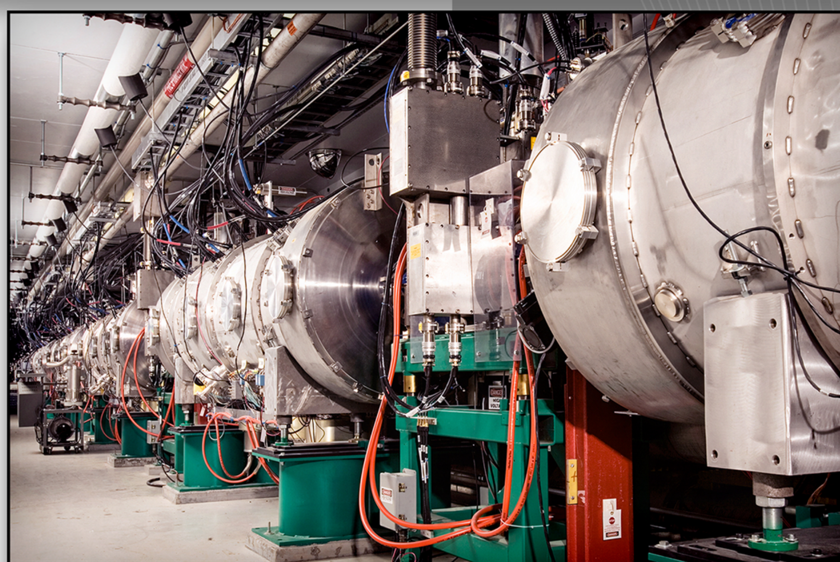
The Spallation Neutron Source Proton Power Upgrade (SNS-PPU)



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MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

Spallation Neutron Proton Power Upgrade

Executive Summary

The Spallation Neutron Source (SNS) upgrade will provide the United States with a world-leading fourth generation neutron source that meets the needs of researchers to address emerging grand challenges of importance to the mission of the Department of Energy (DOE). The upgrade involves two major projects: a proton power upgrade of the existing accelerator structure (SNS-PPU) and construction of a second target station (STS) complex with an initial suite of beam lines (SNS-STS). In a companion document, *Spallation Neutron Source Second Target Station,* the compelling science case for the SNS upgrade, and outline of the SNS-STS project are described. SNS-PPU is a necessary platform for SNS-STS. Their mission need and science case are therefore the same. In this document, a description of the SNS-PPU project to double SNS accelerator power capability is provided. The SNS first target station (FTS) is being expanded towards its design envelope and scientific productivity and impact are growing. However, the global needs and demands for new neutron scattering capabilities are driving the biggest change in neutron facilities in the last 40 years and represent a new phase in neutron science. In Europe, a 5 MW European Spallation Source (ESS), now under construction in Sweden, represents a game-changing level of performance in cold neutrons. As such, ESS is the European response to SNS-FTS and will provide a major advantage in large domains of grand challenge science. STS will ensure the ability of the United States to continue to perform world-leading neutron science.

Delivering World-Leading Science at a Fourth Generation Neutron Source

The SNS at Oak Ridge National Laboratory (ORNL) is the world's most intense pulsed neutron source and is equipped currently with 18 neutron scattering beam lines and one beam line dedicated to fundamental physics. The proposed SNS-PPU project builds on the existing accelerator structure at SNS to provide even greater scientific capabilities to the research community. SNS-PPU is a necessary platform for SNS to reach its full potential in delivering world-leading science in areas of transformative opportunity. SNS has the potential to be a world-leading fourth generation source with increased neutron flux on currently available beam lines, and with STS supporting 22 additional beam lines (described in the accompanying document *Spallation Neutron Source Second Target Station*) with ground-breaking new scientific capabilities. The SNS-PPU project is a foundational step in a three-source strategy to ensure United States leadership in neutron science and to position the nation to address emerging science challenges that are beyond the capability of current ORNL facilities, which includes SNS-FTS and a reactor-based neutron source, the High Flux Isotope Reactor (HFIR).

SNS and HFIR are unique tools for scientific discovery and innovation because of the neutron's fundamental physical properties.[1] Neutrons have wavelengths comparable to atomic and molecular length scales and are electrically neutral, strongly penetrating, and energetically matched to elementary excitations in matter. Neutrons are sensitive to light elements in the presence of heavy ones, with the difference between some isotopes being of particular importance. Neutrons have a magnetic moment and are hence sensitive probes of magnetic ordering and excitations. Finally, neutron scattering is directly connected to a host of phenomena and quantitative measurement enables a direct comparison with theoretical and computational modeling, offering insights into the behavior of complex matter. These properties enable science that is inaccessible to other techniques or where the contribution of neutrons in combination with other probes such as photons and electrons is vital (Fig. 1).

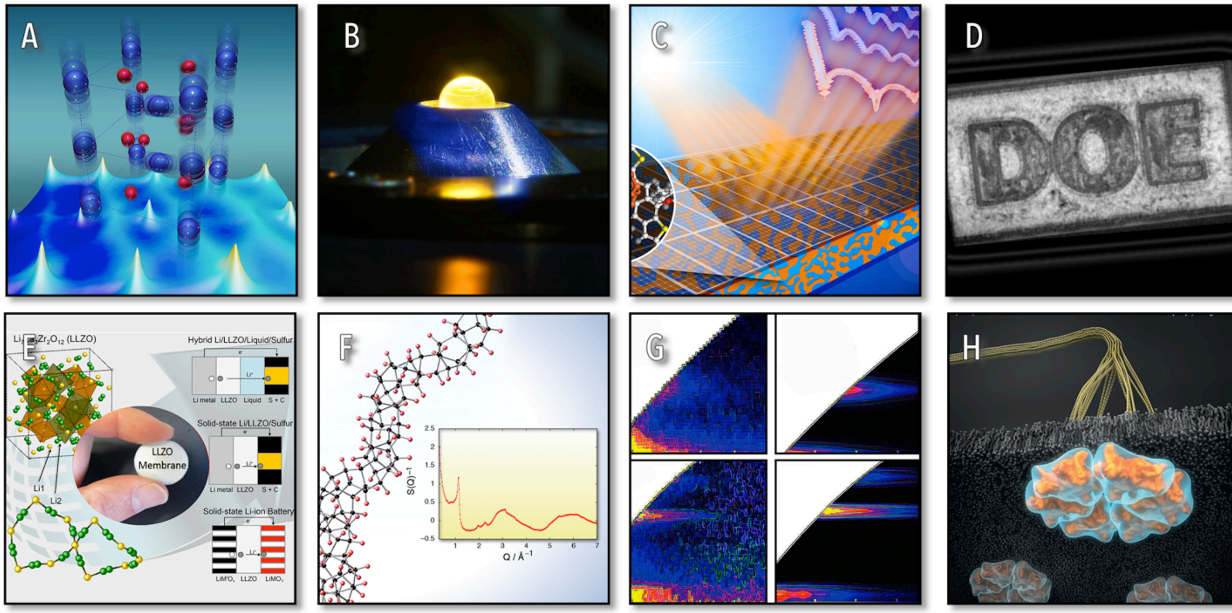

Fig. 1. A) Inelastic neutron scattering explains origin of metal-insulator and thermoelectric materials: Li et al., *Nature Physics* 2015; Budai et al., *Nature* 2014. **B)** Contrast between neutron scattering from different metals reveals elemental distribution in high entropy alloys: Santodonato et al., *Nature Communications* 2015. **C)** Neutron scattering contrast reveals relationship between heterogeneous microstructure and solar cell performance: Das et al., *Nanoscale* 2015. **D)** SNS's unique pulsed source enables mapping of crystalline planes in complicated geometries including textured samples: Dehoff et al, *Materials Science and Technology* 2015. **E)** Neutron penetration and sensitivity to lithium and sodium reveal ion mobility in new battery materials: Thompson et al., *Advanced Energy Materials* 2015. **F)** Neutron sensitivity to hydrogen characterizes new benzene-derived diamond nanothreads created at 20 GPa: Fitzgibbons et al., *Nature Materials* 2015. **G)** Iron atoms form mutually interacting four spin ferromagnetic blocks providing insight into the collective behavior of iron-based superconductors: Mourigal et al., *Physical Review Letters* 2015. **H)** Neutron H/D contrast matching reveals hierarchical structure of cell wall synthesis machinery: Vandavasi et al., *Plant Physiology* 2016. Work at several DOE Energy Frontier Research Centers (EFRCs) including the Solid-State Solar-Thermal Energy Conversion Center, the Energy Frontier Research in Extreme Environments Center, the Center for Lignocellulose Structure and Formation, and other user facilities also contributed to these publications. [2]

Neutron beams for advanced scattering experiments cannot be generated cost-effectively in small-scale academic or industrial laboratories; large-scale facilities such as SNS and HFIR are the only viable option.[3] At SNS, an accelerator and accumulator ring produce pulses of protons that strike a mercury target to produce neutrons. The neutrons are then moderated to thermal or cold energies to produce the world's most intense beams of pulsed neutrons (Fig. 2). The pulsed nature of the beams enables highly innovative time-of-flight experiments. Experiments that require superior wavelength resolution and use either a broad incident wavelength band or broad scattered wavelength band, such as diffraction experiments to determine high resolution structures, depend on peak source brightness—a strength of SNS.[4] Conversely, experiments that require high fluxes of neutrons at long wavelengths, such as small angle scattering experiments to determine nanoscale structures, or that concentrate on small ranges of energy-momentum phase space depend on time-averaged source brightness—a strength of HFIR.[5] The co-location of SNS and HFIR at ORNL allows an experiment to be matched with the best neutron source to maximize scientific opportunities.

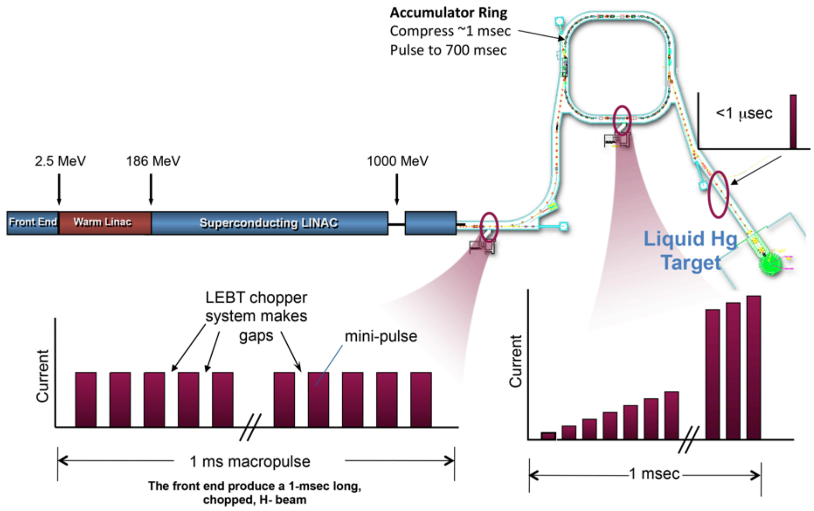

Fig. 2. At SNS, neutrons are produced 60 times a second as a ~1 GeV burst of protons spalls neutrons from the nuclei of a mercury target. The process begins in the front-end where a hydrogen gas plasma creates a pulsed beam of H^- ions that is then accelerated to an energy of 2.5 MeV. The ion pulses are further accelerated through four types of linear accelerator to a final energy of ~1 GeV. Sequential slices of chopped H^- beam, each about 700 nsec long, pass through a stripper foil that removes the electrons allowing the resultant proton pulses to stack on top of each other in the proton accumulator ring. This process intensifies the final accumulated pulse by a factor of about 1000 compared to a single pulse. After accumulation, the intense proton pulse is kicked out of the accumulator ring and transported to the mercury target where each proton generates about 26 neutrons. The high-energy spallation neutrons are moderated to energies suitable for neutron scattering applications by interacting with hydrogen in moderators located above and below the target. One supercritical, cryogenic liquid hydrogen moderator and one ambient water moderator, optimized to produce very short neutron pulses for high-resolution measurements, illuminate two-thirds of the SNS-FTS beam lines. The remaining eight beam lines view two additional hydrogen moderators optimized to produce more intense, but broader pulses of cold neutrons.

Maximizing the Delivery of Neutrons for Science

To ensure a vibrant world-leading neutron science resource in the United States, ORNL is developing next-generation capabilities that lead to solutions for problems of importance to the mission of DOE. Meeting this goal requires continued improvements in neutron sources, technologies, and instrumentation, driven by future scientific needs, as outlined in the *Neutron Sciences Strategic Plan 2014* for neutron sciences.[6]

ORNL is continuing to expand the capability of its neutron sources towards their full design envelope. SNS, which operates for ~220 days per year, achieved 1 MW capability within 3 years of project completion in 2011. A change from beryllium reflector plug coolant to D_2O is planned for early 2017 that will increase the flux from all moderators by 10–20%. Additional upgrades to the accelerator will enable reliable operation at or near 1.4 MW of proton beam

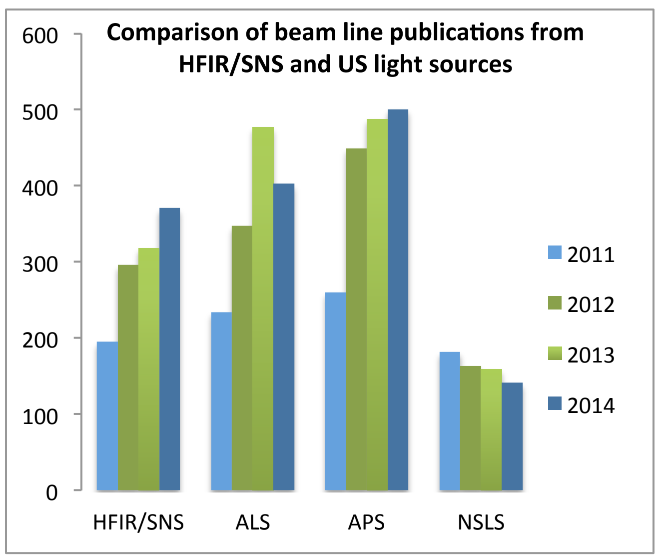

Fig. 3. A comparison of beam line publications from HFIR/SNS with three US light sources. The number of publications from light sources is weighted by the ratio of the number of instruments and operating days at those sources to the number at SNS and HFIR. The weight applied to the number of publications from facility A is as follows: (No. of beam lines at HFIR and SNS/No. of beam lines at facility A) * (No. of available days at HFIR and SNS/No. of available days at facility A).

power.[i] In combination, these two upgrades will effectively double the number of neutrons relative to the 850 kW operations that prevailed throughout most of 2014.

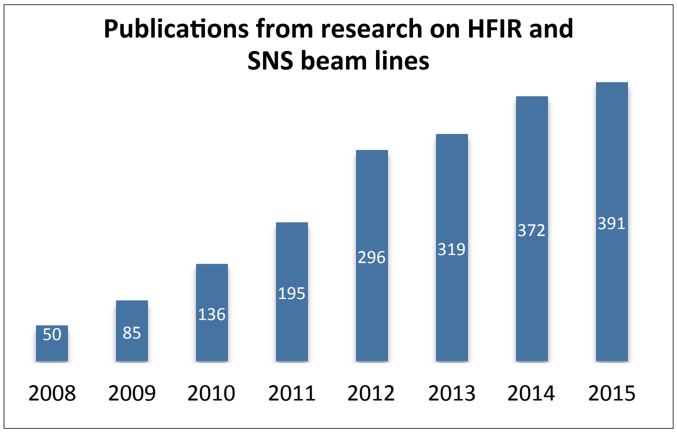

Fig. 4. Publications arising from work on HFIR and SNS beam lines for Calendar Years (CY) 2008 to 2015. These include publications resulting from experiments conducted on HFIR and SNS beam lines.

Neutrons produced at SNS and HFIR are guided to a variety of specialized beam lines. In 2015, SNS and HFIR operated 30 beam lines (compared to 9 in 2008). These beam lines depend on state-of-the-art enabling technologies, including hardware components such as choppers, detectors, neutron optics, and sample environments, and software components and computational methods for instrument control and for data acquisition, analysis, and visualization. Many of these beam lines are relatively new, and will require further improvement of their efficiency through upgrades and automation to reach levels of scientific productivity achieved at US light source facilities (Fig. 3). In FY 2016, a five-year program was initiated to realize the full scientific productivity and impact of each existing beam line through targeted upgrades, complementing plans to construct additional beam lines with new capabilities.[7] A strategy is being executed to better meet the day-to-day needs of the user community for data collection, reduction, and analysis.

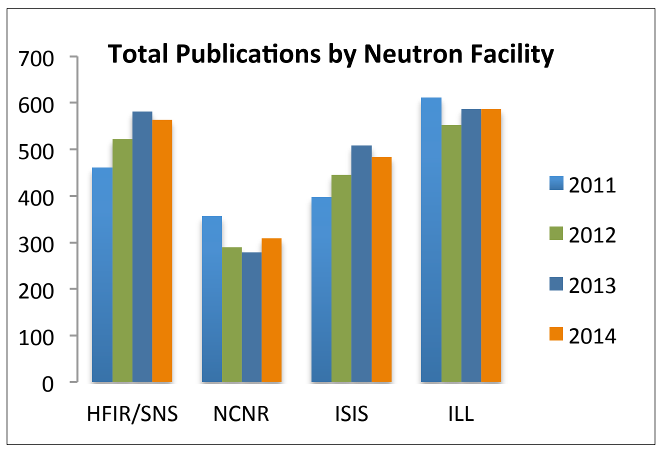

Fig. 5. Comparison of total publications for four major neutron centers in the US and Europe. Publications include all facility and staff publications, as well as instrument publications except for ILL. ILL totals only include instrument-related work because it does not track staff publications for work done at other facilities. Total publications from neutron scattering facilities include those based on experiments conducted on facility beam lines and those based on work conducted by facility staff elsewhere.

Scientific productivity is increasing; the annual number of HFIR and SNS beam line publications has increased from 50 in 2008 to 391 in 2015, and continues to grow (Fig. 4). ORNL is expected to become the neutron scattering center with the largest scientific output this year (2016), surpassing that of other major centers including the National Institute of Standards and Technology's Center for Neutron Research (NCNR) in the US, the Institute Laue-Langevin (ILL) in France, and ISIS in the United Kingdom (Fig. 5).

The user community for ORNL's neutron sources is growing. Since 2007, when a major refurbishment of HFIR was completed, the number of unique users at SNS and HFIR has increased from 99 to 1,336 in 2015. Each year, about 70% of unique users are early-career scientists (under the age of 40), and about 50% are first-time visitors, adding to a user

[i] Because of technical problems with premature failure of mercury targets in 2012 and 2014, the power level was often limited to 850 kW. Early in 2015, a comprehensive plan to develop targets that can reliably operate at high power levels for extended periods of time was developed and is being executed. Recently, targets have operated for up to a year and at power levels of up to 1.4 MW.

community now numbering more than 4,600 researchers. Basic Energy Science (BES)-supported investigators, scientists associated with Energy Frontier Research Centers (EFRCs), and used these facilities to support DOE missions. More than 200 researchers attended the most recent user group meeting in October 2015.

Co-location of SNS and HFIR with the Center for Nanophase Materials Science (CNMS) allows for an integrated Office of BES user program of nanophase materials synthesis, laboratory characterization, theory, modeling and simulation, and neutron scattering. Polymer science is a particular strength, and CNMS provides synthesis of deuterated polymers for neutron scattering experiments. Further, proximity to the forefront resources of the DOE Oak Ridge Leadership Computing Facility (OLCF) provides an opportunity to fully integrate neutron scattering with high-performance computing.

The above activities are continuing to transform SNS and HFIR into world-leading neutron scattering facilities and centers of scientific excellences. Now equipped with a suite of advanced instruments, SNS is progressing strongly with increasing productivity and a growing user community.

The Changing Global Landscape

Global needs and demands for new neutron scattering capabilities are driving the biggest change in neutron facilities in the last 40 years and represent a new phase in neutron science. Reactor-based continuous neutron sources began operating in the 1940s, and improved technology led to the construction of high flux reactors, including HFIR and ILL, that continue to operate today. ILL, built in 1971, integrated the technologies of the day into an optimized source that dominated neutron scattering for the next 40 years. Later upgrades to HFIR, including a cold source, allowed it to maintain scientific excellence. During this period, it was realized that the possible gains by further increasing reactor source fluxes were nearly saturated, and accelerator-based spallation sources emerged. First- and second-generation short pulsed spallation sources, such as the Intense Pulsed Neutron Source (IPNS), the Lujan Neutron Science Center (both now closed), and ISIS, proved to be productive and superior to continuous sources for applications where peak brightness was most important. Commissioning of SNS in 2006 brought a new level of capabilities in the form of the first powerful third-generation 1 MW pulsed spallation source.

Through the European Strategy Forum for Research Infrastructures process, Europe has concluded that a new type of neutron source, a very high intensity long-pulse source capable of dramatic gains, would be needed to address new science challenges.[8] This source, the 5 MW ESS, is now under construction in Sweden, with the intent to deliver the same kind of impact that ILL achieved 40 years ago—representing a game-changing level of performance in cold neutrons. As such, ESS is the European response to SNS and will provide a major advantage in large domains of grand challenge science. The ESS will produce its first neutrons in 2019, and reach full accelerator potential in 2024 as the world's first fourth-generation source. For high-resolution applications, the potential of an upgrade of ISIS has been recognized and is being planned. Although ESS could lead to the phase-out of ILL, at least one other major reactor source, such as the Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRMII) reactor in Germany, remains essential to providing sufficient beam line capacity and development capabilities to meet European needs. Much of the fleet of highly successful medium-flux facilities will be retired as their performance becomes uncompetitive against new capabilities.

The Asia-Pacific research infrastructure is also going through a transition driven by the region's rapidly growing and strengthening materials research. China will build an ISIS-level facility with the China Spallation Neutron Source (CSNS), while the Australian Nuclear Science and Technology Organization (ANSTO) and the High-Flux Advanced Neutron Application Reactor (HANARO) in South Korea are achieving high impact, productivity, and regional capacity. The most advanced source and linchpin of the region, however, is the Material and Life Sciences Facility (MLF) at the Japan Proton Accelerator Research Complex (J-PARC). As this highly advanced source reaches design performance at 1 MW it will rival SNS. In addition, neutron beams at both ESS and J-PARC will have low repetition rates and broad energy bandwidths that are well matched to emerging challenges in complex hierarchical materials.

The Three-Source Strategy for United States Leadership

To provide world-leading capabilities to the scientific community in the US, ORNL has developed a three-source strategy based on further optimization of its two existing sources, HFIR and SNS-FTS, and on construction of a 10 Hz short-pulse STS at SNS.[9] SNS-STS will provide unparalleled neutron peak brightness and dynamic range as a fourth-generation neutron source. The high brightness cold neutron beams and low repetition rate of SNS-STS are well matched to emerging challenges in complex hierarchical systems, and perfectly complement SNS-FTS and HFIR. A second target station at ISIS has already demonstrated the substantial performance gains that can be achieved in emerging areas of grand challenge science, with an optimized low frequency short pulse source. The STS will follow in the same direction but will have an order of magnitude more power. While ESS must put substantial power on target to deliver the integrated flux needed for the highest total flux applications that were addressed by the ILL reactor, ORNL's wide-ranging assessment found that overall needs can be much better met in terms of instrumentation performance, cost effectiveness, and provision of beam lines, by leveraging the existing reactor and accelerator infrastructure at ORNL and matching instruments with the source. In this way, the US can either match or exceed the capabilities of Europe and stay ahead of emerging Asian-Pacific infrastructure. Together, SNS-FTS, SNS-STS, and HFIR form an unbeatable combination that will give the US clear leadership in neutron science capabilities for the next 20 years and beyond, allowing it to go beyond the capabilities of all existing or planned facilities worldwide.

The Proton Power Upgrade: A Platform to Reach the Full Potential of the SNS

The proposed SNS-PPU is a foundational element of the three-source strategy and is a necessary platform for SNS to reach its full potential in delivering world-leading science in areas of transformative opportunity. As noted above, SNS has the potential to be a fourth-generation source with increased neutron flux on available beam lines at the FTS, and with STS supporting 22 additional beam lines with ground-breaking new scientific capabilities.[10] SNS was designed from the outset to accommodate a power upgrade and an additional target station, as recommended in the 1998 report of the Russell Subpanel defining the technical specifications for SNS, which included recommendations to design the facility, "such that it can be operated at a significantly higher power in a later stage" and to include the "capability of additional targets."[11] The *Interim Report on Facilities for the Future of Science* issued by the DOE Office of Science in 2007 identified two projects for realizing the full capability of SNS: a power upgrade for the accelerator complex, meeting the need for additional proton beam power (beyond the 1.4 MW baseline requirement) to feed another target station, and construction of the STS.[12]

SNS-PPU will allow the power of the proton beam delivered to the FTS to be increased to 2 MW. That increase, together with a planned change from beryllium reflector plug coolant to D_2O in 2017, will increase the flux on beam lines by up to a factor of three compared to their flux for the majority of 2014. This increase in flux, together with the five-year instrument upgrade program, will significantly increase the capacity and capability of FTS beam lines. SNS-PPU will also provide a 467 kW 10 Hz proton beam for STS. STS will operate in pulse-stealing mode, with one out of six proton pulses directed to STS and the remaining five pulses continuing to FTS. The STS will double the number of beam lines at SNS and provide new neutron scattering capabilities. These improvements will enable researchers to address a host of compelling scientific and technological challenges for the decade ahead that are inaccessible to other techniques, as summarized in the "Neutron Grand Challenge" workshop reports presented to DOE in October 2014.[13] These scientific challenges and opportunities are discussed in the companion document, *Spallation Neutron Source Second Target Station*, which outlines the SNS-STS project, and the compelling science case for both SNS-STS and SNS-PPU.

Elements of the Proton Power Upgrade Project

The SNS-PPU project scope consists of doubling the proton beam power capability from 1.4 MW to 2.8 MW, and upgrading the FTS target systems to accommodate beam power up to 2 MW. The power doubling is achieved by increasing the proton beam energy by 38% and peak beam current by 45%, relative to current performance using the improvements illustrated in Fig. 6. This upgrade is low risk relative to the original SNS accelerator construction because it primarily uses existing, well-proven technologies. The current project cost is estimated to be approximately $165 million (including 30% contingency and escalation). The project could be completed in approximately 5 to 6 years following approval of Critical Decision (CD)-1. A key constraint in the construction schedule is minimal interruption in SNS operations. Installation of new equipment in the accelerator tunnel will be conducted primarily during planned annual outages. Once completed, operation of the upgraded accelerator systems will result in an increase in operational costs of $4 to $5 million per year, driven by an increase in utility consumption, an increment to maintenance staff for key accelerator systems, and waste disposal costs due to increased target vessel consumption. Several recent advances in accelerator technology are leveraged in the SNS-PPU to provide a cost-effective solution:

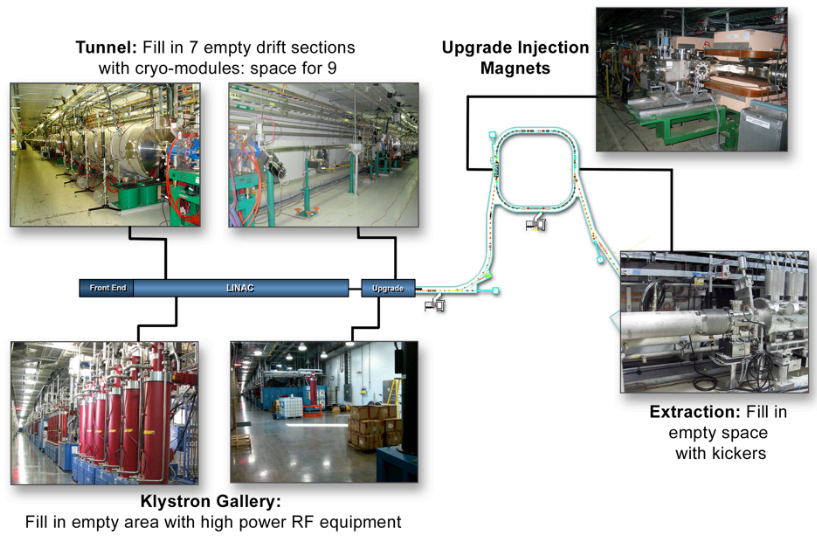

Fig. 6. Accelerator upgrades to accommodate the power upgrade. Empty drift sections at the high-energy end of the linac will be filled out with superconducting RF cryomodules of the type already in use. The supporting RF equipment will be installed in areas provided for in the high-energy end of the Klystron Gallery. Most of the transport line and ring are ready for the energy upgrade. The injection area magnets need replacing, and two additional ring extraction kickers are needed.

- **Cryomodules**. The initial performance of the SNS high-beta cryomodules led to a prediction that 9 new cryomodules would be required to reach 1.3 GeV. However, the performance of a new and upgraded spare cryomodule, combined with the recently demonstrated technique of plasma processing to improve and maintain design gradients, demonstrates that only 7 cryomodules will be needed to achieve 1.3 GeV.
- **Ion source and low-energy beam transport (LEBT)**. Substantial improvements in the operation and performance of the SNS ion source and LEBT have produced a robust system capable of meeting SNS-PPU requirements. This eliminates the need to develop a magnetic LEBT to have a dual source (hot spare) configuration to support SNS-PPU. Improvements in LEBT chopper pulsed power systems and development of "smart chopping" to increase the accumulator ring fill fraction drive down the required peak current at the exit of the RFQ from 59 mA to 46 mA. This is within the capability of the current ion source (54 mA demonstrated) and LEBT system, provided RFQ transmission is maintained at design levels (to be addressed by replacement with a spare RFQ that will be commissioned in 2016 and installed in 2017).

- **Accumulator ring instability**. Increased peak intensity in the accumulator ring increases the chance of developing beam instability. A broadband damper feedback system has been developed to mitigate instabilities that may arise.
- **Ring injection stripper lifetime**. Increased beam intensity increases the possibility of injection stripper foil failure. A foil test laboratory that uses an electron beam to simulate the injected H^- spot heat load is operational. Foils have survived with electron-equivalent heat loads exceeding 1.5 MW, and electron-equivalent loads of 2.8 MW are being studied. Current SNS foil technology has demonstrated suitable lifetime for operation at 1.4 MW.

Beam Energy Upgrade
The SNS-PPU project will provide additional accelerating structures to increase the beam output energy from current routine operation at 0.94 GeV to 1.3 GeV. Seven additional high-beta superconducting RF (SRF) cryomodules will be installed to provide additional acceleration. Space exists in the accelerator tunnel for up to nine additional cryomodules, and the cryogenic fluid distribution lines are already installed at these locations. The new cryomodules will be copies of the spare high-beta cryomodule fabricated at SNS and installed in the linac in 2012. The demonstrated performance of this spare cryomodule is sufficient for SNS-PPU.

The RF equipment for these new cryomodules is largely an extension of that currently in use for the high-beta section of the SNS superconducting linac. The RF klystrons to power the new accelerating structures will be identical to the latest 805 MHz klystrons in operation in the existing SRF section of the SNS linac. Some minor development will be required for the high-voltage modulator systems driving the klystrons for upgrade. The performance requirements for these new modulators are reduced by powering only 9 klystrons per modulator in the upgrade section, compared to 10 klystrons per modulator in the existing linac. Improvement in the performance of some existing installed SRF cavities will be required. SNS staff has developed an in situ plasma processing technique that has been demonstrated to increase the operational gradient of poorly performing cavities in the cryomodules installed in the tunnel.

Beam Current Upgrade
The average beam current with SNS-PPU will be ~45% higher than today's 1.4 MW production level. Operational developments have already substantially increased the ion source capability. The only equipment upgrades supported by SNS-PPU to accommodate the increased beam current are some upgrades of the RF equipment in the warm linac area to handle the associated increased beam-loading effect. Two of the six klystrons powering the Drift Tube Linac (DTL) structures will need to be upgraded from 2.5 MW to 3 MW peak RF power, and the modulators supplying these klystrons will require associated modest upgrades. Also, the windows coupling the RF power into the DTL structures must be upgraded to accommodate the higher peak power.

Ring System Upgrades
The Ring and Transport lines are essentially ready for SNS-PPU: 96% of the magnets and power supplies in these systems are 1.3 GeV capable. The few magnets and associated power supplies that require upgrades to accommodate the higher energy are in the ring injection area. Two new extraction kickers (identical to the existing 12) will be added to accommodate the higher energy. In 2011, a test run was successfully performed with all the Ring and Transport line magnets running at their 1.3 GeV levels, and the only necessary improvement is an increase of the Ring Service Building cooling system capacity.

Target System Upgrades

ORNL is engaged in increasing target robustness at 1.4 MW, and developments undertaken to achieve this goal will be extended to produce a 2 MW capable target design. These developments include (1) injection of gas bubbles to mitigate the stress and cavitation damage from the proton beam–induced pressure pulse, (2) incorporation of a "jet flow" design to increase mercury flow adjacent to the structure wall and reduce cavitation damage, and (3) improved design and fabrication techniques to improve mechanical robustness.

Readiness to Proceed to Construction of the Proton Power Upgrade

A BES facilities prioritization review conducted in 2013 by a subcommittee of the BES Advisory Committee (BESAC) recognized the proposed STS and the associated power upgrade as being "absolutely central" to US science.[14] However, the reviewers at that time stated that this project had "significant scientific/technical issues that must be resolved before construction can be initiated."[15] These issues have now been addressed, as described in two reports, *Instruments for Emerging Science: A Science Case for the Second Target Station* and *Technical Design Report Second Target Station,* published in 2015.[16] Of special importance, a more cost-effective solution to achieving SNS-PPU has been developed, based on several improvements in the requisite accelerator technologies since SNS was constructed. Following the publication of these reports, an STS Project Planning Office was established at ORNL to prepare the project management structure to deliver Conceptual Design Reports (CDRs) for SNS-PPU and SNS-STS to support DOE in making CD-1.[17] A core group of design engineers, physicists, and project control specialists support this effort, largely matrixed from current staff involved in the operation of the SNS. The staff has experience with operation of the SNS accelerator, target, and instrument systems, and the team includes key personnel with experience from the original SNS construction project. Budget legislation for FY 2016 provided $10 million to accelerate progress to CD-1. Having addressed all issues, ORNL is now ready to proceed to construction of SNS-PPU and to deliver ground-breaking new scientific capabilities to meet the needs of US researchers to address emerging challenges, as described in the companion document *Spallation Neutron Source Second Target Station*.

Note: These references are available in pdf format at this website: https://conference.sns.gov/event/21/

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