasingly used worldwide as other facilities transition to it. [DOI: 10.1016/j.xcrp.2022.101112]*

challenge by developing a facility-wide standardized multimodal Internet-of-Things (IoT) ecosystem that will integrate several experimental techniques and enable autonomous workflows, remote operation, and efficient sample lifecycle management.

To support the scientific community and accelerate the pace of discovery, we will enhance our data science capabilities over the next five years as follows:

- Develop and deploy AI-driven autonomous controls for experiments.
- Accelerate discovery through an Internet-of-Things data infrastructure.
- Design and deploy advanced data systems on new and existing beamlines.

All three are closely related and combined will have tremendous impact on NSLS-II operations and research.

Achieving Our Vision and Mission

This five-year strategic plan covers the beginning of the second decade of NSLS-II operations. We will maintain and further improve both accelerator and beamline performance, expand the beamline portfolio, and advance experimental capabilities to meet the evolving needs of the scientific community and advance our science focus areas. Further integrating automation, robotics, and AI-driven research tools will enable a faster pace of discovery and increase the overall impact of our facility.

We are also preparing for the NSLS-II Upgrade (NSLS-IIU) "from source to sample" to transform the performance of our facility. The upgrade will boost the brightness of NSLS-II photon beams by up to two orders of magnitude across the facility's spectral range. We will develop new flagship beamlines to fully leverage the source, and upgrade existing beamlines to remain at the forefront of key scientific fields. Autonomous workflows will be incorporated across all aspects of facility operations, ensuring NSLS-II continues to provide world-class support for groundbreaking research.

To further enable leading science across our focus areas over the next five years, we have identified four key strategic goals, each with specific objectives that we will pursue to achieve our vision and mission (**Figure 10**). These efforts align with our guiding motto "*Together, we shine light on the world's most challenging scientific problems*" and are described in detail in the following sections.

Vision: *To be an extraordinary hub for the use of synchrotron radiation to solve the world's most challenging scientific problems that will improve our lives for decades to come.*

Mission: *To develop and operate a premier user facility that safely and efficiently enables high-impact and cutting-edge science and technology across multiple disciplines for the benefit of society.*

Motto: *Together, we shine light on the world's most challenging scientific problems.*

Figure 10*. NSLS-II's vision, mission, and motto.*

Goal 1: Develop New Synchrotron Capabilities to Meet Science Needs

Advanced insertion devices, optics, detectors, and precise beamline models will enable higher spatial and spectral resolution, along with increased sensitivity, helping to address new scientific questions from the research community. Equally important is the exploration and development of novel experimental methods that harness advanced beam characteristics—such as brightness and coherence. Therefore, our first strategic goal is to develop new synchrotron capabilities, from source to sample, to advance the NSLS-II science focus areas and meet the evolving needs of science both today and in the future.

Develop New Experimental Methods

Working with the scientific user community, NSLS-II will continue to develop new, and improve existing, experimental methods to extract important information about samples of interest in new ways. In this section, we describe experimental X-ray methods being developed at NSLS-II that take advantage of coherent flux and brightness.

Full-field Coherent Imaging

In pioneering experiments, NSLS-II scientists and users demonstrated that the diffracted intensity of coherent X-rays directed onto a magnetic sample is reduced near the domain boundaries (**Figure 11**). Based on this "interference," we can determine the

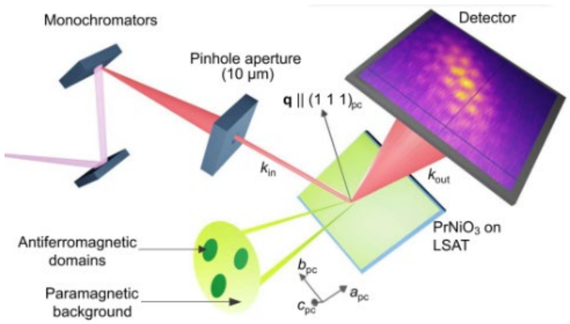


Figure 11. *Experimental geometry for full-field coherent imaging at the CSX beamline. This geometry was used to demonstrate that the arrangements and sizes of antiferromagnetic domains in PrNiO3 can be extracted from a single diffraction pattern. [DOI: 10.1126/sciadv.abn6882]*

spatial arrangement of domain boundaries and study domain morphology, domain transformations, and their time evolution, particularly across magnetic phase transitions in ferro- and antiferromagnetic systems.

The technique reveals state recurrence in magnetic systems, behavioral inhomogeneity, and the selective relevance of specific domain regions and their local excitations (e.g., stripes, bubbles). Understanding these phenomena is important for potential applications in low-power computation and memory electronics.

Extending the technique from the soft to the tender X-ray regime at NSLS-II to cover absorption edges of 4d elements will be particularly valuable to study angular momentum-driven physics in spintronics applications. This includes the development of next-generation memory devices, such as magnetic random-access memory (MRAM), and energy-efficient logic components that leverage spin-orbit coupling for faster data processing. An increase in coherent flux through the NSLS-II upgrade will significantly enhance the spatial and temporal resolution of this full-field coherent imaging technique, enabling real-time visualization of magnetic domain dynamics in complex materials and multilayer heterostructures used in advanced electronics and quantum computing platforms.

Coherent Correlation Imaging (CCI)

NSLS-II has developed a novel direct coherent X-ray imaging method, Coherent Correlation Imaging (CCI), based on classifying recorded images of magnetic domains in Fourier space and averaging selectively over same-state frames. This method allows the study of thermal fluctuations in ferromagnetic materials in real time and real space with nanometer-scale resolution and chemical sensitivity. CCI opens opportunities for video-like imaging of stochastic processes within a finite ensemble of possible states with high spatial resolutions.

The CCI method will benefit from planned advances in fast soft X-ray area detectors at NSLS-II, AI-assisted data analysis and, ultimately, the dramatically increased coherent flux provided by the NSLS-II upgrade. We expect CCI to evolve from a singular experiment into a routine tool for materials science, particularly for in-situ investigations under external stimuli such as magnetic fields, electric currents, temperature changes, or optical switching.

Our goal is to improve CCI's spatial resolution to below 5 nm, enabling detailed observation of nanoscale texture fluctuations at their fundamental length and time scales. This will provide an unprecedented understanding of the underlying physics in these materials. Potential applications include imaging magnetic domain wall profiles in next-generation data storage devices, analyzing spin textures at material defects in quantum computing components, and resolving magnetic structures below the exchange length—such as Bloch points—which are critical for the development of spintronic technologies, high-density magnetic memory, and skyrmion-based devices.

X-ray Quantum Correlation Imaging and Scattering

Conventional imaging methods capture an object's image by monitoring the radiation it transmits, reflects, or scatters. By contrast, "ghost imaging" is a method of nonlocally imaging an object by transmitting a pair of correlated photons through the object

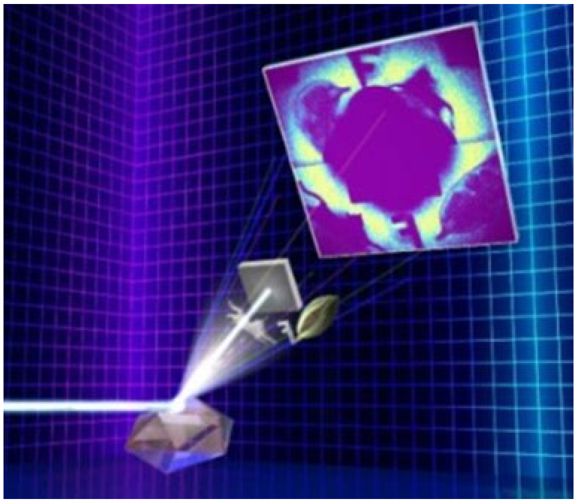


Figure 12. *Ghost imaging is a method of imaging an object by transmitting a pair of correlated photons through the object and a reference optical system, then reconstructing the image from the coincidence rate of these two photons. It will significantly reduce radiation dose on samples to enable new studies at NSLS-II. [DOI: 10.1364/CLEO_FS.2024.FM4B.1]*

and a reference optical system, then reconstructing the image from the coincidence rate of these two photons (**Figure 12**). NSLS-II has advanced amplitude interferometry to pioneer X-ray scattering techniques analogous to "ghost imaging" which has most commonly been performed with visible light. Further developing this novel X-ray imaging method, dubbed 'X-ray quantum correlation imaging/ X-ray quantum correlation scattering' (XQCI/XQCS), will leverage recent advances in X-ray optics and detector technology at NSLS-II to perform coherent diffraction experiments such as coherent diffraction imaging (CDI) and X-ray photon correlation spectroscopy (XPCS) with unprecedented spatial and temporal resolution. It will also significantly reduce radiation dose which is essential for imaging biological and other radiation sensitive materials and enable new studies at NSLS-II.

Nanoscale Reciprocal Space Mapping (nanoRSM)

Strain, i.e., the distortion of a crystal lattice, plays a crucial role in determining the chemical and physical properties of crystalline materials. Quantifying, understanding, and controlling strain at the nanoscale are essential for tailoring material properties to enhance material performance for specific applications – for example improving electron mobility in semiconductors, increasing catalytic activity at surfaces, and enhancing the mechanical properties of materials.

By combining an X-ray nanoprobe with X-ray diffraction techniques, we can achieve high-resolution strain mapping in tiny crystallites where conventional methods fail due to insufficient flux density. Using a nanobeam to measure the reciprocal space map (RSM) at each probed location, we generate spatially resolved strain maps with nanometer precision.

Looking ahead, this technique of nanoRSM will be further enhanced with Bragg ptychography, a method that reconstructs three-dimensional strain fields from coherent diffraction patterns. Its development will be important for characterizing next-generation microelectronics, energy storage materials, and advanced functional materials.

With X-ray's high penetration power and sensitivity to strain, nanoRSM provides critical structural insights inaccessible by other techniques, paving the way for advanced materials design and optimization.

Instrumentation for Sub-10 nm Nanofocusing, Nano-tomography, and Laminography

To achieve sub-10 nm resolution with tomographic nanoprobe instruments, an absolute positioning mechanism with high stiffness, minimal heat dissipation, and fast scanning capabilities is essential.

NSLS-II is developing a novel line-focusing interferometer-based global sensing system that will enable nanoscale resolution 3D tomographic imaging at existing and future nano-imaging beamlines. Initial testing demonstrated over a 1 kHz data acquisition rate with tomography reconstructions with the voxel size below 10 nm.

Based on the results of the ongoing work, we will design and construct a prototype of a laminography instrument to be built for NSLS-II. The instrument will enable fast imaging of 2-inch silicon wafers with the ptychography resolution <10 nm. These wafers have a range of applications, including advanced microelectronics, integrated photonics, and quantum computing devices, where precise structural characterization is essential. They can also be used for the development of novel semiconductor architectures, nanoscale sensors, and MEMS, supporting innovations in next generation computing and communication technologies.

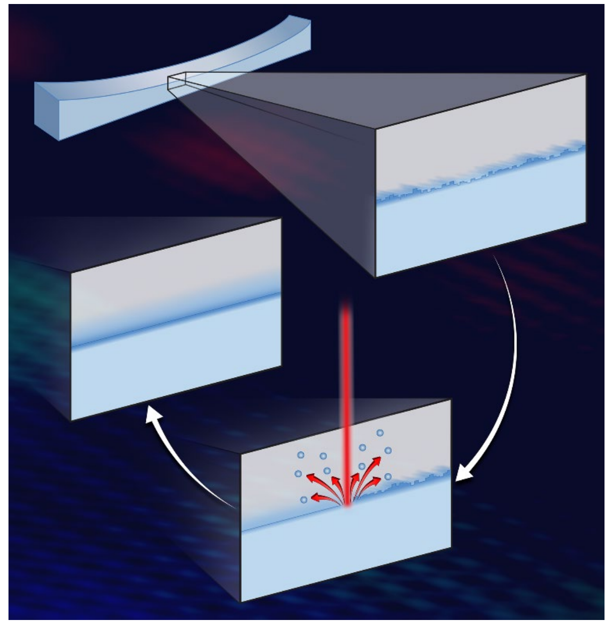


Figure 13. *NSLS-II is further developing X-ray mirror fabrication using ion beam figuring (IBF) as the final step after shaping and polishing to correct residual errors in the height and slope profile and converge to the strict requirements demanded for X-ray applications. IBF is a non-contact method that uses a beam of energetic ions (red) to gently sputter material from the target mirror (blue), ensuring a stable and linear removal with minimal deterioration of surface micro-roughness.*

Develop Novel Insertion Devices to Enhance Beamline Performance

To secure competitiveness of NSLS-II beamlines, our accelerator division is focusing on further developing insertion devices (IDs) with the goal of achieving (1) shorter periods, (2) higher peak fields with low amplitude and phase errors, (3) longer device lengths, and (4) the ability to control and change the polarization of undulator radiation.

A prototype of a superconducting adaptive gap undulator (AGU) is being constructed with the goal of a 5-meter-long device providing a smoothly variable aperture without constraining beam dynamics in the storage ring. The second project is focused on designing short and high-field 3-pole wigglers.

In the context of the NSLS-II upgrade, a novel ID concept based on tandem superconducting undulators (SCUs), separated by a triplet, correctors, a BPM and a phaser, is under consideration. This device would more than triple the brightness of the highest-performance ID currently in the NSLS-II undulator suite, thanks to its optimized beam optics, short period and long undulator design.

Such high brightness is critical for nanoscale applications that rely on tightly focused, highly coherent X-ray beams to probe matter with extreme precision. This includes advanced imaging techniques as well as in situ studies of catalysts, quantum materials, and biological macromolecules—where detecting subtle structural or electronic changes at nanometer or even atomic resolution can drive breakthroughs in materials science, energy security, and biomedical research.

Advance X-ray Optics, Detectors, & Simulation Tools

To provide next-generation X-ray optics, detectors and simulations, NSLS-II will advance several key technologies, including optics fabrication and metrology, R&D of detectors for soft and hard X-ray imaging and spectroscopy, as well as the creation of digital twins for beamlines and imaging experiments.

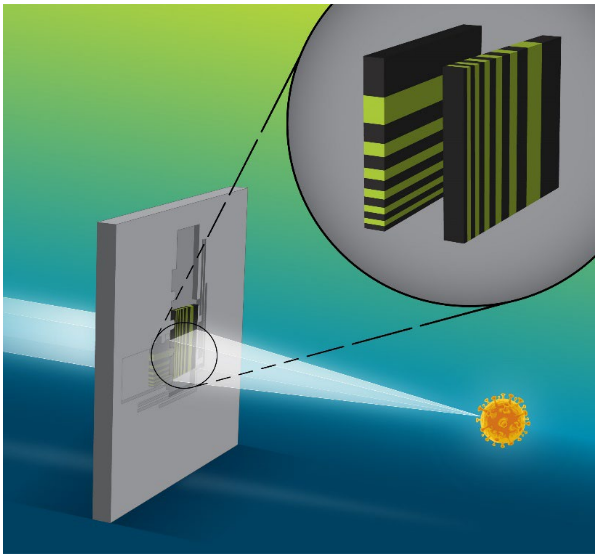


Figure 14. *NSLS-II will continue to advance sub-10 nm focusing by bonding two multilayer Laue lenses (MLLs) into a single 2D optic in a well-defined configuration as shown above. The monolithic 2D MLL devices will become standard hard X-ray nanofocusing optics to be implemented at the existing and future imaging beamlines of NSLS-II and other synchrotron facilities.*

X-ray Optics

Since 2018, NSLS-II has been advancing X-ray mirror fabrication using ion beam figuring (IBF) (**Figure 13**). By leveraging our extensive database of experimental mirror fabrication and metrology data, we will identify the key parameters critical for IBF and further improve the understanding and application of IBF processes in the fabrication of high-curvature X-ray mirrors.

Over the next five years, NSLS-II will continue advancing 2D surface metrology for X-ray optics. Our prototype stitching interferometry platform has already achieved sub-nanometer precision. To support the characterization of mirrors for tender X-rays, we are expanding the angular range to ~5 mrad. In parallel, we are exploring methods such as Collimated Phase Measuring Deflectometry (CPMD) and Optical Coordinate Measuring Machine (OCMM) for strongly curved mirrors (>10 mrad) and complex 2D-curved mirrors, like toroidal and ellipsoidal designs.

NSLS-II has delivered world-leading nano-focusing of hard X-ray beams to 12nm using multilayer Laue lenses (MLLs) (**Figure 14**). To enable sub-10 nm focusing, monolithic 2D MLL devices will be further developed to become the standard hard X-ray nanofocusing optics implemented at existing and future imaging beamlines at NSLS-II and at DOE facilities.

Detectors

NSLS-II will continue to develop unique detectors tailored for specific applications.

We are developing imaging detectors using silicon and germanium sensors, where each 100 µm pixel in the array functions as a high-energy-resolution spectrometer.

R&D on a Deep-Junction Low-Gain Avalanche Detector (DJ-LGAD), optimized for soft X-rays, will continue. The sensors will incorporate precise signal conditioning and allow for easy integration with existing readout solutions, such as Timepix, FFFI, and MM-pad.

We will construct a 384-element Ge detector for fluorescence imaging at photon energies above 20 keV featuring a central hole that enables the probe beam to pass through the detector and reach the sample, providing a large collection solid angle.

A prototype of a germanium-based detector, equivalent to silicon-based drift detectors (SDDs), is under development to enable the construction of large-area, ultra-low-noise Ge detectors.

Finally, we are evaluating new sensor materials for very hard X-rays (>20 keV) to complement Ge and CdZnTe detectors.

These detectors will have high sensitivity in the X-ray energy range for frontier experiments including time-resolved studies, high-throughput spectroscopy, and operando measurements under extreme sample environments. Their advanced capabilities will support next-generation experiments at NSLS-II and beyond, enabling researchers to push the boundaries of spatial, temporal, and energy resolution.

Simulations

A 3D magnetostatics computer code for insertion devices and accelerator magnets, Radia, and an optimizer code for sorting and shimming such magnets, IDBuilder, will be further developed and applied at NSLS-II.

The Synchrotron Radiation Workshop (SRW) simulation code enables high accuracy, high efficiency calculation of partially coherent synchrotron radiation, including its emission and propagation through beamlines. This code will be extended to ensure that all X-ray optical elements in new beamlines can be simulated to a high accuracy.

Simulation capabilities for X-ray photon correlation spectroscopy experiments in SRW will be further expanded to other coherence-demanding imaging techniques, such as X-ray coherent diffraction imaging, holography and ptychography. These simulations will be included into "digital twins" of beamlines, enabling the identification of optimal instrument settings before experiments and facilitating the testing and refinement of experimental data processing algorithms and software.

These digital twins will improve the efficiency and economy in configuration and execution of leading experiments such as operando spectroscopy of catalytic reactions and ultrafast X-ray scattering to probe phase transitions.

Goal 2: Advance Towards the Next Generation of NSLS-II

As part of our long-term strategy, we will continue to optimize our accelerator performance, add new beamlines to fill the existing capability gaps, and prepare for a facility upgrade "from source-to-sample". These initiatives will retain NSLS-II leadership in the field of synchrotron facilities and allow NSLS-II to continue to meet its mission of delivering world-leading science through to the mid-21st Century.

Deliver Ultimate Accelerator Performance

Since 2018, NSLS-II has enhanced accelerator performance through the *Reaching Ultimate Performance (RUP)* Plan, which is expected to be successfully completed by 2029. The plan has two objectives: (a) to improve reliability and resilience of the NSLS-II accelerator complex to faults and failures, ensuring the delivery of synchrotron radiation to users for over 97% of the scheduled 5,000 hours of operation per fiscal year, and (b) to achieve the ultimate design performance of the accelerator, specifically emittances of 700 pm-rad (horizontal) and 10 pm-rad (vertical) at operating currents of 500 mA. Reaching ultimate performance will increase the fraction of spatially coherent X-rays at NSLS-II, advancing and enabling coherence-demanding experiments that require nanometer-sized focused beams, including imaging strain fields in nanoscale materials, studying dynamics in complex fluids, and visualizing nanoscale defects in quantum materials.

The RUP plan consists of several projects, each intended to increase operation reliability and introduce redundancy in the least resilient subsystems, i.e., RF-system, cryo-system, injector, and high-power supplies, while also providing an inventory of spare components that are readily available in case of equipment failures.

As of March 2025, the spare inventory is fully stocked, three RF systems are operational, and the installation and commissioning of the spare superconducting (SC) RF cavity is nearing completion. The cryo-system, which was the largest source of downtime a few years ago, is now equipped with a helium purifier, a redundant compressed air system, and a backup battery system to protect it against power interruptions lasting less than two seconds.

NSLS-II will continue to develop the standby units for storage ring and booster dipole power supplies, the third harmonic cavity system, and the fourth RF system to complete the RUP.

The obsolescence of controls, diagnostics and other instrumentation is becoming an increasing concern, impacting accelerator reliability. A new accelerator reliability project will address the obsolescence of accelerator subsystems, including BPMs, PLCs, LLRF controllers, scopes, etc., to ensure their uninterrupted service in the next five years and beyond.

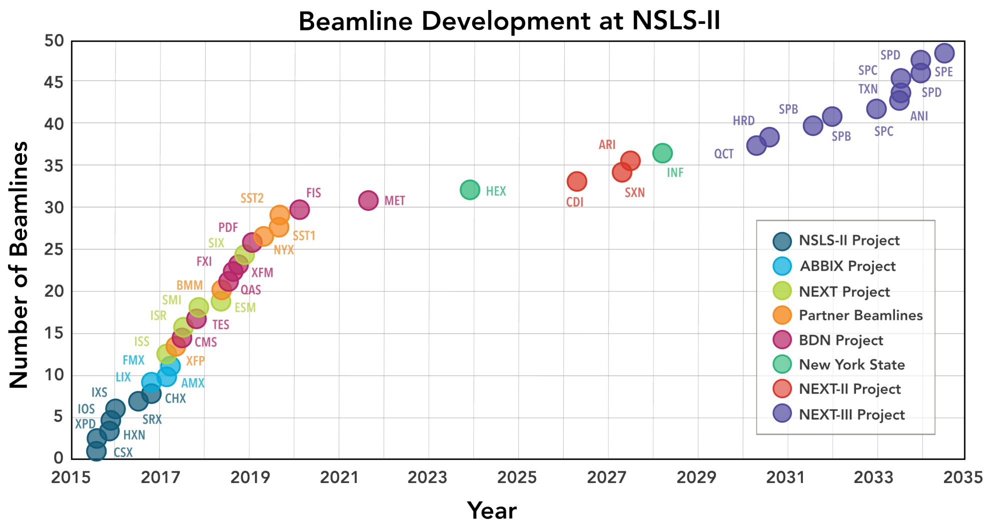


***Figure 15**. During the first 4 years of operation, NSLS-II delivered a new beamline into user operation every 2 months. Since 2020, we have ramped up accelerator operations to approximately 5000 hours of user operations each year to maximize scientific productivity while we continue to expand the NSLS-II portfolio with new beamlines and capabilities. (SPB, SPC, SPD, and SPE are NEXT-III subproject beamlines yet to be determined.)*

Continue to Expand the NSLS-II Beamline Portfolio

The NSLS-II layout can fit up to 58 beamlines and, as of March 2025, 29 beamlines are in operation. Over the next decade, up to 15 additional beamlines will be designed, constructed, and transitioned into user operations (**Figure 15**). Fourteen of these beamlines are funded through two DOE projects and one beamline is funded by New York State. Each new beamline will provide cutting edge capabilities for characterizing and understanding the structure and function of novel materials and systems.

Complete the NEXT-II Beamline Construction and Transition to Operations

The NSLS-II Experimental Tools II (NEXT-II) project is a beamline development and construction project funded by DOE-BES to deliver three world-leading imaging beamlines to NSLS-II by 2028: The Coherent Diffractive Imaging (CDI) beamline, the Angle-Resolved Photo-Electron Spectroscopy & Resonant Inelastic X-ray Scattering Imaging (ARI) beamline, and the Soft X-ray Nanoprobe (SXN) beamline.

The CDI beamline will provide lensless imaging capability in Bragg diffraction and transmission geometries over the energy range from 5 keV to 15 keV with nanoscale spatial resolution. The CDI beamline's novel optical design will provide beam sizes from 1 to 10 microns, with highly uniform wavefronts—a critical capability for imaging strain within crystalline structures. The beamline will feature a selectable energy bandpass that enables delivering longitudinal coherence over large samples or high flux for small samples. The CDI beamline is housed in a new satellite building to provide sufficient space for simultaneous measurements at two separate scattering vectors with a variable sample-to-detector distance from 0.5 to 10 m in a stable environment. When the CDI beamline becomes available to users in 2026, the beamline will deliver a truly unique capability in the US for 3D strain imaging of micron-size samples using full-field illumination, complementing the scanning-probe nanoscale diffraction imaging capability of the NSLS-II HXN beamline. This technique will enable researchers to visualize internal stress distributions in microelectronic devices, monitor strain evolution during in situ mechanical testing of materials, and investigate deformation mechanisms in advanced structural alloys and energy materials.

The ARI and SXN beamlines will share a straight section but operate independently with each having its own undulator installed canted in the straight. The ARI beamline will combine ARPES (electronic bandstructure) and RIXS (quasi-particle excitation) measurements with a 100 nm spot size that is scanned across the sample to create 2D spectral maps. The ARI beamline will be equipped to map out the temperature-dependent, chemical, magnetic, and atomic properties of samples. A sample transfer system will connect measurement and preparation chambers. The use of KB mirrors (>10^{11} ph/s) will enable true nano-imaging revealing novel electronic structures associated with 2D quantum materials and their heterostructures such as graphene for flexible electronics, sensors, or quantum computing platforms.

The SXN beamline will offer state-of-the-art soft X-ray nano-spectromicroscopy tools with world-leading coherent photon flux. The energy range (250 eV – 2500 eV) enables studies of the morphology and chemical composition of a wide range of systems and technologically important materials. Both scanning transmission X-ray microscopy (STXM), and ptychography (<10 nm resolution) will offer simultaneous measurement of X-ray fluorescence, X-ray absorption, and total electron yield (TEY). With these capabilities, the SXN beamline will impact a wide range of scientific disciplines including catalysis, condensed matter physics, and environmental science.

As of March 2025, the designs of the CDI, ARI, and SXN beamlines are complete, and most of the beamline components are awarded for procurement. The CDI beamline is scheduled to receive first light in 2025, and the ARI and SXN beamlines will see first light in 2026. Completing all three beamlines on time and budget is a high priority for NSLS-II.

Advance the NEXT-III Project

We received CD-0 and CD-1 approval for the NEXT-III project in September 2022 and September 2024, respectively. The NEXT-III project will build 8-12 new beamlines with world-class capabilities complementing the existing NSLS-II beamline portfolio. NEXT-III will be executed as a series of 5 subprojects, referred to as Subproject A through E (**Figure 16**). A new subproject is launched every 2-3 years and includes the design and construction of 2-3 new beamlines. This staged approach enables us to design and build beamlines that address emerging research directions and take advantage of the latest technological developments.

NEXT-III beamlines are selected for design and constructions in collaboration with the user community and NSLS-II Science Advisory Committee. Based on the beamline concepts proposed at the 2019 NSLS-II Strategic Planning Workshop and input from the NSLS-II Science Advisory Committee (SAC), 14 full beamline proposals were developed and considered for subprojects A and B. Two ad-hoc external panels were formed, and they reviewed and scored the proposals. The NSLS-II SAC discussed the reviews and categorized the proposals into high, medium, and low priorities. A satellite NEXT-III workshop was held as part of the NSLS-II/CFN Users' Meeting in April 2023 to solicit further user input.

Based on the external review panel reports, the SAC prioritization, and the input from the satellite workshop, NSLS-II management defined the scope of Subproject A to build the High-Resolution Powder Diffraction (HRD) beamline and Quantitative Cellular Tomography (QCT) beamline and to design the Advanced Nanoscale Imaging (ANI) beamline and the Tender X-ray Nanoprobe (TXN) beamline.

The HRD beamline is a dedicated high-resolution powder diffraction instrument optimized for both high-throughput and in-situ studies, delivering unprecedented resolution. For example, it enables precise phase identification and quantification in complex battery electrode materials during charge-

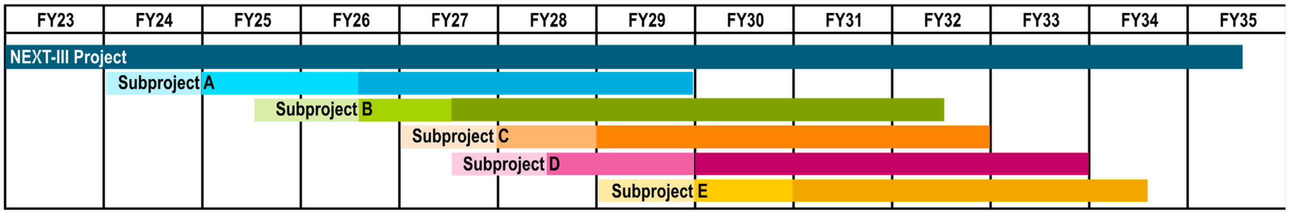


Figure 16. *Timeline for the NEXT-III project. NSLS-II will design and construct 8-12 new beamlines over the next 10 years. NEXT-III will be executed as a series of 5 subprojects, referred to as Subproject A through E. A new subproject is launched every 2-3 years and includes the design and construction of 2-3 new beamlines. This staged approach enables us to design and build beamlines that address emerging research directions and take advantage of the latest technological developments.*

discharge cycles and can resolve subtle structural changes in pharmaceutical compounds under varying temperature and humidity conditions.

The QCT beamline will provide a high-throughput analytical approach for imaging individual frozen-hydrated intact cells. This enables detailed 3D visualization of subcellular structures such as mitochondria or viral entry pathways in infected cells, making it a powerful tool for biomedical research and drug development.

The ANI beamline enables high-throughput and high-resolution 3D imaging using hard X-rays, offering structural, elemental, chemical, and strain characterizations across a wide range of sample systems. For example, researchers can investigate the 3D microstructure of battery electrodes during charge/discharge cycles, revealing how lithium distribution and mechanical strain evolve over time.

The TXN beamline will provide high-throughput, high-sensitivity, and high-resolution scanning probe microscopy with tender X-rays, emphasizing in-situ and operando compatibilities. For example, TXN will be ideal for probing organic electronic materials, such as thin-film semiconductors in flexible devices, where soft interfaces and buried layers require nondestructive, element-specific contrast.

The NEXT-III project also includes the development of a new software platform, *N3XTware*, that will integrate controls, data flows, and data analysis in one data infrastructure, to meet the user data needs for the future. *N3XTware* includes data pipelines, autonomous workflows, remote operations, beamline status indicators, sample lifecycle monitoring and workflows, as well as tools for testing and development.

The NEXT-III Subproject B will include the construction of the ANI and TXN beamlines. Both are long beamlines with endstation hutches in a satellite building about 200 meters from a canted pair of high brightness undulator sources, with a phasing magnet in between, located in a long straight of ~9 meters.

Moreover, the design and construction of the Advanced Materials Process (AMP) beamline is part of Subproject B. The AMP beamline will be optimized for operando studies of materials processing under real conditions similar to those in industrial-scale advanced manufacturing platforms, using SAXS, WAXS, XPCS, and imaging. For example, the AMP beamline could be used to monitor the real-time formation of nanostructures during additive manufacturing of metal alloys, providing insights into phase transitions, grain growth, and defect evolution under processing conditions.

NSLS-II will solicit beamline development proposals for Subproject C-E in 2025 following a similar review and decision process as for Subprojects A and B.

Delivering the NEXT-III project on schedule and within budget is a key priority in the NSLS-II strategic plan. By 2035, 8-12 NEXT-III beamlines are expected to be in user operation.

Completing the Probes for Quantum Information (PQIM) Project

The Probes for Quantum Information (PQIM) project, funded by New York State's Empire State Development Corporation (NYSERDA), will deliver a suite of advanced scanning probe instruments to accelerate the characterization and development of quantum information materials and devices at BNL. Within the scope of this project, NSLS-II will develop the Infrared Nanospectroscopy Facility (INF) beamline. The INF beamline will provide three independent photon beams spanning photon energies ranging from the far-IR (155 cm^{-1}) to the near-IR (5000 cm^{-1}), illuminating three simultaneously operating endstations. The first endstation will feature a scanning near-field nanospectrometer for samples in ambient conditions. The second endstation will provide a nanospectrometer system for cryogenic samples and high magnetic fields. The third endstation will consist of a pair of infrared microscopes. The INF beamline will be designed and constructed over the course of the next 3 years and is expected to transition into operations in 2028. Timely, on-budget completion of the INF beamline is a key NSLS-II strategic priority.

Work with Sponsors to Develop Additional Beamlines

With NEXT-II and NEXT-III projects expected to be completed, NSLS-II will host 41 to 45 beamlines for user research by 2035. NSLS-II will collaborate with our sponsors to secure appropriate funding for staffing and operation of these outstanding capabilities. With a full capacity of 58 beamlines, NSLS-II will continue working with the broader scientific community and potential sponsors to develop additional science cases and funding strategies for the remaining beamlines, as well as ancillary capabilities to meet the evolving research needs of the scientific community.

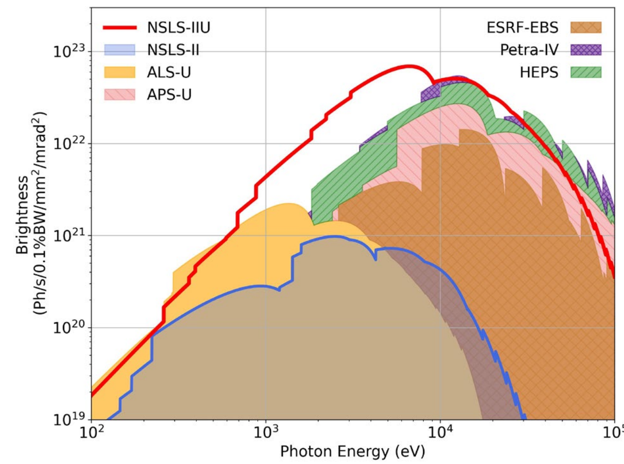


Figure 17. *Calculated brightness curves for current and future synchrotron facilities. The upgrade of NSLS-II (NSLS-IIU) would provide world leading brightness and coherent flux in the soft and tender X-ray range (up to 10 keV) as well as competitively high brightness in the hard X-ray range (> 10 keV). Parameters used for the brightness calculations are as follows: NSLS-II U (4 GeV, 400 mA), ALS-U (2 GeV, 500 mA), ESRF-EBS (6 GeV, 200 mA), HEPS (6 GeV, 200 mA), NSLS-II (3 GeV, 400 mA), APS-U (6 GeV, 200 mA), Petra-IV (6GeV, 200 mA)].*

Progress Towards the NSLS-II Upgrade

In addition to delivering the ultimate performance of the NSLS-II accelerator and expanding the NSLS-II beamline portfolio, we will pursue and prepare for the facility upgrade, NSLS-IIU. NSLS-IIU will revolutionize NSLS-II capabilities from source to sample to meet the rapidly advancing needs of the scientific community (**Figure 17**).

Enhance the Transformative Science Case

As of March 2025, NSLS-II hosts 29 beamlines, excelling in imaging, spectroscopy, diffraction, and scattering. We routinely integrate techniques across multiple beamlines for multimodal experiments and have strong expertise in data science. 15 additional beamlines will be designed, constructed, and transitioned into user operations in the next decade.

However, even at current outstanding performance levels, NSLS-II will not be able to fully meet the needs of future scientific challenges. The systems of interest are heterogenous, complex, and dynamic. To understand the underlying basic science requires characterization methods and instruments that span multiple length, time, and energy scales - delivering exquisite resolution and sensitivity, enabling studies under operando conditions, and integrating results from multimodal experiments.

One compelling example is the challenge of understanding the mechanisms behind solid-state battery degradation. These next-generation energy storage systems involve complex interfacial reactions, nanoscale phase changes, and ion transport phenomena that occur on ultrafast timescales. Tracking these dynamic processes in real time, at the nanoscale, and under realistic operating conditions, requires dramatically brighter X-ray beams than currently available.

To track and image dynamic processes on the relevant time and length scales, will require ~50-fold increase in brightness of the photon beams provided by NSLS-II. Such an increase would make NSLS-IIU the brightest source in the world in the next decade and beyond. Moreover, new X-ray methods, novel sample environments and detectors as well as optimized data and computing infrastructure and capabilities will be necessary.

In close collaboration with the user community, we have developed the concept of a "whole facility" upgrade. This approach optimizes each component of an experiment, including the source, beamline optics, sample environments, detectors, data infrastructure, and ancillary capabilities for sample processing and preparation.

A series of strategic planning and brainstorming workshops with NSLS-II staff and the scientific community led to the development of the science case for the NSLS-II upgrade, documented in the "Proposal to Upgrade NSLS-II" report in 2021.

The Future Scientific Facilities subcommittee of the Basic Energy Sciences Advisory Committee (BESAC) reviewed and rated the NSLS-II Upgrade as "absolutely central" to addressing future science challenges and maintaining US global competitiveness in synchrotron science.

NSLS-II will continue preparing for the upgrade by further developing and strengthening the NSLS-IIU science case. In collaboration with the User Executive Committee (UEC), we will hold additional science workshops at NSLS-II Users' Meetings, such as the one planned for April 2025. Moreover, annual dedicated workshops will engage the scientific community in discussions on emerging scientific questions, novel scientific methods, experimental capabilities, and needs related to data infrastructure, data sciences, AI/ML, automation and robotics. The outcomes of these workshops will be summarized in reports to further refine and enhance the science case for NSLS-IIU.

Understanding and Mitigating Risks in the Accelerator Upgrade

We will continue refining the technical and engineering aspects of the accelerator upgrade, as detailed below.

Prototype Testing of the Complex Bend in the NSLS-II Storage Ring

Proposed and developed at NSLS-II, the complex bend magnet (CBM) is planned as the main building block for the ring lattice of the future facility upgrade. This novel technology promises to push the storage ring design far beyond the state-of-the-art and offers high brightness X-rays, large space in the ring lattice for long undulators, and a considerable savings in electric power needs due to the extensive use of permanent magnets rather than conventional electromagnets.

From FY22 to FY24, a prototype CBM assembly was successfully designed and constructed with support from the Brookhaven Laboratory Directed Research and Development program (**Figure 18**). This prototype consisted of an array of permanent magnets

Figure 18. *Full-scale prototype of a Complex Bend has been developed and tested with BNL funding. The prototype magnet element features 15 PMQs at 130 T/m and 0.5 T producing exquisite field quality.*

providing both dipole and quadrupole fields, along with an associated vacuum chamber. The project provided valuable insights into designing CBMs including sourcing of permanent magnet materials, understanding their magnetic characteristics, and refining the fabrication and installation process for CBMs.

While the CBM function has been well studied theoretically, the next step is to evaluate its performance in an operating electron storage ring. We are seeking funding to design, build and install a set of CBMs and vacuum chambers in the current NSLS-II storage ring, replacing two existing dipole magnets. The CBMs would be commissioned with the NSLS-II electron beam and operated under normal conditions for an extended period allowing the real-world performance evaluation beyond theoretical models.

We note that the CBMs used in this evaluation will differ from those planned for the NSLS-II upgrade. Due to the larger electron beam diameter in the current NSLS-II lattice, the prototype vacuum chambers and magnetic gaps must be larger than those in the final NSLS-IIU design.

Installing CBMs in the NSLS-II storage ring will complement other ongoing efforts—such as simulations, offline prototyping, and experimental evaluations of radiation effects on magnetic properties (via linac installation)—and further validate the CBM concept.

In addition, we plan to design and install horizontal and vertical scrapers in the NSLS-II storage ring to investigate how varying physical aperture impacts injection efficiency. We also plan to design and construct a prototype 12-pole electromagnet corrector to simulate multipole errors in strong focusing CBM and examine the effects on beam dynamics.

Developing A Prototype Injection System for the NSLS-II Upgrade

Current injection methods, such as on-axis swap-out (APS-U, ALS-U) and off-axis linac-based techniques (Spring-8-II, MAX-IV), often require costly injector upgrades (e.g., high-current electron guns) or introduce operational complexity (e.g., FEL-type full-energy low-emittance injectors). For NSLS-IIU, we propose a compact, innovative alternative: two nonlinear kicker magnets (NLKs) strategically placed near the injection point to rapidly suppress injected beam oscillations within a fraction of the first turn.

This approach minimizes dynamic aperture requirements and prevents disturbances to the stored beam by maintaining on-axis, zero-field, and zero-gradient conditions, ensuring seamless top-off injections for users. Additionally, it is a cost-effective and operationally efficient solution.

To validate this concept, we plan to develop nonlinear pulsed magnets and install a prototype in the current NSLS-II ring for beam-based testing. This approach will help mitigate injection efficiency losses due to collective effects in high-intensity stored beams while enhancing the overall performance of the NSLS-II injection system.

Investigating Collective Effects to Ensure High Beam Intensity for NSLS-II Upgrade

The high particle density in short, intense electron bunches leads to strong collective effects that significantly increase emittance, limiting the achievable brightness at operational beam intensities. For the NSLS-II upgrade, we will address this risk through a comprehensive study of collective effects, combining computer simulations, bench tests, and beam-based measurements funded through BNL funds.

Key vacuum system components, including the small-aperture complex bend chamber, tapered transitions, RF-shielded flanged connections, and APS-U-type RF-shielded bellows, will be tested on a dedicated test bench using a 50 GHz network analyzer and Goubau lines to measure their impedances and detect any manufacturing defects, such as poor electrical contacts. Beam-based tests of these components will take place in the test straight section of NSLS-II to assess thermal heating and vacuum performance. Additionally, experimental studies on intrabeam scattering and Touschek lifetime will be conducted to scale these effects for the NSLS-II upgrade.

The successful completion of this research will increase confidence in meeting the expected performance of the upgraded NSLS-II at its operational beam intensity.

Additional R&D Projects Enabling NSLS-IIU

Additional R&D programs to understand and mitigate risks associated with the NSLS-II accelerator complex upgrade include:

- Mechanical engineering of critical magnets
- Engineering of elements of front-end and vacuum systems
- Electronics engineering of high-performance beam diagnostics and machine controls

R&D projects at NSLS-II, focused on developing new methods, optics, detectors, and data infrastructure, are detailed in previous sections of this strategic plan. These initiatives will enhance and expand NSLS-II's capabilities, regardless of the upgrade. However, the upgrade's significantly increased brightness will amplify their impact, maximizing their scientific reach and impact.

Goal 3: Grow and Foster a Collaborative Scientific Community

A synchrotron light source like NSLS-II brings together people with different backgrounds and skills to pursue common goals. NSLS-II's 370+ staff, and its 2300+ users, have vast amounts of scientific, engineering, and technical expertise across scientific and R&D disciplines and each person is contributing their unique part to make a research project or a development task successful. We want to grow and nurture our collaborative scientific community to positively impact the scientific endeavor.

This strategic goal will cover three strategies to enhance scientific collaboration: (1) attract, develop, and retain a talented workforce, (2) extend the user community to expand facility impact, and (3) promote industrial basic research.

Attract, Develop, and Retain a Talented Workforce

We recognize that the impact of NSLS-II is based on the collaboration of individuals with expertise covering a broad range of scientific, engineering, and technical skills. We also recognize the need to nurture these collaborations and to attract, develop, and retain a talented workforce to maintain NSLS-II as a leading research facility. This also includes supporting the continued career development of staff and prioritizing succession planning to ensure knowledge transfer from departing staff.

Career Development and Work-Life Balance

We consider NSLS-II's talented staff its most valuable asset. As the facility continues to grow, attracting and retaining expert staff and supporting their career development is critical. To ensure staff development and retention, we are committed to a structured career development and work-life balance plan.

One component of this effort is BNL's mentoring program, which NSLS-II has implemented and supports. The mentoring program pairs employees with mentors outside their management chain to provide career guidance. NSLS-II human resources managers identify staff who could benefit from mentorship and facilitates participation.

Work-life balance is a concern for many staff, especially given NSLS-II's 24/7 facility operations. BNL has a flexible work policy that allows flexible and compressed work schedules as well as hybrid work arrangements. We support staff to manage the varying workloads associated with beamline operation and maintenance periods. Additional measures include developing a new BNL Staff and User Code of Conduct and establishing a balanced schedule for weekends, holidays, and maintenance shutdowns for NSLS-II staff.

The initiatives are designed to boost staff engagement and satisfaction while ensuring that the facility operates smoothly.

By addressing and emphasizing work-life balance and career development, NSLS-II seeks to foster a supportive work environment that enables staff to thrive as the facility expands its scientific program.

Update the Director's Postdoc and Graduate Student Program

NSLS-II has a director's postdoc and graduate student program that funds several postdocs and graduate students to pursue a research project at NSLS-II in collaboration with NSLS-II scientific staff. This program provides a direct pipeline to attracting and

Figure 19. *Participants from the Brookhaven User Facility Summer School take a lesson in full-field X-ray imaging at the FXI beamline from graduate student Jonathan Goettsch. Over 300 undergraduate and high school students have been trained in synchrotron science at NSLS-II over the past 5 years.*

potentially recruiting scientific and engineering staff at the facility. We are reimagining this program to align with the strategic direction of the facility. Additional NSLS-II postdoc positions are funded through the BNL LDRD program.

Expand Impact of the SkillBridge Program, Community Colleges, and Trade Schools

The Department of Defense's SkillBridge program provides active service members with civilian work experience in their final 180 days of service, connecting them with industry and national laboratory partners.

We welcomed our first SkillBridge interns in 2024 who contributed to the RF/cryo group as well as the electrical engineering group in the NSLS-II accelerator division and eventually accepted technician positions at NSLS-II. We will continue to welcome SkillBridge interns to the facility. The program has been a valuable pipeline for technical talent at BNL.

NSLS-II will continue outreach efforts to regional colleges, including community colleges and trade schools, hosting visits from local and regional groups, and participating in BNL-wide activities like Summer Sundays, i.e. the BNL Open House. These initiatives attract talented individuals and build a strong pipeline for the NSLS-II's workforce.

Engage a Broader User Community to Expand Facility Impact

To maximize the long-term impact of NSLS-II, we will foster relationships with the next generation of scientists, strengthen our connections with the local community, and reach out to new scientific disciplines.

Educate the Next Generation of Staff and Users

NSLS-II developed a graduate-level course on synchrotron sciences in 2015 that is taught by NSLS-II scientific staff in person at regional universities and colleges, e.g. Yale University, University of Pennsylvania, and Stony Brook University, and virtually at institutions across the US and abroad. We will continue this effort in the coming years to further develop and expand the NSLS-II user community and contribute to the development of the next-generation scientific workforce.

We will also continue to hold hands-on training workshops for graduate students on topics including X-ray absorption spectroscopy, macromolecular crystallography, small-angle X-ray scattering, and cryo-electron microscopy (**Figure 19**).

A recent expansion of our programs is the Brookhaven User Facility Summer School that provides community college and high school students with a hands-on STEM experience across three BNL user facilities – the Tandem Van de Graaff Facility, the Center for Functional Nanomaterials (CFN), and NSLS-II.

Hands-on training courses and targeted outreach activities will continue to play a crucial role in educating and training the next generation NSLS-II staff and users.

Figure 20. *Every summer, NSLS-II welcomes over 1,000 visitors from the community to tour the facility. The so-called "Summer Sunday" is one of many outreach events hosted by NSLS-II to inform the public about the scientific discoveries and career opportunities available at NSLS-II.*

Engage the Local Community

We will continue hosting our monthly public tours and annual Summer Sunday event to engage with the local community (**Figure 20**). Members of the public can sign up to visit NSLS-II on guided tours to learn about NSLS-II and select beamlines during a 1.5-hour visit.

Each summer, Summer Sunday offers several full-day BNL open house events where community members get to know NSLS-II through guided tours of the experimental floor and accelerator tunnel. Visitors can become "junior operators" by running a model synchrotron, looking through microscopes, building a crystal structure out of candy and toothpicks, and watching liquid nitrogen demonstrations. These events engage hundreds of local residents, strengthen community relationships, inspire future and current NSLS-II and BNL staff, and foster a supportive local environment.

Support Emerging and Existing Scientific Communities

NSLS-II supports strong programs in catalysis, quantum information science, materials sciences, and structural biology. Synchrotron techniques have the potential for an even broader reach in areas such as paleontology, cultural heritage, and mining and mineral processing. Targeted efforts will continue to engage these and other emerging scientific communities and support their use of the impactful tools provided by NSLS-II.

To support both emerging as well as existing NSLS-II user communities, NSLS-II will continue to work closely with its Science Advisory Committee (SAC) to conduct periodic reviews of the NSLS-II beamline programs to assess the following areas of beamline operations: (a) scientific utilization, output, and impact of the beamlines and how well they serve the associated user communities, (b) programmatic synergies, developments, and future directions, and (c) staffing and operational efficiencies and effectiveness.

Addressing the recommendation by the review committees will strengthen the NSLS-II research program for the future.

Promote Open Communications Culture to Encourage Engagement by Staff and Users

The NSLS-II Users' Executive Committee consists of NSLS-II users elected by the NSLS-II user community and represents user interest to the NSLS-II leadership team and other stakeholders. The NSLS-II leadership team has monthly meetings with the UEC chair and co-chair to discuss topics relevant to the user community.

The NSLS-II Staff Council was formed to enhance communications between NSLS-II management and NSLS-II staff. Staff council members are appointed by the NSLS-II director and represent the range of NSLS-II employees including administrative, technical, engineering, safety, operations, and scientific staff. The Staff Council evaluates topics of interest to the NSLS-II community, e.g., our meeting culture. The NSLS-II director attends the meeting upon invitation by the Council to discuss ideas, concerns, and potential solutions.

The weekly NSLS-II All-Hands Update Meeting is hosted by the NSLS-II director and includes updates on recent and upcoming events at NSLS-II and BNL, safety reminders, summaries of new BNL policies as well as other current topics of interest to the NSLS-II community. The introduction of new staff and recognition of work anniversaries and staff honors are included as well.

"Cookie-Time" occurs every two weeks and is an informal gathering of NSLS-II staff and users to chat about science and related topics over coffee and snacks.

Recurring meetings with NSLS-II stakeholders such as DOE and other sponsors as well as the local community are opportunities to showcase NSLS-II accomplishments and obtain an understanding of stakeholder expectations. BNL Stakeholder Relations typically handle local community interactions through public events and the Community Advisory Council monthly meetings. These activities ensure public support and trust.

NSLS-II will continue these meetings and interactions and add additional channels to promote an open communications culture and to encourage engagement by staff and users.

Promote Industrial Basic Research

Industrial research is a vital part of the NSLS-II research program portfolio and a key component of its mission.

A recent example is the extensive use of NSLS-II and other US light sources during the COVID-19 pandemic by industry as well as academic researchers to study molecular structures of the virus and small-molecule complexes for vaccine and drug development.

NSLS-II supports research and development across industry sectors, including energy generation and storage, advanced materials development, and pharmaceutical R&D along the discovery-to-deployment research pathway.

To promote industrial R&D partnerships and incorporate industry perspectives, NSLS-II includes industry scientists in its proposal review panels and science advisory committee wherever possible.

Through focused workshops, three key areas have been identified to strengthen industrial research at NLS-II: (1) enhanced scientific support for industry users, (2) flexible and timely access to beam time, and (3) common access protocols among National Laboratory facilities.

We are committed to supporting both non-proprietary and proprietary industrial research at our facility. For non-proprietary research, the beam time proposal review criteria include indirect societal and economic impact as an evaluation factor. For proprietary research, NSLS-II proprietary rates are set by DOE Order 522.1A chg. 1 and direction by the Brookhaven Site Office (BHSO). Established policies and procedures guide proprietary research, and users can submit proposals at any time through rapid access, taking advantage of beam time on any NSLS-II beamline.

Over the next five years, we plan to further develop the industrial research program. This development will include advancing scientific capabilities tailored to industrial applications, such as in-situ and operando techniques with automated specimen handling under industry-relevant conditions.

Strong partnerships with industry will be promoted through collaborations with beamline staff, participation in beamline programs via partner users, and pursuit of SBIR/STTR funding. Flexible and timely access modes are implemented to meet industry needs within the framework of the NSLS-II User Access Policy.

Communications and outreach will be expanded through the NSLS-II "For Industry" webpage, targeted workshops, training sessions, and participation in conferences of interest to industrial users. Additionally, NSLS-II will collaborate with industrial liaison offices at universities, other BES light sources, and related organizations to strengthen industry connections.

Tracking industrial research through user statistics, publications, funding sources, and corporate impact statements will provide insights into industry needs and highlight NSLS-II's contributions. Coordination within the DOE complex will help establish common protocols for industry access to user facilities, ensuring a streamlined and effective approach to industrial research at NSLS-II.

Goal 4: Maintain Operational Rigor

NSLS-II strives to create and maintain a vibrant and supportive research environment where everyone – whether a staff member or a visiting researcher – feels secure, confident, empowered, and energized to contribute to the facility's success. Achieving this goal requires a safe and respectful workspace, effective collaboration among scientists and support staff, and the necessary infrastructure to ensure that staff and visiting researchers can work at the NSLS-II facility safely, efficiently, and effectively. As an integral part of our strategy for the next five years, we outline the initiatives and development activities we plan to pursue in the areas of safe and secure operations, transformative user service, mission-critical infrastructure, and securing supply chains for critical components of the NSLS-II accelerator and beamlines.

Ensure Safe and Secure Operation

Advances in several key scientific areas present unique challenges in terms of safety and security. Utilizing highly reactive or radioactive materials necessitates special sample environments designed to contain hazards. Other experiments represent biohazards to staff and users necessitating the use of special containment and spill controls to facilitate this research. Moreover, we need to ensure that samples, technology, and data can only be accessed by authorized staff and users. This section focuses on how

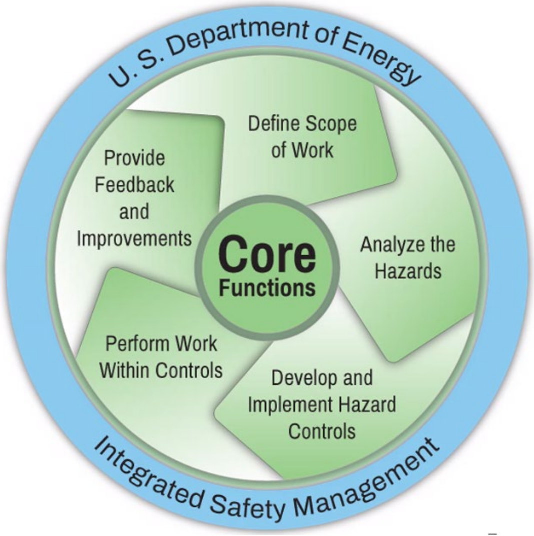


***Figure 21**. NSLS-II follows the Department of Energy's Integrated Safety Management. The five core safety management functions provide an effective structure for any work activity that could potentially affect the workers, the public, and the environment. The functions are applied as a continuous cycle with the degree of rigor appropriate to address the type of work activity and the hazards involved.*

NSLS-II continues to ensure safe and secure research at the facility in the future.

Establish and Implement Effective Safety Policies to Meet Evolving Science Needs

The goal of the ESH&Q program is to enable cutting-edge scientific research while ensuring safety and environmental responsibility (**Figure 21**). Certain scientific advancements introduce extraordinary hazards that require proactive planning to mitigate potential safety and environmental impacts.

The Experimental Safety Review (ESR) and the Safety Approval Form (SAF) processes are mechanisms for reviewing experiments to ensure they are executed in a safe and environmentally sound manner. The ESR process establishes *de minimis* quantities thresholds for hazardous materials, above which a more extensive review is required. These review processes, combined with institutional review requirements, are the primary means of authorizing high-hazard experiments.

NSLS-II will continue to adhere to requirements for determining allowable sample quantities, reviewing and approving procedures, and developing hazard specific sample environments to contain and control the spread of hazardous materials. We plan to expand use of contained gas handling systems for the distribution of gases including monitoring and detection systems.

The goal of our efforts is to support the environment, safety, and health needs of staff and users in an effective and efficient manner.

Deliver Effective Capabilities for Secure Research in Targeted Areas

We recognize that, in some cases, experiments at NSLS-II may require security and protection controls, resulting in specialized handling of technology, samples and data collected from them. To enable these experiments, we will continue to collaborate with scientists to meet their research needs.

Research proposals are evaluated for research security requirements to maintain compliance with DOE directives, laws, institutional requirements, and NSLS-II processes. Screening and extended reviews consider materials, sample environments, technology, technical information, and data. Risk levels will be assessed, and research and development activities are authorized as appropriate.

NSLS-II will continue to coordinate closely with other departments at BNL, as well as other laboratories, to enable research in targeted areas based on mission needs and NSLS-II capabilities. We strive to achieve and maintain effective and efficient processes.

Transform the User Experience

The COVID-19 pandemic highlighted the impact of changing external conditions, evolving expectations, and new opportunities for the collaboration between NSLS-II staff and the user community in achieving research goals. Remote access experiments became routine, and collaborations expanded from single-investigator projects to large-scale partnerships. The unexpected and sudden changes in policy and practice associate with the pandemic helped NSLS-II become nimble when faced with unprecedented challenge – and is a lesson learned for future challenges.

As needs and expectations continue to evolve—along with safety and security requirements, software platforms, and the development of new tools—NSLS-II will adapt its approach to planning and executing science to remain a leading research facility.

User Information Systems

In today's world, we are accustomed to interacting with on-line services through a convenient "dashboard" that provides quick access to essential information. DOE user facilities should be no different. Users need access to a centralized platform to submit proposals and safety forms, complete online training, obtain appointments with the User Office, and access their publications and data. Currently, NSLS-II users navigate these tools through separate systems that we plan to integrate into a streamlined, user-friendly dashboard.

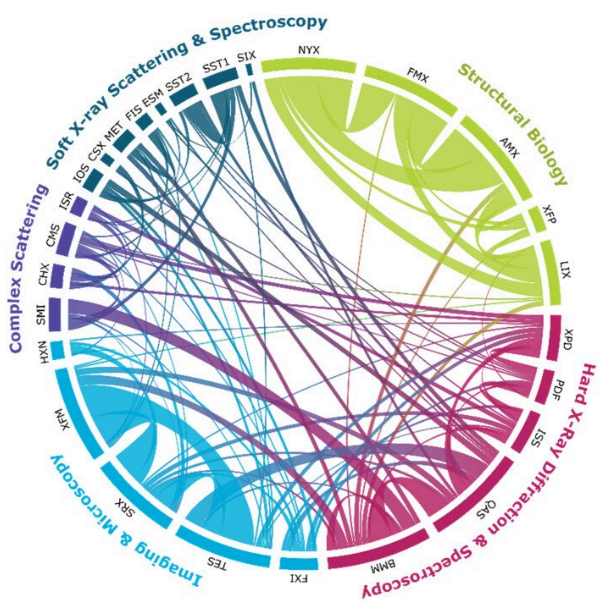


Figure 22. *NSLS-II beamtime proposals allow requesting beamtime at multiple beamlines. About 25% of users at NSLS-II request more than one beamline to address their scientific problems. Key to the NSLS-II user experience is to optimize these multimodal experiments and integrate them with data analysis tools.*

To keep up with these changes, we plan to develop new open-source software modules for the individual components of user services software. The user information system (UIS) modules will include an updated proposal system that accommodates single-investigator proposals, multiple-investigator teams, the growing demand for multimodal research, rapid access for hot topics, proprietary research, and partner groups requiring regular access to beam time in exchange for equipment and/or staff contributions (**Figure 22**). We are considering campaign proposals, which are large, thematic proposals for beam time dedicated to strategic research areas for DOE and other stakeholders.

Safety requirements and expectations for user experiments are continually evolving and user proposals need to be assessed and reviewed accordingly. The proposal review process now includes evaluation of research and data security. The current NSLS-II Safety Approval Form (SAF) system will be updated to accommodate new types of reviews. In the coming years, NSLS-II will evaluate evolving needs and develop a strategy for a new SAF system to address these new requirements.

In addition to the proposal and SAF systems, the new UIS modules for NSLS-II will provide users with access to information on guest appointments, user agreements, training status, keycard access, and data. NSLS-II has established a Software Information Systems (SIS) team that will spearhead this work in collaboration with the User Office, scientific staff, users, and Brookhaven's IT department.

Continue to Evolve the User Proposal Review Process

In FY24, we launched revised proposal review criteria for the first time in 10 years, now including the consideration of indirect societal impact. Proposals are now evaluated based on scientific, technological, industrial, and/or national security importance (45%), the quality of the experimental plan (40%), and indirect societal impact (15%). For the latter, proposals are now evaluated on how the research may impact economic competitiveness, workforce development, education, outreach, and expansion of the user community.

In the coming years, we will continue to refine and improve our proposal review criteria to encourage new user groups to participate and to maintain overall fairness. For example, NSLS-II currently uses a single-blind review process where the reviewers remain unknown to the principal investigator (PI) but the names of the PIs on a proposal are known to the reviewers. NSLS-II is considering piloting a double-blind review process, where the experimenters' names, affiliations, and publications are not revealed to the reviewers. NSLS-II will consult with some of the federal funding agencies already conducting double-blind reviews of their funding proposals and develop an effective method for implementing such a review process.

Other ideas include making the proposal system point-based, where credit would be given to new investigators with proposals that did not make the cut-off, or for PIs from scientific areas new to synchrotron research.

Deliver Effective Communications and Agile Access Processes

For a facility like NSLS-II to thrive and best serve the nation's scientific and technological needs, communicating the expertise, capabilities, and success of the facility is vital. Due to the changing landscape of scientific research and communication tools, our strategies must be adaptable and convey important information. Few people read all of their emails, so alternative means of communication are necessary. This is especially true for time-sensitive tasks such as proposal deadlines, submitting SAFs, and renewing guest appointments. NSLS-II will investigate options such as messaging through mobile devices and possibly social media platforms.

NSLS-II staff give hundreds of tours per year to a wide variety of audiences, from the local general public to Nobel Prize winners. Therefore, communicating our science and mission should involve all our staff. In FY25, we have a goal to train one scientist per beamline to explain the mission of NSLS-II and their beamline to the public in just a few minutes. We will achieve this by using real-world examples of how our research impacts their everyday life. In the future, we plan to extend this training to engineers, technicians, financial analysts, and administrators using the materials developed for the beamlines.

A pain point for users at NSLS-II is the time it takes for a user appointment to be approved, which is necessary for remote as well as in-person access to NSLS-II. For foreign nationals, especially those from sensitive countries, the process can take 45 days or more. A goal for the near future is to analyze the BNL guest registration and expedite our processes while following all security protocols.

Deliver Mission-Critical Infrastructure

Providing mission-critical infrastructure at NSLS-II requires aligning major capability developments like NEXT-II, NEXT-III and NSLS-IIU with long term planning of infrastructure investments. This section focuses on NSLS-II conventional infrastructure needs, including buildings, utilities, and distribution systems. Moreover, addressing supply-chains challenges for critical systems are discussed.

Address NSLS-II's Growing Infrastructure Needs

Although current office, technician, and storage spaces meet our immediate needs, they will become insufficient as the facility grows with the successful completion of beamline projects, including NEXT-II and NEXT-III, as well as space needs for R&D for the NSLS-II upgrade.

Office space constraints will impact operations by requiring relocation of staff to buildings away from NSLS-II on the BNL campus. Technician and storage needs are temporarily addressed through experimental floor space and exterior storage.

Building 742, also referred to as Laboratory Office Building 2 (LOB-2), is directly connected to the NSLS-II experimental floor but remains largely a shelled space without interior finishes. Most of LOB-2 is currently used for storage (**Figure 23**).

We plan to fill out the LOB-2 shell to add offices, labs, technician areas, and storage space near beamlines. Finishing LOB-2 will address some but not all NSLS-II technician and office space requirements, necessitating the takeover of existing buildings in the vicinity of NSLS-II and/or additional construction as facility expansions or as stand-alone buildings.

NSLS-II will continue to monitor the need for support labs near the beamlines to ensure that the appropriate combination of support laboratories is planned, developed, and provided.

Two support laboratories were constructed in LOB-2 in FY23-24. In FY23, NSLS-II submitted a proposal to DOE for the further build-out of LOB-2 to provide additional laboratory spaces. A Metrology Lab in Building 744 (LOB-4) is planned for FY25-26.

The NSLS-II power demand for the current and future scientific priorities can be met by the Laboratory distribution infrastructure and the local provider, Public Service Enterprise Group (PSEG), for electric power. In FY25, the NSLS-II will connect to a secondary electric feed from the Laboratory's main power distribution substation, providing a back-up power distribution line should there be a failure of the primary line. NSLS-II frequently experiences transient power losses due to interruptions mostly on the PSEG distribution system and we will address these as part of the RUP Plan.

***Figure 23**. NSLS-II houses a half-mile long particle accelerator within its circular building which is directly connected to five Laboratory Office Buildings (LOBs) that provide office, lab, and technical space. LOB-2 is currently an empty shell that we plan to fill out with offices tech areas, and laboratories.*

The Central Steam Facility (CSF) provides steam for heating conventional and programmatic spaces at NSLS-II. While the CSF and steam distribution system currently meet heating needs, steam condensate leaks outside the facility exceed acceptable levels. The Laboratory's Energy & Utilities Group is investigating the source, with repairs planned once identified.

The Central Chilled Water Facility (CCWF) supplies chilled water for cooling and compressed air for programmatic needs. While current demands are met, capacity for future NSLS-II satellite buildings is under evaluation.

Compressed air requirements will be met, with redundancy enhancements planned in the NSLS-II RUP to address temporary air loss from the CCWF. However, chilled water quality remains problematic for some experimental capabilities. NSLS-II and the Energy & Utilities Group are working with a consultant to identify and implement solutions.

Secure Supply Chains for Critical Systems

The COVID-19 pandemic highlighted the fragility of global supply chains, which is particularly concerning for DOE facilities like NSLS-II, where essential materials, components, and systems often have limited sources. In response, the DOE Office of Science convened a roundtable on supply chain risk mitigation in 2021, with NSLS-II participating.

As part of the NEXT-II project, NSLS-II conducted a Supply Chain Analysis (SCA) to comply with DOE's Domestic Source Procurement Policy, identifying potential procurement risks and exploring strategies to increase domestic supplier involvement. This process proved valuable in assessing supply chain vulnerabilities and developing mitigation strategies.

Recognizing the importance of supply chain resilience, NSLS-II has integrated SCAs into its standard project planning. This proactive approach helps identify procurement challenges early, engage domestic suppliers, and, when necessary, develop in-house solutions. A notable example was the in-house construction of beamline hutches for NEXT-II, a decision made after vendors could not meet the schedule requirements for the project (due to production capacity and backlog issues). This approach, outlined in the DOE Supply Chain Roundtable report, has since been recognized as a viable alternative for other NSLS-II beamlines and similar DOE projects.

In addition to procuring new equipment, we must also plan for the replacement and recapitalization of existing hardware, much of which will become obsolete in the next few years. The RUP serves as a model for evaluating vulnerabilities, prioritizing countermeasures, and implementing solutions such as system redundancy, spare procurement, and phased upgrades. These proactive measures not only enhance operational reliability but also represent a sound investment that will save money in the long run by reducing emergency repair costs, avoiding downtime, and extending the life of critical systems—demonstrating strong fiscal stewardship.

Looking ahead, NSLS-II plans to formalize its supply chain strategy, refining its approach and establishing a policy framework for ongoing risk mitigation. This effort will include subject matter experts assessing vulnerabilities and developing tailored mitigation strategies. Future initiatives will focus on continuous evaluation, evolving supply chain approaches by subject area, and securing resources to support long-term operational resilience—an approach that reinforces both sustainability and responsible financial management.

All three are closely related and combined will have tremendous impact on NSLS-II operations and research.

List of Acronyms

AGU	Adaptive Gap Undulator
AI	Artificial Intelligence
ALS-U	Advanced Light Source Upgrade
AMX	Automated Macromolecular Crystallography
ANI	Advanced Nanoscale Imaging
APS	Advanced Photon Source
APS-U	Advanced Photon Source Upgrade
ARI	ARPES & RIXS Imaging
ARPES	Angle-Resolved Photo-Electron Spectroscopy
BES	Basic Energy Sciences
BESAC	Basic Energy Sciences Advisory Committee
BHSO	Brookhaven Site Office
BNL	Brookhaven National Laboratory
BPM	Beam Position Monitors
BRN	DOE/BES Basic Research Needs
BSA	Brookhaven Science Associates
BSL	Biosafety Level
CB	Complex Bend
CBM	Complex Bend Magnet
CCI	Coherent Correlation Imaging
CCWF	Central Chilled Water Facility
CD	Critical Decision
CDI	Coherent Diffraction Imaging
CFN	Center for Functional Nanomaterials
COVID	Coronavirus
CPMD	Collimated Phase Measuring Deflectometry
CSF	Central Steam Facility
CSX	Coherent Soft X-ray Scattering
CT	Computed Tomography
DJ-LGAD	Deep Junction Low-Gain Avalanche Detector
DOE	Department of Energy
DOI	Digital Object Identifier
SAF	Safety Approval Form
ESRF-EBS	European Synchrotron Radiation Facility-Extremely Brilliant Source
ESR	Experimental Safety Review
EXAFS	Extended X-ray Absorption Fine Structure
FEL	Free Electron Laser
FFFI	Full-Field Fluorescence Imaging
FMX	Frontier Macromolecular Crystallography
FXI	Full-field X-ray Imaging
FY	Fiscal Year
GeV	Giga Electron Volts
HEPS	High Energy Photon Source
HRD	High Resolution Powder Diffraction
HXN	Hard X-ray Nanoprobe
IBF	Ion Beam Figuring
ID	Insertion Device
INF	Infrared Nanospectroscopy Facility
IoT	Internet of Things
IR/THz	Infrared/Terahertz
IT	Information Technology
KB	Kirkpatrick Baez
LDRD	Laboratory Directed Research and Development
LINAC	Linear Accelerator
LLRF	Low Level Radio Frequency
LOB	Laboratory Office Building
mA	milliamps
ML	Machine Learning
MLL	Multilayer Laue Lens
NEXT-II	NSLS-II Experimental Tools II
NEXT-III	NSLS-II Experimental Tools III

NIST	National Institute of Standards and Technology
NLK	Nonlinear Kicker Magnet
NSLS-II	National Synchrotron Light Source II
NSLS-IIU	NSLS-II Upgrade
NYSERDA	New York State's Empire State Development Corporation
OCMM	Optical Coordinate Measuring Machine
PDF	Pair Distribution Function
PI	Principal Investigator
PQIM	Probes for Quantum Information
PLC	Programmable Logic Controller
PSEG	Public Service Enterprise Group
QAS	Quick X-ray Absorption & Scattering
QCT	Quantitative Cellular Tomography
R&D	Research and Development
RF	Radio Frequency
RIXS	Resonant Inelastic X-ray Scattering
RSM	Reciprocal Space Mapping
RUP	Reaching Ultimate Performance
SAC	Science Advisory Committee
SAF	Safety Approval Form
SBIR	Small Business Innovation Research
SC	Office of Science, DOE
SC	Superconducting
SCA	Supply Chain Analysis
SCU	Super-Conducting Undulator
SDD	Silicon-based Drift Detector
SFA	Science Focus Area
SIS	Software Information Systems
SIX	Soft Inelastic X-ray Scattering
SRW	Synchrotron Radiation Workshop
STEM	Science, Technology, Engineering, Math
STTR	Small Business Technology Transfer
STXM	Scanning Transmission X-ray Microscope
SXN	Soft X-ray Nanoprobe
TEY	Total Electron Yield
TXN	Tender X-ray Nanoprobe
UEC	User Executive Committee
UIS	User Information System
XANES	X-ray Absorption Near Edge Structure
XFM	X-ray Fluorescence Microscope
XPCS	X-ray Photon Correlation Spectroscopy
XRD	X-ray Diffraction
XQCI	X-ray Quantum Correlation Imaging
XQCS	X-ray Quantum Coherent Scattering