A Strategy for
LANSCE Futures

Los Alamos National Laboratory
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On the cover: The Los Alamos Neutron Science Center at Los Alamos National Laboratory.

VISION

The primary mission of the Los Alamos Neutron Science Center (LANSCE) is to measure dynamic material performance and characterize the structural and nuclear properties of materials in support of Los Alamos National Laboratory's (LANL) national security science mission.

A major challenge for stockpile stewardship over the next decades will be understanding the performance of aged and replacement materials throughout the entire stockpile-to-target sequence (STS). Capabilities at LANSCE provide an opportunity to prepare; to characterize and qualify; and to measure the dynamic response of materials, including plutonium (Pu) and high explosives, at a single site. Additionally, LANSCE plays fundamental roles supporting nuclear physics and data underlying stockpile assessment and certification and in producing medical isotopes.

Our strategic goals at LANSCE are: to enable a dynamic Pu capability with improved resolution at the Proton Radiography Facility; to improve our ability to measure neutron capture reactions on radioactive isotopes; to establish a Pu aging research capability in Area A; and to improve our ability to characterize materials using neutron diffraction at the Lujan Center. All these actions are consistent with the Laboratory strategic goal of bringing a Matter-Radiation Interactions in Extremes (MaRIE) facility to the site to meet the established mission need.

Key priority actions are the following.

1. Enable and perform dynamic plutonium experiments at the Proton Radiography Facility.
2. Install a new neutron spallation target at the Lujan Center in 2020. The new target will yield significant improvements in the flux and resolution of keV to MeV neutrons. This will enable new nuclear physics opportunities to address outstanding radiochemical and nuclear forensics issues and nuclear physics measurements in support of the planned neutron diagnosed subcritical experiments (NDSEs) at the Nevada National Security Site (NNSS), while maintaining the Lujan Center's material science capabilities.
3. Establish a Materials Survivability Laboratory in Area A. This facility will enable the scientific study of plutonium aging and the characterization and qualification of space-borne electronics to radiation insults. High-power proton beam operations in Area A would also support the production of clinically relevant levels of Ac-225 and a second proton radiography station.

4. Improve the high-energy neutron radiography station with a larger beam diameter, a turnkey classified capability (with the ability for open storage of classified parts), and a dedicated imaging system.
5. Continue investment in the 45-year-old, 800-MeV proton accelerator to ensure reliable operations with high availability and enhanced performance to support future missions. Such investments will build upon the substantial NNSA infrastructure investments in the LANSCE accelerator over the past five years.
6. Continue to cost effectively support a National Nuclear Security Administration-(NNSA) sponsored national user program and other important national missions such as enhanced surveillance, nuclear energy, the production of medical isotopes for diagnosis and treatment, an industrial electronics irradiation program, and fundamental research in nuclear physics.

BACKGROUND

LANSCE has been delivering critical data in support of LANL's national security science mission since 1972. The long-term success of LANSCE can be attributed to the combination of one of the highest power linear proton accelerators in the world with diagnostic and experimental capabilities that are focused on national security challenges. LANSCE provides materials characterization and testing capability not available elsewhere. These capabilities include: dynamic proton radiography, material characterization using neutron scattering and diffraction, nuclear cross-section measurements, and energy resolved and high-energy neutron radiography.

Three of the LANSCE target stations are NNSA-designated national user facilities (the Proton Radiography Facility [pRad], Weapons Neutron Research Facility [WNR], and the Lujan Center). The LANSCE user program hosted more than 500 users from 89 institutions (and 10 countries) in the latest run cycle (see Appendix 1). LANL scientists collaborate with many of the external users on projects of interest to NNSA, either through inter-Laboratory agreements (Lawrence Livermore National Laboratory, Sandia National Laboratories, Atomic Weapons Establishment [AWE], the French Atomic Energy Commission [CEA], etc.) or universities funded through the Stockpile Stewardship Academic Alliance Program.

LANSCE must continue to support the ongoing needs of the nation while also preparing for the Matter-Radiation Interactions in Extremes (MaRIE) project, expected to become operational sometime after 2030. This document lays out a strategic vision for LANSCE that is responsive to the current and anticipated needs of the NNSA for the next decade.

STRATEGY GOALS AND PRIORITY ACTIONS (1-5 YEARS)

ENABLE A DYNAMIC PLUTONIUM CAPABILITY AT THE PROTON RADIOGRAPHY FACILITY

The current authorization basis at pRad allows for dynamic Pu experiments with a limit of 11 g of Pu and 30 g of high explosives (TNT equivalent). Such experiments were last conducted in 2007. Heightened safety concerns have paused such operations. We are currently working on the design of containment systems, removal of unneeded legacy equipment, and the expansion of our conduct of operations to include safely performing dynamic Pu experiments within the current authorization basis. First experiments are scheduled to be conducted in 2020 and will address key questions in the weapons program. Fielding plutonium experiments is expected to require significantly more time than experiments using only conventional materials. This could significantly impact the number of experiments that can be executed at the pRad facility. Given the demand on the current pRad facility we would establish a second firing site for proton radiography within Area A if the demand warranted such an investment.

REPLACE THE LUJAN NEUTRON SPALLATION TARGET

Radiation damage to the beam entrance window requires that the neutron spallation target at the Lujan Center (hereafter the 1L target) be replaced in ~2020. This provides an opportunity to significantly improve the target performance for neutrons with energies between 1 keV and 1 MeV. A design that improves our figure of merit (flux/resolution squared) by up to 2 orders of magnitude, without significantly impacting the flux of thermal and epithermal neutrons, has been completed. With the new target the Lujan Center will have best-in-class performance over these energies, enabling measurements of capture and scattering reactions on actinides and other isotopes and total neutron cross sections on short-lived isotopes. These measurements are needed to understand radiochemical tracers and neutron transport and to perform nuclear forensics.

IMPROVE HIGH-ENERGY NEUTRON RADIOGRAPHY CAPABILITY

LANSCE currently has two facilities for neutron radiography. Thermal and epithermal neutrons at the Lujan Center are used to perform energy selective neutron imaging, which enables isotope specific tomography of materials. At WNR, high-energy neutrons are used to radiograph thick objects, mostly to investigate nondestructive surveillance methods. The top priority is to improve the high-energy station. The ability to accurately measure and select neutron energy enables us to serve as a test-bed for new radiographic concepts and techniques. A larger beam diameter, a turnkey classified capability (with the ability for open storage of classified parts), and a dedicated imaging system are all needed to efficiently fulfill current and future missions.

IMPROVE ACCELERATOR RELIABILITY

Accelerator reliability improvements are needed to ensure the delivery of high-reliability beam to all areas of LANSCE. Significant investments in the LANSCE accelerator have enabled the machine to operate at the 120-Hz design frequency for the first time since 2004. Funding for LANSCE Risk Mitigation activities ended before a ***modern diagnostics and a modern control system*** could be fully implemented. Recent experience has demonstrated that these are the primary limitations to improving accelerator performance and reducing machine downtime and are therefore the highest priority. The ***performance of the cesiated source*** used to generate the H- beam (used at WNR, Lujan, pRad, and the Ultracold Neutron Facility [UCN]) is limiting the amount of available current to WNR and the Lujan Center. Restoring the source performance to previous levels would enable the delivery of 120 micro-amps, which would compensate for the approximately 25% reduction in thermal neutron flux due to the new Lujan target design.

STRATEGY GOALS (>4 YEARS)

PHASE 1 AREA A DEVELOPMENT

The WNR facility has provided a venue for electronics manufacturers to test component resiliency to neutron upsets. While neutron upsets are the major concern of ground-based and avionics electronics, space-based electronics are exposed to cosmic rays, which are predominantly composed of high-energy protons. The main testing facility (Indiana University Cyclotron Facility) for space-electronics component manufacturers closed in 2014. The delivery of low-power (100 nA) beam to Area A would enable LANSCE to fill this national need. LANL Global Security sponsors, the National Aeronautics and Space Administration (NASA), and industrial users have expressed interest in such a facility. This would be a required first step in the development of a Pu aging facility at LANSCE.

IMPROVED NEUTRON DIFFRACTION CAPABILITY

As existing parts age and replacement components are introduced into the stockpile (potentially made through advanced manufacturing methods), we need to fully characterize their microstructure to enable a predictive manufacturing capability. We propose the development of a flight path dedicated to the fully three-dimensional measurement of texture throughout a given component or material. Such a capability is not available anywhere else in the world.

IMPROVED DYNAMIC RADIOGRAPHY

The Proton Radiography Facility has become a major firing site for NNSA programs. The multi-frame capability is well suited to measuring the detonation and burning of high explosives and the response of materials under high explosive loading. Two potential advancements that would benefit all programs are the development of an achromatic lens, which would improve the spatial resolution without affecting the field of view and the construction of a second radiographic axis to investigate three-dimensional effects. These two capabilities are not mutually exclusive. One or both of the radiographic axes could be composed of achromatic focusing systems. Replacing the current 3-frame cameras with newly developed 10-frame cameras would increase the number of image frames from 31 to 70.

PHASE 2 AREA A DEVELOPMENT

As Pu ages, radiation damage has the potential to alter the microstructure and affect dynamic material properties. As the second phase of the development of Area A, an intense neutron source, driven by a 100-μA proton beam, would enable accelerated aging of Pu. The radiation damage induced by recoiling fission fragments mimics that of the natural alpha-decay process, which creates U-235 recoils. The beam line would include rudimentary in situ measurement capability. With such a capability LANSCE would be able to accelerate the aging of material, characterize its microstructure at the Lujan Center, and investigate its dynamic performance at pRad. Scoping studies are underway to assess the value of such a capability, with its complementary benefits compared to Annular Core Research Reactor exposures at Sandia.

LANSCE ACCELERATOR UPGRADES

The long-term accelerator upgrades are focused on supporting the capability improvements listed above. If the development of Area A proceeds, the Isotope Production Facility (IPF) kicker magnet must be used to enable sharing of the beam between IPF and Area A. The proton irradiation station would require 100 nA of H+ beam, energy tunable between 200 and 800 MeV, which would require reconfiguration of the switchyard. Higher current to Area A for the Materials Survivability Laboratory will require improved tuning of the accelerator and reconfiguration of the beam sharing between IPF and Area A. To support potential pRad capabilities, the accelerator will need to increase the number of protons per pulse to pRad. A second radiographic axis will require a doubling of the current to maintain the current single axis capability. An achromatic lens would require substantially more current (studies are being performed to evaluate requirements) to achieve the potential resolution gains over the large field of view.

STRATEGY DEEP DIVE

The following sections discuss the capability developments for each target station in greater detail.

PROTON RADIOGRAPHY

The pRad target station at LANSCE provides a unique capability to the NNSA's Stockpile Stewardship Program: the ability to generate multiple-frame radiographic movies of dynamic experiments driven by high explosives or other drivers. The LANSCE accelerator can deliver an effectively unlimited number of radiographic pulses of 800-MeV protons at the relevant frame rates (~1-μs interframe spacing). The number of frames in an experiment is limited only by the ability to acquire and store the data. The pRad facility currently includes the capability to record up to 31 frames of radiographic data on each dynamic experiment in combination with other diagnostics such as laser-based velocimetry. The number of frames could be increased to 70 with the deployment of recently developed 10-frame cameras. The facility accepts proposals from around the Laboratory, the NNSA complex, and the world and fires approximately 35 dynamic experiments per annual LANSCE run cycle, most in support of the weapons program.

Two questions central to the Stockpile Stewardship Program are addressed by the pRad experimental capability. To understand the performance of a nuclear weapon, one must understand the *initiation* of detonation in high explosives and the *progress* of detonation fronts through explosives after initiation. These processes are difficult to model numerically and must be studied experimentally, especially for the insensitive high explosives used in the nation's nuclear weapon stockpile. This is especially true at the temperature extremes encountered throughout the entire stockpile-to-target sequence.

Nuclear weapon performance also depends on the *reaction of metals* and other materials to shocked and unshocked high explosive drive. Current areas of study include nonlinear effects such as Richtmyer-Meshkov and Raleigh-Taylor Instability growth, failure of shocked metals caused by shear or strain, measurement of the shocked equation of state of relevant metals, and the effect of age and new manufacturing techniques on material responses. These issues are complicated by the presence of inherently three-dimensional effects that are difficult to study through simulation and experiment.

The pRad target station at LANSCE was constructed in 1998 and consists of multiple proton imaging lenses in Experimental Area C combined with high explosive handling and diagnostic instruments. (A powder gun and a pulsed power system are available as additional drivers.) The fundamental components of a proton radiography system are the proton delivery system, the dynamic drive and confinement system, the proton focusing lens, the image recording system, any secondary diagnostics, and the data acquisition systems used to record the radiographic and secondary data.

The proton delivery system consists of the LANSCE accelerator, a series of beam steering and focusing magnets, and upstream diagnostics to measure the incident beam. The accelerator delivers protons in micropulses ~100 ps long separated by 5 ns over an approximately 1-ms-long macropulse. Any set of these micropulses, each containing about $3\text{x}10^8$ protons, can be selected for delivery to a pRad experiment. Typically, 20 micropulses will be grouped together to form a single 100-ns-long, $6\text{x}10^9$ proton radiographic frame, with up to 31 of these frames delivered to each dynamic experiment—again with any spacing between each pair of frames in 5-ns increments. Upstream diagnostics measure and count the protons delivered.

Three drive systems are available for dynamic experiments: machined high explosives confined in a 6-foot-diameter steel confinement vessel used for ~60% of the dynamic experiments, a 40-mm smoothbore powder gun (30%), and the Precision High Energy Density Liner Implosion eXperiment (PHELIX) pulsed power cylindrical implosion system (10%). Each accesses different physics regimes: high explosives can reach the highest pressures, the powder gun can supply a supported shock instead of the high explosive Taylor wave, and the PHELIX can supply a supported shock in a converging geometry. Typical explosive loads are up to 3 pounds of TNT-equivalent high explosive: an absolute limit of 10 pounds TNT-equivalent is enforced. The present confinement system is qualified for hazardous or radioactive materials such as vanadium or uranium, but not for the more hazardous plutonium or beryllium (Be). (Note that the Accelerator Safety Envelope allows for dynamic Pu and Be experiments.)

Three lens systems are available for radiographic experiments: a one-to-one magnification "identity" lens; a three times (x3) magnifying microscope; and a seven times (x7) magnifier. Each lens has a different tradeoff between image resolution and field of view: 120-mm-square field of view and 250-micron image resolution for the identity lens, and proportionally smaller field of view and finer resolution for the x3 and x7 magnifiers. Each lens can be tuned for the radiographic thickness of a given experiment by installing the optimal "collimator" to maximize the contrast and sensitivity. One limitation is that these lenses can be set for only a single radiographic thickness per experiment; if the experiment *changes* thickness during the dynamic event, as almost all high explosively driven experiments do, then only a single frame of the radiographic movie will be ideally focused; the other frames will be "chromatically blurred" by the effect of the changing object thickness—by an amount proportional to the difference in thickness between the object in a given frame and the single lens setting.

The proton focusing system generates a proton image that must be converted into digital radiographic data. The current imaging system uses a two-stage system in which a scintillating plate converts the proton image into an optical image that is recorded by an array of fast digital cameras. These cameras each record multiple images on sub-microsecond time scales at near-unity quantum efficiency. The present system includes 7 cameras each capable of recording 3 frames and a single second-generation camera capable of recording 10 frames, for a total of 31 frames available for each dynamic experiment. The natural time scale of the imaging system is driven by the 50-ns decay time of the scintillating plastic, which is well matched to the few mm/μs speed of explosively driven experiments and the tens to hundreds of microns pRad resolution.

Secondary diagnostics are specially tailored to each dynamic experiment. About half of the experiments use photon Doppler velocimetry to continuously measure the velocity of discrete points on the surface of an experiment, which complements the ability of proton radiography to measure locations of the continuous interior features of an experiment at discrete times. Other secondary diagnostics include perpendicular x-ray radiography, optical and voltage pins, and other light-based diagnostics.

The pRad capability includes the ability to field and record both unclassified and classified experiments up to the Secret level, even with restricted need to know. Approximately half of the experiments conducted in recent years have been classified. The experimental area can be converted into a limited security area for each experiment series as needed, and a permanently installed classified work and data storage area allows protection of the classified information.

The LANSCE Proton Radiography Facility is the only operational many-frame dynamic radiographic facility in the United States. The closest similar capability is at LANL's Dual-Axis Radiographic Hydrodynamic (DARHT) x-ray facility, which can generate up to five radiographic pulses per experiment (with the advantage that it can radiograph significantly thicker objects than is possible at pRad). The Cygnus x-ray machine at the Nevada National Security Site can radiograph thin plutonium experiments but is limited to two pulses. Russia has a higher energy proton radiography facility, with the ability to radiograph thicker objects at higher resolution than LANSCE or DARHT, but with a limited number of frames. China is constructing or has constructed a facility similar to the LANSCE pRad facility.

POSSIBLE UPGRADES TO MEET FUTURE MISSION

There are three categories of identified mission needs that the present pRad facility cannot meet: 1) the ability to study very hazardous materials such as plutonium or beryllium; 2) the ability to either focus on very small objects such as detonators or maintain the best focus over the duration of an experiment with drastically changing thickness; and 3) the ability to measure three-dimensional effects in a single experiment.

Potential facility upgrades can address each of these mission needs.

Implement a dynamic plutonium experimental capability at pRad. This capability is currently being developed with the support of LANL's weapons program. Initially, the capability will be limited to 11 plutonium-equivalent-grams of material driven by up to 30 TNT-equivalent-grams of high explosive (per experiment). To enable the containment of very hazardous materials, a double-walled containment system is being designed to complement the existing single-walled confinement system. The inner vessel is designed to fully confine the dynamic experiment and hazardous shot debris and will be disposed of intact after each experiment. The outer vessel will provide secondary containment and will be reused for multiple experiments. The first Pu experiments will investigate the reaction of Pu to shock loads and are now being designed. The current schedule calls for fielding in 2020. As mentioned above, fielding these experiments will require significantly more time than conventional experiments. If there is a need for more than 1-2 such experiments per run cycle, it is likely that a second proton radiographic station would need to be established in Area A to meet the demand for the facility.

Improve radiographic resolution. The development of a higher resolution system with faster detectors is closely tied to the development of a proton transport and detector system for experiments at the MaRIE facility's MultiProbe Diagnostic Hall, which is expected to field experiments that are typically a few millimeter or smaller in size.

Two new systems are being studied to improve the resolution of the proton radiographs.

1. The first is *a x21 magnifying lens* that trades off field of view for enhanced resolution. This system will have a field of view 5x5 mm and an image resolution of 10 μm. Combined with a faster proton detector and imaging systems, it will permit experiments on a smaller scale than possible with the existing lenses. The total cost of developing such a lens and detector system is dominated by the R&D costs for the detectors but is expected to be less than $1M.
2. The second new lens system now under development is an *"achromatic" proton lens*, which will have an optimal resolution similar to the existing identity lens but will be far less sensitive to changes in thickness of the dynamic object. Instead of the chromatic blur mentioned above being proportional to the change in the thickness, it will be much more weakly coupled. The existence of such a lens would enable a class of experiments with variable thickness, with either temporal or spatial thickness gradients. An example of the latter is a detonation front passing through high explosive (radiographically thin) then driving a shock wave in a metal plate (radiographically thick). With the existing pRad lenses, such an experiment is technically challenging or even out of reach; with an achromatic lens, it would be relatively straightforward. The cost of such a lens is driven by the acquisition cost of high-power electromagnets and is expected to be $5-10M.

Enable exploration of three-dimensional effects. A second proton beam line in the experimental area at an angle to the first would enable the exploration of three-dimensional effects, with many image frames in both axes. Experiments needing this capability would be investigations of three-dimensional effects in high explosive initiation and nonlinear material failure effects. These are known to exist and be important but are extremely difficult to access experimentally. The best the current pRad facility can do is to field the exact same experiment twice and radiograph it from different angles. This is not sufficient for studying stochastic and nonlinear effects. A two-axis capability could be implemented by taking advantage of the H- ions to split the incoming beam into two secondary beams with identical time structures that are separately transported to the same experiment from different angles. Figure 1 shows a conceptual design of such a magnet system that would fit within the existing Area C footprint. The cost of such a capability is driven by the acquisition of the magnets and corresponding power supplies and is expected to fall into the $5-10M range.

Any of these upgrades to the facility could be completed in a five-year time span and could be located either in the existing Experimental Area C facility or in a new proton radiography facility in Experimental Area A.

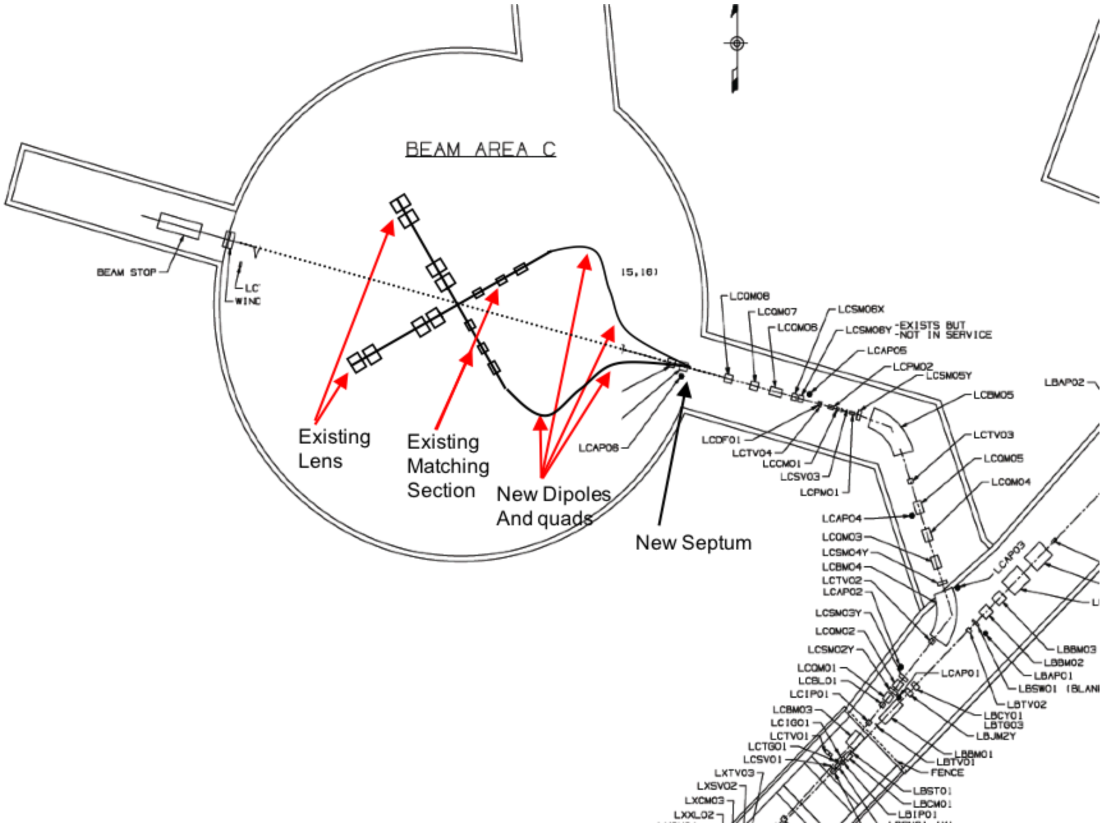

Figure 1. Conceptual design of a dual-axis capability for proton radiography in Area C.

NEUTRON RADIOGRAPHY

Many aspects of the LANL mission, including stockpile stewardship, fundamental research, global security, and nuclear energy, require imaging with penetrating radiation. This need is currently supported by broad x-ray imaging capabilities, proton radiography, and a limited set of neutron imaging capabilities. The ability to combine data from multiple neutron energy ranges with x-ray and proton imaging data at the same laboratory is only available at LANL and would add powerful new insight for complex objects.

In spite of these existing capabilities, there remain key areas where no existing imaging capability exists. This leads to expensive destructive testing, the inability to reuse parts, and a lack of understanding of important phenomenon. Investment in neutron imaging capabilities could realize significant gains in these areas. These include

- imaging of thick, high Z weapons parts and assemblies;
- imaging of low Z materials shielded by high Z materials including liquids and gases;
- imaging of nuclear fuels;
- imaging the isotopic distribution in components; and
- quantitative imaging of individual materials and combinations of materials (e.g., polymer on metal interfaces).

A classified addendum on specific areas of interest for imaging is available.

LANSCE possesses a combination of neutron imaging capabilities. The availability of cold (4 to 13 A), thermal (25 meV), epithermal (1 eV to 10 keV), and high-energy (0.1 to 400 MeV) neutrons offer complementary capabilities and imaging techniques that span applications from characterizing the isotopic homogeneity in nuclear fuel to the tomographic imaging of a dinosaur skull. The current capability has grown with support of a Principal Associate Directorate for Science, Technology, and Engineering (PADSTE) small equipment grant and investment from a few programs (primarily Enhanced Surveillance and Nuclear Energy). LANSCE priorities to enhance this capability are to

1. *develop the high-energy neutron radiography capability into a turnkey operation with the beam diameter needed to image mission-relevant assemblies, including classified operations, and*
2. *develop and instrument a dedicated thermal imaging beamline in the Lujan Center.*

The current capabilities and future enhancements are discussed below.

FAST NEUTRON RADIOGRAPHY

Fast neutron imaging (100 keV-400 MeV) work currently uses flight path 60R at WNR. The energy-integrated neutron flux is approximately 10^6 n cm^{-2} s^{-1} and the beam area is 30 cm x 20 cm. The radiographic imaging system relies on borrowed components such as a lens-coupled camera system from the United Kingdom and fast-gated (1-20 ns) cameras on loan from the Intelligence and Space Research (ISR) Division. Tomography of thick systems can take 24 hours or more of beam exposure, requiring 24/7 attendance for classified components. The current flight path is in the egress path for flight path 30R, used by industrial users and foreign nationals.

To fulfill this mission, the following improvements are needed:

- The area of the neutron beam enlarged and made uniform. A 40 cm x 40 cm or larger beam area at ~20 m is critical to enable the imaging of larger parts. (Note that an inherent strength of fast neutrons is the ability to penetrate large parts). This requires shutter, collimation, and shielding modification. The collimation and shielding should have triple collimation after the shutter and substantial shielding needs to be placed around the collimators.
- Installation of a permanent structure that will enable a fast transition between unclassified and classified operations. The ability to have open, unattended storage of classified components is a second-level priority. This would substantially reduce the cost and risks of the current operations. If built this would support as many other classified experiments as possible (not just radiography).
- Investment in a dedicated tomographic capability. This includes motion stages, imaging systems, data acquisition system, and computers that are dedicated to the radiographic flight path. A dedicated time-of-flight imaging system is the most critical need.

Given the above requirements, implementing this infrastructure on flight path 15R would be the most economical option.

THERMAL AND EPITHERMAL NEUTRON IMAGING

Thermal and epithermal neutron imaging uses flight path 5 at the Lujan Center. Neutron time-of-flight information can be used to make isotope-specific images of objects. This capability at LANSCE is a result of the short neutron pulse width and a specially developed micro-channel plate (MCP) detector[1]. Thermal imaging is performed on larger objects (8 cm to 1 m diameter) and energy resolved imaging with the time-of-flight detector is possible for smaller objects (3 cm x 3 cm), with a resolution of approximately 50 μm. To advance this capability we need to do the following.

1. Develop a dedicated flight path for thermal neutron imaging. Currently this capability shares flight path 5 with the energy resolved imaging. This inhibits the development of thermal neutron radiography, which has substantial potential applications in a wide variety of Laboratory mission areas including for Defense Programs and Global Security sponsors.
2. Deploy a larger MCP detector for energy-selective nuclear-resonance imaging. This will enable increased throughput for larger objects and is essential for computed tomography of larger objects.

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[1] A.S. Tremsin, et al., *J. Nucl. Mater.* **440** 633-646 (2013).

NUCLEAR SCIENCE

The performance of a nuclear weapon or a nuclear reactor cannot be understood without accurate knowledge of the fundamental nuclear processes responsible for energy release in a device. Fission cross sections, neutron capture reactions, neutron scattering, and nuclear fusion reactions all contribute to a weapon's performance. In addition, isotopic signatures may be used as diagnostics to understand both the U.S. stockpile and foreign threats. Recent nuclear science work at LANSCE has concentrated on precisely measuring nuclear fission properties (fission cross sections, neutron output spectra, fission fragment yields, and kinetic energies) and neutron capture reactions at weapons-relevant energies. In the next several years this "precision fission" program will be completed, delivering the fission reaction data needed to understand and predict weapon performance. Going forward, the nuclear science mission at LANSCE will focus on measurements to support radiochemical analysis of past nuclear tests, provide physical data for the technical nuclear forensics program, and support the neutron diagnosed subcritical experiments (NDSE). To support these future missions, LANSCE proposes to

1. *exploit the high-energy (WNR) and keV (Lujan Center) neutron spectra for national security science;*
2. *develop flight path 13 to enable the accurate calculation of neutron capture cross sections on short-lived isotopes; and*
3. *advance and evolve existing detector systems to support future programs including NDSE.*

The success of this program relies on the capability that will be provided by the redesigned Lujan spallation target, which will yield up to 2 orders of magnitude improvement in capability in the energy range between 1 keV and 2 MeV. The target is scheduled to be replaced in 2020. The new design for the Lujan target is discussed below, followed by the proposed new capabilities.

THE LUJAN TARGET REDESIGN[2]

A major focus of the Lujan Center target redesign was to enhance the range of nuclear science questions that could be addressed, while maintaining the materials science capabilities. The primary limitation of the existing target is the poor neutron energy resolution and low flux above 1 keV. The energy range of highest impact for neutron capture measurements is from 500 eV up to 2 MeV. The resolution is driven by the moderator response function and the proton pulse width. The low flux is a result of a prior design decision to optimize the thermal neutron flux. While it is not possible to derive a single "figure-of-merit" (FOM) that can be applied to all experiments, a commonly used figure is the neutron flux divided by the square of the energy resolution, $\phi/\Delta E^2$. (The energy

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[2] The redesign was required because of the approaching end-of-life of the current Lujan target.

resolution is directly proportional to the proton pulse width.) Figure 2 shows the improvement in this FOM relative to the current target for two cases: one in which the flight paths are left as they are ("current") and another where the flight paths are realigned so the detectors and samples have a direct line-of-sight to the moderator ("centered").

The recent ^{239}Pu(n,γ) measurement with the Detector for Advanced Neutron Capture Experiments (DANCE) illustrates how the improved target will improve quality and reliability of the measurements that can be performed. Figure 3 shows the measured cross section with statistical and systematic uncertainties. The uncertainties above 200 keV are driven by a combination of instantaneous count rate, energy uncertainty, and fission and scattering backgrounds. The energy uncertainty comes directly from the broad proton pulse width and the moderator response function, both of which are improved in the new target design.

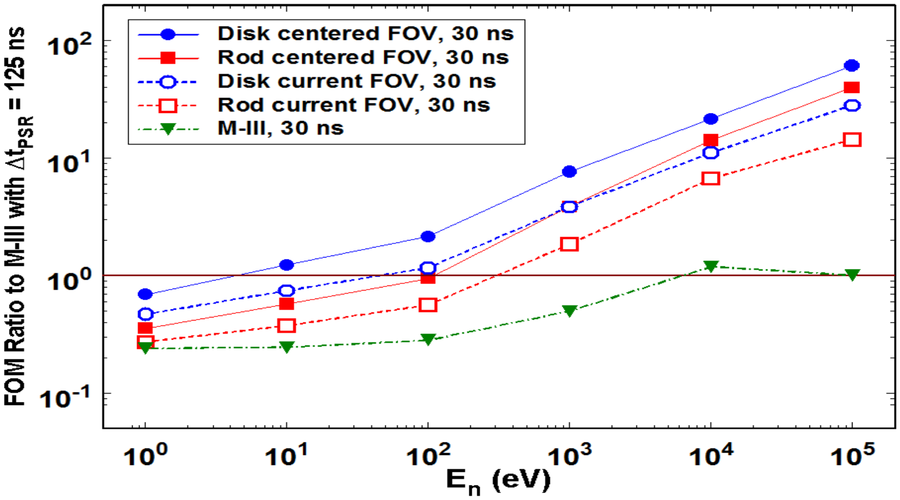

Figure 2. The improvement in the FOM for the redesigned target under a range of pulse structures. Note that for isotopes like ^{88}Y, pulse delivery flexibility is critical for maximizing the target redesign impact.

DEVELOPMENT OF FLIGHT PATH 13

The Device for Indirect Capture Experiments on Radionuclides (DICER), currently under development on flight path 13, will offer the opportunity to directly measure nuclear properties on extremely radioactive samples. This capability is being developed to address future mission needs: the determination of diagnostic quantities (particularly those that are needed for both the radiochemistry detector and tracer programs) and nuclear forensics efforts. There are significant gaps in the knowledge of the cross sections relevant to radiochemical detectors that DICER can fill. This capability, when coupled with the new target, will provide the nuclear data needed to open a new window into radiochemistry diagnostics and nuclear forensics.

The concept behind DICER requires the measurement of at least 50 well-resolved resonances with sufficient statistics[3]. While this is straightforward for well-deformed rare-earth and actinide isotopes (Tm and U, for example), it presents an experimental challenge for isotopes with lower level densities.

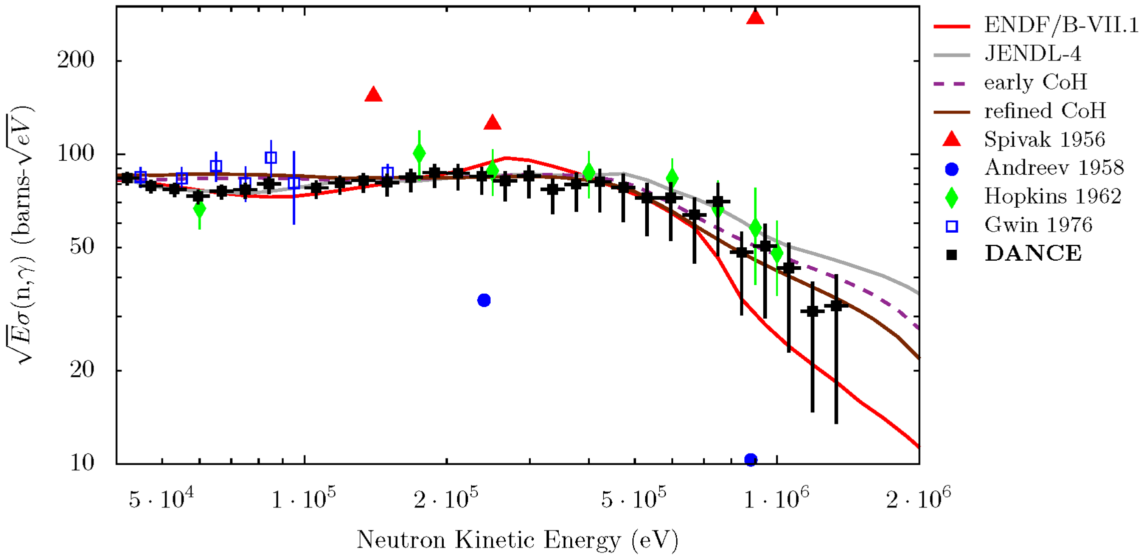

Figure 3. The neutron capture cross section for ^{239}Pu(n,γ) measured with DANCE compared to past measurements, evaluations, and reaction theory calculations. As the neutron energy grows above 200 keV, the uncertainties grow rapidly, limiting the ability of the measurement to distinguish between theoretical models.

ADVANCING EXISTING INSTRUMENTS AND DEVELOPING FUTURE MISSION

As the Chi-Nu effort completes the needed measurements needed for the prompt fission neutron spectra (PFNS) of ^{239}Pu and ^{235}U, an opportunity exists for other programs to take advantage of the previously made significant hardware and software investments. Beyond simply measuring the PFNS of minor actinides, the detector could be repurposed to measure inelastic neutron scattering cross sections. The lack of such data currently allows significant freedom in the evaluation process, making the integral measurements from experiments like Jezebel and FlatTop less stringent than they could be. The existing Chi-Nu scintillator and data acquisition instrumentation would be an ideal starting point for such a program. A concept to measure the inelastic cross section has been developed in collaboration with the University of California, Berkeley and is being disseminated through the inter-agency nuclear data call. These capabilities will directly support the interpretation of the NDSE diagnostic.

The Low-Energy NZ (LENZ) detector being developed at WNR measures charged particle reactions (neutron in, charged particle out). While exisiting programs are limited to WNR due to limitations of the current target at the Lujan Center, the new target will enable measurements with LENZ, that can address a range of issues from device diagnostics to

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[3] P.E. Koehler LA-UR-14-21466 (2014).

yield determinations. As a simple example, arsenic-73 and arsenic-74 are short-lived isotopes with positive Q-values for *(n,p)* and *(n,α)*. The charged particle reaction channels change the detected products from arsenic to other elements, complicating the radiochemical interpretation. With the new target, LENZ will be able to perform the measurement in the keV regime, where no measurements currently exist.

Current transport and simulation tools have well-known deficiencies in γ-ray production from neutron capture. For applications from radiation safety to radiation effects that depend on the spectral information, such deficiencies produce poorly quantified systematic uncertainties. DANCE has begun a campaign of neutron capture measurements focused on studying γ-emission following neutron capture. There is an opportunity to use this experimental information to develop the necessary underlying simulation tools for modeling and benchmarking key γ-ray channels to experimental data. These types of measurements offer the opportunity to expand the funding profile for nuclear science beyond Defense Programs in NNSA's NA-10.

TARGETED INVESTMENTS IN THE NEXT FIVE YEARS

The highest priority investment for the LANSCE nuclear science program is the replacement of the Lujan spallation target to ensure continued operation beyond 2020. The proposed redesign, with the enhancements for nuclear science, will allow next-generation measurements. This need has been recognized and the spallation target replacement is on track. Success of the nuclear science program depends on availability of well-characterized actinide and radioisotope samples from IPF, which will require actinide hot cells for processing. These co-located LANSCE capabilities will be vital to the success of DICER, radioisotope measurements with LENZ, and full exploitation of DANCE capabilities.

Prioritized, near-term needs for new investment in the LANSCE nuclear science program are the following.

1. Stabilization (with small growth) of the scientific and technical staff.
2. Increased investment in the DICER capability to expedite transition from development to first science measurements.
3. Realignment of nuclear physics flight paths at Lujan to optimize flux on sample.
4. Detector development for next-generation experiments.

A LONG-TERM OPPORTUNITY FOR ENHANCED IMPACT

The current suite of measurements at LANSCE faces a fundamental limitation: at some point, the isotopes of interest simply become too short lived to make into a sample and deliver to the experimental site. Another approach has been explored in the literature where the isotope of interest is created and measured essentially simultaneously. This would entail using a spallation neutron source as a continually refreshed neutron target. The basic idea is to have ~1 m ball of thermal neutrons in equilibrium. At the keV to MeV energies of interest for reaction measurements, thermal neutrons are effectively at rest. If a beam of radioisotopes passes through the neutron ball, reactions take place, but kinematics move all of the reaction products through the neutron ball and out the other side. The European nuclear physics community has been considering the physics of ion storage rings, with cycle frequencies on the order of MHz. Combining an ion storage ring with a spallation-generated neutron target could provide six orders of magnitude increase in radioactive beam luminosity. Such a facility would enable measurements not possible even at the Facility for Rare Isotope Beams (FRIB). A storage ring can perform very sensitive mass measurements, easily identifying reaction products in mass-changing reactions like *(n,γ)* and *(n,2n)*. This concept was set forward by Reifarth[4]. If implemented, this capability would directly address neutron-induced cross-sections. Existing, under construction, and planned radioactive beam facilities, including FRIB, are all designed to deliver intense beams of radioisotopes, but are not designed to measure neutron reaction cross sections. At best, they will offer the ability to measure underlying nuclear structure properties used by theoretical models to predict reaction cross sections. This concept is particularly well-suited to address questions of interest to NNSA

This concept would revolutionize neutron cross-section measurements. It would provide *direct, complete* (n,xn) and (n,γ) reaction cross sections. Experimental backgrounds limiting neutron capture measurements from 10 keV up to 2 MeV would be eliminated because of the new approach. New measurements of (n,2n) would be accessible in the fast neutron energy regime for isotopes with half-lives down to minutes. The questions this possibility raises are as tantalizing as the measurement revolution it offers. What new weapon design issues can we contemplate when all relevant cross sections are experimentally measured to better than 10%? Does this offer the possibility of determining all cross-section uncertainties for weapons and other applications? If a huge swath of margin is eliminated in design, how does that change how we perform our mission?

The concept requires three technical capabilities: a high-intensity proton spallation source, an isotope-separation OnLine (ISOL) rare isotope production target (these are typically driven by an intense proton accelerator), and an ion storage ring. Independently, these three pieces are understood. LANSCE provides the proton piece of the first two.

Given the sweeping scale of the new measurements this could offer, investigating what the impact of such a capability would be for LANL mission seems prudent. Further study is needed to understand how such a neutron ball traversed by ions might work. Such a facility would be decadal by nature, but small investments are needed to understand the challenge and possibilities of this concept.

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[4] R. Reifarth and Y.A. Litvinov, *Phys. Rev. AB,* **17,** 014701 (2014), R. Reifarth, et al., *Phys. Rev. AB,* **20,** 044701 (2017).

MATERIAL SCIENCE

The success of the science-based Stockpile Stewardship Program depends upon having confidence in the performance of aged materials and components manufactured using different processes. While “admiral tests,” such as subcritical experiments at the NNSS, will be a critical part of this program, an understanding of the underlying manufacturing science is needed to make the most efficient use of these expensive resources. The materials science program at LANSCE is dedicated to the characterization of material microstructure, residual stress, and texture in components made with new manufacturing methods and in aging materials. The following two priorities for advances in material characterization capability at LANSCE will enable these measurements.

1. *Turnkey classified residual stress and texture measurements.*
2. *A dedicated long-term aging-effects instrument.*

TURNKEY CLASSIFIED RESIDUAL STRESS AND TEXTURE MEASUREMENTS

We propose an instrument in one of the existing flight paths be dedicated to spatially resolved measurements of residual stress and texture in classified components. Over the last 15 years, roughly two residual stress measurements on classified parts have been required per year, including measurements on beryllium welds, uranium shells for the hydro program, gas bottles, and most recently, for additively manufactured components. Given the upcoming life extension programs, the joint technology demonstrator, and potential new systems, we believe that the demand for residual stress measurements will continue to grow. Texture measurements in components made from anisotropic materials such as beryllium, uranium, and uranium alloys are especially important as is the ability to measure the residual stress and texture under the range of environments that spans the STS environment.

While the current Spectrometer for Materials Research at Temperature and Stress (SMARTS) instrument provides world-class residual stress measurements, a dedicated instrument would enable significant improvements. The SMARTS design was compromised to allow for both in situ measurements under extreme environments and residual stress measurements. The open hutch, built to accommodate the complex and large sample environments, results in elevated background levels, which increase the time required to perform any given experiment. Switching between spatially resolved modes requires that the radial collimators be reconfigured, a time-consuming process that requires recalibrating the instrument.

There is no capability worldwide to perform spatially resolved texture measurements at depth in components more complicated than a plate. Destructive testing (component sectioning) must be performed to make such measurements, which prevents any subsequent performance testing of the component. Since many of the components of interest to NNSA are classified, the ability to easily perform classified experiments without the need for 24/7 attendance would provide a significant benefit. Figure 4 shows a map of the thermal expansion of a hydro-formed uranium hemisphere that was calculated for spatially resolved texture measurements on HIPPO. One can see that the thermal expansion varies by ~30%, which will cause large distortions and even plastic deformation with relatively small changes in temperature.

A modest equipment investment would be necessary to implement the proposed capability. The least expensive option would be to develop the current flight path 2 (SMARTS) beamline as it already has the detectors and neutron guide. This comes, however, at the cost of losing the capability for in situ measurements at temperature and stress, etc. Both the dormant flight path 1 (Neutron Powder Diffractometer, NPDF) and flight path 16 (High-resolution Spectrometer, PHAROS) offer space for a dedicated spatially resolved instrument without impacting current capabilities. We estimate the cost of such an instrument at ~$3M plus the cost of a classified environment. Use of these flight paths depends upon leaving the existing mercury shutter systems intact.

A DEDICATED LONG-TERM AGING-EFFECTS INSTRUMENT

An instrument dedicated to understanding the effect of long-term aging on materials such as PuGa alloys would be of great benefit to the weapons program. This capability would be well suited to the flight path 1 (NPDF) beamline and could be realized in two steps. Measurements in relatively simple environments could begin almost immediately, with multi-modal measurements in complicated sample environments being realized with modest investment.

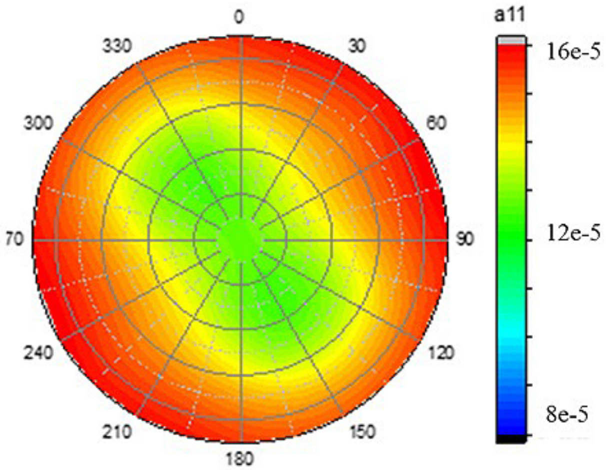

Figure 4. Coefficient of thermal expansion as a function of position on a formed uranium hemisphere.

Figure 5 shows a Williamson-Hall (W-H) plot made using high resolution diffraction data collected on SMARTS on a sample of aged (4 months below 50 K) Pu-2wt%Ga and on the same sample after annealing for 48 hours at 673 K. The W-H plots allow one to make a semi-quantitative determination of the dislocation density, which in this case is ~5x greater in the aged material than in the same sample after annealing. A dedicated aging instrument would enable in situ monitoring of the evolution of damage during the extended aging time (months) and long annealing period.

Continued confidence in the aging stockpile requires understanding how materials respond to time in service in different environments. Environments could include cycling between non-ambient temperatures (above and below room temperature), chemical environments, ionizing radiation, or stress. Materials such as Pu alloys, high explosives, uranium, and uranium alloys are of concern. Program areas outside of the NNSA mission space have similar measurement needs. Recent emphasis on materials in "harsh environments" suggests long-time aging measurements on high temperature superalloys in supercritical steam are important, for instance for lifetime assessment of heat exchangers in power plants. Additive manufacturing of metal results in materials with metastable (high energy) microstructures that will evolve at elevated temperature. These represent areas of potential program development for LANL as a whole.

Aging measurements are currently performed by repeatedly placing and removing the sample in the sample environment, in the beam position, over the desired aging period. This introduces both risk and uncertainty. The sample is often required to be held at an extreme temperature. Moving such sample environment is difficult, and disturbing the environment risks the integrity of the experiment, potentially after months of intermittent data collection. Lattice parameter measurements with sufficient accuracy to monitor changes in stress and/or solute chemistry require the sample to be positioned with sub-mm accuracy, which is very difficult inside an environmental chamber. This can be mitigated by attaching a calibrant to the sample in the environment, but the calibrant must be firmly attached to the sample and the calibrant will be exposed to the environment. These issues add considerable uncertainty to measurements attempting to access changes in microstructure— for instance, changes in lattice parameter of 100 ppm—that may occur over time in extreme environments.

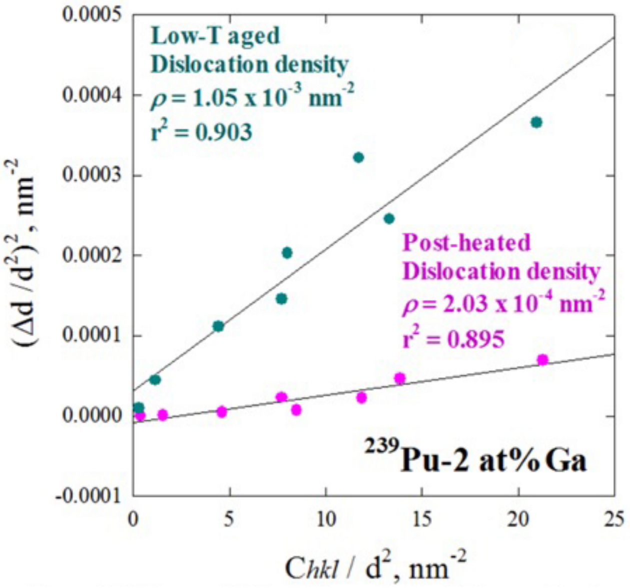

Figure 5. Williamson-Hall plot from a Pu-2wt%Ga sample after aging at <50 K for four months (green) and subsequent annealing (pink) at 673 K for 48 hours. The reduced slope indicated 5x reduction of the dislocation density in the material.

The ideal solution is to leave the environmental chamber intact at the measurement position for the duration of aging. This would remove both the risk of moving the equipment and of changing the instrument calibration. This requires that the instrument be dedicated to these measurements.

Flight path 1 (NPDF) is currently dormant and could be operated in this mode with no loss of capacity, and initially, very little investment. The ability to carry out long-term neutron scattering measurements over many weeks would be unique in the world. This would require a small investment to increase the operating budgets for

Physics and Materials Science and Technology divisions, by about 0.3 FTE each to provide technical and scientific support. This would allow measurements on Pu or U6Nb at temperature.

Significant advances in scope could be realized by developing multi-modal measurement capabilities under relevant environments for about $1.5M. This investment includes extreme temperature (10K-1200 K) and chemical exposure sample environments, small-angle scattering capability, and a positioning system. Further improvement in time resolution could be realized with the installation of a neutron guide system on flight path 1 (NPDF), which would lead to a 5-fold increase in the neutron flux.

ISOTOPE PRODUCTION AT LANSCE

The Isotope Production Program has been producing radioisotopes at LANSCE for more than four decades to meet domestic and international need for these products. Historical production activities used the 800-MeV proton beam at the beam stop at Area A, but this activity was discontinued in the late 1990s. While dispensing of isotope inventory and processing of irradiated targets continued at LANL, there was a clear need to reestablish a dedicated irradiation facility to produce isotopes that were otherwise commercially unavailable or difficult to produce in the required quantities. A multi-year effort was undertaken to construct the Isotope Production Facility, which was commissioned in 2004. IPF was built to accept 100-MeV proton beam, which is diverted from the main axis at the transition region after the 201 linac, taking advantage of the higher purity of isotopes that can be produced at this intermediate energy.

The isotope program’s main focus today is to produce isotopes for medical use, primarily strontium-82 for cardiac imaging and germanium-68 for cancer and other disease imaging. Isotopes produced at LANL impact tens of thousands of patients each month. The program makes a variety of other isotopes for medical, industrial, and environmental applications and nuclear physics research, currently averaging more than 200 shipments a year to customers around the world. In 2009, the isotope program moved into the U.S. Department of Energy, Office of Science, Office of Nuclear Physics (NP). The sponsor directs a robust production and research mission to meet the needs of the isotope user community. While IPF is not a user facility, research is very important to the sponsor and can be conducted at IPF as long as it has no negative impact to the production mission.

To maintain LANL’s position of leadership in domestic accelerator-based isotope production, to meet clinical needs for emerging medical isotopes, and to continue a strong research program into developing new isotope products for the future, the Isotope Production Program has several priorities for investment.

PROCESSING CAPABILITY FOR ALPHA-EMITTING ISOTOPES

LANL's Isotope Production Program has begun to explore accelerator-based production of actinium-225, an isotope showing great promise for cancer therapy. While small clinical trials indicate great potential, broad clinical use of this isotope will not become a reality without a significant increase in available and reliable supply. To address this need, NP initiated a project in 2015 between LANL, Brookhaven National Laboratory, and Oak Ridge National Laboratory to pursue reliable production. LANL has demonstrated capability to produce > 100 mCi amounts through irradiation of thorium targets at IPF. Although some technical hurdles remain, further scale-up of the irradiation to generate >1 Curie amounts in a single target at IPF is feasible. Processing these targets to isolate the Ac-225 product remains a significant challenge. LANL has no facility with appropriate infrastructure capable of conducting the separation of the Ac-225 from the irradiated Th target. The high-level requirement is a robust hot cell bank, with substantial shielding as well as appropriate containment for alpha emitters, located in a facility with authorization basis to work with > hazard category 3 levels of radioactive materials. The facility must have associated radiological laboratory space to support analytical and shipping work. The facility must meet the quality requirements of the U.S. Food and Drug Administration for the production of a product intended for eventual use in humans.

The Area A hot cells are the only currently available option to pursue this radiochemical processing at LANL. The existing hot cell bank has been out of service for over two decades, but the general infrastructure would be sufficient. Establishing processing capability at LANL, coupled in close proximity to the robust irradiation capability of IPF, would establish LANL as a world leader for the production of Ac-225. Preliminary estimates to return the hot cells to service are on the order of $20M. A proposal will shortly be submitted to NP to begin engineering design of the ventilation and other infrastructure upgrades that will be required for the Area A hot cells, with a refined cost estimate for the work.

The age of the Area A hot cells and their current condition may indicate that a new hot cell capability may be a more cost-effective solution than the refurbishment of the existing hot cells. Therefore, the establishment of a stand-alone hot cell capability will also be explored. A follow-on proposal to begin refurbishment or new construction work will be submitted after the costs are better defined and on a timeline matching customer demand. ***The highest priority need for the Isotope Production Program is to obtain hot cell space appropriate for the processing of irradiated thorium targets from IPF for the isolation of Curie scale quantities of Ac-225.***

INCREASED CURRENT FOR ENHANCED PRODUCTION

The second priority would be to increase the current that IPF can accept for routine and research irradiations. Higher current enables increased production capacity. At this time, IPF operates at 230 μA for routine irradiations, which is driven primarily by limitations on the target design for a standard RbCl target irradiated to produce Sr-82. The recently completed Accelerator Improvement Project at IPF has added the ability to change the aperture size of the beam strike area and enabled more complex raster patterns that are anticipated to allow these targets to withstand much higher currents. A recent demonstration experiment successfully exposed RbCl targets to 320 µA of beam, with a corresponding 40% increase in production.

In the short term, the focus will be on removing administrative limits to increase the maximum possible beam current from 360 to 450 μA. This requires a change to the current limiter settings that should be relatively straightforward to accomplish with minimum investment. In the longer term, the program requires ~1 mA current to IPF. This would require an assessment of the adequacy of the target cooling system. A request has been submitted to DOE NP to support a preliminary analysis of the cooling water system to determine the limitations of the current framework. Modeling will be required to understand if boiling is occurring in the cooling water channels and to inform an improved design of the cooling water system. This would require a modest investment (~$400K) in modeling infrastructure and a beam window and target cooling test laboratory for the offline study of thermal performance and boiling. Further testing and demonstration would be required to ensure that high current operation is transparent to other users.

ADDITIONAL HOT CELL PROCESSING CAPABILITY

The program will continue to produce isotopes for nuclear data and to perform R&D into the production of other alpha-emitting isotopes for medical applications. In the past, the isotope program has produced isotopes including Lu-173 and As-73 at IPF and manufactured targets from these materials to be used for neutron cross-section measurements at DANCE. While some isotopes can be handled at the existing processing facility at TA-48, additional hot cell and radiological hood space is needed for the handling of irradiated actinide targets from IPF and the fabrication of actinide or other radioactive targets for other end users. In particular, this capability would benefit proposed nuclear physics experiments at LENZ (As-73,74) and DICER (Y-88), where IPF is uniquely suited to make large quantities of these short-lived isotopes. A separate hot cell would allow a larger suite of isotopes to be produced and allow higher activity targets of actinides to be safely handled. Procurement of a standalone hot cell and associated shielded hood is ~$400K (unburdened). Ventilation to support the hot cell could cost an additional ~$1M, depending on location and the level of existing infrastructure in the space. An alternatives analysis was performed by the program in FY17, identifying several potential locations for the siting of such a hot cell and the pros and cons of each location. A final decision by management for space is still pending. Support would be needed to procure and install the hot cell, hood, and associated ventilation once a final determination for location is made. This activity could be combined with the alpha processing capability depending on location.

RETURN OF SPALLATION PRODUCTION CAPABILITY TO AREA A

A long-term goal is to reestablish spallation production capability at Area A. This capability is required to produce certain radionuclides that are not accessible at the lower energy proton irradiation facilities (100 MeV for IPF or 200 MeV at Brookhaven Linac Isotope Producer (BLIP), and to increase capacity for high priority isotopes such as Ac-225. In addition to re-establishing beam delivery to Area A, this would require a new target irradiation station to be built at Area A to accept the high energy, high current beam, estimated in the $20-30M range.

ESTABLISH A MATERIALS SURVIVABILITY LABORATORY

Material response to radiation insults is an area of interest to NNSA, the nuclear energy program, and electronics manufacturers.

1. NNSA's interests include material response to hostile environments, changes in material performance due to radiation damage, radiation effects on electronics, and the effects of self-induced radiation damage in plutonium. A more detailed description of NNSA needs is given in the classified appendix.
2. Fast nuclear reactors produce less high-level waste while more efficiently burning nuclear fuel. LANSCE was the proposed site for the Material Test Station, which would have qualified fuels for fast reactors in a spallation produced fast neutron spectrum, similar to that experienced in a fast reactor.
3. Electronics deployed in space are subject to proton irradiation in earth orbit and in deep space. Understanding and mitigating the effects of this radiation is necessary to ensure successful space-based missions.

The establishment of a Materials Survivability Laboratory at LANSCE would address all three needs and could be implemented in a phased approach over a 10-year period. Area A at LANSCE is a natural location for such a facility. The accelerator has the ability to deliver 1 MW of 800-MeV protons to the area, there is 10 MW of electrical power available, 30,000 ft^2 of floor space, and two unused hot cells in Area A. We propose a three-stage development of the Materials Survivability Laboratory, with the stages defined by the beam power requirements and facility complexity.

1. *Stage 1.* Low-power proton source (LPPS) for space-electronics irradiation. This would require 100 nA of power delivered to Area A with a small flight path, with minimal shielding requirements.
2. *Stage 2.* Moderate-power facility with neutron spallation target to study plutonium aging. This would require 100 μA of beam power, a neutron spallation target, and basic in situ diagnostic capability.

3. *Stage 3.* High-power facility for testing nuclear fuels. This facility would also be capable of producing Ac-225 in clinincally relevant quantities. This would require 1 mA of beam power delivered to Area A and a substantial amount of shielding.

LOW-POWER PROTON SOURCE

The LPPS would serve the space electronics community for testing the susceptibility of satellite and extra-terrestrial components to proton-induced single-event upsets in the same way that WNR serves the aviation electronics industry using neutrons. Potential customers for such a facility are nonproliferation programs in NNSA's NA-22, the National Reconnaissance Office (NRO), NASA, National Oceanic and Atmospheric Administration (NOAA), and industry. The LPPS would supplant a capability lost to the space electronics community with the recent closure (in 2014) of the Indiana University Cyclotron Facility's Radiation Effects Research Station[5]. That facility delivered 30- to 200-MeV protons with 50-nA beam current and beam spot size ranging from 2 to 30 cm in diameter. The Area A facility could deliver 100 nA of 800-MeV protons to users. With some modification of the switchyard beamline, beam energies as low as 200 MeV could be delivered to Area A, without any impact on beam delivery to existing LANSCE facilities. The 120-Hz proton beam repetition rate would need to be shared between IPF and Area A, with IPF receiving up to 30 Hz (limited by the IPF fast kicker) and Area A receiving the remainder of the pulses (at

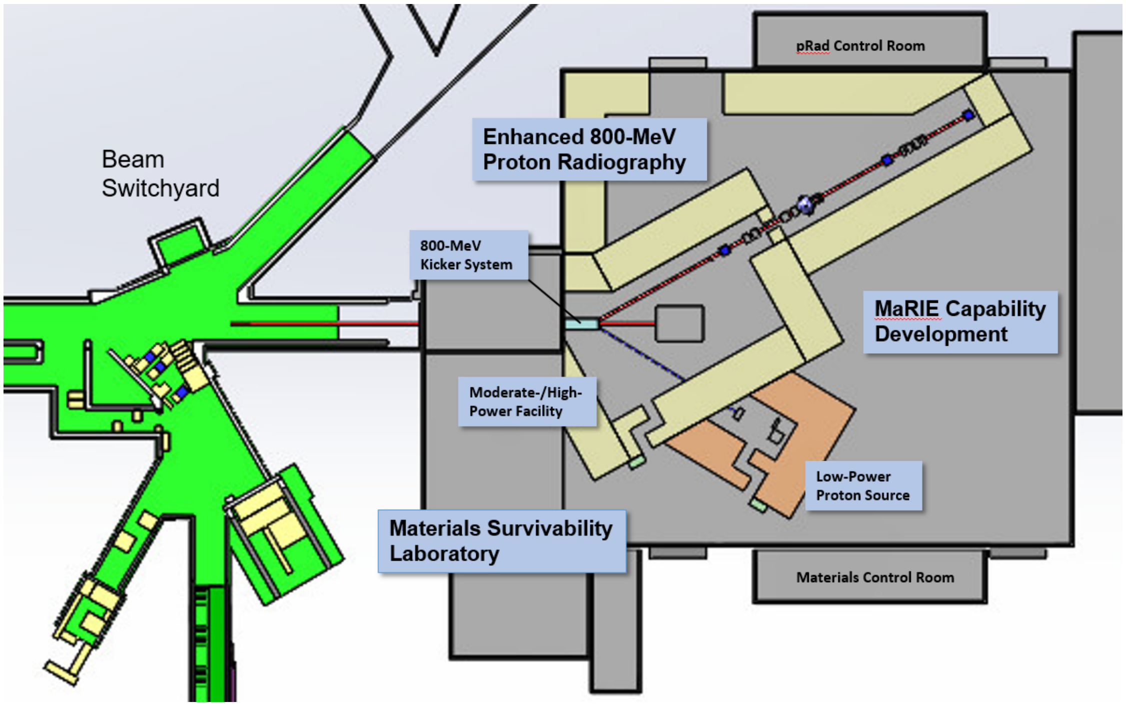

Figure 6. Possible layout of Area A.

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[5] B. Von Przewoski, et al., *MRS Symp. Proc.* **851** NN7.10.1 (2005).

least 90 Hz). There is substantial interest within the space radiation effects community for the realization of the LPPS. Both Intel and SpaceX have written letters of support for the facility, each predicting hundreds of hours per year of beam time use.

MODERATE-POWER NEUTRON SPALLATION SOURCE

The moderate-power station would be used for testing the survivability of materials to intense neutron radiation, in particular to study fission-induced damage and heating in fissile materials. This would primarily serve the weapons community. A proton-driven spallation target would create an intense source of pulsed, moderated neutrons, with pulse widths tunable from sub-μs to 625 μs. A proton beam current of up to 100 μA will produce sufficiently intense neutron pulses for this mission. Further details are provided in a classified addendum to this report.

HIGH-POWER FAST NEUTRON SPALLATION SOURCE

On a decadal time scale, a third, high-power irradiation station is envisaged that can serve multiple missions from medical isotope production to testing nuclear fuel for the next generation of fast reactors. This station would use the full 1-mA capability of the LANSCE linac, delivered to a spallation target to produce an intense source of neutrons exceeding 10^{14} n cm^{-2} s^{-1} neutron flux. The original Los Alamos Meson Physics Facility A6 target provided the medical community with spallation-produced isotopes for decades. Re-establishment of an 800-MeV isotope production capability would complement the IPF capability, delivering different isotopes, including Ac-225. Such a target could even deliver a significant fraction of the current U.S. demand for Mo-99, the most commonly used medical isotope[6]. Spallation sources are well suited for irradiation testing of first-wall materials for fusion systems[7]. At 1 mA of beam current this facility would provide a testing capability for the fusion materials community, delivering a damage rate in iron up to 10 atomic displacements per year concurrent with prototypic helium production rates.
Area A is well suited for housing an accelerator-driven neutron source for small-scale fast reactor fuel testing[8]. Multiple fuel rodlets up to 20 cm in length can be irradiated simultaneously in a fast neutron spectrum approaching 10^{15} n cm^{-2} s^{-1}.

Beam delivery to Area A will require an update of the LANSCE Safety Assessment Document and the Accelerator Safety Envelope and approval by the Los Alamos Field Office.

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[6] E.J. Pitcher, *Proceedings of the International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators 2009, Vienna*, LA-UR-09-04276.

[7] E.J. Pitcher, C.T. Kelsey IV, S.A. Maloy, *Fusion Science and Technology* **62**, 289-294 (2012).

[8] E.J. Pitcher, *Journal of Nuclear Materials* **377** 17-20 (2008).

ULTRACOLD NEUTRON FACILITY

The recent upgrade of the LANL Ultracold Neutron Facility more than tripled the previous output (Figure 6) and has created an opportunity for world-class precision neutron measurements to probe the fundamental symmetries of nature[9]. Over the next 10 years we propose to develop, build, and operate three next-generation experiments to:

1. search for the neutron permanent electric dipole moment (EDM) at the level of 10^{-27} e·cm (a 10-fold improvement over the current state of the art);
2. measure the beta asymmetry in polarized neutron decay at the 0.2% level (3-fold improvement over the state of the art); and
3. measure the neutron lifetime to below 0.1 second precision after completing running of the current UCNt experiment.

For these efforts to remain competitive we will continue to improve the ultracold neutron source and facility.

While the Standard Model (SM) of fundamental interactions provides a remarkably good description of nature up to energies of order 200 GeV, fundamental observations such as the matter-antimatter asymmetry and dark matter remain unexplained. These observations and theoretical considerations point to the existence of new interactions and degrees of freedom. In light of null results from searches for new physics at the Large Hadron Collider, low-energy precision measurements provide important input to the symmetry structure of the universe beyond the SM (BSM). In this context, neutron physics offers opportunities to probe new interactions. The above-mentioned program is aligned with the Nuclear Science Advisory Committee *2015 Long Range Plan for Nuclear Science*[10], which includes pursuing a "targeted program of fundamental symmetries and neutrino research that opens new doors to physics beyond the Standard Model."

NEUTRON ELECTRIC-DIPOLE MOMENT EXPERIMENT

Searches for a non-zero neutron electric-dipole moment (EDM) probe new sources of time reversal symmetry violation and may give insight into the matter-antimatter asymmetry in the universe. The current upper limit, set by an experiment performed more than a decade ago at the Institut Laue Langevin turbine ultracold neutron source, is $d_n < 3.0 \times 10^{-26}$ e·cm (90% C.L.)[11]. Further improvement in the sensitivity of experiments has been hampered by the lack of sufficiently strong sources of ultracold neutrons. It has been shown that systematic effects can be controlled to the level necessary. Our recent work[10] has shown

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[9] T.M. Ito, et al., to appear in *Phys. Rev. C,* arXiv:1710.05182 (2018).

[10] A. Aprahamian, et al., "*Reaching for the horizon: The 2015 long range plan for nuclear science*" (2015).

[11] C.A. Baker, et al., *Phys. Rev. Lett.* **97**, 131801 (2006).

that one can perform a room temperature neutron EDM experiment (with LANL's ultracold neutron source) based on Ramsey's separated oscillatory field method with a one-standard-deviation sensitivity of $\sigma(d_n)=3\times10^{-27}$ e·cm with a running time of five calendar years. The LANL neutron EDM collaboration has recently constructed a demonstration apparatus with which a neutron magnetic resonance measurement based on Ramsey's separated oscillatory field method was demonstrated.

UCNA+ EXPERIMENT

In the UCNA+ experiment, we propose to develop the highest precision ultracold neutron-based measurement of the nucleon axial charge g_A. This combined with the measurement of the neutron lifetime described below will allow an improved determination of V_{ud} without the controversial nuclear corrections required for the analysis of 0+_>0+ nuclear beta decay transitions. Several worldwide efforts aim to measure g_A to increased precision over the state of the art established by PERKEO II[12] and LANL's UCNA[13]. LANL's effort stands out because all other current efforts plan to use cold neutron beams and thus share many inherent systematic uncertainties.

The previous UCNA experiment was limited by the lack of statistics (due to the relatively low density of available ultracold neutrons) and by systematic uncertainties caused by the nonlinear energy response of the beta particle detector systems, which consisted of thin-windowed multiwire proportional chambers in front of plastic scintillators. With the upgraded ultracold neutron source, we have measured a total beta decay rate of 250 Hz in the UCNA decay volume, a nearly 10-fold improvement over the typical decay rates observed during the UCNA run. This improved rate, which is comparable to that of cold neutron beam based experiments, will provide sufficient statistics. Since the construction of UCNA in 2005, particle detector technologies have advanced, enabling us to develop new electron detector systems, with well-characterized energy response. We are investigating the use of magnetic field insensitive detectors such as silicon photomultipliers (SiPMs) to eliminate the light transfer problems of the UCNA detector system.

NEUTRON LIFETIME EXPERIMENT

With the publication of the 2016 data set the UCNt experiment has reached the precision of the most sensitive measurement of the neutron lifetime[14] this year the statistical limit has been pushed down to below 0.3 seconds and it currently looks like the experiment has three more years of running to reach a total uncertainty of less than 0.2 seconds. This work is leading to a concept for a new apparatus that can reach a precision below 0.1 seconds; the development of this experiment will take several years after the completion of UCNt.

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[12] D. Mund, et al., *Phys. Rev. Lett.*, **110**, 172502 (2013).

[13] B. Plaster, et al., *Phys. Rev. C* **86**, 055501 (2012) and M.A.P. Brown, et al., arXiv:1712.00884

[14] R. W. Patti, et al., to appear in Science, (2018) arXiv:1707.01817

NEUTRON SOURCE DEVELOPMENT

All of the proposed experiments are rate limited and benefit from continued improvements to the ultracold neutron source density and beam availability. Ultracold neutron density in the source and in experiments can be increased by more intense proton beam delivery (the average current is limited to 10 uA). This can be achieved by increasing the frequency of proton pulses to the target above the current 20 Hz. This will require some accelerator R&D and the addition of a fast kicker magnet. Additionally, the tungsten target may need redesign. The installation of a shield wall between pRad and UCN beamlines will increase overall statistics in experiments by allowing for daytime running of UCN. This could be further improved with the development of a fast accelerator tune change between the beamlines. These improvements would lead to a factor of ~2 increase in statistics. Additional small gains may be possible by redesigning the current 10-uA ultracold neutron source, but to make substantial increases in UCN production a higher current deuterium or liquid helium source is needed[15].

There are synergies between these experiments and others currently under development by the DOE and National Science Foundation. Carrying out a room temperature measurement of the neutron EDM will facilitate development of techniques, expertise, and scientists needed to successfully complete the Spallation Neutron Source (SNS)-based neutron EDM project. Both the efforts of the beam lifetime experiment (cold neutrons) and UCNt (ultracold neutrons) are needed to move forward on the neutron lifetime measurement; each having significantly different systematics errors. The measurements of UCNA+ and Nab can each be combined with the neutron lifetime to calculate a value for the quark mixing matrix element V_{ud}, but they have very different systematic errors, which is valuable in gaining confidence in high precision beta decay measurements already demonstrated by the pairing of PERKEO II and UCNA.

The current plan for carrying out these three experiments will take us beyond the next 10 years. The current UCNt experiment will run for the next three years studying systematics and gathering statistics. After this development, funding, construction and running of a next-generation neutron lifetime experiment will continue past the end of this 10-year plan. As currently envisioned, UCNA+ will require a year of R&D and construction followed by two years of commissioning and running. After this, other polarized beta decay correlations may be pursued. The capital investment is small and R&D has already begun, so UCNA+ could be completed in the first five years. The building and commissioning of an EDM experiment will take three years. An additional five years of data taking is required to achieve our sensitivity goals.

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[15] A.R. Young, et al. *Physics Procedia* **51** (2014).

In addition to our three main thrusts, there are other efforts that make use of the facility; these activities are sponsored by external collaborators. The SNS neutron EDM program has used the west beamline to perform R&D on its cryogenic storage cell and will continue this effort for several years. The detectors and data acquisition system for the SNS Nab experiment continue to be developed using the large spectrometer. Other smaller efforts are done parasitically while the main experiments are running with minimal impact on our main efforts: fission, gravity, dark matter, detector development, nuclear beta spectroscopy, and quantum information science.

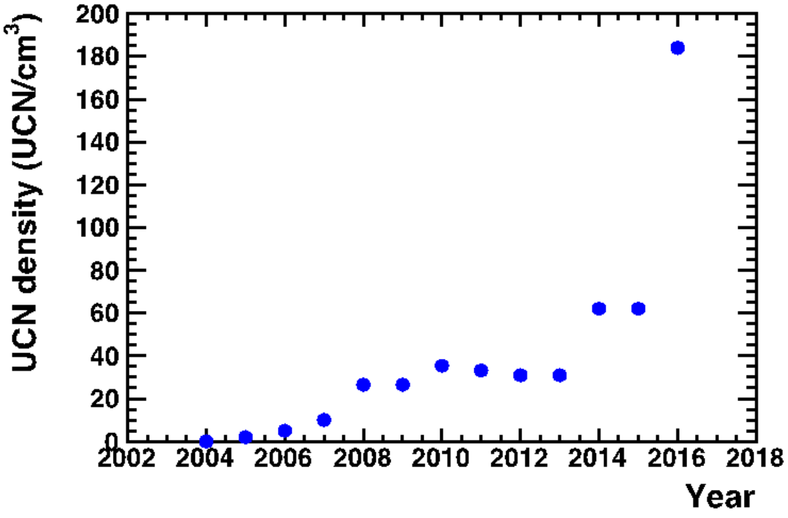

Figure 6. The density of ultracold neutrons produced by the LANL Ultracold Neutron Facility from 2004 to 2016.

ACCELERATOR IMPROVEMENTS

The LANSCE accelerator was commissioned in 1972. Despite the age of the accelerator it is still one of the more powerful proton linacs in the world, capable of generating 1 MW of power in an 800-MeV proton beam. The replacement value of the linac is estimated to be over $1B and for many years required maintenance had been deferred. A LANSCE Risk Mitigation (LRM) activity was undertaken, beginning in 2009 and ending in 2015. Roughly $140M was spent during this period to address long-term maintenance issues and ensure that the accelerator could, with continued investment, continue to operate into the foreseeable future. The LRM activity replaced three of the four high-power RF amplifiers in the 201-MHz drift-tube linac, purchased replacement klystrons for the 805-MHz coupled-cell linac, made progress on the upgrade of the aging controls and diagnostics systems, installed a modern timing system, implemented a digital low-level RF system for the drift-tube linac, upgraded many magnet power supplies and vacuum systems, and generally replaced obsolete parts with modern components whenever possible. The completion of the

LRM activity enabled the return to 120-Hz operation, effectively doubling the beam current and provided significantly more stable operations.

To achieve LANSCE's mission it is imperative that the accelerator be able to run reliably, with high availability (to enable robust experiment scheduling) and stable beams (to ensure stable experimental conditions). To accomplish these goals the top three priorities for the accelerator are to

1. *modernize the diagnostic and control systems,*
2. *improve the performance and lifetime of the H- source, and*
3. *complete the installation of the digital low-level RF (dLLRF) system.*

Longer term prioritized goals are to

1. *replace the 201-MHz Module 1 RF system with its modern counterpart,*
2. *reestablish beam delivery to Area A,*
3. *improve the performance of the proton storage ring,*
4. *replace the Cockroft-Walton with a radio-frequency quadrupole for the H+ source, and*
5. *upgrade the water distribution system on the remaining three drift-tube linacs (DTLs).*

These are discussed in more detail below.

MODERNIZE THE DIAGNOSTIC AND CONTROL SYSTEMS

The present LANSCE linac diagnostics and control system combines obsolete 1980's computer technology and 1960's in-house fabricated remote indication and control equipment, with a partially-implemented, modern Experimental Physics and Industrial Control System (EPICS)-based control system and new beam diagnostics. Components of these systems include the beam position and phase measurement (BPPM) system, industrial controls (hardware and software), the timing system, the accelerator fast-protect system, the timed-data system, and beam measurement devices such as wire scanners, harps, and emittance gear. Many of these systems communicate using an obsolete computer network system with insufficient bandwidth to handle modern data transfer needs. Modernization of the diagnostics and control system with modern computer technology and modular, scalable, and upgradable commercial off-the-shelf components will allow for a flexible event-based timing system and implement a high-speed, high-capacity network infrastructure.

Currently, machine tuning can take days and some problems have taken weeks to diagnose and correct. Interactive machine simulation codes based on fast GPU processors have been developed that should enable a more automated approach to tuning and diagnosis. The upgrade of the diagnostics and control system will enable us to further exploit this capability. The goal is to combine the upgraded diagnostic and control system with procedures that automate many processes to enhance overall beam tuning and control. These procedures will incorporate machine-learning algorithms to enhance complex machine tuning ordinarily carried out by experts, to enable a robust and fast accelerator tuning.

To date the total investment in controls and diagnostics upgrades is $29M. The estimated remaining cost to complete is $12.5M. Of the estimated $12.5M remaining cost, $7.2M is scope beyond what was planned during the LRM activity. The estimated time to complete all remaining tasks is 2.5 to 4 years based on funding profile and ability to execute scope without significantly impacting the LANSCE operating schedule.

IMPROVEMENTS TO THE H^- SOURCE AND MULTI-BEAM OPERATIONS

The current H- source has a lifetime of roughly 28 days delivering 16-mA, 350-ns pulses at 120 Hz. Other facilities, with more modern sources, have demonstrated longer source lifetimes with higher currents for long-pulse operation (high duty factor). The first need for increased current is the neutron diffraction work at the Lujan Center. The new target (2020 installation) will result in a 25% reduction in neutron flux to the material science flight paths. An increase in the H- current can compensate for this reduction, restoring (and even improving upon) the current capability of the material science program. Farther into the future, a second axis or an achromatic lens at pRad will need increased current to obtain optimal performance. At UCN and WNR an increase in current will lead to a proportional reduction in the time needed to complete an experiment.

Incremental increases in performance may be possible by modifying the existing source, however, significant increases in output current and source lifetime will require a new type of source. One alternative is the Spallation Neutron Source external antenna, RF-driven, multi-cusp, cesium-enhanced H- ion source. This source has demonstrated a lifetime in excess of 50 days and output current to ground of 40 mA. It is estimated that design, fabrication, and implementation of a new H^- source will range from $500K-$1,000K.

Another approach to increasing beam current is to install a de-buncher cavity in the H^- transport line upstream of the main buncher. Currently, the two LANSCE beams (H+ and H-) are combined in a common transport system upstream of the linac, which contains a main buncher cavity, of which the phase and amplitude settings are a compromise for the two beams. Installation of a de-buncher cavity in the H^- transport line upstream of the main buncher would decouple the two-beam bunching and capture. Implementation could improve the peak beam current delivered to WNR and pRad by up to 50%. This requires fabrication and installation of a compact 201.25-MHz, quarter-wave cavity and procurement and installation of a low-power RF system (including controls). The estimated cost is $400K. Additional improvements in multi-beam operations can be realized by improving the H^- chopper rise time and phase control at an estimated cost of $100K.

COMPLETE THE INSTALLATION OF THE DIGITAL LOW-LEVEL RF SYSTEM

There are two major RF systems powering the 800-MeV proton linac, one operating at 201.25 MHz and one at the fourth harmonic, 805 MHz. The 201.25-MHz system powers the four DTL accelerating structures (RF Modules 1-4), while the 805-MHz system powers the remaining 104 CCL accelerating structures (RF Modules 5-48). In the DTL, each accelerating structure is driven by its own high-power RF source. In the CCL, four accelerating structures are powered by a single klystron up to a beam energy of 211 MeV (RF Module 12). Beyond this point in the CCL the accelerating cavity length is doubled, requiring a single klystron RF source per two CCL cavities up to 800 MeV (RF Modules 13-48). All of these high-power RF sources require stable phase and amplitude control (typically < 0.1° in phase and < 0.1% in amplitude) to maintain low beam losses in the structures for hands-on maintainability. In addition, such stability must be accomplished in a dynamic environment where various beam patterns create time-varying loads that the RF system must accommodate on a pulse-by-pulse basis, while slow variations, such as temperature, that impact the structure tuning must be also be corrected. Control of the response of the high-power RF systems to these time-varying loads is achieved through the low-level RF (LLRF) system, which uses appropriately placed RF sensors throughout the linac to generate signals used to make the adjustments necessary to maintain the RF phases and amplitudes to within the desired tolerances.

As with many other major systems on the linac, the LLRF system was designed, constructed, and implemented decades ago utilizing analog circuitry and mechanical actuators. While this was a reasonable solution for the original system, today it is obsolete, difficult to maintain, and lacking features such as integration with a modern control system such as EPICS and the bandwidth necessary to fully exploit the potential of the machine. Advanced LLRF systems based on modern digital technology are now used throughout the world. Here at LANSCE we have made some progress implementing a digital LLRF (dLLRF) system for the entire linac. To date, the dLLRF system has been implemented on three of the four 201.25 MHz DTLs, and a system has been designed and tested on two of the 40 805-MHz CCL modules. Full implementation of the dLLRF system will require an additional $3.76M spread over four years.

REPLACE THE 201-MHZ MODULE 1 RF SYSTEM WITH ITS MODERN COUNTERPART

As described earlier, the DTL consist of four accelerating structures, each with its own high-power RF source (Modules 1-4). Modules 2 through 4 have each had their high-power RF systems replaced with new, diacrode-based systems as part of the LANSCE-LRM project. Module 1 is still operating with the original nearly 45-year-old system and needs to be updated. Although the RF power requirement for Module 1 is lower than that of the other

DTL RF modules, this improvement will make Module 1 more reliable, similar to Modules 2-4, and fully compatible with the improved control and dLLRF systems. The modification would take approximately four months to complete, i.e., during the length of a single extended maintenance period, and cost $600k.

RE-ESTABLISH BEAM DELIVERY TO AREA A

The LPPS , the Materials Survivability Laboratory, and a proton radiography second station all require the delivery of H+ beam to Area A. In the case of LPPS, the beam energy should be tunable from 200 MeV to 800 MeV. This requires beam sharing with the IPF, the only other user of the H+ beam. A pulsed kicker magnet system driven by a pulsed modulator was designed and built. However, since the IPF is the sole user of the H^+ beam, this system was never fully completed or implemented. (The modulator is locked out and the kicker magnet is presently operated in dc mode, powered with a dc power supply.)

To deliver beam to Area A the stainless-steel kicker vacuum vessel needs to be replaced with a non-metallic vessel (to eliminate unacceptable eddy currents). A possible solution is the use of a fused quartz vacuum vessel, which must be designed, fabricated, and tested. The expected cost for development and implementation of the vacuum vessel is $250K. The modulator system must be tested and installed at an estimated cost of $200K. To enable the delivery of 200-MeV beam to Area A, the switchyard must be reconfigured, with a large aperture magnet installed to accept the H+ beam from 200 MeV to 800 MeV. To enable the higher current needs of the Materials Survivability Laboratory, the linac must be aligned to avoid unacceptable beam losses and the consequent activation of components.

IMPROVE THE PERFORMANCE OF THE PROTON STORAGE RING (PSR)

As shown above, the nuclear physics program at the Lujan Center can benefit significantly from a shorter pulse width, where the FOM is proportional to the flux times the inverse square of the proton pulse width. We have recently demonstrated the ability to operate the PSR at 30 Hz with a 30-ns pulse width. (The nominal pulse width in the PSR is 125 ns.) An investment of $100K-$200K to increase the PSR harmonic buncher voltage from 15 kV to approximately 25 kV would further shorten the pulse width to approximately 22 ns, FWHM. The FOM for nuclear physics experiments would increase by a factor of 1.8. Significant gains in short-pulse intensity would require a larger investment of approximately $1M-$2M to develop and implement a broadband (40-80 MHz) RF feedback system and add a second RF gap in the PSR (to damp the microwave instability that limits the pulse width and intensity of the 30-Hz short-pulse beam). A factor of 2 increase in beam intensity (and FOM) is expected. This would benefit both the material science and nuclear physics programs at the Lujan Center.

H^+ RFQ TO REPLACE THE COCKCROFT-WALTON (CW) INJECTOR

Catastrophic failure of major components in the CW injector coupled with the unavailability of spare parts can lead to significant down time, perhaps even the loss of an entire run cycle. To reduce this operational risk, the CW systems should be replaced with modern RF quadrupole (RFQ) based injectors. RFQ accelerators are employed worldwide and have demonstrated stable and reliable operation. To mimic the current pulse structure and anticipated multi-beam-delivery requirements, implementation of three (one for the H+ source and two for the H- source) RFQ-based injectors are required. Each injector is estimated to cost $14M. A test stand is being assembled to test a new four-rod, 750-keV, 201.25-MHz RFQ to replace the H^+ CW injector. The test stand will include the ion source, low-energy beam transport, RFQ, medium-energy beam transport downstream of the RFQ, and diagnostics needed to inject beam into the LANSCE drift tube linac.

UPGRADE THE WATER DISTRIBUTION SYSTEM ON THE REMAINING 3 DTLS

Past deferred maintenance to critical water valves on the DTL water distribution systems led to early failure of the water distribution system of the Module 2 DTL and a many-month down time to implement the repair. The repair was a temporary fix with one aspect being to reverse the flow of water in the system to minimize ongoing erosion within the cooling passages. A full repair was implemented a few years ago; however, it is suspected that the other three DTL tanks have also suffered similar damage but have not yet catastrophically ruptured. We need to upgrade the water distribution systems to Modules 1, 3, and 4. The cost for this is estimated to be $4.84M.

LANSCE Los Alamos Neutron Science Center

NNSA National Nuclear Security Administration