Laboratory for Nuclear Science

The Laboratory for Nuclear Science (LNS) provides support for research by faculty and research staff members in the fields of particle, nuclear, and theoretical plasma physics, as well as quantum information theory. This includes activities at the MIT-Bates Linear Accelerator Center and the Center for Theoretical Physics (CTP). Almost half of the Department of Physics faculty conduct research through LNS. During fiscal year 2019, total research volume using funding provided by the US Department of Energy (DOE), the National Science Foundation (NSF), and other sources was $21.4 million, an increase of about $0.3 million from the previous year. LNS researchers are successfully pursuing multiple funding opportunities that should maintain—or even increase—research volume in the future. Some LNS faculty have successfully pursued foundation funding to compensate for reductions in the availability of federal funds. Foundation funding typically runs through the Department of Physics and therefore does not appear as LNS research volume. Five LNS junior faculty currently hold prestigious Early Career/CAREER Awards from the DOE and NSF. Two of them, Professor Tracy Slatyer and Professor Yen-Jie Lee, have been designated as recipients of the Presidential Early Career Awards for Scientists and Engineers. Four LNS faculty received tenure in the past year: Professors Aram Harrow, William Detmold, Tracy Slatyer, and Michael Williams.

Experimental Particle Physics

LNS researchers in experimental, high-energy particle physics are active at the European Council for Nuclear Research (CERN) in Geneva, Switzerland; at the Fermi National Accelerator Laboratory in Illinois (Fermilab); and at a number of other locations around the globe—as well as in space. The overall objective of current research in high-energy particle physics is to seek evidence for physics beyond the Standard Model. This is accomplished by either searching directly for new phenomena or by measuring predicted quantities as precisely as possible and thus testing the Standard Model, which has been very successful in describing a wide variety of phenomena. LNS researchers are playing principal roles in much of this research.

LNS researchers are playing a major role in the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) at CERN in the areas of data acquisition, the massive computing system, detector upgrades, and data analysis. LNS scientists also are leading the program to study high-energy, heavy-ion collisions with the CMS, as discussed below. The LHC has accumulated a significant data sample at the present energy frontier (13 TeV center-of-mass energy) and have collected, by the end of the second run (2015–2018), a sample of over 120 fb^{-1}, a factor of about five times more data, at an energy almost twice as high as that in the first run (2010–2012). While the LHC is now in a long shutdown for repairs and upgrades to the accelerator and detectors, physicists are analyzing this wealth of data. Operations are expected to resume in 2021.

With the discovery of the Higgs boson accomplished in the first run, LNS researchers are using CMS to search for dark matter using the signature of missing energy in the detectors, and to measure detailed properties of the Higgs boson. The CMS dark matter searches have so far found no sign of dark matter in the channels examined. Other LNS researchers are working on the General Antiparticle Spectrometer (GAPS), an astroparticle experiment that will fly on a long-duration Antarctic balloon flight in 2020 to search for antideuterons in low-energy cosmic rays. MIT is responsible for construction of the semiconducting silicon detectors. If cosmic antideuterons are detected, this would be a signal of new physics, and would probe a variety of dark matter models.

The Alpha Magnetic Spectrometer experiment (AMS-02), led by the Electromagnetic Interactions (EMI) group in LNS, is designed to look for cosmic antimatter and evidence for dark matter by operating a large, 6,717-kg magnetic spectrometer above Earth's atmosphere on the International Space Station (ISS). AMS has been collecting data since 2011, and now has collected over 135 billion cosmic ray events, far more than what has been collected in the entire history of cosmic ray physics. The EMI group leads the data analysis effort, and is also responsible for proper operation of the spectrometer, a critical and difficult effort given the hostile thermal environment of the ISS. A major focus of the group for the past several years has been design, construction, and testing of a replacement thermal cooling system for the silicon tracker detector. Astronauts are expected to install the replacement system in the coming year. Results have been published this year on the origins of cosmic positrons and electrons; fine time structures in the cosmic proton; helium, electron, and positron fluxes; and precision measurements of cosmic-ray nitrogen. Data will continue to be collected on electrons, positrons, protons, antiprotons, helium, and other nuclei and anti-nuclei until the end of ISS operations, presently scheduled for 2024.

LNS researchers are studying the fundamental properties of neutrinos using the Booster Neutrino Experiment (MicroBooNE) and related experiments at Fermilab. The group also continues to pursue staged development of a high-powered synchrotron to produce large quantities of neutrinos, and is finalizing construction of a high-intensity ion source to feed the future synchrotron. The group participates in the IceCube collaboration to search for sterile neutrinos in an experiment at the South Pole. In the past year, IceCube reported detection of a high-energy neutrino from a direction consistent with a gamma-ray blazar. Observations of the blazar with telescopes showed it was in a flaring state at the time. This is the first multi-messenger observation involving neutrinos.

Experimental Nuclear Physics

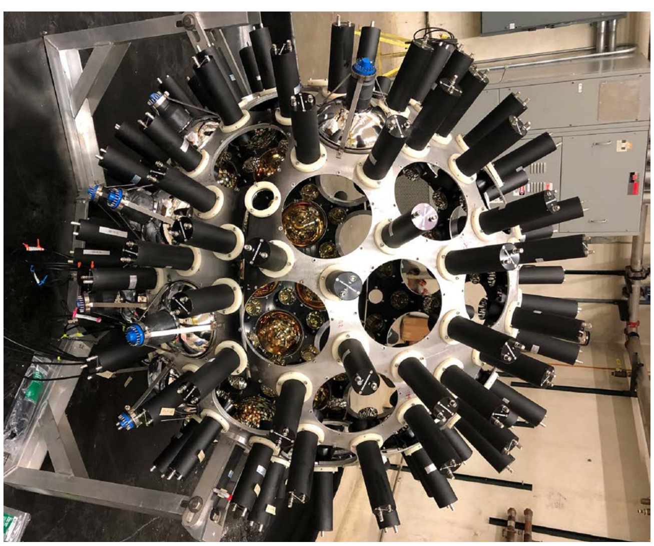
At present, experimental nuclear physics has three main thrusts: heavy-ion physics, hadronic physics, and nuclear structure/fundamental properties. LNS has active groups in all of these subfields.

LNS researchers are prominent in relativistic heavy-ion physics. The Heavy Ion Group (HIG) plays leading roles in the CMS experiment heavy-ion program at CERN and the sPHENIX collaboration at Brookhaven National Laboratory (BNL) in New York. Physics results in FY2019 included the first measurements of photon-tagged jet substructures—allowing direct comparisons to jet quenching models predicting the magnitude of parton energy loss, modifications of the angular and momentum structure of the parton shower, and the medium response to the energy deposited by the propagating parton. It is important to include the medium response in order to describe the observed strong low-momentum and large-angle modifications. At BNL, sPHENIX will be used to study jet quenching in heavy-ion collisions, in a complementary fashion to CMS. A review of the project at BNL in spring 2019 was positive, with permission given to proceed to equipment construction. MIT physicist contributions are in the areas of collaboration leadership and in the design, implementation, and optimization of particle tracking software.

LNS medium-energy nuclear physics researchers are leading several important efforts at accelerator facilities in the US and Europe. These facilities include the Relativistic Heavy Ion Collider (RHIC) at BNL, Jefferson Lab (JLab), the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory in Tennessee, the Mainz Laboratory in Germany, and the Large Hadron Collider beauty (LHCb) experiment at CERN. The main thrust of these experiments is a detailed understanding of the properties of the proton, the neutron, and the light nuclei.

The study of short-range correlations (SRC) and the European Muon Collaboration (EMC) effect continues to shed new light on the role of quark-gluon degrees of freedom in atomic nuclei. In 1983, the EMC found the distributions of quarks in nucleons bound in nuclei differ from the distributions in free nucleons. Using JLab data, MIT members of the JLab data-mining collaboration performed the first simultaneous measurement of the EMC effect and SRC abundances in a selection of medium and heavy nuclei. For the first time, beyond being the most precise measurements of these effects to date, the new analysis bolstered the EMC-SRC relation by extracting a universal modification function for the quark-gluon structure of nucleons in SRC pairs. These predictions are now being tested experimentally via tagged-deep inelastic scattering measurements off deuterium using the CLAS12 spectrometer and the Backward Angel Neutron Detector (BAND) recently built by MIT and collaborators, and commissioned in Hall B of Jefferson Lab.

In fundamental properties, LNS nuclear physicists work in the area of neutrino studies, seeking to measure the neutrino mass and to understand whether the neutrino is its own antiparticle (i.e., a Majorana particle). MIT physicists are part of the Cryogenic Underground Observatory for Rare Events (CUORE) collaboration at Gran Sasso, Italy, and the KAMLAND-Zen collaboration at the Kamioka Observatory, Japan, searching for neutrinoless double beta decay (NDBD). If observed, this would imply the neutrino is its own antiparticle. One step on the path to measure NDBD is to measure 2-neutrino double beta decay, which, while a rare process, is not as rare as NDBD. To make this measurement, MIT physicists are developing NuDot, a liquid scintillator detector with direction reconstruction.



The NuDot detector consists of 140 2-inch photo-multiplier tubes (PMTs) and 72 8-inch PMTs mounted on an aluminum sphere, viewing the inside of the sphere. The 8-inch PMTs in the upper half and along the equator are yet to be mounted in this photo.

Credit: Christopher Vidal.

MIT physicists are also playing a leadership role in the Karlsruhe Tritium Neutrino (KATRIN) experiment at Karlsruhe, Germany, and in the Project 8 experiment, both of which intend to make a new precise measurement of the mass of the electron neutrino using the endpoint of the electron energy spectrum from tritium beta decay. KATRIN and Project 8 are both now running using molecular tritium.

Theoretical Particle and Nuclear Physics

Research at the Center for Theoretical Physics (CTP) seeks to extend and unify our understanding of fundamental physics. Just over one year ago, the CTP celebrated its 50th anniversary. Since then, it has continued its broad goal of providing a unified center for studying theoretical physics spanning a significant number of active research areas. This past year, three junior faculty in the CTP were promoted to tenure in the physics department, including: Aram Harrow, who works on quantum information, quantum algorithms, and complexity theory; Tracy Slatyer, who is an astroparticle physicist specializing in the study of signals and models for dark matter; and William Detmold, who works on calculations for systems governed by the strong force, using sophisticated numerical methods in the field of lattice quantum chromodynamics (QCD). The CTP also recently hired two outstanding young faculty members. Phiala Shanahan started as an assistant professor at the CTP in July 2018. She uses lattice QCD and other approaches to study strongly interacting quantum systems. Netta Engelhardt, a general relativist, has developed a new framework for understanding black hole horizons and related puzzles. She joined CTP as an assistant professor in July 2019. These two hires have increased the number of women faculty in the CTP significantly.

The Standard Model (SM) of particle physics provides a powerful theoretical framework for describing most aspects of fundamental physics that can easily be accessed with existing experiments. This model was completed with the discovery of the Higgs boson, which opened up a new era of questions associated with its nature and the study of its interactions with other matter. However, the SM only describes 5% of the mass-energy in the observed universe, does not explain how gravity fits into the framework of quantum physics that underlies the SM, does not explain cosmology or the very early universe, and contains roughly 19 independent numerical parameters and a set of forces and particles that as yet cannot be explained by any more fundamental theory. Within the SM there are also major practical and conceptual challenges in calculating even some simple quantitative features such as the mass of the proton, which is a bound state of quarks, due to the strong coupling of the strong nuclear force. And there are many puzzles related to quantum physics, black holes, and other accepted features of the SM and Einstein's theory of general relativity that remain to be addressed. Faculty in the CTP are working at the forefront of research on all these questions and others, including related problems that connect to mathematics, condensed matter physics, astrophysics, and quantum information. The CTP is unusual among university groups in both its breadth and unity. A few examples of recent work are mentioned below.

Nuclear Theory Group

The nuclear theory group within the CTP focuses on understanding the strong force, described by QCD. QCD is one of the richest fundamental forces of nature, and the focus of the MIT group includes topics such as: understanding the structure and interactions of the proton and larger nuclei; using methods of effective field theory to understand the formation of jets of hadrons when strongly interacting particles are collided at high energies; and exploiting techniques for handling strongly interacting field theories to understand the strongly coupled quark-gluon plasma discovered in heavy-ion collisions.

Faculty members Detmold and Shanahan lead an effort on lattice QCD, developing theory and algorithms to carry out large-scale numerical simulations which focus on calculating key properties and interactions of nucleons and light nuclei. This past year, Shanahan and Detmold computed the pressure distribution and shear forces inside a proton, providing the first complete results for these fundamental nuclear properties, and providing an elegant picture for the confining nature of the strong interactions that binds together quarks and gluons in the proton. In other work, they demonstrated the importance of accounting for nuclear effects in the analysis of dark matter direct-detection experiments, which is now an important systematic uncertainty. Shanahan and Detmold have also been investigating new ways of performing lattice QCD calculations faster using machine learning and custom hardware.

Professor Krishna Rajagopal's research focuses on how quarks behave in extraordinary conditions such as in the hot quark soup that filled the microseconds-old universe. This past year he proposed a distinctive set of cumulant observables to enhance the prospects of discovering a critical point in the phase diagram of this liquid, providing an important diagnostic for measurements of heavy-ion collisions being carried out at RHIC.

Professor Iain Stewart's research involves developing new quantum field theory methods to study the behavior of strongly interacting particles in high energy collisions over a large range of dynamical scales. This past year he carried out a calculation of the transverse momentum distribution for Higgs bosons produced at the LHC, achieving the highest precision to date. He also proposed a method to compute an important anomalous dimension appearing in transverse momentum observables using lattice QCD, which has spurred new lattice calculations that have been recently initiated by the group led by Shanahan.

High-energy Theorists

CTP high-energy theorists are active in a wide range of areas that include quantum field theory, supersymmetry and supergravity, string theory, jet quenching, dark matter, dark energy, neutrino masses, and connections to condensed matter physics. Members of this group work in collaboration with experimentalists as well as colleagues in condensed matter theory and the Departments of Mathematics, and Electrical Engineering and Computer Science.

One focus area of theoretical research, particularly for faculty members Tracy Slatyer, Jesse Thaler, and Frank Wilczek, is that 80% of matter in the universe is gravitationally interacting "dark matter" that is not described by the SM. During the past year, Slatyer has continued her program of building a comprehensive set of tools for predicting the signatures of dark matter physics in the Milky Way and in the early history of our universe. This includes a new statistical analysis that sheds light on the difficulties of distinguishing dark matter and pulsar sources for annihilation signals from the galactic center. Slatyer and Stewart have made precision calculations to predict signals of heavy dark matter annihilating to gamma-rays, accounting for effects associated with the energy resolution of the gamma-ray telescopes that are searching for these signals.

Another active area of research of the MIT group, and in particular of Jesse Thaler, is developing new techniques to maximize the ability of high-energy colliders to discover signals of new heavy particles or fundamental short-distance forces. Over the past year, he developed an approach to categorizing useful observables through the development of a metric space for collider events, and developed several new search techniques by exploiting the CMS Open Data set. Thaler also has proposed new strategies to hunt for dark matter, including the conceptual design for the MIT-led ABRACADABRA experiment, which has now published results from its first test run.

During this past year, Wilczek proposed a new strategy to search for axion dark matter using tunable cryogenic plasmas that develop resonance by matching the axion mass to a plasma frequency.

String and Quantum Gravity Group

The string and quantum gravity group in the CTP has made progress in several directions.

Assistant Professor Daniel Harlow wrote two important papers which use the anti-de Sitter/conformal field theory (AdS/CFT) correspondence to establish a set of old conjectures about symmetries in quantum gravity. This includes the hypothesis that no global symmetries are possible, that internal gauge symmetries must be compact, and that gauge symmetries occur with objects that transform in all irreducible representations. In part due to this work, Harlow was awarded the New Horizons prize in fundamental physics.

Professor Washington Taylor and his group have been working on a program of identifying fundamental constraints from string theory on how matter fields can be charged under gauge forces, and in particular finding ways in which string theory imposes constraints that are not apparent in quantum field theory. This past year he developed methods to classify "generic" and "exotic" matter representations in six-dimensional gauge theories, providing motivation for the nature of the standard model matter content. He also classified all six- and four-dimensional models derived via the F-theory construction of string theory which have the standard model gauge group.

Professor Barton Zwiebach continued to develop his new program of computing previously unknown minimal area metrics on certain surfaces that describe "Feynman diagrams" of string field theory. Zwiebach also provided a classification scheme for string inspired time-dependent backgrounds that are of interest for cosmological models.

Professor Netta Engelhardt will broaden and strengthen our effort in this area through her expertise in general relativity, gravitational thermodynamics, and quantum gravity.

Quantum Systems, Quantum Information, and Quantum Computing

Other work in the CTP focuses on quantum systems, quantum information, and quantum computing.

This year Professors Alan Guth and David Kaiser (joint CTP/Science Technology and Society) publish a paper on their "Cosmic Bell" experiment, which investigates the fundamental question of whether what Einstein referred to as the "spooky action at a distance" of quantum physics can be shown not to depend on hidden correlations, by studying the quantum behavior of pairs of photons from stars that lie in different directions in the sky. Their paper shows that such correlations cannot come from anywhere within a window extending over seven light-years away.

Professor Hong Liu recently developed a new research program on non-equilibrium effective quantum field theories, using path integral techniques to devise methods for carrying out novel fluctuation calculations. In the past year, he wrote a review of this field and also developed a method of connecting these non-equilibrium calculations to calculations in a gravitational system with a black hole geometry.

Professor Frank Wilczek carried out calculations to predict the effect of emergent photons on the threshold production in a Coulomb spin liquid, showing that they modify the production cross-section dramatically, in broad agreement with recent experimental results.

Quantum information and quantum computation is a growing effort in the CTP with connections to many other areas of the Department of Physics, as well as other departments at MIT. This research program is concerned not only with efficient ways to perform quantum computations (e.g., factoring integers), but also with applications such as quantum cryptography, and with basic theoretical questions about quantum information and quantum entanglement.

Professor Aram Harrow carries out forefront work in these areas. He has recently been investigating how a quantum computer can be useful for machine learning, even for data sets that are far too large to fit on the quantum computer. This is especially relevant as the first fairly small-scale quantum computers come online. In the past year, he has shown how quantum algorithms can improve machine learning techniques for problems where the space of features to be classified becomes large. He has also proven results on the limitations of using semidefinite programs for solving optimization problems in quantum information theory. Professor Harrow's work on quantum information connects with that of Professor Harlow—who earlier demonstrated that ideas associated with quantum error correction play a role in the holographic framework for quantum gravity—and with that of Professor Thaler, through the application of quantum technology to algorithmic problems in jet clustering.

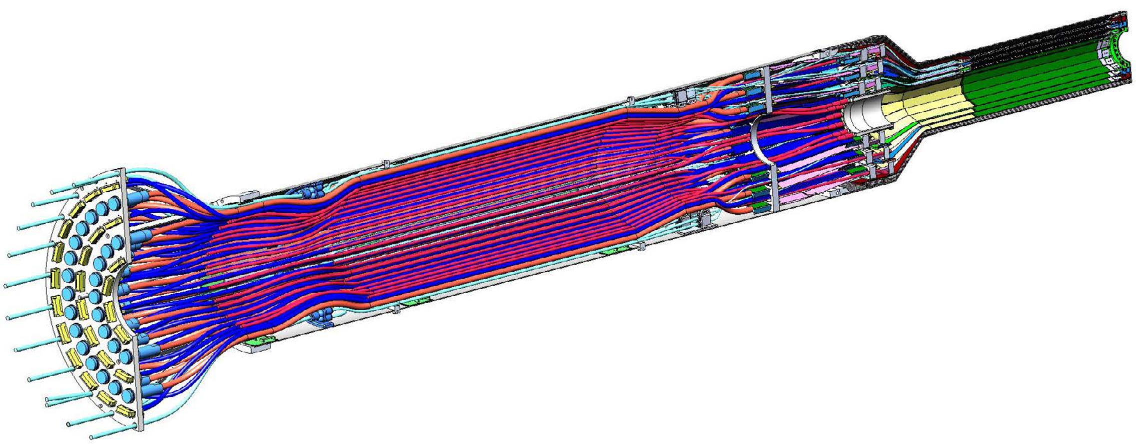
Physics of High-Energy Plasmas

This effort addresses a broad spectrum of subjects in areas that are relevant to fusion research, astrophysics, and space physics. Specifically, LNS researchers are involved in identifying the properties and dynamics of plasmas that are dominated by collective modes, emphasizing fusion-burning plasmas relevant to the upcoming generation of experiments, and high-energy astrophysical plasmas.

MIT-Bates Linear Accelerator Center

DOE provides base support for a research and engineering center where US nuclear physicists, including LNS faculty and their collaborators, develop new instrumentation for frontier research. Funding for specific projects also comes from the NSF, other universities and laboratories, and industry. For example, MIT-Bates engineers and technicians—working with members of the MIT Hadronic Physics Group, the GlueX collaboration, and JLab technical staff—have completed design and construction of two Focusing Boxes for the GlueX Detection of Internally Reflected Cherenkov light (DIRC) detectors. These boxes take the Cherenkov light from the quartz DIRC bars and—using high-quality, large, and optically flat mirrors—reflect it onto an array of multi-anode photomultiplier tubes (MaPMT) detectors for signal readout. Initial tests of the first DIRC with beam in Spring 2019 at JLab showed that the detector, including the Focusing Box, performed as expected.

MIT-Bates engineers are designing the support structure and services for the Monolithic Active Pixel Sensor (MAPS)-based Vertex Detector (MVTX) for the sPHENIX experiment at BNL. As mentioned above, sPHENIX is one of the experiments being pursued by the MIT HIG.



A cut-away view from the 3D model of the Monolithic Active Pixel Sensor (MAPS)-based Vertex Detector (MVTX) for the sPHENIX experiment. The model shows the detector staves (green), cabling (yellow, blue and lavender), cooling lines (red and light blue), and supports. The beam pipe, not shown, runs down the center of the cylindrical detector and support services pipe. Credit: Jason Bessuille and Joseph Dodge.

MIT-Bates physicists, engineers, and technicians have made contributions to many of the experiments discussed above.

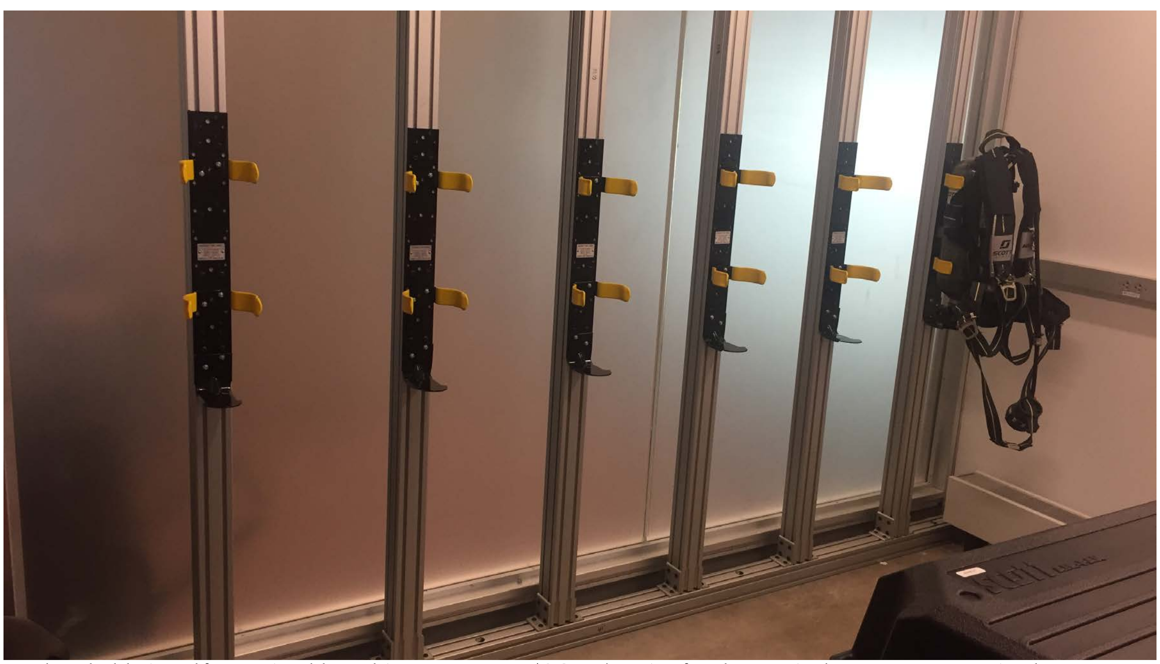
The high-performance research computing facility at Bates supports 70 water-cooled racks and one air-cooled rack, each with up to 12 kW of cooling power for: LHC data analysis; lattice QCD calculations; ocean and climate modeling by a group in the Department of Earth, Atmospheric and Planetary Sciences; computational fluid dynamics relative to ship hull design for the MIT Sea Grant program; the MIT Geospatial Data Center; and for other LNS research uses.

MIT Central Machine Shop

LNS operates the MIT Central Machine Shop as a service center. The shop is widely used across the Institute to build research-related equipment, as well as to perform work for the Department of Facilities and research facilities from off-campus sites. The work ranges from small to large jobs, and/or complex jobs that require precision machining—such as a double-pancake coil assembly for the SPARC project—to test the suitability of various materials for making superconducting magnet coils.

The two halves of a pancake coil fixture for testing new superconducting wire for the SPARC project at the Plasma Science and Fusion Center. Credit: Andrew Gallant.

Another project involved making a rack for self-contained breathing apparatus (SCBA) tanks for the Tactical Response Center in the new MIT.nano building. The rack holds six SCBA tanks, and makes it easy for a responder to walk up to the rack, slip on an SCBA, and get to the emergency.



Rack to hold six self-contained breathing apparatus (SCBA) units for the Tactical Response Team in the new MIT.nano building. One SCBA unit is mounted in the rack. Credit: Andrew Gallant.

Education

Since its founding, LNS has placed education at the forefront of its goals. In the past year, approximately 85 graduate students received their training through LNS research programs. A number of undergraduate students are also heavily involved in LNS research. LNS has educated a significant portion of the leaders of nuclear and particle physics in the US and abroad.

Boleslaw Wyslouch
Director
Professor of Physics