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May 28, 2024

Dr. Harriet Kung, Acting Director
Department of Energy, Office of Science
Washington, DC 20585

Subject: Report on New and Upgraded National User Facilities in Basic Energy Sciences

Dear Dr. Kung,

Please find the report by the Basic Energy Sciences Advisory Committee (BESAC) with assessments of future user facility construction projects proposed by the Office of Basic Energy Sciences. The report responds to the request from Dr. Berhe of December 1, 2023, summarized below.

Charge to BESAC

On December 1, 2023, Dr. Asmeret Asefaw Berhe, Director of the Department of Energy (DOE) Office of Science (SC-1), charged the Basic Energy Sciences Advisory Committee (BESAC) with considering new and upgraded facilities proposed or planned by DOE's Office of Basic Energy Sciences (BES) that will be crucial for making forefront scientific discoveries. The primary elements of the evaluation were the following:

1. *Potential to contribute to world-leading science* in the next decade, categorizing each facility as: (a) absolutely central; (b) important; (c) lower priority; or, (d) don't know enough yet.
2. *Readiness for construction*, classifying as (a) ready to initiate; (b) significant scientific/engineering challenges to resolve before initiating; or (c) mission and technical requirements not yet fully defined.

BESAC was asked to further consider opportunities for cross-program partnerships within the Office of Science that would advance science and user effectiveness. The demographics of future user communities were another consideration, spanning research topics, the number and geographic origin of users, and their level of technical expertise. The considerations and approach of the subcommittee are summarized in Appendix I.

In response to the SC-1 charge, a BESAC Subcommittee on Facilities led by Dr. Eric Isaacs and Prof. Serena DeBeer was created, consisting of eleven members with expertise that span the science and capabilities of X-ray and neutron facilities (Appendix II). The subcommittee was asked to assess eight facility construction projects:

- Two projects at the Neutron Facilities at Oak Ridge National Laboratory
  - High Flux Isotope Reactor Pressure Vessel Replacement (HFIR PVR)
  - Spallation Neutron Source Second Target Station (SNS-STS)
- Upgraded synchrotron and instruments at Brookhaven National Laboratory
  - National Synchrotron Light Source (NSLS)-II NEXT-III instrument suite
  - NSLS-II Upgrade

- Three projects at the Linac Coherent Light Source (LCLS) X-ray Free Electron Laser (XFEL) at SLAC National Accelerator Laboratory
    - LCLS-II-High Energy Upgrade (LCLS-II-HE)
    - Low Emittance Injector (LEI)
    - LCLS-X
- Future Light Source (FLS) – a 'green field' light source, location(s) TBD

Overview

Over the past four decades, the DOE's Office of Science Basic Energy Sciences light, neutron and nanoscience facilities have had a profound impact on scientific discovery and technological innovation in the United States. Research at BES facilities has yielded more than 84,000 publications and nine Nobel Prizes, and served over 260,000 users (FY04-FY23).

The BES light and neutron sources, in conjunction with DOE's computing facilities, have been pivotal for significant breakthroughs in US research and development, in fields such as development of new materials for applications in quantum science, catalysis, semiconductor devices, and the energy transformation—all of which are critical for national security. These facilities also advance drug design, structural biology, and efficient manufacturing design, which impact human health and economic competitiveness.

While BES facilities are generally world-leading, global competition is fierce, putting US leadership at risk. (See the 2021 BESAC International benchmarking report.) China and the EU are aggressively advancing next-generation XFELs, synchrotrons and neutron sources. The EU already has world leading reactor-based research facilities. Hence, there is great urgency for the US to advance the capabilities of these crucial facilities to ensure US leadership in discovery science and technological innovation.

The BESAC Subcommittee commends the forward-thinking leadership of BES in advancing their portfolio of key, major user facilities that will drive discovery and innovation for US scientists and engineers in the future. Notably, BES has made strategic decisions over the past decade to not move forward with some proposed facilities projects, such as the Next Generation Light Source (NGLS), or to delay others, for example, the Second Target Station at the SNS. In addition, BES has engaged in strategic cross-program collaboration that is especially important for planning and implementing state-of-the-art artificial intelligence (AI), robotics, and data management systems, which are considered essential to fully realize the potential of all facilities to execute on their mission of transformational science and technologies. Herein, the subcommittee provides insights into the status of emerging facilities that will enable future breakthroughs.

Summary of the BES Facilities Subcommittee assessments

The Subcommittee has concluded that the eight proposed upgraded and new facilities are absolutely central, or have the potential to be absolutely central, to future US leadership in scientific research and technology. A testament to the strength of BES planning, each new/upgraded facility will provide capabilities that ensure US leadership in discovery science and key technologies that address DOE BES and the Nation's top priorities. Nevertheless, the various facilities are at different stages of readiness, and the BES budget does not permit simultaneous construction of them all, while also adequately supporting research enabled by these facilities. Furthermore, systematic planning for new facilities concepts with capabilities that will drive future breakthroughs far beyond what is possible today is critical and urgent to ensure US leadership in science and technology. Therefore, it is recommended that BES create a plan to sequence the portfolio of planned facilities and to embark on strategic planning for future facilities with a clear eye towards leading the global competition. Furthermore, the unique and differentiating capabilities of each facility for addressing grand challenge basic energy science must be collectively articulated in the near future through a series of roundtable discussions by leadership of these facilities. The basis for the evaluations is enumerated below.

Neutron Facilities at Oak Ridge National Laboratory

Pressure Vessel Replacement (PVR) for the High Flux Isotope Reactor (HFIR):

HFIR is the only source of many isotopes essential for medicine, national security, and energy in the western hemisphere. The HFIR PVR project aims to replace the existing pressure vessel to extend the life of the reactor and thereby avert an extended shutdown while increasing the operating power to 100 MW. The 100 MW reactor will be the brightest continuous neutron source for science in the world. (See 2020 BESAC report).

a) The upgrade is viewed as **absolutely central** given HIFR's key role in producing isotopes critical for energy, medicine, and national security, and its exceptionally sensitive probes for fundamental materials science and engineering.
b) The PVR has a significant **engineering challenge**—to secure regulatory approval before it achieves Critical Decision (CD)-2/3. CD-0 has been achieved and CD-1 is approaching.

The **Second Target Station** at the Spallation Neutron Source (STS):

STS will be the world's brightest source of cold neutrons (up to 100x brighter than existing facilities) and represents a transformative technological advance.

a) As such, it is viewed as having the potential to be **absolutely central** to future world-leading science, with the potential to enable discovery science and technologies, in the fields of quantum materials for computing and sensors, biological and soft materials for science, energy, national security and medicine. The science case must be more fully developed to specify the currently inaccessible grand challenges that the new capabilities can address.
b) STS will be **ready to proceed** to CD-2 once the science case is refined and the instrument suite redefined to support the science. Development of the science case is essential.

Synchrotron Sources of X-rays at Brookhaven National Laboratory

NEXT III instruments at NSLS-II:

NEXT III is a suite of 8-12 new beamlines that will substantially deliver the science capability of NSLS-II and enable multiscale, multimodal (integration of multiple capabilities/beamlines) experiments, which span scattering, spectroscopy, and imaging over a range of time and length scales.

a) The integrated suite of beamlines is viewed as both **important and absolutely central,** depending on whether the beamline adds capacity or enables new science, or both. The addition of this suite of beamlines will enable NSLS-II to fulfil mission critical science in energy storage, catalysis science, and quantum materials science. Beamlines included in the NEXT III suite should also be designed with the capabilities that will be required for NSLS-II-U (see below).
b) **The technical requirements are not yet fully defined**. The capabilities and capacity that the new beamlines will create for science should be clarified by CD-1, scheduled for later in 2024.

NSLS-II Upgrade (NSLS-II-U)

The upgraded NSLS-II will be the world's brightest synchrotron source in the 1-10 keV range and globally competitive above 10 keV. The high brightness will deliver more coherent photons into a smaller spot, powering nanoscale resolution, higher sensitivity, and increased dynamic range.

a) The NSLS-II-U project is **absolutely central** to future world-leading science. The upgrade will enable experiments to address key challenges in microelectronics, clean energy, bio-preparedness, and quantum materials using a multiscale, multimodal approach for studies under operating conditions.
b) **Engineering challenges** remain for the unique Triple Complex Bend Achromat (TCBA) accelerator design that need to be addressed with additional research. Furthermore, technical requirements need to be fully defined, especially for the most innovative experiments (e.g., ghost imaging).

X-ray Free Electron Lasers (XFELs) at SLAC National Accelerator Laboratory

There are three inter-related projects for the XFEL at SLAC with major potential for transformational energy science. However, their impact will be strongly dependent on the timing of the start of operations due to strong global competition for development of XFELs. The European XFEL is planning similar projects for later this decade.

Linac Coherent Light Source II High Energy (LCLS-II-HE):

The LCLS-II-HE project will provide the world's brightest source of ultrafast pulsed X-rays for atomic-resolution structural studies, increasing the average X-ray brightness in the hard X-ray range (up to 13 keV) by 3,000-fold — critical for capturing femtosecond time-scale dynamics at angstrom resolution in biological, soft, and solid materials.

a) The LCLS-II-HE project is **absolutely central** to future world-leading science because its performance will surpass all present generation XFELs, firmly maintaining the U.S. as the international leader in the science enabled by X-ray sources.
b) The project **is ready to initiate.** The facility design is 90% complete and CD-2/3 is planned for May 2024. Major construction is planned to begin in summer 2025, and an early readiness for CD-4 is anticipated by the end of FY 2027.

The Low Emittance Injector (LEI) for LCLS:

The LEI will provide a superconducting electron source that will vastly improve the capability provided by the LCLS-II-HE project by improving the X-ray brightness to extend operation from 13 keV to 20 keV, enabling sub-angstrom atomic resolution—capability that will enable direct measurement of structural dynamics and insights into complex energy systems and quantum materials at the atomic scale.

The LEI will also be central to the future development of LCLS-X (See below).

a) The LEI project is **absolutely central** for the U.S. to maintain leadership in the fundamental science that underpins complex matter.
b) LEI is close to **ready to initiate construction** with essential R&D and modeling underway showing that the required emittance can be reached. However, a more detailed assessment is required after RF gun prototype tests, planned for 2025.

LCLS-X:

LCLS-X will be the first so-called 3rd-generation XFEL in the world, with the potential to understand and control structural dynamics that underpin 21st century science and technology for energy. Ten specialized XFELs and dozens of instruments will enable multiple parallel experiments that will increase scientific throughput and allow greater access to multiple XFELs for a single experiment.

a) LCLS-X is **absolutely central** to future world-leading science because it will dramatically increase the scientific capabilities and output compared to all other XFEL facilities around the world. Currently, the limited number of parallel experiments that can be performed on a single XFEL reduces the impact of XFELs. Further, the ability to host a range of new types of XFEL sources within LCLS-X could provide 100-1,000 fold increase in average spectral brightness compared to LCLS after the high energy upgrade, together with attosecond time scales. These capabilities will enable studies of dilute systems present in nature, under *in vivo* and operating conditions at natural attosecond timescales, while realizing non-destructive 3D imaging on the atomic scale.

b) LCLS-X has **significant scientific and engineering challenges** to resolve before it enters the Critical Decision process (and after the LCLS high energy upgrade is complete) to determine if the accelerator will be sufficiently powerful to feed 10 undulators.

The Future Light Source (FLS):

The FLS project aims to define the next-generation facility that will be necessary to enable transformational science and technology in 20 years and beyond. The FLS is a ‘green field’ opportunity to revolutionize research by fully integrating the entire facility from accelerator to source, sample environment to instruments, detectors, and advanced data analytics. The facility could become a proactive research partner, working alongside the scientists and engineers, perhaps functioning autonomously. The science case and choice of facility, site(s), layout, accelerator source, instruments, and analytical capabilities are not yet defined. Hence, a process should be initiated by BES with urgency to develop strong science cases and a specific facilities plan. The global community, from the EU to China, will likewise be pressing ahead with plans for the equivalent of the FLS.

The subcommittee perceives a clear, critical need for the development of a national Future Light Source for the US to remain a leader in science and technology development. There are important scientific and engineering challenges that cannot yet be addressed with current or planned light sources. For instance, we cannot yet make movies of water or other molecules as they make and break bonds in biological systems or in solvated solids.

Full characterization and control of an entangled pair of states to engineer quantum computers is not achievable now. The case for FLS should be developed as part of a forward-looking strategic plan for BES to target the grand challenges of the future.

a) The FLS has the **potential to be absolutely central** to future world-leading science, but we **don’t know enough yet**. Planning for future accelerator projects beyond those currently imagined is essential for the science of the future. Because of the long lead time for imagining and designing new large-scale facilities, it critical to plan now for the future. Otherwise, the US will lag in global competitiveness in science and technology.

b) The **mission and technical requirements are not yet defined** for the FLS. Future-looking planning and design are necessary.

Summary

The BESAC subcommittee has concluded that all of the *X-ray and neutron facility projects considered either currently are, or have the potential to be, absolutely central to the success of US science and technology* because of the new capabilities they will provide. Each will provide a means of tackling top challenges in basic energy science research in complementary ways because of their abilities to probe different length and time scales and differences in elemental sensitivity. Taken together, the evaluated facilities represent core technical developments that are essential for maintaining and advancing the BES portfolio that will respond to the scientific challenges in the near and medium term. In the committee's view, the full potential of these technical developments can be best realized by encouraging further synergistic interactions among the facilities to capitalize on their unique capabilities and to clearly develop strong and differentiated science cases. While it is natural that there will be scientific overlap, the subcommittee recommends further refinement of the early targets for grand challenge science that will utilize the first instrument suites, emphasizing distinctive and complementary capabilities of each facility. Advanced data management, AI, and autonomous capabilities should be included in this planning.

The facilities considered by the BESAC Subcommittee are in different stages of technological readiness — some mature and others at a very early stage. There is an urgency to bring these facilities to fruition given the major competition worldwide, especially with China and the EU. Several projects are in the later stages of readiness and will contribute to US science and technology in the near term.

Other facilities, especially the Future Light Source, are central but not yet ready and will require BES and community engagement to define a critical path forward. Given the global competition and major challenges facing the world in basic energy sciences, it is essential to plan carefully *now* for new facilities that will drive US innovation in the decades to come. We, therefore, recommend that strategic planning for the long term be embarked upon now.

A detailed description of the capabilities and readiness levels of each of the facilities informed the conclusions of the subcommittee and are provided in Appendix III.

The impact of the BES facilities considered will be even greater because of the potential for synergies with other research programs within the Office of Science, especially Advanced Scientific Computing Research, and of potential partnerships between BES and other Federal agencies. Each of the facilities considered has natural synergies that should be proactively developed by BES to further enhance the impact of the research enabled by them. The potential partnerships for each facility are enumerated in Appendix

IV.

Beyond the facilities themselves, several other considerations surfaced that are key for the success of these facilities projects and for US science and technology overall. First, it is important for BES management to balance funding for facilities development with support of research that will benefit from them. The research funding will drive the ground-breaking discoveries and technologies enabled by the facilities. Second, funding for beamlines and instruments that enable the science in these facilities is critical. NEXT III is an example. Integration of artificial intelligence (AI), robotics, and management of big data sets will be crucial for the success of the large-scale facilities considered, especially FLS. Cutting across all these considerations is the need to develop the workforce to support these research activities and to innovate in the future. Education, training, and employment opportunities are imperative to garner the full value of the powerful capabilities for the facilities planned.

The fact that all facilities considered by the Subcommittee have been deemed currently, or with the potential to be, absolutely central to the success of US science and technology is a testament to the strength of BES planning. This Subcommittee believes that each new facility considered will provide capabilities that ensure the US continues to lead the world in discovery science and key technologies that address the DOE BES and the Nation's top priorities, now and in the future.

Respectfully,

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Appendix I: Key BESAC Facilities Subcommittee Considerations & Approach

Considerations:
The BESAC subcommittee considered the following key elements:

1. Enables transformational science and technology.
2. Provides new capabilities and capacity that will answer important research questions that cannot be addressed by the facilities that are available today.
3. Includes integration of accelerator, source, sample environment, detectors, and data analysis from facility inception (source to sample)
4. Enhances or grows a new, skilled, robust, and geographically diverse national user community. Develops mechanisms to train the next generation of users.
5. Recruits and trains highly qualified facility staff.
6. Identifies cross-cutting opportunities for science, computing, and data, and from other Office of Science programs (BER, ASCR, HEP, NP and FES).

Approach

1. White papers and presentations were prepared for each proposed project.
2. Four subcommittee subgroups for neutrons, synchrotron, XFELs, and a future light source were established.
3. Subgroups met as needed, conducted analyses and benchmarking, and prepared summary recommendations and slides to address the SC-1 charge.
4. Subcommittee met monthly, chair and vice chair met with BESAC chair and BES leadership as needed.

Appendix II: BESAC Subcommittee membership

Name	Institution	Subgroup(s) Assigned
Ken Andersen	Institut Laue-Langevin (ILL)	Neutron Sources
Serena DeBeer (Vice-Chair)	Max Planck Institute	Free Electron Lasers/Synchrotrons
Tabbetha Dobbins*	Rowan University	Synchrotrons
Helmut Dosch*	DESY	Future Light Source*/Free Electron Lasers
Thomas Epps	University of Delaware	Neutron Sources/Synchrotrons
Yan Gao	GE (retired)	Synchrotrons
Jamie Garcia	IBM	Free Electron Lasers/Future Light Source
Ashfia Huq	Sandia National Lab (CA)	Neutron Sources
Eric Isaacs (Chair)	Carnegie Institute of Science	Free Electron Lasers/Future Light Source
Kevin Jones*	European Spallation Source	Neutron Sources
Sakura Pascarelli*	EU XFEL	Free Electron Lasers*/Future Light Source

*Subgroup Lead

Appendix III: Detailed Assessments

III.A. Neutron Facilities

Neutrons have several unique characteristics as probes, including penetration through most materials; light element sensitivity (e.g., hydrogen, deuterium, and lithium); sensitivity to magnetism; and very high energy resolution (down to ~10 µV) and polarization, which together offer high-precision characterization of atomic and spin structure and dynamics. Neutron sources also provide essential and powerful tools that enable production of critical isotopes for medicine, national security, and forensics, along with driving basic research and development. (See BESAC 2020 report on US Domestic High-Performance Reactor-Based Research Facility).

The premier reactor and accelerator-based neutron sources in the U.S. are located at ORNL. The SNS is the most powerful pulsed neutron source in the world and serves a range of disciplines, including physics, chemistry, biology, and materials science. Currently operating at 85 MW, the HFIR provides one of the highest steady-state neutron fluxes of any reactor in the world for neutron scattering research, isotopes production, and materials irradiation. Furthermore, the neutron sources at ORNL are over-subscribed and have sound user bases. In short, the US needs to catch up with global capability in neutron science.

Oak Ridge National Laboratory (ORNL) has proposed an upgrade for the High Flux Isotope Reactor (HFIR) with a pressure vessel replacement and the Second Target Station, a second source at the Spallation Neutron Source (SNS). *The proposed upgrades are part of a two-facility, three-source strategy, which will lead to US leadership in both reactor-based and accelerator-based neutron science.*

The HFIR Pressure Vessel Replacement (PVR) project aims to replace the HFIR Pressure Vessel to extend the life of the reactor and increase operating power to 100 MW thus enabling continued availability of neutron scattering and irradiation capabilities at the facility. When combined with small vessel changes for beam tube HB-2, the facility used for assembly during the PVR could be re-purposed to a new guide hall to increase thermal neutron scattering capabilities. A small change to beam tube HB-4 would improve cold neutron beam quality and flux by factors of 4-9. Changes to the vessel head will enable increased in-cycle access to irradiation positions for isotope production and materials irradiation, including neutron activation analysis. The pressure vessel replacement was a central priority of the BESAC report on Neutron Facilities issued in 2020.

The HFIR core design provides the highest thermal neutron flux density of any reactor operating in the western world yielding unique capabilities in isotope production, materials irradiation, and neutron activation analysis. It is the sole source of critical isotopes needed for industry and national security and is *the sole non-Russian producer* of Californium-252 and of the daughter radioisotope Actinium-227, used for targeted α-radiotherapy. HFIR plays a key role in the production of heavy nuclei for fundamental research. The HFIR irradiation facilities offer unique mixed-field capabilities that enable both fast and thermal neutron flux irradiation positions, which are used to study advanced fuels, helium generation in reactor materials, and fusion materials irradiation capabilities. Neutron activation analysis, important to non-proliferation activities, is also a critical element of the HFIR's capabilities that take advantage of pneumatic systems to allow flexible irradiation times, shorter than the normal duration of the reactor fuel operating cycle. Other neutron scattering facilities include the NIST Center for

Neutron Research (NCNR) in the US, a lower power reactor-based neutron scattering source. The acknowledged world leader in reactor-based neutron scattering capabilities for science is the Institut Laue-Langevin (ILL) in France. Also, the Jules Horowitz Research Reactor (JHR), a mixed-field materials test reactor (100 MW) is under construction at CEA Cadarache, France, and expected to be operational by 2032-34. The Belgian Reactor 2 (BR2) operates at up to 100 MW for the purposes of materials irradiation and isotope production.

While the scope of the PVR project does not include new neutron scattering capabilities, it holds promise for significant enhancement by accommodating a new design for an additional cold source that can substantially increase both capacity and capability. A newly constructed beam tube could deliver neutron beams to up to 10 new instruments and significantly improve signal-to-noise ratios for experiments that require the intense monochromatic brightness of the upgraded reactor.

This project is **absolutely central** to ensure a continuing resource for isotope production, materials irradiation, neutron scattering, and neutron activation analysis in the US beyond the 2030s. It is ready to proceed with engineering design necessary to obtain regulatory approval before commencing construction.

The Second Target Station (STS) project at SNS is a transformative technological advance that has the potential to be **absolutely central** for the US to hold a world-leading position in neutron scattering science. STS will be a next-generation, short-pulse, cold neutron source that provides up to a 100-fold increase in peak brightness at 5 Ångstroms, beyond what is currently available anywhere in the world. These capabilities could be available in the second half of the next decade.

It is imperative to enumerate the unique, transformational science that will be achievable with the STS, not possible today with any other source. In other words, plans for the inaugural experiments using the first suite of instruments, must be clearly stated to highlight the power of the STS. Furthermore, the possible synergies with other Office of Science programs and other Federal agencies (Appendix IV) need to be developed and articulated, with a specific focus on data management and implementation of AI tools.

STS will provide a suite of 8 neutron scattering instruments and capacity for approximately 20 instruments total. The project will leverage the ongoing Proton Power Upgrade (PPU) that doubles the available power from the SNS accelerator from 1.4 MW to 2.8 MW and provides the capability to connect to the STS beam transport system. The STS will utilize 0.7 MW of the 2.8 MW available after the PPU and operate at 15 Hz, utilizing one out of every four pulses from the upgraded accelerator to produce cold neutrons. It will operate simultaneously with the first target station, which will operate at 45 Hz. The closest competitor facility is the J-PARC MLF in Japan. ISIS-TS1/2 in the United Kingdom and the CSNS in China have substantially lower peak and average brightness. The European Spallation Source (ESS) is a long-pulse facility under construction in Sweden and will provide neutrons by 2027 with a ramp-up to a proton beam power of 2 MW serving 15 instruments at 14 Hz by ~2028. Even though Sweden plans to upgrade the facility to 5 MW and 22 instruments in the early 2030s, it will not achieve the anticipated STS peak brightness.

STS and its instruments will generate cold neutrons with unparalleled flux to address scientific grand challenges identified by the Office of Science, including energy, quantum information science (QIS), sustainable manufacturing, and climate science. The construction of this facility will also allow the US to maintain and bolster its world leadership in producing high impact science and engineering research as stated in the BESAC International benchmarking report.

The technical capabilities of STS will be world-leading. STS experiments will leverage the unique interactions of neutrons with matter to simultaneously measure hierarchical structures across a broad range of length and time scales in functional materials, even in very small sample volumes have the potential to accelerate materials discovery. For example, STS would play a role in designing next generation quantum computers, which will require understanding of qubit physics and of individual qubit interactions with the materials and defects in its vicinity, to be sufficiently scalable and fault tolerant. This understanding requires major advances in the microscopic examination of the materials that will form the basis of any future devices. Cold neutrons are a powerful probe for characterizing quantum materials due to their sensitivity to unpaired electron spins and their low energies that are perfectly matched to magnetic excitation energies of these systems. This precision will allow the quantitative comparison with theory and models that will be essential for developing new quantum materials and shaping them into functional qubits for the next generation of quantum computers.

The spatial and temporal resolution provided by STS will enable other advances, such as manufacture of robust polymers that are sustainable and environmentally friendly. The high penetration depth of neutrons ensures that these studies can be performed under manufacturing conditions. Robust polymers that can be rapidly manufactured will benefit from neutron scattering experiments that exploit neutron sensitivity to light elements (e.g., H, O, C) not readily accessible by X-rays, deep penetration, and sensitivity to a broad range of length scales, along with the ability to use hydrogen and deuterium contrast matching. The development of new polymers with the required characteristics also requires investigations of out-of-equilibrium structure and dynamics that are uniquely enabled by the high brightness of cold neutrons at STS.

The instruments at STS will provide capabilities that far exceed those of existing instruments, responding to needs of the current user community, and anticipating those in the future. Instruments at SNS today are oversubscribed by a factor of 3 on average. This level of demand indicates that a strong user base already exists to take advantage of the new capabilities and increased throughput that STS will provide. Nevertheless, it is incumbent upon the SNS to actively engage with potential new research communities to ensure the highest impact in science across the US.

III.B. Synchrotron Sources of X-rays at Brookhaven National Laboratory
NSLS-II NEXT III Project

The NSLS-II NEXT III Project aims to deliver the full promise of the NSLS-II synchrotron by providing a suite of beamlines that will address the complex, multi-scale challenges of contemporary science. A critical component of the project involves identifying gaps in current capabilities, including high throughput scattering, spectroscopy, and imaging. The NEXT-III initiative aims to bridge these gaps through the development of 8-12 beamlines, the first four of which have been identified jointly with the user community.

Future advancements facilitated by NEXT-III will include performance improvements across multiple techniques in the form of enhanced temporal resolution (from minutes to less than 0.1 s), accessible length scales (from 1μm to 100nm), and greater field of view (from 40μm to 1mm). The project also aims to significantly enhance the facility's capabilities for applications in microelectronics and QIS, with a promise of improving imaging resolution and acquisition times from 10nm in 10 hours to 10nm in just 1 hour for specific techniques.

The NSLS-II NEXT-III project has great potential; however, with the continual evolution of the technologies, an expert evaluation of each of the proposed beamlines is needed to establish the needs of the future user community, to quantitatively assess the demands for enhanced data collection speeds for specific experiments, and to evaluate potential requirements for new optic designs on the proposed beamlines. Aspects such as high-resolution and high-throughput powder diffraction, and the capacity for full-field nanoprobe analysis, are highlighted as unique, especially for fields working with biological materials.

The NSLS-II NEXT-III was deemed as "ready to initiate construction." Four of the beamlines planned for the NEXT III project have already been identified—two scanning probes, one full field imaging, and one scattering instrument. The selection and design process for these new beamlines actively involved the user community through workshops and detailed proposal evaluations, ensuring that the new facilities will address the most pressing and unique scientific challenges. The engagement of a broad user community through the next two phases is strongly encouraged, giving special attention to potential synergies with other DOE Offices (Appendix IV).

The NSLS-II NEXT-III project is **important and absolutely central,** depending on how the beamline adds capacity and/or enables new science central for addressing the evolving needs of the scientific research community and presents a unique approach to solving important problems. The approach will lead to standardized sample environments and fiducials needed for performing multiple measurements on the same sample with different methods. The development of associated data analysis and visualization tools for disparate data sets will be beneficial to the broader community. Furthermore, NSLS-II will use NEXT-III to develop the data infrastructure and metadata structure that will be needed for NSLS-II-U. While the scientific cases are compelling, an ongoing assessment of the planned beamlines with other facilities worldwide is necessary as the remaining beamline specifications are defined.

NSLS-II U (Upgrade) Project

The NSLS-II-U project aims to fill a critical niche in the United States' scientific infrastructure for multimodal experiments by developing a ring capable of operating at the highest flux within the 1-10 keV energy range (tender X-rays), a capability that outperforms other facilities in the U.S. and internationally over this energy range. The project addresses the tender X-ray region not well addressed by other upgraded facilities, will introduce unique accelerator design concepts developed at Brookhaven National Laboratory (BNL), and will enable multilength and multi-time scale questions to be addressed in a wide range of scientific disciplines. Potential impact on other disciplines and possible synergies with other Office of Science programs and Federal agencies needs to be defined and cooperation developed.

The science case for NSLS-II-U spans an array of applications. The project is poised for impact because of the brightness in the 5-13 keV X-ray regime and beyond and advanced multimodal techniques that will be provided for exploring phenomena on multiple length and time scales (from microseconds to weeks). Key areas of focus include overcoming Moore's law limitations for nodes below 1 nm through enhanced photon concentration, advancing energy-efficient neuromorphic computing technologies and AI by addressing stochastic switching challenges, and improving clean energy battery materials through innovative use of tender X-rays for *in-situ*/*operando* full cell imaging. Additionally, NSLS-II-U will enable realization of the full potential of the quantum-enabled X-ray microscope and "ghost imaging," promising significant advances in the study of X-ray sensitive samples.

This project is **absolutely central** because of the potential to contribute to world-leading science in the next decade. If the overall improvement across the energy spectrum is realized, the upgraded NSLS-II will be a world-leading facility for capabilities in 1-10 keV range.

Initial observations underscore the project's compelling potential, highlighting an expected 10-20 times brightness increase over current state-of-the-art sources within the U.S., thereby asserting leadership internationally in this domain. This project opens numerous opportunities, including the expanded application of AI/ML for data processing, the necessity for detector development capable of on-pixel processing and fast frame rates, and the exploration of superconducting undulators for adaptive gap adjustments. Besides the notable improvements in the 1-10 keV range, there are also improvements extending beyond 10 keV that will further advance scientific breakthroughs.

NSLS-II-U is currently in an advanced planning stage toward CD-0, after which first light could be achieved in 8 years. The present source locations will be preserved to use existing beamlines and new beamlines that may be developed during NEXT-III. The project employs a novel accelerator concept—a Triple Complex Bend Achromat (TCBA) lattice— which is based on testing of prototype complex bends, enabled by internal funding at BNL. The complex bends would replace long dipole electro-magnets with permanent magnets, thus greatly reducing energy consumption. However, there are some open questions about the engineering challenges that need assessment. The committee recommends further evaluation by accelerator experts prior to committing to the proposed design. The engagement of experts who participated in other recent upgrade projects, including APS-U, CHESS-U, and ALS-U, is strongly encouraged. A further issue that was raised was how the large volumes of data that will be generated can be handled. There is clearly an opportunity for machine learning and AI integration, perhaps building on initial efforts learned from the NEXT-III beamlines. Addressing these hurdles is critical for transitioning from prototype to full-scale operational readiness.

III C: X-ray Free Electron Laser Facilities at SLAC

There are three, inter-related projects for the XFEL at SLAC with major potential for transformational energy science; however, their impact will be strongly dependent on the timing of the start of operations due to strong global competition for development of XFELs. The EU XFEL is planning similar projects for later this decade.

LCLS-II-HE: An ultrafast, ultrabright X-ray nanoscope for transformative insights into the atomic-scale function of materials and devices, dynamics of chemical transformations, and complex biological systems. As such, it is **absolutely central** to the future of the DOE BES light source portfolio.

LCLS-II-HE at SLAC will be a transformational X-ray tool providing deep insights into the atomic structural dynamics that underpin the function of broad classes of complex matter, including: chemical and catalytic assemblies, quantum materials, structural materials, and biological systems in physiologically relevant environments. The broad range of scientific problems that can be addressed with LCLS-II-HE renders it an imperative that strong synergies be established with other DOE programs and other Federal agencies.

LCLS-II-HE will deliver a 3,000-fold performance increase in average X-ray brightness in the hard X-ray range up to 13 keV (~ 1 Å atomic resolution) and spanning the core levels of earth-abundant 3d transition metals that are central to invention of clean energy transformation processes, and energy storage materials of the future. The unique and powerful capabilities of LCLS-II-HE will be indispensable for bridging crucial knowledge gaps, by providing the world's brightest source of X-rays to enable atomic resolution with ultrafast pulse structure to capture the coupled motions of atoms and electrons.

In the area of renewable energy and sustainable catalysis, LCLS-II-HE will measure entire time sequences of non-equilibrium chemical transformations as they happen. This insight will inform the directed design of a new generation of efficient catalytic assemblies, via multi-modal characterization of the coupled electronic and nuclear degrees of freedom that determine reaction pathways in complex chemical systems. In the area of pharmaceuticals and bio-inspired technologies, a deeper understanding is needed that links the structural evolution of a biomolecular system to its function, crucial for human health and biosecurity, and to inform synthetic approaches for harnessing biochemical approaches for green industrial, agricultural and energy solutions. The unique capabilities from the LCLS-II-HE project will be able to map the full range of spontaneous motions and evolving conformations of bio-sample ensembles as they function – for the first time in solvated and room temperature environments. It will start an era of atomic-resolution structural dynamics measurements that will likely be as profound as the impact of X-ray static structures over the past decades. There is the opportunity to work closely with the Office of Science's Biological and Environmental Research program, the National Institutes of Health, and the National Science Foundation (Appendix IV) on this set of critical challenges. In the future, these synergies should be fully developed for LCLS-II-HE.

The project has completed 90% of the facility design. The suite of high-performance cryomodules are in an advanced state of delivery. CD-2/3 is planned for May 2024. Major construction activities are planned to begin in summer 2025, with a projected early finish date of readiness for CD-4 by the end of FY 2027.

LCLS Low Emittance Injector (LEI):
The Low Emittance Injector (LEI) project will provide a superconducting electron source that will yield the world's brightest X-ray laser for model-free structural dynamics and insights into complex energy systems and quantum materials**.** Key features are: (1) improvement in the X-ray beam brightness to extend XFEL operation from 13 keV to 20 keV (sub-Å atomic resolution), with improvement across the full X-ray spectral range; (2) operational redundancy to maximize scientific delivery, and (3) support of ongoing injector performance improvements to maintain US leadership in this rapidly evolving field. The extension of X-ray energy reach from 13 to 20 keV is motivated by the need to observe the evolving atomic structure and transport of ions, electrons, and phonons within the interior of complex matter, bulk materials, and devices under operational conditions. The penetrating power of hard X-rays (20 keV penetrates ~1 mm of Si), combined with the ultrafast time structure enabled by the LEI will be indispensable for revealing the atomic-scale dynamics that determine material properties and functionality. The average coherent X-ray power of LEI in this crucial energy range will exceed that of any proposed diffraction-limited storage ring (DLSR) by nearly 1,000-fold – enabling powerful new approaches for coherent imaging of the structure and dynamics of real-world materials, and chemical and biological systems in the environments in which they naturally operate. As such, the LEI is deemed **absolutely central** to US scientific competitiveness.

The higher photon energy enables revealing atomic pair distributions for direct structure interpretation and the investigation of structural dynamics, disorder, and metastable phases at sub-Ångstrom resolution in complex materials without long-range order. Applications include novel metastable phases created by coherent light-matter interactions and local atomic arrangements in energy materials. Higher photon energy also enables access to bulk properties, *operando* or tailored sample environments (pressure, strain, magnetic field, etc.) and coupling with tailored transient stimuli (resonant THz, optical, etc.) – all necessary for a leap to be made in the understanding of the behavior of complex and quantum materials (phonons, electron/phonon coupling, magnons, etc.)

The range of scientific problems that can be addressed necessitates continued engagement of other funding agencies and other DOE programs (Appendix IV). Advanced tools for data management are also critical. These cases need to be fully developed and articulated.

LEI is in an **advanced state of readiness-to-construct** with essential R&D underway. The design of the injector is largely complete, with modeling showing the required emittance can be reached. A more detailed assessment of readiness of LEI will be enabled after RF gun prototype tests, planned for 2025. Revolutionary advances in data science and the development of a new generation of detectors are needed to fulfill the scientific potential of LCLS-II-HE and LEI.

LCLS-X: The world's first so-called 3rd Generation X-ray Free Electron Laser, providing a suite of dedicated platforms for understanding and controlling the multi-scale structural dynamics that underpin 21st century technology and biologically inspired solutions for energy sustainability and health**.** LCLS-X is **absolutely central** to US global leadership for several decades to come.

LCLS-X is a next-generation infrastructure with an array of X-ray lasers that are each optimized to address urgent science challenges requiring XFEL capabilities. LCLS-X would offer simultaneous operation of ten *specialized scientific* beamlines and dozens of instruments – analogous to modern synchrotron facilities – with the requisite stability, reliability, integrated data systems, and ease-of-use to maximize the impact across broad areas of science. LCLS-X will bring XFEL science into a synchrotron-like era, with a large number of parallel experiments supporting a broad critical mass of the science community, and with an associated order-of-magnitude change in cost per experiment, scientific throughput, and impact.

LCLS-X will usher in a new era of X-ray science to maintain long-term U.S. leadership across a wide range of fundamental and applied areas – from clean energy, to sustainability, to economic competitiveness and human health – where there is an essential need to understand and control the multi-scale structural dynamics that underpin the properties and function of complex matter. One overarching challenge for a sustainable economy is accelerating the discovery and design of new materials with exceptional properties. LCLS-X will characterize with high precision the fundamental processes at play in hierarchical structures fabricated by combinations of novel materials, rationally guiding the design of long-lasting, high efficiency and high-performance devices. LCLS-X will enable significant leaps in performance that are needed to respond to the scientific drivers from a disparate set of communities, enumerated below.

1. Cavity-based XFEL sources will be fielded for the first time (providing 100-1000x increase in average spectral brightness compared to LCLS-II-HE). One of the many applications is in enabling *operando* studies of the fundamental processes controlling

ion diffusion and bridging our present knowledge gap of the atomic-scale processes that mediate ionic diffusion in complex electrode and solid-electrolyte matter. Systematic campaigns will reveal how ion transport processes depend on electrode nanostructure, material crystal structure, diffusion direction, and ion concentration and make fundamental steps towards meeting the demands for high-capacity, efficient, and reliable energy storage devices.

2. LCLS-X will build dedicated multimodal platforms to exploit unprecedented coherent X-ray capabilities for real-time non-destructive 3D imaging at the atomic scale – to see how materials form in manufacturing processes, and how devices function in real-world conditions. Multi-modal methods will be transformative for identifying and imaging heterogeneous nucleation processes and related microstructural black swan events that underpin both the formation of new material phases (e.g., under the nonequilibrium conditions of advanced processing) and represent initial steps in materials degradation and failure. The crucial transition in these processes is the emergence of the critical and stable nucleus from fluctuating clusters. Mastery of these processes comes from controlling the emergence of critical nuclei. It will be possible to monitor simultaneously the fluctuation in the “disorder” state prior to nucleation as well as the changes in the local chemical/bonding environment. The former provides revealing insights into the role of nucleation accelerators and inhibitors, while the latter provides a powerful first-order indicator that a critical nucleation (rare event) has emerged from the fluctuation.

LCLS-X will be **ready to construct after demonstrating that the completed LCLS-II-HE accelerator will be sufficiently powerful to feed 10 undulators**. Delivery of end stations and instruments will be phased to allow staged growth, responsive to new discoveries and emerging national priorities.

Overview of LCLS projects.
The potential of the three projects to significantly contribute to world-leading science and allow the US to maintain leadership in the fundamental science that underpins complex matter in the next decade is very high. Their performance leap, science scope, and impact will extend significantly beyond current X-ray facilities. Nevertheless, further development of a broad user base across scientific disciplines, engaging other programs and agencies (Appendix IV), will be critical for success.

For LCLS-II-HE and LEI, matching or exceeding capabilities may be available in China (SHINE, Shanghai) by the end of the 2020s, and at the European XFEL in the 2030s. Both LCLS-II-HE and LEI are therefore essential next steps for the U.S. to remain competitive. The relevance and uniqueness of these two facilities for transformational science will be dependent on the timing of the start of operations.

For LCLS-X, there are, as yet, no known concrete proposals for similar facilities elsewhere. Currently, the US is lagging Europe and Asia in the *number* of optimized XFEL sources, beamlines, and instruments; therefore, LCLS-X is an opportunity to establish US leadership.

XFEL science and technology have made huge advances in the past 15 years, mostly initiated and led by LCLS. However, the scientific output of these facilities is critically limited by efficiency and limited amount of experimental stations, hampering the production of a critical mass of publications in any specific science area necessary for impact.

LCLS-X has a unique opportunity to project the relevance and the impact of XFEL science to similar levels reached today by synchrotron sources, and with it, an unchallenged potential to advance fundamental scientific discovery and translation to address pressing national priorities. To do so requires sustained and significant support of underlying scientific research programs led by broad mainstream science communities, with ready access to a suite of XFEL sources, beamlines, and instruments optimized for critical science areas.

III D: Future Light Source (FLS)

Planning for the future is critical if the US is to retain technical and scientific leadership in the long term, rendering planning for FLS, a yet-to-be defined facility, essential. Accelerator-based light sources will certainly remain a key component of the United States' energy and technology strategies, making proactive research into their future design crucial. As such, the BESAC Subcommittee on National User Facilities commends the forward-thinking approach of BES to seek ideas for how a future, 'green-field' light source could transform our understanding of nature and technology. The global race to develop such transformative facilities is intense and accelerating.

Anticipating the research environment over the next 15 years involves uncertainties, yet we offer preliminary insights into the science and emerging technologies that will shape FLS. In order to position the US for leadership in the next decades, we recommend that BES create a plan to sequence the portfolio of planned facilities and to embark on strategic planning for future facilities with a clear eye towards leading the global competition. The key features of FLS that will be required to address grand challenge basic energy science, including gaps in the capabilities of existing facilities, should be articulated through a series of roundtable discussions by facilities and scientific leaders.

Three exemplars of critical research important in driving science and technology forward were considered: the design of new materials, the field of soft and bio-matter, and medical applications, and the domain of atomic, molecular, and optical physics. Generally, generation of non-destructive, atomic scale data and investigation of metastable states of matter will be important to address with the FLS.

Non-destructive, atomic-scale precision data generation is essential for advancing nanoelectronics with single atom defects in semiconductors, enhancing the development of quantum technology, and understanding and controlling materials under extreme conditions. Generation of such data will likewise inform models based on artificial intelligence, providing a natural synergy with ASCR. These types of advances will help build US leadership in semiconductor technology, quantum computing, cybersecurity, materials design, national security, and space and planetary exploration.

The investigation of metastable states of matter will probe transients in chemical reactions, non-equilibrium material states, and ultrafast functions for potential applications based on femtosecond time scales. The increasing complexity of material structures with embedded multifunctionality necessitates advanced understanding of local structures akin to crystallography for complex materials.

Specific fields of research that are expected to be critical to the future are soft and biological matter important in medical research, and atomic, molecular, and optical physics to interrogate extremely short time scale processes—even at the attosecond. Future X-ray sources would need to image soft and biological matter with high spatial resolution and minimal radiation dose to avoid damage to these fragile materials. New concepts on the horizon include novel X-ray imaging techniques that use, among others, entangled X-ray quanta ("ghost imaging") or other X-ray channels. Potential applications would include: (1) high-throughput screening of cells, tissues, and organs; (2) nanotoxicology; (3) measuring rapid electronic processes in biomaterials, such as radiation damage to DNA or the bio-catalytic processes of plant photosynthesis (femto- to attosecond timescale); and (4) mapping biological structures and processes in aqueous environments, which requires coherent X-ray light with corresponding temporal resolution.

In the field of AMO, the attosecond sector is a central science driver. If this area can be made accessible via X-ray technology, it opens many highly interesting and fundamental questions, the solutions to which can lead to the highest scientific honors. Images and movies of individual molecules or atoms and their dynamics are believed to be an achievable 'Holy Grail' of X-ray physics, not yet achieved. A film of the formation and breaking of bonds delves quantum behavior, a crucial milestone towards the quantum control of matter and energy.

Enabling technologies and advanced user operation modes. The operation of a future light source must fully integrate data-driven methodologies, leveraging Artificial Intelligence and Machine Learning (AI/ML), as well as robotics in order to create materials with specific functionalities and properties with more efficiently, perhaps even autonomously. High-resolution X-ray techniques will be crucial for innovators and Future Light Source (FLS) users, enabling standardized, extremely precise analytics for science and technology.

Importantly, the FLS will be greatly influenced by new digital concepts. This concerns the operation of the entire facility, from the accelerator to the detector, the sample environment, the collection and analysis of data, and real-time simulations, up to new modalities in remote operation. Thus, cross-DOE and interagency cooperation will be imperative in the planning of the FLS.

Integration of a digital transformation in the FLS could enable creation of digital twins of critical components of the facility, to simulate all aspects of the facility; thus, greatly improving outcomes and efficient use of the facility. Likewise, a fully automated AI/ML-supported operation of the accelerator complex, from "source to sample," would allow rapid startup of the accelerator and user-driven real-time switching between operating modes. Experimental stations equipped with state-of-the-art robotics in sample handling and automated with AI/ML support, with user interventions à la carte, will lead to an acceleration of the analytical processes by several orders of magnitude. Finally, real-time data analyses for direct feedback to users will provide improved control of the experiments (e.g., anomaly detection, intelligent process automation, etc.).

Full-fledged data analyses for users without expertise in X-ray methods will lead to a broader use of an FLS and significantly increase its impact (from "data factories" to "solution factories"). In the area of remote or hybrid access, a wide range of modalities for FLS users can be offered, which is expected to be of great interest for industrial users and in the educational field at schools and universities ("training beamlines").

Access to the experiment must be adapted to the new needs of a broad user base, who typically have projects with which they are in fierce international competition. Currently, synchrotron radiation sources are testing what is called a rolling access procedure, which allows a user to apply for beam time at any time, followed by quick review, which could reduce the time between application and execution of the experiment to just a few weeks so that there will be rapid response to critical problems.

The digital transformation needed is dependent on significant advances and exploitation of cross-cutting computing infrastructure and associated expert staff.

Facilities Layouts. The technical layout for the FLS depends on scientific and technological considerations, the desired user modalities, and future instrument technologies. Accordingly, careful consideration of the synergies and tradeoffs required to optimize impact and cost will be necessary. Currently, there are some layouts at synchrotron radiation sources that could be developed, including the Hybrid Multi-Bend Achromat concept, and at FELs, including superconducting technology and seeding concepts. Furthermore, plasma acceleration is emerging as a completely new technology, which can be 1,000 times more efficient than current linear accelerators (LINACs). The development of plasma acceleration is rapid (including in China) and thus, in 10-15 years, the technology may be mature enough for an FLS. Finally, among other pioneering technologies that have been tested are the FEL oscillator (XFELO), which can significantly increase the longitudinal coherence of the radiation, and the Energy Recovery Linac (ERL), which link the synchrotron- and FEL-worlds.

Overall, careful strategic planning starting now is important to define the technical specifications required for high scientific impact. The subcommittee sees a clear need for the development of a national FLS for the US to remain a leader in science and technology development. The process should be initiated with urgency to develop strong science cases and an approach for a concrete layout. The global community, from the EU to China, will also be pressing ahead with their own ideas for a FLS.

This subcommittee recommends various actions that should be addressed starting now:

(1) Consultation of national and international experts and organization of dedicated workshops to sharpen the focus on science drivers and to anticipate which user needs could be prevalent in 10 to 15 years with a view towards to democratizing access to areas not yet incorporating advanced X-ray sources into their research agenda or in their value chain. In addition to BES, involve representatives from other DOE offices, including ASCR (AI/ML), BER (biological science), Fusion Energy Science (FES, extreme materials), and High Energy Physics (HEP) and Nuclear Physics (NP) (accelerator and detector concepts) and DOE's technology offices (e.g., energy efficiency and renewable energy, fossil energy and carbon management, nuclear energy) as needed.

(2) Initiate pilot programs at existing light sources at an early stage to test feasibility in specific cases. This particularly applies to all new technologies and user modalities that rely on AI/ML concepts.

(3) Consider how to balance "enterprise beamlines" that emphasize increasing the number of experiments with "pioneer beamlines" that aim to establish totally new methods.

(4) Given the diverse X-ray requirements, a distributed FLS system, with satellites tailored to specific scientific needs, technologies, and access models, should be taken into consideration. Additionally, a hybrid approach, combining a centrally located, state-of-the-art facility operated by a specialized team with strategically placed, institutionally distributed data analysis centers, could be viable.

(5) An FLS project with entirely novel enabling technologies and user modalities will require new skills. BES, with Office of Science (SC) programs and National Laboratories, are encouraged to develop a strategy for building and supporting the workforce of tomorrow that will capitalize on the facility of tomorrow.

DOE BES Mission Importance and Facility Readiness

	Capability for science/DOE BES mission relevance	**Readiness for construction**
HFIR	Absolutely central – brightest continuous US source, and only source in the Western Hemisphere for many critical isotopes	Ready for CD-1, engineering challenge - regulatory approval prior to CD-2/3
SNS - STS	Potential to be absolutely central – world's brightest source of cold neutrons; science case and instruments need refining	Ready to proceed to CD-2 once science case is refined and instrument suite defined
NSLS II NEXT III	Both important and central depending on beamline	Tech requirements need to be fully defined by CD-1
NSLS II U	Absolutely central; worlds brightest synchrotron for 1-10keV	Engineering challenges for Triple Complex Bend Achromat; additional research needed
LCLS-II-HE	Absolutely central; world's brightest (x3,000 LCLS), ultrafast XFEL to 13 keV	Ready to initiate; design 90% complete; CD-2/3 estimated May 2024
LCLS - LEI	Absolutely central; brightest XFEL, extends LCLS II HE to 20keV	Getting close to ready with essential R&D underway for emittance target
LCLS - X	Absolutely central; first 3rd generation XFEL; 10 specialized XFELs, integrated ops	Significant engineering challenges before CD process
FLS	Absolutely central to plan facility for future US leadership; science mission/case TBD	Readiness requires technical layout, following science case

Appendix IV: Key Synergies with other DOE Programs and Federal Agencies

Facility	Partnerships with other SC programs, NNSA, EERE, and other agencies
HFIR	Advanced Scientific Computing Research (ASCR), Biological and Environmental Research (BER), Nuclear Physics (NP), Isotope R&D and Production (DOE IP), Fusion Energy Sciences (FES), Nuclear Energy (NE), NNSA; NIH, NSF, DOD
SNS - STS	ASCR, BER, High Energy Physics (HEP), NP, Energy Efficiency and Renewable Energy (EERE); NSF, NIH
NSLS II NEXT III	ASCR, BER, HEP, NP
NSLS II U	ASCR, BER, NP,HEP, EERE
LCLS-II HE	ASCR, BER, FES, HEP, NNSA; NIH, NSF, DOD
LCLS - LEI	ASCR, BER, HEP; NIH, NSF, DOD
LCLS - X	ASCR, BER, HEP, NP, NP, EERE, NNSA; NSF, NIH
FLS	ASCR, BER, HEP, NP, EERE, NNSA; NIH, NSF, DOD