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CINT 2029

Center for Integrated Nanotechnologies Strategic Plan

CINT Mission

The Center for Integrated Nanotechnologies (CINT) is a Department of Energy, Office of Science Nanoscale Science Research Center. CINT operates as a national user facility devoted to studying the design, performance, and integration of nanoscale materials and structures. Through our Core Facility in Albuquerque and Gateway Facility in Los Alamos, CINT provides access to scientific expertise and advanced capabilities for researchers to synthesize, fabricate, characterize, understand, and scale nanostructured materials into the microscopic and macroscopic worlds. This comprehensive approach provides the greatest potential for nanostructured materials to inspire technological innovation with enduring beneficial impact in national S&T research priorities including quantum materials and quantum information science, advanced microelectronics, clean energy, pandemic preparedness, sustainable manufacturing and artificial intelligence/machine learning.

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1 EXECUTIVE SUMMARY

The Center for Integrated Nanotechnologies (CINT) plays a leadership role in the area of nanoscience through its function as a Department of Energy (DOE), Office of Science Nanoscale Science Research Center national user facility. CINT is a collaborative community of diverse users and expert scientific staff; CINT fosters high-impact nanoscience discoveries, leads next-generation technique development, and advances the frontiers of knowledge beyond that which is achievable by individual researchers or any single institution.

Each year we revisit our strategic plan to ensure it is focused on meeting the needs of the user community today and into the future. This plan is based upon the extraordinary scientific opportunities involving nanomaterials and the fundamental science that underpins technology development, organized into six national research priorities inspired by both national research initiatives and current technological challenges facing the nation. These technology areas include: quantum materials and quantum information science, advanced microelectronics, clean energy, pandemic preparedness, sustainable manufacturing and artificial intelligence/machine learning (AI/ML). CINT will create a national impact by providing world-leading research capabilities to investigate the fundamental science that underlies these and related technology areas.

CINT's role is to enable world-leading science towards realizing these priorities, and our strategic objectives describe what is needed to deliver on this promise. As a vibrant partnership between Los Alamos National Laboratory and Sandia National Laboratories, CINT leverages the unmatched scientific and engineering expertise, as well as special capabilities, of our host DOE laboratories in an Office of Science open-access user facility, benefitting hundreds of researchers annually. We have world-leading scientific expertise in four thrust areas, and specialized capabilities to synthesize, fabricate, characterize, and understand nanomaterials in increasingly complex, integrated environments, as described in Section 3.

Building upon our current strengths, we continue to identify capabilities and expertise that the nanoscience community will need in the future and that CINT is well positioned to develop and offer as a user facility.

CINT's transformational and supporting foundational capabilities are made available to the widest possible number of qualified users via a comprehensive communications and outreach effort combined with an efficient user proposal, peer-review, and project management system. We target research leaders in diverse institutions, early career scientists, and innovators in nanotechnology industries to create an expanded national nanoscience user community of the future. CINT is also dedicated to fostering a diverse research community and will continue to offer a comprehensive suite of capabilities in addition the unique, world leading capabilities, in order to assist underrepresented researchers and institutions.

2 INTRODUCTION

The Center for Integrated Nanotechnologies (CINT) is a Department of Energy (DOE), Office of Science Nanoscale Science Research Center (NSRC) operating as national user facility. As a vibrant partnership between Los Alamos National Laboratory (LANL) and Sandia National Laboratories (SNL), CINT leverages the unmatched scientific and engineering expertise, as well as special capabilities, of our host DOE laboratories, creating a unique user facility environment among the NSRCs. Our users and staff conduct research projects within and across the *Core Facility* in Albuquerque, NM, and the *Gateway Facility* in Los Alamos, NM (Figure 2.1). By creating a collaborative community of diverse users matched to expert facility scientists with advanced capabilities, CINT fosters high-impact nanoscience discoveries, leads next-generation technique development, and advances the frontiers of knowledge beyond what is achievable by individual researchers or any single institution.

Figure 2.1 CINT Core Facility (left) and Gateway Facility (right).

Our overarching goal is to be the national resource for research expertise and advanced capabilities to synthesize, fabricate, characterize, understand, and integrate nanostructured materials. In order to achieve this goal, CINT has the following five strategic objectives:

1. CINT will be a nationally recognized leader in nanomaterials.
2. CINT will develop unique experimental and theoretical capabilities to synthesize, fabricate, characterize, and understand nanoscale materials in increasingly complex environments, including our signature Discovery Platforms.
3. CINT will invest to provide foundational capabilities and commercial instrumentation necessary for internationally competitive nanoscience research.
4. CINT will prioritize safety and operational efficiency.
5. CINT will increase the diversity and breadth of our national user community, foster high-impact science, and encourage intellectual risk in basic and use-inspired research.

Together, these CINT strategic objectives support and align with the U.S. DOE's strategy to deliver the scientific discoveries and major scientific tools that transform our understanding of nature and strengthen the connection between advances in fundamental science and technology innovation.

CINT expertise is organized in four scientific thrust areas:

- Quantum Materials Systems (QMS): Understanding and exploiting quantum materials, quantum phenomena, and novel microelectronic materials and architectures.
- Nanophotonics and Optical Nanomaterials (NPON): Exploiting and characterizing emergent or collective electromagnetic and quantum optical phenomena, from nanophotonics and metamaterials to quantum coherence.
- In-situ Characterization and Nanomechanics (ICNM): Developing world-leading capabilities to study the dynamic response of materials and nanosystems to mechanical, electrical, radiation, or other stimuli.
- Soft, Biological, and Composite Nanomaterials (SBCN): Exploring the intersection of nanomaterial and biological systems. Developing world-leading tools to understand nano-bio phenomena.

Working with our DOE sponsors and sister NSRCs, we have identified five National Research Priorities on which to focus future capability development. These areas include current national initiatives for quantum information sciences and advanced microelectronics, as well as other pressing challenges in clean energy, pandemic preparedness, sustainable manufacturing and AI/ML. While these are current challenges and initiatives, they are subject to evolve as challenges facing the nation evolve. Further, these represent investment areas for capacity development – CINT will not restrict our user community to conducting research in these areas.

CINT leverages the strengths of our host DOE laboratories through the alignment of the CINT 2029 strategic plan with the LANL and SNL strategic investments (Figure 2.2). The coordination of SNL, LANL, and CINT strategic plans leads to very visible benefits for all three entities. Researchers from LANL and SNL collaborate extensively through User projects, illustrating that the laboratories value our Center, and that CINT delivers high impact contributions to national research priorities. These host laboratory projects are funded by a wide variety of sponsors including, but not limited to, the Department of Energy's Office of Science, the National Nuclear Security Administration, the Department of Defense, the National Science Foundation, Homeland Security, and the National Institutes of Health.

Figure 2.2 LANL (left) and SNL (right) strategic plans.

Finally, we note the special role the DOE Office of Science user facilities have in supporting key objectives for data sharing and accessibility. CINT is dedicated to supporting and enabling scientific discovery from a wide range of institutions, from leading R-1 type universities to underserved and underrepresented minority institutions. Additionally, CINT will work to implement the data sharing and availability guidance from the Office of Science and Technology Policy, wherein all published, taxpayer funded research data will be made publicly available.

Our vision for CINT in the year 2029 and dedication to continued excellence as a DOE Office of Science user facility ensure that CINT will transform our understanding of nature and strengthen the connection between advances in fundamental science and technology innovation.

3 SCIENCE VISION, FOUNDATIONAL AND TRANSFORMATIVE CAPABILITIES

Nanoscale materials exhibit extraordinary physical, chemical, and/or biological properties. Isolated or individual nanoscale materials are scientifically interesting, but they rarely make significant technological impact. Building blocks comprised of individual nanoscale materials are commonly integrated with other materials into architectures that enhance their properties (up-scaling) or lead to new emergent behaviors. By surveying the integrated environments of greatest potential impact, and by developing a fundamental understanding of the principles that govern the integrated properties and behaviors, we can capitalize on the greatest potential for nanomaterials to have an enduring impact on scientific and technological innovations. Nanoscale integration has the potential to revolutionize the way we live, in the same way that the development of the semiconductor-based integrated circuit (IC) did. The development of the IC required the capability to integrate a large number of resistors, capacitors, diodes, and transistors on a single platform. Once the IC was developed, it enabled countless innovations. CINT envisions similarly transformational technologies will ultimately emerge from nanomaterials integration.

Understanding the principles of nanomaterials integration has been the central theme of CINT since its inception. The CINT2029 Strategic Plan builds upon this foundation by envisioning a new research paradigm wherein novel materials, integration science, advanced characterization, and theory work together to realize the fundamental science that supports innovative and competitive technologies. CINT will bring together expertise and capabilities across our four Science Thrusts. An underlying theme of our Thrusts is a fully integrated feedback loop of synthesis, fabrication, characterization, and modeling, shown in Figure 3.1 (and also described in more detail on the NSRC Portal[1]), that will allow the nanoscience community to realize and develop the ability to predict and a priori design unprecedented materials functionalities and innovative systems.

Figure 3.1 CINT leverages its diverse scientific community in an on-going cycle of scientific discovery.

3.1 Quantum Materials Systems Thrust

The Quantum Materials Systems (QMS) Thrust has deep, integrated expertise in the areas of quantum materials (QM), quantum information sciences (QIS), and microelectronics. We engage in novel research and support user needs in materials synthesis, materials characterization, quantum measurements, and the theoretical understanding of quantum phenomena to better address fundamental science questions related to quantum phenomena. At present, our ongoing science integration challenges include elucidating and utilizing interactions between QIS systems and the environment, precisely controlling the preparing QMs and QIS systems, discovering emergent phenomena in QMs under various excitations, and integrating QMs in solid-state architectures for applications at the macroscale.

[1] https://nsrcportal.sandia.gov/

QMS will support users and DOE initiatives in the national priority areas of microelectronics, quantum information science, and AI / ML. In addition, our scientists use the DOE Basic Research Needs workshop reports in the areas of quantum materials, quantum sciences, microelectronics, and energy storage to motivate future work and capability investments. The integration of quantum science and nanoscience provides QMS with novel opportunities to control charge/information carriers across multiple length scales and, in doing so, tackle the BES grand challenge "Directing matter and energy through control of carriers at an unprecedented level." We will continue to conduct materials research to fabricate architectures composed of QMs and nanomaterials in various dimensions. Our scientists are at the forefront of growing and characterizing high quality semiconductors and quantum materials to enable next-generation microelectronics and QIS systems.

Toward the Future

In the next five years, QMS scientists will work with users to advance science and capabilities in our core areas of microelectronics, quantum materials and quantum systems. High quality materials are critical for these areas. We will synthesize new QMs to enable emergent states in 1D and 2D system and devise theoretical approaches for multi-scale modeling for topological and strongly correlated materials.

We will engineer reconfigurable electronic materials for next generation devices. We will build new characterization platforms to be used across the DOE NSRCs for more reproducible material measurements. We will enhance quantum sensing with quantum defects in new materials and develop ion implant approaches for making and activating new defects. We will extend our capabilities in atomic fabrication to 2D materials and control of quantum defects. AI/ML techniques will be used to improve synthesis, data collection and data analysis. QMS will invest in high quality growth capabilities for semiconductors, topological materials, multi-functional oxides, dichalcogenides and actinides.

3.2 Nanophotonics and Optical Nanomaterials Thrust

The Nanophotonics and Optical Nanomaterials (NPON) Thrust seeks to detect, understand and control fundamental photonic and electromagnetic interactions in nanostructured optical and heterogeneous materials. Through direct synthesis, hetero-integration, and fabrication we create hybrid materials possessing novel photonic properties, as well as more complex behavior, that emerge out of the multi-material interactions. We have moved beyond quantum size effects to capitalize on a new ability to manipulate light and enhance light-matter interactions afforded by precision integration of different material classes.

NPON's foundations for executing this overarching vision include our ability to design and experimentally realize functional materials, our expertise in a broad suite of spectroscopy capabilities, and our physics- and chemistry-informed theory and modeling that is intimately interconnected with our experimental efforts. Specifically, we have extensive experience in bottom-up, colloidal chemistry for the precision synthesis of light-emitting 0D, 1D, and 2D nanomaterials, including non-blinking hetero-structured quantum dots, defect-states in carbon nanotubes, and localized states induced by strain in semiconductor-magnetic heterostructures, as well as functionally complementary magnetic, plasmonic and quantum systems. We are equally experts in top-down fabrication of nanophotonic structures, including optoelectronic, nonlinear and quantum metasurfaces, photonic crystals and topological photonics. Similarly, we pursue two material-integration strategies: bottom-up nanointegration based on scanning-probe-enabled direct-write placement of chemically synthesized nanomaterials into top-down-fabricated antenna and metasurfaces, as well as top-down fabrication of, e.g., III-V and silicon integrated optics. We pair broadband ultrafast spectroscopy with state-of-the art tools for microscopic imaging, spectroscopy, and the dynamical measurements of single nanoelements, while also identifying new ways to achieve ultrafast optical control of materials properties. NPON leverages a diverse range of theoretical modeling capabilities, including atomistic electronic structure simulations of optoelectronic properties, excited-state molecular dynamics, condensed matter models, photonics theory, and data science and ML approaches, which have been extensively applied to nano- and hetero-structured materials.

Toward the future

NPON will address the following opportunities in hybrid photonic materials as we move forward. We will continue to advance precision synthesis/assembly of designed nanomaterial hetero-structures, adding new directions in molecular frameworks for novel magnetic and quantum 2D materials, real-time/inline multimodal characterization of probe-enabled nanointegration, and co-design strategies for ensuring synthesis and manufacturing/application needs are considered simultaneously in development. In the area of metasurfaces, we will strive to harness exotic capabilities, including spatiotemporal control, generation and detection of infrared and THz radiation, excitation and control of nanoscale vectorial photocurrents, and production of entangled photon-pairs. We will also implement self-driving labs for reconfigurable nanophotonics. In our spectroscopy, we will probe more exotic classes of materials, including topological materials, complex oxides, insulating antiferromagnets, and multiferroics, as well as implement control, e.g., controlling spin-driven and emergent phenomena with structured-light pulses. We will realize a time-resolved ARPES capability to directly measure electronic structure after excitation under highly non-equilibrium conditions, filling an NSRC void in understanding important van der Waal material architectures. Finally, we will drive AI and ML to a new level in materials science. We will pursue practical ML tools broadly applicable across Thrust materials efforts. To address the complexity of quantum mechanical simulations, we will advance ML to establish an advanced, predictive quantum-mechanical framework to simulate electronic dynamics, photonic properties, and spectroscopic signals in functional electronic, photonic, and quantum materials.

3.3 Soft, Biological, and Composite Nanomaterials Thrust

The Soft, Biological, and Composite Nanomaterials (SBCN) Thrust engages in fundamental nanoscience, studying the organizational principles of multi-scale assembly and applying them for the design and development of bioinspired, soft, and hybrid nanocomposites. The thrust leverages experimental, computational, and advanced characterization expertise to address key questions in nanoscience, with the goal of generating functionally integrated systems that are broadly applicable to national research priorities. The organizational principles needed to achieve successful and integrated nanoscale-inspired systems require a deep understanding of structure and the coordinated interactions of components across multiple length scales and dimensions. SBCN addresses this challenge by focusing on four key research directions; i) computational materials science, ii) synthesis and fabrication of building blocks, iii) directed assembly and advanced manufacturing, and iv) soft materials characterization. The scientific goals of the thrust are accomplished through a robust internal science program coupled to collaborative interactions with a diverse community of CINT users.

Toward the Future

SBCN supports national research priorities by integrating control of molecular and nanoscale interactions across multiple length scales and dimensions of a diverse range of materials. Our efforts directly support the national research priorities of Clean Energy, Pandemic Preparedness, and Advanced Manufacturing; we also contribute significantly to AI/ML and Quantum Materials, and these remain critical scientific pillars of our broader research goals. We offer distinctive user-accessible capabilities to support these efforts.

In direct response to national research priorities and in support of our wider CINT user community, SBCN's future research efforts will prioritize the integration of molecular and nanoscale building blocks into advanced functional materials. Informed by theory and simulation and propelled by AI/ML, we will leverage our recent strategic investments to develop novel, precisely controlled synthetic procedures to form a diverse range of soft, bio-inspired, and composite nanomaterial building blocks. We will also develop next-generation optical and electron microscopy techniques specifically designed to image soft materials as close to their native state as possible, without perturbing the system. In doing so, SBCN will continue to achieve new fundamental understanding of structure-function-property relationships of integrated materials systems across multiple length scales.

3.4 In-Situ Characterization and Nanomechanics Thrust

The In-situ Characterization and NanoMechanics (ICNM) Thrust works to accelerate the discovery of novel materials by identifying the mechanisms that drive nanomaterials evolution and degradation in characterization settings with real-world-relevant conditions (such as temperature, mechanical loading, irradiation, plasma flux, surface corrosion/chemical reactions, and external electrical/magnetic field). Our goal is to develop and implement cutting-edge experimental tools, modeling methods, and specialized ML algorithms to quantitatively measure, deeply comprehend, and accelerate new understanding of the continuum-of-states exhibited by real-world materials across scales in complex environments.

At ICNM, our research is driven by the three critical materials science questions: *How can we employ ML, high-throughput testing, and in-situ characterization to guide the rapid discovery of novel manufacturing processes? How can we employ far-from-equilibrium processes to control and evolve nano-scale defects in materials? How can we elicit unusual/exceptional material properties by structuring materials at the nanoscale?* By providing multifaceted resources and diverse expertise to our user community, ICNM has cultivated an ecosystem committed to delivering innovative discovery science and research capabilities.

Towards the Future

To facilitate the seamless integration of process-structure-property relationships, we have revamped our strategic research directions for the next five years to align with the evolution in our capabilities and needs of our user base. First, we will develop ML techniques for guided structural fabrication. We will deploy a library of specialized, physics-informed ML algorithms for the analysis, and characterization of complex physico-chemical processes and dynamics at the nanoscale and for the discovery and optimization of deposition and synthesis protocols and materials.

We will create controlled environments in key characterization tools, including transmission electron microscopy, scanning electron microscopy, Raman spectroscopy, and ion beam accelerators. We will sustain our distinctive edge in the field of nanomechanics by enabling high-throughput investigation of diverse material mechanical deformation mechanisms under extreme environments.

3.5 Artificial Intelligence and Machine Learning in Nanoscience Cross-Cut

Recent advances in computing hardware and algorithm development, along with an exponential acceleration in the quantity of scientific data being collected, have triggered the proliferation of ML throughout all fields of science. In the rush to utilize these new tools, there is still much to learn regarding how to apply these methods in a way that advances our fundamental understanding of the physical world, and in our specific case the understanding of nanoscale and quantum phenomena. The most compelling applications of ML will be toward incredibly difficult problems and where the outcomes are not known *a priori*, such as materials with strong correlations or subjected to extreme environments, autonomous optimization of synthetic routes for new materials discovery, and intelligent/autonomous data collection. The largest impacts will be from data analysis that is not tenable by human processing, either because of the needed response time or the enormous quantity of data.

CINT has several well-developed efforts utilizing AI/ML and has partnered with collaborators at academic institutions who are recognized leaders in this area. CINT is also taking advantage of enduring relationships with Sandia’s academic alliance partners as a source for students, postdocs, and collaborators with expertise in AI/ML. These partnerships allow us to leverage existing external capabilities and expertise to address novel nanoscale challenges. Our current ML expertise and capabilities include automated qubit optimization, prediction of new synthesis routes (physical vapor deposition) for novel metastable nanostructured alloys, virtual microscopy, and acceleration of quantum simulations.

Toward the future

As the application of ML toward nanoscience is evolving at an amazing pace, so will our strategy. CINT will naturally focus our ML efforts in areas where we are unique and leading the community. (i) *ML for quantum information science.* CINT will continue supporting and advancing the configuration of large number of quantum-dot-based qubits for quantum computing device design, which is intractable for a human controller. The efforts including providing software tools for perception, control, and intelligent agents, and experimental capabilities and test devices. (ii) *ML for synthesis of nanomaterials.* CINT will develop ML systems for controlling paramagnetic and magnetic nanoparticle reaction platforms. These systems will learn from a wide range of real time diagnostic data and inputs and generate optimal control parameters to achieve the desired synthesis. The machine-driven routes will also be applied to the synthesis of quantum heterostructures and novel nanostructured alloys for resilience against combined extreme environments. (iii) *ML for materials at extreme*. CINT will develop a virtual operando microscopy capability for understanding of degradation mechanism of materials in extremes. Through integration of atomic simulated and spectroscopy measured data, the developed ML will enable fingerprinting complex mechanisms, optimizing functionalities of nanostructured materials, and classification of defect structures. The same co-design approach will be used for designing emergent functionality of quantum materials with strong correlations, which are theoretically hard to simulate and subjected to limited data from advanced experimental measurements.

4 ABOUT CINT

Through a combination of research expertise, specialized capabilities, and essential foundational techniques, CINT enables our users to perform multidisciplinary research that would otherwise not be possible. Therefore, to address the research challenges of the future, CINT is continuously improving its current capabilities, exploring concepts that can lead to new experimental, theoretical and computational methods, and selectively disinvesting in capabilities that are no longer state-of-the-art or required by our current and potential user base (Figure 4.1).

In this section, we identify a selection of leveraged CINT capabilities that are important in addressing future integration challenges and that contribute to the integration research conducted (CINT strategic objective 2).

In addition to the leveraged capabilities highlighted here, CINT has many more that form the foundation for the majority of nanoscience research. The complete list can be viewed on our website.[2] As specified in CINT strategic objectives 2 and 3 CINT must continue to innovate this infrastructure to have unique and baseline instruments that all researchers need to properly measure and control the relevant conditions in their experiments.

By virtue of having two DOE host laboratories, CINT is uniquely able to leverage a wide range of expertise plus substantial prior investment in research infrastructure. We list examples of these synergistic capabilities below.

Figure 4.1 Addressing integration through collaborative capabilities and expertise in fabrication, synthesis, characterization, and theory.

4.1 Leveraging capabilities

Laboratory for Ultrafast Materials and Optical Science (LUMOS)

The LUMOS facility[3] is equipped with ultrafast laser systems covering a broad spectral range that spans the far-infrared to the soft X-ray portion of the electromagnetic spectrum. These systems enable a multitude of ultrafast spectroscopic and imaging experiments, including optical-pump THz-probe spectroscopy, high harmonic generation/extreme ultraviolet spectroscopies, and scanning probe imaging and spectroscopies. These capabilities enable us to understand and control the interaction of photons with the electronic, spin, and structural properties of materials on an ultrafast time scale for scientific and national security missions.

Electron Microscopy Laboratory (EML)

The EML[4] is a state-of-the-art electron microscopy user facility which houses 7 major instruments. Microscopes include an aberration-corrected FEI Titan 80-300 Super Twin monochromated and image aberration-corrected scanning transmission electron microscope (STEM) capable of four-dimensional (4D)-STEM and spectroscopy, two ThermoFisher Apreo scanning electron microscopes (SEMs) with transmission Kikuchi diffraction (TKD) and electron

[2] https://cint.lanl.gov/
[3] https://cint.lanl.gov/facilities/LUMOS/Capabilities.php
[4] https://organizations.lanl.gov/eml

backscattering diffraction (EBSD) capabilities, an FEI Helios 600 SEM with focused ion beam (FIB), and a ThermoFisher Helios G4 Xe plasma FIB for nano-manufacturing and TEM foil preparation. A host of heating, cooling, and biasing holders and a workstation capable of analyzing 4D-STEM and EBSD data sets are available for use on CINT user projects. In late 2024, a major host-lab capability investment will be completed and a new ThermoFisher Scientific Spectra Ultra STEM will be available to CINT users featuring sub-Å STEM imaging and spectroscopy, rapid high-tension switching, an Ultra-X X-ray energy dispersive spectroscopy (XEDS) Spectrometer, a Gatan Continuum K3 system, and an electron microscope pixel array detector (EMPAD) high dynamic range detector.

Ion Beam Materials Laboratory (IBML)

The core of the IBML[5] consists of a 3 MV NEC tandem accelerator, a 200 kV Varian ion implanter, and a 200 kV Danfysik ion implanter totaling 9 end stations. The tandem and Varian have a joint target chamber for performing dual-beam ion implantation/irradiation experiments, which allows the simulation of neutron damage effects in reactors by concurrently performing self-ion irradiation (neutron displacement damage) and helium implantation effects (neutron induced nuclear reactions). The research capabilities include routine ion beam analysis techniques such as Rutherford backscattering spectrometry (RBS), nuclear reaction analysis (NRA), elastic recoil detection (ERD), particle-induced alpha- or gamma-ray emissions (PIXE or PIGE), and ion channeling, etc.; ion-enhanced synthesis and modification of materials through ion implantation; and ion irradiation damage effects in materials, including complex oxide ceramics, metals, semiconductors, and polymers. The coupled positron annihilation spectroscopy (PAS) to Tandem capability allows in-situ characterization of defect dynamics during ion irradiation. The coupled plasma to Tandem capability enables in-situ measurement of dynamic erosion rate of fusion plasma facing materials with ion beam analysis techniques or studying effects of irradiation induced defects on deuterium retention rate in plasma-facing materials. Ultra-low energy ions are able to chemically dope 2D materials.

Ion Beam Laboratory (IBL)

The IBL[6] has a broad range of particle accelerators supporting fundamental and applied research. Compared to the broad beam capabilities at the IBML at the CINT-Gateway, the IBL at the CINT-Core provides users with focused ion beams, the beam spot size ranges from 10’s nanometers to 10’s micrometers, for targeted exposure of materials. The facility consists of four main accelerators that can produce ions from hydrogen to gold over a range of energies from electron volt (eV) to ~100 megaelectron volt (MeV) on target. The IBL has over 22 specialized end-stations enabling a wide range of experimental capabilities including focused ion implantation, in-situ electrical and optical testing, elevated and low temperature irradiations, in-situ SEM and TEM, and nanoimplantation.

Microsystems Engineering and Science Applications Complex (MESA)

SNL has a significant role in advancing the state-of-the-art in microsystems research and development, and in introducing microsystems into the nuclear stockpile. Microsystems incorporate radiation-hardened microelectronics as well as other advanced components such as

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[5] https://www.lanl.gov/science-innovation/science-facilities/ion-beam-materials-lab/index.php

[6] https://www.sandia.gov/m/research/facilities/technology_deployment_centers/ion_beam_lab

micromachines, optoelectronics, and photonic systems. The MESA Complex[7] (Figure 4.2) is designed to integrate the numerous scientific disciplines necessary to produce functional, robust, integrated microsystems and represents the center of Sandia's investment in microsystems research, development, and prototyping activities. This suite of facilities encompasses approximately 400,000 square feet and includes cleanroom facilities, laboratories and offices. CINT currently leverages this NNSA resource by partnering with MESA staff in the design, development, and production of sophisticated CINT Discovery Platforms. We are planning to further leverage MESA by brining selected compound semiconductor synthesis capabilities into the CINT user program.

Figure 4.2 MESA Complex.

LANL National High Magnetic Field Laboratory – Pulsed Field Facility (NHMFL–PFF)

The NHMFL-PFF[8] is an NSF-funded user facility that provides access to some of the highest magnetic fields available for research. The NHMFL–PFF utilizes LANL and DOE assets to enable world-record pulsed magnetic fields up to 100 Tesla. To make the most of these magnets, the NHMFL-PFF provides users with both robust scientific instrumentation engineered to operate in the transient pulsed magnet field environments and the support of scientists who are active researchers with expertise in high magnetic field-drive science. A suite of 6 classes of pulsed magnets provide fields that range from 60–100 Tesla, with varying rise times from 1.8 to 32 ms and pulse durations from 60 ms to 3 s. A variety of sample cells and instrument configurations including high pressure and optically coupled experiments are available.

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[7] https://www.sandia.gov/mesa/

[8] https://nationalmaglab.org/user-facilities/pulsed-field

5 OPERATIONAL EXCELLENCE

The CINT management team is committed to operational excellence and draws on best-practice insights from both of the host labs. Prioritizing efficiency in business operations is one of the ways we can facilitate productivity for our user community. We will continue to explore new ways to position CINT as a user facility that meets the evolving scientific and operational demands of the nanoscience community.

The CINT user program is designed to provide the international scientific community access to the world-class capabilities and scientific expertise available at the CINT Core and Gateway facilities. Access is typically requested through a biannual, peer-reviewed proposal process. Approved user projects are valid for 18 months, during which time users can access the facilities as needed. In addition, Rapid Access proposals can be submitted in the periods between the biannual calls. This provides a mechanism for a prospective user to have limited access to CINT capabilities in advance of the next call for user proposals for projects that are time-critical, small in scope, and high-impact. We regularly assess the effectiveness of our user program to ensure the proposal process is streamlined.

CINT will implement lessons learned during the COVID-19 pandemic with respect to remote access to our facilities. Remote access is an opportunity to increase productivity and turnaround for high impact experiments, improve diversity and lower the environmental impact of travel. Many capabilities including characterization, some instrumented fabrication and synthesis, and practically all theory, modeling, and simulation could be accessed remotely with appropriate investment. In addition, the US government expects improved accessibility for publicly funded data that supports peer-reviewed publications. CINT will invest in the staff and infrastructure to enable increased remote access and data archiving/availability.

In support of the digital age, we have completely revised and updated our website and are also preparing a series of updates to the NSRC Portal[9], a community website featuring a capabilities database and science highlights from the NSRCs. The Portal is a valuable outreach tool for the NSRCs as it enables users to explore capabilities and expertise across all of the centers. We envision the next-generation NSRC Portal to not only feature this comprehensive search function, but also be a hub for user interactions across the centers.

Working with our sister NSRCs, we are committed to implementing a complex-wide proposal process that facilitates access to multiple Centers with a single proposal. We will work to coordinate both user research and Center capability development in support of a cooperative NSRC program that can perform unmatched high impact science across multiple Centers.

Safety is an integral part of CINT's operation. By utilizing continuous feedback through our Integrated Safety Management approach, we are constantly evaluating and improving our Environment, Safety and Health (ES&H) operations as well as the training and qualifications of our staff and users. The ES&H professionals from the Core and Gateway facilities have both performed site visits to familiarize themselves with the different host labs' approaches and have

[9] https://nsrcportal.sandia.gov/

shared experiences on how to improve and unify our procedures. We aim to create a safety culture where staff and users feel empowered to be advocates for a safe and secure workplace.

We have the opportunity to lead the complex in improving cross-laboratory processes, in particular with our activity in creating a safety-training program that is acknowledged at both LANL and SNL. Through CINT's ES&H team, LANL and SNL have jointly standardized the NANO101 and RAD210 trainings. Each lab has also created granting mechanisms to recognize and document these equivalencies. Our ES&H professionals continue to work with the host laboratories to approve reciprocity for additional required trainings that are required for our users accessing both sites.

6 ENGAGING THE SCIENTIFIC COMMUNITY

CINT's adaptive outreach strategy and comprehensive communications plan remain vital to attracting, engaging, and maintaining our diverse, global scientific community and to promoting public awareness of CINT's capabilities and the capabilities made available by the broader NSRC Program.

CINT Outreach Strategy

The most effective component of CINT's outreach strategy is our own scientists and staff, who have been and remain CINT's best advocates. Between 2019 and 2024, CINT scientists shared their research and expertise and invaluable knowledge of CINT and the NSRC program at over 600 events including major scientific conferences, invited talks, CINT User Meetings, and other outreach events, including facilities tours, workshops, and summer student programs.

As we look to the future and consider how best to reach an increasingly diverse user base, we have prioritized two complementary and overlapping outreach efforts: participation in all-NSRC outreach endeavors and targeting smaller conferences with higher UMR attendance.

All-NSRC Outreach: We will continue to enhance our collaborative outreach with the other NSRC facilities. Collaborative all-NSRC outreach has, so far, shown the greatest return on our investment in reaching broad audiences of prospective users (national laboratory scientists, academics, industry partners, students of all ages, and the public in general). To extend this reach, CINT will develop a brief slide deck summarizing all five NSRCs capabilities and key contacts that can be included by CINT staff and users at invited talks and events. Ideally, this deck will become a standard part of presentations at conferences and university outreach events. CINT outreach staff will contribute to the design and implementation of a contemporary NSRC portal, which will be more intuitive for new users and include a comprehensive searchable capability database. The design and functionality of this new portal will also serve as the template for an Ideum NSRC traveling exhibit that will accompany outreach staff to conference booths. Starting in 2024, CINT will also contribute to new all-NSRC marketing collateral (e.g. brochures, fact sheets, banners), plan for future joint NSRC User Meetings, and staff a joint NSRC User Facility Row at future Fall Materials Research Society Conferences.

Diversity Outreach: CINT staff will continue working with the other NSRCs to seek out smaller, more targeted conferences that will allow us to reach greater numbers of prospective URM users with expertise in chemistry, physics, engineering, and biology. At CINT, we are dedicated to increasing awareness of and accessibility to CINT within MSI and HBCU institutions and CINT staff and management look forward to making concerted efforts to reach out to PBI, NASNTI, and ANNH universities. CINT will also utilize Host-Laboratory DEI programs and other resources available to them.

To promote inclusive and equitable research for users and staff, CINT will continue improving its diversity outreach with increased social media posts, specifically on pages dedicated to under-served minorities (NSBP, National Society of Black Engineers (NSBE-UCF), National Organization for the Professional Advancement of Black Chemists and Chemical Engineers, Women Chemists of Color, New Mexico Network for Women in Science and Engineering, Society of Hispanic Engineering and Science Students). We will also explore increasing accessibility by working with host Laboratories to connect MSI researchers to additional funding for travel costs, which can be a contributing factor in a researcher's decision to not submit a proposal. Finally, we also hope to increase outreach to scientists-to-be through the Bradbury

Science Museum Discovery Trailers program, whose mission is to bring together scientists and young learners with interactive STEM experiences designed to inspire curiosity and confidence while modeling potential career paths for young New Mexicans.

The CINT Communications Plan has two primary components:
Communications/Marketing Schedule Matrix: To increase awareness of CINT events, research, achievements, and opportunities, the schedule matrix coordinates CINT's communications activities, allowing us to strategically promote CINT and user research and accomplishments through multiple communications channels, including the CINT website (new in 2022); CINT, LANL, Sandia, and NSRC/Host Lab social media accounts; media releases distributed in collaboration with DOE, LANL, and Sandia communications staff; CINT event postings on both the LANL and Sandia external calendars; and CINT event postings with external organizations, including the Society for Science at User Research Facilities.

7 SUMMARY AND IMPLEMENTATION

CINT2029 presents a vision for new technology development that would be enabled by integrating nanostructured materials to exploit their size-dependent properties or emergent collective properties. Realization of this opportunity requires a sustained effort by researchers to tackle more complex nanosystems; however, the optimal methods to do so may not necessarily exist today or may not be available to researchers with extraordinary ideas and insights.

CINT's differentiating focus on nanomaterials integration and established operation as a DOE Office of Science user facility with a vibrant, growing user community, position us to be a leader at this new frontier in nanoscience. Our focus on six national research priorities drive us towards the goal of being the national resource for research expertise and unique capabilities to synthesize, fabricate, characterize, and understand nanostructured materials in increasingly complex integrated environments.

This strategy involves harnessing the intellectual leadership and scientific expertise of our staff and users by adding CINT scientists and attracting international experts as CINT users. A second strategy complements the people in our community with the capabilities that we invent or optimize for integration research, thereby ensuring that CINT is unsurpassed as an institution for our chosen areas of nanoscience. In an increasingly competitive world, CINT must also continuously focus its efforts and resources on the potentially most impactful research opportunities. This will be done through organized CINT workshops, the CINT Annual Meeting, joint-NSRC workshops, focused symposia at major national scientific conferences, and consultation with the CINT Scientific Advisory Committee and the CINT Users Executive Committee.

When the National Nanotechnology Initiative was launched over 20 years ago, the nation was at the dawn of the next technological revolution. Just as integration transformed the transistor into the integrated circuit, now the scientific community is poised to reveal even greater functionality by learning how to build a world of multifunctional materials and systems that can begin to rival the exquisite examples we see every day in nature. Our vision for CINT in the year 2029 ensures that we will be leaders in transforming our understanding of nature and strengthening the connection between advances in fundamental science and technology innovation.