LANSCE

21st Century Deterrence

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Authors
Gus Sinnis
Mark Chadwick
Kim Scott
Stephen Milton

Contributors
Don Brown
Morgan White

LANSCE: A Center for Materials and Nuclear Research for 21st Century Deterrence

Executive Summary

The LANSCE accelerator is an important tool in the assessment and certification of the nation's nuclear stockpile. LANSCE provides critical materials and nuclear data needed to develop a predictive capability for the performance of nuclear weapons. As the stockpile ages, materials are replaced, and manufacturing processes change, it is critical that we understand how these changes impact device performance. Dynamic proton radiography and neutron diffraction are ideally suited to contribute to this need. These capabilities are essential to enabling the NNSA labs to become more *responsive* and *agile* in advancing the deterrent of the future.

LANSCE has unique capabilities that NNSA Laboratories and our international allies rely upon to answer fundamental questions related to stockpile stewardship. This is enabled by continual advances that have been made in imaging, detectors, and instrumentation technologies. *The proton radiography facility* is unique within the U.S. and allied nations (though Russia has now developed a more advanced proton radiography capability) and provides data on high-explosive and material performance under extreme conditions that can not be obtained through other methods. Together with the neutron diffraction at the Lujan Center that can measure structural material properties, LANSCE can further our understanding of the complex relationships between the manufacturing process, the material properties, and the dynamic oerformance of the materials in a weapons releant environment. *The pulsed high-energy neutrons produced at the Weapons Neutron Research Facility* provides: unique data needed to understand fission/criticality, radiochemical diagnostics, and to exploit NDSE diagnostic advances for subcritical experiments executed at the U1a/ECSE facility. In addition they provide a highly penetrating neutron radiographic capability and the world-leading neutron irradiation facility for defense and civilian component qualification. Beyond NNSA missions, LANSCE serves the broader national interest with our production of medical isotopes and the exploration of fundamental nuclear physics.

In recent decades NNSA has made substantial investments in LANSCE to improve accelerator reliability and field state-of-the art detectors/instruments; current thrusts include establishing a dynamic plutonium pRad capability (Pu@pRad, expected to be operational in 2023), needed for qualifying new Pu manufacturing and for understanding Pu aging, a new and upgraded neutron spallation target for neutron experiments at the Lujan Center, the replacement of the instrumentation and controls systems with modern systems, and the replacement of the antiquated analog low-level RF system with a digital system that will greatly enhance machine operations and stability.

Over the past several years, it has become increasingly clear that the linac's front end accelerating structures (two Cockcroft-Walton accelerators and a drift-tube linac) present a significant risk to the long-term viability of LANSCE. *The purpose of this document is to motivate an upgrade to the front-end of the LANSCE accelerator. This will ensure the long-term viability and reliability of LANSCE, while increasingthe experimental capability. With these upgrades LANSCE will be a critical facility for 21st Century Deterrence.*

LANSCE: A Premier Facility for an Enduring Nuclear Security Mission

For a half century, the United States has relied on the Los Alamos Neutron Science Center (LANSCE) accelerator to deliver high-energy, high-power proton beams in support of national security science. The proton beams enable an imaging capability, produce neutrons used for diffraction (material science), nuclear science. Today the LANSCE Facility is a center for materials and nuclear research supporting National Nuclear Security Administration (NNSA) and Department of Energy (DOE) missions. LANSCE is playing a critical and expanding role in the assessment and certification of an evolving stockpile, and has played an essential role in the B-61-12 Life Extension Program (LEP), the W88 Alt program, the W80-4, and the design of future stockpile options. Users of LANSCE include Sandia National Laboratory, Lawrence Livermore National Laboratory, the Kansas City National Security Campus, PANTEX, and Y12. Our foreign allies - the U.K.'s Atomic Weapons Establishment, and the French Atomic Energy Commission (CEA), also use LANSCE through collaboration agreements.

In the absence of nuclear testing, the continued effectiveness of the nation's nuclear stockpile depends upon a combination of integrated hydrodynamic and subcritical tests and focused experiments that improve the physics input to detailed computer simulations of nuclear devices and serve as a check on the simulation results. LANSCE delivers material science, nuclear science, and dynamic imaging to solve the most challenging problems associated with our long-term ability to certify the stockpile. Examples of focused experiments performed at LANSCE include:

1. Tests of the performance of high explosives (conventional and insensitive) over the entire Stockpile-to-Target Sequence (STS) temperature range,
2. Measurements of detonator performance for both design changes and lot variability,
3. Investigations of the impacts of aging and manufacturing on plutonium and uranium structural properties,
4. Using neutron diffraction to develop a scientific basis for manufacturing,
5. Precision measurements of fission processes to improve understanding of criticality and nuclear device performance.

Driven by a need to address a key gap for stockpile certification and assessment, by 2023 LANSCE's capabilities will be expanded to include dynamic, focused experiments on plutonium coupons at its proton radiography (pRad) facility, "Pu@pRad". This capability will fill the gap between small-scale and subcritical experiments to study plutonium performance in weapons relevant conditions. Plutonium experiments at pRad will be used to study the impact of alloy composition, age, and manufacturing processes on plutonium performance (instability growth, ejecta production and transport, material strength and breakup, etc.). In addition, feature-driven hydrodynamics in plutonium will be studied with unprecedented fidelity. The certification and assessment of the evolving stockpile presents an enduring and expanding need for the protons and neutrons produced at LANSCE, and continued robust and reliable performance of the facility is required to meet this demand. However, the country is at risk of losing the LANSCE capability because of growing reliability concerns with the aging equipment and systems, in particular the front-end of the accelerator system. The front-end of the accelerator system includes the two Cockcroft-Walton accelerators and drift-tube linac system. While significant investment has been make to the drift-tube linac RF power system, this investment has not extended to the nearly half-century old Cockcroft-Walton accelerators and drift-tube linac accelerating structures. Issues with the aging front-end, based in part on technology developed in the 1930s, are contributing to troubling growth in the frequency, severity, and duration of maintenance problems and downtime at LANSCE. A failure of any of the major components in these system could result in a very extensive downtime as either there are no spare or no viable way to readily reproduce and replace the failed component. *The LANSCE front-end must be modernized for LANSCE to reliably deliver the material and nuclear science and dynamic performance data needed to meet the present and growing US deterrence challenges.*

While modernization of the accelerator front-end is essential, we are currently proceeding with other modernization efforts. Foremost among these are the ongoing modernization of the diagnostics and controls systems as well as replacing the '70s vintage analog low-level RF system with a modern and much more capable digital low-level Rf system. These modernization efforts will position LANSCE to reliably serve the needs for certification data into the future. In addition this modernization effort will open considerable opportunities for the stewardship of a resilient US nuclear deterrent through the 21st century that can all be done within the existing LANSCE infrastructure. Potential capability enhancement opportunities are discussed later in this document.

In addition to national security missions, LANSCE is relied upon for:

- *<u>The production of radionuclides</u> for medical applications. LANSCE produces significant quantities of Sr-82, used for cardiac imaging and Ge-68, used for diagnosing cancer, and is producing new therapeutic radionuclides for advanced cancer treatments such as Ac-225 for targeted alpha therapy, which is currently undergoing clinical trials.*
- *<u>The neutron irradiation</u> and qualification of sensitive electronic components for defense and civilian applications.*
- *<u>Generation of ultra-cold neutrons</u> used to probe the fundamental laws of nature.*

<u>LANSCE: A Unique Facility for NNSA Mission</u>

Though LANSCE was built in 1972 it still possesses many unique capabilities that are well matched to NNSA and DOE missions. In 1972 LANSCE was a revolutionary machine – capable of accelerating a milliAmp of protons to 800 MeV (0.8 MWatts of beam power). It was not until 2006 that a more powerful accelerator was made operational – the Spallation Neutron Source (SNS) at Oak Ridge, which accelerates 1.2 milliAmps of protons to 1 GeV (1.2 MWatts of beam power). Despite being a slightly less powerful accelerator, LANSCE's design enables capabilities that do not exist at the SNS.

1. Very short duration pulses (<50 nanoseconds) delivered to the proton radiography facility enable dynamic radiographs of fast phenomena with little to no motion blur.
2. Extremely short duration pulses (125 picoseconds) delivered to the Weapons Neutron Research facility (WNR) enable energy resolved measurements of neutron cross sections relevant to understanding criticality, fission and fusion and radchem cross sections. This also enables energy selective high-energy neutron radiography that cannot be performed elsewhere.
3. Short duration proton pulses to the neutron spallation target enables energy resolved neutron radiography.

a. The pulse length at the SNS is 1 microsecond compared to 250 nanoseconds at the Lujan Center at LANSCE. The short pulse length enables us to resolve epithermal neutron absorption features to image individual elements and isotopes in a material.

4. The unmoderated target station at WNR generates a neutron spectrum that is nearly identical to the cosmic-ray neutron spectrum (with 1 million times the flux). This enables testing of electronics used in defense and civilian applications to cosmic-ray-induced single event effects, a capability that is currently unique in the world.
5. Simultaneous H- and H+ acceleration, enables LANSCE to generate medical isotopes while simultaneously operating 3 of 4 other target stations with 15 beam lines.

Table 1. Legend: ● (green) Existing capability, ● (yellow) Potential capability with significant investment, ● (red) Not feasible

	LANSCE	Brookhaven	FermiLab	SNS
Proton Radiography	green	yellow	red	red
High Explosive Drive	green	yellow	red	red
Classified Experiments	green	yellow	red	red
Dynamic Plutonium Capability	green	red	red	red
Low-energy Nuclear Physics	green	red	red	yellow
Isotope Production	green	green	red	yellow
Neutron Diffraction	green	red	red	green
Static Plutonium	green	red	red	green
Neutron Radiography	green	red	red	green
Energy-resolved Tomography	green	red	red	red
Neutron Irradiation for Defense and Civilian Applications	green	red	red	yellow

In addition to the accelerator itself, the LANSCE facility possesses an Authorization Basis that enables us to conduct classified experiments, study plutonium in both a static and dynamic environment, and conduct experiments using high explosives. In Table I we compare NNSA relevant capabilities at LANSCE to other accelerator facilities within the U.S. While each of these facilities possesses unique capabilities, here we concentrate on capabilities that make LANSCE unique and relevant to NNSA and DOE missions.

Proton Radiography at LANSCE

The LANSCE pRad facility utilizes an 800-MeV proton beam to image the dynamic behavior of materials and components. The penetrating power of high-energy protons, like that of x-rays, makes them an excellent probe of a wide range of materials under extreme pressures, strains, and strain rates. The incredible efficacy and versatility of proton radiography also stems from the LANSCE accelerator's ability to produce multiple proton pulses that, when coupled with multiple optical viewing systems, can produce 30 frame movies with frames spaced as closely as ~200 ns and spread over up to 1 millisecond.

LANSCE pRad provides the Nation's only dynamic performance testing proton radiography capability for sustainment of the stockpile and for developing options for the future deterrent. pRad is used to address Significant Finding Investigations (SFIs) for the stockpile; to qualify material and component performance for LEPs and Alts (like the current B61-12, W88 Alt, and W80-4), such as high explosives, detonators, and enhanced safety features; to perform platform development for subcritical experiments at the NNSS U1a site, and to develop new options for the future deterrent.

As noted above, by 2023 the Pu@pRad project will be complete, expanding pRad capability to include dynamic, focused experiments on plutonium coupons. This capability will fill a gap between small-scale and subcritical experiments to study plutonium performance in weapons relevant conditions, for the certification and assessment of the future stockpile. Plutonium experiments at pRad will be used to study the impact of alloy composition, age, and manufacturing processes on plutonium performance (instability growth, ejecta production and transport, material strength and breakup, etc.). In addition, feature-driven hydrodynamics in plutonium will be studied with unprecedented fidelity. Data from pRad will be used to qualify and certify pits produced with modern manufacturing methods, to understand plutonium aging, to resolve SFIs that involve plutonium, and to examine the equation of state of plutonium at high compressions. In order to realize the intended benefit of plutonium experiments at pRad, the LANSCE front end must be modernized to ensure long-term, reliable delivery of 800-MeV proton pulses to pRad.

Neutron Diffraction at LANSCE

Enhanced understanding of materials is critical for future stockpile design, certification, and assessment. The properties and performance of stockpile materials present scientific challenges because of changes resulting from aging, new manufacturing processes, evolving threat environments, new requirements for a tailored deterrent, and the need to replace legacy materials. As discussed above, pRad probes the dynamic performance of stockpile materials with radiography. Diffraction of the low energy neutrons produced at the Lujan Center are used to probe the *in situ* structural properties of materials. The *in situ* characterization environments include conditions materials would undergo due to STS changes, aging, and manufacturing processes. The next generation Lujan Center neutron target is currently under construction and will be installed in the Spring of 2021, ensuring another decade of high-quality neutron diffraction capability at LANSCE.

Lujan's Spectrometer for Materials Research at Temperature and Stress, SMARTS, and High-Pressure-Preferred Orientation, HIPPO, instruments are third-generation neutron diffractometers.

- SMARTS is optimized for the measurement of deformation under stress and extreme temperature and of spatially resolved strain fields. With an extensive array of *in situ* capabilities for sample environments, it enables measurements on small ($1mm^3$) or large ($1m^3$) samples. Components with dimensions up to 1m and up to 1,500kg can be positioned precisely in the beam. The furnace and load frame suite allow research on materials under extreme loads (250 kN) and at extreme temperatures (1,500°C).
- HIPPO achieves very high neutron count rates by virtue of a short (9m) initial flight path on a high-intensity water moderator. HIPPO supports studies of crystal orientation distribution (texture), amorphous solids, liquids, magnetic diffraction, small crystalline

samples, and samples subjected to non-ambient environments such as temperature, pressure, or uniaxial stress. The exceptionally high data rates of HIPPO also make it useful for time-resolved studies. HIPPO has unique high-pressure anvil cells capable of achieving pressures of 30 GPa at ambient and high (2000 K) temperatures with samples up to 100 mm^3 in volume.

Nuclear Science at LANSCE

Weapons derive military yield from nuclear fission and thermonuclear fusion in the boost processes. They operate on the principle of neutron multiplication, and LANSCE is *the f*acility that quantifies these neutron reaction processes, needed for weapons performance simulation code calculations and for the diagnostic interpretation of historical underground test data.

LANSCE is the premier US facility for such studies and the only US facility that allows for accurate neutron measurements at all relevant weapons energies - hence the facility is used by LANL, LLNL and CEA in their nuclear science measurement campaigns. LANSCE also provides essential data for other mission areas including criticality safety, non- and counter-proliferation safeguards and nuclear detection and forensics, and nuclear energy/waste applications. The data measured at LANSCE are subsequently used by theory and modeling researchers at LANL and LLNL (and in collaboration with BNL and ORNL) to create Evaluated Nuclear Data Files (ENDF) that are used in our US nuclear technology applications. We are a world leader in providing trusted nuclear capabilities through use of such accurate data in concert with our simulation codes (MCNP being a notable example).

Nuclear science research at LANL has continued to advance through the development of increasingly-capable detectors. In recent years, we have developed the capability for high-precision fission measurements with the Chi-nu and TPC detectors (a LANL-LLNL collaboration), and SPIDER, DANCE, NUEANCE, and DICER, and these capabilities are now being extended to measure other important processes. The new spallation target that is being developed will further enhance our measurement capabilities.

National nuclear security applications will continue to need LANSCE to provide essential nuclear data in the following areas:

- Nuclear cross sections for precise weapons performance and diagnostic/forensic assessments, for the stockpile of today and the future. Future thrusts will build upon the fission detection advances to measure actinide neutron scattering and capture data for these applications – neutronic reactivity sensitivity studies continue to point to the need to refine our understanding of these reactions.
- Nuclear data for understanding foreign threats, including anticipating technological surprise by our adversaries.
- Nuclear science to advance and exploit subcritical experiments at U1a, especially neutron-diagnosed subcritical experiments (NDSE) – a priority identified by NNSA. LANSCE data are needed for diagnostic development and for refined simulations of NDSE (including accounting for the softer neutron spectrum) in subcritical processes.

- Nuclear criticality safety; ENDF cross section advances based on LANSCE data have, and will continue, to contribute to an understanding of safety margins at facilities that include TA55, U1a, DAF and NCERC.

An Aging Accelerator

The LANSCE accelerator was commissioned in 1972, and NA50 continues to support valuable modernization investments (see the sidebar for a description of the various accelerator components). The LANSCE-RM (Risk Mitigation) program was the first significant investment into the accelerator since its inception. The result of this investment was the upgrading of the radio-frequency (RF) power systems for the drift-tube linac (DTL) and the purchasing of critical spares for obsolete components (such as the high-power RF tubes for the cavity-coupled linac). These investments enabled LANSCE to resume full-power operations for the first time in a decade. None of the investments impacted the accelerating structures themselves nor the Cockcroft-Walton accelerators.

LANSCE is comprised of three coupled, but distinct accelerating systems. At the front end there are two 750-KV Cockcroft-Walton (CW) accelerators, one used to accelerate protons and the other to accelerate H- ions. The beams from these two accelerators are chopped in time as required by the experimental programs, prebunched for improved acceptance into the downstream RF accelerators, merged, and injected into the drift-tube linac (DTL) system where they are simultaneously accelerated to 100 MeV. The DTL consists of four similar, but unique modules. The beams are then separated magnetically. The protons are directed toward the isotope production facility, while the H- beam is injected into the cavity-coupled-cavity linac. Here they are further accelerated to a kinetic energy of 800 MeV.

During the 2018 run cycle, problems with one of the accelerating structures forced us to return to half-power (60 Hz) operations. During the following extended maintenance period the problem was found to be a large crack in a weld within the drift-tube linac. The repair required a welder to crawl roughly 25 ft into the accelerating structure. During the welding operation new cracks formed, which required further welding. The additional cracking was most likely due to significant residual stresses within the original weld and surrounding material. In addition, we found other deformations within the accelerator that appear to be the beginning of future cracks. There are a total of 4 modules in the DTL system, and it is imperative that these structures be replaced in a timely fashion to ensure longterm operation of the LANSCE facility. The ISIS facility at the Rutherford Appleton Laboratory in the UK, fearing similar issues with their aging machine, is currently replacing their DTL. Upstream of the DTL are the Cockcroft-Walton (C-W) accelerators. This technology was developed in 1932 and was once ubiquitous at major accelerator facilities. With the exception of LANSCE and the Paul Scherrer Institute in Switzerland every other major accelerator facility has replaced their C-W accelerators with modern radio-frequency quadrupole (RFQ) systems. C-W systems are large (approximately 3 stories high) and difficult to maintain. Because of their age and obsolescence, replacement parts must be custom made. This presents a significant risk to the facility, with the potential for a major loss of operational time if a critical component fails.

Ensuring Continued Longterm Operations of LANSCE

The current machine has served us well, but to ensure operations for years to come we must address some major risks, the most immediate and significant of which is the front-end of the accelerator, comprised of the C-W and DTL systems. In addition to retiring risk, the replacement systems will enhance LANSCE's ability to respond to the future mission needs of the NNSA.

The radiation vault (tunnel) containing the linac is sufficiently wide in the region of the DTL that a fully functioning C-W/DTL replacement could be built in-situ. Once fully commissioned, the output beam from the replacement linac front end would be transported to the existing half-mile long 800-MeV accelerator.

The new system, as presently envisioned, would replace both the H- and H+ C-W systems with two radio-frequency quadrupole (RFQ) accelerators (one each for the H+ and H- ions) for the initial acceleration to a few MeV. RFQs are now used around the world for the initial acceleration of protons and ion beams. A more modern DTL, with a higher accelerating gradient and capable of higher power operation, would replace the existing DTL.

Potential Capability Enhancements

In the process of modernizing the LANSCE machines, and in particular the linac front-end, we plan to design and construct a machine that will have equal or better performance in all essential metrics as well as have potential for expansion to future enhanced capabilities of the LANSCE complex. A modern front-end to the LANSCE accelerator would immediately enable enhanced capability for LANSCE including:

1. higher peak and integrated beam current to all target stations, which will result in
    a. improved resolution at pRad,
    b. increased throughput at the Lujan Center
    c. increased capability at the WNR facility, and
    d. increased production capability at the IPF
2. improved beam tuning into the existing 805 MHz system for fast startup and increased reliability.

The replacement of the CW injector and the DTL with modern systems will ensure that LANSCE can reliably deliver enhanced capability beyond 2050 to serve NNSA mission needs.

In addition to the above immediate payoffs, additional investments into improved experimental capability will further increase LANSCE's impact on mission delivery. This would require additional investments in accelerator systems as well as the user experimental programs. Potential capability improvements include:

Dedicated 3-dimensional stress and texture measurement beamline at the Lujan Center. New manufacturing techniques (additive manufacturing) and materials will be needed to support the future stockpile. The properties and performance of these materials must be understood before they can be inserted into the stockpile. The three dimensional residual stress states and microstructure are key to understanding how these materials will perform. This flight-path will enable a unique capability to non-destructively, spatially profile crystallographic texture in 3-dimensions, allowing *in-situ* measurements on components throughout the manufacturing process (for example the hydroforming of uranium hemispheres). Such an instrument would greatly increase the capacity and throughput of material characterization and *in-situ* measurements under extreme environments at the Lujan Center. This improvement is strictly an enhancement to the user experimental program, but would certainly benefit from any enhancements to beam availability and integrated current.

Dual-axis proton radiography in Area A. Feature-driven hydrodynamics often leads to 3-dimensional behavior in systems. As the stockpile ages, our need to understand how emerging features will impact performance increases. A time-resolved 3-d imaging capability such as that provided by a dual-axis proton radiography capability will enable one to probe the nature of 3-dimensional effects in weapons relevant environments. In addition, a second axis can be used to provide a view of dynamic events with two different magnifications and spatial resolutions. This would enable the simultaneous measurement of system behavior along with high-resolution measurements of key features. Such an improvement would fall mostly into the accelerator system improvement category as it involves the additional of new beam transport lines, but the net result would be a vastly improved user experimental program for proton radiography.

High-energy proton radiography capability. Available accelerator technology in the 1970s limited the beam energy of LANSCE to 800 MeV. Modern accelerating structures are capable of significantly higher accelerating gradients that would enable the construction of a higher-energy proton radiography capability within the existing infrastructure. At 5-GeV, easily achievable with modern systems, the spatial resolution of proton radiography would be roughly 10 microns. Such a resolution is well-matched to the needs of the Dynamic Mesoscale Material Science Capability (DMMSC) and would dramatically improve the impact of proton radiography as a secondary diagnostic coupled to an XFEL capability and as a tool for stockpile stewardship. The new front-end linac will be designed with this improvement in mind, thus allowing expansion in the future to achieve this capability.

A modern proton storage ring. The existing proton storage ring was designed and construted in an era without a deep understanding of beam physics effects and the computational capability that we have today. A modern proton storage ring could achieve 2 to 3 times the current of the existing machine, Greatly enhancing the material science capabilities of the Lujan Center.