Final Draft

September 24, 2021
NSLS-II Mission

To develop and operate a premier user facility that embraces diversity to safely and efficiently deliver high-impact and cutting-edge science and technology for the benefit of society.
# Table of Contents

## Executive Summary

## Beamline Science Programs
- Soft X-ray Spectroscopy and Scattering ......................................................... 3
- Hard X-ray Scattering and Spectroscopy .......................................................... 7
- Complex Scattering ......................................................................................... 9
- Imaging and Microscopy .............................................................................. 11
- Structural Biology ......................................................................................... 14

## Enabling Technology and Support Facilities
- Accelerator Science and Technology ............................................................... 16
- Experimental Development ........................................................................... 18
- Remote Access and Data Infrastructure ......................................................... 21
- Operations Excellence .................................................................................. 23

## Future Outlook
- New Beamlines ............................................................................................. 28
- Future Facility Upgrade ................................................................................ 30
- Summary ....................................................................................................... 31

## List of Acronyms

---

iv
Executive Summary

The National Synchrotron Light Source II (NSLS-II) is a state-of-the-art synchrotron facility that provides extremely stable and bright photon beams, from infrared to hard X-rays, and data infrastructure to enable multiscale, multimodal, high-resolution studies on diverse systems of materials. As a DOE BES scientific user facility, NSLS-II vision is to be a hub for the use of synchrotron light to solve the world’s most challenging problems and improve our lives for the future.

Currently, NSLS-II has 28 beamlines in operation, and 4 additional beamlines under construction. The storage ring is routinely operated at 400 mA and 30 pm-rad vertical emittance, and at 8 pm-rad during special running periods. NSLS-II has been implementing a multi-year development plan for the accelerator systems. Once this is completed, it will allow the NSLS-II storage ring to be reliably operated at its mature performance specifications of 500 mA and 8 pm-rad vertical emittance.

NSLS-II began user operations in 2015. In fiscal year 2019, 1755 distinct researchers used NSLS-II beamlines for their research. This number in fiscal year 2020 was 1355 due to the impact of the global COVID-19 pandemic. Despite this, NSLS-II saw 577 publications in calendar year 2020, with more than 40% of these publications in journals with impact factor greater than 7.0, demonstrating the high impact of our relatively young facility.

NSLS-II continues to develop new beamlines to meet the research needs of the scientific community. Currently NSLS-II is constructing a high-energy x-ray scattering and imaging beamline (HEX), funded by New York State, to be completed in 2022. In addition, three undulator beamlines, Coherent Diffraction Imaging (CDI), ARPES and RIXS Imaging (ARI), and Soft X-ray Nanoprobe (SXN), are under construction in a DOE major items of equipment project, NEXT-II, to be completed in 2026-28 timeframe. At that time, NSLS-II will have 32 beamlines in operations, out of its capacity of ~60 beamlines.

NSLS-II will seek funding to develop additional new beamlines to complete its beamline portfolio in the next decade. Based on community discussions at the 2019 Strategic Planning Workshop, “Exploring New Science Frontiers at NSLS-II”, NSLS-II has identified 22 new beamlines to be developed to balance the beamlines portfolio and provide additional capabilities to meet the research needs of the broad
scientific community. These include 12 enterprise beamlines based on mature techniques, 7 high-performance beamlines with additional cutting-edge capabilities, and 3 mission-specific beamlines to meet the needs of the targeted research communities. Together these new beamlines will support multimodal research and enhance the overall impact and productivity of the facility.

The pandemic has heightened the needs for advanced, readily available capabilities at NSLS-II, as well as the need for improved experiment infrastructure and processes to allow these capabilities be operated and accessed remotely, both by staff and by the users. NSLS-II has been aggressively ramping up the infrastructure and capabilities for remote access, along with associated cyber security measures. This is both a short-term need driven by the current pandemic, and a long-term need to take full advantage of the high-brightness and high-throughput capabilities that NSLS-II provides. As the time for a single measurement decreases, the need for tools such as AI/ML to reduce human intervention increases. Thus the remote experiments capabilities are of high strategic importance for the future health of the facility.

Looking further into the next decade and beyond, NSLS-II will plan for a facility upgrade to position NSLS-II as the ultimate medium-energy synchrotron with a full suite of transformative capabilities for the scientific community.

In short, our high-level strategy for the next 5 years is to:
- Deliver mature accelerator performance of 500 mA & 8 pm-rad vertical emittance in reliable user operations,
- Recapitalize existing beamlines and keep them competitive with new access modalities in post-COVID era,
- Achieve our data vision for seamless access to experimental capabilities, compute and storage,
- Complete the HEX beamline and the NEXT-II project,
- Work with DOE-BES and other funding partners to add new beamlines to increase capacity, enhance capability, support multimodal research, and balance our beamline portfolio,
- Position the facility for a transformative upgrade in the coming decade that includes a source optimized as the ultimate medium-energy synchrotron, a suite of beamlines with transformative multimodal tools, and a modern data infrastructure that seamlessly integrates experiment, theory, & computation.

The following Chapters describe components of this strategy in more detail and a set of tactical projects that we will pursue in FY22 as the next step in these strategies.
Beamline Science Programs

NSLS-II beamlines are organized into five beamline programs – Soft X-ray Spectroscopy and Scattering, Hard X-ray Scattering and Spectroscopy, Complex Scattering, Imaging and Microscopy, and Structural Biology. Together these beamline programs provide a large suite of experimental capabilities and scientific expertise that enable a diverse and strong user science program at NSLS-II. The word cloud at right, based on word frequencies in user beamtime proposals, shows the diverse range of research being conducted at NSLS-II beamlines. The following sections describe the strategic directions and the primary near-term activities in FY22 in each of the five beamline programs.

Soft X-ray Spectroscopy and Scattering

**Mission:** The soft X-ray spectroscopy and scattering (SXSS) program’s mission is to understand and ultimately control emergent quantum phenomena and novel chemical phenomena by providing a suite of cutting-edge infrared, soft, and tender X-ray capabilities that enable studies of the electronic and magnetic properties in condensed matter and chemical and electronic properties in catalytic and energy storage materials, to inform the design of practical devices for information and energy technologies of the future.

**Strategy:** The beamlines in the SXSS program are developed and operated to meet the research needs in three science thrust areas of interest to the Department of Energy: materials, quantum information science (QIS), and chemistry.

In materials, our efforts are to probe and understand the phenomena that stem from the interactions of electrons through their degrees of freedom (charge, spin, and orbital), especially when those interactions result in novel ordered states. Many such states occur in confined systems such as 2D materials or as edge states in topological materials. The interactions can sometimes be controlled by external means such an applied field or pressure, or intrinsically through the oriented stacking of 2D materials such as graphene ("twistronics"). Measurement techniques are geared toward sensing electronic energies and interactions as a function of wavevector (momentum) using the source coherence at the CSX beamline and the state-of-the-art energy resolution at the ESM and SIX beamlines. High magnetic field (to 7T or 10T) is being implemented at the MET beamline and diamond anvil cells are used for achieving extreme pressures at FIS - both for infrared spectroscopy. Nanoprobes are being developed for interrogating confined systems, or the spatial variations in electronic properties that can stem from intrinsic inhomogeneity, competing orders or Moiré effects. Several new beamlines are in the design or project development phase for achieving 10 nm spatial resolution in combination with 2 meV energy resolution.

Research in materials for next-generation computing, includes exploration and integration of novel quantum materials, materials that are well-suited to fundamental investigations at SXSS beamlines. For example, SXSS beamline capabilities can be leveraged to enable research in the electronic and magnetic properties of ultrathin samples, in studies of electron spin and spin wave excitations as potential means to transport and process information, and in investigations of the structural and electronic behavior of transition metal oxides, which are among the best candidates for neuromorphic applications. Of particular current interest, novel quantum materials
can be candidates for new types of qubit systems that are part of BNL’s Quantum Information Science (QIS) initiative. The SXSS strategy in the QIS area draws upon the world-leading coherence and energy resolution of the SXSS beamlines to tackle the two biggest challenges in quantum computation today – limited coherence times and gate fidelities of qubits. We will pursue two fronts: (a) diagnosis and optimization of relevant material properties in existing qubit designs, such as superconducting qubits and nitrogen vacancy centers, in close collaboration with the partner institutions in the newly funded BNL-led QIS Center – Co-Design Center for Quantum Advantage (C²QA), and (b) development of next-generation systems based on the exotic electronic properties of quantum materials such as topological insulators and high-temperature superconductors. For all these systems, the combination of best-in-class energy resolution and microfocus of the ESM and SIX beamlines, together with the nano-focus and world-leading coherence of the CSX beamline, promise to have a major impact.

In chemistry, our strategy is to provide world-class in situ soft X-ray spectroscopy capabilities for investigations of the chemical and electronic states of energy materials such as catalysts, batteries, and fuel cell electrodes under operating conditions using ambient pressure X-ray photoelectron spectroscopy and X-ray absorption spectroscopy. The aim is to unravel the complex and dynamic changes in the chemical and electronic properties of the materials to understand and control factors that determine their functional properties. This will establish principles for rational design of next-generation energy materials and optimization of operating conditions to achieve the best performance. The focus for the next few years will be to upgrade the IOS beamline with a new multi-modal endstation known as INSPIRE, which will enable in situ investigations of catalysts, batteries, and fuel cell electrodes to obtain a combined chemical and electronic picture of the material under the same sample preparation and operating conditions.

**FY22 Activities:**

**Inelastic Scattering, Photoemission, and Infrared Endstation (INSPIRE):** Funded through an internal Facilities Improvement Project (FIP), INSPIRE comprises an optics upgrade at the IOS beamline and a new endstation that will offer a unique combination of state-of-the-art ambient pressure XPS, XAS, IR, and XES/RIXS capabilities to study energy and catalytic systems under realistic operating conditions and time scales. It will capitalize on a focused beam spot of 2 μm x 20 μm with spectral brightness enabling very fast RIXS (~1 sec) and AP-XPS (sub second) data acquisition. Procurement of the KB mirror system and other optical components commenced in FY21. Design of the new endstation will begin in FY22. The INSPIRE project is designed with modularity to enable a phased construction process to balance the demands of existing user operations with instrument development, with an estimated completion date late in FY24.

**Liquid electrochemical cell and gas reaction cell for XAS at IOS:** Science commissioning for an in situ electrochemical cell to study liquid-solid interfaces with XAS was started in FY20 and was paused due to Covid-19 and restricted on-site staffing. Commissioning will resume in late FY21/early FY22 as on-site user operations and staffing levels return to closer to normal values. A reaction cell for studying gas-solid interfaces at atmospheric pressures is under construction and is expected to be ready for technical commissioning late in FY22.

**Ambient pressure partial fluorescence yield XAS at IOS:** The addition of a Vortex silicon drift detector to the APPES endstation at IOS is planned in FY22. This will enable experiments using partial fluorescence yield XAS under ambient pressure conditions in combination with AP-XPS and partial electron yield XAS for multimodal investigations of the surface and bulk states of materials in the same sample environment. Test experiments using AP-PFY-XAS in FY18 were successful and resulted in two publications.

**Study of potential qubit materials at CSX:** An LDRD-funded project that focuses on the investigation of dense Josephson junction arrays based on high-temperature superconductors for potential qubit applications started at CSX in FY20 and will continue in FY21. In collaboration with Harvard U., in-operando investigations of next-generation qubit systems will also be pursued at CSX by the new addition of a dedicated refrigerated glovebox.

**Coherent imaging and ptychography at CSX:** The new innovative nano-scanning system recently installed and commissioned at CSX required some time for optimization and tuning due to its complexity. Recently, maps have been acquired with excellent resolution. During FY22, commissioning will continue to further optimize
performance. Re-opening of the ptychography capability to general users is expected to take place early in FY22. During FY22, the ReconsTeam activity (collaboration between MIT, LANL, Univ. of Marseille – France, ALS, and led by CSX) is expected to conclude its activity with the delivery of advanced reconstruction codes specifically tuned for the resonant soft x-ray regime.

**Fourier transform holography at CSX:** This project was slowed down due to the Covid-19 pandemic, a shift of one staff member to other activities, and problems with the detector. The situation will improve by the end of CY2021 and experimental activities in the new chamber should resume sometime around mid-CY2022, pending availability of suitable detectors.

**Enhancing x-ray stability and performance at CSX:** During FY21 a new water-cooling system has been implemented on the CSX monochromator and first mirror. Initial results show significant improvement of the energy stability and the horizontal beam jitter. Fine tuning of this system will continue during FY22 to optimize performance. Also in FY21, a phasing magnet was inserted between the undulators of the 23-ID straight section. Commissioning of this magnet, which was delayed due to the Covid-19 pandemic, will continue in FY22. In addition, an effort is ongoing to reduce deleterious effects associated with special undulator polarization modes (heat load changes on the beamline optics and perturbations to the NSLS-II accelerator). Assembly, installation, and commissioning of a newly designed Polarization Analyzer to measure the CSX beam polarization is expected to be completed in FY22. This analyzer, together with the improvements listed above, will enable unprecedented control of the polarization for advanced experiments. Finally, a new grating for the CSX monochromator is currently in procurement, with expected delivery in late FY22 or early FY23. Its commissioning, together with planned minor changes in the CSX beamline optical layout, will reduce the sensitivity to angular instabilities and improve energy resolution and harmonic rejection.

**High resolution ARPES spectroscopy at ESM:** The ARPES experiment at ESM operates over a wide photon energy range (20-1500 eV), with full control of the light polarization (two in-line EPUs) and a micro-focused beam (~ 5 microns at the sample). High quality ARPES maps are routinely collected with a DA30 Scienta analyzer with an energy and angle resolution of ~ 6 meV and < 0.1 degree, respectively. The replacement of the ARPES endstation initiated in FY21 will be completed in FY22. In particular, the 6-degree-of-freedom cryostat (lowest temperature ~7K) will be equipped with a close-cycle LHe refrigerator. Additionally, a high magnification camera will be added to the endstation for in-situ micron resolution images of the samples during ARPES measurement.

**Synthesis of quantum materials at ESM:** Since electron spectroscopies are extremely surface sensitive, ESM pays particular attention to in-situ preparation techniques. Currently, two sample preparation techniques are supported: (i) MBE growth (two existing MBE systems exist: Yale-MBE for oxides and an MBE for chalcogenides) and (ii) exfoliation (provided by a glovebox equipped with piezo motions and an optical microscope). The combination of these two capabilities is expected to be highly effective at ESM, allowing the study of artificial heterostructures prepared under different conditions and forms. Furthermore, the preparation of unique hybrid sample systems, taking advantage of the various growth capabilities, will be possible. For example, the study of proximity effects between chalcogenides and high-Tc superconductors is currently a topic of high interest to be pursued by combining the growth capabilities of the two MBE systems. Similarly, exfoliated materials prepared in the glovebox or in the Quantum Material Press at CFN can be combined with the other preparation techniques. A railway system is under development at ESM, to transfer samples from the growth/preparation facilities to the ARPES and XPEEM endstations under UHV-conditions.

**XPEEM/LEEM microscopy at ESM:** The XPEEM/LEEM microscope provides direct, full-field imaging of the topographic, chemical, and magnetic properties of surfaces, as well as the electronic band structure with few nm spatial resolution. Use of synchrotron radiation (XPEEM) enables measurements of electronic states (µARPES), magnetic imaging of nanostructures (x-ray magnetic circular dichroism, XMCD), and chemical analysis (µXPS, µXAS) with an energy resolution of ~100 meV and spatial resolution better than ~20 nm. The XPEEM/LEEM microscope is equipped with in-situ sample preparation facilities including material deposition, gas dosing, temperature treatment up to 2000 K as well as low-temperature measurement capabilities (down to ~100 K in XPEEM). The instrument is also compatible with CFN’s Universal Sample Holder (USH) system, allowing sample transfer via an ultrahigh vacuum (UHV) “suitcase” between the microscopes (including XPEEM/LEEM)
and sample fabrication facilities. The microscope has been recently upgraded with a state-of-the-art, CMOS-based solid-state detector, which replaced the old multichannel plate (MCP) detector. The new detector has a 4K maximum resolution and superior dynamic range. The microscope will be further upgraded with a new energy analyzer towards the end of CY2021, improving the energy resolution for XPEEM to ~60 meV, which will be a record for such instrument operating at a user facility. Further planned upgrades include sample cooling capabilities, with a target temperature below ~20K. This is not a trivial task, requiring a redesign of the sample manipulator that operates at 20,000 V during measurements. Components in the electron optics of the microscope, including an objective lens, are integral parts of the sample environment that also need to be cooled; this portion of the upgrade will be undertaken in close collaboration with the microscope vendor. In parallel, specialized sample holders and methodologies for \textit{operando} measurements will be developed to enable low-temperature spectro-microscopy of 2D and quantum materials-based structures and devices that are fabricated at facilities such as CFN’s Quantum Materials Press.

\textbf{XPEEM catalysis and energy storage materials program at ESM}: the XPEEM microscope, with its spatially resolved chemical imaging capabilities (µXPS, µXAS) is well suited for surface studies of catalytically relevant and energy storage materials systems. In recent work, XPEEM was used to elucidate morphology and structure, and provide elemental mapping a number of such systems (3 publications on this work in FY21). An environmental sample holder for the XPEEM/LEEM will be developed in FY22 to enable study of surfaces under increased partial pressure, further expanding the potential for catalysis research with XPEEM.

\textbf{High and ultra-high energy resolution RIXS at SIX}: Currently, the SIX beamline routinely achieves a total resolving power (beamline plus spectrometer) of 32,000 - 35,000. The goal for FY22 is to reach the resolving power design goal of ~70,000 by resolving mechanical instabilities associated with the water-cooled optics. In addition, a 1250 l/mm spectrometer grating needed to enhance throughput in the high energy resolution mode will be purchased. Similarly, a more efficient high energy resolution monochromator grating and its improved-design holder will be installed in FY22.

\textbf{RIXS with continuous momentum tunability and upgraded sample manipulation & cooling at SIX}: The RIXS endstation at SIX was designed using the concept of a triple rotating flange (TRF) connecting the spectrometer to the sample chamber and enabling RIXS measurements at continuously tunable momentum transfers. The TRF was received in February 2020 and successfully installed in May-June 2021. Further commissioning activities will continue during FY21-22 to provide a stable functioning of the continuous arm rotation. Additionally, an R&D project is ongoing to realize a piezo-based sample manipulator offering precise, motorized control of all six degrees of freedom at the sample while achieving cryogenic temperatures at the sample itself. This project represents a major upgrade with respect to the current flow-cryostat manipulator controlled with external XYZ+Theta stages. Design of the new sample manipulator is planned to be completed in FY22 and installed in FY23.

\textbf{RIXS under device-operating conditions}: Through the Early Career Award of Valentina Bisogni, RIXS studies of spin dynamics in model materials subjected to device-operating conditions will be developed at SIX. This is particularly important as spin dynamics hold promise for high-speed, low-power functional devices. To enable these measurements, a unique sample environment, called OPERA, is being developed to replicate device-working conditions. The test version of OPERA – capable of supplying electric field, current, and a temperature gradient to the sample – is fully functional and commissioned, though changing samples requires venting the sample chamber. A complete version of OPERA will be implemented and commissioned through FY22, together with the possibility of performing sample transfers under vacuum.

\textbf{Investigation of laser-induced “hidden phases”}: Funded by an LDRD, this project, just began in FY21, will use an ultrafast laser to induce “hidden” phases in materials (\textit{i.e.} those not reachable in thermodynamic equilibrium). Soft RIXS at SIX will then be used to study these phases, uncovering elementary excitations and their evolution from pristine to photo-induced phases. This work is important because these transitions are well known in the ultrafast community, but their mechanism is still not understood, precluding any prediction. These novel
metastable phases are promising from the application perspective, as the switching of properties such as resistance or magnetism is useful for novel device concepts.

**Commissioning and Operation of Infrared and THz spectroscopy at FIS and MET:** The FIS beamline will continue to operate for General Users in FY22, enabling studies of materials under extreme conditions of pressure and temperature. The FIS program is focused on diamond anvil cell (DAC) techniques for reaching 100s of GPa in combination with temperatures from \(\sim 10\)K (cryo-cooling) to a few thousand K (CO\(_2\) laser heating). Studies include vibrational spectroscopy of mineral phases as found deep inside the Earth or other planets and the incorporation of water as complex hydrates. Studies also include electronic spectroscopy to sense the metallization of various hydrogen compounds, including evidence of superconductivity at high temperatures. Capabilities include IR, Raman, and fluorescence spectroscopies. The MET beamline will transition to General User operations in FY21 and the user program will ramp up in FY22. MET enables investigations of novel solid-state systems. The widest possible spectral range of 1 meV to 5 eV will be available for reflectance spectroscopies with Kramers-Kronig analysis. A spectroscopic ellipsometer system being developed by NJIT will be completed in FY21, which consists of a 7T dry magnet allowing for measurements of samples in high magnetic field. Systems of interest include complex oxides displaying competing orders, topologically controlled phases, and 2D materials such as graphene, h-BN & metal dichalcogenides, and nanomaterials. During FY22 we will complete the development of a near-field nano-spectroscopy system -- currently on loan from NeaSpec -- by constructing a fully purged enclosure, a fast-mirror feedback system for reducing beam motion stemming from mechanical noise, and fast detectors for reaching longer wavelengths.

**Ultra-fast laser for studies of material dynamics:** A near-infrared, mode-locked laser system will begin operations for transient disruption of ordered phases in materials, initially at the CSX and MET beamlines, enabling studies of photo-excited states of matter and the relaxation processes that control the return to equilibrium order. The pulse structure resulting from electron bunches in NSLS-II will allow for a temporal resolution approaching 15 ps, complementing the capabilities at the x-ray FELs.

**Hard X-ray Scattering and Spectroscopy**

**Mission:** The HXSS program mission is to develop and use x-ray scattering and spectroscopy techniques to describe and explore the structural and chemical features of functional and naturally-occurring materials at the atomic level under non-ambient and dynamic conditions.

The program focuses on materials for energy storage and conversion, heterogeneous catalysts, quantum materials and systems, ceramics, alloys and porous organo-minerals.

**Strategy:** The strategy is to deliver world-class x-ray capabilities for studying complex and heterogeneous materials with a strong emphasis on *in-situ*, operando & extreme environments, high throughput and real-time observation. *In situ* and operando approaches enable the study of transient or metastable states along different synthesis or process pathways, and not just of the end products. The beamline portfolio of HXSS includes specialized spectroscopy, diffraction, and imaging tools, supported by computational resources for high-throughput data analysis and modeling. The portfolio includes: Beamline for Materials Measurement (6-BM), Quick x-ray Absorption and Scattering (7-BM), Inner Shell Spectroscopy (8-ID), High-energy Engineering X-ray Scattering (27-ID), Pair Distribution Function (28-ID-1), and X-ray Powder Diffraction (28-ID-2). There are three science thrusts to the HSS program:

Thrust 1 is related to chemical sciences and relies on *in-situ*/operando characterization using high resolution hard x-ray spectroscopy (x-ray emission spectroscopy, high resolution fluorescence detection, resonant inelastic scattering) and high energy x-ray diffraction, to understand the critical electronic and structural properties of the materials and establish their relation to the pathways of chemical reactions on all relevant spatial and temporal scales.
Thrust 2 addresses fundamental and applied problems in materials science and engineering and focuses on the study of a variety of syntheses, treatments and processes (e.g., doping, coating, high pressure, quenching, annealing, field assisted sintering, synthesis, gas exposure). Atomic structures and microstructures are characterized and the results are used to inform computational modeling of the processes.

Thrust 3 is to explore the structural origins of technologically important properties in quantum and/or strongly correlated materials, such as, superconductivity, charge and spin density waves, frustrated magnetism, and colossal magnetoresistance.

FY22 Activities: To achieve its mission, the HXSS program will pursue development in the following directions:

*Improve beamline’s performance.* i) deploy a CdTe pixel-array, photon counting detector at XPD for high energy diffraction, featuring much faster measurement times, lower noise, finer resolution, and no image-ghosting; ii) integrate an energy discriminating silicon drift detector into fly scan data acquisition at ISS and QAS; iii) purchase a Si-based, single photon counting pixelated detector for combined operando XAS/XRD particularly on materials containing 3d transition metals; iv) commission strip and area detectors for high resolution spectroscopy at ISS; v) upgrade the PDF side bounce monochromator for fast energy changeover; vi) start commissioning the XPD analyzer crystal optic for high resolution, high energy x-ray diffraction.

We recognize that beamline automation is a key element to improve operation reliability and speed. Several HXSS beamlines aim to develop robotic sample changers to increase throughput and enable remote data collection.

With its world-leading flux (up to $10^{14}$ ph/sec), ISS is designed to be a cutting-edge high-resolution (HR) spectroscopy beamline for X-ray emission spectroscopy, high energy resolution fluorescence detection and resonance X-ray scattering. A robust back scattering analyzer spectrometer with three crystals will be commissioned and the design and fabrication of a von Hamos type spectrometer will be completed. This HR spectroscopy capability will be extended into the tender range with a dispersive spectrometer design covering 2.3-4 keV range, funded by a Facility Improvement program.

*Develop new in-situ/operando capabilities.* The HXSS beamlines integrate an extensive range of operando/in situ devices, e.g., potentiostats for battery and electrochemical research, reactors for catalysis and synthesis, residual gas analysis and gas chromatography, electrochemical cells, ALD reactor, furnaces (resistive, radiative or electromagnetic heating) and cryostats, etc.

A combined XAS/DRIFTS instrument with gas flow capability is being constructed in hutch C of QAS, in collaboration with the Synchrotron Catalysis Consortium Partner User, and is expected to start commissioning at the end of CY2021.

On-going developments at the high energy diffraction beamlines include: i) a 5T superconducting magnet coupled with a liquid He cryostat; ii) a large volume, multi-anvil 1,100-ton hydraulic press (developed and operated in partnership with the Consortium for Materials Properties Research in Earth Sciences (COMPRES) and the Mineral Research Institute of Stony Brook University) for measurements at extreme conditions (20GPa, 2000K); iii) a combined imaging/diffraction equipment (partnership with Idaho's Nuclear Science User Facility and Brookhaven's Nuclear Science Department) for 2D or 3D reconstructions of sample morphology directly from diffraction with $30\times20$ µm² spatial resolution and full-field (2×2 mm²) X-ray radiography.

*Optimize throughput & productivity through AI/ML driven automation and advanced data analytics.* High-throughput experiments call for rapid measurements and equally fast (quasi on-line) reduction, visualization and assessment of the data. Experiments can be dramatically sped up by incorporating AI and ML techniques in their workflow. Sampling a complex, multidimensional parameter space (e.g. tuning temperature and pressure and composition simultaneously) using AI can be far more effective than an exhaustive grid-scan of that phase-space. Self-similarity or Principal-Component-Analysis (PCA) algorithms to detect on the fly changes in a flow of XRD/XAS patterns over time can reveal a genuine structural effect like a phase transition and distinguish it from...
an instrument artefact like a beam energy shift. These developments are an essential requisite for remote user operations. A BES funded multi-laboratory effort is underway to implement AI-directed analysis of multimodal data collected at multiple instruments at NSLS-II and other BES SUFs. In order to implement this strategy we are building a software infrastructure, extending the Bluesky/Data Broker framework to capture, integrate and cross-correlate experimental, processed and synthetic data from multiple instruments and facilities. Second, ML-driven processing pipelines for data reduction, conditioning and analytics that consume raw data and extract physical signals of interest will be designed. Finally, multimodal ML tools that correlate these signals will be developed, trained, and applied to gain new complementary scientific insights.

**Enhance and facilitate external partnerships** (NIST, IBM, DOE-NE, SCC, DTRA, ...). HXSS thrives on the additional support from several sponsors and on successful, established partnerships with several consortia and universities:

- BMM is part of a suite of three beamlines focused on material science applications in energy, health, environment, microelectronics, and national security, and is funded and operated by the National Institute of Standards and Technology (NIST). IBM participates in the operation of BMM through a CRADA with NIST.
- HEX beamline is currently under construction and funded by New York State Energy Research and Development Association (NYSERDA).
- PDF beamline’s combined program with NOMAD beamline at Oak Ridge’s Spallation Neutron Source (SNS) provides complementary neutron and x-ray PDF data to general users. A joint SNS/NSLS-II “Total Scattering Analysis” school is conducted annually.

**Multimodal approaches including imaging.** In FY22 we plan to develop experimental and data analysis methods that combine *in situ* and operando synchrotron x-ray with transmission electron microscopy techniques to offer new opportunities for in-depth studies of ion transport, electrochemical reactions, and phase transformations over multiple length and time scales. Paring FTIR/DRIFTS and UV-Vis spectroscopy, XAS, PDF, SAXS and DSC/XRD analyses also provides invaluable information on the evolution of surface adsorbates and structural dynamics of materials. Tracking and fiducializing the samples across several instruments and combining different datasets in a common analysis framework will considerably leverage the amount and quality of science that can be produced. Recently awarded LDRD projects on the application of AI to interpret large multimodal datasets is critical to achieve this goal.

**Advance HEX construction and community outreach.** HEX consists of 3 independent endstations and a satellite building to provide hard x-ray diffraction and imaging probes in the 30-200 keV range for studies of engineering materials under operating conditions. The central branchline is under construction (first light mid 2022), with affordances for 2 other side branches. In FY22, the HXSS program will continue to work with potential partners in NYS and other funding agencies to fund the HEX branch-lines and to develop the HEX user community ahead of first light.

**Complex Scattering**

**Mission:** The Complex Scattering program’s mission is to develop cutting-edge x-ray scattering techniques to advance scientific understanding of the spatiotemporal behavior of complex soft, hard, and bio materials to drive transformative discoveries by optimizing material synthesis and processing conditions as well as material behavior under extreme conditions for applications that impact the national health, energy and environmental security.

**Strategy:** Our high-level strategy to achieve our mission consists of the following:

- Broaden users served by our overburdened undulator SAXS/WAXS beamline, which currently supports 5 distinct techniques, by the construction of an independent canted undulator branch, Processing and Liquid Surfaces (PLS) that will specialize in open-platform processing and liquid interface measurements that utilizes the existing second SMI endstation.
Engage and effectively serve the microelectronics, film coating, and polymer processing/upcycling industries by the construction of new beamlines for fundamental studies of applications driven science. These new beamlines include a proposed undulator Advanced Manufacturing Processing (AMP) beamline for in-situ coherent and incoherent scattering that is optimized for accommodating scalable industrial processing set-ups and large materials growth chambers and a proposed 3PW Materials Structure and Processing (MSP) beamline with instruments to study thin film device structures, defect formation/repair, and reliability; next step is developing detailed beamline conceptual designs.

Complement the soft and tender resonant scattering programs at the SMI and SST-1 beamlines by the construction of the proposed STX beamline that incorporates a soft/tender x-ray microscope (STXM) for the compositional analysis and functional performance of soft matter compounds in operando conditions.

Finally, enhance the effectiveness of all aspects of our program, from measurement workflow to real-time analysis feedback, by developing AI/ML approaches, refine remote operations, and implement beamline enhancements needed to remain state-of-the-art.

FY22 Activities

I. Advance Existing Forefront Science and Technology Research

- Advanced Manufacturing
  - Continue to develop and strengthen the world-leading status of the complex scattering program in the area of incoherent and coherent scattering methods applied to additive manufacturing processes of polymeric materials; integrate a second-generation larger format, multiple printhead, 3D printing platform on CHX, CMS, and SMI and integrate the new CFN-contributed wide-area WAXS detector in the CMS open sample area as well as at CHX and the SMI-OPLS.
  - Develop simultaneous, multimodal x-ray and non-x-ray in situ characterization capabilities for studies of materials under processing and material testing/response conditions (e.g., optical spectroscopy for nanoparticle assembly, electromechanical measurements for piezoelectric polymers, tensile/shear stress/strain, differential scanning calorimetry, high-temperature/high-throughput characterizations for polymers and liquid crystals).
  - Complete the construction and start the operation of the new sample preparation laboratory for additive manufacturing related experiments.
  - Actively explore opportunities to join relevant initiatives (call for Transformative Manufacturing EFRC expected).

- Tender X-rays for Soft Matter (SMI)
  - The available sample environments compatible with tender x-rays are currently limited and users lack standard data treatment protocols. Continue developing in situ sample environments and analysis tools for resonant tender x-ray scattering measurements. Extend the SMI SAXS pipe to allow measurements into the USAXS region and integrate the new SMI wide horizontal q-range WAXS detector that extends the angular range by a factor of 4.

- AI/ML
  - Extend autonomous experiments to not only steer characterizations but also control material processing on the fly (e.g., blade coating, 3D printing, rapid thermal annealing) to optimize structural formation kinetics and ordering at the nanoscale. Incorporate expert physical knowledge into decision-making algorithms to enhance autonomous experiments.
  - Use AI/ML approaches to enable real-time analysis of XPCS measurements of nonequilibrium dynamics.

- Phononics (IXS)
  - Strengthen the soft matter research capabilities of IXS by improving the counting efficiency and the energy resolution towards the initial project goal of 1 meV. With the improved counting efficiency, explore expanding the science areas to hard condensed matter systems that benefit from the moderate operation energy of the beamline, especially systems of reduced dimensionality such as surfaces, interfaces and thin films.
  - Explore theoretically new analyzer concepts aiming for an order of magnitude enhancement in the counting efficiency of the meV-resolution IXS spectrometer.

- Quantum Systems (ISR)
Commission new capabilities on ISR for studies of electronic order in quantum materials, specifically, tender resonant x-ray scattering and variable linear polarization with hard x-rays for pseudo-azimuthal scans; add low temperature, moderate magnetic field and high-pressure sample environments for hard x-ray scattering experiments.

**Materials Growth (ISR)**
- Enhance capabilities on ISR for in-situ studies of materials growth and processing with the availability of hazardous gases, optimized secondary focusing, and coherent scattering during growth.
- Commission a processing chem-prep lab with a fume hood rated for working with highly corrosive acids (including HF) used for cleaning substrates.
- Commission a small, ~200 nm beam, endstation on ISR for hard x-ray scattering in transmission SAXS geometry.

### II. Expand Program into New Forefront Science and Technology Research

**Quantum Entanglement and Domain Dynamics (CHX)**
- Launch the DOE-BER funded project on the use of quantum entanglement and other non-local correlations in scattering experiments for reducing the illumination dose on sensitive samples and enabling otherwise impossible coherent scattering experiments on soft and biological materials.
- Integrate a new sample chamber for coherent-WAXS and a new closed-loop cryostat enabling low-temperature operations (4-10 K) for both coherent-SAXS and WAXS setups.
- Integrate a new *Timepix* detector at the CHX beamline for a 2x enhancement of the optical contrast and a time resolution of 2 ns for studies of phase fluctuations in quantum materials using coherent-WAXS and other fast XPCS approaches.
- Fabricate kinoform focusing optics for resonant coherent x-ray scattering to study phase fluctuations in quantum materials.

**Liquid Surfaces (SMI)**
- Commence a general users program at the OPLS endstation on SMI, supporting 4 user proposals in the 2021-3 cycle.
- Continue to develop liquid scattering software and specialized sample environments. Start user experiments based on the newly available environmental chamber with four separate liquid troughs, two with surface tension measurement capabilities and a commercial Kibron Langmuir Trough.

**Microelectronics**
- Explore interest in the AI-guided laser spike annealing technique, which provides dramatic thermal gradient enhancements over the traditional rapid thermal annealing approach.
- Working with the NSLS-II/APS Diffraction Software User Group, develop diffraction software for the *Bluesky* environment necessary for efficient reciprocal lattice mapping using an area detector.

### Imaging and Microscopy

**Mission:** The imaging and microscopy program is committed to developing cutting-edge x-ray imaging and microscopy techniques and offering them for diverse scientific applications. In recognition of broad scientific needs, emphasis is placed on providing a suite of tools with multiscale and multimodal capabilities, while taking inherent advantages of x-rays for generating imaging contrasts.

**Strategy:** Three primary thrusts define the strategic directions in the imaging and microscopy program. The *first* is achieving and maintaining the world-wide leadership and competitiveness. This goal provides a natural strategic path for FXI which has world-leading nanoscale imaging throughput (~10X faster than the current competitors) and HXN which provides multimodal imaging capabilities with a spot size down to ~10 nm. It is critical to ensure that these beamlines retain world-wide leadership. Construction of the CDI and SXN beamlines in NEXT-II also fits into this strategic thrust.
The second is attracting targeted scientific communities to establish substantial capabilities at the NSLS-II that will result in continuing growth and competitiveness. One obvious area of growth, well-aligned to NSLS-II as a medium storage ring energy, is bio-environmental imaging. There is a strong growth potential by strengthening the research areas that are aligned with DOE-BER mission science and attracting additional funding for developing new capabilities at NSLS-II, such as a Bio-Environmental STXM (BEST). Another growth area is to enhance in-situ/operando full-field imaging at a micron resolution. While a number of scientific communities are moving aggressively toward in-situ/operando research to examine material structure and properties over wider length scales (nanometers to centimeters), NSLS-II presently lacks a micron-scale full-field imaging capability that can work effectively with the existing imaging capabilities over the comparable energy range. This is a long term goal of the Imaging and Microscopy program. It is also important to point out that microelectronic research is becoming an important science area for DOE and other US funding agencies, where NSLS-II’s current (FXI and HXN) and near-future (CDI) capabilities offer tremendous opportunities. The ultimate goal is to build sufficient interests and justification for the construction of one or more beamlines specialized for microelectronic research.

The third thrust is targeted investment in enhancements of the existing capabilities, including beamline instrumentation and further developing end-to-end data analysis workflow. These strategic thrusts and approaches are summarized in Table 1.

Table 1: High-level strategic thrusts and approaches for the Imaging and Microscopy Program

<table>
<thead>
<tr>
<th>Thrusts</th>
<th>Approaches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieving &amp; maintaining world-wide leadership</td>
<td>- Continuing development of 5 nm-resolution imaging using MLLs and incorporation of the developed capability into the HXN user instrument.</td>
</tr>
<tr>
<td></td>
<td>- Enhancement of in-situ 3D imaging at FXI, including diverse in-situ environments, larger probing volumes, and higher resolutions.</td>
</tr>
<tr>
<td></td>
<td>- Completion of the CDI and SXN beamlines</td>
</tr>
<tr>
<td>Attracting targeted scientific communities</td>
<td>- Targeted outreach for biological and environmental science communities to attract substantial investment from DOE-BER or relevant funding agencies, building the case for a Bio-Environmental STXM</td>
</tr>
<tr>
<td></td>
<td>- Development of a micro-CT beamline operating in 8-30 keV range optimized for in-situ/operando 3D imaging, filling a critically important imaging capability gap.</td>
</tr>
<tr>
<td></td>
<td>- Development of HXN-II beamline, optimized for strain imaging, ptychography, and projection imaging, complementing the existing imaging capabilities at NSLS-II.</td>
</tr>
<tr>
<td></td>
<td>- Aggressive exploration for growth opportunities for microelectronics research with a goal of building beamlines optimized for microelectronic imaging.</td>
</tr>
<tr>
<td>Enhancement of existing capabilities</td>
<td>- Allocation of resources for enhancing data analysis, including incorporation of end-to-end data analysis pipeline, machine-learning algorithms, high-speed computation, user-friendly interfaces, and portability of the analyzed data.</td>
</tr>
<tr>
<td></td>
<td>- Enhancement of nanoscale imaging capability at SRX, bridging the current resolution gap between HXN/FXI and XFM/TES.</td>
</tr>
<tr>
<td></td>
<td>- Enhancement of the TES capabilities, strengthening in-situ/operando and robust imaging/spectroscopy, and extending the lower energy limit to below 2 keV.</td>
</tr>
<tr>
<td></td>
<td>- Continuing development of pink-beam based high-throughput imaging at XFM.</td>
</tr>
<tr>
<td></td>
<td>- Allocation of resources for modernizing fly-scanning capabilities to achieve photo-limited data collection.</td>
</tr>
<tr>
<td></td>
<td>- Enhancement of nanoscale imaging capabilities at FXI and HXN for higher scientific productivity.</td>
</tr>
</tbody>
</table>

**FY22 Activities**

**Strengthening bioenvironmental research capabilities:** Several projects are underway to strengthen bio-environmental research at NSLS-II -- sponsored in part by DOE-BER as TR&D (Technology Research and Development)
Projects. These include 1) development of cryo-XRF imaging capability, 2) development of user-friendly tools for multimodal image visualization and quantitative analysis, and 3) development of long-working-distance confocal-XRF (cXRF) imaging/spectroscopy. Key milestones for this effort in FY22 are the testing of the high-resolution cXRF optic to be delivered by a vendor (dual paraboloidal mirror lens) and development of the data analysis software, which is elaborated below.

Enhancing data visualization and analysis: The imaging and microscopy program has a detailed plan for enhancing data visualization and analysis. In FY21, the major effort was directed to completing a new data analysis software called NSLS-II MIDAS (Multimodal Imaging Data Analysis Software). MIDAS offers diverse analysis features for analyzing spectromicroscopy data sets. Some of the important features include cross visualization of XRF imaging and XANES spectra, principal component analysis, cluster analysis, unsupervised XANES fitting, conditional mask generation, multi-color visualization (beyond a standard RGB representation), and batch job capability. Software for visualizing correlative microscopy images is prototyped and deployed for x-ray imaging experiments at the HXN beamline by general users. The software is currently deployed at HXN, SRX, and TES beamline. In FY22, we will focus on deploying NSLS-II MIDAS to the general users and making it more robust.

Commissioning of the SRX nano-endstation: Initial commissioning of the new nano-KB endstation at SRX is complete. Currently, the instrument is providing reliable XRF imaging and XANES spectroscopy at sub-500 nm spatial resolution. The focusing optics have demonstrated a focused X-ray beam down to 250 nm for high-resolution experiments. 2D XRF imaging and XANES spectroscopy are available to general users. In FY22, commissioning efforts will focus on enabling interferometer feedback for more accurate positioning and extending imaging capabilities to include tomography for imaging 3D volumes. The ability to nondestructively image the interior of samples is critical to understanding a diverse range of scientific problems, such as evolution of elemental distributions in energy materials during electrochemical cycling.

Vertical mirror upgrade at HXN: Funded through a FIP, a vertical mirror system is under development. The vertical mirror system, replacing the existing CRLs, will enable achromatic pre-focusing and significantly boost HXN’s nano-XANES capability. This new instrument will also provide an opportunity for exploring nano-EXAFS capability. The final design was completed in Jan 2021. Its technical commissioning using x-rays will take place during the 2022-1 cycle.

High-energy extension at FXI: Funded through a FIP, high-energy optics will be installed at FXI. This improvement will increase the energy range up to 15 keV and increase the probing volume of the sample. The high-energy TXM will provide the nanoscale imaging capability on length scales up to hundreds of micrometers at a spatial resolution ~100 nm. This new capability will have great impact on investigating complex 3D hierarchical structures under various in-situ conditions, resulting in significant synergy with other imaging and microscopy beamlines at NSLS-II. The FXI team completed the optics design and are working on the control system design. The sub-system test is planned in 2022-Q1, and the whole system will be commissioned in 2022-Q2.

Operando high-throughput tender XAS endstation: Funded through a FIP, this new endstation at the TES beamline will enable world-leading operando XAS studies of battery, catalyst, and molten salt samples in tender x-ray range. In FY21, the design of the XAS endstation was completed and the final design review was held in late July 2021. The installation is expected in August 2022, and its technical commissioning is planned for the 2022-3 cycle.

Enhancement of ptychography imaging speed at HXN: In FY 21, a facility improvement proposal (FIP) was funded to upgrade the ptychography detector at HXN. The plan is to integrate the Eiger2 X 1M detector into the HXN’s data collection pipeline to remove the measurement throughput bottleneck associated with the detector and realize over 1 kHz data acquisition. The new detector will be commissioned in the latter part of FY 22.
Strengthening the microelectronic research capabilities: Here a two-pronged approach will be used. First, the FXI staff will collaborate with DMEA on extending the FXI’s IC imaging capability. Second, the HXN staff will expand collaboration on microelectronic research to explore funding opportunities for microelectronic research. In FY 21, the HXN staff participated in submitting two BNL microelectronics proposals to DOE. In addition, a postdoctoral support is provided by the BNL Program Development Fund. Hire is expected to be made in early FY22. In FY22, a focused effort will be made to enhance the 3D nanoscale imaging capability at FXI and HXN by exploring advanced 3D imaging methodologies (including ML/AI) and incorporating them into the data analysis pipeline.

Exploring funding opportunities for BEST: Significant efforts on community outreach will take place to explore possible external funding for BEST (Bio-Environmental STXM). During a planning meeting at BNL, the bio-environmental science community outlined the necessary specifications of a next-generation STXM. Especially, in the field of atmospheric research, the need for a STXM at NSLS-II became obvious and key players in the field expressed a strong desire to use a STXM for that research. The current strategy is to secure funding for an endstation microscope, potentially to be installed as the second endstation at the Soft X-ray Nanoprobe (SXN) beamline, currently being constructed as a part of the NEXT-II project. Funding opportunities are being explored in collaboration with Stony Brook University.

Structural Biology

Mission: Our mission is to develop instruments and methods to understand how macromolecules are structured at the atomic level, and how they are organized in biological cells to conduct specific processes.

Strategy: To achieve our mission, we combine macromolecular crystallography (MX), small angle X-ray scattering, cryo-electron microscopy and tomography, X-ray imaging, and the computing approaches to tackle grand challenge science questions in molecular and cell biology.

Based on genome sequence analysis, we know there are ~200-300 essential biological processes in cells, all carried out by assemblies of molecules, or molecular machines. X-ray crystallography and cryo-EM have been successful in delineating atomic structures of many of these molecules and machines. The next grand challenge is to understand how these molecules are organized at the cellular level, and how they are reorganized in different physiological or pathological states. Given the diversity of cellular function, the opportunities for breakthrough knowledge are almost boundless, here are some examples:

- What is special about the structural organization of molecules that function within membrane-bound organelles to enable them to perform specific functions?
- How are molecules organized as they transmit signals from the cell surface to internal components?
- What are the structural details that form distinct aggregates, or of membrane-less organelles?
- The disease states of cells may be morphologically different; can we devise more sophisticated imaging techniques to allow for understanding of the impact of disease on the cell function?
- Ultimately, we need a four-dimensional (3D and time) understanding of the structure, function, and dynamics of molecules in a cellular context.

Our strategy to address these questions is to pursue developments along three directions. First, we will continue to develop cutting-edge integrated structural biology methods including tools for measurements at ambient conditions and to establish new methods for studies of dynamic processes in solution states of macromolecules. Second, we will seize the opportunity from advances in cell imaging and the associated improvements in analysis and partitioning of the images to understand biomolecular structure and function in the cellular context by correlating data available through tomography, light microscopy, and correlative data analysis. Third, to make most of the enormous quantities of data that will be generated, we will work with our funders so that needs for data processing, analysis, management, and curation meet agreed norms. Standardization of data management
and analysis will contribute to, and ease the transition from data acquisition, through interpretation, to publication.

**FY22 Activities**

**Develop an integrated center for sequence-to-function discovery**: Understanding the molecular basis of protein function requires an integrative approach that involves data from multiple sources coupled with computer modeling. This project aims to develop computational capabilities for integrative molecular characterization across scales such that we expose the scientific capabilities (e.g., protein-protein interaction, ligand binding, dynamics) instead of the technical instrumentation to our users. This will lower the barrier for the users who have scientific problems that are well matched to our capabilities but are not experienced enough to navigate the research resources we have.

**Develop plans for multimodal imaging and for a soft X-ray cryo-tomography beamline**: We will develop advanced methods for identification and preparation of biological samples for multi-scale and complimentary imaging techniques. To enable deeper investigation, we will develop high resolution 4D light microscopy, cryo-X-ray tomography and cryo-electron tomography (cryo-ET) workflow for multi-scale imaging. However, absolutely key to our approach will be to work with the community and seek funding for a soft X-ray cryo-tomography beamline dedicated to biological cellular imaging.

**Multiscale imaging and data integration**: The challenges we will overcome are manifold: data volume, data standardization, access to these data, provenance and versioning history, repeatability, and the algorithms to create the full picture. The scale of this endeavor is beyond the capacity of an individual PI’s laboratory to support. Leveraging LDRD funding, we will develop a framework for multiscale, multimodal imaging data integration to respond to grand challenges.

**Develop and mature Serial MX**: Microcrystals offer a unique opportunity to study conformational changes and dynamics relevant to function. By treating microcrystals with different triggers, a series of conformational states may be generated. We will further develop serial crystallography methods including automated microdiffraction data collection, and the associated heterogenous data- and structure- analysis. We will apply these methods to topics of interest to our research community and sponsors to stimulate research at NSLS-II on the production of functional states and dynamics in microcrystals.

**Establish biological cryogenic electron microscopy**: The creation of the new facility for cryo-EM at BNL, and adjacent to NSLS-II, has allowed us to establish a new, complementary, facility for the structural biology community. We plan to further our research goals through operation of this world class facility, through the development of new data analysis techniques. We will integrate these unique data with those available from the biophysical methods available at NSLS-II. Further by collaborating with experts in the cryogenic-electron-tomography we will apply this approach to systems of importance to our sponsors and research community.
Enabling Technology and Support Facilities

In addition to the beamline programs discussed in the previous chapter, we plan to pursue development in the following key enabling technology and operations areas in support of our strategy:

- **Accelerator science and technology** that is the foundation for stable and reliable operations and for enhancing the performance of NSLS-II accelerator systems,
- **Experimental development** in x-ray optics and detectors, in nano-positioning and engineering, and in experimental simulations that are required for innovative world-leading programs and to keep NSLS-II beamlines competitive,
- **Remote access and data infrastructure**, to enable new user access modalities and new ways of experimentation involving advanced simulation, multi-modal experiments, and machine learning driven data analysis,
- **Operations excellence, facility infrastructure, and user services** that are all critically important for the success of the NSLS-II facility.

The development plans in these areas are discussed in this Chapter.

Accelerator Science and Technology

**Mature performance plan:** NSLS-II was built with affordances such that it can ultimately operate reliably at 500 mA with emittances of 600/8 pm·rad in the horizontal and vertical planes, respectively. In line with these goals, the storage ring design included four RF systems, two third harmonic RF cavities for bunch stretching and a cryo plant of adequate capacity and redundancy. This complement of RF and cryo systems was planned be sufficient with a full build-out of insertion devices (i.e. a total radiated power of about 1 MW), to provide a sufficient electron beam lifetime and to cause only moderate wakefield heating of the ring chambers. Six years after machine commissioning, the facility operates 5000 hours per year, delivering 400 mA with X/Y beam emittances of 800/30 pm·rad. The NSLS-II storage ring contains three cavities, supplying 0.4 MW of RF power after successful completion of the 3rd RF system in FY21.

Informed by our operating experience, we developed a plan on securing high reliability operations and reaching mature performance. The plan contains several work packages, listed below in priority order:

- Spare 500 MHz RF cryo module - underway
- Spares not in hand (critical priority) – completed in FY20
- 3rd RF system – completed in FY21
- Spare cold box - funded in FY21
- Injector and dipole power supplies
- Spares not in hand (intermediate priority)
- Two third harmonic 1.5 GHz RF cavities
- Fourth 500 MHz RF system with RF cryo module and solid-state amplifier.

We note that, depending on the outcome from our ongoing studies of high operating current, we may start operating with 500 mA at the present vertical emittance in FY22. Our cost estimate for this plan is built from vendor quotes and an analysis of the systems that we have built and put into operations in the past several years. The cost profile will follow a tentative 10-year-long schedule as shown below.
The schedule is designed to achieve 500 mA performance at the earliest possible date and is driven by the estimates we received from vendors (Linde, Toshiba, RI, etc.), as well as by the timelines of the manufacturing and assembly sequences developed in-house. To address potential delays with delivery of complex systems by industry and the risks of failures during acceptance testing of cryogenic equipment, we added one year of float to the schedule. This is based on our analysis of risks associated with long lead time items and the discrete nature of the available shutdowns for installation. We are targeting early completion of the entire plan by September 2028, though actual timeline is contingent on yearly funds.

**Accelerator R&D:** NSLS-II accelerator physicists provide scientific support of facility operations and work on further improvements of machine performance and reliability. A list of major projects and activities related to the NSLS-II operation and developments includes:

- Common tools program on development shared high level applications; online optimization of injector and storage ring performance
- Studies of beam dynamics with three main RF cavities and 3rd harmonic cavities for bunch lengthening
- High current studies: towards routine operations with 500mA, comparison of beam-induced heating with physical models
- Routine lattice characterization and improvement of the nonlinear machine model
- Accelerator physics studies of beam dynamics with HEX superconducting wiggler
- Enabling high-chromaticity operation mode
- Improvement of orbit feedbacks including bandwidth control, long-term drift suppression, development of interface software tools.
- Development of the new operation mode with a high single-bunch current for time-resolved experiments: studies of beam-induced heating and bunch lengthening.

In parallel with the facility support and development, the NSLS-II team will continue actively working on several research and development projects benefitting light source physics and engineering at large and including the following that are essential for the future NSLS-II upgrade.

- Lattice development (TBA, MBA, Complex Bend); optics correction, optimization of nonlinear beam dynamics; lattice and magnet specifications; magnet tolerances.
- Beam-induced heating: radiation; coherent beam energy loss; gap and length limitations for insertion devices.
- Longitudinal beam dynamics and RF specifications: main RF system and harmonic cavities for bunch lengthening.
- Collective effects: single-bunch and multi-bunch instabilities, intra-beam scattering, ion-driven effects and their impact on the beam lifetime.
- BPM electronics: NSLS-II is developing a new generation of in-house Radio-Frequency Beam Position Monitor (RF BPM) receivers, incorporating the latest technology available in the RF, digital, and software domains.
- Instrumentation front end is being developed to perform R&D in light source engineering and metrology with high power X-ray beams.
- Insertion device (ID) development: our research on IDs is focused on maximizing the brightness and flux of synchrotron radiation in a broad spectral range for user experiments.
• Timing modes: seven NSLS-II beamlines have explored the potential timing-based experiments, which will be enabled by developing and testing flexible bunch patterns in the storage ring current and tight synchronization of these with the beamline detectors.

Work for others (WFO): NSLS-II Accelerator Division (AD) engages in WFO for several reasons. First, it keeps the AD stuff involved in cutting edge instrumentation, of direct benefit to the staff and to the facility. Second, it provides the staff involved a venue to be seen outside of NSLS-II, which is beneficial for career development. Third, the funding it brings in allows us to support a larger staff size than would otherwise be possible, increasing the bench depth and skill set, which is beneficial to the operations of the facility.

AD is supporting upgrade projects at the other DOE light source facilities: APS-U (ANL), ALS-U (LBNL), and LCLS-II (SLAC). This WFO serves the Division well in developing & upgrading NSLS-II instrumentation and positioning us as the provider of choice in the light source business. Under several MOUs, the Accelerator Physics group also makes a significant contribution to the Electron-Ion Collider R&D at BNL.

In engaging in all these activities, work is carefully balanced such that operation of NSLS-II is not compromised.

Exploring NSLS-II upgrade options: NSLS-II is in its sixth year of operations. To keep NSLS-II competitive for the next decade, we are starting to explore upgrade options for our facility in the future. After some early discussions, in FY21 we started exploring four possible scenarios to understand the available phase space for an upgrade, with all options using the existing building infrastructure:

• Medium-scale upgrade that would result in incremental improvements in brightness,
• High-flux upgrade with 2 Amp current and 100 pm-rad horizontal emittance,
• Low-emittance upgrade with 500 mA current and 20 pm-rad horizontal emittance, and
• High-energy upgrade with potential 4 GeV, 500 mA, and 35 pm-rad horizontal emittance.

After substantial discussions in FY21, we have made the decision not to pursue the 2 Amp high-flux option. This conclusion is based on the heat load challenges on accelerator and beamline components as well as the RF power requirements that would take the valuable straight sections away from the user program. Our decision is to continue to evaluate in FY22 the option to operate the accelerator systems for higher-current (>500 mA) operations without a major upgrade. A working group has been formed to do such preliminary evaluation, including effects on the beamlines.

In FY22, we will continue to assess the remaining three upgrade options with a focus on the high(er) energy and low-emittance upgrade. Our goal is to converge on a firm plan for the future upgrade with the optimal beam emittance and current, and consequently brightness and spectral flux of synchrotron radiation from the optimized IDs. The machine lattice that is being considered is based on the novel concept of Complex Bend Achromat (CBA), developed by the NSLS-II accelerator physics group [G. Wang et al., PRAB 21, 100703 (2018); G. Wang et al., PRAB 22, 110703 (2019)]. Furthermore, we plan to continue to study future directions in the Insertion Devices for the upgraded NSLS-II, including IPMU, SCU, and double undulator configurations for high-brightness beamlines.

To date, the development of the CBA lattice concept has been supported by two LDRDs from BNL. This funding is not sufficient to develop prototype lattice hardware components for CBA. We plan to work with BES to seek support of the required R&D activities to demonstrate the feasibility of the novel CBA concept. With additional support, R&D for the NSLS-II will continue to ramp-up in FY22 and beyond.

Experimental Development

The Experimental Development Program is the home of facility supported R&D program as integral part of the NSLS-II operations. The role of the R&D program is to support and foster NSLS-II leadership in the field of synchrotron science and technology. The scope of the R&D program is primarily focused on detectors
development, optical metrology, development of advanced x-ray mirrors and nanofocusing optics, precision engineering and nanopositioning, as well as experimental simulations. In addition, the Experimental Development Program works with beamline staff to develop a beamline recapitalization plan to keep the NSLS-II beamlines capabilities up to date. Activities planned in FY22 and beyond include the following.

**In house development of detectors with a focus on spectroscopic capabilities:** In FY22, we plan to continue to pursue the following detector projects with spectroscopic capabilities:

- **HERA, an upgrade of the Maia detector to improve throughput and energy resolution.** Maia was a many-element spectroscopy detector based on simple diode sensors and a low-noise ASIC developed by BNL’s Instrumentation Division. Hera will adopt SDD sensors, but with the same degree of parallelism and an improved ASIC, to yield better energy resolution and higher throughput. The prototype will have 96 SDDs in a monolithic array. Completion of this prototype has been delayed due to restrictions imposed by COVID, but should be completed in FY22. Once tested, larger arrays will be implemented.

- **Germanium strip detectors for high-energy spectroscopy and diffraction.** We are now able to provide these detectors routinely. We have all the required capability in-house. A detector for energy-dispersive high-energy diffraction to be deployed at the new HEX beamline has been delivered.

- **Ge drift detectors.** In collaboration with Dr. T. Krings at Forschungszentrum Jülich, we are developing the germanium equivalent of the SDD, which will allow large area, very low noise Ge detectors to be built. Again, COVID has significantly slowed down this effort.

- **Imaging detectors with energy-resolution or time-resolution per pixel.** We have begun two projects to develop imaging detectors in which every pixel in the array is a spectrometer. The two detectors will be very similar, except for the sensor used. One (FFFI) will use silicon sensors, while the other (GALAHAD) will use germanium. The former is funded by DOE-BER, the latter by DOE-BES through separate FWPs. Both will have 100um pixels and high energy resolution.

- **VIPIC detector for XPCS experiments:** Based on the most advanced CMOS technology, the VIPIC (*Vertically Integrated Photon Imaging Chip*) is a unique pixel-array detector for accessing micro-second time regimes in X-ray photon correlation spectroscopy experiments. Funded by DOE-BES and in collaboration with FNAL and ANL, we are currently executing a plan to make a full-scale test version of this detector. In FY22, we expect to receive a test chip of 192 x 192 pixels (65um x 65um each pixel) fabricated from the foundry. Testing of this chip will be a critical step for the VIPIC project. If the chip works, we will be able to make a prototype detector as the next step.

- **Evaluation of Hi-Z detector materials for X-ray science:** The goal of this multi-institutional project is to evaluate promising materials and qualify them for use as sensors for experiments with very hard X-rays (energies >20 keV). Partners in this collaboration include detector groups from Argonne, Brookhaven and SLAC National Labs and Cornell University who propose to perform laboratory and beamline tests. The deliverable is an evaluation of the options to BES, supported by test data and prototype devices built on mature and representative detector readout ASICs for XFELs and storage rings. The mature sensor materials to be evaluated are Ge and CdZnTe. In addition, a new and promising Hi-Z material, CsPbBr3 is being evaluated for use as a sensor when bonded to ASICs.

- **Amorphous Selenium for hard X-ray:** In collaboration with Stony Brook Medicine, we are developing a-Se detector for hard x-rays. The advantage of a-Se is the high spatial resolution it offers at hard x-ray. Furthermore, the low temperature growth process makes it easy to directly grow the semiconductor on the read-out chip. We have started working on growing a-Se on MM-pad and UFXC ASICs.

- **7 channel low noise Ge pixel detector for EXAFS:** We plan to develop few channel Ge pixels which will be read by low noise CUBE electronics. We anticipate the noise to be Fano limited. The detector would be ideal for EXAFS measurement where silicon based drift detector has the problem of the silicon escape peak.

**Continued development of MLL optics:** We plan to continue to lead the development of MLL optics to fabricate and deploy tilted and wedged MLLs. As the aimed focal spot size decreases, the tolerances on the fabrication process tighten. This applies as much to the deposition of the multilayer as to the sectioning of the lenses. Thus, our efforts in FY21 and FY22 focus on improving the accuracy of the metrology data acquired during the fabrication process and improving fabrication steps specific to wedged MLLs. These developments will be applied to the fabrication of wedged MLLs to achieve a 5 nm focus in the 10-20keV range as well as for bonded MLL
optics. The upgrade of our deposition chamber control system continued in FY21 with the completion of several key steps. The work is planned to be completed in FY22, allowing the chamber to be better supported by the NSLS-II Data Science and Systems Integration team. In FY22, we will continue to conduct all post-deposition fabrication and metrology tasks to produce cutting-edge MLLs for routine operations of nanoprobes at NSLS-II.

**Bonding of MLL optics using microfabricated templates**: The HXN endstation employs state-of-the-art piezo-mechanical components and provides positioning accuracy down to a few nm. Alignment of two 1D MLL optics is a complex procedure which involves eight degrees of motion. Moreover, when approaching a sub-10 nm point focus, conventional alignment approaches may not work due to geometrical constraints. We plan to enable sub-10 nm focusing by bonding two MLLs together using microfabricated templates. Initial experiments carried out in FY19-FY20 demonstrated ~12 nm point focus. We plan to further improve fabrication of Si templates through a FWP proposal submitted and approved in FY21. Once fully developed, such monolithic 2D MLL devices will become standard hard x-ray nanofocusing optics with a potential of being implemented at the existing and future imaging beamlines of NSLS-II (including a sub-10 nm resolution HXN upgrade contingent of available funding) and other DOE facilities.

**Next-generation testbed for sub-10 nm nanofocusing and nano-tomography**: This project tackles the key issues of global absolute sensing, high stiffness, and minimal heat dissipation that play a critical role in the development of a sub-10 nm tomographic nanoprobe instrument. With an approved facility improvement project, we are in a process of assembling and testing of the developed system. Commissioning will begin in FY21. The developed instrument is equipped with a novel line focusing interferometer-based global sensing system, and will enable nanoscale resolution 3D tomographic imaging at existing and future nano-imaging beamlines.

**Development of stitching interferometer and improvements to the Nano Surface Profiler**: To fully exploit NSLS-II capabilities, diffraction limited optics with surface figure, slope errors reaching less than 100 nm rad rms or surface figure errors close to 1 nm are required. The corresponding mirror inspection needs to be at least at the sub-nm RMS metrology level. Conventional inspection tools at synchrotron facilities are based on one-dimensional (1D) scanning deflectometry, with the measurement angular range typically limited to 10 mrad. Recently, we have developed a prototype interferometry-based two-dimensional (2D) stitching platform capable of achieving a similar measuring precision but with the angular range limited to ~1 mrad. For 1D flat or near-flat mirrors (mainly hard X-ray mirrors), the mirror metrology can be performed with repeatable and reliable results. Funded recently through an FIP, we will improve our internal metrology capabilities for more challenging, steeply curved mirrors (total slope range reaching 60 mrad) necessary for diffraction limited focusing optics for the ARI and other soft X-ray beamlines at NSLS-II.

**Diffraction limited Mirror development**: Recently, we demonstrated the ability to produce a diffraction limited elliptical mirror with sub-nm RMS surface height errors using our Ion Beam Figuring instrument. We plan to produce a small number of test mirrors for NSLS-II beamlines and other DOE facilities in order to obtain real beamline measurements for validation. We will also seek additional funding to extend our current capabilities beyond the current mirror limit of 300 mm.

**Continued development of beamline simulation software for beamlines**: Two electrodynamics simulation codes are, and will continue to be developed and supported: Radia, a 3D magnetostatics computer code for insertion devices and accelerator magnets, and “Synchrotron Radiation Workshop” (SRW), a physical optics computer code for the calculation of synchrotron radiation and wave-optics based simulation of the radiation propagation from source to sample. A number of extensions and improvements were implemented over the last years, enabling detailed magnetic simulations of different types of insertion devices and high-accuracy simulations of partially-coherent synchrotron radiation propagation through X-ray optical elements. At the same time, the scientific program is setting more and more ambitious goals for new X-ray beamlines, and this requires continuous improvement of the electrodynamics simulation methods and software. For instance, the new hard X-ray Bragg CDI beamline requires independent control of both the spot size and degree of coherence, while preserving the X-ray beam waist at the sample position. The large parameter space for optimization is challenging and current codes take too much time to be usable. Thus, partially-coherent calculations in SRW code have to be further improved in speed and be combined with optimization functions. Similarly, the new soft X-ray ARI and SXN
beamline designs require the use of highly curved KB mirrors and zone plates with very large number of zones. To make reliable prediction of these optics, one needs to perform partially-coherent physical-optics calculations that remain valid beyond the traditionally-used paraxial approximation. Special developments are under way, to ensure full support of such calculations with SRW.

**Continue development of experiment simulation capabilities:** In FY22, specific plans include: extending SRW to support simulation of coherent X-ray scattering and imaging experiments via its Sirepo web interface, validating the simulations with experimental data, improving the reliability, generality, accuracy and efficiency of the simulations, and implementing optimization algorithms to address inverse problem solving.

**Development of beamlines recapitalization plan.** A plan for recapitalization of the existing beamlines to keep these operating as state-of-the-art instruments is under development and will continue in FY22. This is important for several reasons: The first NSLS-II Project beamlines started operating in 2014, and are based on designs and optical specifications that are now 10 years old. Other NSLS-II beamlines were constructed with optical components, endstations, detectors and insertion devices that were in use at the NSLS, and will need to be replaced soon to assure continued reliable operations of those beamlines. Further, most detectors have a useful life of 8 – 10 years and therefore even the most recently constructed beamlines should plan for detector replacements in that timeframe. In addition, the manufacture and fabrication of x-ray optical components continues to improve, and NSLS-II beamlines can exploit better focusing or improved wavefront preservation (coherence). Without improvements in optics, detectors, etc., NSLS-II beamlines will lose their competitive advantage. Finally, it is far more cost effective to make regular recurring investments in current operating beamlines than allowing these to fall into disrepair and then have to build a new state-of-the-art beamline at NSLS-II or elsewhere.

The discussions with each individual beamline teams started in FY21 and will continue in FY22. These discussions include considerations of key components such as detectors, optics, endstations, etc. that would need be upgraded in the next 5-10 years for optimal performance. Several different aspects of recapitalization are being considered, including:

- First, replacements of optics and detectors that have a finite lifetime or are no longer state of the art. These replacements would keep the beamline performing at a high level;
- Second, new instruments (detectors, experimental endstations, monochromators, KB mirrors, etc.) that would extend our capabilities and the scientific impact of the beamline. Often, the original beamline designs provided affordances for adding new capabilities (such as multilayer monochromators or KB mirror systems) as the beamline operation matured;
- Third, new instruments and equipment that are needed for enhanced remote operations. This might include increased automation, diagnostics and auto-tuning capabilities, etc. In some cases, one endstation might be useful for routine, highly automated remote experiments and another endstation might be useful for more complex experiments with users on-site;
- Finally, major beamline upgrades that involve relocating optics, adding branchlines, new hutchess, etc. For example, in some cases the original beamline designs anticipated major upgrades such as a branched beamline on a canted undulator port. In these cases, the front end is already canted, hutchess are available, and space is reserved for the branchline optical components.

**Remote Access and Data Infrastructure**

**Remote access and tele-experiments.** There has been a trend to increasing remote access to synchrotrons in recent years, thanks to the ongoing advances in robotic sample handling, and in automated data acquisition and data management. The current COVID-19 restrictions have accelerated such demands. Furthermore, increasingly brighter synchrotron sources and faster detectors have dramatically shortened the data collection times, to the point that data collection is the least time-consuming activity in an increasing number of experiments.

Working with other BES light source facilities, we have formed a remote experiments task force to work on implementing remote access and tele-experiments at NSLS-II, and to look at access policies, procedures and user...
experience. We see remote experiments as essential for NSLS-II to maintain leadership and attract the best science in an increasingly connected world.

The FY22 activities and goals are:

- Establish enhanced computing infrastructure (purchased in FY20) that includes a 3.2 Pb central storage, new home directory for all NSLS-II users and staff, servers for centralized Bluesky installation, and virtualization cluster for NSLS-II resources (proxy, etc.).
- Start pilot of beamline automation, including assessment of beamlines which would benefit, selection of pilot beamline (potentially PDF/XPD), development of needed hardware and software solutions, and rolling-out to other beamlines as needed.
- Establish reliable remote desktop connection for remote access, including reassessment of use of NX family of solutions, removing requirement for VPN and establishing border connection, and ensuring the solution works effectively for all beamlines.
- Improve network connection for beamlines - install new fiber connections from computer rooms to cells, pilot with HEX beamline installation. Connect beamlines as needed.
- Continue to improve and streamline workflow for samples mailed to the facility.

**Data infrastructure.** NSLS-II has been working closely with the other four BES light source facilities in this arena, coordinated through the 5-way Light Source Data and Computing Steering Committee (LSDCSC). In FY20 this group produced a unified vision for the distributed data infrastructure to enable user science. NSLS-II is an integral part of this vision.

Our vision in data and computing is to establish a transformative computational fabric that covers the full lifecycle of the data generated at the BES Light Sources, which

- Facilitates all aspects the data lifecycle across the complex, including theory/modeling and simulation, experiment design, data generation at scientific instruments, data reduction and processing, analysis and interpretation, and publication and dissemination,
- Connects 200+ instruments at BES light sources with a multi-tiered computing landscape including edge, local, Laboratory, ASCR (ALCS, NERSC, OLCF), data repositories, and high-performance, robust, feature rich network using ASCR ESnet, and
- Serves 10,000+ BES Light Source users per year.

To achieve this vision, a complete suite of tools and capabilities in data infrastructure and computing need to be created and developed (see figure below). In addition to experimental control and data acquisition, these tools and capabilities include algorithms and AI/ML, scalable software libraries, workflow and orchestration tools, seamless real-time on-demand computing, network improvements, and discoverable data repositories.
NSLS-II will pursue the following activities in FY22 towards this grand vision:

- **Centralizing data storage.** As each beamline was built at NSLS-II, data storage was built into each beamline. While there are some advantages as the data volumes have grown, this has become less than optimal. NSLS-II will therefore move to a single consolidated long-term data store for all beamlines while retaining local data caches at individual beamlines to allow certain fast operations. In order to achieve this, the current central storage needs to be updated with a faster and larger capability, and the network topology needs realignment. Steps are underway to specify such storage solutions and to alter the networks. These alterations are also required for remote experimentation purposes, progressively started in FY21, which will continue in FY22. The current total raw data amount created by all operational beamlines in pre-pandemic 2019 was just less than one Petabyte. This dropped in 2020 and 2021 due to the impact of COVID-19, but in 2022 and beyond, we expect this will increase significantly. The facility has committed to storing data and to making it available to users for at least one year after the experiments and best effort beyond that. Our current plan is that 3.2 Petabytes will be commissioned in FY22.

- **Improving data curation – storage, archive, longer term access.** Data storage also encompasses how the data is stored, owned, accessed, archived and deleted. The vision is for the full experimental results to be accessible via the use of metadata in conjunction with the data. The provision of the data and metadata must allow for easy user requested copies of the data in multiple commonly supported formats. This allows the user to use a variety of codes and analysis software provided by others. Our approach is to create a software and hardware solution using mostly off the shelf and minimal custom components that allows the data to be stored with a set of metadata such that the data can be transformed on user request into compatible data formats. The Bluesky databroker, currently at v1.0 achieves many of these goals. In addition, the vision requires a fully flexible, secure system for ownership and security allowing for a wide range of possibilities from highly private to fully open access.

- **Seamless data movement and transfer in a user-friendly fashion.** Data stored centrally can be more easily and consistently moved to other locations. Web-based portals and other user-friendly transfer mechanisms need to be invented, instantiated and maintained just once. Data stored in multiple physical/logical locations requires multiple instances of many different transfer mechanisms. Data security when centralized is much easier as there can be a separation between the beamline and the data, and even the physical movement of data via hard disks or USB drives can be facilitated as they can be supported via specialist workstation setup just for that very task. Standardized network mechanisms and naming are a part of this vision.

- **Data processing onsite and computing.** The provisioning of onsite computing for both immediate and post experiment processing is also a part of the vision. The use of high-performance computing for reconstruction of data during an experiment and immediately after the “run” is crucial. Close connection to the data and larger amounts of “scratch space” and the staff who support the analysis for the users are a part of the vision.

- **Near real-time processing of data for beamlines.** Near real-time means the provisioning of sufficient data processing capability inside the data acquisition processing loop. This can be used to directly modify and improve the experimental workflow as the experiment progresses, rather than the usual scan-processing-and-repeat process. Our plan is to allow this to be expanded to “Edge computing” as this technology evolves.

**Operations Excellence**

Creating a vibrant research environment includes having the staff, the support, and the infrastructure necessary for staff and visiting users to safely, securely, and effectively work at the NSLS-II facility. As an integral part of the NSLS-II strategic plan for the next five years, this Section describes the initiatives and development activities
we plan to pursue in the areas of workforce development and inclusion and diversity, career development and work-life balance, environmental safety and health, facility infrastructure, user services, and communications.

**Workforce Development and Inclusion & Diversity.** Workforce skill mix and matrix assignment of staff resources at NSLS-II will continue to evolve to meet mission needs. NSLS-II recognizes the strength associated with a diverse staff and user population and is working aggressively to create an inclusive environment for people of all backgrounds, gender, and ethnicity. The initiatives that support these goals include: (a) promoting leadership and staff awareness of implicit bias with a goal to reduce unconscious bias during recruitment, performance evaluation, and promotions and (b) increasing representation and inclusion of women and underrepresented minorities in management, scientific, and engineering job classifications via specific I&D goals for hiring managers. Examples include plans for increasing awareness and outreach to partner with universities with a high number of women or underrepresented minorities in relevant scientific program. Two directorate initiatives include requiring each NSLS-II staff member to have an annual I&D goal and utilizing a hiring process designed to assure a representative candidate pool and promote inclusion for new hires. Aging of the NSLS-II workforce will continue to drive an increased emphasis on succession planning and provisions for knowledge transfer over the next several years.

**Career Development and Work-Life Balance.** NSLS-II considers its talented and enthusiastic staff as the single most important asset of the facility. As a newly developed synchrotron facility, NSLS-II has been able to attract many high-quality and expert staff to join our facility and the continued career development of our staff as we ramp-up and mature science programs is a critical aspect of NSLS-II facility operations. Recognizing this need of talent management, NSLS-II will continue to implement in FY22 a staff career development and work-life balance plan that includes the following elements.

- **Scientific Staff Promotions:** Following BNL guidelines for scientific staff promotions and recognizing the special situations in balancing scientific and support activities, NSLS-II will continue to work with the Laboratory to develop and implement a more optimized scientific staff career development process; This includes developing a new scientific staff review process for the new R&D classification to be introduced in mid CY21.

- **Mentoring:** BNL has a Laboratory-wide mentoring program that allows a non-supervisory mentor to interact closely with an employee outside the person’s management chain. The mentor may provide useful advice to the employee’s career development from a more neutral point of view. NSLS-II strongly supports this program. The human resources manager for NSLS-II will provide the NSLS-II management team the details on who has participated in the mentor program, as well as plans for others who should participate in the outyears.

- **Work-Life Balance for Scientific Staff:** NSLS-II will continue to address the work-life balance issues that were identified in the 2019 lab-wide survey. A Working Group was assembled to review and evaluate NSLS-II employee responses and develop recommendations to senior management to improve staff engagement and morale. These recommendations were detailed in a report dated March 2020 and included a wide range of suggestions ranging from extending flex time beyond a single month so that staff can better utilize excess time accumulated during periods of beam operations, providing opportunities for a bottoms up performance feedback, establish new policies for use of personal and sick time, restoration of onsite services (e.g. food, child care and automotive) and improved/more timely staff feedback, Several of these recommendations have been accepted and efforts started to address them. The COVID pandemic has however, been an obstacle to full implementation. Measures will be implemented including a Beamline Users Guide to provide clear guidance and expectations on user assistance by beamline staff, remote access and experiments, a beamline policy that allows ‘unused’ beam time at beamlines, and a more balanced operating schedule for weekends, holidays, and maintenance shutdowns. The new BNL telework policy, to be introduced in late FY21 is also designed to give staff more freedom in balancing their lives. NSLS-II is working with Human Resources to develop a new Flex Time Pilot for NSLS-II staff to be able to extend flex time beyond the pay period. This will be beneficial for our staff who are working on projects and supporting the User Program under periods of tight time constraints.
• Revised Postdoc and Graduate Student program: NSLS-II Director’s postdoc and graduate student program is designed to help NSLS-II scientific staff to maintain their research in strategic science areas in partnership with researchers in the scientific community. NSLS-II plans to allocate these postdocs and students as follows:
  o Director’s Postdocs: 8 postdoctoral researchers at 50% support each year, with cost sharing required from non NSLS-II operating funds. Default allocations of these 8 postdocs will be one each in each of the five beamline programs, plus one each in experimental development program, in data science and system integration (DSSI) program, and in the Accelerator Division; Cost sharing between these programs are allowed based on mutual consensus. In the case of cost-sharing with another BNL department or an external institution, the postdoc is expected to spend at least 50% of his/her time on-site at NSLS-II. In all cases, efforts will be made to solicit candidates from under-represented communities to further enhance diversity, equity, and inclusion at NSLS-II.
  o Graduate Students: 8 graduate students at up to $25,000 (direct cost) annually for each student. The allocations of these students will be the same as Director’s Postdocs and will be at the discretions of the managers of the Photon Science beamline programs, experimental development program, DSSI, and the Accelerator Division. A copy of the graduate student’s Ph.D or Master thesis should be submitted to NSLS-II after the student completes thesis work and included in the NSLS-II publication data base.

Environmental Safety, Security, Health & Quality Assurance (ESS&H and QA). ESS&H performance remains a primary objective and strong safety leadership will continue. Other key elements are sustaining a culture where all staff: look out for each other, as well as users, students, and visitors; continuously learn from events and issues; and rigorously plan all scientific and conventional work within a safe, secure and environmentally sound workplace. As we examine our past events and their causes, we are focusing on strengthening our operational discipline in order to raise the rigor of the NSLS-II conduct of operations. QA programs continue to support current operations and will underpin the success of future accelerator and beamline development projects. NSLS-II conducts periodic functional assessments and a broad array of performance measures and metrics are monitored by senior management. Development and updates of security plans for NSLS-II continue to evolve to provide general protection for new DOE security initiatives as well as support DOE and user needs to conduct remote experiments requiring additional security measures.

Buildout of User Laboratories and Offices in LOBs. The primary infrastructure goal for NSLS-II is to provide facilities to attract and retain the scientific and operations workforce, including the user population, and assure safe, secure, reliable facilities to enable the NSLS-II mission. The strategies we deploy to meet this goal are:
  • Maintain, renew, and enhance infrastructure and capabilities to enable the mission, and enhance the quality of work life
  • Enhance critical infrastructure for mature operations and reliability
  • Develop infrastructure to support future beamline build-out, growth of staff and users
  • Optimize the footprint of the space

BNL established an IGPP approach to develop labs for institutional use and make them available to BNL organizations such as NSLS-II under the landlord-tenant model. The first IGPP using this approach was approved in FY21 and will be used for buildout of labs in LOBs 4 and 5. IGPP projects are a subset of CURL projects funded with internal G&A funds, and are prioritized and approved by BNL’s Policy Council on an annual basis. The Laboratory included in the CURL projects list a phased approach for design-construct IGPPs for the construction of 12 laboratories in LOB-2, a combination of dry and wet laboratories, over the next 5 years. Construction of the laboratories is the priority at this time to support the HEX and ARI/SXN beamlines. As of August 2021, of the five Laboratory Office Buildings (LOBs), LOBs 1 and 3 are fully built-out with all office/cubicle/conference/laboratory spaces finished and occupied. LOBs 4 and 5 have office/cubicles/conference spaces finished. LOB 2 remains unfinished.

FY21 IGPP projects are two-year design-construct projects. In FY21, designs were completed for two labs, one lab in LOB 4 and one lab in LOB 5, in support of the Complex Scattering and Structural Biology Programs. Construction will be completed in the first half of FY22. Additionally, a NSLS-II Facility Improvement Project
(FIP) was established to develop a Modern Fabrication Shop to support all of the Photon Science Programs. The CURL and FIP projects are listed below.

- Bldg 744, Lab 5: The Dry Laboratory was designed for use by the Complex Scattering Program and has with the controls, services and laboratory casework to support high-performance research.
- Bldg. 745 Lab 10: The Wet Lab was designed for use by the Structural Biology Program and will be a double lab. It will also provide a biological safety cabinet, chemical fume hood, shaker, floor mounted centrifuge, refrigerator, minus 80 freezer, autoclave/sterilizer, ice maker, and glass washer to support for the life science beamlines in this sector, i.e. LIX (16-ID), AMX (17-ID-1), and FMX (17-ID-2), and shared work space with XFP (17-BM), NYX (19-ID), and the LBMS. The Wet Laboratory design will be completed, and the construction contract will be established in FY 21. Construction will be completed in the first half of FY22.
- Bldg. 744 Lab 10: The Modern Fabrication Laboratory was established for fabrication of small components required for the beamlines. The laboratory will not be a production lab however will provide for development of prototypes or short-term needs for three or less components for any given project.

Although this IGPP approach allows for larger scale projects needed for non-shelled spaces in LOB-2, the time horizon is still long due to the limited internal G&A funds for IGPPs and the total cost will rise substantially. Under the current IGPP rules, BNL is also exploring an approach for the buildout of LOB 2 office space for future growth of staff to support the future beamlines as part of the landlord-tenant model.

As a result of the COVID-19 Pandemic, we made temporary and permanent facility modifications. Temporary wellness screens were installed at receptions desks and beamlines, and office space cubicle walls were permanently raised to provide a barrier where staff sit facing each other in open areas and shared offices. All space planning is now considering future use in a pandemic and post-pandemic environment. Impacts may include reduced occupancy levels, the need for flexible space, the design of high-wall cubicle spaces; incorporation of wellness barriers, and ventilation considerations. Additionally, a hybrid environment of remote staff and on-site staff is being considered including designs of equipment in conference rooms that can accommodate both.

The schedule for the remaining LOB buildouts is critical. With the previous aggressive IGPP buildout plans, the available labs and offices were keeping just slightly ahead of projected staff and user growth. A stretch-out program which delivers at most 1-2 labs per year could cause a disruption to the NSLS-II mission within the next 5 years.

**Discovery Park.** Discovery Park is a new vision for the gateway to BNL. The concept for Discovery Park at BNL’s entryway includes creation of more than 600,000 gross square feet on approximately 60 acres of previously developed, publicly accessible land. Developers, collaborators, and entrepreneurs may propose, build, and operate facilities that complement the DOE and Brookhaven Lab’s missions. Discovery Park is envisioned to include a welcome center, housing accommodations for visiting researchers, a privately funded public science education center, and a technology park where collaborators and entrepreneurs can leverage privately funded research and development with close proximity to BNL.

**Science User Support Center.** The laboratory will be constructing a new welcome center, called the Science User Support Center (SUSC), located in Discovery Park for BNL’s thousands of guest researchers and facility users. This federally funded building will offer workspace for approximately 250 Brookhaven employees as well as space for collaboration and conferences. Groundbreaking is scheduled for late 2021.

**New User Proposal Administration System.** At NSLS-II, the Proposal, Allocation, Safety, and Scheduling (PASS) system is currently the electronic mechanism by which users request beam time. The system also includes the feasibility review by the beamline staff, scientific review and allocation by the Proposal Review Panel, and a fully functional Safety Approval Form system. However, the evolving user science needs require substantial improvements to and possibly a revamp of this PASS system. In FY19-20, we conducted two external reviews of the PASS system to determine its strengths and limitations both at present, but more importantly, in the future. In FY 20, the decision was made to replace PASS. In FY21, NSLS-II began the execution of a plan to do so in close collaboration with APS and LCLS. The common proposal management system should be delivered in FY22.
**Extending the Block Allocation Group Program.** Given the highly successful Block Allocation Group proposals at structural biology beamlines, NSLS-II has extended this program to non-biology beamlines that are based on routine techniques – XAS, XRD, and SAXS/WAXS at ISS, XPD, and CMS beamlines. To date this development has been well received by the user community. NSLS-II will continue to monitor the implementations of these new access programs and make necessary changes to further meet the users’ needs.

**NSLS-II Communication Strategy.** For a facility such as NSLS-II to strive, communicating the expertise, capabilities, and success of the facility is vital. Due to the continuously changing landscape of scientific research and modern communication tools, the overall communication strategy needs to be adaptable on a yearly basis, while still pursuing the overall essential goals. This is achieved by a strategy that defines long-term goals over the course of five years, mid-term milestones in between, and short-term plans for the following year.

Our long-term goals are:

1. Raise awareness for NSLS-II capabilities among key audiences
2. Support NSLS-II growth into a center for discovery-class research in the nation
3. Grow positive relations with all stakeholders; including DOE and partners
4. Strengthen NSLS-II position as a core facility within Brookhaven Lab; integrate the facility into Brookhaven labs long-term strategy without losing its identity
5. Create a visible, coherent, concise, and engaging external presence for NSLS-II.

The top three goals are strongly supported by the last two goals, which create the base for NSLS-II communication within Brookhaven Lab, the DOE complex, and all other external audiences.
Future Outlook

NSLS-II’s mission is to tackle the science and technology challenges facing society today by providing world-leading capabilities to researchers. Today’s challenges, are complex and multi-scaled in both time and space, and require a multimodal approach to make progress, an approach necessarily enabled by an advanced data infrastructure. It is only by applying tools with different resolutions, sensitivities, and modalities that the required depth of understanding can be obtained to make substantive progress in these areas.

To achieve its mission, NSLS-II must continue to assemble an optimized portfolio of world-leading capabilities together with the scientific expertise to use them. The facility is well positioned to do so. First, as a medium energy, high-brightness storage ring, it can deliver exceptional performance from the far-IR to the hard x-ray region of the spectrum. As shown in the figure above, this is what is required to tackle the broad range of problems that society is facing today. Second, NSLS-II is designed to house ~60 beamlines and as of now is nearly half built out, thus offering the scientific potential to build out the rest of the beamline program with new and needed capabilities in a cost-effective way.

As part of our 10+ year strategy, we will pursue two large-scale development initiatives to help achieve our mission – to develop a suite of additional new beamlines to fill the capabilities gaps and to prepare for a future accelerator upgrade in the next decade. Together the two initiatives will retain NSLS-II leadership in the field of medium-energy storage rings and allow NSLS-II to continue to meet its mission of delivering world-leading science through to the mid-21st Century.

New Beamlines

Based on discussions through engagement with our user community, input from the broad scientific community at the 2019 NSLS-II Strategic Planning Workshop, and the advice from NSLS-II Science Advisory Committee (SAC), we are pursuing a new beamlines development strategy that include the considerations of the following factors:

- capability gaps and capacity needs in the current beamlines portfolio,
- potential scientific, programmatic, and societal impact,
- critical role in enabling and supporting multimodal research,
- alignment with NSLS-II and BNL strengths,
- the national light sources landscape, and
maturity and readiness of the new beamline concept.

In the national synchrotron landscape, NSLS-II is the only high-brightness medium-energy facility. As such NSLS-II has unique strength in the photon energy range of tender and soft X-rays through infrared, and a competitive strength in the traditional hard X-ray range around 10-15 keV. These strengths in high-brightness are supplemented by the competitive high-flux capabilities in the high-energy X-ray range that have attracted a regional scientific community to conduct in-situ and operando materials research including under extreme conditions. We have been working with our SAC and our community to take into account these national and regional interests in the development of our new beamlines concepts.

These extensive discussions have led to our conceptualization of 22 new beamlines that will be required to meet the research needs and fill the capability gaps in the current NSLS-II portfolio, particularly in such key technology areas as:

- High-resolution X-ray spectroscopic chemical mapping,
- Full-field X-ray imaging for materials and biology, and
- High-throughput, high-resolution structural analysis.

Together these 22 new beamlines will provide the needed capabilities and capacity to support a wide range of multimodal, multiscale, operando research at NSLS-II. We categorize these 22 new beamlines in following three groups:

- 12 enterprise beamlines with mature techniques to balance our beamlines portfolio and support broad range of science, typically high-throughput and remote friendly, with a large mature scientific user base;
- 7 performance beamlines that provide cutting-edge high-resolution capabilities, enabling high-impact research beyond what can be done using mature techniques;
- 3 mission-specific beamlines to meet targeted mission needs of other federal agencies.

The following table shows the list of these 22 beamlines in enterprise, performance, and mission-specific categories and how they map to the capabilities development needs in high-resolution chemical imaging, multiscale full-field imaging, and high-resolution structural analysis at NSLS-II:

<table>
<thead>
<tr>
<th>Enterprise beamlines (12)</th>
<th>Performance beamlines (7)</th>
<th>High-throughput high-resolution structural science (9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-resolution X-ray spectroscopic chemical imaging (7)</td>
<td>Full-field X-ray imaging for materials and biological sciences (6)</td>
<td>Materials structure and processing (MSP)</td>
</tr>
<tr>
<td>Micron resolution X-ray spectroscopy (MRX)</td>
<td>Micro-CT and instrumentation (MCT)</td>
<td>Processing and liquid surfaces (PLS)</td>
</tr>
<tr>
<td>Scanning transmission X-ray microscope (STX)</td>
<td>Microelectronics imaging (MCT-II)</td>
<td>Massively automated MX – 3PW-based (MAX)</td>
</tr>
<tr>
<td>Soft X-ray tomography for cell imaging (SXT)</td>
<td>High-resolution pair-distribution function (HEX-II)</td>
<td>High-reso pair-distribution function (HEX-III)</td>
</tr>
<tr>
<td>Full-field nano-CT for microelectronics (FXI-II)</td>
<td>Energy dispersive X-ray diffraction (HEX-III)</td>
<td>High-resolution X-ray powder diffraction (HRD)</td>
</tr>
<tr>
<td>X-ray Raman spectroscopy (XRS)</td>
<td>Advanced manufacturing and processing (AMP)</td>
<td>Massively automated MX – IVU-based (MAX-U)</td>
</tr>
<tr>
<td>High-resolution emission spectroscopy (HRS)</td>
<td>High-resolution X-ray powder diffraction (HRD)</td>
<td>Massively automated MX – IVU-based (MAX-U)</td>
</tr>
<tr>
<td>Tender and hard X-ray RIXS nanoprobe (TIN)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In FY22, we will continue to work with the community and with our SAC to (a) further develop and refine the concept and scope for each beamline and capture the conclusions in updated 1-pagers, (b) establish the priorities for the development sequence of the 19 enterprise and performance beamlines, (c) develop a white paper to summarize the science cases for each of the high-priority new beamlines, and (d) engage potential funding agencies to start develop these beamlines.

**Future Facility Upgrade**

As described in the previous section and shown in the figure below, NSLS-II has a vision to develop and operate a balanced portfolio of 54 high-performance, enterprise, and mission-specific beamlines in the coming decade. To fully meet the science needs of the community and to remain competitive in the evolving synchrotron world, an upgrade NSLS-II facility is needed in the next 10+ years.

In our vision, an upgraded NSLS-II (NSLS-IIU) will be a transformative scientific user facility in the 21st century, consisting of three integral parts:

- **Upgraded source** with photon flux & coherence optimized as the ultimate medium-energy storage ring,
- **Optimized beamlines** and detectors to take full advantage of the upgraded source across,
- **Automated data flow** integrated with artificial intelligence, discoverable repository, theory and modelling, and on-demand experiment feedback and data analysis.

In FY22 and beyond, we will continue to explore the available parameter space for an upgraded source, as described on p.18. In addition, we will work with the scientific community to identify key science areas and refine science case examples that will take full advantage of an upgraded NSLS-II source. We will develop a white paper to capture our discussion and conclusions.

In addition to accelerator systems, there is also the need to improve NSLS-II existing beamlines so that all beamlines would benefit from such a future upgrade. In FY20-21, two taskforces were formed to look into the two critical technology areas – optics and detectors. Initial reports from these taskforces have been developed. In FY22, we will continue this work, particularly with a focus on the likely one or two options selected for the accelerator upgrade. These activities will help to optimize future X-ray optical system designs, X-ray detector strategies, and integrated schemes for photon detection and data acquisition, when constructing the suite of new beamlines at NSLS-II.

Finally, further development of the conventional facilities complex will be critical to meet the science needs of the growing NSLS-II facility. In particular, as discussed on p.25, there is already an unmet demand in user science
laboratories and office spaces with the current set of 32 beamlines. To fully meet the future science needs of a substantial built-out portfolio of 54 beamlines, additional laboratories and offices are clearly required. In FY22, we will discuss within BNL to develop an NSLS-II Conventional Facilities Master Plan. This plan will take into account the staff and user needs in the post-COVID era and will serve as our master guide for conventional space development at NSLS-II in the next decade and beyond.

Summary

It is an exciting time at NSLS-II. Entering the 2\textsuperscript{nd} five-years since its start of user operations, NSLS-II is delivering on its promise to be a premier synchrotron facility.

Looking to the future, in the next five years, we will:
- deliver reliable accelerator performance of 500 mA & 8 pm-rad vertical emittance,
- invest in existing beamlines to keep them competitive, with new access modalities post-COVID,
- provide data infrastructure for seamless access to experimental capabilities, compute and storage
- complete the NEXT-II project,
- develop new beamlines to increase capacity, enhance capability, support multimodal approaches, and balance beamline portfolio, and
- develop an upgrade plan for a transformative NSLS-IIU facility

We look forward to working with our stakeholders and the scientific community to make our vision a reality.
# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3PW</td>
<td>Three-Pole Wiggler</td>
</tr>
<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
</tr>
<tr>
<td>ALS</td>
<td>Advanced Light Source</td>
</tr>
<tr>
<td>AM</td>
<td>Additive Manufacturing</td>
</tr>
<tr>
<td>ANL</td>
<td>Argonne National Laboratory</td>
</tr>
<tr>
<td>AP-PES</td>
<td>Ambient Pressure Photo-Electron Spectroscopy</td>
</tr>
<tr>
<td>APS</td>
<td>Advanced Photon Source</td>
</tr>
<tr>
<td>AP-XPS</td>
<td>Ambient Pressure X-ray Photo-emission Spectroscopy</td>
</tr>
<tr>
<td>ARPES</td>
<td>Angle-Resolved Photo-Electron Spectroscopy</td>
</tr>
<tr>
<td>ASCR</td>
<td>Advanced Scientific Computing Research</td>
</tr>
<tr>
<td>ASIC</td>
<td>Application-Specific Integrated Circuit</td>
</tr>
<tr>
<td>BER</td>
<td>Biological and Environmental Research</td>
</tr>
<tr>
<td>BES</td>
<td>Basic Energy Science</td>
</tr>
<tr>
<td>BL</td>
<td>Beamline</td>
</tr>
<tr>
<td>BM</td>
<td>Bending Magnet</td>
</tr>
<tr>
<td>BNL</td>
<td>Brookhaven National Laboratory</td>
</tr>
<tr>
<td>CBA</td>
<td>Complex Bend Achromat</td>
</tr>
<tr>
<td>CDI</td>
<td>Coherent Diffractive Imaging</td>
</tr>
<tr>
<td>CFN</td>
<td>Center for Functional Nanomaterials</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal–Oxide–Semiconductor</td>
</tr>
<tr>
<td>COMPRES</td>
<td>Consortium for Materials Properties Research in Earth Sciences</td>
</tr>
<tr>
<td>COVID</td>
<td>Coronavirus Disease</td>
</tr>
<tr>
<td>Cryo-EM</td>
<td>Cryogenic Electron Microscopy</td>
</tr>
<tr>
<td>CY</td>
<td>Calendar Year</td>
</tr>
<tr>
<td>DAC</td>
<td>Diamond Anvil Cell</td>
</tr>
<tr>
<td>DAMA</td>
<td>Data Acquisition, Management, and Analysis</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>DTRA</td>
<td>Defense Threat Reduction Agency</td>
</tr>
<tr>
<td>ESS&amp;H</td>
<td>Environment, Safety, Security &amp; Health</td>
</tr>
<tr>
<td>FIP</td>
<td>Facility Improvement Project</td>
</tr>
<tr>
<td>FWP</td>
<td>Field Work Proposal</td>
</tr>
<tr>
<td>FY</td>
<td>Fiscal Year</td>
</tr>
<tr>
<td>GU</td>
<td>General User</td>
</tr>
<tr>
<td>HSS</td>
<td>Hard x-ray Scattering and Spectroscopy</td>
</tr>
<tr>
<td>I&amp;D</td>
<td>Inclusion and Diversity</td>
</tr>
<tr>
<td>ID</td>
<td>Insertion Device</td>
</tr>
<tr>
<td>IGPP</td>
<td>Institutional General Plant Projects</td>
</tr>
<tr>
<td>INSPIRE</td>
<td>Inelastic Scattering, Photoemission, and Infrared Endstation</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>KB</td>
<td>Kirkpatrick Baez</td>
</tr>
<tr>
<td>LBNL</td>
<td>Lawrence Berkeley National Laboratory</td>
</tr>
<tr>
<td>LCLS</td>
<td>Linac Coherent Light Source</td>
</tr>
<tr>
<td>LDRD</td>
<td>Laboratory Directed Research and Development</td>
</tr>
<tr>
<td>LOB</td>
<td>Laboratory Office Building</td>
</tr>
<tr>
<td>MBA</td>
<td>Multi-Bend Achromat</td>
</tr>
<tr>
<td>MBE</td>
<td>Molecular Beam Epitaxy</td>
</tr>
<tr>
<td>MID</td>
<td>Metrology and Instrumentation Development</td>
</tr>
<tr>
<td>ML</td>
<td>Machine Learning</td>
</tr>
<tr>
<td>MLL</td>
<td>Multilayer Laue Lens</td>
</tr>
<tr>
<td>MOU</td>
<td>Memorandum of Understanding</td>
</tr>
<tr>
<td>MX</td>
<td>Macromolecular Crystallography</td>
</tr>
<tr>
<td>NE</td>
<td>Nuclear Energy</td>
</tr>
<tr>
<td>NEXT-II</td>
<td>NSLS-II Experimental Tools II</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standard and Technology</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>NSLS-II</td>
<td>National Synchrotron Light Source II</td>
</tr>
<tr>
<td>NYSERDA</td>
<td>New York State Energy Research &amp; Development Authority</td>
</tr>
<tr>
<td>NV</td>
<td>Nitrogen vacancy</td>
</tr>
<tr>
<td>OPLS</td>
<td>Open Platform and Liquids Scattering endstation</td>
</tr>
<tr>
<td>PASS</td>
<td>Proposal Administration, Safety, and Scheduling</td>
</tr>
<tr>
<td>QA</td>
<td>Quality Assurance</td>
</tr>
<tr>
<td>QIS</td>
<td>Quantum Information Science</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RIXS</td>
<td>Resonant Inelastic X-ray Scattering</td>
</tr>
<tr>
<td>SAC</td>
<td>Science Advisory Committee</td>
</tr>
<tr>
<td>SAXS</td>
<td>Small Angle X-ray Scattering</td>
</tr>
<tr>
<td>SBIR</td>
<td>Small Business Innovation Research</td>
</tr>
<tr>
<td>SCC</td>
<td>Synchrotron Catalysis Consortium</td>
</tr>
<tr>
<td>SDD</td>
<td>Silicon Drift Diode</td>
</tr>
<tr>
<td>SRW</td>
<td>Synchrotron Radiation Workshop</td>
</tr>
<tr>
<td>STXM</td>
<td>Scanning Transmission X-ray Microscope</td>
</tr>
<tr>
<td>SXSS</td>
<td>Soft X-ray Spectroscopy and Scattering</td>
</tr>
<tr>
<td>TEM</td>
<td>Transmission Electron Microscopy</td>
</tr>
<tr>
<td>TRF</td>
<td>Triple Rotation Flange</td>
</tr>
<tr>
<td>TXM</td>
<td>Transmission X-ray Microscope</td>
</tr>
<tr>
<td>WAXS</td>
<td>Wide Angle X-ray Scattering</td>
</tr>
<tr>
<td>WFO</td>
<td>Work for Others</td>
</tr>
<tr>
<td>XAS</td>
<td>X-ray Absorption Spectroscopy</td>
</tr>
<tr>
<td>XES</td>
<td>X-ray Emission Spectroscopy</td>
</tr>
<tr>
<td>XPCS</td>
<td>X-ray Photon Correlation Spectroscopy</td>
</tr>
<tr>
<td>XPEEM</td>
<td>X-ray Photo-emission Electron Microscopy</td>
</tr>
<tr>
<td>XPS</td>
<td>X-ray Photon-emission Spectroscopy</td>
</tr>
<tr>
<td>XRD</td>
<td>X-ray Diffraction</td>
</tr>
<tr>
<td>XRF</td>
<td>X-ray Fluorescence</td>
</tr>
</tbody>
</table>