Brookhaven National Laboratory

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Appendix 1
Laboratory Core Capabilities
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3. Laboratory Core Capabilities

Eighteen existing and two emerging core technical capabilities underpin all activities at Brookhaven National Laboratory. Each one is comprised of a substantial combination of facilities, teams of people, and equipment that has a unique and often world-leading component and relevance to national needs, as well as to the education of the next generation of scientists from grades K – 12 and through graduate school. They arise from long-standing strengths and synergies in fundamental nuclear and particle physics, in chemical, materials, biological, environmental, isotope, and data sciences with applications to today's problems; in developing and operating major user facilities; and in targeted applications in national security. These core capabilities enable BNL to deliver transformative science and technology (S&T) that is relevant to the DOE (including the National Nuclear Security Administration [NNSA]) and the Department of Homeland Security (DHS) missions and external partners.

3.1 Accelerator and Detector Science and Technology

Accelerator science and technology development has been central to BNL's mission since the construction of the Cosmotron in 1948. The Laboratory operates three Office of Science User Facilities based on its accelerator capabilities – the Relativistic Heavy Ion collider (RHIC), the National Synchrotron Light Source II (NSLS-II), and the Accelerator Test Facility (ATF) – and several smaller accelerators that provide unique platforms for specialized applications. BNL expertise spans the delivery of electron and hadron beams over a wide range of parameters. Core technology areas include the design and construction of magnets (from permanent to superconducting), including the unique direct-wind technology for complex field profiles developed in the Magnet Division and the "complex bend" design for the proposed NSLS-II upgrade; high-intensity high-brightness electron and hadron beam sources (unpolarized and polarized); high-power mid- and long-wave infrared laser systems; development of radiofrequency (RF) and superconducting RF components and systems; beam instrumentation; beam vacuum systems (including coating capabilities); power supply systems; cryogenic systems; and control systems. Expertise in beam dynamics ranges from low-emittance beams at NSLS-II that produce some of the brightest X-ray beams in the world, to the unique electron and laser interactions at the ATF, to multiple hadron beam cooling techniques implemented in RHIC. This expertise drives critical advances for accelerator-based science and technology in the U.S. and around the world.

BNL has pioneered some of the most innovative detectors that are the cornerstone of scientific experiments. BNL's research seeks to extend capabilities and develop technologies to advance programs in science, energy, security, and industry. BNL's detector research and development (R&D) covers a broad range of technologies from silicon and other solid-state materials to gas, liquid scintillators, and noble liquid detectors. Integral to these developments is microelectronics, particularly operating in extreme environments, and signal processing using the most modern techniques (e.g., Machine Learning/Artificial Intelligence [ML/AI]). BNL's unique facilities and expertise are key to the development of state-of-the-art detectors. Synergistic developments and collaborations with other laboratories and universities enable innovation and implementation of new concepts and technologies.

DOE support for BNL's accelerator capabilities comes from the Offices of Nuclear Physics (NP), Basic Energy Sciences (BES), Fusion Energy Sciences (FES), High Energy Physics (HEP), and Accelerator R&D and Production (ARDAP), and Laboratory Discretionary Funds. Support for BNL's detector R&D also comes from DOE and Other Government Agencies (OGA) and industrial partners.

3.2 Advanced Computer Science, Visualization & Data

BNL has long-standing research, development, and operational programs in advanced computer and data science methods, applied mathematics, algorithms, tools, and infrastructures — particularly in support of experimental facilities - making it one of the largest data science Labs in the DOE complex. Scientists have built an extensive research program in ML and AI that focuses on scalable, robust, trustworthy, streaming, and foundation ML algorithms beyond deep learning, including causal analysis, manifold learning, and natural language processing. The technologies developed are applied to projects in other DOE offices, such as the Office of Biological and Environmental Research (BER) RadBio and low-dose (LUCID), two Biopreparedness Research Virtual Environment (BRaVE) centers, and the BES Automated Sorting of High Repetition Rate Coherent Diffraction Data from X-ray Free Electron Lasers and the Angstrom Era Semiconductor Patterning Material Development Accelerator. This program is complemented by research into AI explainability and reproducibility and supported by research into programming models, runtime systems for ML, and new performance portability approaches that provide a capability to enable the effective use of novel architectures. Advanced workflow management tool concepts including the Exascale Computing Project (ECP) ExaWorks are used to create high throughput workflows that can effectively leverage exascale systems in projects, such as CANDLE, ExaLearn, the completed award winning BER National Virtual Biotechnology Laboratory Medical Therapeutics project, and the HEP Center for Computational Excellence. The Office of Advanced Scientific Computing Research (ASCR) REDWOOD project addresses efficiently managing extreme volumes of data as part of complex workflows in a distributed heterogeneous computing infrastructure. The research is supported by a state-of-the-art 60,000 sf data center. BNL is a leading computing center for high-throughput and data-intensive computing, supporting HEP and NP experiments, (ATLAS, Belle II, Deep Underground Neutrino Experiment [DUNE], STAR, sPHENIX) and BNL, U.S., and international efforts: Lattice Quantum Chromodynamics (LQCD), National Synchrotron Light Source II (NSLS-II), the Center for Functional Nanomaterials (CFN), the Nonproliferation and National Security Department, the Energy and Photon Sciences Directorate, the Worldwide LHC Computing Grid, and the Open Science Grid. BNL operates one of the top ten archives in the world, with over 255 PB of actively managed data and 1.2 EB were analyzed in 2023. Data traffic exceeds 200 PB/year. The primary sources of funding are from ASCR, HEP, NP, BES, BER, the Office of Electricity (OE), the Office of Energy Efficiency and Renewable Energy (EERE), NNSA, New York State, OGA, and Laboratory Discretionary Funds.

3.3 Applied Materials Science and Engineering

BNL capabilities in applied materials encompass materials for energy storage and growing capabilities for studies of materials in extreme environments for nuclear applications, as well as applications in catalysis, and solar energy conversion (3.7), molten salts for energy applications (3.7), fuel cells and electrolyzers (3.8), quantum information science (3.10), and microelectronics (3.18). Capabilities in energy storage include materials synthesis, characterization and functional electrochemical evaluation, high energy density cell technology, evaluation of thermal stability and functional limits of battery materials, fundamental studies of charge and discharge mechanisms and the associated material-structure evolution. BNL has established expertise and capabilities for in-situ and spatio-temporal characterization under operando conditions of energy storage materials by X-ray methods at NSLS-II and electron microscopy at the CFN. BNL has capabilities to study materials in extreme environments for nuclear applications that include a specialized robotic system at NSLS-II for the rapid characterization of radioactive materials, X-ray diffraction computed tomography, which enables three-dimensional (3D) imaging of the microstructure of engineering-scale samples, and a unique suite of environmental cells for the in-situ characterization of highly corrosive reactor materials and molten salt samples. The 200 MeV proton beam of the Linac and the Brookhaven Linac Isotope Producer (BLIP) target facility allow for the investigation of radiation damage of beam collimators, beam windows, and high-power targets, and have been used by the RaDIATE collaboration. The primary sources of funding are BES, the EERE Vehicle Technologies Program (VTO), the Office of Electricity (OE), the Office of Nuclear Energy (NE), New York State, and Laboratory Discretionary Funds.

3.4 Applied Mathematics

Over BNL's long history, its mathematics research has traditionally focused on areas relevant to HEP, NP, synchrotron science (BES), and accelerator physics. Today BNL emphasizes a number of cross cutting themes such as optimal experimental design under uncertainty and broader decision making and optimization of complex systems under uncertainty. The Lab is a partner in ASCR's Mathematical Multifaceted Integrated Capabilities Center, called Multifaceted Mathematics for Digital Twins (M2dt), two ASCR epidemiological decision making projects (EMERGE and RADIUM), the BER RadBio and LUCID projects on low-dose radiation biology that include experimental design, and an NP project on AI for accelerator control, with the CFN and NSLS-II in a Laboratory Directed Research and Development (LDRD) project, which develops new optimal experimental design concepts in autonomous systems, and an LDRD with the Environmental and Climate Sciences Department on optimal observing system design. A second theme centers on multiscale modeling and digital twins that address the bridging of scales and integration of data from experiments/observations and from simulations. Initial focus areas are nuclear physics, climate, biology, and chemical processes, including partnerships on a BER/ASCR Scientific Discovery through Advanced Computing (SciDAC) project Framework for Antarctic System Science in E3SM, M2dt, LDRD investment in a Digital Twin for a new BER Cloud Chamber, and the development of a digital twin for plants. Applied math for scalable AI and ML that will provide key foundations needed for BNL's AI research program is another cross-cutting theme. An added focus involves exploring how to achieve AI explainability through foundational applied mathematics work. BNL's ASCR-funded Noether Fellowship in Applied Mathematics supports work in AI uncertainty quantification, digital twins, and generative modeling. Additional work is being carried out on the development of numerical methods for solving functional renormalization group equations for strongly coupled physics problems. Support comes primarily from ASCR, BER, and Laboratory Discretionary Funds.

3.6 Biological Systems Science

The goal of BNL's program is to develop a systems-level understanding of complex biological processes relevant to the DOE mission. This involves generating and testing hypotheses using approaches that include genomics, molecular biology, biochemistry, structural biology, computation, imaging, and biosystems design. This capability lays the foundation for desired manipulations of growth rates, biomass accumulation, resistance to stresses, and the accumulation of desired products that constitute feedstocks for biofuel and bioproduct production in bioenergy crops relevant to the BER mission. This program is synergistic with programs in physical biosciences (funded by BES, Core Capability [CC] 7). BNL is a major contributor to DOE's BRaVE program with a focus on developing molecular-level insights into the interactions between pathogens and plants to lay the foundation for improved resilience of bioenergy crops to biothreats. BNL also contributes to three Bioenergy Research Centers and participates in ECON, a component of the BER Sustainability Research for Bioenergy program. Biological Systems Science research at BNL drives and enhances the biomolecular characterization and imaging user facilities, through the development of new microscopes, sample environments, integration of advanced computing techniques into experimental workflows, and the development of digital twins of biological systems. BNL's biomolecular characterization and imaging user facilities support BER mission research. BNL is developing computational platforms for biological science as a key contributor to KBase and by establishing the collaborative SciServer environment as part of BRaVE research. BNL's biological systems science activities are supported by: BER, the Joint Genome Institute Community Science Programs, the Environmental Molecular Sciences Laboratory's user program, Facilities Integrating Collaborations for User Science, ASCR, New York State, the National Institutes of Health (NIH), and Laboratory Discretionary Funds.

3.7 Chemical and Molecular Science

BNL's chemical and molecular sciences develop foundational knowledge to support the rational design of chemical and biological processes to enable solutions toward a net-zero carbon economy. The programs are leaders in fundamental research for sustainable carbon and hydrogen conversion in engineered and natural processes, including heterogeneous catalysis of C1 chemistry for fuels; electrocatalysis for hydrogen production and use; light capture and catalytic conversion by molecular systems for solar fuels; and carbon capture, conversion, and storage in plants. The research utilizes BNL user facilities (NSLS-II and CFN) and the divisional Accelerator Center for Energy Research (ACER).

BNL expertise in thermal heterogeneous catalysis is applied to improve understanding of catalysts for the conversion of difficult-to-activate small molecule feedstocks like carbon dioxide and methane to synthesize fuels and high value chemical intermediates. The research, including that conducted through the Synchrotron Catalysis Consortium, combines operando studies of powder catalysts, in-situ studies of model nanocatalysts at NSLS-II and CFN, and quantum chemical computation. Electrocatalysis research pursues mechanistic understanding leading to high activity and durable catalysts for electrolyzer and fuel cell applications using low or non-platinum group metals. The physical biosciences program focuses on a fundamental understanding of plant regulatory and metabolic mechanisms that can inform use-inspired modification of biological pathways to enhance bioproduction with emphasis on highly reduced (energy-dense) forms of carbon. BNL's program in solar photochemistry has expertise in the design, synthesis, and characterization of inorganic molecular catalysts and chromophores to understand and improve chemical processes for solar-to-fuels conversion in artificial photosynthesis. The radiation chemistry program develops and applies advanced pulse radiolysis capabilities at ACER for fundamental mechanistic studies of charged and radical species in condensed phase. BNL has growing capabilities in chemistry of extreme environments focused on structure, dynamics, and radiation chemistry of molten salts for future energy applications, using high temperature molten salt experimental capabilities at NSLS-II and ACER. The programs are funded by BES, EERE Hydrogen and Fuel Cell Technologies Office (HFTO), and Laboratory Discretionary Funds.

3.8 Chemical Engineering

BNL has a small, but high-impact and visible effort in applied chemistry research that translates scientific discovery into deployable technologies. Electrocatalysis research builds on expertise in synthesis and characterization of nanostructured core-shell metal, metal-oxide, and metal-nitride nanostructures for design of cost-effective, durable electrocatalysts for electrical-chemical energy conversion in fuel cells and electrolyzers. BNL developed innovative electrocatalysts with the potential to solve problems of low energy-conversion efficiency and high platinum loading in fuel cells. These catalysts contain smaller amounts of precious metal than conventional ones and improve durability, facilitating commercial applications of fuel cells in electric vehicles. The BNL program participates in the five-year program to develop high performance, high durability fuel cell systems for heavy vehicles in the Million Mile Fuel Cell Truck Consortium funded by HFTO. BNL also partners in L'Innovator with Los Alamos National Laboratory and NREL to demonstrate the incorporation of Lab expertise into new high temperature fuel cells in partnership with Advent Technologies. Scale-up of other electrocatalyst materials is also underway with additional industry partners. These programs are funded by EERE HFTO, and through Strategic Partnership Projects and Cooperative Research and Development Agreements with industrial partners.

3.9 Computational Science

Computational science, both numerical modeling and data analytics, is essential to enabling advanced scientific discovery at BNL's facilities – RHIC and EIC (NP), the BLIP (Isotope R&D and Production [IRP]); ATLAS and Belle II (HEP); the ATF (ARDAP); NSLS-II and CFN (BES); cryo-EM and ARM (BER) - and supporting science programs. Collaborations around numerical modeling applications benefit from the Computational Science Initiative's (CSI) ECP-funded research into performance portability (SOLLVE), ML-enabled surrogate modeling (ExaLearn, SciDAC RAPIDS), and LDRD-funded applied math for multiscale modeling and inverse problems. Examples are ECP LQCD, computational chemistry (NWChemEx), and the

HEP Center for Computational Excellence that supports the ATLAS and DUNE experiments. CSI has also made significant advances in enhancing existing numerical modeling solutions with AI, ML driven solutions for predictive modeling. Examples include cloud-aerosol-turbulence simulations, climate modeling, solar power, and load forecasting. CSI partners with the Interdisciplinary Science Department on a new EERC to design geothermal materials with the assistance of High-Performance Computing (HPC) and ML techniques. In collaboration with the Instrumentation Division, the Scientific Data and Computing Center (SDCC), and facilities such as NSLS-II, cryo-EM, and CFN, BNL's Center for Advanced Technologies for Artificial Intelligence co-design new experimental capabilities that integrate advanced imaging technologies with high powered edge computing devices and streaming ML and AI. New efforts will focus on the development of digital twins, where advanced modeling and simulation capabilities will be employed to help design, guide, and improve experimental setups and workflows. A digital twin that simulates the physical experiments will be able to respond to environmental changes quickly and learn from past experiments. This will require the integration of HPC, AI, and advanced mathematical modeling methods. The primary sources of funding come from ASCR, HEP, NP, BES, BER, New York State, OGA, EERE, OE, and Laboratory Discretionary Funds.

3.10 Condensed Matter Physics and Materials Science

BNL conducts frontier research in Condensed Matter Physics and Materials Science, focusing on new and improved complex, nanostructured, and correlated-electron materials. The research is increasingly focused on quantum materials for quantum information science, building on strengths in high T_c superconductivity and chiral materials. Ongoing research also addresses renewable energy, energy storage, and energy efficiency. Research is pursued through interdisciplinary and tightly coupled programs in materials synthesis, advanced characterization using a range of experimental techniques, both lab and facility based, and theoretical approaches. A unique tool, known as OASIS (that integrates oxide molecular beam epitaxy, angle-resolved photoemission, and spectroscopic imaging scanning tunneling microscopy), brings together in one system the ability to fabricate thin films and examine their properties in situ using scanning tunneling microscopy and angle-resolved photoemission. OASIS capabilities have been applied to study strongly correlated cuprates and new research directions including 2D materials and heterostructures that can support topological excitations. The Condensed Matter Physics and Materials Science groups are all engaged in NSLS-II activities, including developing new capabilities that have led to proposals for new NSLS-II beamlines. A complementary ultrafast X-ray research program focuses on the unique science that can be performed at ultrafast X-ray free electron laser facilities. Ultrafast capabilities include an electron pulser device capable of "tabletop" ultrafast electron microscopy. Newer efforts focus on applications of ML and data science to materials science and understanding the many-body properties of rare earth materials and their potential applications to quantum technologies. BES and Laboratory Discretionary Funds are the primary sources of funding for these ongoing efforts.

3.14 Earth, Environmental, and Atmospheric Science

BNL's atmospheric science efforts develop process-level insight into the role of aerosol and clouds in a changing climate through long-standing expertise in climate science and measurement science. BNL researchers are advancing the understanding of interactions along the aerosol-cloud-precipitation continuum and their impacts on climate for the Atmospheric Systems Research Program through a joint Science Focus Area program with Argonne National Laboratory. Scientific staff support the Atmospheric Radiation Measurement (ARM) User Facility and data archive as instrument mentors and as data science specialists and contribute to the design and interpretation of ARM measurements. BNL staff are serving as lead scientists for a long-term mobile ARM observatory in northern Alabama to study clouds, aerosols, and land-atmosphere interactions that will feed forward into Earth system models. Climate modeling scientists support the Energy Exascale Earth System Model (E3SM) and the Large Eddy Simulation ARM Symbiotic Simulation and Observation project. Observation techniques and strategies must evolve to support the development of DOE'S E3SM. BNL staff are developing novel measurement methodologies, instrumentation, and Laboratory facilities to support the research community. A focal point is a BNL-led, DOE and National Science Foundation-funded research consortium to inform the design of a convection cloud chamber to study the aerosol-cloud-drizzle continuum. As part of this effort, BNL has spearheaded research and development on the next generation of measurement technologies that will enable non-contact, in-situ detection of this continuum. In parallel, CSI is building capabilities for very high-resolution and data-driven simulations of the atmosphere and climate. BNL maintains a mobile remote-sensing platform to support research of atmospheric conditions in urban systems. This capability supports BER's Integrated Field Laboratories project in Arizona and, along with BNL's long-standing Perfluorocarbon Tracer technology, is used to support urban dispersion studies. Funding comes from BER, EERE, DHS, and Laboratory Discretionary Funds.

3.15 Isotope Science and Engineering

BNL has unique core expertise to produce isotopes for research and industrial distribution. This includes know-how in targetry and modeling, chemical separations capabilities including proficiency in nuclear and radiochemistry, isotope production, radiation shielding, nuclear data, AI/ML, robotics, chemical engineering, and automation to broaden the availability of isotopes needed for applications in industry, environmental, medical, and national security purposes. The Lab has unique accelerator facilities for irradiation such as the BLIP that can accept protons from 66-200 MeV from the Linac to bombard targets for isotope production and radiation damage studies to evaluate materials for use in reactors and accelerators. The Isotope Research and Production (IP) Department is bringing online a 13-19 MeV energy cyclotron to expand isotope production. BNL houses the Radionuclide Research and Production Laboratory that contains radioanalytical laboratories, equipment, and hot cells to study and process irradiated materials for providing isotopes for both internal and external use. The facility is fully equipped to conduct processing of isotopes, characterization, and evaluation in applications. The IP Department has expertise in the production of isotopes following current Good Manufacturing Practices and has filed two Drug master files with the Food and Drug Administration. The Lab has been deemed an acceptable supplier of isotopes. Materials irradiated at BNL's facilities can be further studied at NSLS-II at a specially outfitted beamline for evaluating the changes in structure that result from exposures. This effort is funded by IRP and Lab Discretionary Funds.

3.16 Large-Scale User Facilities/R&D Facilities/Advanced Instrumentation

BNL's large scale user facilities, R&D facilities, and advanced instrumentation are extending the frontiers of knowledge and enabling studies of important scientific challenges. In FY 2023, BNL served nearly 3600 users at its DOE designated user facilities, RHIC, NSLS-II, CFN, and the ATF and close to 900 at the NASA Space Radiation Laboratory (NSRL), the Tandems, RHIC-ATLAS Computing Facility and U.S. ATLAS Analysis Support Center. BNL continues to invest in detector and accelerator upgrades for its community of nearly 1000 **RHIC** users. **RHIC** completed Run 2023 with the upgraded STAR detector and started commissioning the newly built sPHENIX detector, which will enable precision measurements on hard probes (jets and heavy quarks). BNL will host the **EIC**, a facility that builds on **RHIC**, that will provide high-energy electron-ion collisions for studies of cold nuclear matter at extreme gluon densities and precision measurements of the structure and properties of protons and complex nuclei at the quark-gluon level. **NSLS-II** has strengths in imaging and dynamics and world-leading R&D programs in nano-focusing optics and nano-precision engineering. **NSLS-II** hosted 1885 users in FY 2023. **NSLS-II** is executing the NEXT-II beamline project and preparing for a CD-1 decision late in FY 2024 for NEXT-III. NEXT-III beamlines will complement the existing suite and provide capabilities in high throughput scattering, spectroscopy, and imaging. The **CFN** hosted 655 unique users in FY 2023. **CFN** continues to upgrade its portfolio to maintain leading-edge status, in instruments for synthesis and characterization of nanomaterials created by assembly, and tools for in-situ and operando nanoscience. A focus is in developing and installing an integrated set of four unique characterization and fabrication instruments for 2D material heterostructures assembled by the Quantum Material Press. BNL leads the Nanoscale Science Research Centers (NSRC)-Recap project for the benefit of the five NSRCs. The **ATF** supports a unique suite of advanced accelerator and laser experiments as part of the Accelerator Stewardship Program managed by ARDAP. BNL makes key contributions to international facilities – the **Large Hadron Collider (LHC)**, **SuperKEKB**, and future facilities such as a **Long Baseline Neutrino Facility (LBNF)/DUNE** and the **Rubin Observatory**. BNL plays a significant role in the globally deployed **ARM** User Facility for climate research, which serves more than 1000 users annually. BNL scientists lead the five-year **ARM** deployment to the Southeast U.S.; with partial funding from ARM, BNL has established a Center for Atmospheric Measurement Science. BNL's **cryo-EM facility,** run as a non-designated user facility with funding from BER, supports BER users and the General user community, including BES-funded researchers. BNL hosts the **Long Island Solar Farm**, a privately owned 32-megawatt solar photovoltaic power plant. BNL's **Northeast Solar Energy Research Center** enables field tests of solar technologies under actual northeastern weather conditions. From concept through construction, the **Instrumentation Division** makes major contributions to instruments and experiments at BNL and other accelerator- and reactor-based facilities worldwide. Major sources of funding are: ARDAP, BES, NP, HEP, BER, NASA, New York State, NIH, and BNL Discretionary Funds.

3.17 Mechanical Design and Engineering

At BNL, Mechanical Design and Engineering is practiced across a wide range of disciplines, programs, and projects. This ranges from conventional facilities to sophisticated and often complex systems for scientific research at the Lab or offsite, including the moon for LuSEE-Night and particle accelerator and storage ring components closer to home. BNL has advanced mechanical engineering and design capabilities including CAD software, finite element analysis, and modeling tools to realize intricate components for particle accelerators, detectors, and other scientific instruments. BNL collaborates closely with stakeholders to gather and translate research requirements into innovative engineering solutions that ensure optimal performance and reliability in challenging environments. BNL Mechanical Engineering includes: 1) Cryogenic and pressure system engineering with liquid helium used in the operation of RHIC, NSLS-II, and test facilities for superconducting magnets and cavities; 2) Magnetic design and analysis for superconducting magnets and conventional conductor magnets and permanent magnet devices; 3) Vacuum engineering with large high and ultra-high vacuum systems in the BNL accelerators; 4) Mechanical design of specialized particle beamline diagnostic instrumentation equipment including additive manufacturing; and 5) Multi-physics analysis for structural, thermal, hydraulic, stress, and electrical characteristics of a wide range of components and structures.

BNL's Mechanical Engineers fill leading roles in working with procurement, vendors, and BNL staff through the cycle of engineering, design, procurement/production, work control, installation, and coordination from concept through completion of projects and often in their subsequent operation. BNL continues to nurture its culture of safety by design while striving to standardize engineering practices, implement unified design and analysis tools, and building on the mechatronics capabilities of the staff and establishing career development paths across the Laboratory. This holistic approach should enhance efficiency, consistency, and professional growth within the organization. Sources of funding include BES, NP, HEP, ARDAP, IRP and BNL Discretionary Funds as well as BER, NASA, New York State, NIH, and other DOE laboratories.

3.18 Microelectronics

A core foundation of multidisciplinary scientific expertise and leading technical facilities positions BNL well to make significant contributions to both near-term technology issues and longer-term, microelectronics research. NSLS-II hosts world-leading, synchrotron X-ray imaging and spectroscopy instruments that are proven, unique tools for characterizing leading-edge microelectronics. The CFN complements X-ray characterization methods with state-of-the-art electron microscopy and optical probes, while also supporting synthesis of electronic materials, including 2D materials by the Quantum Material Press, and innovative self-assembly approaches using polymers and DNA. BNL expertise in circuits design, especially for unique detectors, covers device modeling, low-noise Application-specific integrated circuit (aka ASIC) design, and cryo- complementary metal-oxide-semiconductor (aka CMOS) technology. Software proficiency includes developing quantitative codesign tools, systems simulation, and design of AI algorithms. Coordinating these key strengths enables BNL to address key technology and research questions in microelectronics. These capabilities are funded by BES, NP, HEP, NNSA, DOD and Laboratory Discretionary Funds.

3.19 Nuclear & Radio Chemistry

BNL's nuclear science programs span the range from applications in medicine to national security. The BLIP uses the 200 MeV Linac and target processing facilities to produce isotopes not commercially available, mostly for nuclear medicine. BNL brought online a hot cell to routinely produce actinium 225 (Ac-225) in sufficient quantities to support clinical trials for cancer. Ac-225 is an alpha emitter that has demonstrated reduced toxicity and improved cure rates in clinical trials. A cyclotron has been refurbished and completed readiness reviews to produce needed isotopes that can't be produced at BLIP, expanding production capabilities. Ongoing work to upgrade facilities includes doubling of the beam current and installation of a second irradiation site to increase output in the future. The irradiation facilities are also used to conduct radiation damage studies. BNL hosts the Nuclear and Radiochemistry summer school that provides twelve undergraduates with hands-on experience. Next year BNL will host the annual meeting of the Horizon Broadening Isotope Production Pipeline Opportunities designed to bring together a diverse group of students from across the country - exposing them to the activities required to provide the nation with radioisotopes needed for science and applications. BNL's expertise has led to a patent for a Rapid Cycling Medical Synchrotron and for low-mass beam delivery gantries, technologies for the next generation of proton- and ion-based cancer therapy. The effects of ionizing radiation on living systems are studied at NSRL, a flagship international user facility supported by NASA. BNL is home to the NNSA Radiological Assistance Program's Region 1 team and a United States Agency for International Development (USAID)-funded international radiological/nuclear crisis operations and consequence-management events response capability. BNL supports NNSA's Defense Nuclear Nonproliferation programs by using its unique facilities, such as NSLS-II, and expertise in instrument development, chemistry, data science, safeguards, and nuclear data analysis. BNL has extensive expertise in nuclear nonproliferation and international nuclear safeguards that includes more than forty years of program management delivered by the International Safeguards Project Office, which provides technical and administrative management of the U.S. Support Program to International Atomic Energy Agency (IAEA) Safeguards. Brookhaven also develops curricula and provides safeguards implementation training for international IAEA inspectors and officials. Funding comes from sources that include NP, IPR, BES, BER, the Department of State, NASA, NNSA, USAID, and DHS.

3.20 Nuclear Engineering (Emerging)

BNL's nuclear engineering capability encompasses three major areas: Materials for Nuclear Energy Applications, Nuclear Systems and Structural Analysis, and Nuclear Data. In the area of materials for nuclear energy applications, BNL researchers are developing fundamental insights into the molecular structure of molten salts relevant to novel nuclear fuel systems as well as the interaction of these types of fuels with containment materials. To study these systems, BNL develops synchrotron characterization techniques explicitly for the investigation of materials for nuclear energy systems, including using robots for handling radioactive samples, X-ray diffraction tomography to investigate material degradation, and high temperature in-situ experiments for the annealing, corrosion, and molten salts. In the area of nuclear systems and structural analysis, BNL has experience with all phases of the design and assessment/evaluation of advanced nuclear systems, such as reactors and accelerator-driven-systems and fuel cycles, resulting from decades of support to the Nuclear Regulatory Commission (NRC) and the DOE. BNL also conducts research on next-generation reactors and alternative fuel cycles and safeguards for these systems. State-of-the-art NRC and DOE-developed computational tools are utilized for the full scope neutronics and thermal hydraulics analyses of reactor performance and safety characteristics. In the area of nuclear data, BNL hosts the National Nuclear Data Center (CC 21), which is also the lead unit of the U.S. Nuclear Data Program (USNDP) and BNL chairs the Cross Section Evaluation Working Group. BNL's National Nuclear Data Center (NNDC) is a DOE Office of Science Public Reusable Research Data Resource. BNL's nuclear data research supports a variety of national and international efforts in reactor physics, the nuclear fuel cycle, defense, nuclear non-proliferation, and isotope production. The NNDC has decades of experience in performing high-precision gamma-ray spectroscopy experiments. The major U.S. spectrometers Gammasphere and Gamma-Ray Energy Tracking In-beam Nuclear Array and new dedicated in-house measuring capabilities are used to improve decay data relevant to isotope production, non-proliferation, and reactor applications. The programs are funded by NE, NP, NNSA, NRC, the National Institute of Standards and Technology (NIST), and Laboratory Discretionary Funds.

3.21 Nuclear Physics

BNL conducts pioneering explorations of the most fundamental aspects of matter governed by the strong nuclear force. RHIC is a unique facility allowing for a wide range of heavy ion collisions and polarized proton-proton collisions. RHIC experiments discovered that quark-gluon plasma, which existed microseconds after the Big Bang, is a nearly perfect liquid and that gluons' spins have a nonnegligible role in making up the proton spin and aligning in its direction. The success of the RHIC program benefits from BNL's strong program of advanced accelerator R&D, the support of the BNL Physics Department, the SDCC, and the Instrumentation Division. The successful completion of the RHIC science mission relies on the recently completed upgrades – STAR iTPC, STAR forward upgrade, and the completed sPHENIX detector. As a DOE user facility, RHIC has nearly 1000 users from over 21 countries. To date, the RHIC program has produced more than 370 Ph.D. nuclear physicists. Nuclear theory efforts at BNL and throughout the international theory community continue to contribute to the success of the RHIC program, including BNL's role as a lead institution in two new Topical Collaborations in Nuclear Theory. Experimental, theoretical, computational research, and nuclear science workforce development are enhanced by the presence of the RIKEN BNL Research Center. BNL develops advanced software and computing facilities for applications in nuclear physics experiments and theory, including lattice QCD simulations. Key expertise has been developed in the management and processing of near-exabyte-scale data sets generated at high rates and distributed computing for analysis, facilitated by the RHIC Computing Facility, a component of BNL's SDCC. RHIC will be transformed into the EIC through the addition of an electron accelerator and storage ring. The EIC will facilitate a rich science program based on collisions of high-energy electrons with heavy ion, polarized proton and polarized helium-3 beams to precisely image the quark-gluon structure of the proton and atomic nuclei and elucidate the origin of visible matter in the universe. BNL and the Thomas Jefferson National Accelerator Facility are the two DOE host labs for the EIC project. BNL operates the NNDC, a resource for the open dissemination of nuclear structure, decay, and reaction data that serves as the focal point for the USNDP and reactor design. The program also addresses gaps in the data, through targeted experimental studies and the use of theoretical models. Last year, there were over fifteen million data retrievals from the NNDC websites. Support is provided by NP, RIKEN, and Laboratory Discretionary Funds.

3.22 Particle Physics

BNL has key roles in developing and operating particle physics experiments that seek answers to seminal questions about the mysteries of neutrinos, secrets of the Higgs Boson, the nature of the Dark Matter and Cosmic evolution, search for new particles and interactions and quantum imprints of new physics phenomena. BNL's major capabilities are: host institution for U.S. contributions to the ATLAS detector at the LHC, consisting of managing the U.S. ATLAS Operations Program including the Tier 1 Data Center and the upgrade project and construction and testing of the high field quadrupole magnets for the LHC accelerator upgrade; leadership in neutrino oscillation experiments, including a leading role in the DUNE Technical Coordination and second DUNE module design and construction; leading roles in the short-baseline experiments at Fermi National Accelerator Laboratory (MicroBooNE, ICARUS, and the Short Baseline Near Detector); leading the U.S. Operations program of the Belle II experiment at KEK, including computing facilities, commissioning, and operations; commissioning and data analysis of the Rubin Observatory cosmological survey; and construction of the Lunar Surface Electromagnetics Experiment (LuSEE)-Night program and coordination of its operations and science programs. BNL develops advanced software and computing facilities for applications in high energy physics experiments and theory. Key expertise in high throughput computing has been developed in the management and processing of multi-petabyte-scale data sets generated at high rates and in distributed computing for data analysis. Development of new instrumentation technologies for elementary particles and data collection and storage systems provides the foundation for present and future particle physics experiments. These roles are enhanced by BNL high energy physics theory efforts and by BNL's leadership in advanced accelerator research and development, including high field magnet development, which is critical for the next generation of high energy physics experiments and accelerator facilities. Funding for this work comes from HEP and Laboratory Discretionary Funds.

3.24 Power Systems and Electrical Engineering (Emerging)

BNL focuses on research to advance the deployment and grid integration of renewable energy systems and the development of new technologies to enable the next generation smart grid. BNL has significant expertise in power system modeling and simulation, and in transmission and distribution system design, operation, and planning that can be used to analyze the systems and determine their appropriate use as solutions for grid integration of renewable generation. BNL also has capabilities in the development of control algorithms that can be applied to the operation of energy storage systems for applications to renewable integration. BNL has developed a portfolio of grid modernization research projects and will continue to build capabilities in this area. Previous and ongoing R&D projects at BNL that are related to the research areas funded by the DOE Office of Electricity include the development of a probabilistic technique for sizing energy storage systems, development of probabilistic techniques for transmission system planning, formal analysis for dynamic stability assessment, and a deep learning based online platform for critical anomaly detection and emergency control to enhance grid reliability and resiliency. BNL has invested LDRD funds for investigation of the use of energy storage systems to improve grid inertial response that are broadening these efforts. Programs funded by New York State include the evaluation of grid impacts from utility scale solar generation on sub-transmission and distribution systems and the use of Radar in real-time damage forecasting and response for restoration of electric utility systems. BNL's Interdisciplinary Science Department leads efforts that will enable simulation and validation of innovative new technologies to address the challenges for integrating renewables and energy storage systems on the grid and reduce the risk to utilities of deploying these new technologies. New York State, OE, and Laboratory Discretionary Funds are the primary sources of funding.

3.25 Systems Engineering and Integration

BNL designs, constructs, and operates large-scale facilities and advanced instrumentation to address some of the most challenging questions in fundamental science, applied science, and national security, underpinned by a highly trained, multidisciplinary, and internationally recognized workforce. The successful construction of NSLS-II and its X-ray beam lines is based on state-of-the-art technologies integrated into NSLS-II including superconducting RF systems utilizing both high powered klystron and solid-state drivers; novel RF and X-ray beam position monitors; high heat-load front-end components; and novel X-ray optics and detectors. The RHIC accelerator complex includes the only collider in the U.S. Technologies developed and employed at RHIC include high-intensity high-brightness ion sources; high-power proton targets for medical isotopes; rapid cycling synchrotrons; advanced beam cooling; and superconducting accelerators components to produce high luminosity ion and polarized proton collisions. The EIC requires strong systems engineering and integration that includes all the above and high intensity polarized electron beams, rapid cycling electron synchrotrons, and extensive superconducting RF installations at 2K temperatures. Accelerator systems engineering includes integration of modern computing, often powered by AI, and software as elements of monitoring, control, and data acquisition. BNL develops large and complex particle detectors for high energy and nuclear physics at BNL, CERN, Fermilab, and other centers around the world. Such detectors include noble liquid detectors, cold electronics, silicon-based precision trackers, particle identification, large area muon detectors, and many others. Particle detector developments include systems engineering and integration of mechanics, high voltage, cryogenics, power supplies, microelectronics, readout electronics, and computing. The major sources of funding are BES, NP, HEP, BER, NE, NIST, NRC, and BNL Discretionary Funds.

Summary: These core capabilities, along with BNL's proven expertise in large science project management, will enable the Lab to deliver its mission and customer focus, to perform a complementary role in the DOE laboratory system, and to implement its vision.

*The numbering scheme for the core capabilities follows Enclosure 2 of the Annual Lab Plan guidance.